STUDIES OF COPPER HALIDE LASERS

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A Thesis Submitted for the Degree of PhD
at the
University of St Andrews

1992

Studies of Copper Halide Lasers

A thesis presented by

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to the

University of St. Andrews

in application for the degree of

Doctor of Philosophy

June 1991

Declaration.

I hereby certify that this thesis has been composed by me and is a record of work done by me and has not previously been presented for a higher degree.

This research was carried out in the Physical Sciences Laboratory of St. Salvator's College, in the University of St. Andrews under the supervision of Dr. A. Maitland

I was admitted to the Faculty of Science of the University of St. Andrews under Ordinance General No. 12 in October 1987 and as a candidate for the degree of Ph.D. in October 1988.

E. S. Livingstone

Certificate.

I certify that E.S. Livingstone has spent nine terms at research in the Physical Sciences Laboratory of St. Salvator's College, in the University of St. Andrews under my direction, that he has fulfilled the conditions of Ordinance No. 16 (St. Andrews) and that he is qualified to submit the thesis in application for the degree of Doctor of Philosophy.

A. Maitland

Research Supervisor

Acknowledgements.

I would like to thank Dr. Arthur Maitland for his valued guidance and encouragement throughout this work. I would also like to thank Cliff Weatherup and Graeme Clark, for many helpful discussions.

I am grateful to Frits Akerboom for his expertise in fabricating the discharge tubes used in this work. Thanks also go to the members of the mechanical and electronic workshops who contributed greatly to these studies.

I wish to thank my friends and colleagues who have made life enjoyable and given valuable help. In particular I would thank Andy Kidd, Low Kum-Sang, Colin Pirrie and Natalie Ridge.

I also thank EEV for their considerable interest and support, both financial and technical. In particular, I would like to thank Chris Neale for his help and patience.

Finally, I would like to thank my parents for their many years of help, support and encouragement.

Contents.

Abstract.

Copper Halide lasers are discussed and the results of experiments reported.

It is found that the presence of small quantities of an electron attaching gas (such as bromine) cause discharge instability. Specially designed electrodes which remove excess bromine cure this problem and yield a stable discharge.

A 4W copper bromide laser is operated, sealed-off, for 100 hours. This laser has an apertured discharge tube with side-arm reservoirs to control copper bromide vapour pressure, a feature essential to stable operation. The addition of small amounts of hydrogen changes the beam from an annular to a gaussian-like profile. The estimated lifetime of this laser tube is 1,000 hours.

Exploiting the theory of metallic walls for discharge confinement, it is found that metal segments shorter than about 1m can support a stable discharge at high pulse repetition rates (5 - 20kHz). On the basis of this, a novel copper halide laser containing cylindrical copper segments is demonstrated. Neon and halogen gases flow through the tube. The reaction between the halogen and the copper segment walls forms copper halide in-situ. Hydrogen bromide, bromine and chlorine have been used. Hydrogen bromide proves to be the most suitable. A one metre long laser tube of this design produces 40W.

Pulsed power supplies for metal vapour lasers are discussed. The conventional form of the capacitor-transfer circuit has the peaking capacitor value around one half of the storage capacitor value. It is found that equal capacitor values produce the best results for the gold vapour laser system we describe.

The reliability of a gold vapour laser is improved by replacing the hollow anode thyratron (which has a high latch rate) with a solid anode thyratron. The replacement thyratron, in combination with a saturating charging choke, significantly reduces the latch rate. The laser is used for studies of photodynamic therapy of cancer in a local hospital.

Chapter 1

The copper vapour laser.

1.1 Introduction.

The copper vapour laser is the best known member of the family of cyclic (pulsed) metal vapour lasers. It is noted for its ability to deliver high output powers on two lines in the visible spectrum (510.6, 578.2 nm), at efficiencies which no other visible laser can match. Conventional copper vapour lasers employ a low pressure, high repetition rate, pulsed gas discharge to melt and vapourize metallic copper. When the copper atoms forming the vapour are excited by electron collisons in the discharge into the upper laser levels of the neutral atom, spontaneous or stimulated emission takes place as the atom de-excites into the lower laser levels which are metastable. Because the lower levels are metastable, the population inversion is self terminating and lasts for a few tens of nanoseconds. The discharge must then be removed to allow de-excitation of the metastable levels between pulses.

The high operating temperatures of conventional copper vapour lasers (about 1550°C) bring many problems to laser design and operating conditions. The main problems arising are materials failure in the laser head and contamination of the buffer gas carrying the discharge current. A flow of buffer gas must therefore be arranged to sweep out the contaminants and regular maintenance of the laser head must be observed to reload with copper or to repair any damage that may arise

Alternative methods of achieving high (0.5 Torr) copper vapour pressures (fig 1.1) at lower temperatures have been sought. The most promising devices to have emerged are those based on the halides of copper, particularly copper bromide (fig. 1.2). The low melting point of copper bromide (492°C) and its high vapour pressure, enables the required vapour pressure of copper to be achieved at about 500°C. The high repetition rate, pulsed discharge dissociates the copper bromide and pumps the copper. Efficiencies have been reported for copper bromide lasers which exceed those achieved in elemental copper lasers by 60%. The low temperatures required by copper halide lasers mean that fused silica tubes may be used in construction. There is no requirement for much of the thermal insulation used in high temperature devices and which is a major cause of contamination.

1.2 Development of copper vapour lasers.

In 1965, laser action was reported on self-terminating transitions in lead (ref 1), manganese (ref 2) and copper (ref 3). The study of cyclic metal vapour lasers began at this time and in the intervening years, many more metals have been shown to produce laser light under similar conditions (fig 1.3). Copper lasers remain the most powerful of all visible lasers with commercial devices capable of emitting over 100 W from a single laser tube (ref 4).

Initial development of copper vapour lasers was spurred by the main application considered for these devices. The high power and high efficiency of copper lasers made them very attractive as an alternative to argon ion lasers as pump sources for dye lasers involved in the photo-ionization and separation of U_{235} from other uranium isotopes. The uranium isotope separation projects in the United States and the U.S.S.R. resulted in many technical breakthroughs and the progress of copper laser technology became rapid. The first copper lasers relied on external furnaces to heat the laser tubes sufficiently for copper vapour to be produced. A spark gap driven circuit discharged a capacitor through the gas in the laser tube and a pulse of laser light was emitted. A major step forward in both output power and efficiency came when self heated lasers were introduced by Isaev et al, (ref 5). The waste heat from a high pulse repetition frequency discharge was used to heat the well-insulated laser tube and an output of 15 W at 1% efficiency was reached . Shortly after this device was announced the first intensive research on copper halide lasers began. Devices were constructed using copper bromide, copper chloride and copper iodide but the bromide proved to be the one which gave the strongest laser output (refs 6,7). Continuing interest in the halide lasers have brought copper bromide devices into commercial production with a 7 watt, sealed off device (ref 8) but in general they are not readily available. Problems with the control of excess bromine partial pressure in sealed off tubes has led to low reliability and short lifetimes. Once these problems are overcome, the copper bromide laser will challenge both the high temperature copper laser and the argon ion laser in the market place.

1.3 Atomic energy level structure of copper.

The energy levels of the neutral copper atom are low lying, with the upper laser levels having an energy of around 3.8 eV. When this value is contrasted with the 36 eV required to reach the upper argon II laser level, the potential advantages of copper lasers are obvious. The upper laser levels of copper are strongly connected to the ground state and are easily pumped by electron collision. Although the lifetime of these upper laser levels is short, of the order of a few nanoseconds, radiation trapping at high copper densities extends this lifetime to a value comparable with that of current risetimes in fast discharge circuits. (Radiation trapping in copper is where upper laser level resonance radiation (324.8, 327.4 nm) is emitted by one atom and absorbed by another, so retaining the quanta of energy within the vapour.)

Stimulated emission occurs on the two laser lines (510.6, 578.2 nm) to the lower laser levels. These levels are metastable with lifetimes up to 20 μs so the populations of these levels rise rapidly during a laser pulse and destroy the population inversion. Laser output lasts for a few tens of nanoseconds, only. The discharge must then be discontinued until the metastable laser levels have de-excited and it becomes possible to build up another population inversion.

The dynamics of the energy level populations in copper halide lasers and high temperature copper vapour lasers are very similar. The dissociation energy of copper bromide is 2.5 eV. Once this energy has been supplied by the discharge, the copper atom behaves as if it were in an elemental copper laser. There is a net recombination rate associated with copper and bromine but this can be reduced by maintaining the discharge at a high pulse repetition frequency. Once copper bromide has been dissociated, energy is released as waste heat if the atoms are allowed to recombine. The electron attaching nature of bromine has been a major stumbling block in the development of sealed-off copper bromide lasers. Due to the relatively cool walls in these devices, copper condenses and leaves free bromine in the discharge volume. This process allows the bromine partial pressure to build up and eventually the discharge becomes unstable and constricts into a 'twisted wire' form. At this stage, laser output is extinguished and the tube requires pumping out and a fresh charge of buffer gas installed.

1.4 The discharge circuit.

Pulsed power is supplied to the laser head by a thyratron-switched capacitor-transfer circuit (fig 1.4). A storage capacitor is resonantly charged to a high voltage (10-20 kV) and is discharged through the thyratron into a peaking capacitor, generally of smaller value than the storage capacitor. The peaking capacitor is mounted as close to the laser head as possible and the laser head generally has a coaxial current return from one of the electrodes (anode usually) to reduce laser head inductance. With a small value of inductance, generally 200-500 nH, the discharge current will rise quickly and pump the upper laser levels efficiently. There is a strong interaction between the behaviour of the laser as a load and the performance of the thyratron. This interaction is not well understood but it has consequences for both laser output power and thyratron lifetime. The modulator used for a particular design of laser head should be tailored to that design for maximum effectiveness.

1.5 Laser tubes with insulating and conducting walls.

Copper vapour lasers are divided into the high and low temperature types. Both of these types use thermally and electrically insulating materials for the discharge tube. The high temperature copper laser generally makes use of alumina (aluminium oxide), zirconia or beryllia tubes but lasers have been designed and operated with metallic walls (ref 9). Copper halide lasers generally take advantage of the properties of fused silica and tube construction is normally with this material. Metal segmented laser tubes have not been used with copper halide lasers but appear to perform well when so used (chapter 6). Pulsed discharges in metal tubes appear to pose few problems as long as the basic physics is understood and allowed modes of operation adhered to. The high pulse repetition frequencies of copper and copper halide lasers are ideal for use with metal discharge tubes as an ionized pathway is established on the tube axis which will break down in preference to the intersegment gaps. The maximum segment length which will support an axial discharge is dependent on the ratio of electron temperature to electric field (chapter 5), so the buffer gas pressure and discharge current both affect the choice of segment length. Metal segmented tubes have proven successful as copper halide lasers with the operation of one of the most powerful copper bromide lasers to date. The design and operation of this 40 W laser is discussed in chapter 6.

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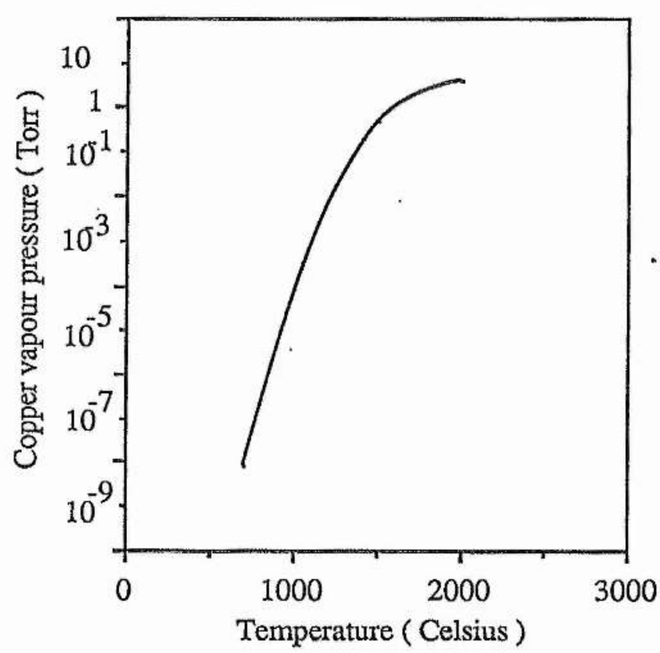

Figure 1.1: Vapour pressure of copper.

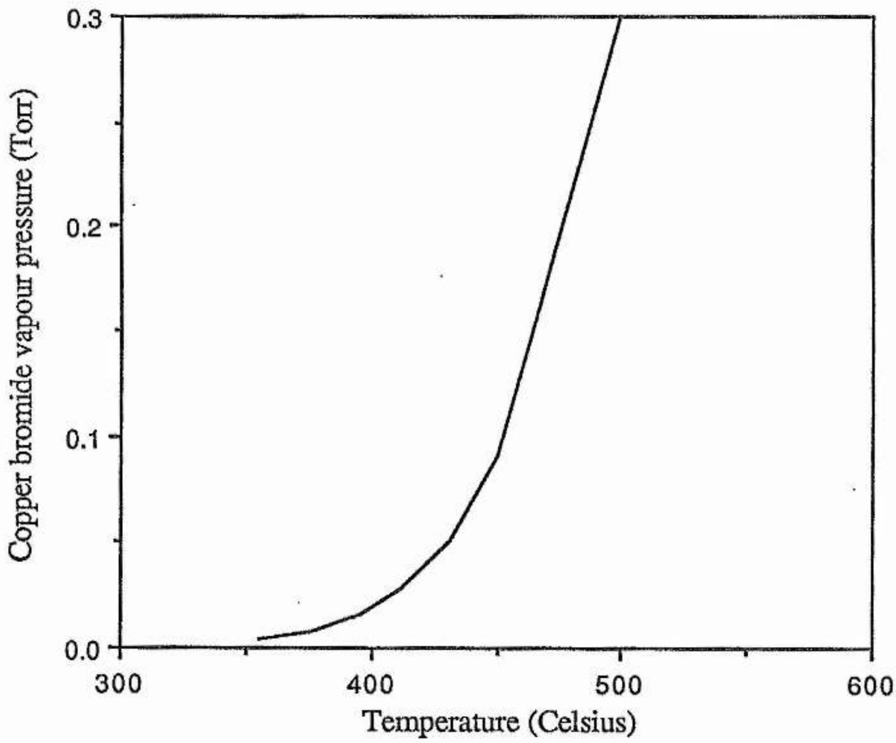

Figure 1.2: Vapour pressure of copper bromide.

Figure 1.3. Some metals which exhibit lasing under the cyclic excitation scheme.

Metal	Wavelength (nm)	Relative Power	Operating Temp. (°C)
Copper (Cu)	510.6 578.2	0.66 0.33	1550
Gold (Au)	312.2 627.8	0.01 0.1-0.3	1800
Barium (Ba)	1130 1500	low 0.3	800
Lead (Pb)	722.9	0.2-0.3	900
Manganese (Mn)	543.1 1290	0.2-0.3 low	1200
Calcium (Ca)	852 866	low low	700
Iron (Fe)	452.9	-	1700
Tellurium (Te)	535.1	-	650
Strontium (Sr)	645.7	-	700

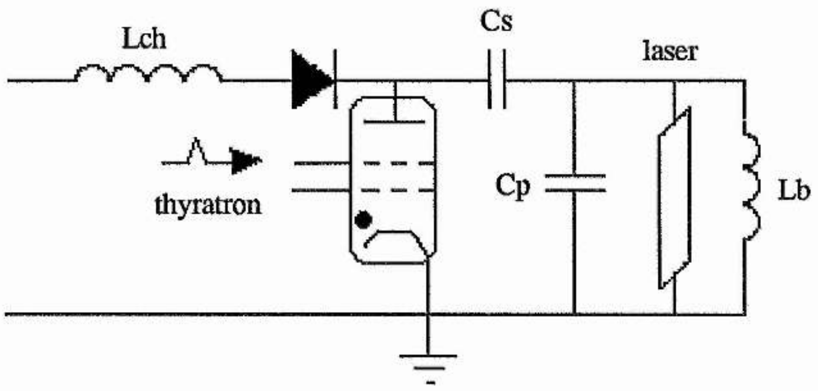

Figure 1.4 Capacitor-transfer discharge circuit.

Chapter 2

Energy level population dynamics and gas discharges.

2.1 Introduction.

This chapter is concerned with the concept of the metal vapour cyclic laser in general and with copper as the metal of interest. The requirements for an efficient pulsed laser are set out and discussed in detail. Copper is then examined as the metal which comes closest to fulfilling these ideals. There are certain implications for laser tube design which arise from the nature of the cyclic laser pumping requirements. These are outlined, along with the effect of an attaching gas (in the case of a halide laser) on pumping and design considerations. The effects of additives on laser parameters are discussed. Those found to be advantageous are alkali halides and hydrogen. Finally there is a short section on the role of other, less welcome contaminants.

2.2 The cyclic laser.

In this section, the term 'cyclic laser' will be discussed in detail. Cyclic lasers are devices where the energy level structure of the active media are such, that continuous generation of laser radiation is not possible. The laser discharge then, is pulsed and the pumping of the energy levels, stimulated emission and de-excitation of the laser media take place in a cyclic manner. The energy level structure of atomic metal vapours will be examined to find the conditions necessary for their high efficiency operation as laser media. The effects of the requirements of discharge pumping the laser transitions, on laser head design parameters will be determined.

In a laser such as copper, the energy level structure can be considered as a three level system having a ground state, an upper laser level and a lower laser level which is metastable and acts (on the short timescale) as a virtual ground state. The metastable level is not connected to the true atomic ground state by an allowed transition path. The upper laser level is a resonance level which should be strongly connected to the ground level so that efficient electron impact pumping can take place between the ground and upper laser levels, (fig. 2.1). In this way, once a population inversion is established, the upper levels drain into the lower levels as stimulated emission occurs. The stimulated emission intensity peaks and then tails off sharply as the lower level population builds up, reducing the population inversion. It is then necessary to wait until the metastable level population has been reduced to its initial low value before pulsing the discharge once more. The basic three level system described above must have a number of additional attributes which are necessary if the laser is to be useful and efficient. First of all, if the level system as given in fig. 2.1 is pumped by a discharge, the branching ratio would have to be such that most, if not all, of the upper level population relaxes through the laser transition. This means that although the resonance between the ground and upper laser level is very strong, giving efficient pumping, the radiation emitted when a metal atom relaxes directly to the ground state must be trapped somehow and retained until it can be utilised in the laser transition. This is radiation trapping. If resonance radiation is passed from one metal atom to another then this will extend the effective lifetime of the upper laser level population. In copper, the radiative lifetimes of the upper levels are increased by over an order of magnitude, from a few nanoseconds to a time which is compatible with the current risetimes in high voltage switching circuits. Thus, once the metal atoms reach the upper laser level, they are effectively channelled into the laser transition path, providing there are no other competing transitions from the upper laser level.

The preceding points deal with the pumping of the laser transitions. Of equal significance, is the ratio of the energy in a laser photon to the energy required to excite an atom to emit such a photon. This ratio is called the quantum efficiency. In laser systems such as the argon or krypton ion, a large amount of energy has to be deposited in the discharge for the gas atoms to ionize and reach the upper laser levels. After pumping and de-excitation by spontaneous or stimulated emission, the gas ion is left in the lower laser level from where it is swiftly removed by de-excitation to the ion ground state. A proportion of these ions can be excited to the upper laser level again. The rest undergo further loss of energy in transitions to the atomic ground state before re-excitation through the laser scheme again. The energy lost as heat in this cycle may come very close to 100% of the invested energy. A typical electrical/optical conversion efficiency for argon laser is 0.05 - 0.1%. If a laser system is low lying then the quantum efficiency can be that much higher for the same, or similar, output wavelengths from two different laser types. The example shown in figure 2.2 shows argon ion (488nm) and copper (510nm) levels. The advantage that copper has in terms of quantum efficiency is obvious as two thirds of the input energy is returned as a laser photon making this type of device potentially very efficient.

The operating temperature must also be considered here as the level system which makes lasing possible would be defeated if the lower laser level were to be thermally populated. This level may also be filled by low energy discharge electrons at the beginning of a current pulse (refs 2,3), so it is important that the electron temperature is raised quickly above this energy.

The cyclic laser, then, should have a set of low lying energy levels which comprise a ground level and laser upper and lower levels, the upper level being well connected to the ground level for ease of population by electron impact excitation. The lower level should be metastable and not so low lying in energy terms that it will be significantly thermally populated. Radiation trapping in the upper level is also necessary if lasing is to be possible with high output powers.

2.3 The copper vapour laser.

The copper vapour laser has proven itself as the type which satisfies the conditions discussed in the preceding section. The energy level diagram shown in figure 2.3 confirms that the group of levels involved in the lasing scheme are indeed low lying for excellent quantum efficiency and have no other competing levels between the upper laser levels and the ground level. When radiation trapping comes into effect at copper densities around 10^{12} /cc (ref 4), the branching ratio becomes close to 1 in favour of the laser transitions. During the discharge pulse, however, it is possible not only to pump into the upper laser level but to pump beyond them into higher lying states and even ionize the copper. The energy required for ionization, 7.72eV, is sufficiently close to the upper laser level energy of around 4eV, that some of the copper will always be ionized during a current pulse. Discharge energy is wasted in the ionization of copper, in directly populating the 2D lower laser levels and also in populating the upper (2P) laser levels to compensate for for the population of the lower levels. The energy used for these purposes is not returned as light. Some detailed computer modeling of the discharge kinetics in copper lasers has been done (refs 5,6,7,8), so it is not proposed to do more here than explain the mechanisms by which laser action is produced.

As the discharge pulse begins, the electron temperature and density are rising. The average electron energy passes through the region required to excite the copper atoms into the lower laser levels and the population of these levels will begin to increase. It is therefore very important to have a fast rise of current (and hence electron energy) so that the action of populating the lower levels is minimised and that the pumping of the upper laser levels can begin as quickly as possible before the lower levels are substantially filled by low energy electrons. To achieve a population inversion it is of course necessary to provide more than one atom in the upper state to compensate for each one in the lower state. The reason behind the external design of the laser tubes and the discharge circuitry itself (see chapter 3) is to increase the rate of current rise to efficiently populate the upper laser levels. To this end it is necessary either to increase the voltage across the laser tube or to decrease the laser head and circuit inductance.

From,

$$\frac{dI}{dt} = \frac{V}{L},$$

it can be seen that this is the case. In practice, both of these measures are taken and the designer strives for a compact laser head with a current loop that is physically as small as possible.

Once a population inversion is created, spontaneous or stimulated emission begins to deplete the upper levels and fill the metastable states below. As these levels have very long lifetimes in comparison with the upper levels then this retards the copper atoms in their return to the ground state. Early copper lasers operated at low pressures (< 20 Torr) to allow rapid deactivation of metastables by wall collisions (refs 9,10). This imposed a maximum on the pulse repetition frequency (15 - 20kHz) and consequently on the output power. Scaling up of the bore diameter requires a reduction in the pulse repetition frequency due to the radial diffusion times involved. From an engineering point of view, the low pressure also allows a fast migration of copper to the cold zones of the laser reducing the intervals between replacement of the copper charge.

It was discovered that increasing the buffer gas pressure actually led to a new operating regime (refs 11,12) where the dominant deactivation processes for the metastables occur in the bulk of the discharge volume rather than at the boundaries. The main processes in action here may be;

(a) $Cu^* + Ne \rightleftarrows Cu + Ne + \Delta E$

(b) $Cu^* + Cu \rightleftarrows 2Cu + \Delta E$

(c) $Cu^* + e \rightleftarrows Cu^{**} + e$; $Cu^{**} \rightleftarrows Cu + h\nu$

(d) $Cu^* + e \rightleftarrows Cu + e$

The data presented in reference 13 shows that the reaction labeled (a) is of little importance in deactivating the lower laser levels. Also, since the optimum pulse repetition frequency (PRF) appears to be reduced in the presence of high copper densities, (ref 9), then the reaction labelled (b) cannot be dominant as an increased copper density would lead to an increase in the reaction to the right, effectively creating more copper ground states and the opportunity to increase the PRF. A prolonged afterglow (of 50 - 70μs) was observed in ref 14; this suggests that the reactions in (c) may provide a substantial contribution to the deactivation of these long lived species. Straightforward quenching by cooling discharge electrons is the last reaction mentioned, (reaction (d)). The rate at which this proceeds depends on buffer gas pressure which is a controlling factor on the electron temperature and density. As the buffer gas pressure rises and the plasma density increases, so recombination rates are increased and this reduces the numbers of electrons available to de-excite the copper metastables. With an increase in gas density, the electron temperature will decrease and thus bring the mean electron temperature closer to that required for metastable deactivation, reaction (d), but will reduce the probability that the radiative path, (reaction (c)) will be taken.

Various buffer gases have been used in the copper vapour laser but normally neon is the one preferred. Its use consistently leads to higher output powers and the possibility of using higher pressures which reduces the copper diffusion rate.

2.4 The copper halide vapour laser.

Various compounds of copper have been used to generate the required vapour pressure of copper at artificially low temperatures. Copper acetylacetonate operates at 40°C, copper nitrate between 150 and 215° and the halides, copper iodide, chloride and bromide between 300 and 600°C (ref 15). The non-halides above have low operating temperatures but when high input powers are applied there are severe cooling problems and output powers are limited. The operating temperatures of the halides allow fused silica tubes to be used and as will be shown later, this is a major advantage over the high temperature copper laser.

As far as the energy levels involved with the laser transitions are concerned, there is no difference between a copper laser operating at about 1500^{o}C and a copper halide laser operating at about 1000^{o} less. Once the copper halide molecule has dissociated, the free copper atom behaves as in the high temperature device. The copper and halogen atoms will recombine if they are left to do so in a low repetition rate device. A further investment of energy is then required to re-dissociate the molecule before the copper atom may be pumped again.Many investigations were undertaken into the copper halide lasers between the mid 1970s and the early 1980s (refs 16,17,18). The main discoveries were, that in a double pulse laser (dissociation pulse followed by pumping pulse), the copper bromide gave out twice as much optical energy as the copper chloride laser, which in turn was more productive than the iodide. It then followed that copper bromide and chloride were investigated further but the widespread interest in both devices waned in the mid 1980s. Further work on copper bromide by Dr. N.V. Sabotinov and his co-workers in Bulgaria, has proved that the copper bromide laser has a place in the world laser market.

In the double discharge devices, many experiments were done to determine the optimum time delay between the two current pulses. It was found (ref 16) that the optimum delays for the bromide , chloride and iodide devices were in the same order as their electron affinities, that is, chlorine has the greatest electron affinity of the three and has the fastest recombination rate with copper. The best time for the pumping pulse, then, is before the ground state population has been seriously depleted by recombination. Bromine is less reactive than chlorine and so the ground state population is reduced at a lower rate. Iodine is less reactive again and the optimum interpulse delay was found to be greatest in this case. The actual values of these delay times are very dependent on buffer gas pressure, tube diameter and wall temperature, the latter controlling the vapour pressure of the particular halide of copper in use.

During the course of the work described here the compound used was copper bromide because the bromide always produced greater output than any of the other halides.

In a discharge tube with a density of copper bromide (CuBr) molecules around 10^{14} - 10^{15}/cc, there is very little thermal dissociation as the temperature is only 450 - 500°C. It therefore requires at least two discharge pulses to produce laser output. The first pulse is responsible for dissociating the CuBr molecule and the second and subsequent pulses, providing they occur sufficiently close in time to the dissociating pulse, excite the free copper atoms to produce the laser emission (fig. 2.4). The dissociation energy of CuBr is ~ 2.5eV (ref 19) is supplied to the molecule by electron impact. After dissociation, the copper atom is left in the lower laser level, metastable. An immediate excitation pulse would be wasted as there are insufficient ground state atoms to create a population inversion. A time delay is now necessary to allow the metastable population to decay and fill the ground state. Meanwhile, the ground state atoms that do exist are being removed by recombination with free halogen. There is a 'window' during which the metastable level and ground state populations are such that laser action is possible on pumping (fig 2.5). At one extreme of this range the metastable population is too high and at the other, the ground state population too low to achieve lasing threshold on pumping. The actual number densities and delay times involved are dependent on tube parameters and buffer gas attributes (refs 20, 21). It has been found, however, that the ground state depletion effect is less serious in a continuously pulsed laser as the ground state population can build up over a few cycles to a substantial value allowing higher repetition rate operation than is possible with a double pulsed device (ref 22). It then becomes advantageous to operate the laser at high pulse repetition rates to cycle the copper atom through the laser system as many times as possible before it recombines with a bromine atom and gives up its dissociation energy as heat. The recombination time of copper and bromine depends very much on the geometry and temperature of the discharge tube and the buffer gas type and pressure. Typical curves are shown in figure 2.6 for a laser tube in which a dissociation pulse has just taken place. The continuing increase in copper ground state population after the end of the pulse is due, both, to the relaxation of metastable copper and the relaxation of higher lying levels transforming energy within the plasma and causing further CuBr dissociation.

2.4.1 Discharges in an attaching gas.

When copper bromide laser is operating, the free bromine and copper concentrations are both about 10^{15}/cc. The wall temperature is in the region of 450 - 500^{o}C so there will be some condensation of copper on the wall. The vapour pressure of copper being reduced by copper condensation leads to the vaporization of more CuBr to maintain equilibrium. By the mechanism of copper loss to the walls and replacement with CuBr, the concentration of free bromine slowly increases with time in the discharge. Work described in chapter 6 shows that high bromine concentrations lead to instabilities and discharge hopping on the electrodes. As the bromine concentration increases further, the discharge becomes unstable and lasing ceases altogether. Work done on this problem (refs 23, 24) has shown that as the bromine concentration increases, the electron density in the afterglow drops more rapidly due to the attaching nature of the bromine. The drop in electron density during the afterglow has two consequences of great importance for copper lasers, the first being that the preionization density for the subsequent pulse is reduced. Lack of sufficient preionization both creates non-uniform discharges and reduces the pumping rate to the upper laser levels. Laser output is then reduced in power and may be spatially altered in intensity between pulses or else the discharge may flicker and spiral into a 'twisted wire' shape. The second consequence is that fewer electrons are available to interact with the metastable copper atoms as the average electron temperature drops through the interaction region. The pre-pulse metastable population remains high and laser output is reduced in the subsequent pulse. It is important to have a good system to manage the bromine vapour pressure over extended operating periods. In a sealed off copper bromide laser, some device would be required to maintain the bromine pressure at an optimum value. This value would not be, 'as low as possible', because the bromine is also responsible for regeneration of the primary laser material and for tube lives expected to reach thousands of hours, this is an important process.

2.4.2 Additives.

The problems of excess bromine concentrations mentioned in section 2.4.1 are serious and warrant detailed investigation. An approach to the control of bromine (or chlorine in copper chloride devices) has come in the form of chemical additives. The most successful of these additives have been shown to double laser output power for a given input power, to improve beam quality and to improve discharge stability. The compounds tested have been alkali chlorides such as sodium and potassium (ref 25), hydrogen chloride (ref 26) and hydrogen itself (ref 27, 28). The results showed that, although the mechanisms are not understood, the alkali chlorides, especially NaCl can increase the energy per pulse and the tolerance of the discharge to excess bromine concentration. Operation at temperatures elevated far above those normally reached are also possible with none of the degradation of discharge quality found in copper halide lasers with no additives. In the copper chloride laser for example, on addition of an alkali chloride the reaction,

$$MCl + Cu \rightleftharpoons M + CuCl,$$

where M signifies the metal, is driven to the right with increasing temperature and so forces a higher-than-normal vapour pressure of copper halide. This allows operation at temperatures where, normally, the free halogen concentration would render the discharge fillamentary and unstable.

The addition of HCl to a copper chloride laser (ref 26) had the effect of increasing the output power of the device and also the maximum possible pulse repetition frequency. It was suggested that this was due to an increased decay in the copper metastable population during the interpulse period. When chlorine and hydrogen were introduced, in separate experiments, to the same tube, it was found that chlorine suppressed output and brought on instability whilst hydrogen replicated the HCl results. In a similar experiment with HBr in a copper bromide laser, performed during the course of this work, the output power was also seen to rise and the laser beam, which had previously been annular due to axial gas heating at high pulse repetition frequency, lost its annular shape and became the standard copper vapour laser 'top hat' profile. Further, increasing the HBr pressure made the profile more gaussian-like before the beam finally extinguished. This experiment is described in chapter 6 of this thesis.

Hydrogen has been used as an additive in copper chloride (described above) and in copper bromide lasers, where it is now becoming part of a sealed tube design (Technik, Bulgaria). The effect of hydrogen in increasing the output power of not only the copper bromide laser but elemental copper (ref 29) and gold (ref 30) have been documented. The physical manifestations of the 'hydrogen effect' are;

1. Up to 100% increase in output power. At optimum hydrogen partial pressure in neon, (found to be 0.3 Torr, independent of neon pressure in CuBr, Cu and Au lasers) the output power increases, peaks and decreases over a narrower reservoir temperature range than in pure neon (approximately 2/3 of the range), (fig. 2.7). A factor of two is available in power and efficiency over a laser with a conventional gas-fill.

2. A change in laser beam profile. As the hydrogen pressure is increased from the background to around one Torr, the beam profile in a copper bromide laser at high pulse repetition rate changes from annular through top hat, as the hole fills in, to gaussian-like, as the centre brightens. Narrowing of the beam is also noticed at this point. The output power of the laser continues to increase until the beam has gone fully gaussian-like and then as the hydrogen pressure is increased further towards 1Torr, the beam power falls whilst maintaining this profile until, at 1 Torr hydrogen partial pressure, the beam power is similar to that of the annular beam with no hydrogen present.

3. Increase in the laser breakdown voltage. At the hydrogen partial pressure found to give greatest output power, the laser breakdown voltage increases from the usual 2-4kV, (in tubes of 2-3cm internal diameter and between 50 and 100cm long) to the unusually high value of 10-12kV. This may substantially increase the pumping rate making this process more efficient.

The reasons behind these physical changes which accompany the addition of hydrogen are not clear. One possible explanation may be that during the initial voltage rise on the laser tube, electrons collide with hydrogen molecules and dissipate their energies by exciting the vibrational levels. This continues until the voltage rises high enough for sufficient ionization to build up and for breakdown to occur. The average electron energy then rises much more quickly due to the high fields present and the copper metastable levels have less time to be populated. The establishment of a population inversion is then much more easily attained making the laser more powerful. In a pulsed discharge containing helium, sodium and hydrogen, it was shown (ref 31) that the electron temperature and density were significantly reduced in the initial stages of the discharge. Figure 2.8 shows that at low electron energies (2-4eV) the hydrogen molecule can soak up the electron energy in the vibrational levels. The cross section for the lower copper laser levels (2D) at 6eV are both around 1 x $10^{-17}cm^2$ and for the upper 2P levels, the cross sections are around 5 x $10^{-16}cm^2$. Therefore, the metastable levels compete against the greater cross section of the hydrogen and the upper laser levels have a much larger cross section. The population inversion meets threshold more rapidly and a greater amount of energy can be converted into light.

An alternative explanation put forward by Sabotinov and his co-workers (ref 28), holds that the hydrogen atoms left in the discharge volume by the previous pulse, soak up high energy electrons to become negative ions. This process has a high cross section (ref 32) and so a large population of these ions is built up. During the initial stages of the next pulse the detachment rate of electrons is greater than the ionization rate of copper by over an order of magnitude (fig 2.9). Copper atoms which would otherwise be ionised are left in the ground state whose population is now increased in the presence of hydrogen and can now contribute more to the upper level population.

2.5 Contaminants: sources and effects.

In lasers such as the copper and copper halide which operate at elevated temperatures, the ingress of contaminants from the materials used in the structure of the laser tube is very difficult to avoid. The best processed tubes still exude deep seated species from the zirconia, alumina, quartz or metal construction materials by diffusion under low pressures and high temperatures. As may be expected, the higher operating temperature of the copper vapour laser encourages contaminants to migrate into the discharge at a higher rate than from a copper bromide device. This difference means that the bromide laser may be sealed off for its lifetime and (at the moment, at least) the high temperature device cannot. The thermally insulating materials used in a copper vapour laser, alumina for instance, are formed and fired at high temperatures in atmospheres which ensure that oxygen, nitrogen and various trace metals from manufacture, such as sodium, calcium and magnesium are incorporated deep in the bulk of the material. Heating the laser tube to its operating temperature enables a stream of contaminants, like a slow leak from a vast reservoir, to work their way into the discharge. A high concentration of contaminants can raise the laser impedance and cause latching of the thyratron by altering the modulator circuit characteristics. The effect on lasing is the same as if an attaching gas had been admitted to the tube. Oxygen and nitrogen both reduce the electron temperature and soak up electrons making it more difficult to reach threshold. It becomes far more difficult to predict the behaviour of a contaminated laser.

2.6 Conclusions.

Copper and copper bromide lasers differ mainly in that the bromide device operates at temperatures where the lower laser levels are unlikely to be substantially thermally populated. Furthermore, there is a relatively high vapour pressure of CuBr and free bromine in the discharge tube. The copper energy levels involved in lasing are similar in both types as are the vapour pressures of copper required for radiation trapping and efficient stimulated emission to begin. It has been found that to optimise the output power of copper bromide lasers, the pulse repetition rate must be higher than in conventional copper types. This is to maintain a dissociated population of copper and bromine atoms.

The use of additives, in particular hydrogen, can lead to a doubling of the operating efficiency and output power of some lasers. This effect has been noted in copper, copper bromide and gold lasers although no explanation of this effect has proven conclusive enough to gain general acceptance.

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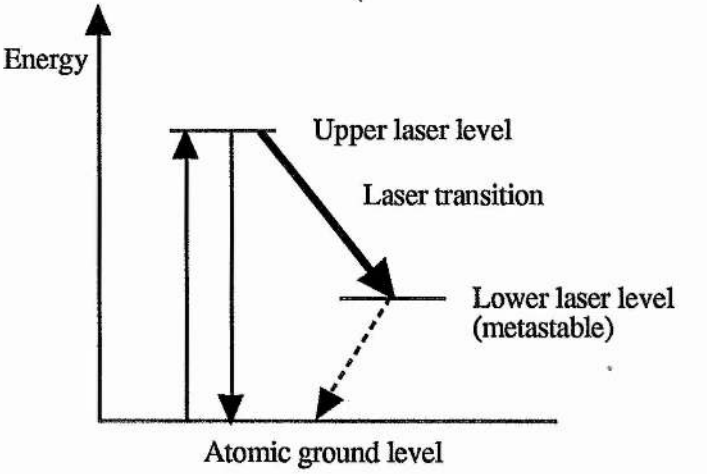

Figure 2.1 Basic three level cyclic laser system.

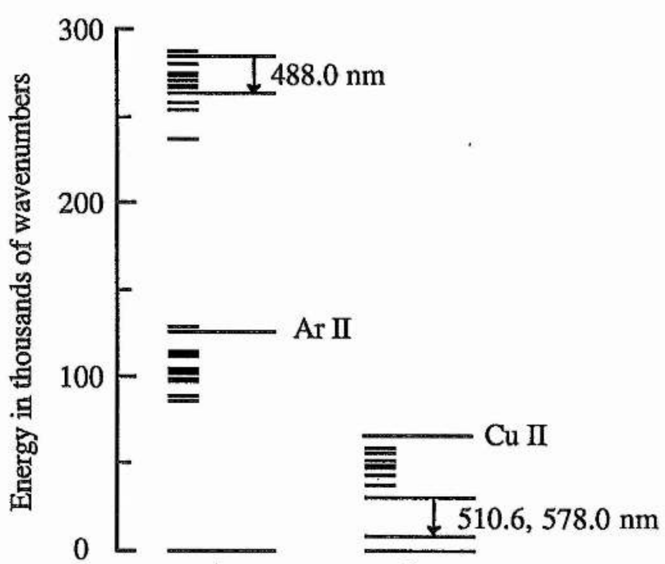

Figure 2.2 Comparison of argon and copper energy levels.

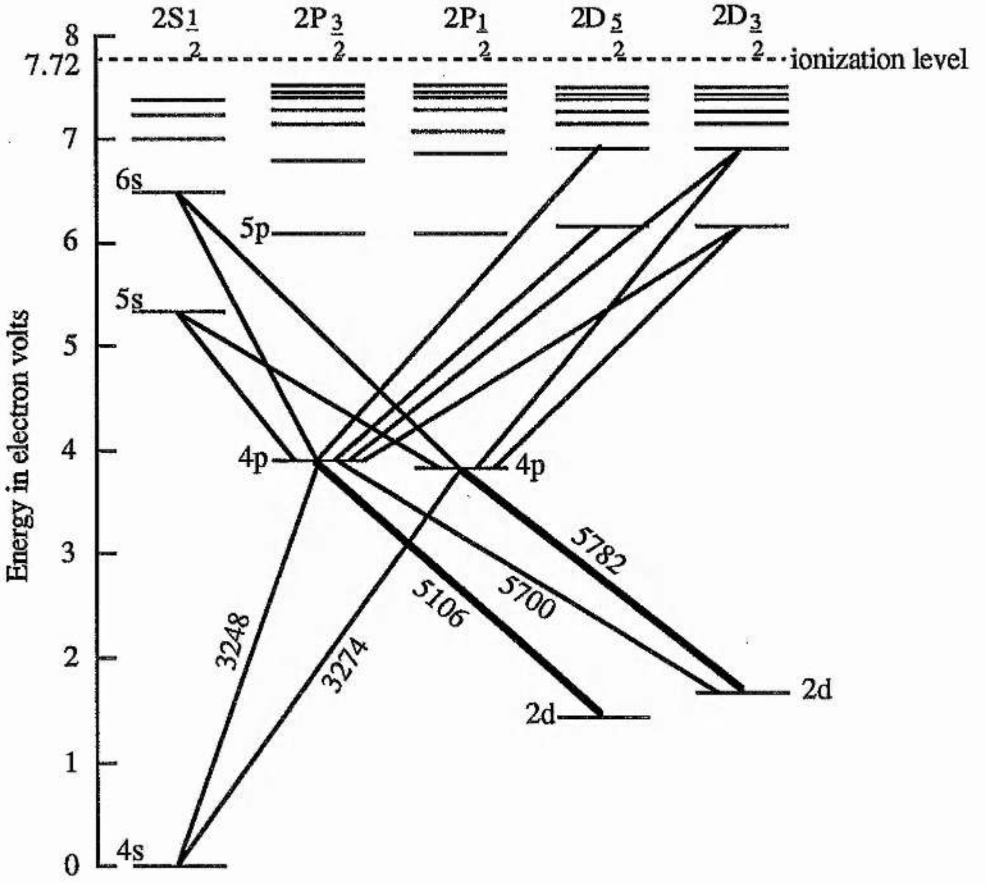

Figure 2.3 Copper energy levels and pump scheme.

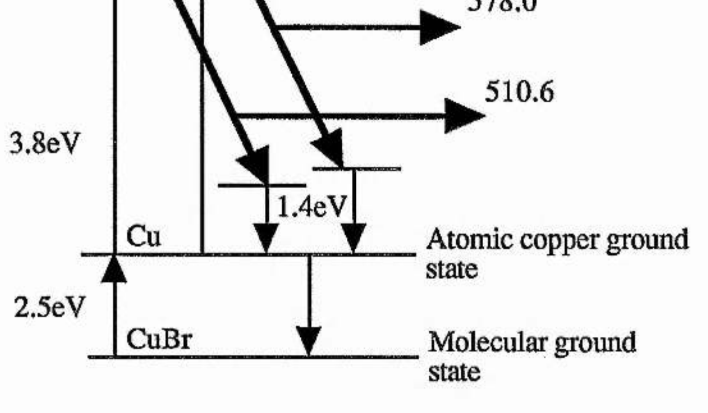

Figure 2.4 Simplified energy level diagram for CuBr laser.

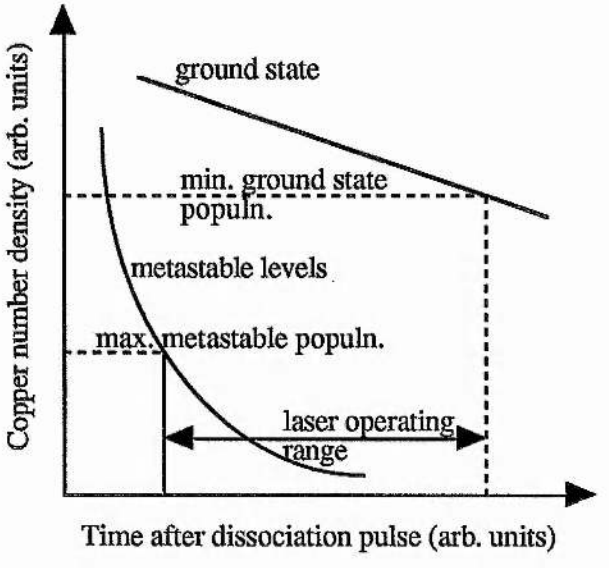

Figure 2.5 Laser 'window' effect , showing populations of energy levels in atomic copper.

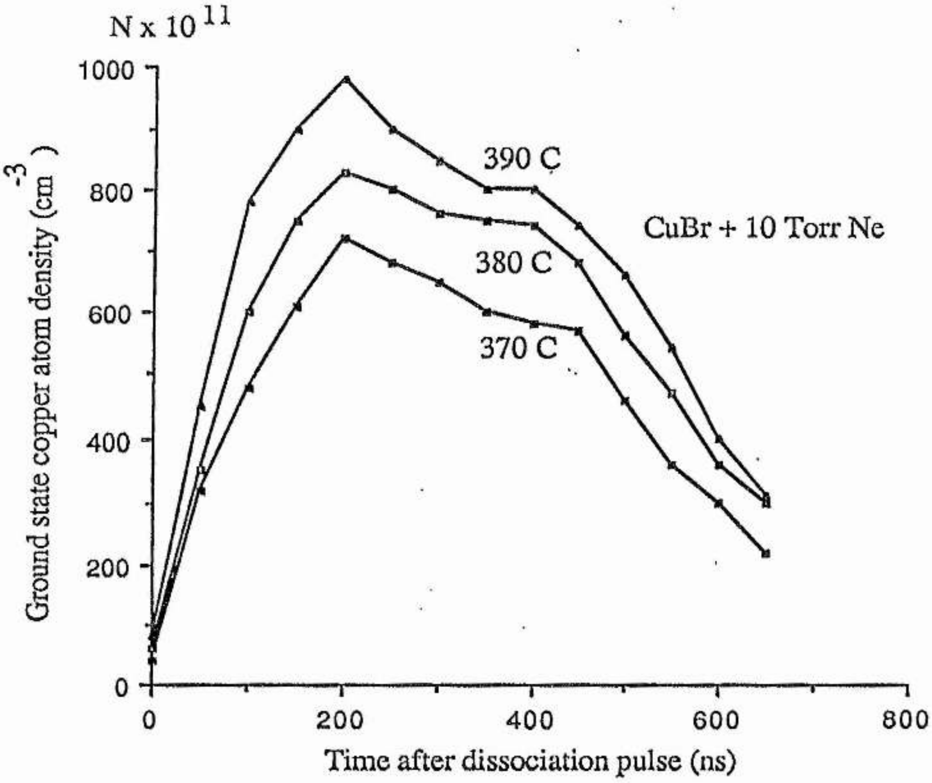

Figure 2.6 Time variation of copper ground state density at different temperatures.

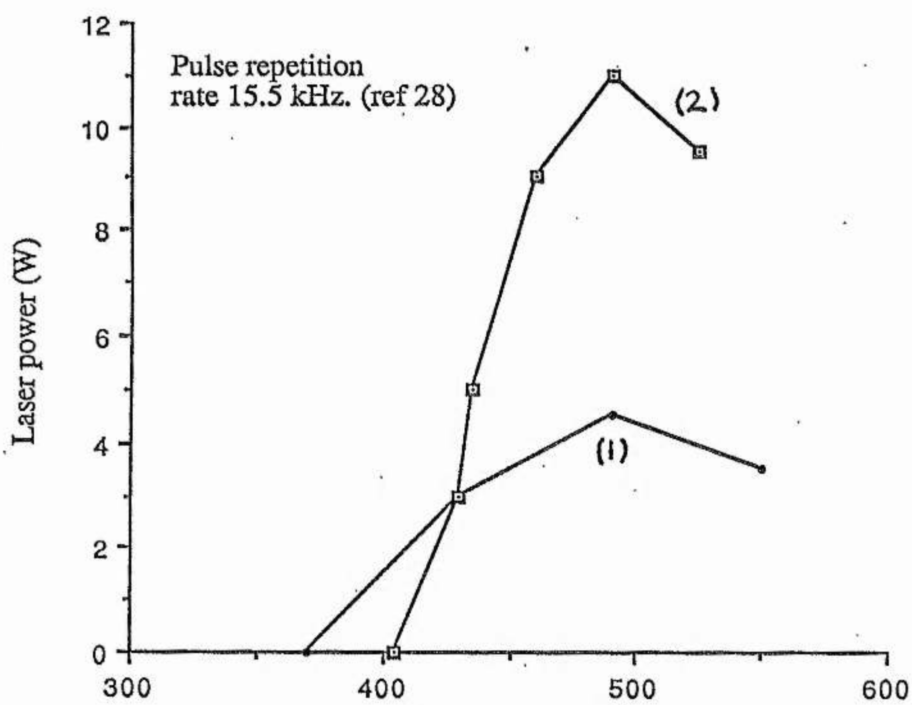

Figure 2.7: Laser power dependence on reservoir temperature. (1) 15 Torr neon. (2) 15 Torr neon + 0.3 Torr hydrogen.

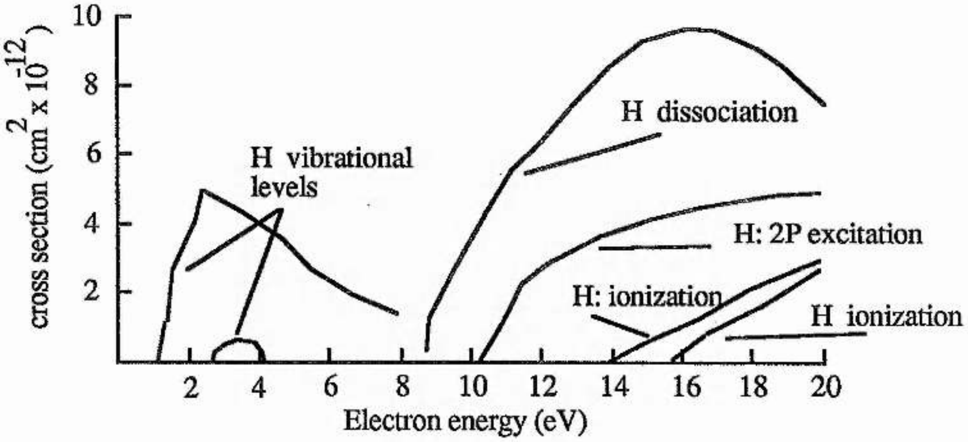

Figure 2.8 Hydrogen cross sections (refs. 28 - 32).

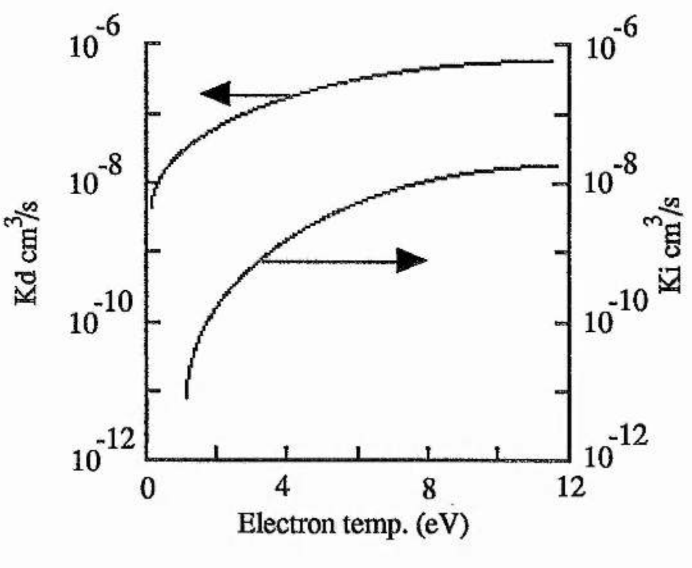

Figure 2.9 Detachment rate (Kd) of electrons from H- ions and ionization rate (Ki) of copper atoms by electron impact.

Chapter 3.

Power Conditioning.

3.1 Introduction.

The power requirements of the copper vapour laser are dictated by the atomic energy level dynamics of copper. A fast rising current pulse is necessary to create the non-equilibrium situation in which lasing takes place. Beyond 50 - 80 nanoseconds from discharge current initiation, lasing has ceased and so any current still flowing is serving only to heat the discharge volume and prevent relaxation of the lower laser levels. Short current pulses are therefore in order and at a repetition rate commensurate with lower level recovery time. Depending on bore diameter and operating pressure, the pulse repetition frequency (p.r.f.) will be optimum somewhere between 5 and 25 kHz, (ref 1), the lower values corresponding to large diameter, low pressure devices where wall collisions dominate over other relaxation processes. The power conditioning needs are usually met by a high voltage power supply capable of 10 - 15 kV and with sufficient current capacity to meet the input wattage requirements. This power is then modulated with a high voltage switching circuit producing short pulses at the desired repetition rate. Normally a hydrogen thyratron is used as the switching element in this circuit but, depending on requirements and the laser head design, spark gaps or semiconductor switch arrays may be employed successfully. For the experimental work documented here, two types of hydrogen thyratron were used, they were EEV types CX 1535 and CX 1825, both pentode (triple grid) tubes, (refs 2,3).

3.2 High Voltage Power Supply.

Primary high voltage is normally obtained by transforming up from the three phase mains supply and using a diode bridge to rectify the output. There are usually some large value capacitors and inductors in the output line to smooth any voltage ripple from the half or full wave rectification. These elements also help to protect the bridge from any transients which originate in the load or modulator circuits. In the more compact switched mode power supplies where semiconductors such as MOSFETs switch relatively low (600 V) voltage through pulse transformers at very high frequencies, voltage ripple on the output is negligible so very little smoothing is needed and the high switching frequencies mean that these power supply units can be made very small, (ref 4). Unfortunately they are easily damaged by transients generated outwith the power supply and so it is unusual to find switched mode devices associated with loads requiring more than 3 or 4 kilowatts.

3.3 Power Modulator.

3.3.1 Hydrogen Thyratrons.

The hydrogen thyratron, (refs 5,6), is a high voltage switching device capable of passing large peak currents at high repetition rates and with very little jitter associated with the accuracy of the firing time.

In its simplest form, the thyratron consists of an anode and a cathode separated by a control grid, these electrodes are housed in a glass or ceramic envelope which is filled to a low pressure with hydrogen or deuterium gas. The gas pressure and electrode separation are such that the switch operates on the left hand side of the Paschen curve. This means that small electrode gaps can hold off high voltages and be triggered to conduction by relatively low voltage. Each high voltage gap can hold off 25 -30kV so by stacking a few in series within a single envelope, extremely high voltages can be switched.

3.3.1.1 Triggering.

The EEV types CX 1535 and CX 1825 both have three grids. Grid 1, closest to the cathode and grid 2 are responsible for turning the tube on while grid 3, closest to the anode, promotes recovery and allows operation at high p.r.f. In the particular circuit configuration used here, a constant discharge was maintained between G1 and the cathode. The control grid, G2, was kept at a negative potential with respect to the cathode to suppress electron invasion of the grid anode space. A positive trigger pulse of 2-3 kV was applied to G2 from an EEV sub-modulator to initiate G2 - cathode breakdown. Plasma from this discharge then leaks through the slots in G2 into the anode space causing sufficient ionisation to initiate full anode current flow. This is the process of commutation.

Gas pressure in the CX 1535 and the CX 1825 is set by a separate reservoir heater. Control over pressure is useful when running at high repetition rates and at voltages lower than the rated value for the thyratron. The gas pressure can be increased to the point where the tube will still hold off the required voltage but will give a higher rate of current rise. The minimum recovery time will be increased, however, as this process is dominated by wall collisions. A higher gas pressure slows diffusion and can therefore restrict the maximum repetition rate possible without thyratron recovery failure (latching).

3.3.1.2 Recovery

When forward conduction ceases in the thyratron, the plasma will begin to decay. The rate of decay determines how soon voltage may be reapplied to the anode and hence gives a limit to repetition rate attainable. Recovery time can be shortened by arranging the discharge circuit such that a negative voltage is applied to the anode at the end of the current pulse. This cuts off the forward current and encourages the plasma to decay by drawing off the ionic content. The third grid (G3) is normally grounded to the cathode through a small valued resistor and this also helps to increase the decay rate. In general, small volume tubes recover faster as the surface area to volume ratio is greater. During the experiments which were performed, it was noted that the minimum time for recovery of the CX 1535 was 3 - 4 μS but the large CX 1825 required 7 - 8 μS if latching was to be avoided. The main trigger grid, G2, loses control when the tube is in conduction but once the plasma has begun to decay the negative bias can begin to assert influence over it and remove some ions, this is an important recovery mechanism as a high resistance in the trigger line may cause severe latching problems [see Appendix A, The gold vapour laser].

3.3.1.3 Cooling

The ceramic/metal bodied tube used in the work reported in this thesis requires cooling by immersion in oil. Shell Diala B.G. transformer oil was used and water based heat exchanger systems were set up. A stream of cooled oil was directed at the cathode base plate to maintain constant gas pressure within the thyratron. For the small tube, convection in the oil was sufficient to cool the rest of the body but the larger tube required oil to be forced past the grid structures.

3.4 Charging Circuit.

The part of the CVL circuit responsible for charging the storage capacitor, C_S, also plays a vital role in other aspects of the total system performance. Between the power supply and the discharge circuit is the charging element, (figure 3.1), which has to perform the dual functions of holding off forward voltage until the thyratron has recovered and then limiting the charging current to the storage capacitor. The bypass element lies in parallel with the laser and serves to control the proportion of current which passes through the partially ionised laser during the charging period. It also blocks the discharge pulse current from leaking to ground when the thyratron switches. There are two main methods of charging C_S to high voltage, these are resistive and inductive charging. Resistive charging, as its name suggests, uses a suitably valued resistor to limit charging current and whose time constant, in conjunction with the storage capacitor and bypass element, is less than or equal to that required for the maximum repetition frequency to be used. One major disadvantage of resistive charging is the substantial power dissipation in the charging element. For example, if a power supply of voltage V_S is to place a charge Q on a capacitor of value C_S, then the energy transferred out of the power supply is QV_S. However, the stored energy in the capacitor is equal to $\frac{1}{2}C_S V_S^2 = \frac{1}{2}QV_S$, giving an energy loss of 50%. Half of the input energy is converted to heat in the charging resistor. Inductive charging is inherently more efficient as the charging element is reactive rather than dissipative. Immediately after a pulse, the capacitor C_S is discharged and the current through the charging inductor, L_{ch}, is zero. Following the characteristics of an LC, low resistance circuit, the voltage across C_S will begin to oscillate, shown by the dashed line in figure 3.2, the peak voltage will be slightly less than $2V_S$ due to losses in the circuit. If left undisturbed this voltage oscillation will decay until a steady state voltage of V_S appears across the capacitor C_S. Again 50% of the input energy will have been dissipated in the circuit by this time and the advantages of inductive charging lost. If, however, the pulse repetition frequency is such that the switch closes when the voltage across C_S, (V_{CS}) reaches a maximum, then, as V_{CS} is approximately $1.9V_S$, the charging efficiency is in the region of 95%. At this time the current through L_{ch} is zero so each successive charging cycle is identical to the previous one. The operating frequency of the switch for maximum efficiency is determined by the values of L_{ch} and C_S. If it is assumed that the duration of the switched pulse is negligible with respect to that of the charging pulse (normally the two are separated by two or three orders of magnitude), then T_r, the repetition period, is half of the charging period, T

$$T = 2\pi\sqrt{L_{ch}C_S} \quad ,$$

$$T_r = \pi\sqrt{L_{ch}C_S} \quad .$$

For many applications, the p.r.f. constraint is unacceptable so, at the expense of a few more watts, a diode is incorporated in the circuit between the charging inductor and C_S, to prevent the capacitor discharging during the reverse part of the oscillation; the effect can be seen in figure 3.3. With this modification, the period between pulses can be any value greater than T_r. Some leakage will occur if high voltage remains across the capacitor for extended periods but a suitable value for L_c may be chosen such that at maximum p.r.f., the voltage does not remain on the thyratron for long. This method is known as resonant charging and is employed, with or without a diode, in most CVL driving circuits.

A modified form of resonant charging is becoming more widespread as the value of magnetic materials for switching is realised. If a saturable inductor is used as the charging element, then it can be arranged that the unsaturated inductance is large enough to give ample recovery time to the thyratron and then, on saturating, the high voltage is restored to the anode in a much reduced time giving an increase in the maximum p.r.f. A saturating charging inductor was designed and built for a gold vapour laser system suffering from chronic latching of the thyratron. The inductor proved enormously successful in curing this problem. A discussion of this subject can be found in appendix A.

As with the main charging element, the bypass element can be resistive or reactive. Due to the nature of the laser load, the type and size of the bypass element has a large impact on both laser and charging circuit operation, (ref 7). When the laser is at its operating temperature, the gas conductivity is high due to the residual ionisation from the previous pulse and the metal vapour present. If the impedance of the bypass element is too high then a significant fraction of the charging current will flow through the laser volume, maintaining a high level of ionisation and reducing the laser breakdown voltage for the subsequent pulse. This leads to a drop in the laser output power. Alternatively, if the impedance is too low the discharge current will be able to leak through the bypass to ground, effectively shorting the load. An inductor is preferred over a resistor here as it provides a low impedance to the slow charging current yet blocks the discharge current.

In a contaminated laser, the impedance is high, so more energy than normal is lost to the circuit components. If an inductor is used as a bypass element the discharge voltage will oscillate between the inductor and peaking capacitor. This leaves a negative voltage on the thyratron, helping recovery but the inductor will be forced to pass an unusually high current and will heat up. A resistor, on the other hand will damp any oscillation and bleed the voltage to ground but will also leave a positive voltage on the thyratron anode, delaying recovery and possibly causing the thyratron to latch. In this case, it has been found beneficial to have a resistor and an inductor in series as a bypass arm. The inductor still returns a negative reflection to the thyratron and the resistor damps out the oscillation. Normally the resistor may be removed when the laser is at its operating temperature and the plasma impedance is low but on starting from cold with a tube containing traces of water vapour or nitrogen the resistor is necessary. The subject of bypass elements and their effect on circuit performance has never been rigorously treated for the case of metal vapour or other high repetition rate lasers.

3.5 Discharge Circuit.

3.5.1 Introduction.

To deliver an electrical pulse of known characteristics to a load it is usual to charge a capacitor to a known voltage and discharge it through a switch into the load circuit. If all the component values and physical parameters such as current loop sizes are known then it is possible to predict both the duration and peak value of the current pulse. This concept is the basis for all copper vapour laser modulator circuits. Some modifications to this basic circuit must be made to accommodate the requirements of the load and the switching device. Thyratron operational lifetimes increase markedly with a reduction in the rate of rise of current, however, the nature of the copper vapour laser requires a fast rising current pulse for efficient pumping of the medium. To overcome this conflict in excimer and nitrogen lasers, the capacitor transfer circuit was developed and with the advent of metal vapour lasers this circuit was seen to be adequate while the engineering of the laser heads was the priority.

3.5.2 The capacitor transfer circuit and its optimisation.

The capacitor transfer circuit normally employed in a copper or gold vapour laser system is shown in figure 3.1. A set of storage capacitors, C_s, of the order of a few nanofarads is charged resonantly through the inductor, L_{ch}, to typically 10 - 20 kV. When the thyratron is triggered, part of the charge stored in C_s is transferred through the thyratron to a set of smaller peaking capacitors, C_p. These peaking capacitors are normally mounted directly across the laser tube and so provide a much lower inductance discharge circuit than is possible with the thyratron and storage capacitors in the main current loop. By assuming negligible damping due to the thyratron impedance after breakdown, the voltage across C_p and hence the laser tube can be readily shown to swing to a maximum negative voltage, Vmax, equal to,

$$V_{max} = \frac{-2C_s}{C_s + C_p} V_o \qquad (3.1),$$

where Vo is the voltage applied across C_s. For optimum performance from the capacitor transfer circuit, the laser should break down only when the maximum possible voltage has developed across the peaking capacitor The corresponding amounts of charge and energy transferred to the peaking capacitor are then given by,

$$Q = \frac{2C_pC_s}{C_s + C_p} V_o = \frac{2C_p}{C_s + C_p} Q_o \qquad (3.2)$$

and

$$E = \tfrac{1}{2}C_pV_{max}^2 = \frac{4C_pC_s}{(C_s + C_p)^2} V_o \qquad (3.3),$$

where Q_o and E_o are the charge and energy stored in the main capacitor prior to discharge. As a function of the peaking capacitor value, the energy transferred from the storage capacitor becomes a maximum when $C_p = C_s$. However, for efficient pumping of self-terminating lasers, one has also to consider the risetime of the current pulse in the laser. This is governed by,

$$\frac{T}{4} = \frac{\pi}{2} \sqrt{L_c C_p} \qquad (3.4),$$

where L_c is the inductance of the discharge circuit formed by the laser tube and peaking capacitors. It is obvious that there is a trade-off between the maximum transferable energy and the rise time of the current in the laser. In most of the work reported to date, the peaking capacitor value is chosen to range from 0.2 to 0.5 of the storage capacitor value (ref 8). With these ratios, the maximum voltage developed across the peaking capacitor ranges from 1.67 to 1.33 times the value of the charging voltage. Correspondingly, one third to two thirds of the stored energy will be transferred to the peaking capacitor. The remaining energy will subsequently discharge through the thyratron and the laser as a secondary, slower current pulse. In this way the laser current pulse becomes double humped and is broad.

For high peak power lasers such as excimer and nitrogen, the rate of rise of the first current pulse from the peaking capacitor is critical to performance. With short upper state lifetimes, of the order of tens of nanoseconds, very high electron temperatures must be quickly established to obtain satisfactory pumping of the laser levels.

A small valued peaking capacitor and a low inductance transverse discharge design will give an initial current spike to pump the laser. The much larger inductance of the main switching device circuit does not allow the second current pulse, which contains most of the energy, to effectively pump the active medium. In these lasers, the requirement for a fast rising current pulse invariably leads to an optimum ratio where the value of C_p is a fraction, typically one half to one third, of the value of C_s ,(refs 9,10).

For metal vapour lasers, the upper state lifetime is of the order of hundreds of nanoseconds due to radiation trapping, (ref 11). The duration of the laser pulse is limited mainly by the metastable lower levels with lifetimes of the order of tens of microseconds. It is thus expected that stimulated emission could be maintained for much longer than in excimer or nitrogen lasers. However, with the longitudinal cavity design of metal vapour lasers, the current risetime is limited by the inductance inherent in the current return path. It is therefore not obvious that the conventional capacitor transfer configuration is optimum for use in these lasers. More importantly, it is noted that as the laser warms up to its operating temperature, it will break down well before the maximum peaking capacitor voltage is achieved. This is due to the high level of residual ionisation in the laser tube and is particularly manifest in metal vapour lasers operating at high repetition frequencies. When this occurs, the peaking capacitor becomes less effective as it is not fully charged prior to breakdown. If the breakdown voltage of the laser is such that the voltage on C_p is less than that remaining on C_s, then the peaking capacitor is completely ineffective and the discharge now draws its main current from the storage capacitor through the high inductance switch loop. This feature ultimately limits the operation of capacitor transfer circuits as effective pulsers for metal vapour lasers. In fact, for some of the lasers reported, peaking capacitors were not used at all in order to obtain simpler current and voltage dynamics in the discharge circuits.

In view of the non-constant operating conditions of metal vapour lasers, it is important that the characteristics of the discharge circuits be examined in further detail. In essence, the optimum circuit configuration adopted for relatively low repetition rate, low inductance, transverse discharge lasers, is not necessarily optimum for metal vapour lasers.

Experimental apparatus.

For this study, a gold vapour laser of conventional self heating design, operating at temperatures between 1850 and 1900 ^{o}C, was used. All temperatures were measured with a Minolta/Land Cyclops 52 optical pyrometer. The laser consists of a high purity alumina tube of 20mm internal diameter and 900mm length, wrapped in zirconia thermal insulation felt and placed inside a quartz tube, (figure 3.4). An outer pyrex tube of larger diameter forms a vacuum jacket to aid in thermally insulating the discharge tube. The whole laser body is water cooled inside a metallic jacket which also acts as a coaxial current return. The effective discharge length is 800mm and the pressure of the neon buffer gas is maintained at 15mb with a slow flow to remove contaminants.

The high voltage power supply resonantly charges the system at a rate of 10kHz through a series inductance of 150mH (T.E.C.). A hydrogen thyratron (EEV type CX 1535) was used as the switching device. The discharge characteristics of the laser were monitored by measuring the voltages and currents associated with the thyratron and the laser tube. Tektronix P6015 voltage probes and Ion Physics current transformers were used for this purpose. The waveforms were displayed on a four channel HP 54112D (400 Megasamples per second) digitizing oscilloscope. Laser output power was measured with a Scientec S200 power meter, calibrated with respect to an argon ion power meter (Spectra Physics 210).

Results.

Laser output power was measured when the device was operated with a charging voltage of 12kV on a storage capacitance of 8nF. The pulse repetition frequency was maintained at 10kHz. The peaking capacitance was varied between 2 and 12nF. Figure 3.5(a) shows that the maximum output power occurs when $C_p = C_s = 8nF$. This is contrary to the ratio normally quoted for high power pulsed lasers.

The voltage and current waveforms corresponding to $C_p = 2nF$ and $C_p = 8nF$ are shown in figure 3.6. In all cases the measurements were taken when the laser reached steady-state conditions. Due to discharge instabilities, however, the amplitude of the measured waveforms would deviate from the average by up to 5%. In both figures 3.6(a) and 3.6(b), the two oscilloscope traces show the voltage across and the current through the thyratron. As the probe could not be connected directly across the thyratron, the voltage measured includes the effect of a small part of the circuit loop inductance. The two traces, 3.6(c) and 3.6(d), show the voltage across and the current through the laser tube.

For the case of $C_p = 2nF$, (fig.3.6 (a),(c)), it is seen that both the voltage across the thyratron and the laser tube are strongly oscillatory due to impedance mismatching in the circuit. After thyratron breakdown, the voltage drops from 12kV to -5kV with a fall time of 80 ± 5ns, (half periodic time). This gives a value of 400 ± 40nH for the inductance of the thyratron loop. The voltage across the laser tube reaches a maximum magnitude of -12kV, substantially less than the expected maximum of -20kV as given by Equation (2). The incomplete voltage swing indicates that the laser begins to conduct relatively early in the C_s - C_p transfer cycle. At this voltage, only 24% of the stored charge is transferred to C_p, compared with the 40% expected when $C_p = C_s/4$. The peaking capacitor here is not being used to best advantage. Examination of the current waveforms will also clarify the role played by the peaking capacitor. The thyratron current is double humped with much more energy transferred in the second part of the pulse. Laser current begins to flow at a C_p voltage less than 5kV, this is due mainly to residual ionization in the laser tube lowering the breakdown voltage. It should be noted that the laser current scale is different from that of the thyratron current. The laser output pulse begins 50ns after the laser current pulse commences and it has a full width at half maximum, (FWHM), value of approximately 50nS, so with the bulk of the stored energy being deposited in the gas after this time, pumping efficiency is relatively low and most of the energy is used simply to heat the tube.

For the case of C_p = 8nF, (fig 3.6 (b) and (d)), it can be seen that there is less oscillation of voltage and current due to improved circuit impedance matching. From the voltage fall-time of 170 ± 10nS, a circuit inductance of 360 ± 60nH is inferred, in agreement with the previous calculation for C_p = 2nF. Laser breakdown is again observed to occur at relatively low voltage. The maximum peaking capacitor voltage is measured at -8.2kV giving a 66% transfer of charge compared with the 100% which is theoretically possible. As the laser voltage reverses to a maximum of 4.5kV the discharge goes out and conduction ceases. A current pulse has been passed with a single peak and which is 25% shorter in FWHM than when C_p = 2nF. There is, however, a substantial voltage reversal across the laser (indicating impedance mismatch). This mismatch gives rise to a forward voltage across the thyratron and so results in a second current pulse. After this pulse, the thyratron anode is left with a negative charge which aids recovery. Under the $C_s = C_p$ scheme it was noted that the failure rate for thyratron recovery was substantialy reduced.

In an attempt to optimise the coupling of electrical energy into the useful part of the discharge (that is the first 50nS) the same $C_s = C_p$ scheme was used but the value of the capacitance was progressively reduced with a corresponding increase in charging voltage to maintain a constant input energy. The result, shown in figure 3.5(b), is that by increasing the voltage on a smaller capacitor, the energy coupling becomes more effective and the electrical–to–optical efficiency increases. By reducing the capacitor value and increasing V_O, the rate of rise of current, dI/dt, is increased. This allows more power, ($P = I^2R$), to be deposited in the gas before the metastable levels are substantially populated. Hence, power output and overall efficiency are increased. A maximum of 18kV was available at the thyratron anode due to power supply limitation. The capacitance could not, therefore, be reduced below 4nF and still provide the average input power required to maintain a constant laser tube temperature.

Discussion.

It appears from the above results that the rate of rise of current in the laser is not the only important parameter in the discharge circuit. It has been shown that by coupling more energy into the first part of the current pulse, laser power is increased, even though the rate of rise of current is been markedly reduced. By operating the laser with equal values for the storage and peaking capacitors, several benefits can be realised. The laser current is a fast, smooth pulse, which has a single peak and terminates cleanly. Output power is improved over the original scheme and can be further improved with a reduction in the capacitor value and an increased charging voltage. The thyratron is subject to less voltage oscillation and fewer recovery failures take place. The low breakdown voltages associated with these devices mean that the discharge circuits should be designed for hot tubes with high residual ionization. It should not be assumed then, that the conventional storage to peaking capacitor ratio is optimal for use with metal vapour lasers.

3.5.3 Double pulse excitation.

Many of the early copper halide lasers were driven by double pulse discharge circuits. These devices were externally heated to decouple the copper halide vapour pressure from the discharge input power. In many cases it was found that an optimum delay time existed between the first pulse which dissociated the copper halide and the second pulse which created the population inversion, (refs 12,13,14). The optimum time delay would depend on many physical factors, including tube diameter and gas pressure, but would be in the interval of 50 - 200μs. In a continuously pumped (self heated) laser, this would correspond to operation between 5 and 20 kHz. Copper halide lasers now run at these high repetition frequencies with one pulse acting as pump for the current cycle and also dissociating any copper halide molecules which have recombined. Double pulse excitation is now rarely used unless for investigations of discharge kinetics.

3.5.4 Geometrical constraints on circuit design.

Throughout the development of driving circuits for copper lasers, it has been evident that in order to increase efficiency in the system, much attention has to be paid to the layout of circuit components. As with excimer lasers, when the discharge circuit inductance is reduced, the output power generally increases. For this reason, the thyratron should be mounted as close to the laser tube as is practicable and all interconnections made with high voltage coaxial cable to reduce inductance. Many workers are now turning to magnetic switches in order to increase the performance of their systems. These devices have many advantages but are not simple to engineer and each design will only work well within a very narrow operating range. Consequently, as we make many design and operational changes in the lasers discussed here no magnetics were used in the discharge circuit. Some references are included, however, for completeness, (refs 15,16,17,18).

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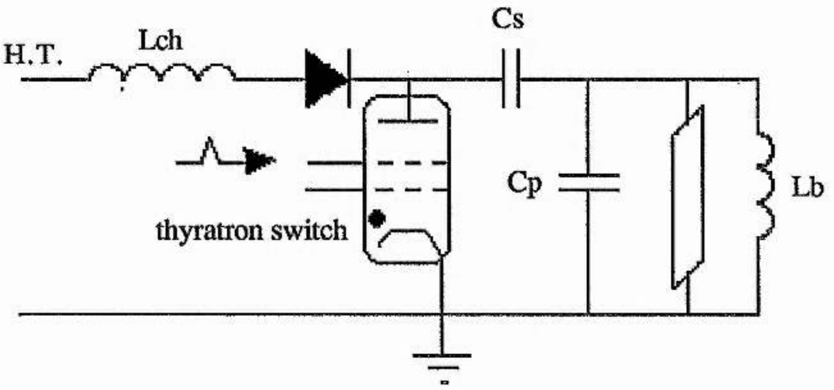


Figure 3.1 Charge - discharge circuit for copper vapour laser.

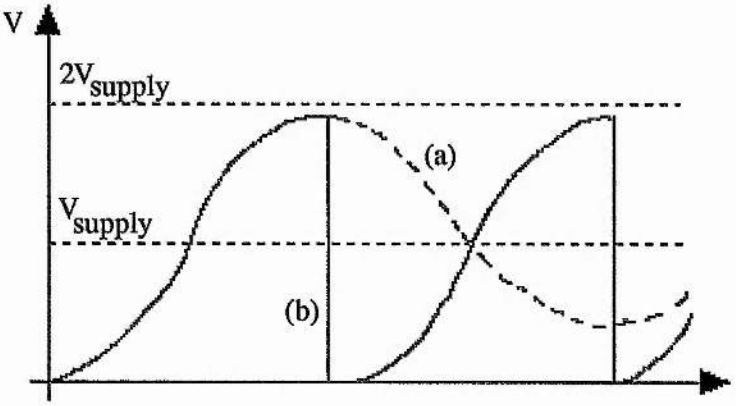


Figure 3.2 Resonant charging, (a) without switching and (b) with switching.

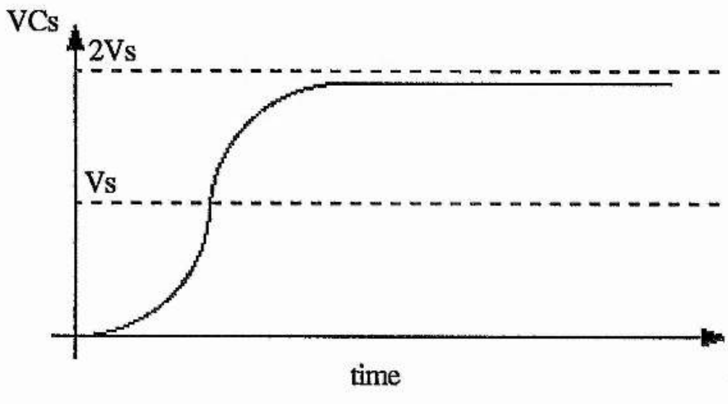


Figure 3.3 Inductive charging with diode.

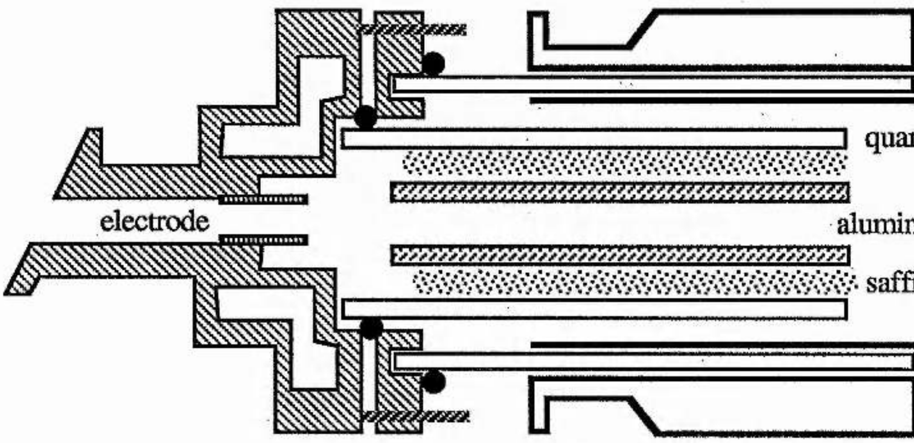


Figure 3.4 Copper / gold vapour laser head

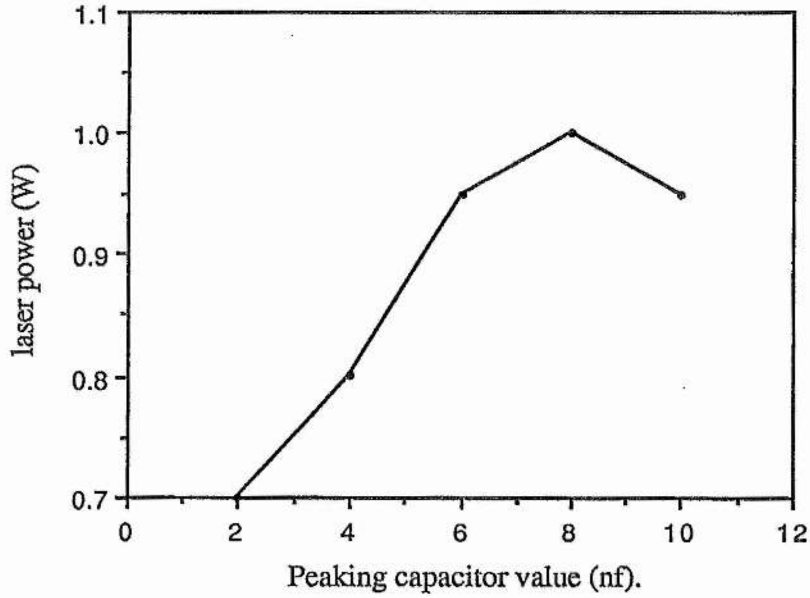


Figure 3.5 (a) Variation of laser output power with peaking capacitor value (Cs = 8nF).

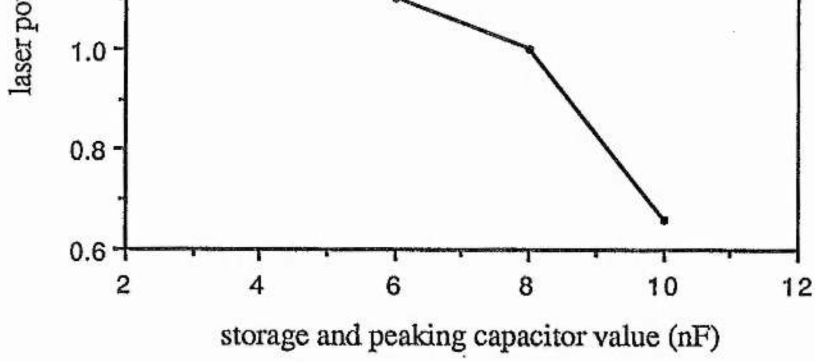
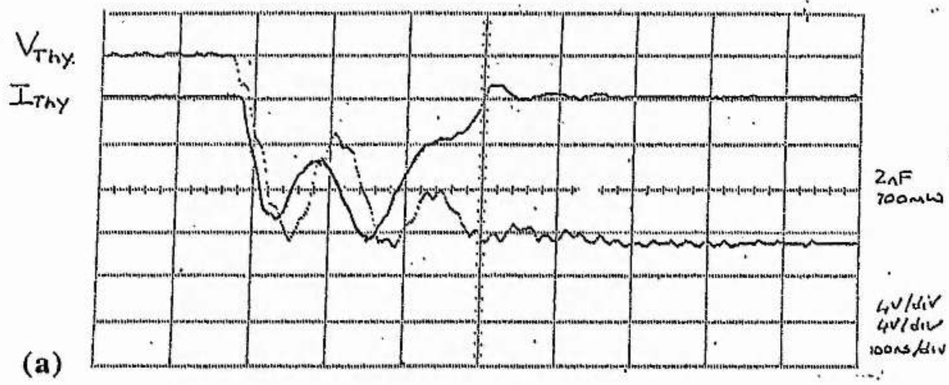
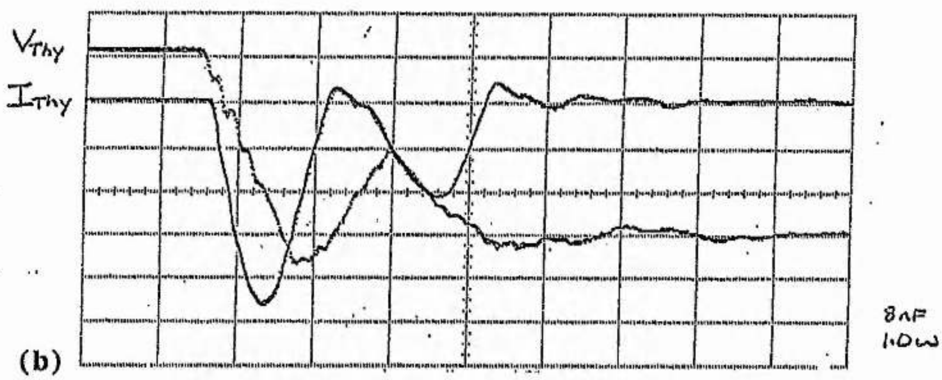


Figure 3.5 (b) Variation of laser output power with capacitor value (Cs = Cp).

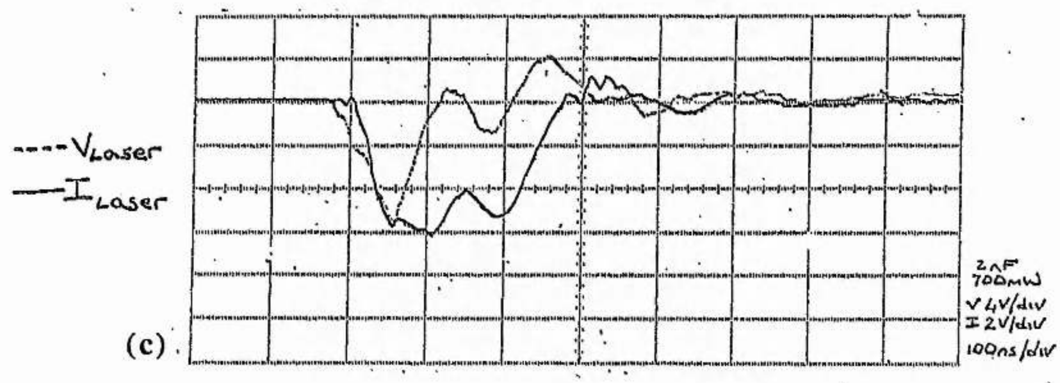


(a)

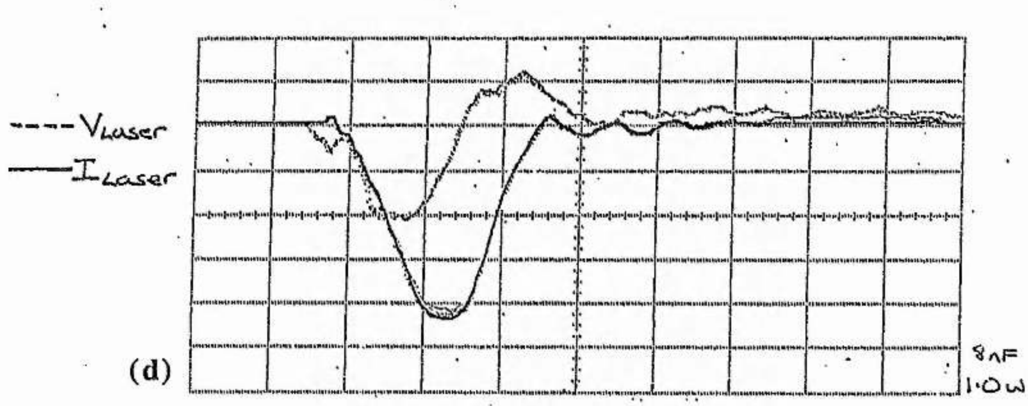


(b)

Figure 3.6 Voltage and current waveforms for the thyratron and laser tube, Cs = 8nF, Cp = 2nF (a) and (c), Cp = 8nF (b) and (d).



(c)



(d)

Chapter 4.

Thermal insulation.

4.1 Introduction.

One of the major design factors in CVL engineering is the need to produce sufficient vapour pressure for laser action to be possible. This problem does not exist in the majority of lasers in commercial production such as CO_2, excimer, solid state and noble gas ion lasers. In order to obtain the vapour pressure necessary for laser action to be possible, the copper charge in a CVL must be raised to 1500°C. At this temperature, the vapour pressure of copper is around 0.5 Torr, (fig.4.1), giving a copper density in the discharge tube of around 0.5×10^{15} atoms/cm^3. The demands in the copper halide vapour laser (CHVL) are not so stringent, with the correct density (of molecules) reached at 500°C (fig. 4.2). Again this is around 0.5×10^{15} CuBr molecules/cm^3. The radiation trapping effects discussed in chapter 2 are operative at this copper density and so laser oscillation can take place. High temperatures are therefore a precondition for lasing in copper and the methods and materials for retaining this heat are among the most important considerations when designing a laser head.

Many forms of thermal insulation have been used in the construction of copper vapour lasers. Previous devices used firebrick and corundum, (refs 1, 2, 3) while the latest models use alumina or zirconia in loose fibre or sheet forms, or in rigid, high density preformed shapes such as boards or cylinders. Metal foil radiation shields and coaxial vacuum jackets have also been used in a number of designs (refs 4, 5) but poor reliability due to insufficient development have led to these methods being left behind.

In many ways, the insulation affects the physical design of the laser head. Its qualities determine the overall diameter of the laser, the operating efficiency, construction materials and whether the laser can be sealed off or must have a flowing buffer gas.

This last point will become the telling one, as most copper lasers, currently in commercial production, require a gas flow, making a vacuum pump, gas cylinder and gas handling system a necessary but unwelcome expense and encumberance. The small sealed off copper bromide lasers, however, suffer none of these disadvantages and are now beginning to enter the market .

In this chapter the role of thermal insulation in the CVL and CHVL will be examined and the various types and forms available will be discussed. Implications of insulation properties for laser head design and performance will be looked at along with the heat transfer processes in action. It will be shown that certain trade-offs in performance will have to be accepted and that, with present insulation technology, any practical device is still far from the ideal.

4.2 Insulation requirements of the CVL and CHVL

For efficient electrical to optical conversion to take place in either the copper or copper halide laser it is necessary to retain some waste discharge heat in the laser tube assembly. Due to the significantly lower operating temperature of the halide device (500°C), the demands on thermal insulation are not as extreme as for the copper laser at 1500°C. Normally, however, the environments to which the thermal insulation is exposed are different in the two cases. In the high temperature variety, the insulation is exclusively located inside the vacuum envelope where it is exposed to severe heating under reduced pressure in an environment which needs to be maintained free of contaminants. This is an almost impossible task with large surface area, ceramic insulation, as the manufacturing and pre-firing process ensures that impurities are tightly bound and escape very slowly, even at these temperatures. One of the great attractions of copper halide devices, is that any insulation required can be removed to the outside of the vacuum envelope and heated in air. Thus, a major source of contaminants is removed from the laser tube and the coaxial return can be more tightly coupled at the same time allowing more efficient discharge pumping and also permitting the tube to be processed until it is very clean and then sealed off with no worries over contamination build up from thermal insulation. The properties of the thermal insulation do not, then, need to be similar. In practice, however, the same materials are used in both types of laser and the requirements for the copper laser are given below.

1. Ability to withstand the operating temperatures of the laser, that is 1500 - 1800^{o}C. The melting point of the thermal insulation should be substantially higher than the maximum laser working temperature. Also, the insulation material should not soften or have an appreciable vapour pressure at this temperature.

2. Low thermal conductivity.
The thermal conductivity should be as low as possible to minimise the amount of material necessary inside the clean zone of the laser head. This allows the current return to be as physically close to the laser tube as possible to reduce inductance and aid discharge pumping efficiency.

3. Chemical composition, stability and compatibility with operating environment.
The material comprising the thermal insulation should be such that it is very stable and unreactive with any chemical species found in the laser tube at the temperatures involved. It should undergo no changes of phase which may result in altered thermal properties and/or changes in physical size. The environment in which the thermal insulation is to operate must be clean and free of dust or debris, so the material should be as pure and uncontaminated as possible with no binders which may enter the plasma tube and react with the laser walls or windows. The material, if fibrous, should also not break into small pieces and drift around as the beam quality will suffer badly due to the scattering effect in combination with the very high gain associated with these devices.

4. Practicality of use, toxicity and ease of handling.
Safety and convenience are major considerations for the users of copper lasers and also in the development laboratory. As a uniform "blanket" of thermal insulation is usually

required around the alumina plasma tube the ease with which this can be achieved in both small and large bore lasers is often a deciding factor in using that material or material in a particular form, be it felt or low density mat. The nature of the material as regards toxicity, is also important as the laser must be opened every so often to recharge the copper load. Toxic materials may require awkward and expensive handling procedures to be enforced, thereby making the laser very "user unfriendly" and ruling out its use in many applications.

5. Low initial shrinkage and low coefficient of thermal expansion.

When the laser is packed with thermal insulation, it is normally filled with a known mass of material to a particular density. This allows more accurate control of the thermal conductivity. If the material shrinks or expands during heating, this may leave the plasma tube loose and off-centre or else risk placing excess stress on the vacuum envelope and stretching or rupturing it.

4.3 Insulating materials.

The two most popular materials for use as insulation in copper vapour lasers are the oxides of aluminium and zirconium, alumina and zirconia. These can be fabricated in forms convenient for use. Construction methods involving vacuum jackets with metal radiation reflectors and all metal designs have been proven to work but are difficult to assemble and maintain.

Zirconia and alumina have been used in the experiments described in this work but in different forms. The zirconia was in the form of sheets of felt, nominally 2.5mm thick and prefired to reduce outgassing and reactivity. The zirconia is stabilised by the addition of 8% by weight, yttria (Y_2O_3) to prevent a change of phase and subsequent shrinkage at around 1000^{o}C. The felt is quite easily damaged or torn so it is difficult to use on a small bore or a long tube. It is wrapped around the recrystalised alumina plasma tube to the required thickness and the whole assembly is pushed into a quartz or pyrex tube which provides a vacuum envelope.

Once heated to over 1300^{o}C the felt loses its flexibility and becomes stiff and friable. It is virtually impossible to re-use the felt from one laser tube in another and so, due to the expense of this material, it was used infrequently.

The demand for high purity, high temperature vacuum furnaces has prompted the development of new forms of zirconia. The most useful being those of rigid boards and cylinders. They have long been attractive due to the mechanical strength, high density, low outgassing and lack of reactivity. The presence of volatile binders, organic and inorganic, has precluded their use in most cases up till now. The latest types have no organic binders and the inorganic ones are stabilised to prevent 'dust' from entering the discharge tube. Some types have no binders at all and are readily machinable, these will be utilised in the next generation of copper lasers. None of the above preforms were used in any of the lasers described here, but in an experiment, two 'low binder' types were heated in air with an electric fire element. Both turned brown and fumed badly at 200^{o}C, showing that a small amount of organic material can produce an unacceptable amount of contamination, rendering them unsuitable for inclusion in a laser. The characteristics of zirconia felt, showing thermal conductivity and other important parameters, can be found at the end of this chapter, (table 4.1).

Alumina, in its recrystalised form, was used exclusively for laser tubes in the high temperature lasers, (copper and gold). It was also used in some of the copper halide devices where quartz was not considered to have sufficient structural strength at the temperatures reached. Alumina in this form has two main disadvantages from the viewpoint of the laser engineer. The inclusion of deep seated impurities means that extended vacuum baking or processing is required if anything approaching clean conditions is to be achieved in the laser head. The molecules most often encountered in outgassing from alumina tubes are O_2, N_2 and H_2 with metals such as Na and Ca also showing their presence when heat is applied, (ref. 7).

The second characteristic of recrystallised alumina which causes concern is the coefficient of thermal expansion (table 4.2). Over a number of thermal cycles it becomes physically difficult to locate an alumina tube accurately. Large temperature gradients imposed on the alumina by non uniform heating or rapid cooling can cause thermal shock and subsequent fracture of the tube. Although the maximum working temperature recommended for alumina tubes is 1950°C, softening can take place at temperatures below this and seriously warp or deform the tube. The gold vapour laser is more prone to this because of its higher operating temperature but it has also been observed in copper lasers, (ref. 8).

Alumina which is in the form of thin fibres and made into a low density mat, (I.C.I. Saffil), was used as the primary insulation on all of the copper vapour lasers described here, whether as packing round the alumina laser tube or as an external blanket around the current return. This form is easier to use and is much less expensive than the zirconia felt described previously. The thermal conductivity of this form is higher, however, (table 4.3) which means that more material must be placed between the laser tube and the current return. If this entails increasing the current return diameter, then the laser head inductance will increase. The practical advantage is that an alumina tube can be held centrally inside the vacuum envelope with a jig and then chunks of fibre can be torn from the mat and packed around it. This is not a pleasant task as the fibre breaks up into tiny needles and forms a thick cloud which irritates skin and makes goggles and face masks a pre-requisite. However, a relatively uniform packing density can be achieved and the alumina tube more accurately located than with rolled zirconia felt.

4.4 Heat transfer in copper lasers.

Virtually all CVL's made today are self heated devices. It is therefore very important that the waste heat from the discharge should be used to best effect to maintain the high efficiency inherent in copper vapour lasers. The thermal insulation should act to retain sufficient heat for the operating temperature to be reached and yet not allow the laser to overheat when full input power is applied. If the power loading on the laser tube wall is known, then the radial temperature profile can be calculated for various types and thicknesses of material in the surrounding assembly. Where constraints have to be met, such as the maximum operating temperature of ~1000^{o}C for fused silica, this can be taken into consideration when applying boundary conditions. Corresponding radial temperatures in the plasma during laser operation are not so simple to calculate, however, but since the copper vapour pressure is proportional to the source temperature, this can be taken as the temperature at the wall in a CVL where the copper is distributed randomly. In a CHVL, the source temperature is taken as either that of the reservoir or wall, depending on the tube construction . The plasma temperature limits the gain to a great extent and many CVL's which are run at too high a pulse repetition frequency have annular outputs due to gas heating on axis populating the lower laser levels.

4.4.1 Basic analysis of heat transfer processes.

The three ways in which heat can be transported through a system are conduction, convection and radiation. The first quantity, conduction, is regarded as the most influential mechanism as far as the transfer of heat from the laser tube to the outer wall is concerned. Convection plays a large part in passively cooled lasers, tending to be in the 1-3kW range and is mostly ignored in the larger water cooled devices. The part played by radiation in laser cooling is difficult to calculate accurately due to the nature of the materials and their geometry as will be made clear in the following sections.

A general analysis in basic form is given below for a conventional copper vapour laser designed as in figure 4.3. An alumina tube of length L, internal diameter r_1 and outer diameter r_2, is surrounded by an annulus of ceramic thermal insulation, thermal conductivity k_s, contained in a fused silica tube of internal diameter r_3 and outer diameter r_4 with thermal conductivity k_q. Most modern CVL's follow this design up to this point but outside the vacuum envelope, many different forms of heat management and removal are used. Some devices have more insulation contained within a water cooled jacket, some have only a water jacket and others simply a metallic jacket for forced air or natural convection cooling.

A treatment follows for the general vacuum envelope design and two of the above cases, (1) more insulation followed by a water cooled jacket and (2) an air cooled metallic casing. The important parameter from an engineering point of view is the pyrex/quartz inner wall temperature, T_3.

The heat flux, q, between two cylindrical surfaces is given by, (ref. 9)

$$q = \frac{2\pi k_A L\left(T_2 - T_1\right)}{\ln\left(\frac{r_2}{r_1}\right)} . \qquad (4.1)$$

Where k_A is the thermal conductivity of alumina,

k_S is the thermal conductivity of saffil at ~100 kg/m^3,

k_q is the thermal conductivity of quartz.

$$T_2 = T_1 + \frac{q \ln\left(\frac{r_2}{r_1}\right)}{2\pi k_A L} , \qquad T_3 = T_2 + \frac{q \ln\left(\frac{r_3}{r_2}\right)}{2\pi k_S L} ,$$

$$T_3 = T_1 + \frac{q}{2\pi L}\left[\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_A} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_S}\right] \quad (4.2).$$

If this temperature is in the range 400 - 1000^o C, then pyrex cannot be used and either fused silica must be employed instead or a thicker blanket of insulation placed between the plasma tube and the vacuum envelope. The use of insulation with a lower coefficient of thermal conductivity will also help to reduce the temperature at the vacuum envelope wall.

The outer wall temperature is given by,

$$T_4 = T_3 + \frac{q \ln\left(\frac{r_4}{r_3}\right)}{2\pi k_q L},$$

$$T_4 = T_1 + \frac{q}{2\pi L}\left[\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_A} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_S} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{k_q}\right] \quad (4.3)$$

As an illustration of the difference in vacuum envelope diameter possible between alumina fibre and zirconia felt, a laser tube configuration is given and the boundary conditions fixed.

$q = 3$ kW	$r_2 = 17$ mm	$k_A = 5$ W/m^{o}K
$L = 1$ m	$T_1 = 1500^o$ C	$k_S = 0.37$ W/m^{o}K
$r_1 = 12$ mm	$T_3 = 800^o$ C	$k_Z = 0.25$ W/m^{o}K

From equation 4.2, rearranging, we have,

$$\ln\left(\frac{r_3}{r_2}\right) = k_S\left[\frac{2\pi L}{q}\left(T_3 - T_1\right) - \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_A}\right],$$

therefore,

$$r_3 = r_2 \exp k_S\left[\frac{2\pi L}{q}\left(T_1 - T_3\right) - \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_A}\right],$$

$= 28.5$ mm

=> 57 mm diameter.

With the value for k_Z substituted for k_S the radius becomes,

$r_3 = 24.4$ mm

=> 48.8 mm diameter.

This saving of ~ 1 cm on the diameter represents a possible lowering of laser head inductance with a consequent increase in operating efficiency (section 4.5).

The effect of radiative heat transfer is difficult to estimate. If the alumina laser tube were radiating to a coaxial water jacket then it would lose, (ref. 10),

$$q = AF_s e\sigma(T_1^4 - T_2^4) \text{ Watts} \qquad (4.4),$$

where A is the surface area of the alumina tube, σ is Stefan's constant, e is the emissivity and F_s is the shape factor, which for infinite cylinders is,

$$F_s = \frac{1}{\frac{1}{e_1} + \frac{A_1}{A_2}\left(\frac{1}{e_2} - 1\right)} \qquad (4.5).$$

This process is complicated by the alumina radiating to the surrounding saffil or zirconia fibres and the heat being passed on by conduction and radiation. The radiation formula above would then indicate that much more heat was being lost through radiation than in actuality. Radiative losses are proportional to T^4 so that the outer surface of insulation, saffil or quartz, will lose heat by radiating to the cold metal jacket. The temperature difference here will be only a fraction of that between the alumina and the metal jacket. It would therefore be more realistic to take the temperatures of the insulation and jacket surfaces as the major radiation transfer parameters, assuming the quartz to be a transparent, non radiator.

As before, with $L = 1$ m

$r_3 = 57$ mm,

and assuming a wall thickness of 3 mm for the quartz, this gives a water jacket radius of

$r_j = 61$ mm, say.

Other data required to calculate the radiative heat flux;

$e_{saffil} = 0.5$	$\sigma = 5.676 \times 10^{-8}$ W/m^{2}K^4
$e_{stainless\ st.} = 0.4$	$T_1 = 600^o$ K
$F_s = 0.294$	$T_2 = 300^o$ K

This gives a heat flux of,

$$q = 363 \text{ Watts.}$$

This value will vary by a large amount depending on the surface quality and finish of the metal. Rough or oxidised steel will absorb radiation more readily than if polished and consequently will transfer more heat. This, however, is not the full story, as visible radiation is seen to be transmitted through the saffil when lasers of this construction are run up to operating temperature and the power input is switched off. More heat is being lost through radiation than can be simply accounted for.

The desired laser output power gives an idea, through the projected operating efficiency, of the required power input to the laser head. In general, if the power to be dissipated is above 2 - 3kW, then the laser will require water cooling. If not then air cooling is an option which makes the laser more attractive from the point of view of the user. This approximate figure comes from the wide base of work done by many researchers in this field. To give some impression of the capabilities of both water and natural convection cooling, an outer jacket/current return diameter of 50 mm is arbitrarily chosen and analysed for the two cases.

1. water cooling.

Water jacket	o.d. 100 mm,	i.d. 94 mm,
	Length 1m,	Water temperature 10^{o} C,
	Inner wall temperature 100^{o} C,	$k_{stainless\ steel}$ @ 50^{o} C = 16.9

From equation 4.1 we have,

$$q = \frac{2\pi kL\left(T_{out} - T_{inn}\right)}{\ln\left(\frac{r_{out}}{r_{inn}}\right)}$$ and inserting the values above, we get,

$$q = 154\ \text{kW}.$$

This is a large amount of heat and shows the capability of water cooling if sufficient care is put into flow management to maintain a constant water temperature over the whole surface. This figure will be reduced substantially by the thermal conductivity of the air gap between the water jacket and the hot wall which will set an upper limit on heat transfer. Even assuming that the cooling is much less effective than this leaves the designer with the potential over-cooling of the laser. It is then necessary to increase the thickness of insulation around the tube to reduce the temperature of the wall to be cooled. This can lead to the laser becoming bulky and inductive.

2. convection cooling

Removal of heat by natural or forced convection of air is a complex subject involving fluid dynamics on both the macroscopic and microscopic levels. It is important to have some idea of how the fluid, air in this case, will move past the surface to be cooled. Depending on surface finish and temperature, the flow may be laminar, turbulent, or a mixture of the two with one type dominating for a short time and then changing to the other type. If the surface is smooth and not too hot, then the flow will be laminar. As there is minimal mixing of the fluid from adjacent lamina the transport of heat is by molecular conduction. This is very resistive to heat transfer and the layers can act more as insulators than as a heat removal system. As the air moves faster over the surface or is disturbed by irregularities then the boundary layer of laminar flow becomes confined closer to the surface and eventually separates with the layers mixing together as the flow becomes turbulent. Chaotic or turbulent flow is a much more effective way of cooling a hot body but due to the nature of the flow, prediction or control of the process is inexact and difficult to model. In some lasers, such as axial CO_2 devices, a wire turbulator is wound into the coaxial water space around the laser tube. This forces the cooling water to become turbulent and the tube is cooled more evenly and effectively.

The basic rate equation for convective energy exchange is, (ref. 9)

$$q = h\,A\,\Delta T \qquad (4.6).$$

Where ΔT is the temperature difference between the surface and the fluid. A, is the contact area and h is the convective heat transfer coefficient. This coefficient is related to the fluid flow mechanism, the properties of the particular fluid and the system geometry. The expressions involved in finding a value for h are complex but can be simplified by assuming that the cooling takes place by natural convection in air.

The expression becomes,

$$h = a\left(\frac{\Delta T}{L_S}\right)^b \qquad (4.7),$$

where a and b are constants which depend on geometry and flow conditions. The quantity, L_S, is a characteristic length and is dependent on the flow type, whether it is laminar or tends towards turbulence. Values are suggested for a, b and L_S in ref. 11, relating to flow around cylinders. They are $a = 1.32$, $b = 0.25$ and L_S equal to the diameter of the cylinder.

For the cylindrical current return assumed earlier with diameter 100 mm and wall temperature $200^{o}C$ the rate of convective cooling in still air at $20^{o}C$ would be,

$$q = 25.133\ h.$$

With h given by equation 4.7 $\qquad h = 8.6$,

therefore, we have $q = 486$ Watts.

Cooling of the metal cylinder in this case would be aided to a great extent by the radiation transfer of heat to the cool surrounding room. In the case of our laboratory lasers, the current returns were normally made from brass tubing which oxidises very quickly over all of its surface. This is an ideal situation for efficient radiative transfer as the emissivity of oxidised metals is usually much higher than even an unpolished sample of the metal itself. Returning to equation 4.4, we can see that, as

$$e_{\text{oxidised brass}} = 0.96,$$
$$T_1 = 473 \text{ K and } T_2 = 273 \text{ K}$$

then, $q = 731$ Watts.

Thus, radiative transfer seems to account for a greater proportion of the tube cooling than does convection in laminar flow. It is unlikely, however, that convective flow over this surface will be laminar as no attempt was made to remove surface imperfections which cause boundary layer seperation and turbulence. In most designs of this type it was possible to dissipate 2 - 2.5kW of power without raising the current return temperature above 200^{o}C.

4.5. Implications of heat management on laser head design.

It has been shown above that the various types and sizes of laser head have widely varying requirements in terms of thermal management. Pure copper lasers have the problem that expensive, high temperature and high purity materials must be used if the physical size of the head is to be minimised. This is an important consideration from the point of view of efficiency as laser head inductance has a direct bearing on discharge pumping of the copper laser levels.

Other considerations which assume importance in different applications are input power and warm-up time. If the input power is limited, then there is a protracted warm-up time, especially if the laser head has a large thermal mass. If this is the case, then one positive point is that the thermal mass will tend to buffer any transient change in input power if the supply is not stabilised. The tube temperature will change only slightly and very slowly, maintaining stability of the beam quality and wavelength power ratio. A laser with low thermal mass and with lasant vapour pressure dependent on tube temperature will warm up quickly but will follow the input power more closely, in that, if the matching changes for a few moments due to the ingress of contaminants, the tube temperature will rise or fall giving a change in output power, beam profile and the ratio of the wavelength intensities. One way to avoid this is to decouple the copper vapour pressure from the discharge input power and this can be done effectively in copper halide laser devices (chapter 6).

As a consequence of the fused silica construction often employed in copper halide lasers, it is possible to make devices with very low thermal mass. If metal tubes are used for discharge containment and the quartz vacuum envelope is sandwiched between this and the closely coupled metal current return (fig.4.4), then the laser head inductance can be drastically reduced. The inductance of a coaxial system such as a copper laser head is given by,

$$L = \frac{\mu_o}{8} + \frac{\mu_o}{2} \ln\left(\frac{r_2}{r_1}\right) \text{ Henrys/m}, \qquad (4.8)$$

where r_1 and r_2 are the radii of the inner conductor (discharge tube) and outer conductor (current return) respectively. Figure 4.5, shows the values of the inductance of a coaxial laser head when the discharge tube internal diameter is 20mm and the current return diameter is varied from 22mm to 100mm. In evaluating equation 4.8 for fixed discharge tube diameters, it is assumed that the discharge fills the tube. If the discharge is constricted then the effective inductance of the discharge circuit will increase. It is also possible to remove heat at a much greater rate from the laser tube as the limiting factors are now conduction through the quartz and the air cooling of the current return. One such device, constructed in our laboratory, started from cold and produced 10 Watts after 38 seconds. This demonstrates that copper lasers need no longer be associated with unacceptably long warm-up times but as virtually instant light systems with the limiting factor being thyratron warm-up time.

It is possible to take the theme of high flux, heat extraction another step forward. If instead of using a tubular metal current return with air (or water) cooling, the laser tube is surrounded by a material which can withstand the temperatures involved, conduct heat very well and act as a current carrier, then the laser may be made less inductive and the large thermal gradients which shorten tube lives can be moved further from the critical vacuum envelope (ref 12). Liquid metal best fits this requirement and in particular tin. The melting point of tin is 232^{o}C and it boils at 2720^{o}C giving it a very large liquidus indeed. If the laser tube is surrounded by tin, then at the plasma tube/tin interface, the tin will be molten (copper or copper halide lasers) and will conduct heat extremely well. The tin may either be flowed through heat exchangers using electromagnetic pumps or may be allowed to sit stationary in its containment. In the latter case, a liquid/solid interface will form at some radial distance from the laser tube. Heat will be rapidly conducted away from the laser tube to some external cooling system where the thermal shock can be more easily dealt with, say by a cooled metal wall. In this device, (which has been proven in principle) an inordinately large amount of heat is deposited by the discharge in the laser tube, for a 1metre long 1cm diameter tube this may be in the region of 100kW. If laser efficiency can be maintained at, or around 1%, then a huge amount of laser light can be extracted from a relatively small laser tube. Calculations show that 1kW of light output may be expected from a 1m long laser tube such as described above. The presence of liquid metal on the outer wall of the tube provides a method of maintaining the tube at a constant temperature which optimises laser output. The metal can also act as a very tightly coupled current return. As with the design of the argon ion laser where the power loading on the tube walls is enormous, the thermal management, if done correctly, will remove this heat with little or no detraction from the laser output power.

These, then, are the two extremes. The fat, bulky CVL with much insulation, operating under conditions requiring high heat retention but limited in output power due to the ease of overheating, or the slim copper halide laser where heat removal is the priority and the problem of insulation borne contamination does not arise.

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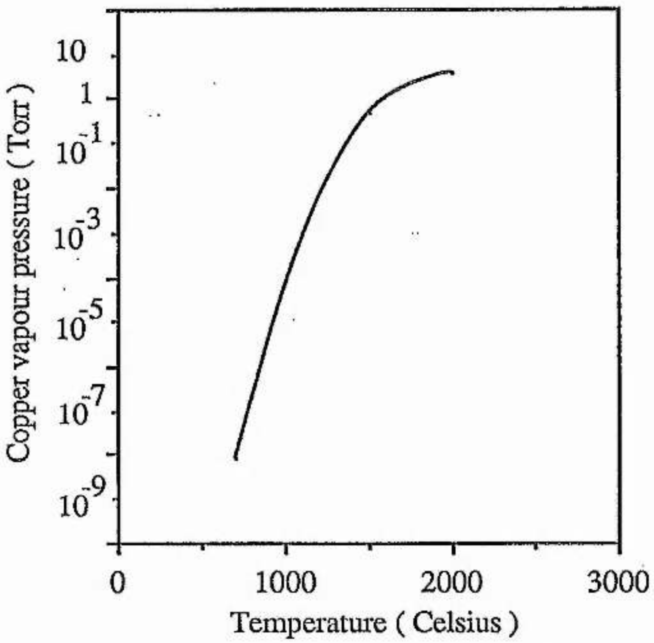

Figure 4.1: Vapour pressure of copper.

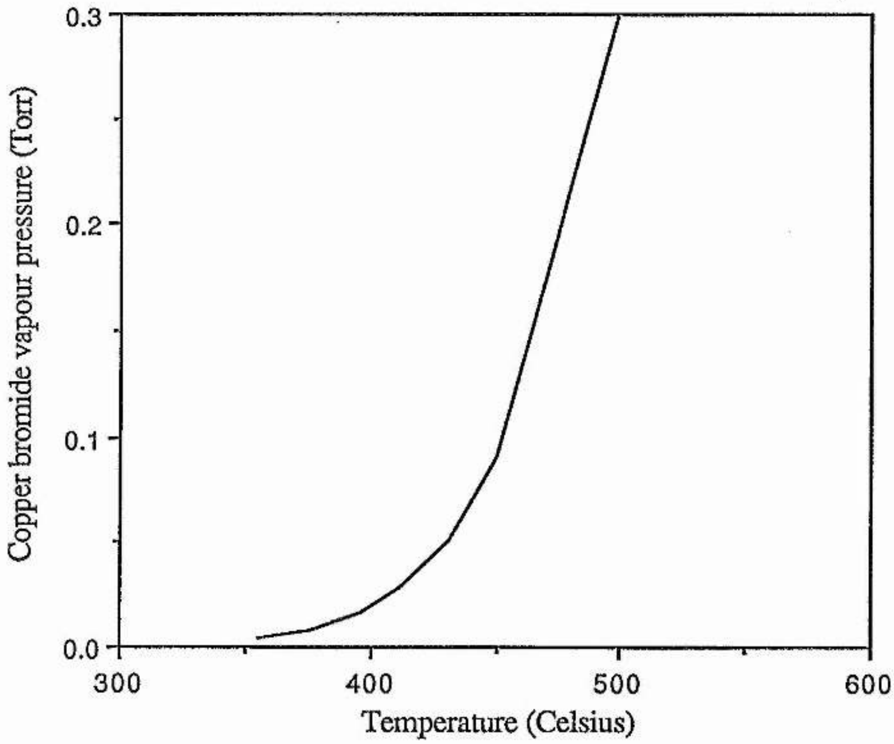

Figure 4.2: Vapour pressure of copper bromide.

Table 4.1: Properties of zirconia insulation products, (Zircar products inc.).

Material form	**Rigid boards Cylinders**	**Felt**
Product code	ZYFB6	Felt
Description	Rigid preforms containing no binder; 100% ZrO_2 fibres sintered together. low outgassing and reactivity	Mechanically locked ZrO_2 felts fired to a high temperature, having low reactivity and low outgassing. Good flexibility.
Availability	Square boards Disks Cylinders	18" x 24" rectangles, nominal thickness 0.05" or 0.1".
Composition	YrO_2 92% Y_2O_3 8% SiO_2 < 0.3%	YrO_2 92% Y_2O_3 8% SiO_2 < 0.3%
Porosity	84%	96%
Bulk density	1000 kg/m^3	240 kg/m^3
Stability, shrinkage after hours @ temp.	0.5% 1 hour @ 1650°C	4.6% 1 hour @ 1650°C
Melting temp.	2590°C	2590°C
Maximum use temp.	1650°C	2200°C
Thermal conductivity W/m^2K @		
400°C	0.16	0.1
800°C	0.19	0.15
1100°C	0.22	0.2
1400°C	0.25	0.26
1650°C	0.27	0.32

Figure 4.2: Properties of alumina tubes.

(Friedrichsfeld Degussit)

Material grade	**Al 23**	
Composition	typical 99.7% Al_2O_3 minimum 99.5%	
Density	3700 - 3950 kg/m^3	
Grain size	10 - 20 µm	
Porosity	0%	
Hardness	23000 N/mm^2	
Elastic modulus	3.5×10^5 N/mm^2	
Resistance to thermal shock	good	
Melting point	2030°C	
Max. working temperature	1950°C	
Specific	850 J/kg K	
Thermal conductivity	100°C 1000°C	25 - 30 W/m^2K 5 W/m^2K
Coeff. of linear expansion between 0 and 1000°C.	8.1×10^{-6}/K	
Emissivity at 1000°C.	21%	
Electrical resistance at	20°C 1000°C 1500°C	$>10^{14}$ Ohm cm 5×10^6 1×10^4
Electrical breakdown strength	22kV/mm	

Table 4.3: Properties of Saffil low density mat.
(I.C.I. Chemicals and polymers)

Maximum use temperature	1600°C	
Shot content	negligible	
Main components	Al_2O_3	95%
	SiO_2	5%
Trace components	iron	400ppm
	chromium	60
	nickel	140
	sodium	875
	magnesium	130
	calcium	525
	chloride (total)	80
	chloride (leachable)	5
Chemical resistance	Very good resistance to acids, alkalis and reducing atmospheres.	
Thermal conductivity @ density of 96kg/m^3	°C	W/mK
	200	0.062
	600	0.106
	1000	0.182
	1400	0.314
	1600	0.412
Linear thermal shrinkage 24 hours @ temperature	°C	Shrinkage %
	1200	0
	1400	< 2
	1500	< 3
	1600	< 4

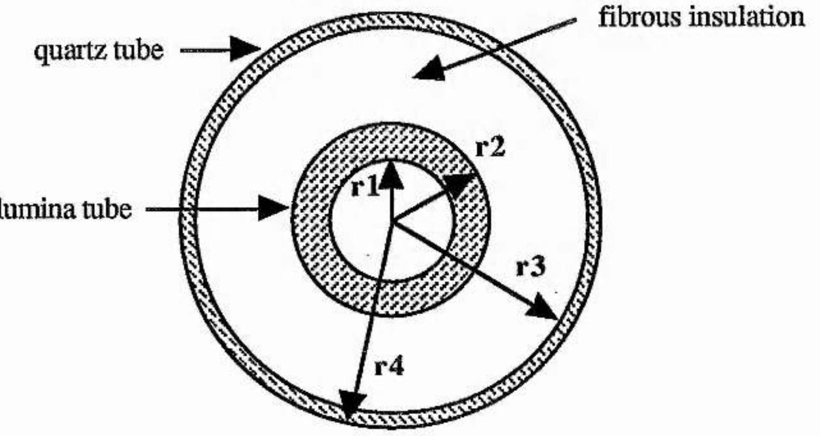

Figure 4.3: Design scheme for copper vapour laser.

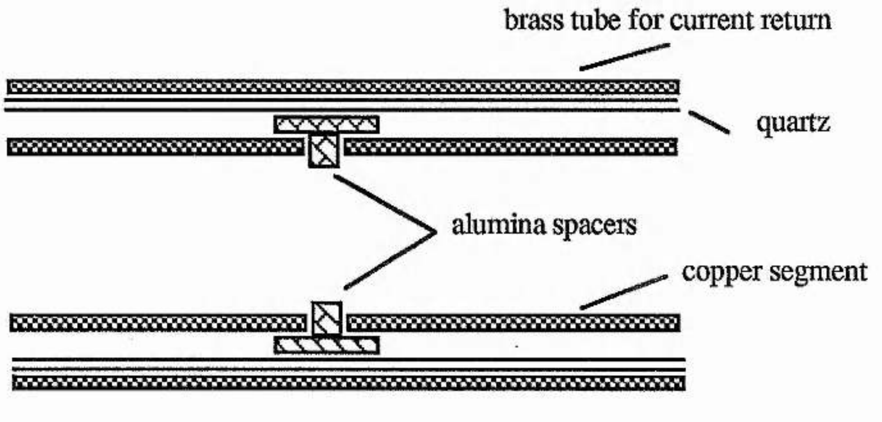

Figure 4.4 Low inductance tube with metal segments.

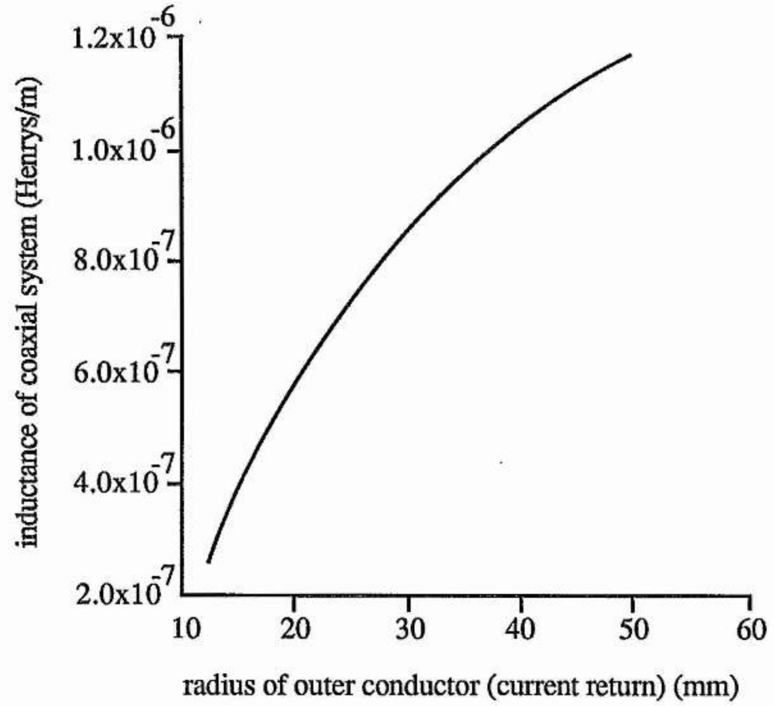

Figure 4.5 Variation of the inductance of a coaxial circuit with the outer conductor radius, assuming an inner conductor (plasma) radius of 10mm.

Chapter 5.

Discharges confined by metal tubes.

5.1 Introduction.

The use of metal tubes for the confinement of laser discharges began with the argon ion laser (ref 1). At this time, laser tubes were made of quartz which suffered badly from ion bombardment of the walls. Tube lives were short and in sealed devices the lasing gas was trapped by these impacting ions and quickly cleaned up. It was these problems which prompted the search for an operating regime which lent itself better to prolonged tube life. One solution which became accepted was the use of metal segments to form the discharge tube. Each segment was insulated from its neighbour by separation, so that its potential could vary independently of the others according to its position in the potential gradient between anode and cathode. In this way and at the pressures involved in argon ion discharges, it was found that metal segmented laser tubes not only worked but had some major advantages.

One problem encountered with quartz laser tubes was decomposition of the wall material and contamination of the discharge. This is not only a problem in ion lasers but any laser which requires a high purity environment for optimum performance. Metallic walls do not decompose but rather sputter, producing no contamination to upset the power supply matching to the discharge (chapter 3). The metallic wall makes the plasma tube more robust and resistant to thermal shock. When used in a copper vapour laser, for example, the problems associated with refractory ceramic tubes are legion. They crack due to thermal shock and due to electric field stress, have a great tendency to 'creep' and collapse at temperatures much less than their stated softening point and perhaps worst of all they contain a relatively massive amount of deep seated impurites which diffuse out slowly when the tube is heated. Metal has none (or very few) of these problems. In addition metallic segments or walls can remove discharge heat at a vastly greater rate than quartz or alumina (see chapter 4).

5.2 D.C. Theory

As metallic walls became important for argon ion lasers, the theory behind the operation of metal as a plasma confinement material began to develop (ref 2,3). It emerged that, as the gas in the segmented tube is ionised, there is a drift of ions and electrons to the wall. It can be seen from kinetic theory equations that the average velocity of a gas particle is (ref 4),

$$v = \left(\frac{8kT}{\pi m}\right)^{\frac{1}{2}} . \qquad (5.1)$$

So that with $m_+ \simeq 1000\ m_e$ and, in an ionization non-equilibrium state such as exists in the rising edge of a current pulse, T_e, the electron temperature, much greater than T_+, the ion temperature, we see that,

$$v_e \geq v_+ .$$

Normally the ratio of these velocities is of the order of 1000 : 1, for the gases used in laser discharges.

The greater velocities of the electrons means that, as the discharge develops, more electrons than ions will collide with the metal segment. If this segment is not connected to an external voltage source, then it will acquire a negative potential with respect to the plasma. As this potential grows, electrons arriving from the plasma will be repelled and ions attracted. A region will develop between the plasma and the wall which contains positive ions almost exclusively . A few high energy electrons will still penetrate this sheath, sufficient to maintain the steady state negative potential of the segment. Figure 5.1 shows the situation in this case. If a dielectric tube (alumina, zirconia) were used, then its wall potential would follow the dashed line. Since a metal segment has an equipotential surface there must be a difference in potential (with respect to the plasma) between the ends of the segment. Therefore, at the anode end of the segment, the potential difference between the plasma and the segment is greatest. The segment appears more negative here and as such, will attract a greater ion than electron current. The positive ion sheath will be at its greatest thickness here. As we move towards the cathode end of the segment the ion current is reduced and the electrons can penetrate the sheath more easily. There is a ring on the surface at some distance from the anode at which the ion and electron currents are equal before the electron current increases towards the cathode end. The point at which the currents are equal occurs when the potential of the segment with respect to the plasma is V_f. Over the total surface area of the segment, by conservation of charge, the total ion and electron currents are equal. If one or more metal segments are present in a discharge tube, then prior to breakdown, the electric fields between the segments and between the electrodes and the segments will be increased, Figure 5.2.

It has also been shown, (ref 2) that, for discharges with fixed conditions, (gas type, pressure and electric field) there is a maximum segment length permitted. This length (in a steady state discharge in neon) is given by,

$$d_{max} = 1.32 \times 10^{-2}\, T_e / X \quad \text{metres} \qquad (5.2),$$

where T_e is the electron temperature and X is the potential gradient in the discharge tube given by,

$$X = (\text{voltage across tube})/(\text{tube length}) \qquad \text{Volts/metre.}$$

If the segment is too long (Figure 5.3), then the cathode end will become positive with respect to the plasma. The anode end is still negative with respect to the plasma so all or part of the interelectrode current will then run through the tube walls. The ratio of the wall current to the plasma current will be the inverse ratio of the impedances of the wall and axial paths.

For segments with short gaps between them, the electric fields in the gaps may be high. In discharge tubes at relatively high pressures (100 Torr - atmospheric) this may cause a problem due to short-gap breakdown. Paschens law shows that the breakdown voltage of a gap between two conductors is dependent on the product of the gap distance and the gas pressure (for a given gas). Figure 5.4 shows the relationship (Paschen curves) for neon and hydrogen. It can be seen that for short gaps, it is advantageous to work at low pressures, on the left of the Paschen minimum, as the breakdown voltages here rise rapidly. This is the regime under which hydrogen thyratrons operate. Very short gaps can hold off many thousands of volts. No theoretical consideration has been given to the optimum gap distance which is very much dependent on the specific operating conditions.

5.3 Pulsed Discharges

In a pulsed discharge after breakdown, the current rapidly increases, peaks and then decreases to zero. In a copper vapour laser discharge, (high temperature or halide), much depends on the immediate past history of the tube. If the tube is cold, there will be little ionization remaining at the end of the interpulse period. As the plasma recombines, the potential of the adjacent segment becomes less negative (reduced electron current to the segment) and approaches that of the plasma. When voltage is applied for the subsequent pulse, both the gas and the segment - gap combination present themselves as potential discharge paths but with different breakdown voltages. If the sum of the breakdown voltages in the gaps is less than that of the gas in the discharge channel, then the discharge will indeed run through the metal and through randomly sited arcs between the segments. In a hot tube, there is normally a well pre-ionized path available with a low breakdown voltage, as the plasma has a high density of electrons, ions and metal vapour. It is an advantage then, to start a metal segment pulsed laser from cold at a high pulse repetition frequency to maximise the pre-pulse ion-electron density.

By examining the time which is taken by the ions and electrons in the plasma to respond to changing electric fields, it can be shown that if the Debye length is small compared with the tube radius, then charges in the periphery of the plasma will move to screen the bulk of the plasma from any change in wall potential.

As the electron temperature increases rapidly as the current increases, the walls become more negatively charged and the maximum sustainable segment length increases.

If the ratio T_e/X is increased suddenly (on a timescale short compared with the plasma response time) then the maximum segment length, d_{max}, increases to the new equilibrium value and because the plasma response is relatively slow, this length will continue to increase but will then peak and decrease to the equilibrium value as the plasma begins to 'perceive' the new distribution of charge and responds accordingly. The parameters which determine the degree of overshoot of d_{max}, if there is an overshoot at all, are the Debye length and the plasma frequency, ω_p. These are given by, (ref 6),

$$\lambda_d = \left(\frac{kT_e\varepsilon_o}{ne^2}\right)^{\frac{1}{2}} \quad \text{metres and} \quad \omega_p = \left(\frac{ne^2}{m_e\varepsilon_o}\right)^{\frac{1}{2}} \quad \text{rads/sec.}$$

where the symbols have their usual meaning. Assuming an initial electron temperature value close to that of the gas temperature (2000 K) and an initial electron density n_{eo} of $1\text{x}10^{13}$/cc, (ref 7), the Debye length and plasma response times on discharge initiation are estimated at 1mm and 5ns, respectively. These values mean, that, at this stage in the discharge development, the walls are not well screened from the plasma. The maximum segment length will follow the electron temperature closely and increase. As the electron density increases, the Debye length and plasma response time both decrease and as the current pulse peaks there may be a slight over-shoot in the maximum segment length. It is seen then, from equation 5.2 that, as both T_e and X are functions of time in a pulsed discharge, then d_{max} must also be time-dependent. The electric field which has built up before breakdown, collapses as the current rises. The electron temperature will have a low initial value and rise during this time. Both of these effects will increase d_{max} and help the discharge, in that, if the segments in a real laser are slightly too long, then the discharge will be initiated in the gaps between them. Through subsequent pulses, sufficient ionisation will build up within the segment volume to carry some of the current axially. As the current during a pulse begins to flow, it will begin by being attached to the segments (as they are longer than the allowed d_{max} at that time) and as the current increases, the discharge will 'peel' away from the segments towards the axis of the tube. Using a model for the electron temperature which is based on experimental observation (ref 9) and taking a generalised capacitive fall as a basis for the collapsing electric field, we have,

$$T_e = T_o \exp\text{-}\left(\frac{at}{t'}\right), \tag{5.3}$$

where a is a constant and t' is the full width of the current pulse, (assumed here to be 200 ns). Inserting boundary conditions,

1. at $t = 0$, $T_e = 2000$ K

2. at $t = 100$ ns, $T_e = 54180$ K (= 7eV) (ref 8),

we obtain,

$$T_e(t) = 2 \times 10^3\, e^{3.3 \times 10^7 t}, \tag{5.4}$$

these conditions are valid during the current rise time.

Also, we have

$$X = X_o \exp\left(-\frac{t}{\tau}\right) \tag{5.5}$$

where τ is a constant which sets the rate at which the electric field falls. The boundary conditions here are:

1. at $t = 0$, $X = 5 \times 10^3$ Volts/metre
2. at $t = 100$ns, $X = 5 \times 10^2$ Volts/metre (sustaining field).

The electric field, X, is given by,

$$X(t) = 5 \times 10^3 \, e^{-\left(\frac{t}{4.34 \times 10^{-8}}\right)} \text{ volts/metre.} \qquad (5.6)$$

The functions for electron temperature and electric field are plotted in figures 5.5 and 5.6. The corresponding time-dependence of d_{max}, is seen to be, from equation 5.2

$$d_{max} = \frac{26.4 e^{3.3 \times 10^7 t}}{5 \times 10^{-2.3 \times 10^7 t}} \text{ metres,}$$

so we get

$$d_{max} \sim 5.28 \times 10^{-3} \, e^{5.6 \times 10^7 t} \text{ metres,} \qquad (5.7)$$

since the electric field exponent is dominant. The form of d_{max} can be seen in figure 5.7. From the shape of the function it can be seen that discharge attachment to the segmented walls of a laser tube should last for only a small part of the current risetime before the discharge exits the metal and moves towards the tube axis. It is possible to use a metal tube which is too long for the discharge and yet escape some of the consequences due to the effect of the changing maximum segment length. This makes the use of metal segments very flexible, as one set of segments of fixed dimensions can accommodate a variety of discharge conditions.

The effect of reducing or increasing the buffer gas pressure has an effect on the electron temperature. As the pressure is increased for example, the electron temperature is reduced and the maximum sustainable segment length becomes shorter.

The high repetition rate of copper lasers has an important consequence for the establishment of a uniform axial discharge. Due to incomplete recombination between discharge pulses there will be some portion of the plasma still in evidence when the voltage is reapplied for the subsequent pulse. As there is plasma already in the tube, there is also the remains of the sheath on the walls, the negative charge on the metal segments decaying with the plasma. Thus, the initial charge on the segment wall depends to a great extent on the tube temperature and proximity to its operating region. If the tube is cold, there is a low ionization level and small wall charge which will brings a greater chance of Paschen breakdown between the segments. At higher temperatures and with metal vapour in the discharge tube, the pre-pulse ionization level (and hence wall charges) are substantially greater. The axial path has a much lower breakdown voltage and so the discharge is more likely to establish itself along the tube axis. In some of the experiments described in chapter 6, it was necessary to run discharge devices at low pressures until the ionization level had risen sufficiently to allow an axial discharge at the desired, higher operating pressures.

5.4 Comparison of dielectric and metal walled tubes in a discharge circuit.

In order to determine the effect of a discharge tube composed of metal segments on the electrical behaviour of an established circuit, the following experiment was conducted. A glass tube of 50 mm internal diameter with two metal end flanges was prepared. The end flanges are provided with windows and electrode holders. The electrodes are rolled molybdenum sheet and are separated by 365 mm. Gas inlet and outlet pipes are also provided on the end flanges. The modulator circuit used is the standard copper laser circuit but with no peaking capacitor. Fig 5.8. The storage capacitor is 2 nF and in each part of the experiment the pulse repetition frequency (prf) is fixed at 2kHz , the voltage on the storage capacitor is fixed at 10kV and the buffer gas neon) pressure is held at 10 mb.

The tube was first operated under the above conditions with no metal segments. The voltage across the tube and the current through it may be seen in Fig 5.9 (a). A copper tube of internal diameter 43 mm and length 240 mm was placed inside the glass tube, centrally between the electrodes. Again a discharge was struck and measurements of voltage and current taken Fig 5.9 (b). The copper tube was then cut into three equal sections of 80 mm length electrode-segment and segment-segment spacing were equal. The results of a pulsed discharge in this arrangement are shown in Fig 5.9 (c).

Examination of the waveforms from the three cases above show that only minor differences exist between them. The tube which contains no segments has a peak current 10% greater than the two segmented tubes and this current pulse appears to terminate 30 ns (or 6% of the base width) before the other two. For such a major alteration in the material bounding the discharge, there are surprisingly few effects impressed on the behaviour of the tube as a load. The length/diameter ratio appears not to disturb the operation of the circuit and so these segments may be used where previously insulating walls only have been applied.

5.5 Conclusions

The adoption of segmented metal tubes for argon ion lasers was a significant step forward in terms of tube life, reliability and robustness. The theory of operation has been extended to cover pulsed discharges and, in particular, those associated with copper vapour lasers. In this chapter, the behavior of metal segments during a pulsed discharge has been described theoretically. The time-dependence of the maximum segment length has also been calculated and the conclusions drawn from the results are that, in a discharge tube with metal segments, the maximum segment length increases from a level determined by the pre-pulse plasma density. The fall of the axial electric field, dominates the equation which determines d_{max}, (equation 5.2). The maximum segment length increases rapidly during the current pulse rise and so forces any current which is running through the wall, to leave the metal and fill the axial discharge volume. No reasons have been found why segmented metal tubes cannot form the basis of a successful copper vapour laser.

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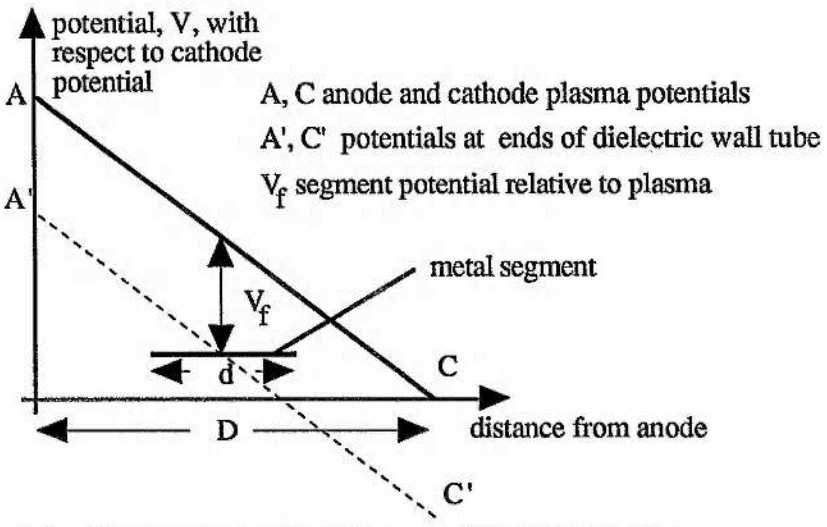


Figure 5.1 Comparison of plasma, metal segment and dielectric tube potentials.

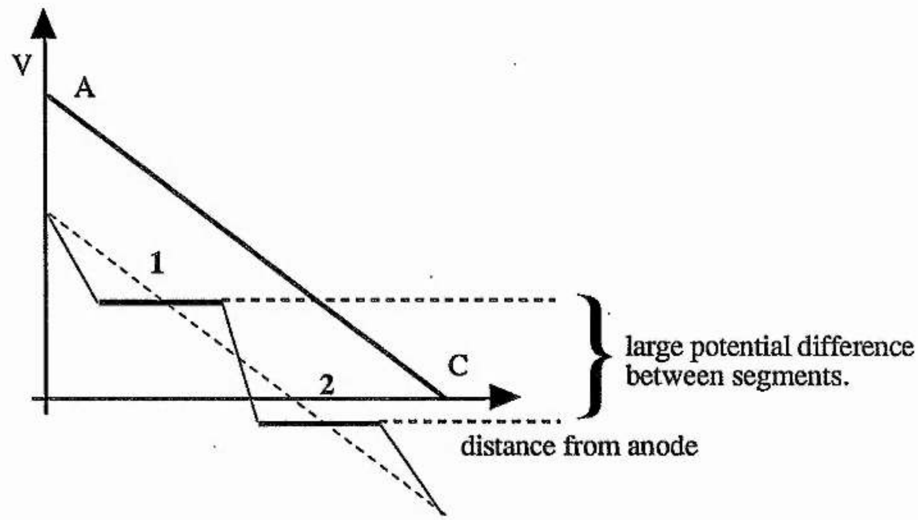


Figure 5.2 Field increase between segments.

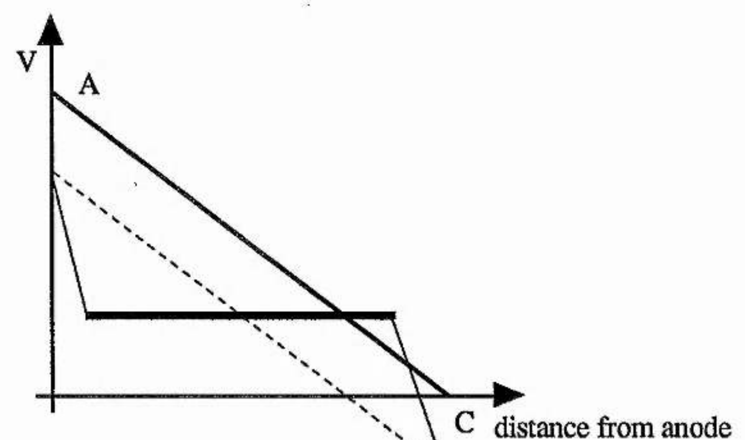


Figure 5.3 Length of metal segment is too great to support axial discharge.

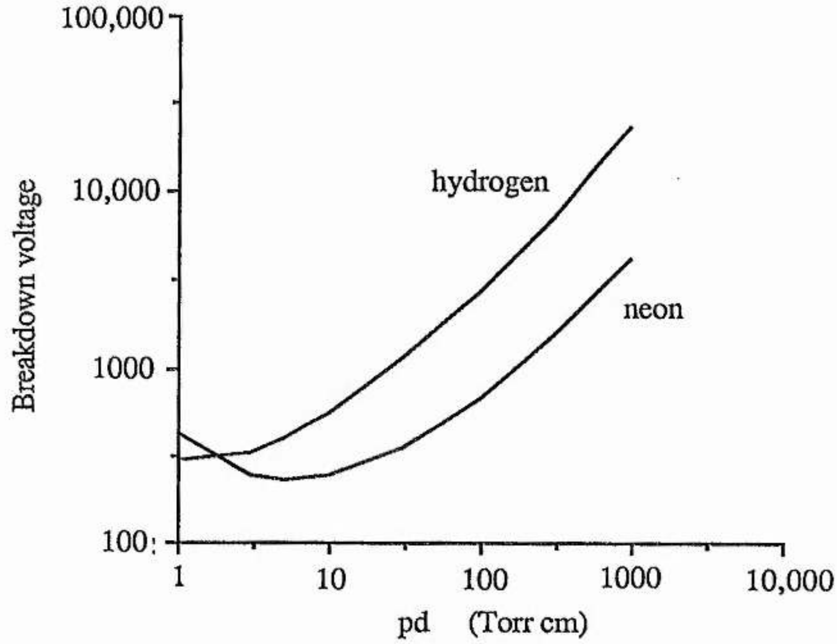


Figure 5.4: Paschen curves for hydrogen and neon

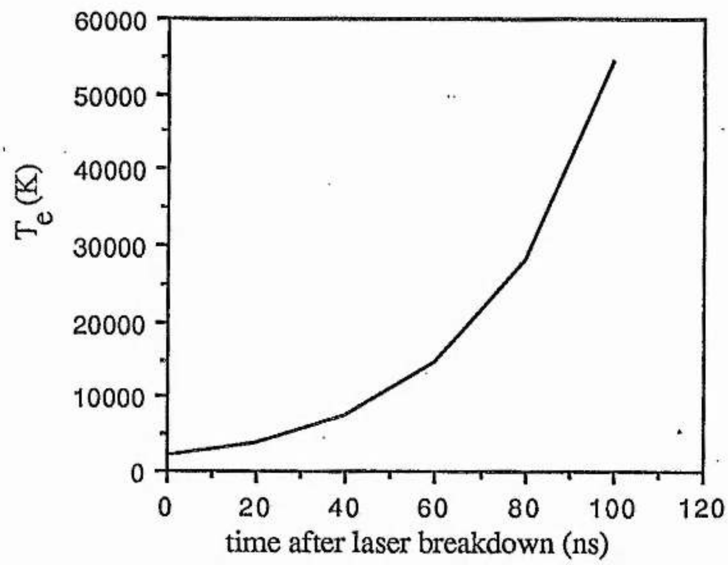


Figure 5.5: Model for electron temperature evolution. (ref 9).

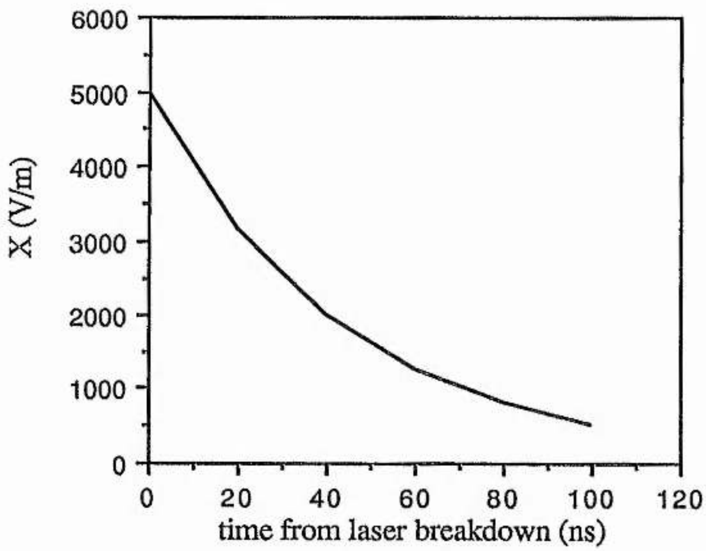


Figure 5.6: Model for axial electric field during discharge evolution

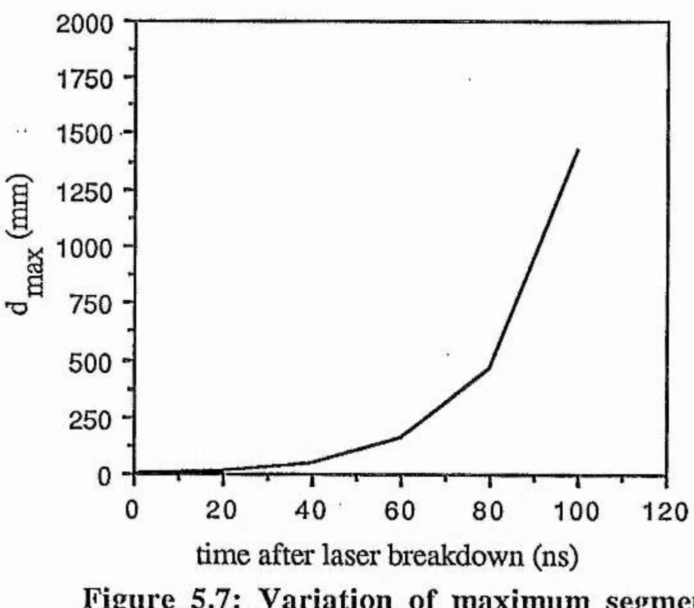


Figure 5.7: Variation of maximum segment length as discharge evolves.

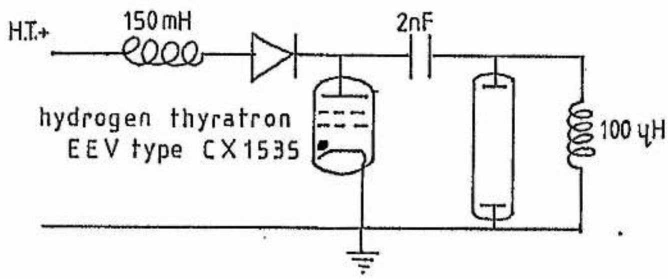
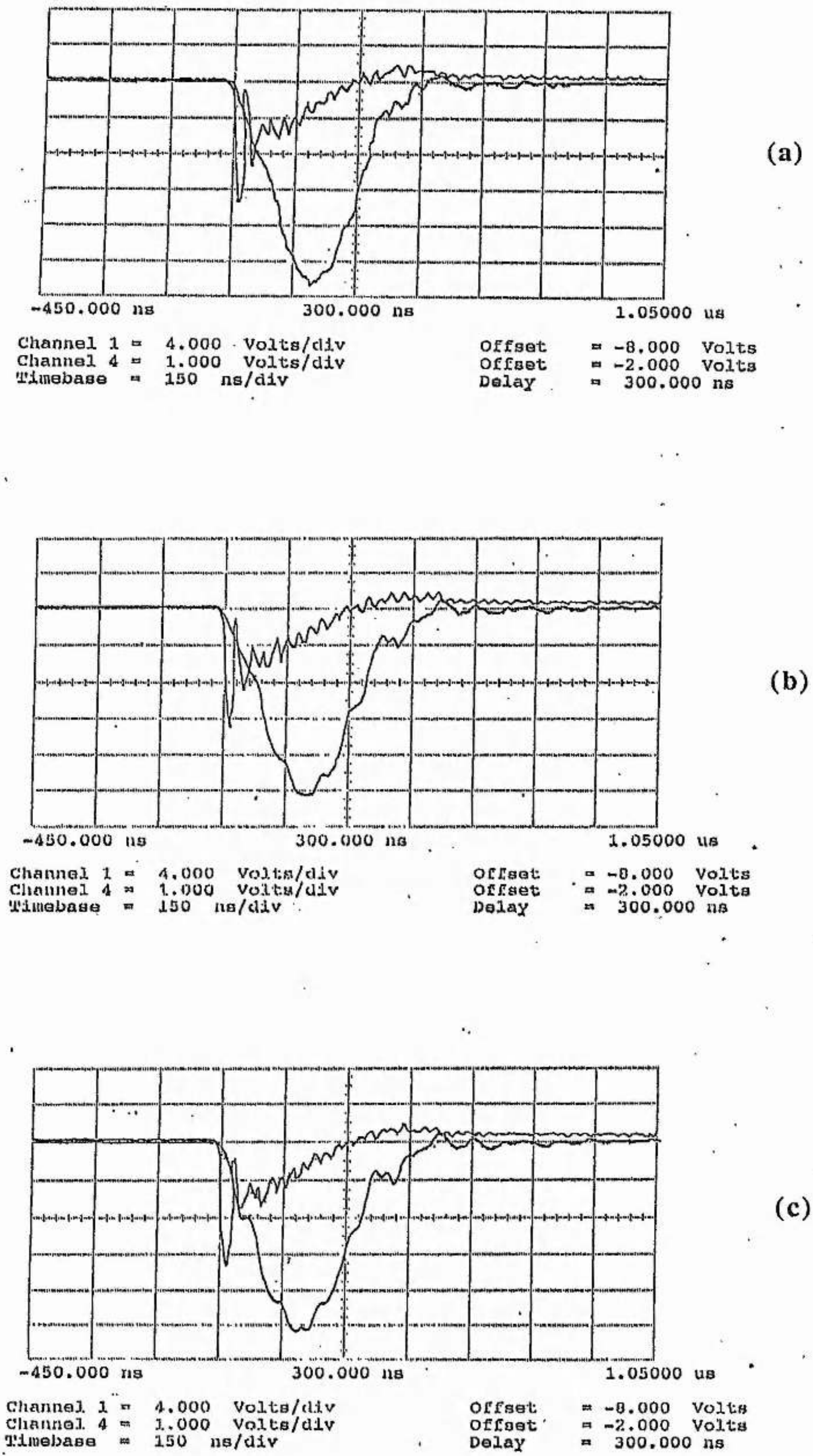


Figure 5.8 Circuit arrangement for comparison of discharges in tubes with metallic and insulating walls.



<u>**Figure 5.9 Voltage and current associated with discharge tube of fig.5.8. (a) no segments, (b) one segment of 240mm, (c) three segments of 80mm each.**</u>

Chapter 6.

Copper halide lasers: experimental results.

6.1 Introduction

The work described in this chapter concerns the development of copper halide vapour lasers at the University of St Andrews. From the first, crude, experiments with copper bromide (CuBr) powders and pellets, through more sophisticated tubes, designed to counteract the various problems which became evident as a consequence of using copper halides. A final design for the series of lasers without metal segments was built and tested. It performs well and produced 5W of laser light during a 100 hour period of sealed-off operation. After termination of the test period there was estimated to be a 10 - 15 % loss of CuBr from the reservoirs indicating a possible 1000 hour sealed-off lifetime.

Work performed concurrently with the above is also described in section 6.5. This section deals with the application of segmented metal discharge tubes to copper bromide lasers. As with the series of designs not incorporating metal tubes, problems were found with the control and management of free bromide molecules which cause instabilities in the discharge. A novel method of obtaining copper halide by reacting a halogen gas (entrained in the flowing buffer gas) with the hot copper segments is described and the performance of various halogens and a halogen donor are assessed.

6.2 Initial experiments

Prior to work beginning on copper halide lasers in their conventional form, some attempts were made to prove the principle of the copper halide flame laser. A description of this proposed device can be found in Appendix B. One method of introducing copper halide to the flame was later used in the setting of a conventional discharge tube. A flow of buffer gas (helium in this case) is arranged through a glass tube which has a bulge in it. This bulge contains copper bromide powder which, when heated, gives off CuBr vapour. The vapour is then entrained in the buffer gas flow and drawn through the laser tube, undergoing dissociation and excitation in the pulsed discharge to produce copper vapour laser light.

The modulator circuit is standard for most of the initial experiments (Fig 6.1); the storage capacitance is 4nF, charged through a 150mH choke. The storage capacitor is discharged through an EEV CX1535 thyratron into the peaking capacitor (2nf). Power input is controlled by varying the charging voltage. The pulse repetition frequency (PRF) is fixed at 1kHz to avoid overheating the tube.

The discharge tube is simply a 30cm length of fused silica tubing with a 15mm internal diameter. An aluminium flange at each end of the tube acts as a window holder and as a gas inlet/outlet port. The flanges are sealed to the tube with O-rings. Electrodes are made by rolling molybdenum foil into cylinders and partially inserting them into the end flanges. The tube is operated under various buffer gas pressures, and several effects are noted. Initially the discharge in the tube is the pink-white of helium but after a few seconds of applying gentle heat from a bunsen burner to the CuBr reservoir bulge, the discharge colour can be seen to turn blue and become both constricted and unstable. This chaotic behaviour ceases when heating is discontinued. Under more intense heating, the discharge becomes first blue (as above) and then white, with a slight green tinge around the periphery of the axially emitted light. At this point, when the pulse repetition frequency is increased momentarily to 10kHz, more green emission is noted but no oscillation takes place, even with two 100% reflecting mirrors defining the cavity.

The above tube is no longer to be used for the reasons that (a); an external heat source is required for the reservoir and this reduced efficiency, (b); very little control is available over the bromine pressure in the discharge tube -thus rendering the device unreliable. To simplify the design, it is necessary to incorporate the copper halide in the laser tube, so that self heating can play a part in determining the vapour pressure.

6.3 Copper bromide distributed in dielectric walled tubes.

A copper bromide laser tube design should take into account the energy which is dissipated by the discharge. This energy is deposited as heat in the laser tube and if not properly managed, excess heat can cause problems by damaging the tube structure or by raising the CuBr vapour pressure above the desired level. Water cooling a laser tube is an efficient way of removing heat (chapter 4). If the outer wall of the tube is cooled by water flow (fig 6.2(a)), then heat deposited in the plasma will be conducted through the fused silica walls and removed by the water. The copper bromide which is in contact with the inner tube wall will be heated by the discharge and cooled by conduction through the wall. The effect of directly water cooling the tube outer wall is to increase the heat transfer from the laser over that of a tube with a water cooled jacket which has an air gap between the jacket and the wall to be cooled. Direct cooling allows more energy to be deposited by the discharge without overheating the CuBr. Increasing the PRF or the charging voltage should increase the laser output power. This theme is discussed in Chapter 4 with further refinements.

A copper bromide laser, made of quartz with an integral water cooling space is designed. An alumina liner is inserted in the quartz tube to protect it from copper migration and devitrification. The copper bromide is placed in this liner (fig 6.2(b)). The alumina tube is 500mm long by 10mm internal diameter. Tantalum cylinders, fixed to the end flanges, act as electrodes and the mirrors are mounted on bellows and are part of the vacuum envelope. A brass gauze is wrapped around the outer laser wall to act as a cylindrical current return path. The circuit shown in figure 6.1 is employed and temperature control in the laser tube is achieved by varying the pulse repetition frequency or charging voltage.

Copper bromide (CuBr) powder is distributed in 5 heaps of 5 grams each, equally spaced along the alumina tube. When evacuating the tube, the powder sometimes creeps along the floor of the tube in the direction of gas flow. This creep can be avoided by reducing the pressure very slowly. Once a discharge has been struck at low power (100 watts) in the buffer gas, (usually neon at 5-10 Torr) it is possible to see the green and yellow copper laser lines (510, 578 nm) within a few seconds. These characteristic spectral lines are probably due to CuBr dust being caught in the discharge and dissociating to leave a small amount of atomic copper which is then excited. As the power input is increased, the following changes can be seen in the colour distribution of the laser tube side light. The pattern of colour distribution changes may be observed in most copper bromide lasers with distributed lasant. The appearance of copper lines at a particular point in the laser tube is an indication of the wall temperature at that point reaching about 470^{o}C. There is a constant pink neon light but a green glow which begins at the cathode, spreads towards the centre of the tube. The anode region then begins to glow green. The green glows, spreading from both ends, then coalesce in the tube centre, generally accompanied by the onset of lasing. In the case of the tube described here, however, when the whole tube is glowing green, a strong blue (bromine), 478.6, 470.5 emission is seen in the light emitted from the output coupler. It is in the midst of this blue light that the first tinges of a green laser beam are seen which slowly build up from an irregular shape on axis, to a complete circle of 2/3 of the laser tube diameter. Once lasing has started, it typically continues for between 1 and 2 minutes before becoming unstable and flickering out amidst intense blue end emission. It is supposed that at the temperature required for lasing, an excess of bromine is being liberated and this is attaching electrons and preventing both lasing and the maintenance of a stable discharge.

To remove excess bromine from a charge of copper bromide, the laser tube can be repeatedly discharge heated to just below the temperature required for lasing to commence and then pumped down. Bromine gas which has been trapped in the CuBr powder is then released from the molten compound and removed. After processing in this way, the discharge becomes more stable, with less emission on the bromine lines at the temperatures required for lasing. Stability of the discharge is a problem with this tube until the CuBr charge is exhausted. The discharge then becomes stabilised in the laser tube and ceases to hop from point to point on the electrodes.

When the voltage of the storage capacitor reaches 11kV and the pulse repetition frequency is 10kHz, lasing begins on the yellow (578 nm) line only. There is a very faint green (510 nm) emission which may be seen by the spectroscope (Zeiss hand held model), but cannot be discerned by eye alone. The yellow beam had a power of 500mW and it can be seen that if the neon pressure is doubled to 10 Torr, the green line appears and the beam power is reduced, but divides into the green and yellow components. At 15 Torr the yellow line disappears and only the green remains but at a power of only 50mW. By scanning the pressure between the two extrema (5 and 15 Torr) any ratio of green to yellow can be obtained (Fig 6.3).

The reason proposed for the pressure dependent wavelength effect is related to the minimum value of gas and electron temperature in the interpulse period. If the pressure is low then a greater gas temperature will ensue due to the higher electron energies in the pulse and the lower bulk plasma recombination rate. The lower levels of both laser lines will be populated by thermal and cooling electrons. The green (510 nm) line will be affected more so than the yellow (578 nm) due to its lower energy level being situated closer to the ground state and hence being more easily populated by low energy electrons. Thus at low pressures the green line will be suppressed. As the pressure is increased, the electron temperature and the wall temperature fall, lowering the population of the lower laser levels and bringing the green transition into action. As the wall temperature falls further, the vapour pressure of CuBr is reduced and, with it, the vapour pressure of copper. As the copper vapour pressure drops to about 10^{14}/cc, the yellow line ceases to lase, leaving only the green transition . If the input power were increased at this point, the wall temperature and hence the vapour pressures of CuBr and copper would rise and the yellow line would again begin to lase.

Problems associated with the particular design of this laser soon became apparent. The gas outlet tubes were narrow and easily blocked by CuBr powder. The windows became coated with this powder after only a few hours, and the tantalum electrodes were damaged by bromine attack. A purpose-built tube was required which would incorporate means for controlling the bromine pressure, the CuBr vapour pressure and the diffusion of CuBr to the window areas.

In order to remove any contribution to the above problems by the flowing buffer gas, a design was sought which could be processed with a flowing buffer gas and sealed-off when the tube was deemed to be substantially free of contaminants. Further experiments using flowing gases were conducted under different circumstances and are described in section 6.5.

6.4 The sealed off copper bromide laser.

6.4.1 Requirements for reliable operation.

To produce a sealed copper bromide laser with its inherent advantages, a few problems must be solved. These are, principally :

(1) efficient control of CuBr vapour pressure;

(2) reduction of excess bromine partial pressure;

(3) contamination of the windows.

It is noted from the previous experiments that if CuBr is coated on the tube walls and is in direct contact with the discharge, then the vapour pressure of CuBr becomes uncontrollable and a large amount of bromine is liberated by dissociation of the CuBr. This makes the discharge unstable. If, however, sidearms or wells are used where the

CuBr powder can be placed so that the discharge is not in direct contact, then better control of the CuBr vapour pressure can be achieved.

6.4.2 A simple tube with CuBr reservoirs.

A tube which has a 20mm internal diameter and a distance of 500mm between electrodes is shown in figure 6.4. The cathode is an open copper cylinder, mounted coaxially within the tube and the anode is a tungsten rod mounted off-axis in a sidearm. The tube itself is made of quartz and has three sidearms acting as copper bromide reservoirs. Brass gauze is used for a co-axial current return and the tube is cooled by convection.

To prevent powder fouling of the windows by CuBr powder during evacuation, copper bromide pellets are used . CuBr powder is compressed in a 5 ton/cm^2 press, then the pellets (6 pellets of 10mm diameter and 2mm thick) are each broken into two pieces and the pieces placed in the sidearms. Heater tape (Hotfoil) is wrapped around the laser tube assembly and the whole tube is baked under vacuum at 300 ^oC for 24 hours.

Neon is used a a buffer gas at a pressure of 10 Torr. The tube is sealed at the gas inlet and outlet taps before testing commences. Reservoir heating comes both from the discharge and from two 1kW firebars attached in parallel to a variac and placed beneath the reservoirs. It is found that after a few minutes, CuBr 'dust' begins to gather at the tube ends and stick to the windows. Cylindrical heaters may be used to keep the windows free of condensing CuBr by evaporating any which condenses there.

It is possible to vary the laser output power and discharge characteristics of the above laser by varying the heat supplied by the firebars under the reservoirs (Fig 6.5). Maximum output power is 0.8W, which occurs at a reservoir temperature of 490^{o}C. The temperature is measured with a Ni-Cr/Ni-Al thermocouple attached to a Fluke 80TKthermocouple/voltmeter adaptor. The temperature readings are taken when the tube is in steady state operation and the discharge switched off momentarily. Above

500^oC the laser power drops sharply and becomes unsteady until at around 505^oC a stable discharge can no longer be maintained. As has previously been noted in describing the performance of the laser tube of section 6.3, there was much blue emission indicating a bromine overpressure.

6.4.3 Laser tube with diaphragms and CuBr reservoirs.

Previously reported work (refs 1,2,3,4) has suggested that a laser tube which contains a coaxial sequence of annular diaphragms helps to stabilise the discharge over a wider range of bromine partial pressures. The diaphragms prevent the discharge from touching the wall where the CuBr density is unpredictable. The discharge is constrained by the apertures and, with sidearm reservoirs, a more precise control over CuBr pressure can be kept. Some method of controlling the partial pressure of free bromine is also required. As elemental copper is deposited by condensation on various parts of the tube, the bromine liberated can act as an attaching agent in the discharge or may poison the cathode. Both of these effects are detrimental to efficient long-lived operation. An electrode structure is designed (ref 5) which consists of the electrode and a surrounding CuBr trap. The electrode itself, is made of compressed copper wire and moulded into a hollow cylinder, closed at one end. (Fig 6.6). Surrounding this electrode is a perforated wall of quartz, on the outside of which are pieces of copper wire wound into tight spirals and contained in a bulge in the quartz vacuum envelope. The concept behind this arrangement is to ensure that free bromine in the discharge tube will strike the electrode and react with the large surface area of hot copper. The copper bromide thus formed either evaporates and returns to the discharge or may diffuse towards the copper spirals and the cool outer wall. This maintains the free bromine concentration at a low value and allows stable operation of the discharge.

The laser tube to which the above electrodes are attached, is shown in figure 6.7. The most striking features are the quartz diaphragms which define the discharge diameter and hence that of the laser beam. The diaphragms between the electrodes serve to distance the discharge from the wall and hence remove the effect of flash heating CuBr into evaporation straight from the walls. Diaphragms placed between the electrodes and the windows create convection cells, in which the buffer gas and any dust which it carries cannot move straight to the window. Due to the absorption of heat radiated and conducted from the discharge volume, gas and dust particles become trapped in a convection vortex in each cell bounded by diaphragms. CuBr which would normally drift straight to the windows, now becomes trapped in these vortices until it comes into contact with the tube wall and condenses. The pollution of the windows is markedly reduced over lasers with no diaphragms and the need for window heating is removed.

6.4.4 Tube construction and processing.

The dimensions of the tube are;

Electrode Separation	50 cm
Diaphragm i.d.	2 cm
Diaphragm o.d.	4 cm
Electrode/window separation	25 cm

Fused silica is used exclusively as the material of contruction. One window is glass (BK7 grade) and the other UV fused silica to facilitate optical spectroscopy. The current return path from the anode is formed from two sheets of aluminium which are mounted along the sides of the laser tube and shaped to cover as much of the tube surface as possible. Material is cut from the aluminium sheets to allow space for the reservoir heaters.

A detailed procedure for construction and processing is listed as follows.

1. Prepare electrode structures

2. Mount diaphragms in laser tube (held by 'tucks' in quartz wall)

3. Attach sidearms and electrode structures

4. Seal poor quality windows on with 'Torr seal"

5. Evacuate and bake out tube, refilling with Ne at atmospheric pressure

6. Prepare CuBr charges by melting powder and cooling under vacuum (see later)

7. Remove windows under slowly flowing buffer gas and insert CuBr slugs

8. Fit good windows, again with 'Torr seal', evacuate and re-bake tube at $200^{o}C$

9. Run discharge in flowing Ne for a few hours at less than input power required for lasing

10. Increase power until lasing begins

11. Evacuate tube, refill with Ne to working pressure and seal off.

The slugs of copper bromide are prepared by weighing 33 grams of powder into each of three quartz furnace tubes, designed so that when melted and solidified, the CuBr will fit neatly into the laser tube sidearms. Each tube in turn is connected through a graded glass/quartz seal to a vacuum system. Two liquid nitrogen cold traps are included to prevent damage to the sensitive vacuum gauges by either the CuBr vapour or pump vapours backstreaming through the pump lines. The furnace tube is pumped slowly to its ultimate vacuum of 10 Torr and a nichrome wire heater placed over the tube. Once the CuBr has melted totally, it is left molten for one hour whilst pumping continues. It is then allowed to slowly cool and solidify under vacuum before the furnace tube is filled with neon to atmospheric pressure and sealed off. Once all the CuBr slugs are prepared and the laser tube is ready, the quartz is cracked off the CuBr and the slugs are quickly inserted into the sidearms using a tube and rod arrangement. Once the windows are in place, the Torr seal is 'quick cured' by heating to $60^{o}C$ for an hour. After this, the tube may be evacuated whilst the Torr seal cures hard (12 hours at room temperature).

6.4.5 Reservoir heaters.

Reservoir heaters are made up using quartz tube, castellated at each end, with flat nichrome ribbon wound from end to end. Each heater is wrapped in a little zirconia felt to increase efficiency and placed so that it encloses a CuBr reservoir sidearm. Initial experiments are carried out using independent variacs for the reservoir heaters. Before working on a system of temperature stabilisation using proportional controllers, the laser will be operated and its performance assessed. If accurate control of temperature is to be maintained electronically in the high interference environment surrounding a pulsed discharge laser such as the copper bromide device then much effort is required to protect the sensitive diagnostic and control units. Each heater has a resistance of 4 ohms and requires a driving voltage of up to 20V. The maximum output power of each heater is around 100W, so, with a (pulsed) power supply input, to the tube, of 1.3kW, the reservoir heaters provide almost 20% of the total energy input. The relatively large proportion of energy which may be supplied by the heaters, means that changes in heater voltage have a rapid effect on the laser characteristics. In a thermally efficient laser with low heater power, the response time of the laser to changes in heater power would be long.

During the course of the experiments performed on this laser, the laser tube is sealed off by taps rather than by hard sealing the quartz pump tubes. The gas piping up to the inlet and leading from the outlet are both evacuated after the tube is filled and the taps closed. This arrangement is not ideal but allows the tube characteristics to be measured under a variety of operating conditions, before it is sealed off with the optimum gas pressure and mixture inside.

6.4.6 Experimental results.

The laser is operated with a conventional capacitor transfer circuit (fig 6.1) but with a storage capacitance of 1.3nF and a peaking capacitance of 0.7nF. Initial observations are that the tube supports a very stable discharge. The discharge attachment to the electrodes appears to be diffuse and originates inside the hollow copper cylinders. The tube warms up in a few minutes but it is found to be necessary that one layer (2.5mm thick) of zirconia felt is wrapped around the tube, inside the shaped aluminimum sheets comprising the current return, in order to maintain the desired tube and reservoir temperature without overheating the electrodes. When the tube is operating under these conditions with 10kV on the storage capacitor and at 16kHz (power input 1.0 kW) with no heater power applied, the copper lines may be seen with a spectroscope but are faint. Once heating is applied to the reservoirs, however, the lines increase in intensity and lasing begins within 5 minutes (fig 6.8). The heaters are maintained at a constant voltage and the buffer gas at a constant pressure (tube sealed) while the pulse repetition frequency is varied briefly to discover the effect on output power without unduly upsetting the thermal balance previously attained at steady state. The results are shown in fig 6.9. The maximum occurs at 16kHz with a secondary peak at 19kHz. The optimum time between pulses is found to be 62.5μS. This is the point at which the copper ground state and metastable state populations, coupled with residual electron density, are optimum to maximise the stimulated emission flux. It was noted that above 14kHz the beam continues to increase in power but becomes annular and at peak average output is a sharply defined annulus with an 8 mm diameter 'hole' in the centre. This is most likely due to gas heating on axis causing high population of the metastable lower laser levels. When the power input is held constant at a pulse repetition frequency (prf) of 16 kHz and a constant heater power, variation of the output power with neon pressure is determined (fig 6.10). Below about 5 Torr, the discharge fills almost all of the tube volume, extending out to the windows and filling the CuBr trap regions of the electrodes. Between 5 and 15 Torr, the laser power climbs rapidly to a maximum and then decays slowly. Above 50 Torr, the power continues to drop steadily until lasing is extinguished at around 200 Torr. The temperatures of the reservoirs are controlled under conditions of constant discharge input power and buffer gas pressure. The results (fig 6.11) show that, as with the previous sidearm tube, the maximum output occurs at a temperature around 495°C. This corresponds to a CuBr partial pressure of around 0.4 Torr. Above 500°C the power drops rapidly until the discharge becomes unstable, constricted and twisting. When the reservoir heat is reduced or removed, the discharge stabilises and output power returns to that plotted in fig 6.11.

It is found that the beam is 85% polarised by the Brewster angled windows. When the output light is split into its two components these are also found to be polarised to the same degree. The high gain of the system means that many of the photons in the output beam are the result of single pass gain and therefore only traverse one Brewster window. The attenuation caused by the window to the light, which is not of the favoured polarity, is not 100% therefore a substantial amount of this light is transmitted.

To determine the effects of different CuBr vapour pressures on the output power and the electrical characteristics of the modulator circuit driving the laser, the heater voltages were maintained equal and the laser was operated under three different sets of heater input conditions. Voltage and current waveforms for this diaphragm apertured tube may be seen in fig 6.12 and information on the matching of the laser load to the electrical driving circuit obtained. The tube is sealed with 15 Torr of neon and operated with 10kV on the storage capacitor and a prf of 16kHz. Initially, the discharge is operated in the tube without reservoir heating applied (fig 6.12 (a) and (e)). The heaters are then set for optimum laser output power (each heater delivering 56 Watts) and the laser allowed to reach equilibrium.

This corresponds to an output power of 5.5W (fig 6.12 (b) and (e)). A further increase in heater power (each one delivering 100W) reduces the output power level to a new equilibrium of 2.3W but the green/yellow ratio remains constant at 3:1, fig 6.12 (c) and (f). It can be seen from the thyratron voltage and current waveforms in 6.12(a), (b) and (c) that as the CuBr concentration is increased, the slight mismatch between the driving voltage and the laser tube (seen in the magnitude of the voltage oscillation) becomes greater due to the increasing impedance of the gas mixture which is becoming more attaching as the bromine concentration increases. This is shown more clearly by the voltage appearing across the peaking capacitor when the thyratron is triggered. In this series of photographs, (fig 6.12 (d), (e) and (f)), it can be seen that as the copper bromide/bromine concentration is increased, the voltage at which the laser breaks down is raised from 6.4kV in (a) to an optimum of 7.6kV in (b) and then to a high of 9.4kV. A flint glass prism can be used to separate the two wavelengths in the output beam and a photo-detector (ITL) used to show the difference in amplitude, pulse shape and timing between the two.

Figure 6.13 (a) shows the green (510.6 nm) component of the laser pulse compared with the laser voltage to establish the timing of the light pulse. Laser emission begins about 10ns after breakdown begins and the voltage across the laser stops increasing and turns over. The yellow (578.2 nm) component begins approximately 5ns after the green line begins and reaches a peak intensity which is approximately 60% of that reached by the green line. The yellow line reaches its peak intensity 10ns after the green line has peaked but its full width at half maximum value, 35ns, is greater than that of the green, 25ns. The front edge of the laser pulse, then, is predominantly green, whereas the final 20ns or so is entirely yellow.

6.4.7 The effect of hydrogen as an additive.

The addition of small amounts of hydrogen, to the gas mix in this tube, has a great effect on the laser output. When the laser is operated at maximum output power, the beam is annular and has a green to yellow ration of 3:1. As hydrogen is slowly bled into the laser tube, the power increases by a maximum of 10% but a major change occurs in the beam profile. From a sharply defined annulus, the beam profile becomes the 'top-hat' shape normally associated with copper lasers and continues to change, as the hydrogen partial pressure is increased, to an intense (same power) on-axis beam which is predominantly yellow with a diameter of 10mm (cf 20mm diaphragm internal diameter). Although the breakdown voltage of the laser tube is increased by a few hundred volts at most, there are no other obvious differences in the electrical characteristics of the tubes with and without hydrogen.

6.4.8 Lifetest of the sealed-off laser tube.

To determine the factors which lead to end-of-life in a laser tube such as the one described here, a period of continuous operation is required. When the laser is subsequently examined after such a period of operation, valuable information may be obtained which will extend the lifetime of the next generation of sealed-off CuBr laser tube. After 100 hours of stable, sealed-off operation at 4.5W with a variation of 0.2W, the power supply failed and the lifetest was terminated. As it is relatively easy to view the inside of the reservoirs through the very thin copper coating on the walls, it is estimated that 10-15% of the CuBr has evaporated and been transported elsewhere in the tube, giving rise to the belief that the tube may run for up to 1000 hours. There are no traces of CuBr on the windows but the traps in the electrode structures show that a substantial amount has condensed there. During operation, the electrodes are red hot. The heat from the electrodes evaporates CuBr from the traps and forces it back into the bulk of the electrode which may eventually cause discharge instabilities. The cathode has risen to such a temperature during operation, that the hard solder joint holding it to the tungsten rod has melted and allowed the copper cylinder to slump down approximately 1 cm further in the housing. Apart from minor damage to the cathode, there is no damage to the structure of the tube and the windows appear to be completely free of contamination. During operation of the laser it can be seen that the discharge touches the wall of the vacuum envelope at each electrode opening as it bends to enter the aperture in the annulus adjacent to the opening. If copper is deposited on the wall on these corners, then diffusion of the copper into the quartz will take place in the heat of the discharge, leading to devitrification of the quartz.

6.4.9 Improvements to the sealed-off laser tube.

A second tube, which is identical to the first, but has the following modifications is to be tested. The electrodes are still composed of crushed and shaped copper wire but the tungsten support rods are threaded and screwed into the base of the electrode. In this way, heat has no serious effect on the joint. Another modification applies to the positioning of the annulae closest to the electrodes in the discharge section of the tube. Previously, these annulae have not been placed directly adjacent to the electrode openings and the discharge touches the quartz wall of the tube as it bends round from the electrode to the main tube axis. To prevent damage by the discharge or by copper diffusion, an annulus is placed directly adjacent to each electrode opening so that the discharge is forced to continue upwards and only bend when it approaches the aperture in the annulus. As the annulus is not a load bearing structure, it is not important if copper diffuses into the bulk of the quartz forming it. The final modification is in doubling the diameter and depth of the electrode based CuBr traps to reduce the temperature of the outer wall and retain more CuBr. The laser tube with these modifications has not yet been processed and tested.

6.5 Copper halide lasers with segmented metal tubes.

Following on the success of the argon ion laser with high aspect ratio metal segments (ref 6) and the subsequent use of metal dispenser segments in high temperature copper lasers (ref 7), it is a natural extension to employ metal segments in copper halide devices. The merits of using such segments and the ensuing electrical consequences for the discharge are discussed in chapter 5. There is a strong case for their use but prior to publication of the first work from this section, no other researcher has published in this field.

6.5.1 Segmented metal tubes with CuBr powder.

The work described in section 6.3 with quartz and alumina walled tubes is also conducted in metal walled tubes. The basic laser head used in performing the following experiments has water cooled end flanges with window apertures of 25mm diameter. A circular cut-out of 40 mm diameter in each end-flange provides a holder for open cylindrical electrodes, normally made of molybdenum. A quartz tube of 55mm internal diameter and 1m length, forms the vacuum envelope between O-ring seals to the end flanges. The quartz tube contains the metal segments and any alumina rings supporting or separating them. The quartz tube is held within an evacuable pyrex outer sleeve (diameter 120 mm) which is enclosed by a water cooled jacket/current return.

To avoid problems with spurious arcing between segments, a relatively low aspect ratio (length/diameter) is chosen for the segments themselves. The segments are cut from a copper pipe (99.5% purity) and measured 100mm long by 53mm outside diameter and 51mm internal diameter. As they were a close fit to the quartz tube, discharges do not run in the space between the outer segment wall and the quartz.

Power supply and modulator circuitry to drive the metal segment laser are as shown in Figure 6.1. A charging voltage of 10kV is available, which can be almost doubled by the use of inductive charging with a diode. Capacitor values are chosen to be 4nF (storage) and 2nF (peaking). This combination has previously been successful in dielectric walled tubes and the intention is to investigate the performance of various laser head arrangements under a common driving circuit.

In the first experiment to determine the effect of metal segments on a high repetition rate discharge, the segments are placed in the quartz tube such that they are separated by 2cm. The ends of each segment are smoothed so that they have no rough or projecting points which will give electric field enchancement and aid inter-segment breakdown. The establishment of a discharge in this tube is straightforward if the buffer gas (helium or neon) pressure is below 50 Torr. Above this pressure, spurious arcing between segments and axial discharges over part of the tube length may be seen. Towards the high pressure end of the range noted above it is also helpful to have a pulse repetition frequency above a few kiloherz. The high repetition frequency allows ionization to spread into the segments, reaching further with each pulse until an axial discharge path is established and has a lower breakdown voltage than the sum of the segment-segment and electrode-segment gaps (ref 8). On dismantling the tube after a few hours of operation with a flowing buffer gas (neon at 25 Torr) it is found that inter-segment arcing has deposited copper on the wall of the quartz vacuum envelope and subsequent heating has caused this copper to diffuse into the wall, devitrifying it. The laser head is re-assembled with copper segments of the same length as before but of 44mm outside and 42mm inside diameters. The copper segments are supported at each end by an alumina sleeve (fig 6.14) which also protects the quartz wall.

Copper bromide powder is placed in a small mound at the centre of each metal segment. The tube is evacuated slowly before a slow flow of neon at 25 Torr is started. A discharge is struck in the tube at 10 kHz and with 6 kV on the storage capacitor. The tube barely has time to warm up, when arcing between segment ends begins to disrupt the discharge and causes the thyratron to latch. A modified alumina spacer is used to aperture the tube by projecting into the discharge volume and removing the possibility of any direct 'line of sight' contact between segments (fig 6.15). Again CuBr powder is placed in the centre of each segment and a slow neon flow arranged at a pressure of 25 Torr. As before, the neon pressure and prf are fixed, with input power being controlled by the magnitude of the charging voltage. The tube is allowed to warm up slowly and no arcing is observed. When the voltage on the storage capacitor reaches 8kV a strong blue (bromine) emission is observed along with increasingly unstable behaviour of the discharge. As with the dielectric walled tubes described in section 6.3, repeated heating and pumping of the tube is required to drive off the excess bromine. Once this is done, lasing at output powers up to 5 W is achieved but again, little or no control is possible over the discharge heating of CuBr deposits on the walls. Invariably, unstable behaviour follows the onset of lasing by as little as three minutes. This approach to the copper bromide laser with metal segments results in very similar problems to the dielectric walled tubes.

6.5.2 Segmented metal tubes with flowing buffer gas and bromine.

To try to gain some measure of control over the vapour pressure of CuBr and to decouple this vapour pressure from the laser tube temperature a novel approach is taken (refs 9,10). A laser tube is constructed with the same basic structure as described in section 6.5.1. A segmented copper tube with segments 100mm long and an internal diameter of 45mm. The electrodes are molybdenum foil and are separated by 800mm. To protect the quartz wall and also prevent arcing between segments, the alumina spacers are as shown in figure 6.15. If a small amount of bromine is entrained in the flowing buffer gas, then it will enter the laser tube. The bromine then reacts with the hot copper walls to form CuBr. At the temperatures reached on the metal surface (600-800^{o}C), the CuBr evaporates immediately and is dissociated in the discharge. In this way, copper is made available for excitation and laser action. The bromine atoms either recombine in the bulk of the discharge volume, to be dissociated again, or will transport more copper from the wall. By controlling the amount of bromine entering the discharge tube, a control may be kept over the CuBr vapour pressure and hence that of free bromine. Eventually each bromine atom will combine with copper and condense on the cool part of the wall at each end of the discharge tube. The tube is operated at a pulse repetition frequency (prf) of 11kHz (limit of trigger generator available) for a few hours under the same discharge conditions as in the previous section. The buffer gas is again neon at similar (25 Torr) pressures and flowing slowly (1-2 litre atmos/hr).

Most of the impurities on the inner surface of the laser tube are outgassed during a few hours of operation and are removed by the buffer gas flow. The laser is allowed to reach thermal equilibrium with 13.5 kV on the 4 nF storage capacitor. This corresponds to an overall switched power of 4 kW. Bromine vapour, at the top of a glass vessel containing liquid bromine and attached to the gas inlet, is allowed to mix with the incoming neon and be drawn into the laser tube. Within 60 seconds of bromine flow beginning, a change in discharge colour is observed. After a further 30 seconds, green emission is seen from the anode (gas inlet) window. This spontaneous emission grows brighter over the following 60 seconds before lasing begins. The beam begins as an annulus, with a green/yellow ratio of 3:1, but becomes more like the 'top hat' profile normally encountered with copper lasers. As the profile changes, so the output power builds up steadily to a peak of 20 watts, before dropping to a few watts again. The discharge becomes confined to a thin annulus very close to the walls where some arcing and flashing is noted. The laser beam follows the discharge and also becomes a thin annulus. The laser then grows unsteady as an intense blue emission signals the presence of excess bromine. In dielectric walled tubes with a surfeit of bromine, the discharge becomes constricted and sometimes helical with the attachment points to the anode and cathode jumping randomly over the electrode surfaces. The absence of this behaviour in the metal wall tube is beneficial to the matching between the laser and the modulator, as there are no large changes in discharge impedance between pulses. The stability of the discharge at high bromine partial pressures appears to be attributable to the metal walls. By removing the discharge and flushing the hot tube with neon, most of the bromine existing as free atoms or as CuBr are swept out.

A steady state power output of 22 W is the maximum produced from the segmented copper laser tube with flowing bromine. At optimum power output, the partial pressure of bromine is estimated at 1.0 Torr, that is, 4% of the gas entering the laser. With a power input to the modulator/laser circuit of 4 kW, this represents 0.55% efficiency. The bromine vapour is drawn from liquid bromine by reducing the pressure in the glass flask containing the bromine. Accurate metering of the pressure is difficult to achive and so continuous adjustments have to be made to the bromine concentration entering the laser. Changes in the bromine concentration have little effect on the laser performance for up to 10 minutes due to the slow flow rate of gas and the large volume of the laser tube.

6.5.3 Segmented metal tubes with flowing buffer gas and chlorine.

The use of chlorine enables much more accurate control to be maintained over the halogen partial pressure. Chlorine is used in the same manner as bromine in the laser tube design described above. Lasing begins with 5 minutes of initiating chlorine flow and is controlled by increasing or reducing the chlorine input. Again, if the halogen partial pressure is allowed to increase beyond about 5 Torr then the discharge becomes unstable. Power output can be controlled easily but there still remains the ten minute feedback time of the laser tube. Faster gas flow reduces this response time to a few minutes but a much larger amount of gas is pumped through the system (up to 10 litre atmos/hr).

At optimum steady state operation, the chlorine based, flowing gas laser produces 18 watts. At this power level, the chlorine comprises about 4% of the gas, similar to the optimum bromine concentration. Laser efficiency is slightly less than with bromine, at 0.45% but the system is much easier to operate.

6.5.4 Segmented metal tubes with flowing buffer gas and hydrogen bromide.

Both bromine and chlorine have problems associated with their use. Bromine is liquid at room temperature and so it is difficult to control the amount of vapour which is entrained in the flowing buffer gas. The slow gas flow rate makes the laser response time long and so makes stable operation over a period of time difficult to achieve. Chlorine is a gas at room temperature and so it can be drawn at constant pressure from a cylinder, making flow management simpler. Chlorine has been found less effective then bromine when used in a copper halide laser (ref 11). The use of hydrogen bromide (HBr) combines the desired characteristics of both bromine and chlorine, as it can donate bromine atoms to the discharge, yet as a gas it can be entrained in the neon flow in reproducible quantities (ref 12). The hydrogen liberated by the reaction of HBr with copper does not pose a problem in the small quantities present. Indeed, hydrogen has been shown to have a beneficial effect when present in quantities similar to those present in the HBr-Cu laser (ref 13). Furthermore, hydrogen has been used exclusively as a buffer gas in elemental copper lasers, with output power under optimum conditions, being up to 50% of that achieved with neon (ref 14).

The laser tube of section 6.5.2 can be cleaned and re-used under similar conditions to those recorded above. The laser emits a total of 40 watts of green and yellow light which is stable and reproducible. Lasing is observed to continue at reduced power as the neon pressure is increased to 225 Torr. Beyond this point, lasing becomes erratic and faint as the discharge becomes a thin annulus, close to the wall. At optimum power, the hydrogen bromide comprises about 5% of the gas entering the laser, with the flow rate of the gas mixture being 2-3 litre atmos/hr.

An interesting property of the HBr-Cu laser is that it may be brought from cold to lasing in a very short period of time. If the tube has been operated previously, so that a thin layer of CuBr is attached to the walls, then the application of higher input powers on start-up (up to 200% of normal), will flash heat the CuBr and bring lasing on much more quickly than would be the case in a clean walled tube (no CuBr). Once the tube has reached its operating output power, the high input power may be reduced to normal and with the continuing flow of neon-HBr, the 'reservoir' of CuBr which is used on fast start-up will be replenished. The laser described above begins to lase within 30 seconds of discharge initiation in a cold tube and reaches 10 W within 45 seconds. Full power requires around 120 seconds to achieve.

When the Ne-HBr laser tube is dismantled, it is seen that the alumina spacers have become coated in places with copper. Some of the spacers become conducting, and in all, 60% of the total tube length is acting as a single segment. No noticeable loss of power has occurred due to this effect but part of the discharge current is probably travelling down the wall of this 'long segment'. The copper deposited on the spacers, appears as growths protruding from the segment rims (fig 16) . Initially, a whisker of copper would grow into the discharge volume and this then attracts copper which is deposited on the tips of the whiskers to form tree-like structures. The effect on the laser beam is to make the beam periphery ill defined. In continuing operation, these structures grow to about 5-8mm in height (projecting into the discharge) and then collapse. They do not appear to be a long term threat towards substantial aperturing of the beam.

Laser head inductance is the factor which most influences the rate of rise of discharge current. To reduce the laser head inductance it is necessary to reduce the gap separating the discharge tube from the current return path. In high temperature copper lasers, this is a limiting factor due to the (necessary) presence of thermal insulation. No such requirement exists for the copper halide laser however, so the coupling between the two conductor radii may be as close as is electrically safe. In the case of the tube discussed above, the water jacket/current return and pyrex sleeve were removed. They were replaced by a close fitting brass tube of 60mm internal diameter.

As the previous current return had been 110mm internal diameter and the discharge channel is 40mm in diameter, the factor governing inductance, $\ln \frac{r_2}{r_1}$, where r_1 and r_2 are the inner and outer conductor diameters respectively, is reduced by 40%. Thus the rate of rise of current is increased theoretically by the same amount. Experiment has verified this but as yet no output power greater than 7 W has been achieved from this device although at 1 kW input, the efficiency is 0.7%. Contamination of the HBr is a problem, as hydrobromic acid is formed when water molecules trapped in the cylinder wall react with HBr. The hydrobromic acid then etches the wall further and more water molecules are released to react with HBr. Lack of laser output and a dim, constricted discharge, points towards contamination of the HBr. Further work on this discharge tube has yet to be carried out.

6.5.5 Proposed single segment laser tube.

One tube which is proposed but as yet has not been demonstrated, has a single copper tube as a discharge channel, separated by a short distance at each end from the electrodes. During operation at high (25-50 Torr) pressure, the discharge penetrates a proportion of the way through this segment. The centre part of the segment has the discharge current running through the copper wall for a distance before it breaks from the wall and returns to the axis of the tube. In a flowing halogen/buffer gas regime, the copper halide formed is used to produce laser light where the discharge is axial but condenses on any part of the wall where the discharge passes in the metal. Thus a reservoir of copper halide builds up in the centre of the tube during operation (Fig. 6.17(a)). For fast start up times, the system pressure may be lowered which increases the electron temperature and hence the maximum allowable segment length (Chapter 5). The discharge now runs the entire segment length on the tube axis, quickly heating and evaporating the copper halide laid down during previous high pressure operation (Fig. 6.17(b)). The buffer gas pressure is slowly increased as the wall temperature rises and CuBr becomes available from the reaction of entrained HBr on the copper segments. In this way, both fast start-up and high power long term operation are achieved.

6.6 Conclusions.

In this chapter it is shown that copper halide lasers may be constructed in a wide variety of ways. Metal, glass and ceramic materials may all be used to advantage when the operating temperature of the laser is reduced from that of elemental copper devices to that of the halides. The design of copper halide lasers based on simple quartz tubes is found to be inadequate, as two main problems continually appear. These problems are connected with the control of excess bromine in the discharge tube and the effect of the discharge coming into contact with the copper halide powders used. Once these problems are dealt with, to some degree, by the design features described in this section, a tube can be built which appears to be capable of operating in a sealed off condition for a few hundred hours, at least. This type of operation sets the copper halide laser apart from its high temperature contemporary and makes it very attractive to non-expert users.

The application of metal bounded discharge tubes to copper halide lasers brings many interesting problems and some encouraging results. It is shown that, as with dielectric walled tubes, the discharge must be kept remote from the walls, by diaphragms or apertures, to avoid discharge instabilities. A novel method of obtaining high output powers is demonstrated by entraining a halogen such as bromine, chlorine or a halogen donor such as hydrogen bromide, in the buffer gas which is flowed slowly through the copper walled laser tube. Although the alumina spacers separating the copper segments become conducting, due to deposition of copper vapour, output powers of 40 W are achieved at 1% overall efficiency. On the basis of the very large amounts of copper present which act as both discharge confinement and lasant reservoir, the projected lifetime of this type of laser is many hundreds, or thousands, of hours . The copper walls of the devices described above are 1mm thick but in practice, any thickness may be used to give increased reservoir capacity.

Two different embodiments of the same laser type are developed. One is a low power, sealed off tube with potential applications where mobility is a requirement. The other laser tube uses a glass-metal-ceramic construction to produce high power output from an inexpensive and essentially, low technology, laser tube.

6.7 Suggestions for future work.

There is a general requirement for a low cost, low maintenance, efficient laser in the visible (particularly green/yellow) part of the spectrum. Also, the effect of small amounts of hydrogen on the efficiency of copper bromide lasers has yet to be explained to general satisfaction. Hence, the pursuit of a sealed-off copper halide laser is desirable from both the engineering and physics points of view. Spectroscopic studies of the role of hydrogen in this laser system would form an excellent continuation of the work described.

A number of metals present problems when used as laser media in their elemental form. The method of using a flowing halogen or halogen donor, such as hydrogen bromide, for achieving high metal vapour pressures at artificially low temperatures may be applied to such metals and others in order to make laser action easier to achieve.

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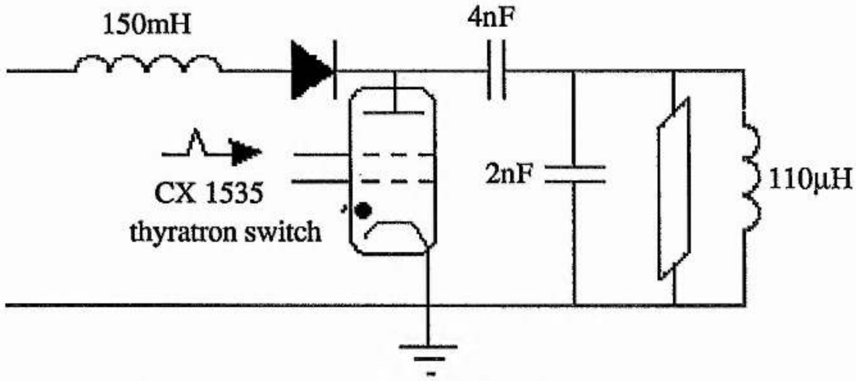


Figure 6.1 Standard modulator configuration for most of the laser tubes studied.

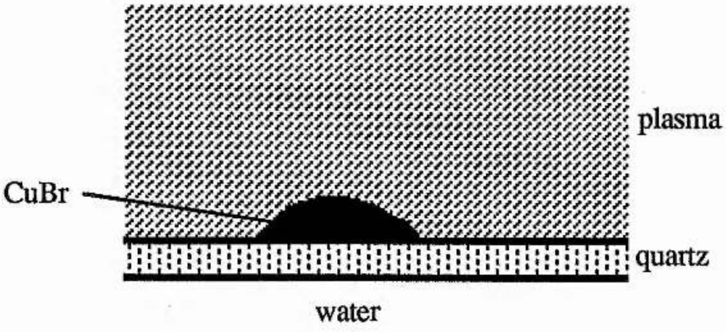


Figure 6.2 (a) Direct water cooling of laser tube.

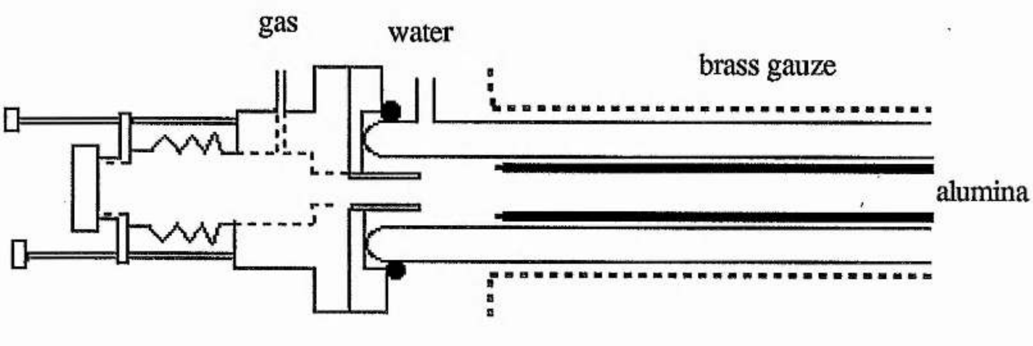


Figure 6.2 (b) Water cooled copper bromide laser tube.

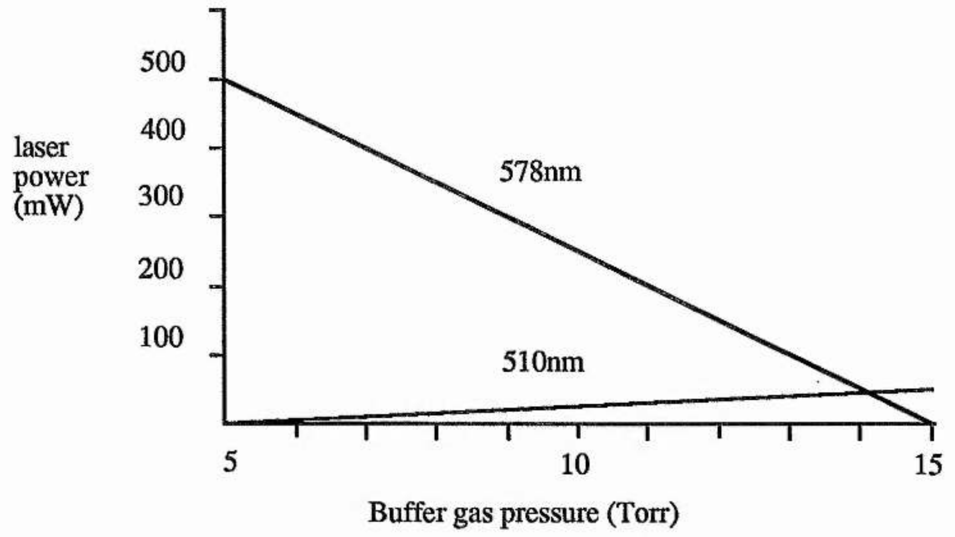


Figure 6.3 Change in line intensities with buffer gas pressure.

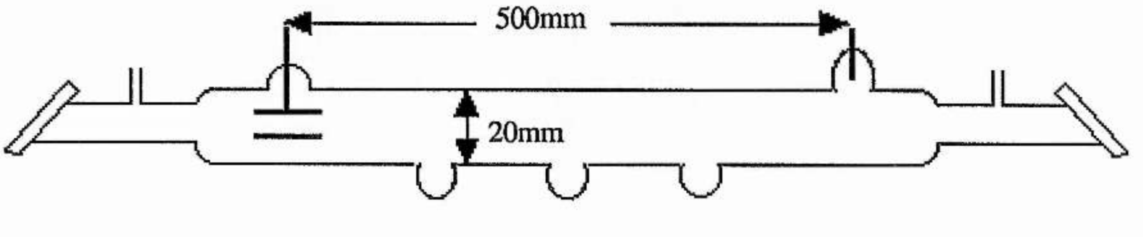


Figure 6.4 First copper bromide laser tube with sidearms.

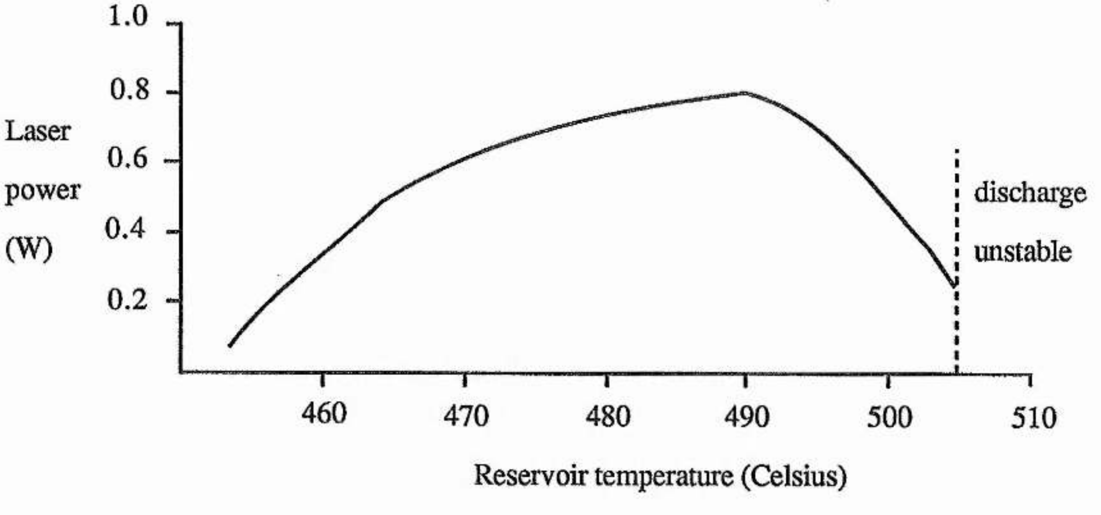


Figure 6.5 Laser output power against reservoir temperature for first sealed-off CuBr laser.

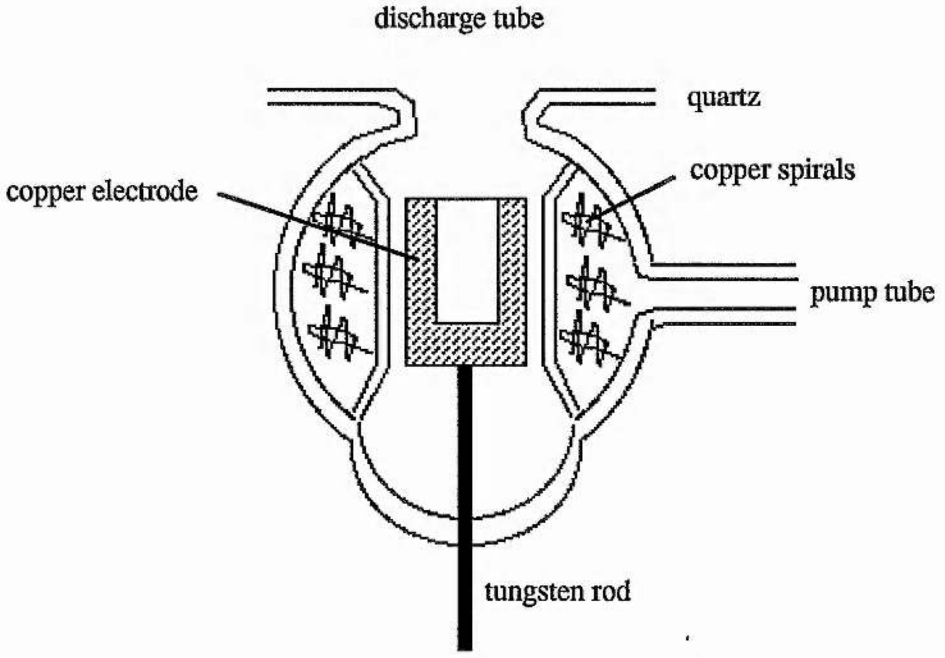


Figure 6.6 Electrode structure for the second CuBr laser tube, with sidearms.

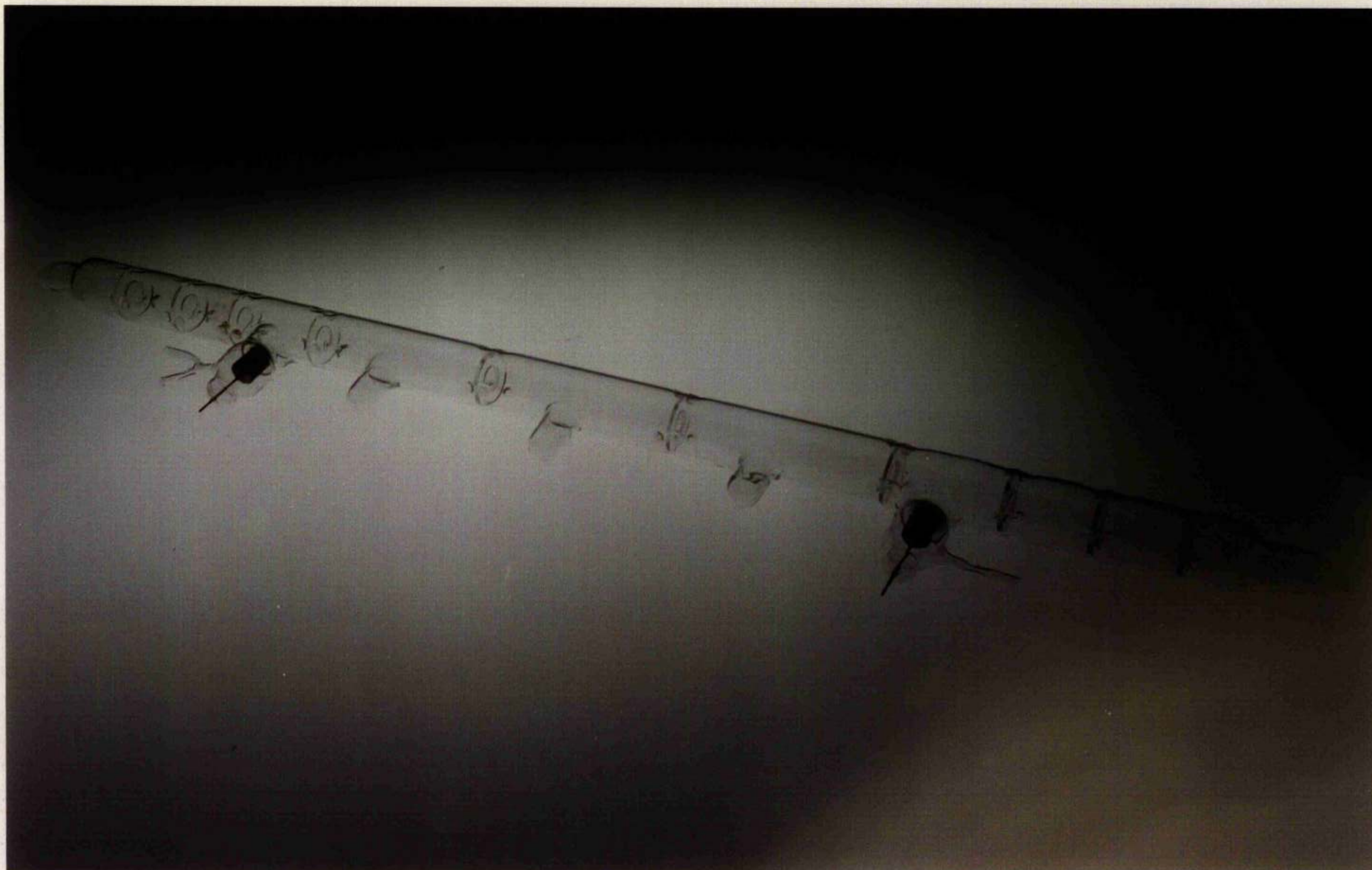


Figure 6.7 Second sidearm laser tube showing diaphragms and electrodes.

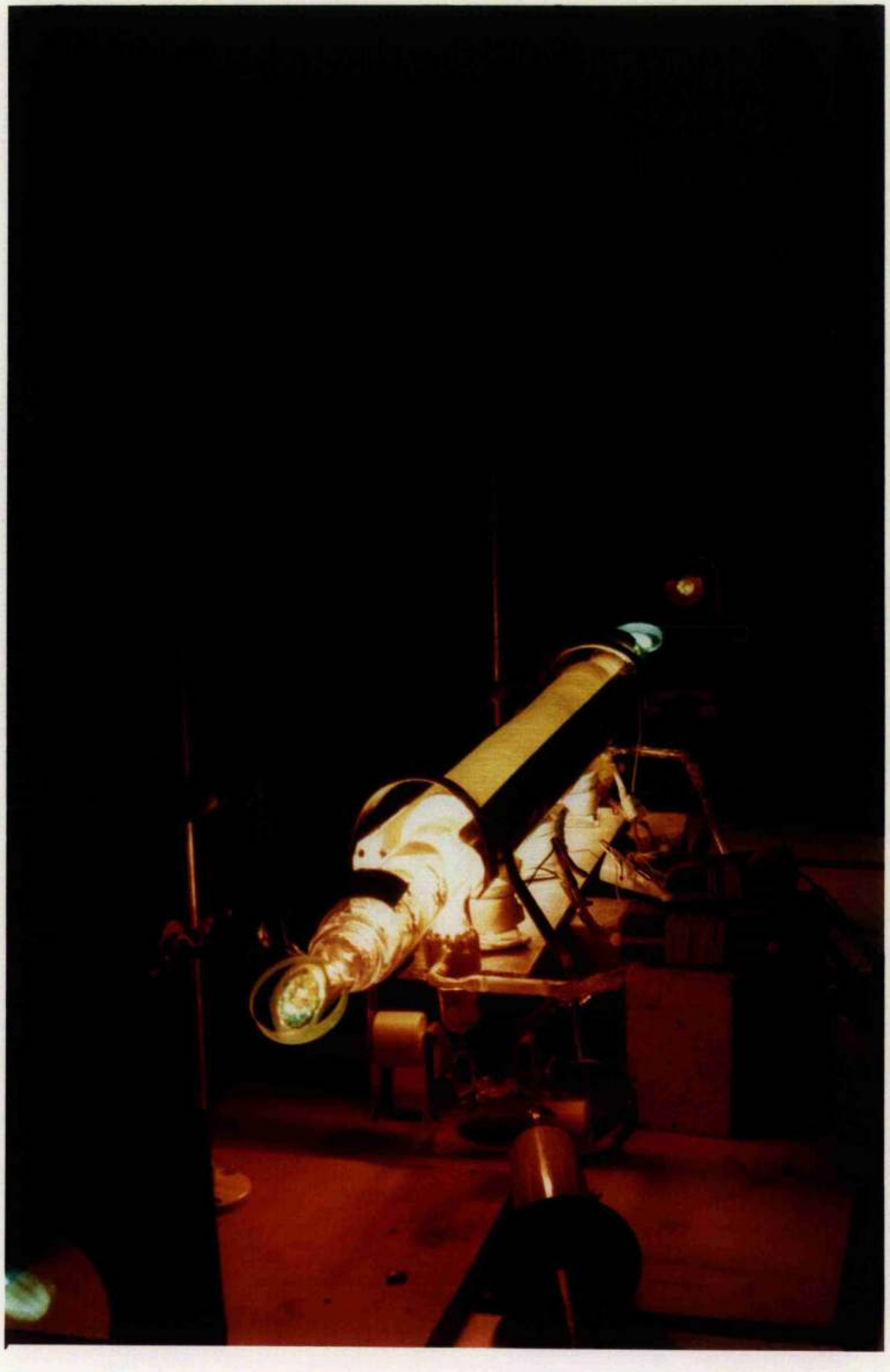


Figure 6.8 Sealed-off sidearm tube in operation.

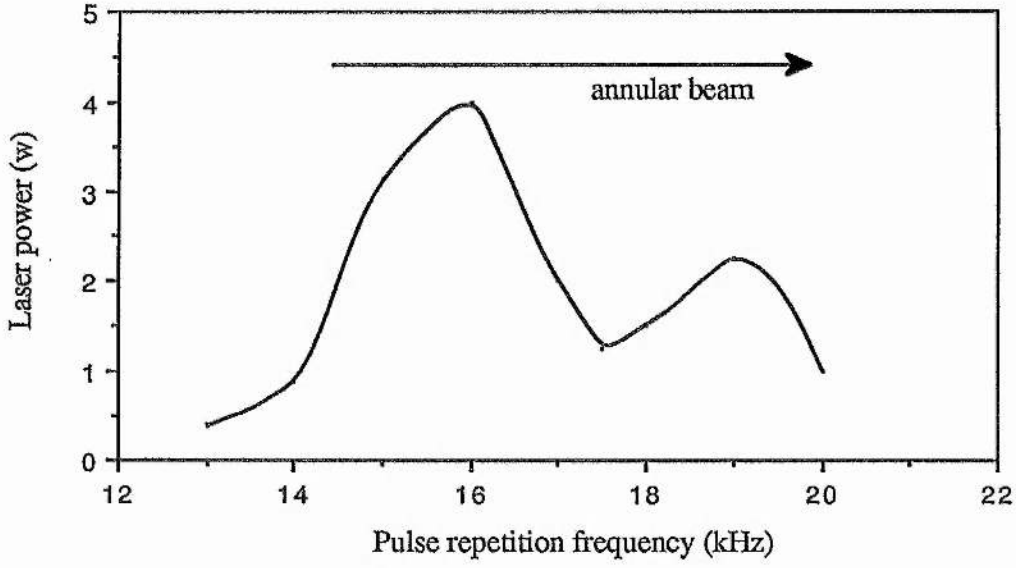


Figure 6.9 Variation of laser output power with pulse repetition frequency.

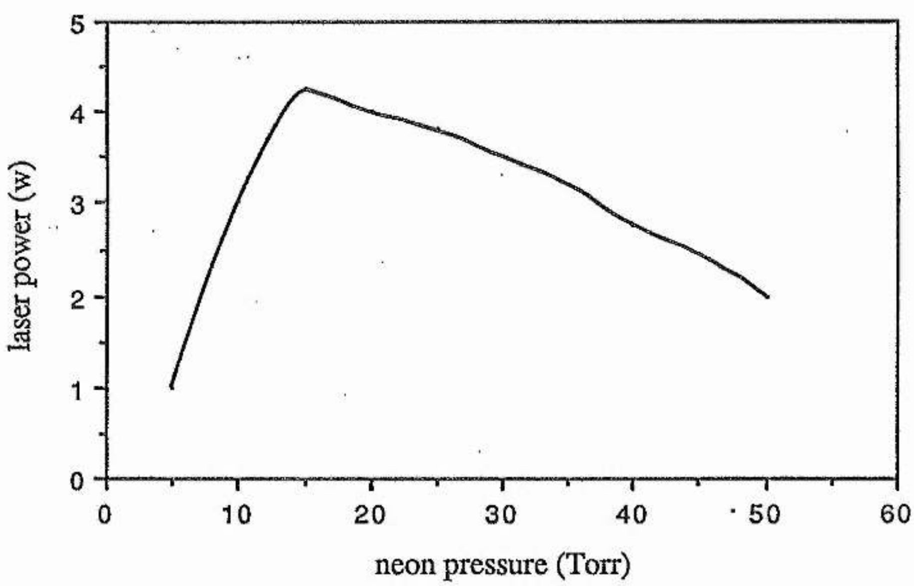


Figure 6.10 Variation of output power with neon pressure

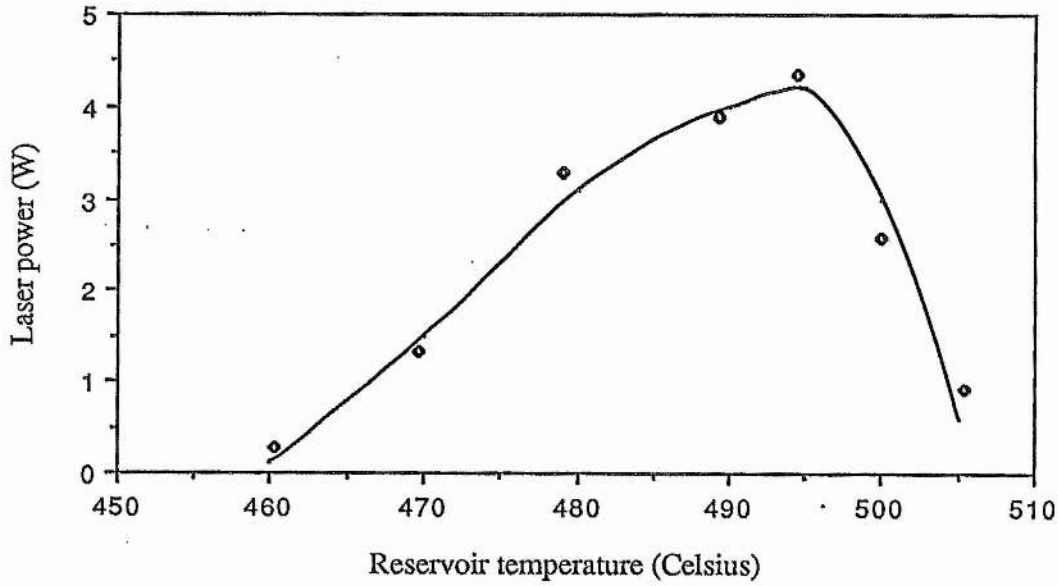
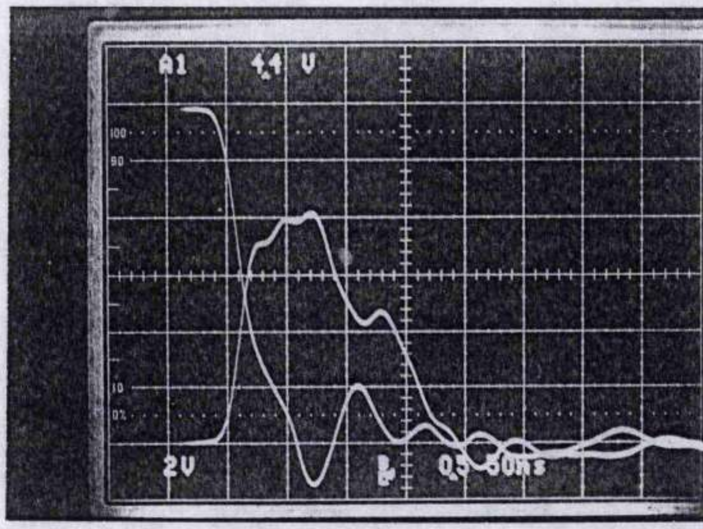


Figure 6.11 Variation of output power with reservoir temperature

V thy.
2kV/div

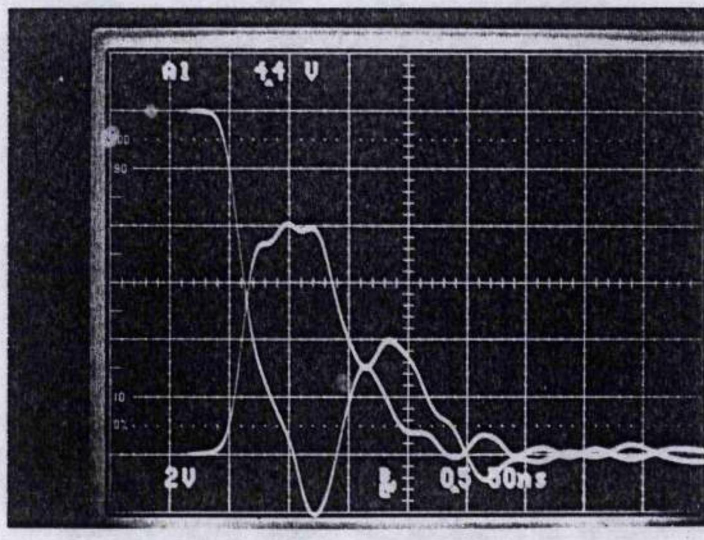
I thy.
200A/div



(a)

V thy.
2kV/div

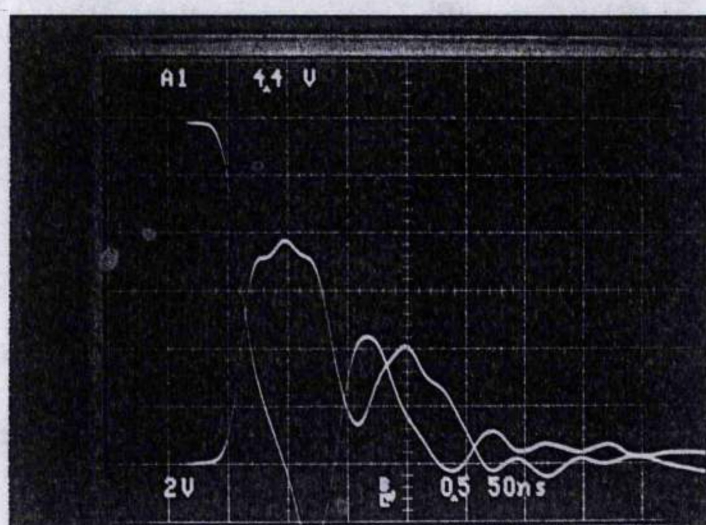
I thy.
200A/div



(b)

V thy.
2kV/div

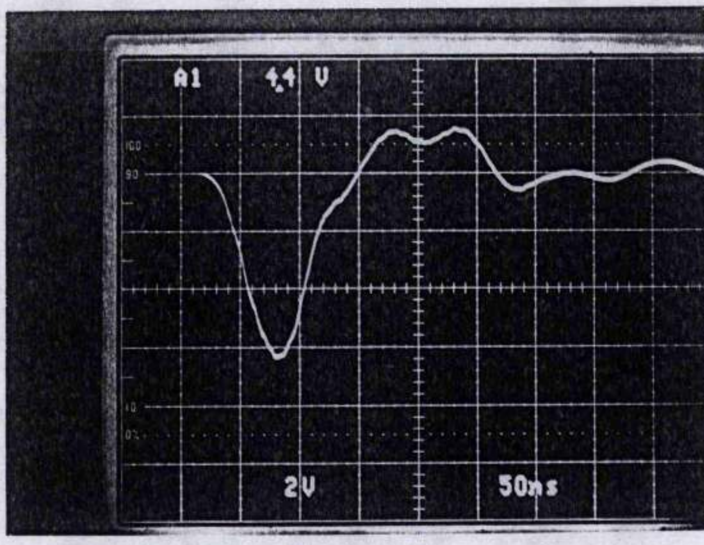
I thy.
200A/div



(c)

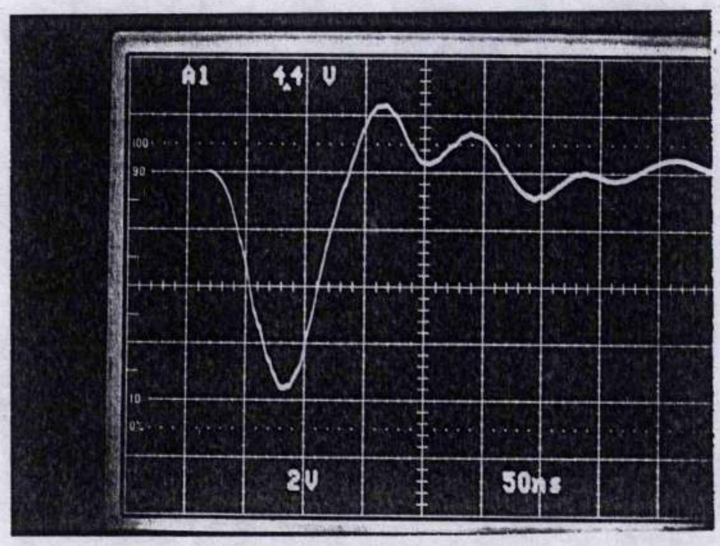
Figure 6.12 (a), (b) and (c). Thyratron voltage and current for sealed-off CuBr tube with increasing reservoir temperature (a to c).

V laser
2kV/div.



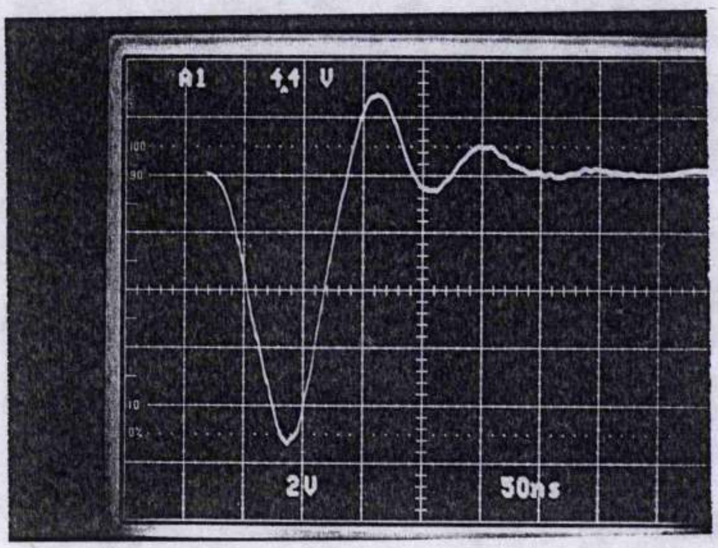
(d)

V laser
2kV/div.



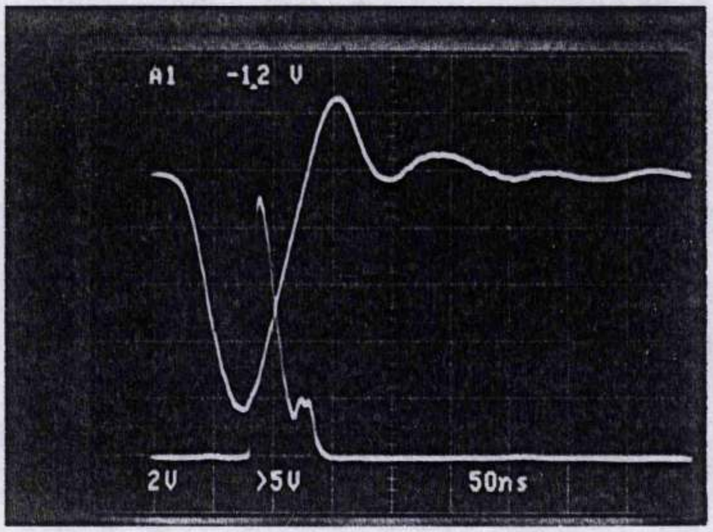
(e)

V laser
2kV/div.

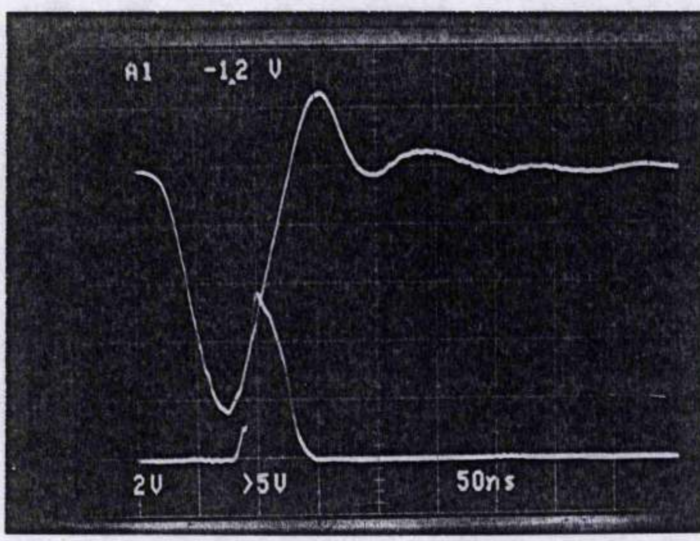


(f)

Figure 6.12 (d), (e) and (f) Laser tube voltage for sealed-off CuBr tube with increasing reservoir temperature (d to f).



(a) 510.6 nm laser line



(b) 578.2 nm laser line

Figure 6.13 Voltage across sealed-off CuBr tube (upper trace) with (a) green (510.6nm) line and (b) yellow (578.2nm) line. Note timing variation.

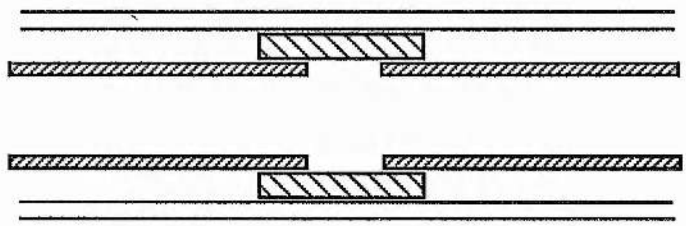


Figure 6.14 Alumina supports for segmented metal tube (surface tracking problems).

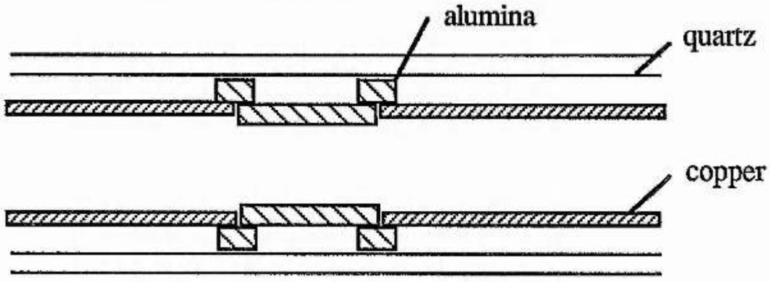


Figure 6.15 Modified alumina spacer arrangement.

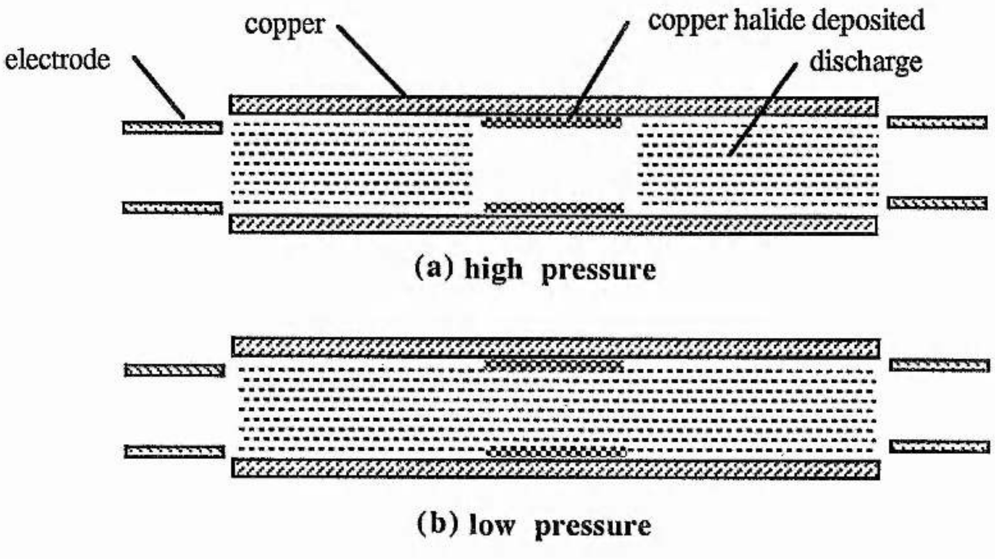


Figure 6.17 proposed single metal segment tube operated at (a) high and (b) low pressure.

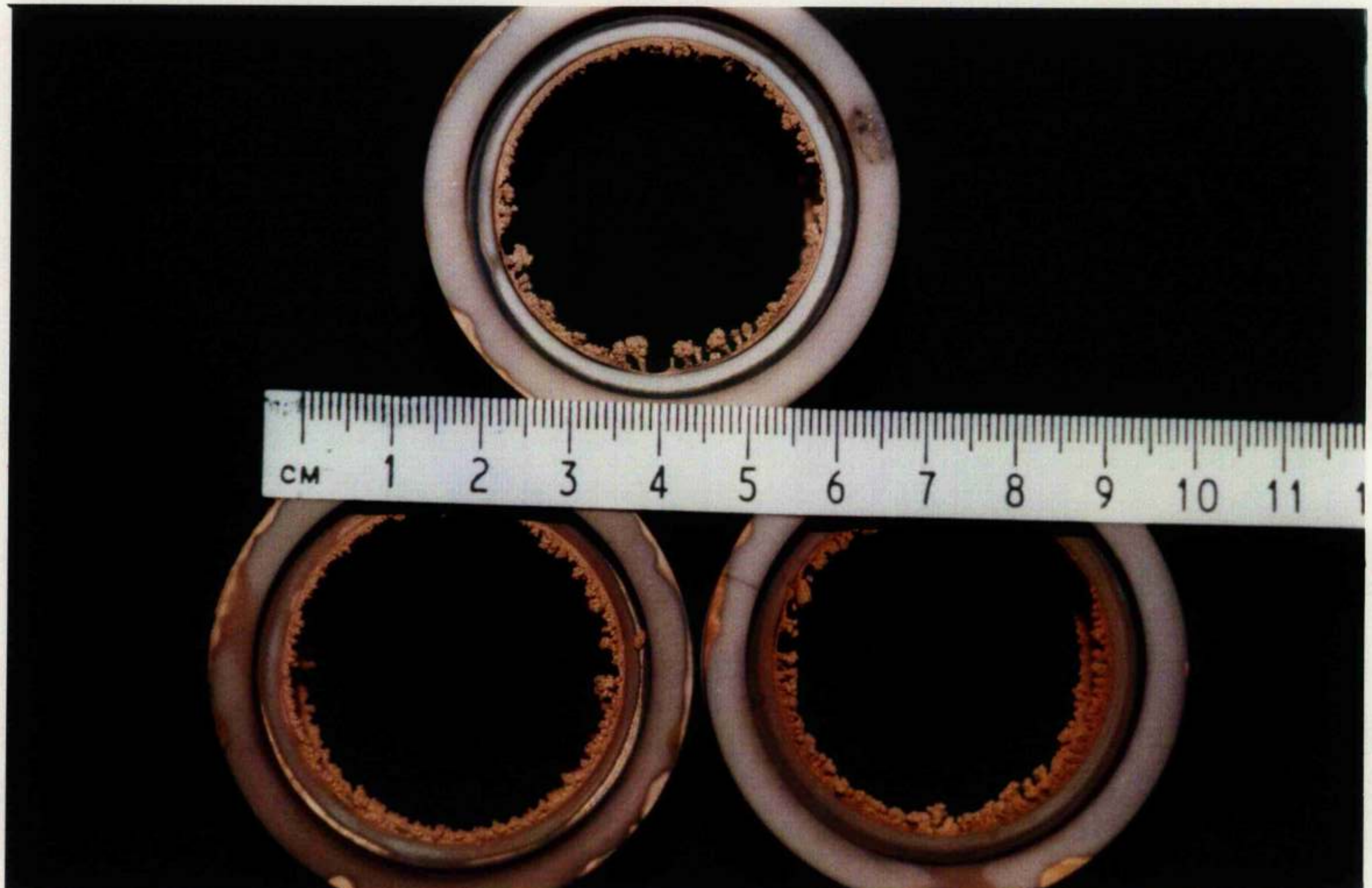


Figure 6.16 Copper build-up on alumina spacers in Cu-HBr laser.

Chapter 7

Overview and conclusions.

Copper vapour laser technology has advanced rapidly in the last decade. Laser tubes have been designed recently to give hundreds of watts of output power but their lifetimes are limited by the need to recharge with copper at intervals of a few hundred hours. The fundamental problems associated with these high temperature devices have not changed during this time and continue to cause difficulty and inconvenience in modern copper vapour lasers. The cause of most of the inconvenience associated with conventional copper lasers lies in the high operating temperatures of 1450 - 1500^{o}C. An alumina tube with insulating material wrapped around it will outgas for a very long period at these temperatures. The continuing ingress of contaminants means that the tube cannot be sealed off, but must have a flow of buffer gas to maintain a high purity discharge channel. The physical size of the container for the thermal insulation means that the current return path is separated from the discharge tube and hence laser head inductance is increased with a consequent reduction in discharge pumping efficiency. Furthermore, the thermal mass of such lasers is large and the alumina laser tube has relatively poor resistance to thermal shock. These characteristics combine to cause long heating and cooling times if tube fracture is to be avoided.

The use of copper halide as a laser material can dramatically alter the design of a copper laser tube and so avoid or reduce some of the problems associated with high temperature copper lasers. Copper halide devices, whilst having their own unique drawbacks, can address and to a large extent eliminate most of the problems associated with high temperature CVLs. The operating temperature of around 500 - 600^{o}C means that fused silica may be used as the laser tube. The adoption of fused silica brings three distinct advantages, these are, the ease of laser tube fabrication, improved thermal shock properties and the very low outgassing rate. Any fibrous thermal insulation required may be placed on the outside of the vacuum envelope where it cannot contaminate the discharge volume. Such lasers may be processed to remove surface and absorbed contaminants, then sealed-off with the optimum content of buffer gas. The reduced requirement for thermal insulation allows the current return to be brought closer to the discharge tube and the laser head inductance lowered. Improving the thermal shock properties of the discharge tube whilst reducing the thermal mass enables the operating temperature to be achieved in a much reduced time.

Two approaches to the design of a copper bromide laser are described in this thesis. The first approach addresses the ideal situation of a rapid warm-up, sealed-off laser tube capable of being mounted in a mobile system. A laser tube was built to demonstrate the feasibility of a sealed-off, air cooled, copper halide laser with low inductance to show that commercially acceptable lifetimes may be attained. The laser tube design is such that it is inexpensive to fabricate and may be considered as disposable at end-of-life, with a new tube simply plugging into the existing socket. The tube operated sealed-off at around 5W for 100 hours and showed potential for several hundreds of hours more life before the CuBr charge was exhausted. Although this tube did not contain metal segments, it may be advantageous to include these in future designs as they will provide another means of reducing the bromine concentration in a useful manner.

The addition of small amounts (< 1 Torr) of hydrogen, leads to a large change in the laser beam profile. The effects of hydrogen on the detailed laser kinetics are not yet clear but the advantages of hydrogen in improving both beam quality and power are so marked as to warrant a large scale spectroscopic investigation.

The sealed-off laser tube described above may be incorporated in a mobile, air-cooled, single phase laser system with short warm-up and warm-down times. The absence of a flowing buffer gas lends this type of device to microprocessor control and turnkey operation. Such a system would find many applications in a research, medical or industrial environment. Some applications which already use copper vapour lasers are listed here;

1. Uranium isotope separation.
2. Treatment of vascular lesions (port-wine stains).
3. Latent fingerprint detection.
4. High speed photography.
5. Flow visualisation.
6. Video projection (simulators).
7. Ultrashort pulse amplification.
8. Projection microscopy and surface treatment.

The theory of discharges in metal walled tubes was exploited in the design and operation of a high power copper bromide laser. The novel method of operation of this device led to the granting of a patent and subsequent industrial interest. A mixture of neon and hydrogen bromide is flowed through a segmented metal walled tube at a rate slightly above the flow rate of buffer gas in a conventional copper vapour laser. The hydrogen bromide is dissociated by the discharge and the bromine released reacts with the copper wall to form copper bromide. At the operating temperature of the device (500 - 600^{o}C) the CuBr will evaporate from the wall to be dissociated in the discharge volume. The copper liberated then participates in the cyclic laser excitation and de-excitation scheme until such time as it recombines with a bromine atom or condenses on the wall. The simplicity of this device, a fused silica tube with alternating copper and alumina cylinders, makes it very inexpensive and again the tube may be disposed of at end-of-life. The usage of the copper cylinders dictates the lifetime of such a tube and so thick walled copper may be used to provide a copper reservoir which is very large indeed. A laser tube of this construction gave 40W of light output from an unoptimised cavity (a world record for a copper halide laser). The application of scaling theory, coupled with novel cooling techniques (also patented) will see lasers of this type produce hundreds of watts.

The importance of the power modulator circuitry to drive metal vapour lasers was demonstrated in the improvements made to the reliability and output power of a gold vapour laser. By considering the thyratron as a gas discharge in its own right and not a a simple switch, the charging and discharging circuits were altered to better allow the thyratron to recover its non-conducting state between pulses. The gold vapour laser improved by this means was used as the radiation source for the photodynamic therapy of cancer at Ninewells hospital, Dundee. Experiments showed that a new technique involving early irradiation of the tumour after photosensitization was more effective than the accepted protocol of 24 - 48 hours delay between photosensitization and subsequent irradiation.

We have demonstrated the feasibility of operating copper halide lasers as sealed-off units for times which are commercially useful. Such sealed lasers will make an impact on the world marked for lasers in the low to medium power range. Along with the general scientific applications, there is scope for its widespread use in hospitals and clinics where the optical characteristics of the light are in increasing demand for dermatological and cancer therapies. The indications of our results are that such systems will be highly reliable and stable. Ultimately, they will be under the control of self teaching neural network programs. Industrial use of copper vapour lasers will continue in isotope separation and may extend to material processing where research is already underway. In addition, the unique properties of copper as a gain medium enable high quality projection microscopy to be undertaken in the microelectronic industries and biological fields. The use of hydrogen bromide has recently enabled many metals to give greater power output from systems of greatly simplified design and operational characteristics. The technology and understanding of segmented metal systems developed as described here may equally well be applied to all metals which form halides having substantial vapour pressures at temperatures below 1100^{o}C. The realization of reliable metal halide laser systems which provide a broad coverage of the infra-red, visible and ultra-violet spectral regions must open up new avenues for scientific, medical and industrial applications.

Appendix A.

The gold vapour laser.

The gold vapour laser (GVL) belongs to the same family as the copper vapour laser. The gold laser operates on two lines at 312.2 nm and 627.8 nm. Similar tube construction and power conditioning criteria to the copper laser also apply to the GVL, as the energy transfer through the atomic levels concerned follows similar rules. The essential differences between copper and gold lasers are twofold. Firstly, the vapour pressure required to support lasing in gold is achieved at about 1700-1800°C. This high temperature increases the problems associated with material failure and contamination, over those of the copper laser. The second difference between copper and gold lasers is that the electrical-optical efficiency is lower in gold by almost an order of magnitude. Hence gold vapour lasers are normally relatively low power devices.

An application arose locally for a GVL emitting up to 5 W in the 627.8 nm line. The application was the detection and treatment of cancerous tissue (tumours) using wavelength specific photosensitizing dyes in photodynamic therapy. Some of the work carried out on this project is described in Chapter 7.

A gold vapour laser was built (ref 1) for the application but after a few tens of hours of operation, became troublesome with the thyratron continually latching (failing to recover its non-conducting state after a current pulse), even at moderate voltages and pulse repetition frequencies. Increasing the buffer gas pressure in the laser tube from 20 Torr to 50 Torr reduced the latching rate but from a clinical point of view, the latching rate was still such that no experiments could be undertaken with the required confidence level of stable laser output power. The cause of the latching was finally traced to the thyratron itself, after all of the circuit components had been examined for damage and breakdown at high voltage. Examination of the thyratron anode voltage (fig A.1) showed that the EEV CX1825 hollow anode thyratron was performing as designed and conducting in reverse. The hollow anode thyratron, as its name suggests, has a large cavity within the anode where discharge plasma is retained after a current pulse. If the discharge circuit is such that a large reverse (-ve) voltage appears on the cathode, then instead of breaking down via a metal vapour arc from anode (-ve) to cathode (+ve), the plasma present in the anode will begin the conduction at a low voltage and encourage a glow discharge to form. The anode is not then bombarded by high energy ions and damaged. From the voltage waveform (fig A.1) it can be seen that once switching has taken place and the forward current has ceased, the circuit swings so that a negative voltage appears on the thyratron anode. Reverse breakdown occurs and the voltage is held constant for a time. The series of peaks and plateaus show that reverse conduction is taking place throughout the period when the thyratron should be recovering. When forward voltage is reapplied after 22 μs or so there still remains some plasma in the hollow anode which lowers the voltage hold-off capability and causes latching of the thyratron. When this thyratron was replaced by one of equivalent size but with a solid anode (EEV CX1825) it was noted that the anode voltage (fig A.2) became negative but the thyratron did not conduct in reverse. In this case a negative voltage remains on the anode, gradually diminishing, as the storage capacitor is recharged through the charging choke. As no current is passed through the thyratron for over 20 μs, recovery can be substantially complete when the next pulse is applied and the rate of latching is thus decreased considerably.

During the warm-up phase of operation, the latch rate would increase as gold began to vapourize and enter the discharge tube. The magnitude of the reverse voltage on the thyratron anode had decreased to the point where it was being brought positive in approximately 8-10 μs by the charging of the storage capacitor through the 150 mH charging choke. To maintain a negative voltage until the thyratron had fully recovered (15-20 μs), a saturating charging choke was designed and built (ref 2). This choke had an unsaturated inductance such that the reverse thyratron anode voltage was maintained for 17 μs. The choke would then saturate and charge the storage capacitor in around half the time taken by the non-saturating choke. The inclusion of this charging element reduced the latch rate to virtually zero and allowed the experiments to be performed with the confidence of a reliable light source. Figure A.3 shows the working gold vapour laser and fibre optic beam delivery system.

References.

1. G.L. Clark, PhD Thesis, University of St. Andrews, 1988.

2. S. Shepherd, 'Magnetic switches used in a copper vapour laser', MSc Report, University of St. Andrews, 1989.

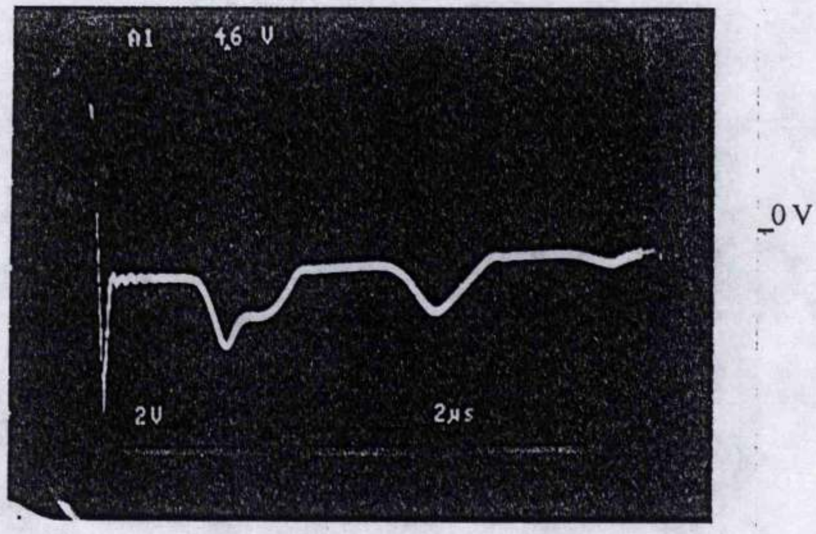


Figure A.1 Charging voltage on CX1625 hollow anode thyratron.

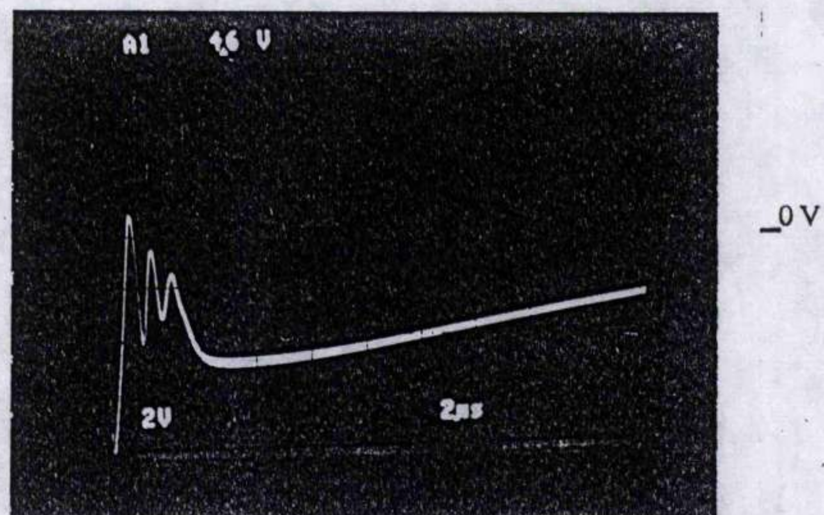


Figure A.2 Charging voltage on CX1825 solid anode thyratron.

Figure A.3 Gold vapour laser and fibre-optic beam delivery system.

Appendix B.

Patents and publications.

B.1 U.K. Patent application G.B. 2 219 128 A, April 1988.

B.2 U.K. Patent application G.B. 2 213 313 A, June 1988.

B.3 U.K. Patent application 9024733.9, November 1990.

B.4 Breakdown Voltages of attaching gas mixtures in metal segmented tubes.

B.5 A low temperature, segmented metal, copper vapour laser.

B.6 A high power, segmented metal, copper bromide laser.

B.7 Early illumination in experimental photodynamic therapy: Comparison with conventional treatment.

B.1

U.K. Patent application G.B. 2 219 128 A

This patent relates to laser tubes in which the lasant is formed in-situ by the reaction of a halogen or halogen donor with metal located in the discharge tube. The metal halide thus formed is evaporated by discharge heating and enters the discharge volume. High repetition rate pulsed discharges both dissociate the metal halide and excite the metal vapour to form a population inversion. Laser action may then take place in the metal vapour.

If the metal is in the form of cylindrical segments, separated by spacers, then the laser tube may be operated in any orientation as there is no liquid or solid lasant free to move within the tube.The laser tube itself, if composed of fused silica, metal and alumina may be inexpensive and have a long lifetime.

Experiments conducted on segmented metal tube lasers with flowing halogens are described in Chapter 6 (section 6.5.2) and in this Chapter (B.5, B.6,B.7).

(12) UK Patent Application (19) GB (11) 2 219 128 (13) A

(43) Date of A publication 29.11.1989

(21) Application No 8909555.8

(22) Date of filing 26.04.1989

(30) Priority data
(31) 8812276 (32) 24.05.1988 (33) GB

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(51) INT CL[4]
H01S 3/22 3/097

(52) UK CL (Edition J)
H1C CBBC C202 C210 C229 C235 C279 C34Y C340 C341 C363 C471

(56) Documents cited
None

(58) Field of search
UK CL (Edition J) H1C CBBA CBBC CBBD CJ
INT CL[4] H01S

(54) **Metal vapour laser apparatus**

(57) Metal vapour laser apparatus comprises an envelope 1 including electrodes 4 and 5 and cylindrical metal (e.g. Cu, Au) segments 6 wherein during operation a halogen gas (e.g. bromine with helium buffer gas) or halogen donor gas flows through the envelope, causing metal halide (e.g. copper bromide) to be produced. When a discharge is established between electrodes 4 and 5, the metal halide vaporizes and dissociates to give, for example, copper vapour which is then excited to produce a population inversion. Such apparatus is able to operate at relatively low temperatures, in the region of 600°c.

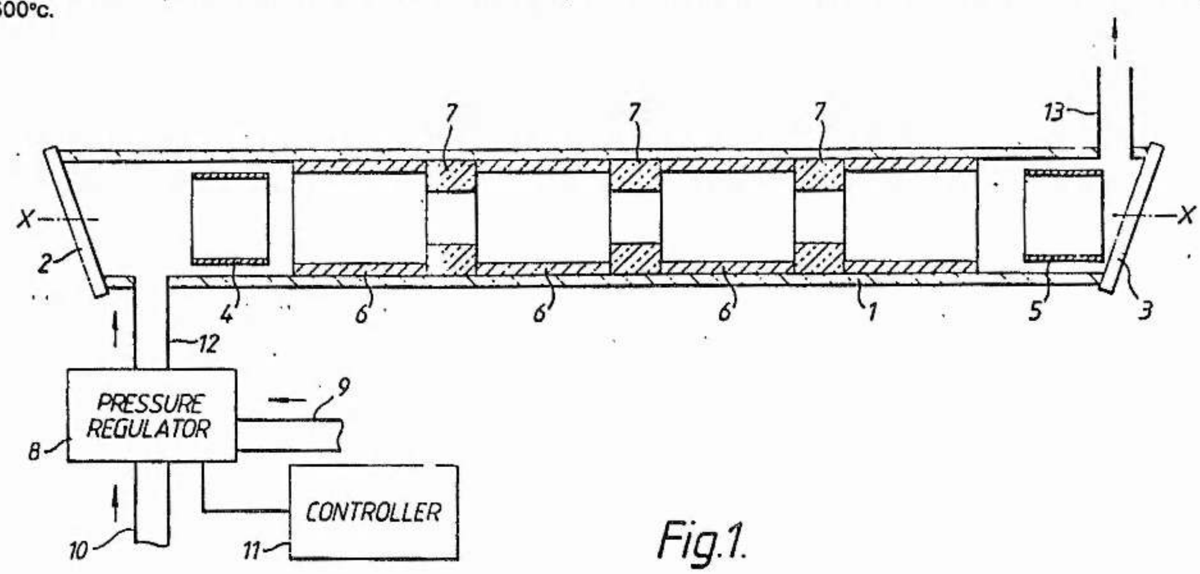

Fig.1.

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

GB 2 219 128 A

I/7605/EEV

LASER APPARATUS

This invention relates to laser apparatus and more particularly to such apparatus in which metal vapour constitutes the laser amplifying medium.

In a known copper vapour laser, copper metal is distributed along the length of a discharge tube and is heated by a discharge or discharges within the tube to produce copper vapour. The discharge energy also acts to produce a population inversion and achieve laser action. The operating temperatures of such a laser are typically around 1500°C, requiring a considerable amount of thermal insulation around the discharge tube.

The present invention arose from an attempt to provide an improved metal vapour laser.

According to a first aspect of the invention, there is provided metal vapour laser apparatus comprising an envelope, which contains metal, and means arranged to flow a halogen gas or halogen donor gas through the envelope to produce a metal halide which vaporizes and dissociates on heating to produce metal vapour.

A halogen donor gas is a halogen compound, such as hydrogen bromide, which readily dissociates during operation of the laser apparatus to give halogen molecules or ions. When a halogen donor gas is used, means must be included to cause it to dissociate and thus release free halogen which then reacts with the metal to form a metal halide. Dissociation of the halogen donor gas is preferably achieved by passing an electrical discharge through it. The halogen gas reacts with the metal at its surface to produce a film of metal halide which can be of very high purity if the purity of the copper and halogen, or halogen donor, is also high.

Apparatus in accordance with the invention is able to operate at low temperatures, for example in the region of 600°C for a copper vapour laser. This avoids the need for extensive thermal insulation around the envelope and also enables a fast start-up time to be achieved.

In an advantageous embodiment of the invention, means are included for varying the pressure within the envelope such that initially it is relatively low to establish stable discharge conditions and subsequently, during heating of the metal halide, it is relatively high to optimize performance in accordance with the changing composition of the gas mixture. The pressures involved depend on the particular dimensions of the laser apparatus and its contents. In a typical arrangement, the pressure is initially less than about 5 torr and then it is increased to about 30 torr.

In a particularly convenient embodiment of the invention, the metal is in the form of a single hollow cylinder arranged coaxially with the longitudinal axis of the envelope. In another embodiment of the invention, a plurality of hollow cylinders is included, the cylinders being spaced apart in the direction of the longitudinal axis. The introduction of copper in the form of a cylindrical segment or segments, in conjunction with the flow of halogen gas, or halogen donor gas over it, enables a particularly uniform distribution of the laser amplifying medium to be produced.

The invention is particularly applicable where the metal is copper, although other metals such as gold may be used, and it is preferred that the halogen, or halogen donated, is bromine.

According to a second aspect of the invention there is provided metal vapour laser apparatus arranged to operate in a sealed-off mode comprising an envelope containing a metal halide and wherein, prior to laser operation, a halogen gas or halogen donor gas is arranged to flow over metal within the envelope to produce a metal halide.

Preferably, a buffer gas is arranged to flow through the envelope with the halogen or its donor and it is preferred that the buffer gas is one of, or a mixture of, the inert gases such as neon.

Some ways in which the invention may be performed are now described by way of example with reference to the accompanying drawings, in which:

Figures 1, 2 and 3 are schematic longitudinal sections of respective metal vapour lasers in accordance with the invention.

With reference to Figure 1, copper vapour laser apparatus in accordance with the invention includes a quartz envelope 1 having end windows 2 and 3. Two cylindrical electrodes 4 and 5 are arranged with one at each end of the envelope coaxially with the longitudinal axis X-X. A plurality of cylindrical copper segments 6 are located between the electrodes 4 and 5. The segments 6 are spaced apart by ceramic spacers 7 of smaller internal diameter (id) than the id of the metal segments 6. Each segment 6 has a length which is about twice its diameter and is arranged coaxially with the longitudinal axis X-X. The apparatus includes a pressure regulator 8 to which helium buffer gas and bromine are supplied through lines 9 and 10, respectively. A control circuit 11 governs the proportions and pressure of the gases applied to the envelope 1 via the regulator 8.

During operation of the laser apparatus, a mixture of helium buffer gas and bromine is arranged to flow through the envelope 1, and over the copper segments 6. The gases are applied at an input port 12 and taken from a port 13 at the other end of the envelope 1. The bromine reacts with copper at the surface of the segments 6 to give copper bromide. The control circuit 11 initially acts to maintain the pressure within the envelope 1 at a relatively low level, which in this case is about 5 torr, for a given time to heat the copper segments 6. The control circuit then increases the pressure within the envelope 1 to about 30 torr. Discharges established between the electrodes 4 and 5 cause the copper bromide to vaporize and dissociate to produce copper vapour. The copper vapour is then excited to establish a population inversion and laser action occurs.

When the laser apparatus is operating in its higher pressure mode, the centre of the laser tube is cooler than its ends. Thus, copper bromide tends to condense at the centre rather than on the windows 2 and 3 and forms a "reservoir" of copper bromide which is used during the low pressure stage of the next cycle of operation.

The inner surfaces of the ceramic spacers 7 are nearer the centre of the tube than the copper segments 6 and thus are warmer. The tendency for copper to condense on the spacers 7 is therefore less than would be the case if the spacers 7 had the same internal diameter as the copper segments 6. This difference in internal diameters also reduces movement of any debris or particles along the tube, which is particularly useful in cases where it is wished to operate the laser in a vertical orientation. If such operation is intended, the spacers 7 may be modified by including a depression in one or both of their transverse surfaces so as to retain debris within them.

With reference to Figure 2, another laser apparatus in accordance with the invention includes a quartz envelope 14 which contains electrodes 15 and 16 and a copper tube 17 located between them, the tube 17 being about 1 metre in length.

During operation, the pressure within the envelope 14 is maintained at a relatively low pressure, which in this case is about 5 torr. The bromine combines with copper at the surface of the tube 17 to give copper chloride. A control circuit 18 maintains the pressure at this lower level for a given time to heat the copper tube 14. It then acts to increase the pressure within the envelope 14 to about 30 torr. Discharges established within the envelope 14 cause the copper chloride to vaporize and dissociate to give copper vapour and excite it to produce a population inversion.

In another copper vapour laser in accordance with the invention, the metal halide is produced within the envelope of the laser by flowing a halogen donor gas, which in this case is hydrogen bromide, over a single long copper cylinder. As the hydrogen bromide is passing over the surface of the metal segment, an electrical discharge is established within the envelope, causing the halogen donor to dissociate and release free halogen. This then combines with the copper at the surface of the copper tube to give copper bromide.

After the copper bromide has been produced, the laser envelope is "sealed off" to give apparatus as illustrated in Figure 3. The envelope includes helium buffer gas, the copper tube 19 and the copper bromide 20 on the surface of the tube. Electrodes 21 and 22, which were used to produce the initial electrical discharges during production of the copper bromide, are used to establish further discharges within the tube to heat it. The copper bromide 20 vaporises and dissociates to give the copper vapour which is used as the laser amplifying medium.

CLAIMS

1. Metal vapour laser apparatus comprising an envelope which contains metal, and means arranged to flow a halogen gas or halogen donor gas through the envelope to produce metal halide which vaporizes and dissociates on heating to produce metal vapour.

2. Laser apparatus as claimed in claim 1 and including means for varying the pressure within the envelope such that initially it is relatively low and subsequently, during heating of the metal halide, it is relatively high.

3. Metal vapour laser apparatus arranged to operate in sealed-off mode comprising an envelope containing a metal halide and wherein, prior to laser operation, a halogen gas or halogen donor gas is arranged to flow over metal within the envelope to produce a metal halide.

4. Laser apparatus as claimed in claim 3 and including means for producing an electrical discharge within the envelope to produce the metal halide.

5. Laser apparatus as claimed in any preceding claim and, where halogen donor gas is arranged to flow, comprising means for causing dissociation of the halogen donor gas to release free halogen for reaction with the metal.

6. Laser apparatus as claimed in claim 5 wherein the said means for causing the dissociation is arranged to pass an electrical discharge through the halogen donor gas.

7. Laser apparatus as claimed in any preceding claim

wherein the metal is in the form of a single hollow cylinder arranged coaxially with the longitudinal axis of the envelope.

8. Laser apparatus as claimed in any of claims 1 to 6 wherein the metal is in the form of a plurality of hollow cylinders spaced apart in the direction of the longitudinal axis.

9. Laser apparatus as claimed in claim 8 wherein each cylinder has a length which is up to approximately twice its diameter.

10. Laser apparatus as claimed in any preceding claim and including means arranged to produce a discharge within the envelope which provides heating of the metal halide.

11. Laser apparatus as claimed in any preceding claim wherein the metal is copper.

12. Laser apparatus as claimed in any preceding claim wherein the halogen, or donated halogen, is bromine.

13. Laser apparatus as claimed in any preceding claim wherein a buffer gas is arranged to flow through the envelope with the halogen or halogen donor gas.

14. Laser apparatus as claimed in claim 13 wherein the buffer gas is an inert gas.

15. Laser apparatus as claimed in any preceding claim wherein the envelope is of quartz.

16. Metal vapour laser apparatus substantially as illustrated in and described with reference to Figure 1, 2 or 3 of the accompanying drawings.

Published 1989 at The Patent Office, State House, 66/71 High Holborn, London WC1R 4TP. Further copies may be obtained from The Patent Office. Sales Branch, St Mary Cray, Orpington, Kent BR5 3RD. Printed by Multiplex techniques ltd, St Mary Cray, Kent, Con. 1/87

ABSTRACT

METAL VAPOUR LASER APPARATUS

Metal vapour laser apparatus includes an envelope 1 within which is contained electrodes 4 and 5 and a plurality of cylindrical copper segments 6 arranged between the electrodes 4 and 5. During operation of the laser, bromine and helium buffer gas are arranged to flow through the envelope 1, causing copper bromide to be produced. When a discharge is established between the electrodes 4 and 5, the copper bromide vaporizes and dissociates to give copper vapour which is then excited to produce a population inversion. Such apparatus is able to operate at relatively low temperatures, in the region of 600°C.

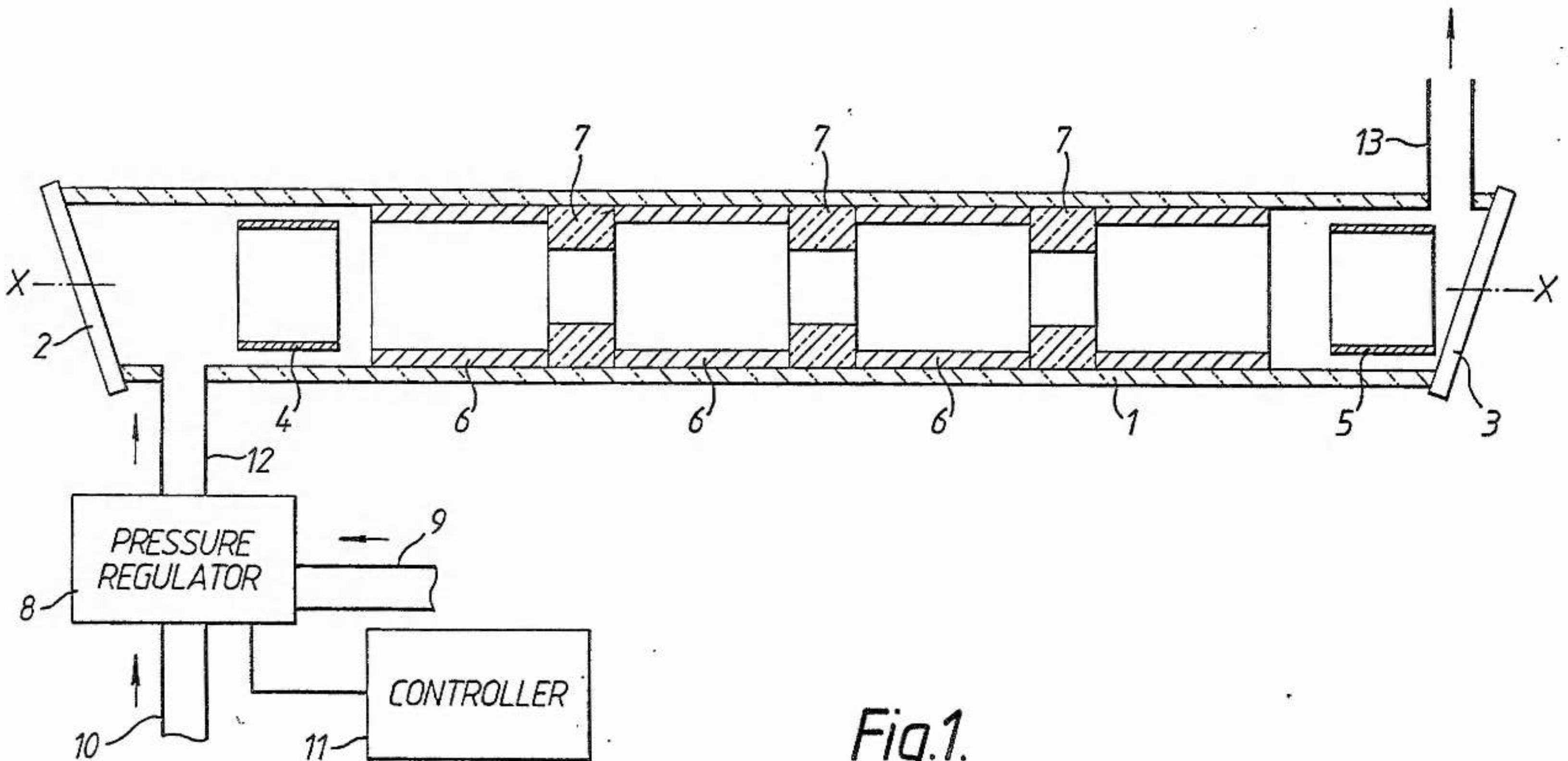
7
7
7
13
X
X
2
4
6
6
6
1
5
3
12
PRESSURE
REGULATOR
8
9
10
CONTROLLER
11

Fig.1.

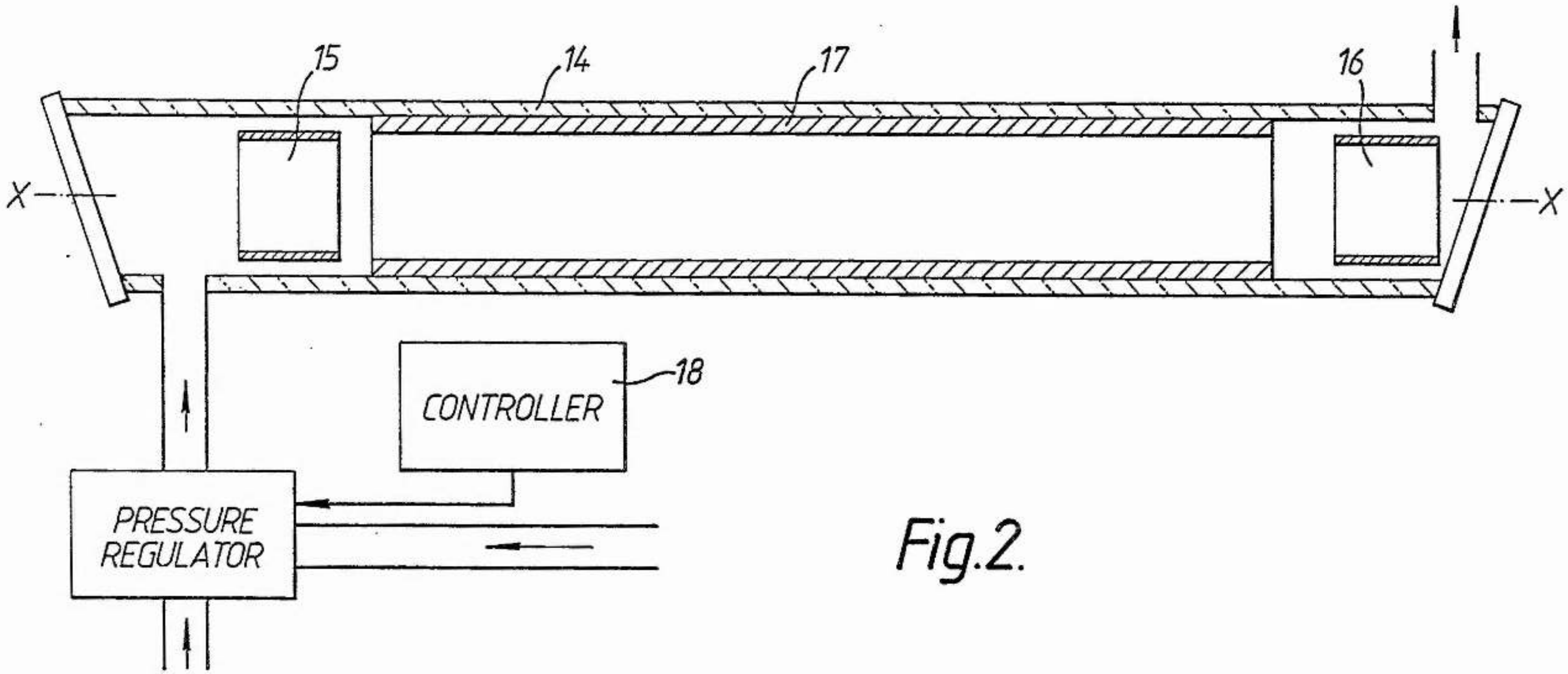

Fig.2.

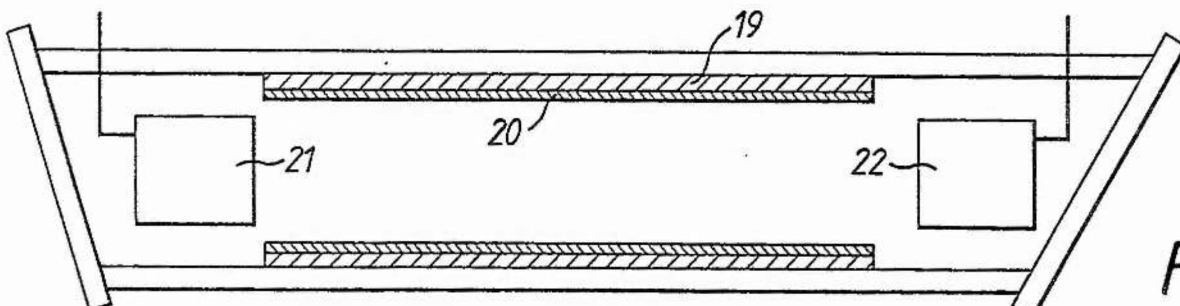

Fig.3.

B.2

U.K. Patent application G.B. 2 213 313 A

This patent relates to a method of introducing laser amplifying media into a gas discharge tube in a form suitable for excitation by discharge pumping. The general method described is the atomisation of liquid or solid lasant or lasant in solution, and the subsequent introduction of this lasant to the discharge tube by means of flowing gas.

In a particular embodiment of this method a mixture of combustible gas, oxygen and inert gas (helium or neon) is drawn past an atomiser which seeds the gas flow with an atomised solution of a copper compound (copper sulphate, copper bromede etc). This solution is entrained in the gas flow and taken into a discharge tube where a flame is burning at low pressure (between 1 and 50 Torr). The flame evaporates any solvent attached to the copper compound and may dissociate the compound. A pulsed electrical discharge is then arranged between two electrodes, either longitudinal or transverse, and the copper is then dissociated from its compound if it has not been already and then excited to form a population inversion from which laser light is produced.

The main advantages of such a device are that laser action may be initiated in a very few seconds and many different metals may be used singly, or simultaneously to give multi-wavelength output.

(12) UK Patent Application (19) GB (11) 2 213 313 (13) A

(43) Date of A publication 09.06.1989

(21) Application No 8813347.5

(22) Date of filing 06.06.1988

(30) Priority data
(31) 8728422 (32) 04.12.1987 (33) GB
8801022 18.01.1988

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(51) INT CL⁴
H01S 3/03

(52) UK CL (Edition J)
H1C CBBC C201 C206 C208 C216 C229 C253 C31X C34Y C341 C490 C532 C720

(56) Documents cited
None

(58) Field of search
UK CL (Edition J) H1C CBBA CBBC CBBD CJ
INT CL⁴ H01S

(54) **Laser arrangement**

(57) In a laser arrangement, a solid or liquid material 3, at least part of which comprises a laser amplifying medium, is atomised in a gas 2 prior to being applied to a discharge region 6. In one embodiment of the invention, the gas is combustible and is ignited to produce a flame 16 which provides heating of the material.

In another embodiment of the invention, the material is atomised in an inert gas and discharge within a laser discharge tube is used to provide excitation. The invention is particularly applicable to metal vapour lasers.

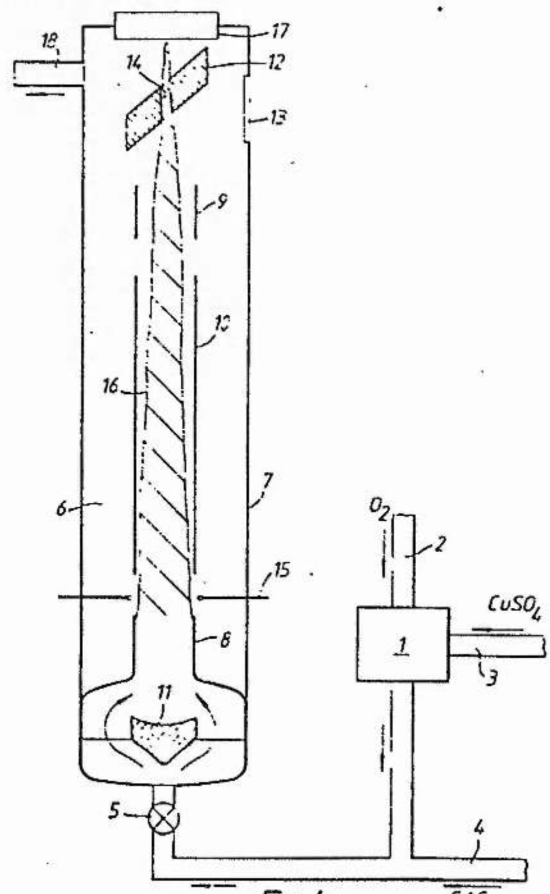

FIG.1.

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LASER ARRANGEMENTS

This invention relates to laser arrangements and more particularly, but not exclusively, to metal vapour lasers.

Presently known metal vapour lasers usually operate in gaseous electrical discharges at pressures below 1 bar. Metal, or a metallic compound, is contained in the laser discharge tube. The metal or metal compound is heated to a temperature at which the metal vapour pressure is sufficient to support laser action when the vapour is suitably pumped to establish a population inversion. One disadvantage of presently known metal vapour lasers is that the time required to achieve the operating temperature (termed the "warm-up" time) for laser action can be unacceptably long. Another disadvantage is that a laser tube containing free metal or a metallic compound cannot be moved, tilted or operated vertically without some provision being made to retain the solid or liquid in position along the tube.

The present invention aims to provide an improved laser arrangement in which the above disadvantages are reduced or eliminated.

According to the invention there is provided a laser arrangement in which solid or liquid material, at least part of which is to comprise a laser amplifying medium, is atomised and dispensed into a gas flow prior to being introduced to a discharge region. Atomisers are known devices in which a solution, or fine particles, is sprayed through a nozzle into the gas flow. As the particles or droplets are small, when they reach the discharge region only small amounts of additional energy are required to vaporise them and bring the laser amplifying medium to a state ready for lasing. The warm-up times necessary are correspondingly reduced.

The invention may be particularly advantageously employed if the laser amplifying medium is to be a metal vapour.

In one advantageous embodiment of the invention, gas in which the material is atomised is combustible and means are included to ignite the gas to produce a flame whereby the atomised material is vaporised. Thus, the flame can be "seeded" with atoms or molecules which are to form the laser amplifying medium. Further excitation may then be provided by an electrical discharge to obtain a population inversion. In one embodiment of the invention the material is methyl iodide, which preferably is atomised in a mixture of propane and oxygen. On combustion, an oxy-iodine reaction occurs which results in laser radiation being generated in the infra-red part of the spectrum, at 1.3 μm.

The solid or liquid material may be applied to an atomiser to directly atomise it in the combustible gas, or it could be atomised in a non-combustible gas which is then mixed with another gas to obtain a combustible mixture. The laser action may be arranged to occur at atmospheric pressure, in which case no containing envelope is required, although it may be desirable in some circumstances to provide shielding of the flame from atmospheric disturbances. The combustible gas carrying atomised material may be arranged to pass through a burner where it is ignited. The burner may be made of metal, in which case it may act as an electrode in a discharge circuit arranged to produce a discharge in the flame. In an alternative arrangement, the burner may be made of ceramic. In one particularly advantageous configuration, the burner is elongate and has a passage along its length (a longitudinal passage) through which gas is arranged to flow and a plurality of apertures transverse to the longitudinal passage which connect it to the atmosphere surrounding the burner, with the length of the burner horizontal. A flame which is substantially uniform burns vertically along the length of the burner. It is preferred that an electrode of a discharge circuit is essentially parallel to the length of the burner so as to produce a uniform discharge in the flame.

Where the burner is of metal it may be arranged to act as the other electrode of the discharge circuit. Alternatively, the metallic burner may be electrically isolated from the two electrodes in the discharge circuit. If the burner is of ceramic, or another insulating material, another electrode parallel to the length of the burner must be provided.

In an alternative advantageous arrangement, laser action is arranged to occur at low pressure within an envelope. By "low pressure" it is meant that the pressure is sub-atmospheric, and it may be as low as a few torr. In such an arrangement, two electrodes may be positioned such that a discharge established between them in the flame causes longitudinal excitation of the amplifying medium. One of the electrodes may be annular and arranged to hold the base of the flame, that is, the flame may be arranged to originate at the electrode. Preferably, a tube is arranged to surround the flame within the envelope, as this is helpful in enabling a laminar flow of the flame to be established. This is desirable as it tends to reduce variations in refractive index along the length of the envelope. Advantageously, a mirror defining part of the laser resonant cavity has an aperture therethrough. This enables the flame to pass through the mirror.

In another arrangement in accordance with the invention, instead of using combustible gas and causing it to ignite, the gas in which the material is atomized is an inert gas. In such an arrangement it is preferred that laser action is arranged to occur within an envelope at low pressure. Such an arrangement is particularly advantageous where the material is a metal bromide, such as copper bromide, as such compounds may sublime.

Some ways in which the invention may be performed are now described by way of example with reference to the accompanying drawings, in which:

Figures 1 to 5 schematically illustrate different laser arrangements in accordance with the invention.

With reference to Figure 1, a laser arrangement in accordance with the invention employs a combustible gas in which atomised copper sulphate solution is entrained. When the gas is ignited within an envelope, copper vapour is produced by dissociation of the sulphate molecules and is then excited to provide a population inversion in the copper atoms to generate laser radiation. The arrangement includes an atomizer 1 to which oxygen gas is applied via a pipe 2 and copper sulphate solution via a pipe 3. The atomiser 1 causes droplets of the copper sulphate solution to be injected into the oxygen so that they become suspended in it. The atomised solution in the gas is then mixed with natural gas flowing in a pipe 4 to give a combustible gas mixture which is then supplied via a regulator 5 to a laser discharge tube 6. The laser discharge tube 6 is arranged with its optical axis substantially vertical. It comprises an envelope 7 within which are contained two annular electrodes 8 and 9 having a cylindrical quartz tube 10 located between them. The laser resonant cavity is defined by three mirrors 11, 12 and 13. The mirror 11 has a concave reflecting surface. The mirror 12 is a folding mirror which has a planar surface inclined to the optical axis and an aperture 14 passing through it along the optical axis. The mirror 13 is partially transmissive and is aligned with respect to the mirror 11 so as to form a resonant cavity via mirror 12.

The gas mixture carrying the suspended atomised copper sulphate solution is arranged to pass into the envelope via the regulator 5 and flow around the outside of the concave mirror 11. The gas is constrained to pass through the annular electrode 8 nearest the concave mirror 11 where a spark produced between electrodes 15 located near the electrode 8 ignites the gas. The flame 16 which results extends along the envelope 7 and is confined by the tube 10 and the second annular electrode 9, the base of the flame being held by the electrode 8. The end of the flame is arranged to pass through the aperture 13 in the planar mirror 12 and impinges on a water-cooled heat sink 17 located at the end of the envelope 7. As the atomized copper sulphate solution enters the flame, the solvent evaporates and the sulphate dissociates to yield the copper atoms required. When it is desired to produce laser radiation, a discharge is established between the electrodes 8 and 9, using a conventional laser discharge circuit, and the longitudinal excitation initiates laser action. Copper which condenses or which does not become vaporised as it travels along the discharge tube is carried by the flame through the aperture 14 and deposited on the heat sink 17.

An outlet 18 enables gas to be drawn out of the laser discharge tube 6 so that pressure within the envelope 7 may be controlled. The pressure must be maintained at a low value so that a glow discharge can be established within the laser discharge tube 6.

With reference to Figure 2, in another laser arrangement, laser action is arranged to occur at atmospheric pressure. As in the arrangement shown in Figure 1, copper sulphate solution is atomised in oxygen using an atomizer 19 and the resulting suspension is mixed with natural gas to form a combustible mixture in which the copper sulphate droplets are suspended. The combustible gas is applied via a pipe 20 to an elongate burner 21. The burner 21 is made of metal and has a passage 22 which is extensive along its length and a plurality of apertures 23 which connect the passage 22 with its external surroundings. It should be noted that the burner 21 is shown in cross-section for a clearer understanding of its configuration. As the gas leaves the burner 21, it is ignited by a spark and the resulting flame 24 containing vaporised copper is produced along the length of the burner 21.

The burner 21 is arranged to act as an electrode in a laser discharge circuit. The circuit also comprises two capacitors 25 and 26, a thyratron switch 27 and a plurality of electrodes 28. The electrodes 28 are distributed along the length of the flame 24. Resistors

29 limit the current to the individual electrodes 28. When it is desired to initiate laser action within the flame 24, the capacitor 25 is charged and then the switch 27 is closed so that charge is transferred to the other capacitor 26. When the breakdown voltage between the electrodes 28 and the burner 21 is reached, discharges are established between them. The resistors 29 ensure that the discharges occur simultaneously and uniformly along the length of the flame 24. The copper vapour, excited by the discharge enables laser radiation to be generated.

With reference to Figure 3, in an alternative arrangement to that shown in Figure 2, the burner 30 is made of ceramic material. A pair of electrodes 31 and 32 are located such that, when a flame 33 is present, it is located between them.

With reference to Figure 4, another laser arrangement in accordance with the invention is similar to that illustrated in Figure 2 but includes an envelope 34 within which the burner 35 is contained, and the laser operates at a few torr pressure.

With reference to Figure 5, in another laser arrangement in accordance with the invention, a solid material is atomised in an inert gas and then supplied to a laser discharge tube. Unlike the other illustrated arrangements, a flame is not used in this arrangement. The laser discharge tube is similar to that shown in Figure 1, but electrodes 15 are omitted. During operation of the arrangement, fine copper bromide powder is entrained in argon gas in the mixer 36. The resulting suspension is supplied via a regulator 37 to the laser discharge tube 38. When it is wished to establish laser operation within the discharge tube 38, a discharge is established between two electrodes 39 and 40 within the discharge tube. The heat of the discharge causes the copper bromide to vaporise and to dissociate, with the formation of copper vapour. Further discharges between the electrodes 39 and 40 excite the copper vapour and enable laser action to be initiated.

CLAIMS

1. A laser arrangement in which solid or liquid material, at least part of which is to comprise a laser amplifying medium, is atomised and dispensed into a gas flow prior to being introduced to a discharge region.

2. An arrangement as claimed in claim 1 wherein the laser amplifying medium is a metal vapour.

3. An arrangement as claimed in claim 1 wherein the material is methyl iodide.

4. An arrangement as claimed in claim 1, 2 or 3 wherein gas in which the material is atomised is combustible and including means arranged to ignite the gas to produce a flame whereby the atomised material is vaporised.

5. An arrangement as claimed in claim 4 when dependent on claim 3 wherein the gas is a mixture of propane and oxygen.

6. An arrangement as claimed in claim 4 or 5 wherein laser action is arranged to occur at substantially atmospheric pressure.

7. An arrangement as claimed in claim 4, 5 or 6 wherein the combustible gas carrying atomised material is arranged to pass through a burner where it is ignited.

8. An arrangement as claimed in claim 7 wherein the burner is made of metal.

9. An arrangement as claimed in claim 8 wherein the burner acts as an electrode in a discharge circuit arranged to produce a discharge in the flamne.

10. An arrangement as claimed in claim 7 wherein the burner is made of electrically insulating material.

11. An arrangement as claimed in claim 7, 8, 9 or 10 wherein the burner is elongate with a passage along its length through which gas is arranged to flow to leave from a plurality of apertures transverse to the passage in the burner wall.

12. An arrangement as claimed in claim 11 wherein an electrode of a discharge circuit arranged to produce a discharge in the flame is substantially parallel to the burner along its length.

13. An arrangement as claimed in claim 4 or 5 wherein laser action is arranged to occur within an envelope.

14. An arrangement as claimed in claim 13 wherein laser action is arranged to occur at sub-atmospheric pressure.

15. An arrangement as claimed in claim 13 or 14 and including two electrodes positioned such that a discharge established between them in the flame causes longitudinal excitation of the amplifying medium.

16. An arrangement as claimed in claim 15 wherein one of the electrodes is annular and is arranged to hold the base of the flame.

17. An arrangement as claimed in any of claims 13 to 16 wherein a tube is arranged to surround the flame within the envelope.

18. An arrangement as claimed in any of claims 13 to 17 and including a mirror defining part of the laser resonant

cavity and having an aperture therethrough through which the flame is arranged to pass.

19. An arrangement as claimed in claim 18 wherein the mirror has a planar reflective surface and is inclined with respect to the optical axis of the laser.

20. An arrangement as claimed in claim 1 or 2 wherein the gas in which the material is atomised is an inert gas.

21. An arangement as claimed in claim 3 wherein the gas in which the material is atomised is an inert gas.

22. An arrangement as claimed in claim 20 or 21 wherein laser action is arranged to occur within an envelope.

23. An arrangement as claimed in claim 20, 21 or 22 and including a mirror defining part of the laser resonant cavity and having an aperture therethrough, through which hot gases are arranged to pass.

24. An arrangement as claimed in claim 20, 22 or 23 wherein the material is a metallic compound.

25. An arrangement as claimed in any preceding claim and including a laser discharge tube arranged to operate in an oprientation such that the optical axis of the discharge tube is substantially vertical.

26. A laser arrangement substantially as illustrated in and described with reference to Figure 1, 2, 3 or 4 of the accompanying drawings.

Published 1989 at The Patent Office, State House, 66 71 High Holborn, London WC1R 4TP. Further copies may be obtained from The Patent Office. Sales Branch, St Mary Cray, Orpington, Kent BR5 3RD. Printed by Multiplex techniques ltd, St Mary Cray, Kent, Con. 1/87

ABSTRACT

LASER ARRANGEMENT

In a laser arrangement, solid or liquid material, at least part of which comprises a laser amplifying medium, is atomised in a gas prior to being applied to a discharge region. In one embodiment of the invention, the gas is combustible and is ignited to produce a flame which provides heating of the material. The invention is particularly applicable to metal vapour lasers.

In another embodiment of the invention, the material is atomised in an inert gas and a discharge within a laser discharge tube is used to provide excitation.

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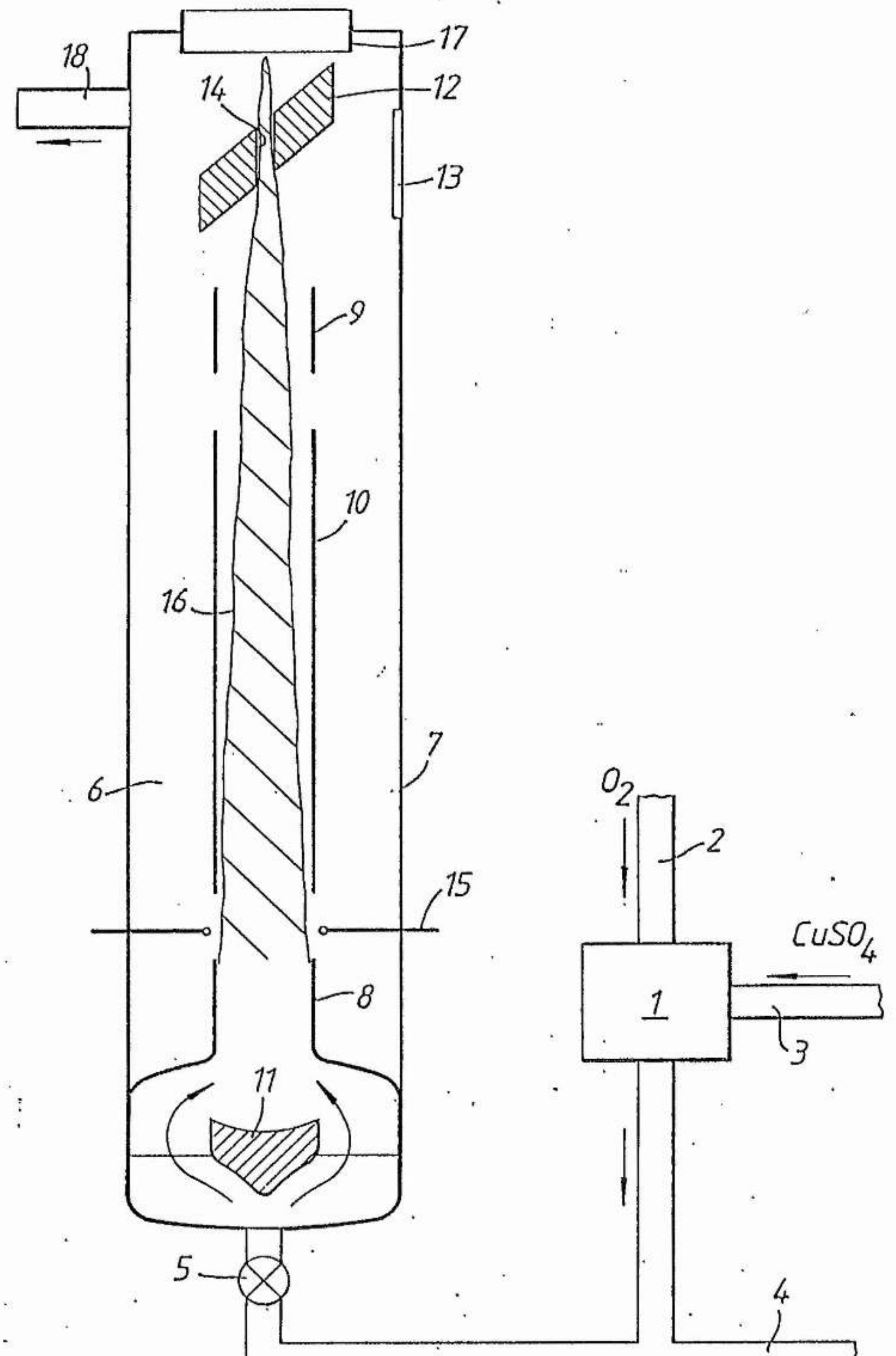

FIG.1.

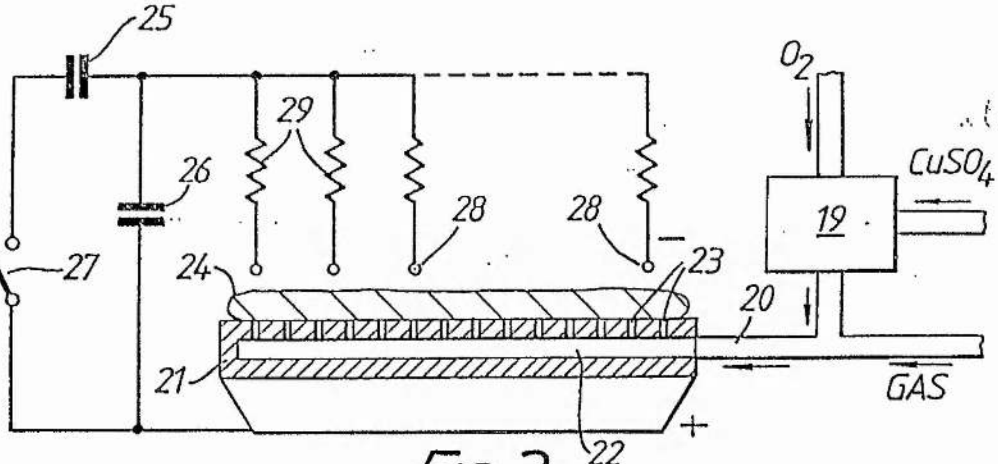

FIG. 2.

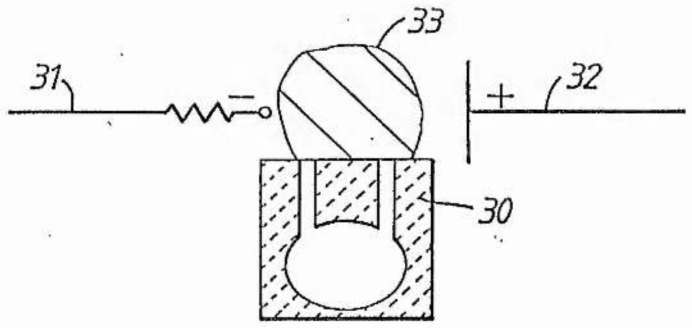

FIG. 3.

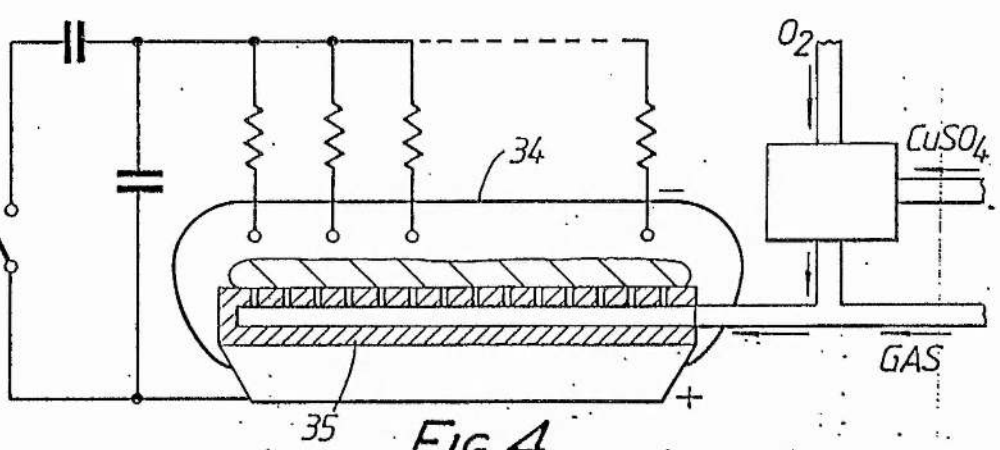

FIG. 4.

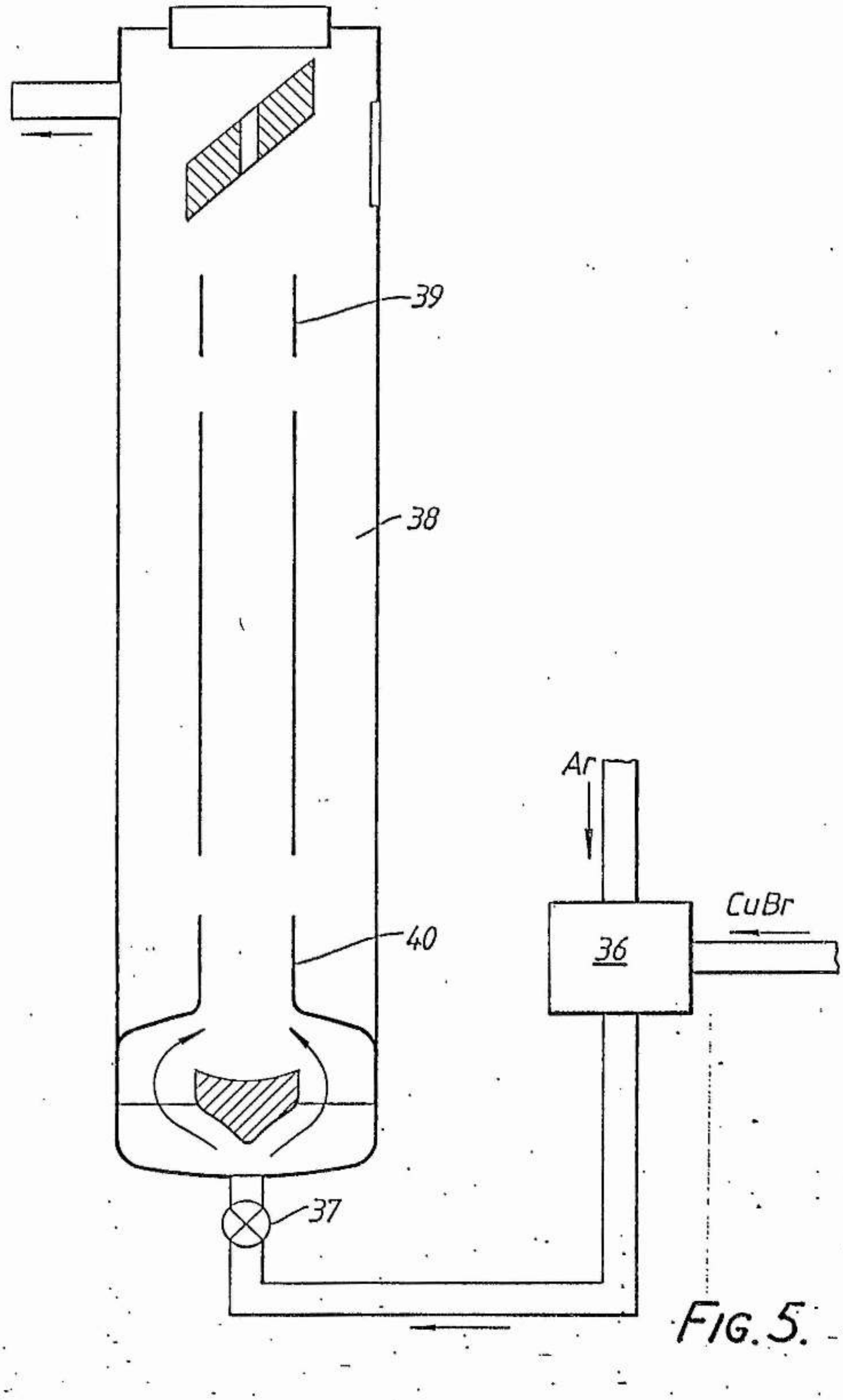

FIG. 5.

B.3

U.K. Patent application 9024733.9

This patent describes a method of constructing and operating a metal vapour laser, whereby, instead of providing thermal insulation to raise the temperature of the laser tube, the tube is maintained at its operating temperature by being cooled. In this way, the input power from the pulsed discharge may be increased by a large amount while the laser tube remains at its optimum operating temperature (see Chapter 1 figure 1.3). Output power from most of the metals exhibiting cyclic laser action is proportional to input power, therefore, high output powers may be attained.

If a copper laser tube is constructed such that the central plasma tube is cooled directly by molten tin (melting point 232^{o}C, boiling point 2720^{o}C) then the temperature of the plasma tube may be raised by discharge heating to the operating temperatutre of copper (1500^{o}C) while the excess heat is carried off by the tin to a heat exchanger. The liquid tin surrounding the laser tube also acts as a coaxial current return, providing the laser head with a very low inductance circuit and increasing discharge pumping efficiency.

File No: I/7495/EEV/GC

Class:

Appl. No: 8813347.

Appl. Date: 6-6-88

PATENTS ACT 1977

PATENT SPECIFICATION

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PRIORITY CLAIMED:- U.K. Patent Applications No.
8728422 dated 4th December, 1987, and
8801022 dated 18th January, 1988.

AGENT:- G.Cockayne.

Laser Apparatus

This invention relates to a laser apparatus and more particularly to apparatus in which metal vapour forms the laser amplifying medium.

Lasers which use metal vapour as the amplifying medium, for example copper or gold vapour, require a high temperature to be maintained within the laser tube within which laser amplification occurs. This is necessary in order to maintain the vapour at a suitable operating pressure which is typically about one torr. For example, in a copper vapour laser, it is necessary to maintain the temperature within the laser tube at about 1600° C. In presently available lasers, this is achieved by using thermally insulating material around the laser tube so as to reduce heat losses to a minimum and attain the high temperatures required.

In one class of metal vapour laser, the amplifying medium is derived from a metal halide which dissociates at a lower temperature than that required to produce vapour from a solid metal. For example, in a copper vapour laser, copper bromide may be used which has a dissociatation temperature in the region of 600 - 700 degrees C. However, although this temperature is relatively low when compared to a laser in which the metal vapour is produced from solid metal, it is still necessary to provide a large mass of thermally insulating material around the laser tube to enable the system to be heated from room temperature to the operating temperature and also to ensure that at the operating temperature, power applied to the amplifying medium is available to the laser process.

The present invention seeks to provide improved metal vapour laser apparatus in which high output powers may be achieved.

According to the invention, there is provided metal vapour laser apparatus comprising a laser tube within which laser action occurs during operation of the apparatus and means for flowing coolant over the outer surface of the tube. The inventors have realised that cooling of the tube, rather than using the conventional technique of surrounding it with thermal insulation, allows greater input powers to be used and hence results in higher laser output powers. The coolant, which may be a liquid or a gas, directly cools the outer surface of the tube, removing heat from the interior of the tube. The coolant can then in turn be cooled, after passing over the tube, at some remote location. The power which is applied to the laser medium must be sufficiently great so as to maintain it at the optimum temperature at which laser radiation is generated against thermal losses from the tube. For copper vapour, for example, the optimum temperature is 1600°C and it is desirable not to exceed 2500°C in the laser medium. As thermal losses increase, the input power may also be increased so as to maintain the optimum temperature. Therefore the power of the laser output is also increased, this being a function of the input power.

In a particularly advantageous embodiment of the invention, a metal envelope is included and surrounds the tube and the coolant path, the envelope being arranged to act as a return current path. As the envelope may have a smaller diameter than would be the case were conventional thermal shielding to be included in the assembly, the inductance of the laser apparatus is relatively low, especially if a laser tube of small diameter is used. Thus, a current pulse having a short rise time may be obtained, giving an increase in efficiency. The envelope may conveniently be arranged to partly define the volume through which the coolant flows.

Preferably, the tube is of quartz as this is a material which is particularly good at withstanding thermal shock and thus enables large thermal gradients to be maintained across it without fracture. The inner surface of the tube may be maintained at temperatures of up to 1000 degrees C whilst the outer surface is kept at a temperature of less than 50 degrees C by the flow of coolant, which conveniently is water, over it.

Advantageously, the coolant is molten tin, as this has a large thermal capacity and is capable of removing large quantities of thermal energy from the surface of the laser tube.

The metal vapour may be produced from solid metal located within the tube or from a metal halide. For example, copper bromide may be formed within the tube by flowing the halogen gas over the surface of metal within the tube. Heating of the laser amplifying medium may be achieved using a discharge produced between electrodes located within the tube. The flow of coolant over the outer surface enables high repetition rated to be used.

One way in which the invention may be performed is now described by way of example with reference to the accompanying drawings in which:-

Figure 1 is a schematic transverse section through a laser in accordance with the invention; and

Figure 2 is a schematic longitudinal section of the laser shown in Figure 1.

With reference to Figures 1 and 2, a copper halide vapour laser includes a quartz tube 1 which has an internal diameter of approximately 1 cm and a wall which is about 1 mm thick. The quartz tube is about 1 m in length and includes wider end portions 2 and 3 within which are located copper electrodes 4 and 5. An outer metal envelope 6 is arranged around the quartz tube 1, being spaced from it to leave a volume 7 through which, in operation, tin is arranged to flow in the direction illustrated by the arrows. The envelope 6 also provides a current return path.

In this embodiment of the invention, copper bromide is produced within the tube by flowing bromine mixed with an inert gas through the laser so that it passes over the hot surface of at least one of the copper electrodes 4 and 5.

When it is wished to obtain laser action a discharge is produced between the electrodes 4 and 5, causing heating and dissociation of the copper bromide and exitation of the resulting copper vapour.

The tin is arranged to flow through the volume 7 at a rate which maintains the outer surface of the tube 1 at a temperature below 50 degrees C whilst the interior of the tube reaches temperatures in the region of 600 - 700 degrees C. This enables up to 10kW to be applied to the contents of the tube 1 and output powers in the region of 1000 to 50 W to be reached.

CLAIMS

1. Metal vapour laser apparatus comprising a laser tube within which laser action occurs during operation of the apparatus and means for flowing a coolant over the outer surface of the tube.

2. Apparatus as claimed in claim 1 and including a metal envelope surrounding the tube and the coolant path, the envelope being arranged to act as a current return path.

3. Apparatus as claimed in claim 2 wherein the metal envelope partly defines the volume through which the coolant is arranged to flow.

4. Apparatus as claimed in claim 1, 2 or 3 wherein the tube is of quartz.

5. Apparatus as claimed in claim 4 wherein the tube has an internal diameter of approximately 1 cm and is approximately 1 mm thick.

6. Apparatus as claimed in any preceding claim wherein the coolant is water.

7. Apparatus as claimed in any preceding claim wherein the coolant is a molten metal.

8. Apparatus as claimed in any preceding claim wherein the metal vapour is obtained by heating metal located within the tube.

9. Apparatus as claimed in any of claims 1 to 7 wherein the metal vapour is obtained from metal halide located within the tube.

10. Apparatus as claimed in any preceding claim wherein heating of the laser amplifying medium to produce laser action is obtained using a discharge established between electrodes within the tube.

11. Metal vapour apparatus substantially as illustrated in and described with reference to the accompanying drawings.

ABSTRACT

Metal vapour laser apparatus includes a small diameter laser tube 1 which is surrounded by a metal envelope 6. During operation of the laser, coolant, conveniently water, is arranged to flow through the volume 7, and over the outer surface of the tube 1 enabling high output powers to be achieved.

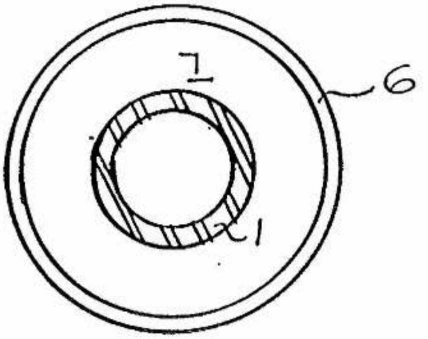

Fig. 1

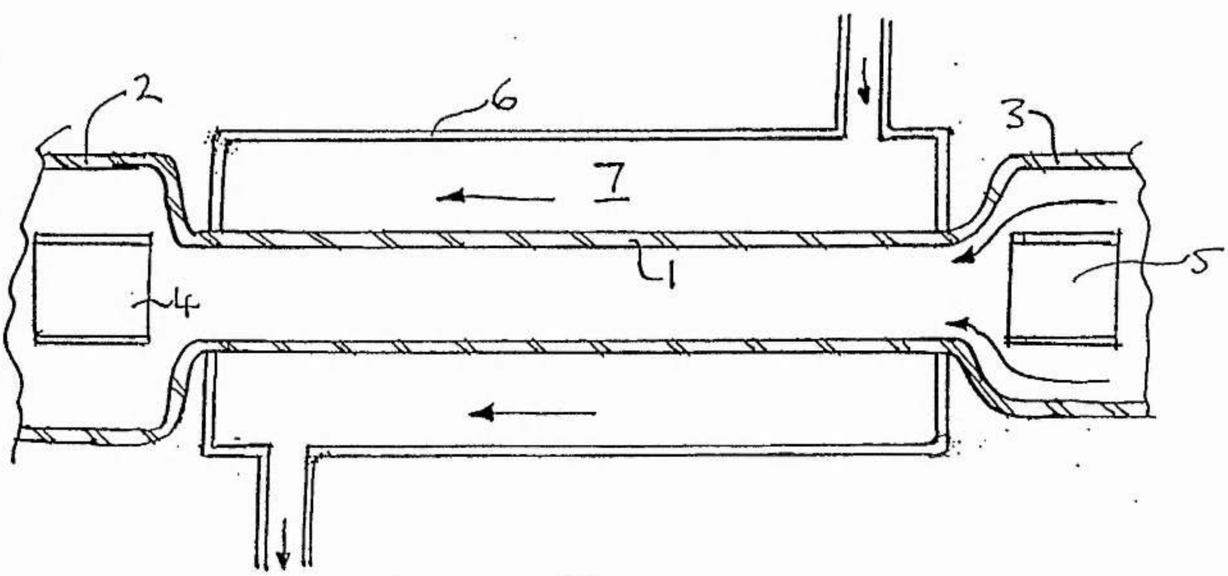

Fig. 2

B.4

Breakdown Voltages of attaching gas mixtures in metal segmented tubes.

E.S.Livingstone and A .Maitland.

Contributed papers, 19th International Conference on Phenomena in Ionized Gases, Belgrade 1989.

The breakdown voltages of various mixtures of gas are given for quartz and metal bounded discharge tubes. It is found that the breakdown voltage of the gas in a discharge tube is lowered when metal tubes are introduced and then increases with the number of these tubes. The effect of adding chlorine to a He-Ne gas mixture is to raise the breakdown voltage and also raise the voltage required to sustain a continuous d.c. discharge.

Breakdown voltages of attaching gas mixtures in metal segmented tubes.

E.S. Livingstone and A. Maitland

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1. Introduction.

The copper vapour laser is perhaps the most widely studied of all the metal vapour laser family. Its efficiency and ability to produce high average output powers are well known, as are the problems associated with maintaining a plasma tube at ~1550^{o}C. Utilising the halides of copper is a good way of reducing the operating temperature of the tube to around 600^{o}C which is compatible with fused silica working temperatures. Although many successful copper halide vapour lasers (CHVLs) have been demonstrated, only one company presently offers a commercial model. To-date, CHVLs have produced efficiencies which equal and sometimes exceed that of the high temperature lasers. The most appealing attributes of the CHVL, however, are the simplicity and longevity of the laser tube. Work on the CHVL at St Andrews involves gas discharges confined by metal walls. Some data is presented here on the DC breakdown voltages of various gas mixtures including neon, helium and chlorine. Many metal wall configurations are also included to show the effect on the breakdown voltage. The approach to these experiments was primarily to provide useful information for practical applications and to raise questions on the fundamental processes involved. At our present level of data collecting and understanding, any explanations of the mechanisms at work in metal bounded systems would be premature and speculative.

2. Discharge tube.

The discharge tube used for this work was a quartz envelope of diameter 45mm containing electrodes of molybdenum foil rolled to cylinders of 38mm diameter and separated by 365mm. A single piece of brass tube of diameter 43mm and length 320mm was placed between the electrodes coaxially. This metal tube was repeatedly cut in half to produce the shorter segments. A pipe cutter was used to ensure no loss of material. The high voltage supply was a Hartley Measurements 20kV unit which was connected across the electrodes with a current limiting resistor of 20 kOhms in series.

3. Experiment.

The discharge tube was evacuated by a two stage rotary pump filled with a chlorine compatible oil and was then back-filled with the gas mixture under test. Voltage was applied slowly to the electrodes and measured with a Tektronix P6015 high voltage probe and a Tektronix 2445A oscilloscope.

Metal segments were placed inside the quartz envelope at equal distances from each electrode and its adjacent segment. The spacing between segments was maintained at 5mm in each experiment whilst keeping the total non-metallic path length constant between the anode and cathode. That is, we have,

where A is the anode to first segment spacing, Bn is the spacing between segments n and (n+1) and C is the spacing between the last segment and the cathode. The cathode dark space region was not invaded as, when metal segments are introduced, the space between each segment becomes a discharge gap in its own right and has its own dark space and positive column.

4. Results.

Figure 1 shows the breakdown voltages in pure neon in quartz and with metal segments. Figures 2 and 3 relate to attaching gas mixes in quartz alone and in the quartz tube with the tubular metal segments. Breakdown voltages are plotted against chlorine partial pressure for each gas mixture. In all cases the breakdown voltage of a given total non-metallic spacing between anode and cathode decreases when metal segments are introduced. This breakdown voltage then increases as the number of segments increase, even though the total length of metal and the total length of gas remain constant. It was also noted that the sustaining voltage for a discharge increased with the number of segments.

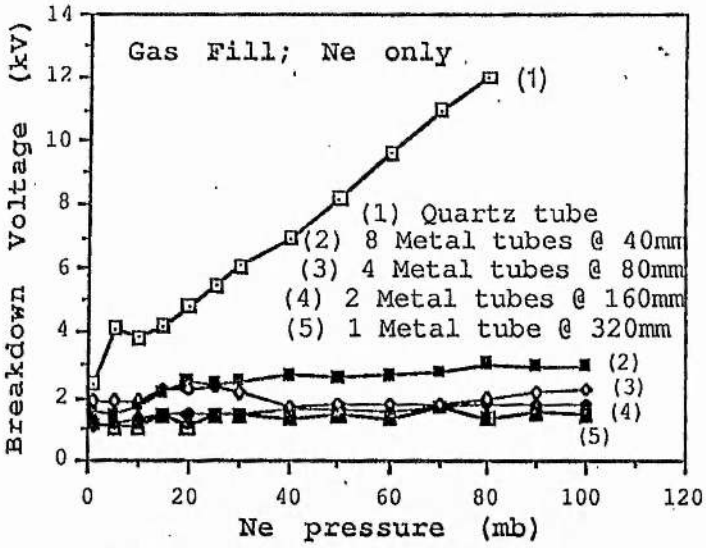

Fig 1. Breakdown voltages of various wall types in pure neon.

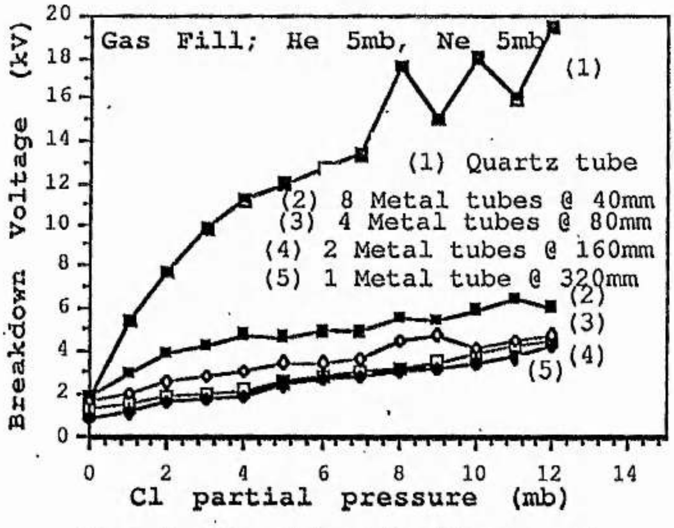

Fig 2. Breakdown voltages of various wall types in an attaching gas mix.

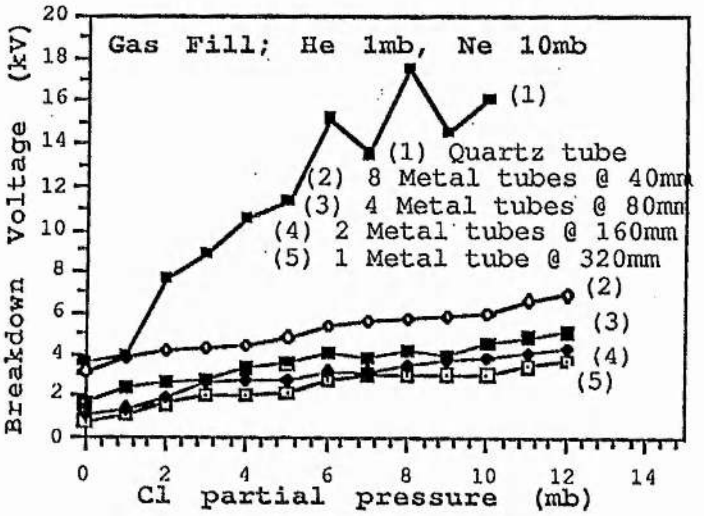

Fig 3. Breakdown voltages of various wall types in a more realistic laser gas mix.

B.5

A low temperature, segmented metal, copper vapour laser.

E.S. Livingstone and A. Maitland.

J. Phys. E: Sci. Instrum. **22**, (1989), 63.

This paper describes a copper halide laser which operates with a segmented copper discharge tube and a flowing buffer gas / halogen mixture. The results of using bromine and chlorine as the halogens of interest are given. Output powers of 22W and 18W are achieved with bromine and chlorine respectively. This work is described in Chapter 6, section 6.5.2 and the associated patent is repoduced in section B.1.

A Low Temperature, Segmented Metal, Copper Vapour Laser.

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Received 1 August 1988

Abstract

A copper vapour laser is described which uses in-situ formation of copper halide by a flowing mixture of halogen and inert gas. The discharge is confined by copper segments which also act as the copper reservoir.

Modern copper vapour lasers stand out amongst visible lasers for their ability to produce high average powers at efficiencies up to 1%. In many areas they are beginning to supercede the less efficient and more expensive argon ion lasers. It is obviously preferable for applications such as dye pumping, high speed motion analysis and scientific research to have a 10 or 15 watt compact, single phase, air cooled laser rather than one which needs three phase supplies and water cooling for the same output power.

Although commercial 100W copper vapour laser systems are now available, the laser user still has to maintain the laser tube to ensure continuity of performance. This maintenance usually means removing a window and renewing the copper charge along the laser tube. Sometimes maintenance can involve tasks such as removing broken laser tubes and replacing them in new insulation inside the metal outer jacket. Such maintenance is essentially due to the high operating temperatures used.

At the operating temperature of around 1650^{o}C alumina will 'creep' and eventually sag to obscure the beam. Cracks in the alumina also become serious when molten copper is lost from the tube by soaking into the fibrous insulation. Migration of copper vapour to the cool end zones of the laser limits the lifetime to a few hundred hours for the copper reservoir before the laser must be opened and recharged. Recharging is always accompanied by some contamination.

The operating temperature of copper vapour lasers may be reduced to about 600^{o}C by using the copper halides; CuBr, CuI and CuCl. (1 - 6). The halides have been shown to give similar efficiencies to pure copper both in average and peak powers. There is, however, a short lifetime still associated with these lasers which necessitates removal of the windows and insertion of fresh halide.

We have found that a compact, high power and virtually maintenance free copper vapour laser is possible at very little cost. The laser consists of a quartz tube containing segments cut from copper tubing and seperated by alumina rings. The quartz tube is held within a pyrex outer sleeve which is also in a water cooled jacket/current return.

A mixture of helium or neon with a halogen is flowed slowly through the tube at the same flow rates as are usual with copper lasers. The halogen reacts with the discharge heated copper wall to produce copper halide which then evaporates into the main discharge volume. The pulsed discharge dissociates the metal halide molecules and excites the free copper atoms so that laser action can take place. The discharge tube is 40mm in diameter with 800mm between the molybdenum foil electrodes. The copper segments measure 100mm in length and have an internal diameter of 45mm.

Because the discharge tube is quartz lined with copper segments, contaminant outgassing is many times less than with the conventional alumina tube operating at

1600^{o}C. Experiments conducted to date have included both bromine and chlorine, with helium and neon as buffer gases. Lasing was achieved with small (few percent) partial pressures of bromine and chlorine at total pressures varying from 5mb to 300mb; above this pressure the discharge became unstable and began to arc to the walls. It was noted that increasing the halogen partial pressure did not cause an unstable discharge but forced it into a thin annulus very close to the walls where some arcing and flashing was noted. This appears to be attributable to the metal walls as similar conditions in a bare quartz tube produced a constricted, unstable discharge.

All experiments were carried out at 11KHz and power input was controlled by the charging voltage. The 4nF storage capacitor was charged through a 150mH choke and discharged into a 2nF peaking capacitor through an EEV CX1535 thyratron. Little attempt was made to optimise the output power by manipulating the charging voltage or repetition rate but emphasis was placed on the gas pressure and composition. Maximum power obtained with bromine was 22W, with the beam apertured to 25mm diameter by the original window structure. Using chlorine the highest power achieved to date is 18W with a 40mm aperture.

At present a mass spectrometer is being used to determine the halogen fractions under various operating conditions at which laser power is a maximum.

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B.6

A high power, segmented metal, copper bromide laser.

E.S. Livingstone and A. Maitland.

Accepted for publication in J. Phys. E: Sci. Instrum. (submitted May 1991).

This paper continues the work described in the paper of section B.5. The paper introduces the use of hydrogen bromide (HBr) as a bromine donor in flowing halogen, metal vapour lasers. In a copper vapour laser described in the text, a maximum output of 40W is achieved at an overall electrical / optical efficiency of 1%. The applications of this method of obtaining high metal vapour pressures at artificially low temperatures are recognised, with reference to metals which may or may not present problems when used as laser media in their elemental state.

A high power, segmented metal, copper bromide laser.

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Scotland,
1st May 1991

Abstract.

A copper bromide laser which delivers high average power (40 Watts) is described. Copper bromide is formed in-situ by using hydrogen bromide flowing through a segmented copper discharge tube. The buffer gas is neon.

Introduction.

Within the last decade, copper vapour lasers have become an increasingly important source of visible (510.6, 578.2nm) laser light. Copper vapour lasers are divided into two distinct types; high and low temperature. The high temperature type uses molten copper and gives powers of up to 100W in commercial devices. The low temperature type uses a compound of copper having high vapour pressure at low temperature; copper halides are suitable. Examples of these halide devices producing over 10W are rare. In general, copper lasers of either type have the advantage of greater efficiency and lower operating costs than most other visible gas laser sources. However, one of the drawbacks to using high temperature copper vapour lasers is maintenance of the plasma tube. This typically involves replacement of the copper charge at intervals of a few hundred hours but may also require the user to rebuild the laser head if the central alumina tube has failed. Most faults which develop in the laser envelope have their origin in the high (1550^{o}C) operating temperatures involved.

Copper halide lasers have been studied as a way of reducing the operating temperature of copper vapour lasers to a more manageable level but are still not readily available commercially. Using CuCl, CuI or CuBr, the operating temperatures can be reduced to around 600^{o}C thus enabling fused silica laser tubes to be used. The advantages contributed by the improved thermal shock properties of fused silica, together with the general reduction in contamination levels reduce the maintenance required for such lasers.

It was shown (Livingstone and Maitland 1989) that a copper halide laser could be made by using a segmented metal laser tube and a flowing mixture of halogen and either helium or neon through the tube. If the metal is copper, then the corresponding copper halide is formed and then evaporated from the discharge heated wall where its vapour is first dissociated and then excited by successive discharge pulses at repetition rates above about 5 kHz or so. Bromine and chlorine have both been used successfully as the halogen in this scheme but both have practical problems associated with them. Bromine is liquid at room temperature and so we have found it to be difficult to control the amount of vapour which is entrained in the flowing buffer gas. As the laser appears to be very sensitive to halogen partial pressure and the slow flow rate of gas makes the laser response time long (~10 minutes), stable operation over a period of hours becomes difficult to maintain. Chlorine is a gas at room temperature, which allows for more simple handling and metering but has been found to be inferior to bromine when in combination with copper as a laser material, (Gabay et al 1977). The use of hydrogen bromide combines the best characteristics of both bromine and chlorine, being able to donate bromine to the discharge, yet, as a gas, making flow control more simple. Hydrogen has also been shown to have beneficial properties when present in small quantities (Astadjov et al 1988). Laser action has been observed using hydrogen exclusively as a buffer gas, with power output in this case being 50% of that achieved using neon under optimum conditions (Clark and Maitland 1988).

Experiments.

The laser consists of a quartz tube containing segments cut from copper tubing and separated by alumina rings. The discharge tube is 40mm in diameter with the molybdenum foil electrodes separated by 800mm. The copper segments are each 100mm in length and have a 45mm internal diameter, the tube being apertured to 40mm by the alumina ring spacers. The quartz tube is held within a pyrex outer sleeve which is also in a water-cooled jacket/current return. The experiments were carried out at 11kHz with input power being controlled by the charging voltage. The storage capacitor (4nF) was charged through a 150mH choke and discharged through an EEV CX1535 thyratron into a 2nF peaking capacitor. During the experiments, input power to the laser was held constant at a chosen value and laser power was optimised by varying the gas composition and pressure. Maximum output from the laser was 40W. This occurred when the gas pressure was 3.3kPa, with a flow rate of approximately 2-3 litre atmosphres/hr. At maximum power, the hydrogen bromide comprised approximately 5% of the gas entering the laser, the remainder being neon. A stable discharge could be maintained at pressures up to 30kPa but lasing was faint and increasingly erratic at higher pressures. Very short warm-up times were possible in this device, with laser emission beginning within 30 seconds after start-up of a cold tube. Powers of up to 10 Watts or so were reached in about 45 seconds.

Conclusion.

A number of metals present problems when used as laser media in their elemental form (Sh'penik and Kel'man 1989).The method described in this paper for achieving high metal vapour pressures at artificially low temperatures by the use of flowing halogen, or a halogen donor such as hydrogen bromide, may be applied to such metals and others in order to make laser action easier to achieve.

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B.7

Early illumination in experimental photodynamic therapy: Comparison with conventional treatment.

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Presented at the Third Biennial Meeting of the International Photodynamic Association, Buffalo, N.Y., July 1990.

To be published in the Journal of Photochemistry and Photobiology.

Photodynamic therapy (PDT) involves the interaction of light with a previously administered photosensitizer in the treatment of cancer. The photosensitizer, in the prescence of oxygen and light of the correct wavelength, results in the production of singlet oxygen and other reactive oxygen species. The end result is the destruction of targeted tissues containing the photosensitizer.

Conventional protocol for PDT requires a delay of 24-48 hours between administration of the photosensitizer and subsequent photoirradiation. This protocol is compared with a new one, in which photoirradiation is carried out within three hours of photosensitization. It is found that (a) both early and delayed forms of treatment have significant effects on tumour size and (b) that early treatment causes a much longer tumour regression period than delayed treatment.

EARLY ILLUMINATION IN EXPERIMENTAL PHOTODYNAMIC THERAPY: COMPARISON WITH CONVENTIONAL TREATMENT[1]

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Running Title: EARLY PHOTODYNAMIC THERAPY

Keywords: photodynamic therapy, hematoporphyrin derivative, pharmacokinetics, irradiation

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+Abbreviation: PDT, photodynamic therapy.

ABSTRACT

We have compared a new protocol for photodynamic therapy, in which illumination of the tumor is carried out within three hours of photosensitization, with conventional therapy in which there is a delay of 24-48 hours before illumination. In our experimental system of xenografts of human colorectal tumor cells (COLO 320DM) growing as subcutaneous masses in nude mice, we find (a) that both early and delayed forms of treatment have significant effects on tumor size and (b) that early treatment causes a much longer tumor regression period than conventional treatment. This correlates well with the higher circulating levels of photosensitizer at the earlier time, reinforcing the evidence for a vascular mechanism of action of photodynamic therapy and suggesting new methods of treatment in humans.

INTRODUCTION

PDT+ involves the interaction between light and a previously administered photosensitizer which, in the presence of triplet (ground-state) oxygen, leads to the production of singlet oxygen and other reactive oxygen species. The end result is the destruction of targeted tissues containing the photosensitizer. The procedure has been adopted with success in the treatment of experimental and human cancer (reviewed by Dougherty 1989).

The conventional protocol for PDT requires that a delay of 24-48 hr be introduced between the administration of the photosensitizer and subsequent photoirradiation. The rationale for this delay is based on the observation that tumor tissues often retain sensitizers such as hematoporphyrin derivative more selectively than normal tissues and that the tumor : normal tissue ratio reaches its highest value at about this time (Gomer and Dougherty 1979; Bugelski et al. 1981). Thus, photoirradiation after this interval should result in a high degree of tumor destruction coupled with minimal damage to surrounding normal tissues.

There is, however, an increasing body of evidence that the mechanism of action of PDT _in vivo_ involves a primary vascular occlusive effect followed by ischemic damage to the tumor (Henderson et al. 1985; Wieman et al. 1988; Nelson et al. 1988). If this is the case, the levels of photosensitizer in the blood vessels, rather than the tumor tissue, at the time of treatment may be the more important. By 24-48 hr after administration, these are likely to have fallen considerably from their peak and as a result the tumors may not be maximally photosensitive during conventional "delayed" photoirradiation.

A beneficial effect of irradiation 5 minutes after i.v. injection of hematoporphyrin derivative in a rat tumor system has previously been demonstrated (Olivo et al. 1989). This time would be expected to coincide approximately with the serum peak level of photosensitizer. Henderson & Bellnier (1989) have also reported data on mice carrying the RIF tumor, using intracardiac administration of photosensitizer and immediate photoirradiation. We decided to use i.p. injection, with consequent slower pharmacokinetics, in order to be able to characterize the relationship between circulating photosensitizer levels and anti-tumor effect.

MATERIALS AND METHODS

Pharmacokinetics. Five six-week-old male MF1 nu/nu mice were injected i.p. with 10 mg/kg "hematoporphyrin esters" (a preparation very similar to hematoporphyrin derivative and given by Prof. T.G. Truscott, University of Keele, UK). Peripheral blood samples were obtained by tail-tipping and serum was stored frozen until assay for total hematoporphyrin, essentially by a published method (Kessel and Cheng 1985), correcting for the efficiency of extraction of the porphyrins into the chloroform : methanol layer.

Experimental tumor model. Human colorectal tumor cells COLO 320 DM were obtained from the European Collection of Animal Cell Cultures (Porton Down, UK) and cultured in Dulbecco's modified Eagle medium supplemented with 10 % fetal calf serum, 50 units/ml penicillin and 50 ug/ml streptomycin. They were harvested by gentle trypsinization and 10^7 viable cells were injected s.c. into the flank of nu/nu mice. Tumors grew to volumes of 30-50 mm^3 after 10-14 days, at which time they were used for treatment.

Photodynamic therapy. Animals bearing tumors of 30-50 mm^3 in volume were divided into three groups matched for mean tumor size. The control group (10 animals) received no treatment. The "early PDT" group (7 animals) were photoirradiated 3 hours after administration of hematoporphyrin esters as above. Animals in the "conventional PDT" group were photoirradiated after a delay of 24 hours. In all cases a blood sample was taken immediately prior to irradiation for assay of the circulating photosensitizer level.

The light source was a gold vapor laser (built in the Department of Physics and Astronomy, University of St. Andrews), producing monochromatic red light at 628 nm. The output was coupled into an optic fiber and the laser run under such conditions that the incident power density at the tumor surface was 150 mW/cm^2. The animals were lightly anesthetized and all except the tumor plus a margin of about 0.5 cm was protected with thick black card. The irradiation time in all cases was 16 minutes, resulting in a total energy delivery of 150 J/cm^2. No photothermal effects were noted (data not shown). Animals were housed under subdued lighting for the remainder of the experiment.

Assessment of response and data analysis. Tumor growth was measured by calipers, taking three orthogonal axes and calculating the volume of the equivalent ellipsoid. This method has been reported to yield the most accurate estimate of tumor size (Tomayko and Reynolds 1989). The volumes were normalized to a value of unity on the day of treatment in order to prevent small differences in absolute size from confusing the analysis. The growth of each tumor in terms of the number of days for which it remained at or below its pretreatment volume and the overall time taken to reach a fixed endpoint size of ten times this size was calculated. The doubling time was also assessed once the tumor had regrown to five times the pretreatment volume, in order to minimize any interference from remaining dead tissue (Begg 1980).

RESULTS

Serum levels of porphyrin. The total fluorescent porphyrin level reached a maximum 3 hours after i.p. injection (Fig. 1) and then declined with a half-life of 3-6 h. The levels at the peak were about 3-fold higher than those at 24 h. Our results are entirely consistent with previously reported data from another laboratory (Henderson and Bellnier 1989), showing similar kinetics for i.p. ^{14}C-labelled Photofrin II in DBA/2Ha mice. It should be noted that neither method of assay can quantitate the photodynamically active component(s) of the injected compounds since these remain chemically ill-defined. We elected to compare the effects of PDT administered 3 hours after photosensitization with conventional treatment at 24 h.

Tumor growth. The mean growth curves are shown in Fig. 2. Both protocols caused a cessation in tumor growth in all cases and complete disappearance of palpable tumor in some individuals (5 in the "early" group and one in the conventionally-treated group). We have never observed spontaneous COLO 320 DM tumor regression in any animal (approx. 100 studied).

The period during which tumors remained at or below their pre-treatment size was significantly longer in the "early" group than in the group receiving conventional treatment and this was also reflected in the time taken to reach the chosen endpoint (Fig. 3). All tumors eventually regrew. Their doubling times were slightly longer in the two treated groups than in the control group, but these differences were not statistically significant (early, 3.9 ± 0.1 d; delayed, 4.4 ± 0.6 d; control, 3.3 ± 0.3 d).

Serum levels of total hematoporphyrin-related species at the time of irradiation were 3.6-fold higher in those animals receiving early PDT than in those receiving conventional treatment (Fig. 3.).

Treatment-induced damage to normal tissue surrounding the tumor was generally only mild (rapidly reversible oedema and erythema). In some cases the skin overlying the tumor formed a scab which was eventually lost to reveal a whitish area of normal skin whose revascularization coincided with tumor regrowth (data not shown).

DISCUSSION

Our results are entirely consistent with those of other groups (Olivo et al. 1989; Henderson and Bellnier 1989), once the slower pharmacokinetics associated with the i.p. route are taken into account. An advantage of this route is that it allows these pharmacokinetics to be measured and it ensures that relatively stable serum levels of photosensitizer are maintained during the course of early illumination (options not available where the route of administration results in rapidly rising and/or falling levels).

The present work demonstrates that conventional therapy results in shortlived tumor regression in our experimental system. Early therapy, timed to coincide with maximum circulating levels of the photosensitizer, is more effective. A key observation is that the ratio of the tumor regrowth delays induced by the two treatments (3.3) is similar to that of the serum levels of photosensitizer at the time of rradiation (3.2). Our current work is directed towards discovering whether this relationship holds for a variety of serum concentrations at the time of treatment, irrespective of the delay between drug injection and illumination.

Although early irradiation would appear to be of possible clinical benefit, its effect on normal tissue must be taken into consideration. It may find application in cases where the tumors can be accurately targeted with light, such as skin tumors or those readily accessible and visible through an endoscope.

Rather than employ the same dose of photosensitizer in early PDT as is used in conventional therapy, it may be possible to use a lower dose and maintain the existing therapeutic efficacy. This could result in useful reduction of the duration and severity of cutaneous photosensitivity, which is a common clinical side-effect of PDT (Razum et al. 1987). Experiments to test this hypothesis are underway in our laboratories.

ACKNOWLEDGEMENTS

This work was supported by grants from the British Council and the Research Initiatives Fund of the University of Dundee. We would like to thank George Truscott for providing the HPD and Wilson Sibbett and Arthur Maitland for building the laser. Chris Little provided valuable assistance in its running.

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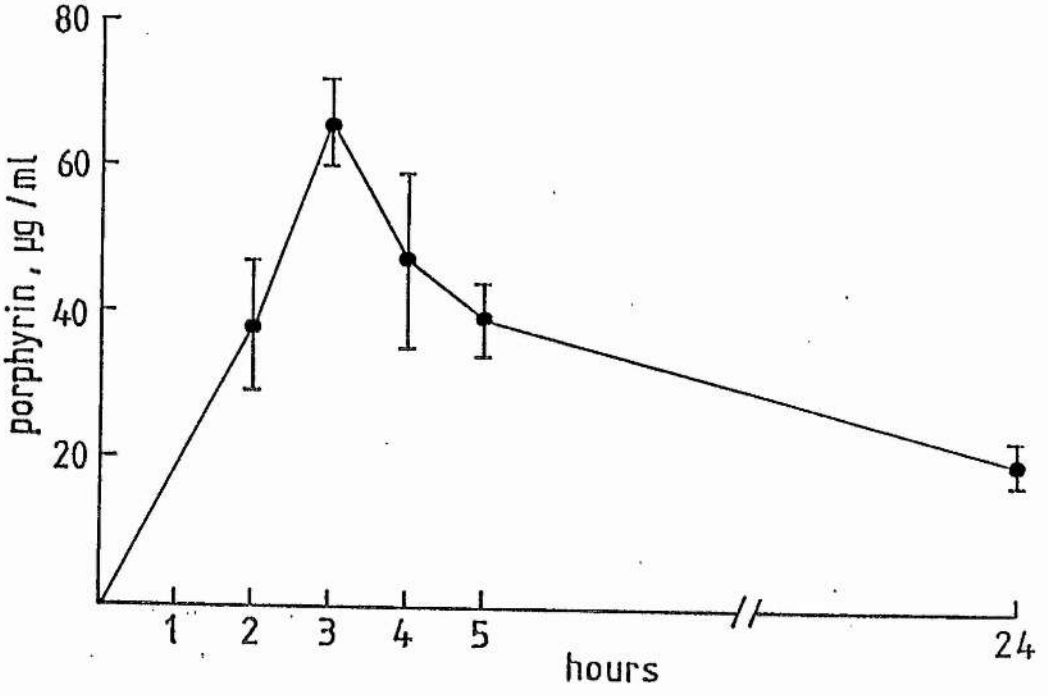
FIGURE CAPTIONS

Figure 1. Serum porphyrin pharmacokinetics. Five nude mice were injected i.p. with 10 mg/kg hematoporphyrin esters and blood samples taken from the tail. The graph shows the mean (+/- standard deviation) serum levels at each time point.

Figure 2. Effects of early and delayed PDT on tumor growth. The tumor volumes were normalized to unity at the time of treatment. Their mean values on each day have been plotted on a logarithmic scale to reveal the exponential regrowth. o—o untreated control animals, △—△ early photoirradiation (3 hr after sensitization), ▲—▲ delayed photoirradiation (24 hr after sensitization).

Figure 3. Results of treatment in the two groups. The open bars represent the early treatment group and the hatched bars the delayed treatment group. A: Levels of photosensitizer were measured in serum samples collected immediately before photoirradiation. B: The regrowth delay was calculated as the time taken by each tumor to recover its pretreatment volume. The time taken for each tumor to grow to an endpoint size of ten times its pretreatment volume was also recorded. The mean values (+/- standard deviation) of these two growth parameters are shown. Note that these are different from estimates obtained by interpolation in Figure 2, because of the different averaging domains in the two methods of analysis. All differences between the two treatment groups were significant ($P < 0.005$, Student's t test).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20
porphyrin, µg/ml
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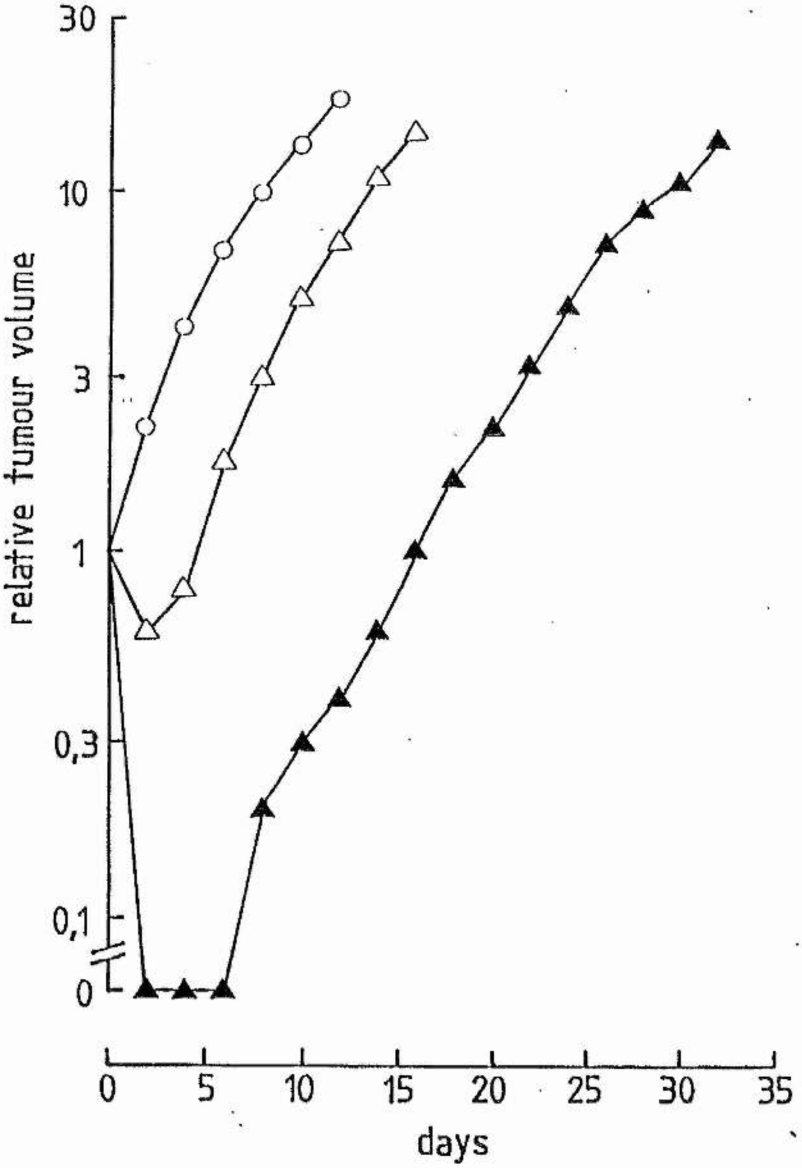
hours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10
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relative tumour volume
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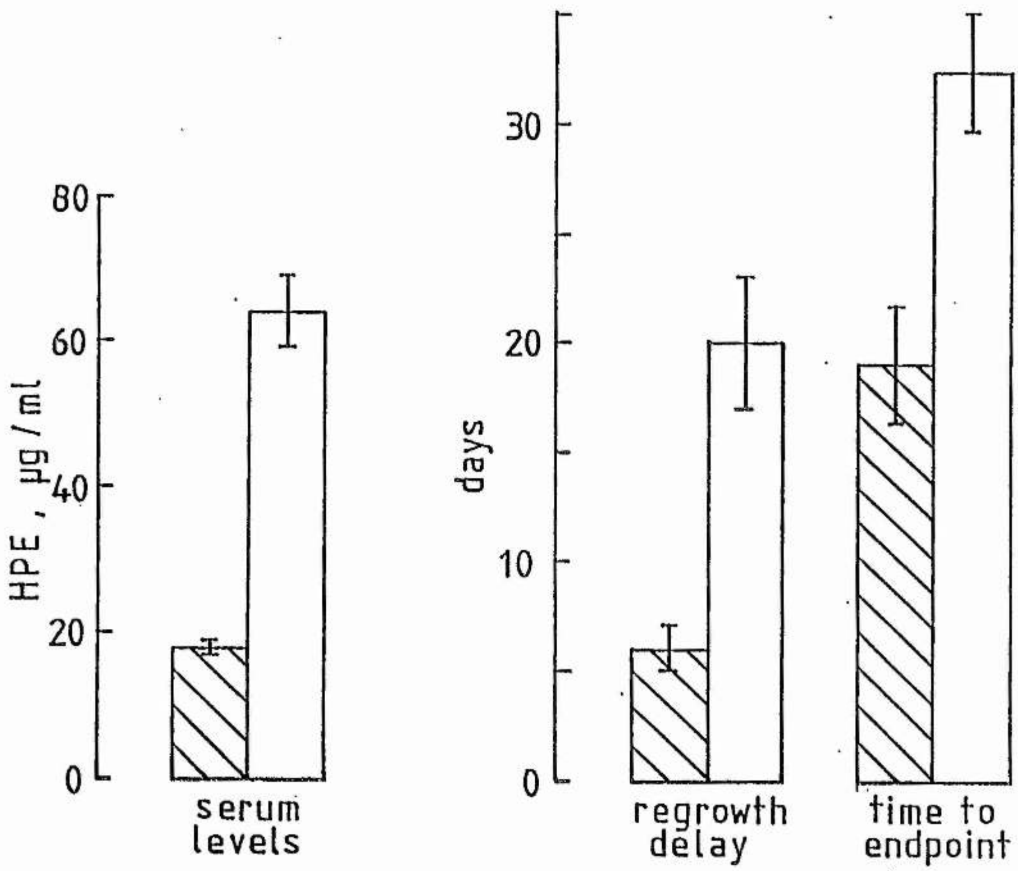

80
60
40
20
0
HPE , µg / ml
serum levels
30
20
10
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days
regrowth delay
time to endpoint