Integrated polymer microprisms for free space optical beam deflecting

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Abstract: We demonstrate beam deflection and multiple channel communication in free space optical communications using microprisms integrated directly onto an array of vertical cavity surface emitting lasers (VCSELs). The design and fabrication of such a transmitter is presented, and shown to achieve beam deflection of up to 10° in a planar configuration. A location discovery application, for use within a distributed network, is put forward and analysed.

OCIS codes: (130.3120) Integrated optics devices; (130.3990) Micro-optical devices; (140.7260) Vertical cavity surface emitting lasers; (200.2605) Free-space optical communication; (220.3740) Lithography.

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1. Introduction

Transmitting optical information via a free space beam is advantageous in many areas of technology, such as computer board-to-board interconnects [1], optical sensing and optical communications, including distributed networks [2-4], that consist of simple subunits employing sensors, power supplies, and basic processors and that function as a whole by exchanging information.

Beam deflection has the role of addressing the receivers of information in such systems and is best done dynamically; dynamic beam deflection accounts for movement in the network as well facilitating the initial setup. Beam deflection can be done by moving a single beam, e.g. via micro-electro-mechanical system (MEMS) [5] mirrors, or by "redundancy". Redundancy means that the information is encoded onto one out of a large array of emitters, each of which points in a different direction. By activating the emitter that points into the desired direction, the information is sent to the correct recipient. While the latter approach appears wasteful at first sight, it is, in fact, more power efficient than actively moving the beam, since no power is consumed for the purpose of redirecting the beam. The fact that multiple emitters are required can be tolerated given the fact that current technology allows the placement of large arrays of emitters on a small area. For example, a large number of vertical cavity surface emitting lasers (VCSELs) [6] can be placed onto to a mm-size chip. Here, we discuss the "redundancy" approach and demonstrate it by integrating polymer microprisms onto a set of GaAs/AlGaAs VCSELs.

We use electron-beam greyscale lithography to create the microprisms. Greyscale lithography depends on partial cross-linking of a polymer, with the resulting film thickness being controlled by the electron dose. Unlike other approaches, such as thermal reflow [7], greyscale lithography gives full control over the shape of the structure, and a number of interesting elements, such as axicons and spiral-phase-plates, can be produced via this route [8].

This approach to beam deflection, at the microscopic scale, is similar to previous work where micro-optical elements have been mounted onto finished laser arrays [9, 10, 11], but we are not aware of a greyscale fabrication method being employed to integrate micro-elements directly onto the device. Integration of micro-optic elements has been achieved before but has involved alternate fabrication techniques, further to the device construction [12, 13].

In the following sections we describe the fabrication of the VCSEL transmitter array and demonstrate beam deflection via microprisms. We then discuss the experimental results and finally propose a location discovery setup based on this system.

2. Design and fabrication

We utilised top emitting VCSELs (emitting at 980 nm) with oxide apertures in the experiment. The devices were fabricated by photolithography, chemically assisted ion beam etching (CAIBE) with chlorine as the reactive gas, and steam oxidation (450 °C, 25 min.). Individual devices were then isolated using photo-patterned SU-8 with separate Cr-Au contacts [14].

To create the microprisms, a layer of SU-8 polymer was spun onto the chip to a thickness of approx. 10 µm. SU-8 is a negative electron beam resist that cross-links and becomes insoluble on exposure to electrons. The maximum thickness of polymer that can be exposed is given by the penetration depth of the electrons into the polymer layer, which, in our case, is of order 10-12 µm [15], given the 30 kV acceleration voltage of our e-beam system. Experiments using thicker layers resulted in films peeling off due to insufficient exposure at the bottom of the film.

Figure 1 shows a chart of e-beam dose against resulting polymer film thickness, measured using a scanning electron microscope (SEM). A linear region is observed between the doses of 0.2 $\mu As/cm^2$ and 0.8 $\mu As/cm^2$ with a useful thickness range of approximately 5 µm.

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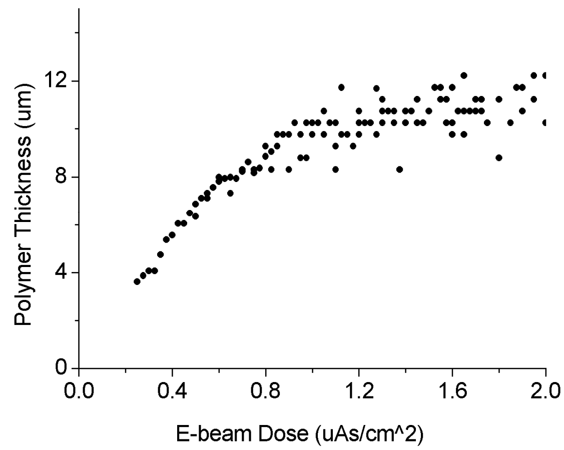

Fig. 1. Resulting polymer thickness against electron-beam dose measured using a scanning electron microscope

The SU-8 was exposed accordingly in order to create prisms on top of the finished VCSEL. After exposure, the sample was developed in microposit EC solvent (Rohm and Haas Electronic Materials) for 2 minutes, and then rinsed in isopropyl alcohol (IPA). Hard-baking, of the polymer, is only carried out after development (180 °C, 10 min.); this hard-bake is also responsible for a small-scale smoothing of the prism surface (with final roughness well below λ/50 (i.e. less than 20 nm)). Since the overall height of the elements cannot be increased beyond 10 µm, the maximum angle of the prisms is limited; fig. 2(a) shows the profiles of three VCSELs with prisms of different lateral dimensions acquired with a surface profiler (Dektak 3 Auto 1). We measured angles of: $\alpha_1 = 5.2°$, $\alpha_2 = 10.3°$ and $\alpha_3 = 10.2°$ for 50- , 30- and 20-µm base-dimension prisms, respectively.

Figure 2(a) also gives an indication of the usable area (delimited by dotted lines) within each prism (defined as the point at which the angle of the prism changes by 10%). This area decreases as the slope of the prism is increased. Since the prisms are fabricated on top of 6 µm high mesas of 40 µm diameter, edge-effects are also seen to play a role. The 30 µm base prism appeared the best choice and was used in subsequent experiments. Figure 2(b) shows a completed device including a contact pad for wire-bonding and subsequent packaging of the transmitter array.

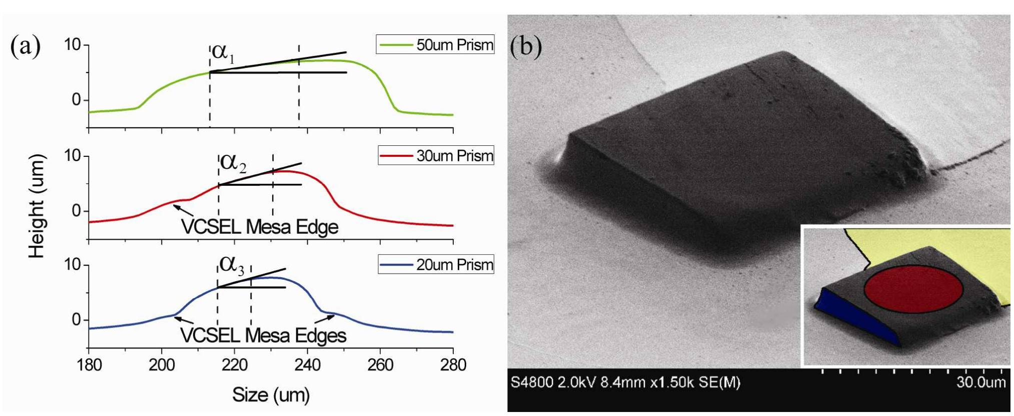

Fig. 2. (a) Surface profiles of three VCSELs with prisms of differing lateral dimensions. (b) SEM micrograph of a VCSEL with integrated microprism. Inset showing VCSEL contact pad (yellow), location of VCSEL emission aperture (red), and microprism angle profile (blue)

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3. Experimental results

The emission lobes of the VCSELs were recorded via a detector mounted on a rotating arm, and are shown in fig. 3. The lobes of the two outer VCSELs in each array are deflected by ±5° from normal as a result of the 10° prism angle, given the n = 1.56 refractive index of SU-8. It is worth noting that the emission cone of each individual emitter is not compromised by passing through the microprism since all three emitters show equally wide cones and equal output for the same drive current, even though there is no prism on top of the central device. This is an advantage over diffractive-optic-elements (DOEs) and micro step-based blazed gratings, as they create higher order lobes alongside the desired steered-lobe [16].

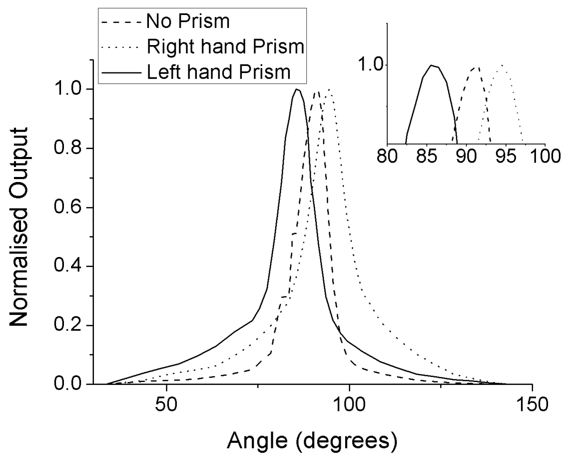

Fig. 3. Emission lobe measurements of a microprism-steered VCSEL array. Inset shows a close-up of the deflection angle achieved.

On the other hand, it is obvious that the deflection angle is rather limited and one would like to achieve more than the ±5° demonstrated here. The most obvious approach would be to increase the thickness of the SU-8 layer and thereby the prism angle. This could be done by exposing the polymer on an e-beam system with a higher acceleration voltage, e.g. 50 kV or 100 kV. Alternatively, the pattern could be transferred into the semiconductor, which amplifies the beam deflection due to the considerably higher refractive index. This would require increasing the top-emitting VCSELs capping layer or the use of bottom-emitting VCSELs, since etching into the top mirror would compromise the laser feedback mechanism.

A key application area for this type of beam-deflection array is location discovery within a distributed network. Location discovery is a necessary step in identifying the source of information and their relative position in such a network. Here we show how a beam-deflection array can facilitate location discovery by identifying each transmitter with a different code, or in the simplest case, a different frequency.

A receiver was positioned at a distance of 30 cm from the transmitter chip and translated across the field of view with an automatic rotation stage. The three transmitters were modulated at different frequencies (6, 7 and 8 kHz, respectively) and the relative signal strengths at each position recorded. From the ratio between the signals received at the respective frequencies, it is then possible to deduce the position of the detector in the field of view. Figure 4 shows the corresponding translation measurements and fig. 5 shows the error in the position calculated from the experiment against the actual position of the detector.

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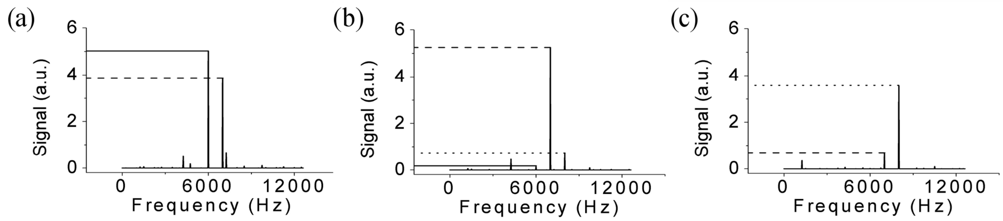

Fig. 4. Received signal strength measurements as the detector is scanned across the VCSEL array from left to right

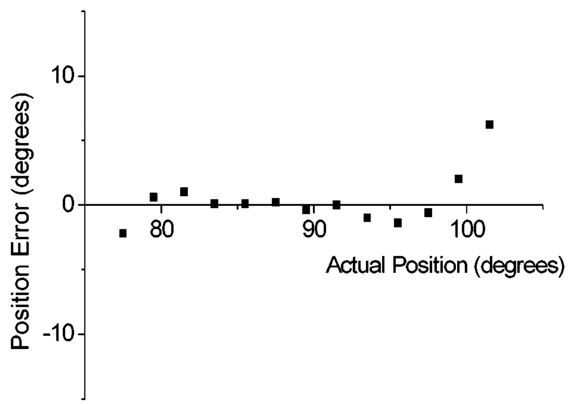

Fig. 5. Position error, of the detector obtained via the ratio of received signal powers from the transmitter (±1° error highlighted)

4. Conclusions

We have shown that, using greyscale e-beam lithography, it is possible to fabricate optical elements, (in this case microprisms), and integrate such elements onto an active laser device, in this case a VCSEL. We investigated the properties of the fabricated microprisms and found that a lateral dimension of 30 µm, resulted in a prism angle of 10.2° and a deflection angle of ±5°. We then demonstrated a potential application for such a system, namely its use for location discovery in a distributed network. We achieved such location discovery to an accuracy of ±1° over the useful range of ±10° of the array. By making prisms out of thicker SU-8 polymer and exposing it in an e-beam system with higher acceleration voltage, a larger range of angles could be covered with similar accuracy. This technique is particularly useful for prototyping devices but can be scaled up in volume in one of two ways. The use of electron beam lithography (EBL) on a large scale is not prohibitively difficult, each microelement takes a matter of seconds to expose and commercial EBL systems are widely available. This process could also be done with high energy beam sensitive (HEBS) glass as a grayscale mask, for increasing production volume.

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