Electrical and optical switching in the bistable regime of an electrically injected polariton laser

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We report on electrically and non-resonant optically induced switching in the bistable regime of an electrically pumped polariton laser. Electrical switching effects can be observed by adding controlled noise to the electrical pump of the system. Noise is expected to influence the hysteresis characteristics of a bistable device and determines its application robustness. We find that the hysteresis width decreases symmetrically with a linear dependency until we observe a quenching of the bistability at a certain noise level and the output of the system becomes monostable. Furthermore, we explore the possibility to switch between the two bistable branches by a non-resonant optical pulse. Our experimental findings can be described by a set of rate equations modeling the population dynamics with additional noise terms.

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Introduction.— Exciton-polaritons are light-matter quasi-particles created in a microcavity system in the strong coupling regime1–2. Since polaritons are bosons in the presence of gain and loss, they can form a dynamic quasi-condensate in a distinct energy state3,4. The emission from such a condensate shows properties resembling a conventional laser5 including good temporal6,7 and spatial8,9 coherence. As polariton lasing does not necessarily rely on population inversion, thresholds up to two magnitudes below conventional VCSEL devices are possible10. Adding the fact that condensation can be observed at room temperature in semiconductors like GaN11, ZnO12 and organic materials13–15, this makes the polariton laser an attractive next generation device. For many future applications, an electrical injection scheme is a necessary prerequisite16,17. Polariton condensates are also of fundamental interest due to their interesting relaxation and formation mechanism. In a non-resonant pumping configuration, relaxation occurs from a long lived reservoir towards the lower polariton branch18. At sufficient densities stimulated scattering19 allows for the formation of this new coherent state. Furthermore, polariton condensates exhibit striking phenomena like single- and half-quantum vortices22,23, superfluidity20 and quantum turbulence21. Since polaritons interact with their environment via their excitonic part24, they enable energy efficient switching processes in a variety of polariton waveguide based logical architecture elements25–29, which promise highly integrated logic devices. Optical bistability effects in semiconductors have also been proposed and used for applications in optical signal amplification30,31 and can also potentially be used in all optical transistors and memories in an integrated optical circuit, demonstrated on Si basis32. The advantages of such bistability based devices are their simplicity, robustness, low power operation33 and high operation switching speed34. A variety of experimental bistable and multistable effects based on polaritons have already been reported35–43. Recently, sub-femtojoule levels switching have been reached with a nonresonant electrical spin switch35 and switching based on bistable polariton systems has been theoretically investigated36. All these optical bistability effects have in common that near-resonant excitation is necessary for their observation. However, a non-resonant bistability in an electrically injected system44 represents a much more application friendly driving scheme. In such a scheme, the switching times would be limited by the reservoir lifetimes, which typically range on the order of a few hundred picoseconds in GaAs45. The application of noise to a bistable system can induce transitions between the two states, and can lead to a variety of interesting effects. Refs.46,47 studied the possibility for stochastic resonance in a polariton system, in which a noisy excitation is used to coherently amplify the system response. The effects of noise on the bistability of an optically excited polariton condensate has been investigated in Ref.48, in which a narrowing of the hysteresis has been observed for increased excitation noise. In our experiment, we investigate the effect of controlled noise in addition to a direct electrical injection of polaritons and study its impact on the bistability properties of our device. We observe a direct correlation between the input noise and the bistable properties of our condensate, including the transition to complete monostable behaviour upon a specific input noise. Furthermore, we demonstrate that it is possible to use a short nonresonant optical excitation pulse superimposed to the electrical injection to switch between the lower to the upper state of the two bistability branches.
Experiment The investigated sample has 23(27) doped AlAs/GaAs distributed Bragg reflectors (DBRs) above(below) its cavity and is comparable to the device which has been investigated in Ref.\textsuperscript{16}. The top mirror is carbon doped, supporting the injection of holes and the bottom mirror is silicon doped for injection of electrons. The cavity is a $\lambda$ thick, intrinsic GaAs spacer which contains four InGaAs quantum wells (QWs) with a thickness of 8 nm. The QWs are arranged in a single stack in the vertical center of the cavity spacer. In order to facilitate efficient current injection and to provide an in-plane photonic confinement, micropillars with a diameter of 20 $\mu$m were etched into the planar cavity. Subsequently, the sample has been planarized by a polymer (benzocyclobuthene, BCB). To implement the current injection, ring shaped gold contacts were deposited onto the micropillar. A 10 $\mu$m diameter aperture has been left open to allow for decay of the polaritons out of the structure for investigation. A sketch of the device in fig. 1a) presents the electrical injection method via a gold contact.

The device was put in a magneto-cryostat, which was set to a magnetic field of 5 T. This magnetic field increases light-matter coupling\textsuperscript{49} and has been shown to promote polariton relaxation\textsuperscript{16}. The sample exhibits a Rabi splitting of 5.5 meV, which increases to approx. 6 meV at a magnetic field of 5 T. All experiments have been performed at the same micropillar device with a detuning of -3.5 meV, which corresponds to an exciton fraction of 25% and a photon fraction of 75% at 5 T. The Q factor was experimentally estimated at a micropillar device with high photonic content to be 6000\textsuperscript{16}. Moreover, the measurements were performed at a temperature of 5 K.

The electrical noise in the experiment was provided by an arbitrary waveform generator Model 3390 from Keithley in a bias tee configuration with a standard dc voltage generator. The noise output characteristics are shown in Fig. 1b) and 1c). Fig. 1b) depicts a Gaussian noise distribution and c) the time resolved noise signal. The cut-off frequency of the arbitrary waveform generator is 20 MHz, which is on the order of the carrier lifetime. This timescale however is much longer than the polariton formation from the reservoir and decay which takes place in picoseconds.

The noise strength is defined as the standard deviation of our Gaussian noise signal $\sigma$ compared to the device hysteresis width $\Delta A$.

The optical measurements have been performed with an angle resolved Fourier space setup with the possibility for real space imaging\textsuperscript{50}. Fig 1d) shows the angle resolved electroluminescence characteristics of our device. At a low injection current of $j = 14$ A/cm\textsuperscript{2}, the device operates in the linear regime. The luminescence follows the lower polariton branch, which is calculated with a standard coupled oscillator approach and plotted in Fig 1d). At a current density of 78 A/cm\textsuperscript{2}, stimulated scattering processes enable the formation of a polariton condensate. The emission from this condensate at an injection current of 165 A/cm\textsuperscript{2}, centered around $k = 0$ $\mu$m$^{-1}$, is shown in Fig. 1e). Figure 1f) presents an input-output intensity characteristic of our device. It has been extracted from a Lorentzian fit of the integrated emission around $k = 0 \pm 0.1$ $\mu$m$^{-1}$. The emission properties show a jump at the first threshold in the intensity output and energy position. This is identified as a commonly observed phenomenon in bistable systems. Moreover, figure 1g) demonstrates a persistent blueshift after the first threshold. This evidences continued strong coupling conditions of the system, attributable to increased exciton-exciton interaction\textsuperscript{51}. A second threshold at approximately 180 A/cm\textsuperscript{2} reveals itself in a second nonlinear intensity increase and a pinning of the emission energy, demarking photon lasing.

The two graphs (Figs. 1f/g)) also show the hysteresis curve without any applied noise. The hysteresis width $\Delta A$ amounts in this case to 70 A/cm\textsuperscript{2}. It is important to notice that this hysteresis width does not correspond to the true width without any external influences, since in every system there is an internal noise level.

The hysteresis itself shows a width reduction with increased magnetic field and is absent under non-resonant optical pumping. Furthermore, the photon lasing threshold does not show a bistable character. The origin of the bistability has been previously explained by a dependence of the electron-hole tunneling lifetime on the carrier density, which creates a positive feedback loop\textsuperscript{44}.

Experiment. Since it is not self evident that the system remains in strong coupling with a high amount of applied noise, figures 2a) and 2b) show the input-output characterization with a relatively high noise level of 0.21 $\Delta A$. The analysis shows all the same features (continued blueshift, two threshold behavior) as observed before, which supports the existence of an electrical polariton lasing regime with a high level of noise in the excitation current. It is also noticeable that the hysteresis has not only vanished, but it is possible to observe a gradual onset of polariton lasing at the first threshold under these conditions.

To analyze the hysteresis dependency on applied noise, we record the input-output curves for up and down current injection for a variety of noise levels. The results can be seen in figure 2c). The hysteresis width decreases with increased applied noise. Figure 2d) shows the corresponding emission energy analysis. At a noise level of 0.13 $\Delta A$, we no longer observe a hysteresis, which means there exists a threshold noise for which the system loses its bistable character. Figure 2e) shows the linear decrease of the hysteresis width with applied noise strength. As can be seen in figure 2f), the center position of the hysteresis cycle does not change with noise (maximum deviation of 2 A/cm\textsuperscript{2}), meaning the hysteresis undergoes a symmetric narrowing process.

We will now address the properties of our bistable
device at a magnetic field of 5T under an additional non-resonant spectrally narrow cw-excitation with a laser. Figure 3a) depicts the excitation configuration which takes advantage of the bistability in combination with an optical excitation to trigger the bistable state of the lower polariton branch (indicated by arrows). It is implemented by injecting additional free carriers with a non-resonant laser at a wavelength of 658 nm, which was applied for various seconds (0.5 mW peak power). The laser is spectrally far off resonance with the emission wavelength of the polariton condensate at 874 nm and therefore introduces hot carriers into the system. The laser is positioned in the center of the ring contact, while an injection current in the bistable regime of the lower branch is applied. A pulse of the laser then triggers the polariton condensate emission on the upper bistable branch, which is indicated by the blue arrows in fig 3a). This emission persists as the laser is switched off. These switched states have exactly the same emission properties as can also be observed by simple electrical injection at the upper bistability branch. Figure 3b) and c) present the dispersion relation before and after the non-resonant optical pulse, where c) clearly shows a condensate emission characteristic. Figure 3d) displays the real space image of the emitting micropillar device with a constant applied injection current illuminated by white light. In figure 3e), the optical excitation pulse has switched on the electrical polariton condensate. The significant relative increase in emission intensity indicates the polariton condensate state. In the case when the system is driven with a noisy excitation, this optical switching is only observable in the remaining area of the hysteresis. Once the hysteresis quenches, optical switching is no longer observed.

Theory.— The bistability in our system has been previously described by a density dependent renormalization of the decay rate of high energy carriers in Ref. 44. In this approach, we describe the system as a set of rate equations that model the relaxation dynamics between the carrier reservoir, the exciton population and the polaritons in the system. These population dynamics crucially depend on the carrier decay rate. This carrier decay rate in turn depends on the carrier population already present in the active region, due to their screening of the internal electric field. This loss rate dependency on the carrier population generates the positive feedback effect which is responsible for the existence of a bistability in our polaritonic system. The details are given in the supplemental material52, where the theoretical model was extended to include Gaussian noise in the electrical pumping via a distributed random variable in the excitation term. Figure 4a) shows the results of modeling, including the analytical stationary solution in the absence of noise (dashed
FIG. 2: a)/b) Intensity/energy as a function of excitation current density with an applied noise strength of 0.21 \( \Delta A \). c)/d) Input-output graphs of the polariton emission intensity/energy hysteresis cycle for 0 - 0.13 \( \Delta A \) noise strengths. The hysteresis decreases until a threshold noise makes the system exhibit monostable behavior. e) Hysteresis width as a function of injected noise. The dependence of hysteresis width on excitation noise is linear as shown with the red line fit. f) Hysteresis center as a function of applied noise. Since the center does not shift with applied noise, the hysteresis decreases symmetrically.

FIG. 3: a) The graph shows the creation of artificial states in the upper bistability branch with a short external optical pulse in addition to a stable electrical injection current. b)/d) and c)/e) are the dispersion relations/real space images of the polariton emission before and after the non-resonant optical pulse with a constant applied current of \( j = 90 \text{ A/cm}^2 \).
FIG. 4: a) Theoretical dependence of the polariton density on the pumping rate, with different levels of noise added stochastically to the system. The dashed curve shows the stationary state, obtained in the absence of noise with turning points at the positions of the black spots. b) Theoretical switching process with an optical pulse at t=500ps, triggering the polariton condensate.

curve) and numerically obtained hysteresis curves in the presence of noise. As in the experiment, we observe a significant narrowing of the hysteresis curves with increasing noise. Furthermore, the model allows the simulation of the nonresonant optical switching process. Fig 4b) shows theoretical simulation of the time-dynamics of the system for a pump power in the middle of the hysteresis zone. The system initially forms in a low density state, but the addition of a non-resonant pulse at t=500 ps causes switching to the high power branch of the hysteresis curve.

Conclusion.— We have demonstrated the possibility to fine tune the hysteresis width of an electrical polariton laser with a controlled noise input. Furthermore, the origin of the bistability in the carrier reservoir makes it possible to switch between the lower of the two bistable polariton emission states to the upper one by nonresonant optical injection of additional carriers to produce the necessary positive feedback effect. The theoretical description based on rate equations with a simulated stochastic noise term serves as an explanation for the observed phenomena and matches the experiment. These results can be used as a first guiding point for the noise analysis of electrically driven polariton coherent light sources and especially for the robustness of a bistability based logic encoding. Additionally, they give fundamental insight into the nature of a non-resonant optical bistability due to an electrical polariton injection scheme and provide the possibility for further investigation of electrical polariton bistability devices to serve as a next generation logic architecture.

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