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INJECTION LOCKING OF HIGH-β QUANTUM DOT-MICROLASERS

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Abstract
In this experimental work, we control the nonlinear properties of microlasers by means of external optical injection. We achieve this in the particularly interesting system of a quantum dot based microlaser operating in the regime where cavity quantum electrodynamics (cQED) effects are significant. The investigated quantum dot micropillar laser possesses two competing modes with orthogonal polarization. Under optical injection in one mode, the microlaser partially locks to the master laser, enabling the suppression or enhancement of the non-injected mode via control of the detuning. In addition, cross-correlation measurements prove that temporal switching between both modes can drastically be increased by optical injection.

Key words
Nonlinear dynamics, Optical injection, High-β laser, Microlaser, Micro- and Nano-technologies

1 Introduction

Semiconductor-based microlasers promise big advantages from both technological and fundamental points of view. Their ultra-low lasing threshold and size will reduce the consumption energy with simultaneous enhancement of modulation speeds [1]. From the fundamental physics perspective, microlasers are interesting because they exhibit enhanced light-matter coupling due to reduced mode volumes inside high-quality cavities. The spontaneous emission factor β is therefore enlarged and lasing can be observed for low pump and only tens of photons in the cavity [2].
The nonlinear behavior in our particular devices is enhanced by the competition between the two perpendicularly polarized modes in such micropillar structures [3]. In the present work, we investigate the effects of external optical injection on the modal emission of quantum dot micropillar lasers. We report on the influence of partial injection locking [4] in the intrinsic switching between the two orthogonally polarized modes, and how we can control it by means of optical injection.
These results are interesting for applications that use the nonlinear laser behavior, like reservoir computing [5, 6] or secure key distribution [7].

2 Sample and experimental methods

The used micropillar laser possesses a single layer of self-assembled InGaAs-quantum dots. This lambda-cavity with the quantum dots layer in the center is sandwiched by two AlAs/GaAs distributed Bragg reflector mirrors. With a reflection > 99 % they build a high-quality cavity. Electron beam lithography and plasma etching shape micropillars of various diameters between $2 - 5$ µm, where about 10-100 quantum dots contribute effectively to lasing action, depending on the pillar diameter. Afterwards, the sample is planarized with benzocyclobutene and electrically contacted with circular gold contacts. See [8] for details on the sample fabrication.
The microlaser sample is arranged in a continuous flow He-cryostat and cooled down to a temperature of $T = 30$ K. The microlasers are pumped electrically using a precision current source. An aspheric lens collects the emission.
Our master laser is an infrared broadly tunable narrow-linewidth (~ 100 kHz) laser. In this experiment we control three parameters of the injection laser emission, namely the polarization, the output intensity and

frequency. By means of tuning these parameters we can influence the injected mode, the injection strength and the frequency detuning, respectively.
In the detection path, polarization optics are used to select the mode to be detected, and a spectrometer (7 GHz resolution) is used for spectral selection. After the spectrometer, a high resolution Fabry-Perot Interferometer (resolution of 100 MHz) and a Mach-Zender Interferometer are used to respectively analyze frequency- and phase-locking. With a Hanbury-Brown and Twiss setup (56 ps timing resolution) the second order autocorrelation function and cross-correlation is investigated.

3 Experimental Results

3.1 Input/ output characteristics

When we investigate the input/output characteristics, we observe the typical behavior of cQED enhanced lasers [9, 10]. Our microlaser shows a smooth transition to lasing (cf. Fig. 1 (top)), with a threshold of about 7 V (indicated with a dashed vertical line). Both orthogonally polarized modes increase the intensity gain. Around 7.5 V, one mode (from now on, **strong mode**) wins the gain competition and reaches the lasing regime, while the second mode (**weak mode**) decreases in intensity. Both modes are competing for the common gain medium, and their emission energies are separated ~ 100 μeV.

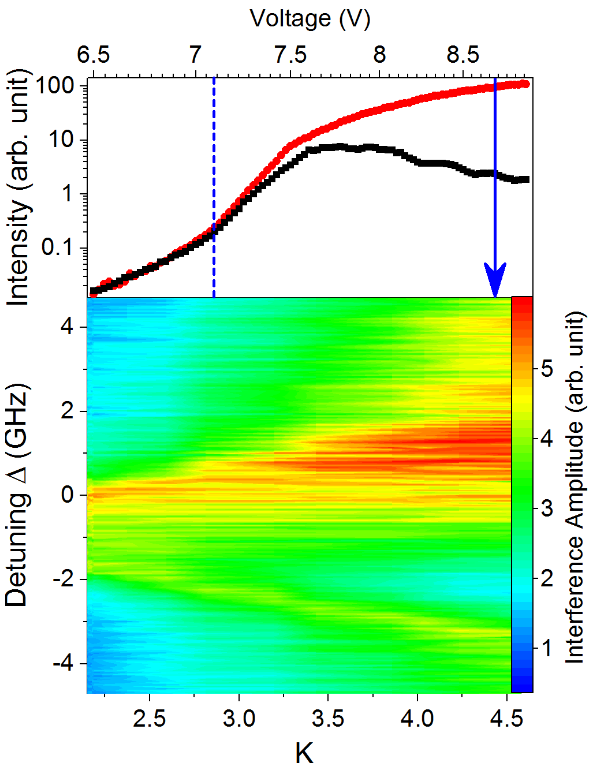

Figure 1: (top) Input/ output characteristics of the microlaser shows a s-shape indicating the transition to lasing. The strong mode (red) and weak mode (black) intensities diverge by more than one order of magnitude above threshold. (bottom) Interference of master- and frequency-locked emission is plotted versus the coupling strength K and reveals a locking cone.

3.2 Phase-locking

We use a fiber-based Mach-Zender interferometer to prove phase synchronization between the master laser and the cQED microlaser. In this configuration, the amplitude of the interference fringes directly corresponds to the phase-locked oscillation amplitude of the slave.
Figure 1 (bottom) shows a map of this amplitude depending on injection rate K and spectral detuning $\Lambda = f_{Master} - f_{Slave}$ between the master and slave. A locking cone for a voltage of 8.7 V (blue arrow) is recorded. Injection is introduced to the polarization of the strong mode with an injection strength $K = \sqrt{\frac{I_{Master}}{I_{Slave}}}$. For positive detuning, phase-locking of the strong mode and the master laser is observed and enlarges with increasing K. Interestingly, the interference amplitude decreases for negative detuning. Semiconductor lasers with a large amplitude-phase coupling reveals asymmetric locking cones [11].

3.3 Frequency-locking

In the Fabry-Perot spectrogram, the influence on the spectral behavior is examined (cf. Fig. 2). The master laser is in the polarization basis of the strong mode. For the detection, the polarization selection is slightly detuned to the weak mode, to observe weak and strong mode simultaneously. The voltage is set to 8.7 V. On the left side, the strong mode and the detuned master laser are visible. For detuning values ~ 2 GHz, an enhancement of the master laser and still a simultaneous emission on the strong mode energy are visible. This partial injection locking effect is characteristic for high-β microlasers, where it has been first observed [4]. For lower detunings, the strong mode frequency is pulled to the master frequency and the intensity is strongly enhanced. Surprisingly, with a change in the sign, both frequencies are suppressed.
Additionally the weak mode, which is not under injection, but shares the gain medium with the strong mode, is influenced by the injection. Shown on the right side, in the area where the strong mode is enhanced, the weak mode suffers by a suppression. This is caused by a more effective coupling of the injected strong mode to the gain medium and therefore less gain for the weak mode. Interestingly, the maximum suppression is not at the same detuning as the maximum enhancement of the strong mode. The reciprocal is also true: for suppression conditions of the strong mode, the gain medium feeds stronger the weak mode that is consequently enhanced.

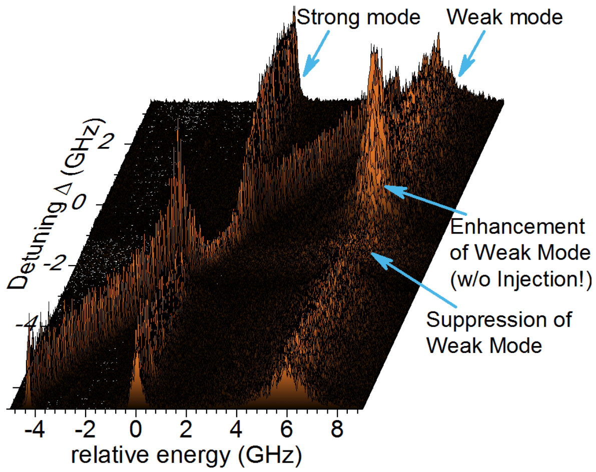

Figure 2: Waterfall of Fabry-Perot Spectra with the strong mode (centered at 0 GHz) and the weak mode (centered at ~6 GHz). The master laser is tuned over the strong mode frequency in its polarization. Both modes experience suppression or enhancement, depending on the detuning.

3.4 Photon statistics

Irregular switching can occur in bimodal micropillar lasers [3,12]. To study the influence of optical injection in the switching dynamics of our microlasers, we use straightforward measurement of the cross-correlation between both modes emission. Experimentally, the signal is split at a polarizing beam splitter to weak and strong mode signal and, on each arm, a single photon counting module (avalanche photo diode in Geiger operation mode, timing resolution 56 ps) detects the arrival time. The time difference between the detection on each arm is plotted to a histogram (cf. Fig. 3 (top)). Without injection (blue curve), no distinct switching behavior is observed. This is indicated by a negligible antibunching amplitude, in the order of the measurement noise.

When the master laser is copolarized with the weak mode, pronounced antibunching occurs for $K = 1$ and the microlaser enters a bistable state. The strong and weak modes alternate lasing in the time scales of ns, given by the dip width [12]. Thus, a detection of a photon from weak and strong mode without a time delay is unlikely and $g^{(2)}(0) < 1$ is observed. With a low injection strength $0 < K < 1$, switching processes become more frequent and $g^{(2)}(0)$ decreases. For $K > 1$, the weak mode becomes the leading mode of the micropillar and the rate of switching decreases. For $K > 3$, the microlaser is again in a stable mode, but this now the weak mode is lasing.

4 Conclusion

In this contribution, we have characterized the emission properties of a quantum dot bimodal micropillar laser under optical injection. We have found that the injected mode experiences phase- and frequency-locking.

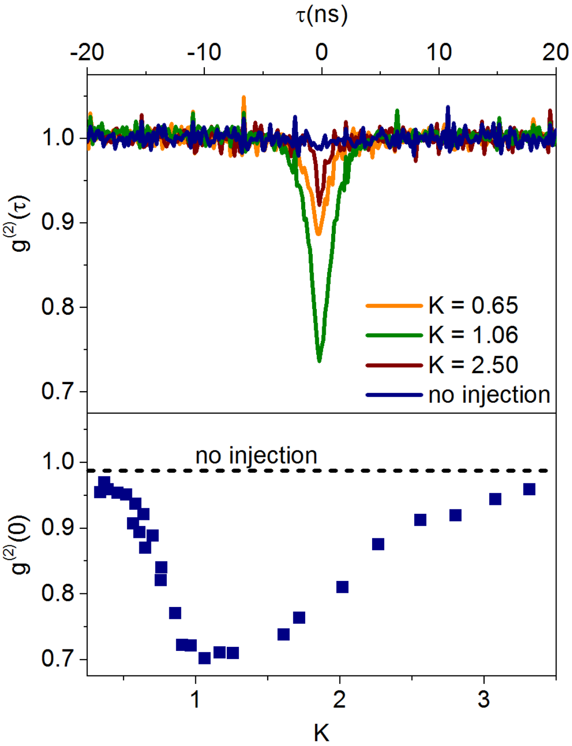

Figure 3: (top) cross-correlation $g^{(2)}(\tau)$ for various injection strengths K. While without injection almost no switching occurs, it is strongly enhanced with injection into the weak mode. (bottom) $g^{(2)}(0)$ is plotted as a function of the injection strength K. With $K = 1$ the weak mode becomes dominant and switching is reduced.

Depending on the detuning, the microlaser shows partial locking with simultaneous emission of master and slave laser, enhancement or suppression of the master laser. Furthermore, the non-injected mode is also influenced via the common gain medium and can changes its intensity. Injection with the weak mode polarization can cause irregular switching. In conclusion, we have demonstrated the possibility to control the nonlinear dynamics of our microlaser by means of optical injection.

5 References

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