Nonlinear Trapping and Interfering Modes in a Quasi-One-Dimensional Microcavity Laser

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Keywords: Nonlinear Optics, Microcavities, VCSEL, Exciton-polaritons.

Abstract: Experimental studies of the emission from one-dimensional microcavity laser structure under nonresonant optical excitation are presented. The one-dimensional laser was prepared by electron-beam lithography and reactive ion etching from a planar microcavity sample. Below the lasing threshold, the system was in the strong coupling regime, where the emission exhibits the common exciton-polariton far-field dispersion. Above the threshold, the system switched to the weak coupling regime and the photon lasing was observed. Interestingly, under higher pumping powers above the threshold, a strong blueshift of the lasing mode was observed, with localisation of the far-field emission at finite wavevectors. The near-field images showed interference fringes corresponding to the interference of propagating modes in k-space. This is interpreted in terms of self-interfering modes confined between the pumping spot and the edges of the 1D microlaser.

1 INTRODUCTION

Light confinement in the sub-micrometre scale has led to the realisation of novel nonlinear sources of coherent light and paved the way for studies of quantum electrodynamics in the semiconductor material platform (Reithmaier et al. 2004). Since reaching the strong coupling between the exciton and photon (quasiparticles called exciton-polaritons) in planar semiconductor cavities (Weisbuch et al. 1992), there is a vast interest in nonlinear phenomena in quantum bosonic fluids of light and matter realized in a solid state system (Byrnes et al. 2014; Carusotto & Ciuti 2013).

Due to the excellent development of etching techniques in semiconductor technology, there is a possibility to harness the photonic confinement into any desired pattern. On the other hand, spatial shaping of the nonresonant optical excitation can create an effective potential for exciton-polaritons (Schneider et al. 2017) or create nonlinear coupled structures in photon lasers (Pal et al. 2017). In view of the abovementioned approaches, one can combine the etching techniques with strong nonresonant excitation to provide custom photonic confinement for the lasing modes.

In this paper, we present investigations of a one-dimensional microcavity laser with nonresonant optical excitation. Under strong pumping, the system reaches the weak coupling regime and photon lasing is observed at finite wavevectors in the far-field spectrum. The emission is strongly blueshifted with respect to the bare cavity mode resonance at low pumping power densities. Power dependent measurements in near and far field spectra give insight into the observed phenomena, which are interpreted in terms of nonlinear confinement of the modes outside the pump region.

2 EXPERIMENTAL DETAILS

2.1 Optical Setup

The experiments were performed on the setup depicted in Fig. 1. Excitation was provided with the mode-locked femtosecond pulsed Ti: Sapphire laser (parameters are indicated in the figure), tuned around

Pieczarka, M., Schneider, C., Höfling, S. and Sęk, G.
Nonlinear Trapping and Interfering Modes in a Quasi-One-Dimensional Microcavity Laser.
DOI: 10.5220/0006637302420246
In *Proceedings of the 6th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2018)*, pages 242-246
ISBN: 978-989-758-286-8

800 nm for efficient absorption in the GaAs material. The laser beam was focused with a high numerical aperture microscope objective (NA = 0.42) to a diffraction limited Gaussian spot of diameter around 3 µm on the sample. The laser power is controlled with the optical power meter placed after the beam splitter. The investigated sample was kept in the continuous-flow liquid-helium cryostat in order to cool it down to the cryogenic temperature of 5 K.

Luminescence from the sample is collected with the same objective and imaged with a set of achromatic lenses onto the entrance slit of a monochromator. A two-lens setup is used to efficiently switch between near-field and far-field images (one of the lenses is placed on a kinematic mount). Cuts of the sample emission images are analysed with the half-meter focal-length monochromator coupled to a 2D InGaAs-based near-infrared CCD camera. To conveniently adjust the direction of the cuts done by the monochromator slit a Dove prism on a rotational mount is placed in the optical path, which enables rotation of the image with respect to the detection system.

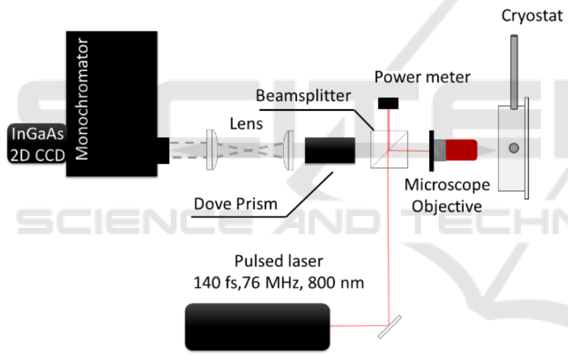

Figure 1: Scheme of the experimental setup.

2.2 Sample Details

We investigated a microcavity sample, which was used in the previous work (Pieczarka et al. 2017). The planar microcavity is grown in molecular beam epitaxy technique (MBE) on a semi-insulation GaAs substrate. It consists of two GaAs/AlGaAs distributed Bragg reflectors (16 bottom and 12 top layer pairs respectively), where the active region consists of two stacks of four $In_{0.28}Ga_{0.72}As$ 7 nm thick quantum wells (QWs) placed at the antinodes of the confined fundamental photon mode (in the growth direction). The sample is characterized by the normal mode splitting of the exciton and photon modes, with Rabi splitting of 7.5 meV, where the theoretical exciton resonance appears around 1.2605 eV. The cavity mode is characterized by a quality factor exceeding 1000 (measured spectrally far from the exciton-polariton resonance).

To obtain high-quality one-dimensional micro-wires, a piece of the sample was etched in the post-processing. Microwires of the length of tens to hundreds of micrometres and widths of few micro-metres were created via electron beam lithography and etched deeply into the structure using electron-cyclotron-resonance reactive-ion-etching. Due to the optimized etching technique resulting in smooth and steep sidewalls of extremely low roughness, no detrimental influence on the cavity quality factor was observed (Fischer et al. 2014). In this work, we focus on a microwire of 75 µm length and width of 8 µm, which is presented in the inset of Fig. 2.

The planar sample was characterized previously with the high impact of local fluctuations of photonic and excitonic disorder, which influences the exciton-polariton fluid flow in the strong coupling regime (Pieczarka et al. 2015). To check the level of disorder in the investigated microwire, we excited the sample with a defocused laser spot (with an additional lens in the laser path) with low power density, very far from the lasing threshold. Photoluminescence (PL) along the wire was cut with the monochromator slit and analysed spectrally. One can see in Fig. 2 that the PL is fragmented, as the low-density polaritons are confined in the local potential minima. However, the amplitude of the local energy fluctuations is around 1 meV only, being much smaller from the disorder in the planar sample observed previously.

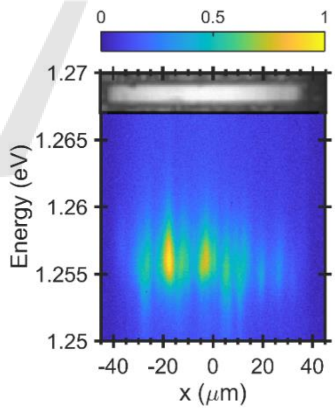

Figure 2: Emission spectrum at wide spot excitation below lasing threshold along the investigated microwire. Top view white-light microscope image of the investigated microlaser is in the top inset.

3 RESULTS

Excitation power dependent measurements of the polariton and photon luminescence from the microwire were performed in the wide range of pump powers. Results of the data analysis are presented in Fig. 3. In the integrated intensity power curve in Fig. 3a, one can observe a distinct nonlinear threshold (P_{th} = 13 mW) with a simultaneous drop in the linewidth and blueshift of the emission resonance, Figs. 3b and 3c. This is an indication of the transition to a coherent lasing state, as the spectrally narrow lasing resonance is located around the bare cavity mode, Fig. 3c.

Moreover, in the range of low pumping power density below the threshold, the emission is located at energies lower than the bare cavity mode, Fig. 3b and the far-field dispersion corresponds to the lower exciton-polariton branch (LPB), see Fig. 4a. The emission is fragmented, which indicates the influence of disorder, as presented in Fig. 2. At lasing threshold, the emission is located around the bare cavity mode, Fig. 4b, although the far-field dispersion is rather flat, indicating a localised mode in real space, perhaps at a local defect near the pump region. The observation of the intensity dependence threshold, linewidth narrowing and blueshift of the emission from LBP to the cavity mode resonance are signatures of the

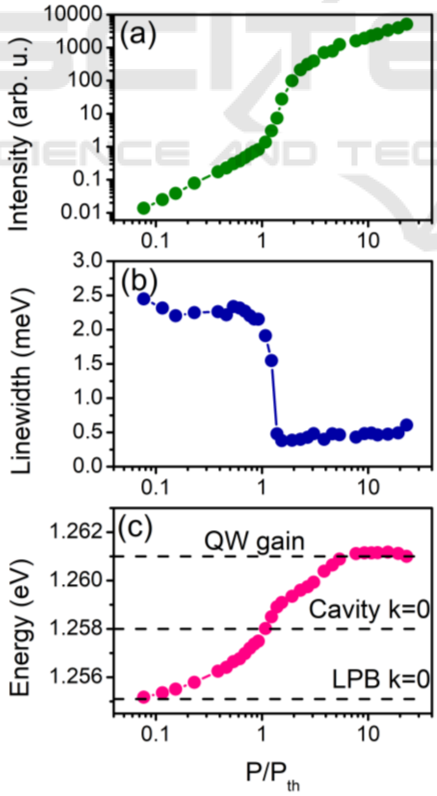

Figure 3: Power dependent analysis. (a) Integrated intensity, (b) linewidth of the emission and (c) energy of the lasing resonance.

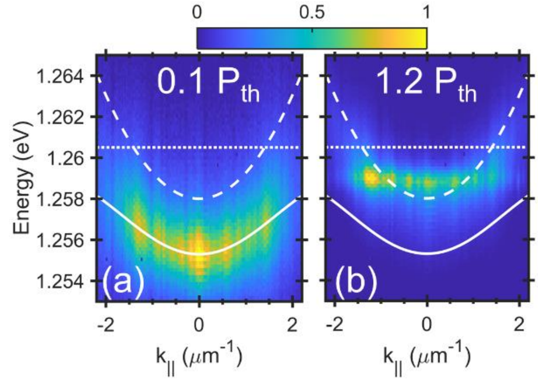

Figure 4: Normalised far-field emission spectra below (a) and slightly above the lasing threshold (b). LPB is depicted (solid line) together with bare cavity photon dispersion (dashed line) and QW exciton resonance (dotted line).

transition from strong to weak coupling regime and occurrence of the photon lasing (Tempel et al. 2012). The most important observation has been made at pumping levels exceeding the threshold power. The emission energy shows a continuous blueshift with the pumping power up to P = 6P_{th}, see Fig. 3c. This kind of spectral behaviour is expected rather for a polariton laser than for weak coupling photon lasing (Bajoni et al. 2008). The far-field characteristics in this power range show a flat and blueshifted dispersion around the theoretical cavity mode, Fig. 5a. Further increase of the pumping level leads to the pinning of the emission energy around the bare QW exciton energy at 1.261 eV, Fig. 3. indicates the maximum spectral gain at this energy, which amplifies the lasing mode. Nevertheless, the far-field dispersion showed a very distinct change, where lasing at a well-defined wavevector is observed, Fig. 5b. This is a result of two counter-propagating coherent wave packets along the microwire.

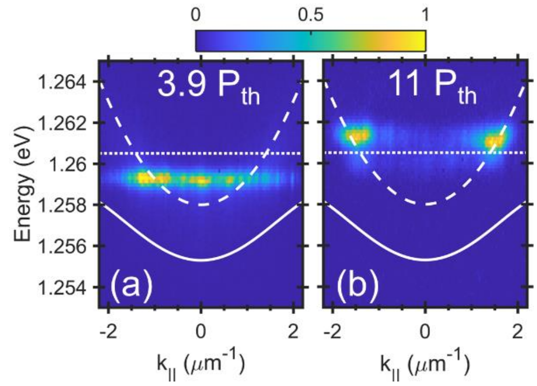

Figure 5: Normalised far-field emission spectra at higher pumping powers. Flat and blueshifted dispersion (a) and well-defined finite wavevector lasing (b).

In order to verify this observation, we performed a near-field imaging along the one-dimensional microcavity at the highest pumping level. The result is shown in Fig 6a. At the pump spot position (x = 0 μm) the strongest emission is observed with signatures of the occupation of higher energy confined modes in the perpendicular direction, see Fig. 6b. Moreover, the spatially extended emission is detected, being spread around 20 μm in both directions from the pump spot along the microwire at the main lasing energy, Fig. 6a. This feature is characterised by distinct interference fringes at both sides of the near-field image. Interestingly, the fringe spacing is equidistant and is equal to d = 2.2 μm. This spacing corresponds almost exactly to the interference of wave-packets travelling with the emission wavevector observed in the far-field luminescence $k = \pi/d \approx 1.43\ \mu m^{-1}$. It is worth noting that the equidistant spacing cannot be caused by the irregular defect pattern, see Fig. 2.

The observed features can be interpreted in terms of self-interference of coherent photon waves travelling along the one-dimensional laser cavity. Photons are emitted locally within the pump spot and propagate in positive and negative directions in the wire. Further, they are reflected from the cavity ends, providing the counter propagating mode. This mode

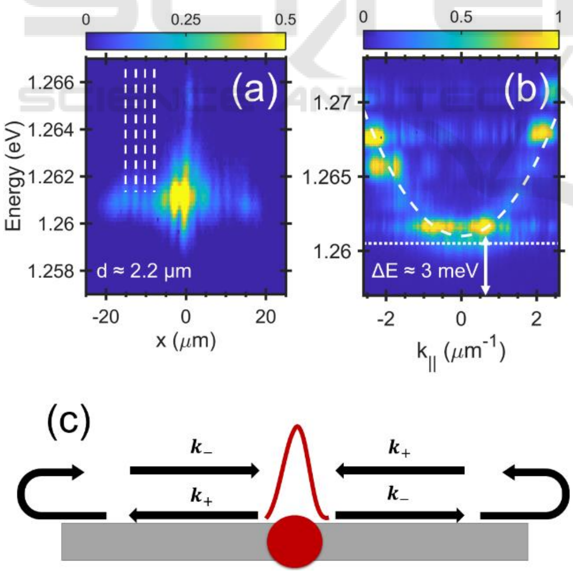

Figure 6: Normalised near-field emission spectra at high pumping power $P = 23P_{th}$ (a) (dashed lines indicate equidistant interference maxima). The colour scale is saturated at 0.5 to enhance the visibility of fringes. Far-field spectrum in the perpendicular direction to the microwire at the pumping spot (b). (c) Schematic picture of the interpretation of the described phenomena. The red dot indicates the pump spot, local blueshift as a red peak and black arrows indicate travelling waves along the wire.

can be once again enhanced with the remnant gain in the pump region. This mechanism provides amplification of the propagating waves, similarly to one-dimensional polariton condensates (Wertz et al. 2012). The scheme of the proposed interpretation is presented in Fig. 6c.

Propagation outside of the pump spot is possible by a local change in the refractive index due to the excess carriers generated in the GaAs material (Henry et al. 1981), which creates an effective potential gradient. This change of the refractive index is evidenced in the far field spectrum measured at the pump spot in the direction perpendicular to the wire, see fig. 6b. One can observe a series of confined transversal modes following the strongly blueshifted cavity dispersion curve. The local blueshift at k = 0 is as large as 3 meV and is definitely not caused by any strong coupling phenomena, like polariton-polariton nonlinear interactions. The observed blueshift of the emission occurs in the weak coupling regime, so it is solely caused by the nonlinear refractive index change in the microcavity. This effective potential hill provides an additional spatial confinement of the modes propagating in both directions between the spot and the edges of the microwire.

4 CONCLUSIONS

To conclude, we investigated lasing properties of a quasi-one-dimensional microcavity laser. We observed continuous blueshift of the emission with the increase of the pumping power below and above the photon lasing threshold, although the system entered the weak coupling regime. Well defined, oblique angle lasing was observed, which is described as self-interference of confined modes between the blueshifted pump spot and the microwire edges. Further investigation will be conducted to verify the proposed interpretation, especially time-resolved measurements of the near-field and far-field patterns, which can give insight into the dynamics of the observed propagating laser modes and its amplification.

ACKNOWLEDGEMENTS

Authors would like to acknowledge useful discussions with Elena Ostrovskaya. This work is supported by National Science Centre, grant PRELUDIUM 2016/23/N/ST3/01350.

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