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High-temperature lasing in diode microdisk lasers with InAs/InGaAs quantum dots

E I Moiseev[1], N V Kryzhanovskaya[1,2], Yu S Polubavkina[1], M V Maximov[1], M M Kulagina[2], S I Troshkov[2], Yu M Zadiranov[2], A A Lipovskii[1,5], I S Mukhin[1,3], M Guina[4], T Niemi[4], A E Zhukov[1]

[1]St Petersburg Academic University, 8/3 Khlopina, 194021, St Petersburg, Russia
[2]Ioffe Institute, 26 Polytechnicheskaya, St Petersburg, 194021, Russia
[3]ITMO University, Kronverkskii 49, St Petersburg, 197101, Russia
[4] Optoelectronics Research Centre, Tampere University of Technology, Tampere, Finland
[5]Peter the Great St.Petersburg Polytechnic University, St. Petersburg, 195251 Russia

E-mail: moiseev@spbau.com

Abstract. We demonstrate that quantum dot microdisk lasers are able to operate under continuous wave current injection at 100 °C. We also present a novel method for increasing a side mode suppression ratio in microdisk lasers.

1. Introduction

High-temperature operating diode lasers are attractive for a variety of applications including on-chip communication. For this purpose, microlasers are more suitable owing to their small footprint. In(Ga)As quantum dots (QDs) are successfully used in edge-emitting (macro) lasers capable of operating at temperatures as high as 163-220 °C [1, 2]. However, the maximal temperature of CW lasing reported for QD micodisk laser is 50 °C [3]. It is strongly desired to have a single-frequency lasing spectrum for optical communication. However, QD-based microring and microdisk lasers typically demonstrate multi-frequency lasing on whispering gallery modes of different azimuthal and/or radial orders. In order to enhance single frequency lasing, various methods have been proposed (for example, [4, 5]), which are usually based on suppression of side modes, whereas intensity of a dominant mode remains unchanged or even degrade.

In this work, we present results on high-temperature operation of microdisk laser. The key modification, which results in successful lasing even at 100 °C, was the use of deep localized quantum dots in combination with their multiple stacking. We also present our preliminary results on characterization of QD microdisks with nano-antennas attached to the microdisk side wall. Owing to more effective light outcoupling, side mode suppression ratio in such microdisk increases owing to enhancement of the dominant mode intensity rather than introducing additional loss for some undesired modes.

2. Injection-pumped microdisk lasers

An epitaxial structure was grown by molecular beam epitaxy on an n+ GaAs(100) substrate. An active region comprises 10 layers of InAs/InGaAs quantum dots. We used a 0.44-µm-thick GaAs waveguiding layer with $Al_{0.25}Ga_{0.75}As$ *n*- and *p*-type doped claddings. A 31-µm – diameter microdisk was etched with chemical plasma process. Ohmic contacts were formed to p+ GaAs cap layer and n+ substrate. Microlaser was mounted on a copper heatsink and tested at room temperature and elevated temperatures under continuous wave injection. In-plane emitted light was collected with a piezoelectrically adjustable ×100 Olympus LMPlan IR objective and analysed with a Horiba FHR 1000 monochromator and a Horiba Symphony InGaAs CCD array (spectral resolution 30 pm).

Emission spectra taken at 100 °C under various bias current are shown in figure 1(a). The spectra contains a series of narrow lines, which correspond to $TE_{1,1,m}$ whispering gallery modes of different azimuthal number *m*. The dominant mode, which is $TE_{1,1,242}$, is centred near 1304 nm. The next most intensive modes are $TE_{1,1,243}$ and $TE_{1,1,241}$. Integrated intensities against bias current for these three modes are shown in figure 1(b). The light-current characteristic of the dominant mode is shown in figure 1(b). A pronounced threshold behaviour is observed with the threshold current of 13.8 mA (1.8 kA/cm^2). To our best knowledge, this is the highest CW lasing temperature among QD microdisk/microring lasers grown on GaAs substrates. The intensities of the side modes start decreasing as the injection current exceeds the lasing threshold.

a) b)

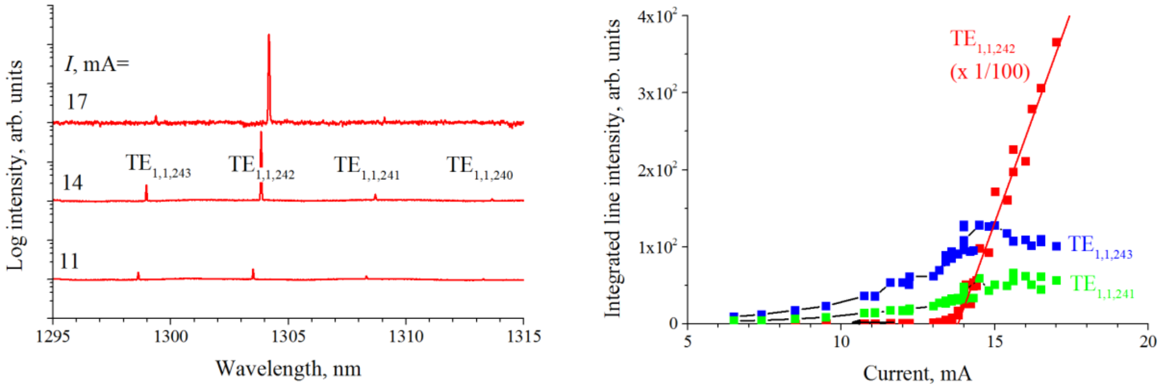

Figure 1. 100 °C emission spectra (a) and integrated intensity of WGMs as a function of bias current (b).

Threshold current is shown in figure 2 as a function of temperature. At 25 °C lasing starts at 4.4 mA. The characteristic temperature in the 25-100 °C interval was estimated to be 66 K. At 110 °C the microdisk does not lase.

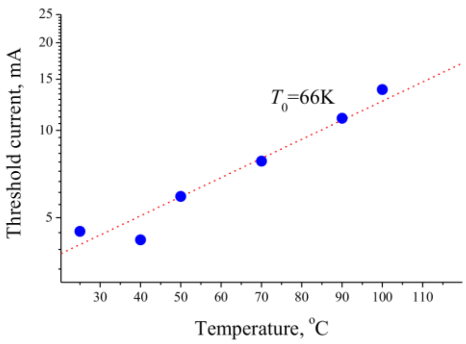

Figure 2. Temperature dependence of threshold current and its fit with characteristic temperature of 66 K.

3. Modification of micro-resonator spectral characteristics using nano-antennas

A far-field emission of the microdisk lasers is isotropic making coupling into waveguide inefficient. Another drawback of the microdisk geometry is multi-mode lasing due to the small free spectral range, whereas many applications require a single-mode emission. In order to increase the output without increasing the threshold and improve the side-mode suppression ratio we propose to introduce a nano-antenna to the edge of the resonator. Proposed method was tested using optically pumped QD micodisk laser. The epitaxial structure was synthesized by molecular-beam epitaxy on a GaAs(100) substrate with a Riber-49 MBE machine. An active region represents 5 layers of InAs/InGaAs quantum dots inserted into a 0.22-µm-thick GaAs waveguiding layer cladded with 400-nm-thick $Al_{0.98}Ga_{0.02}As$ layer from the substrate side. Spectral position of quantum dot ground-state transition was located around 1.28 µm at room temperature. Microdisk resonators were fabricated using photolithography and Ar+ ion beam etching. Outer diameter of the microdisks was 6 µm. The $Al_{0.98}Ga_{0.02}As$ bottom cladding layer was selectively oxidized to be transformed into an AlGaO oxide.

Nano-antennas were formed by means of electron-beam induced deposition with $C_9H_{16}Pt$ precursor gas using a Carl Zeiss CrossBeam 1540XB microscope. The precursor gas was injected trough a micro-nozzle into a spatial region of electron beam focus. An operation pressure in the microscope chamber was $2*10^{-5}$ mBarr, electron beam diameter and current was 2-3 nm and 50 pA, respectively, Pt-C nano-antenna growth rate was about 160 n/s. The nano-antennas formed under such growth conditions have a polycrystalline structure representing an array of Pt nano-crystallites of 2-3 nm inserted into an amorphous carbon matrix. Figure 3 depicts a microscopic image of the microdisk with a nano-antenna attached to the microdisk. The nano-antenna diameter is 150 nm, its height is 1.3 µm.

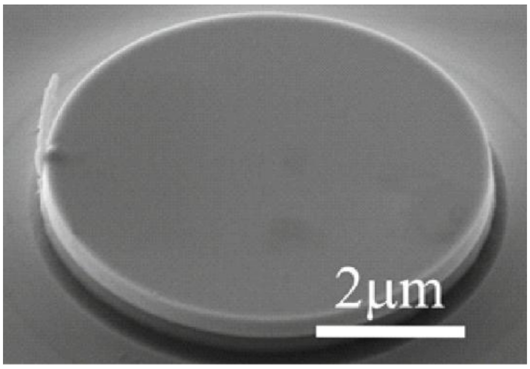

Figure 3. Scanning electron microscopy image of 6-µm-diameter microdisk with 150-nm-wide 1.3 µm-high nano-antenna.

Optical characteristics were studied under an YAG:Nd laser excitation (λ=532 nm) with laser beam focused on a sample surface with an Olympus LMPlan IR 100 NA0.8 objective lens. The same lens was used for luminescence signal collection. An FHR1000 monochromator and a Horiba Symphony multi-channel cooled InGaAs photodetector were used for signal detection (spectral resolution was 0.03 nm). Measurements were conducted at room temperature with various excitation power.

In order to clarify effect of nano-antennas on microdisk performance we compare properties of the microlaser before and after formation of the nano-antenna (as shown in figure 3). Luminescence spectra are shown in figure 4. In both cases the microdisk has the dominant mode wavelength around 1277 nm. The next most intense modes are located near 1290 and 1303 nm.

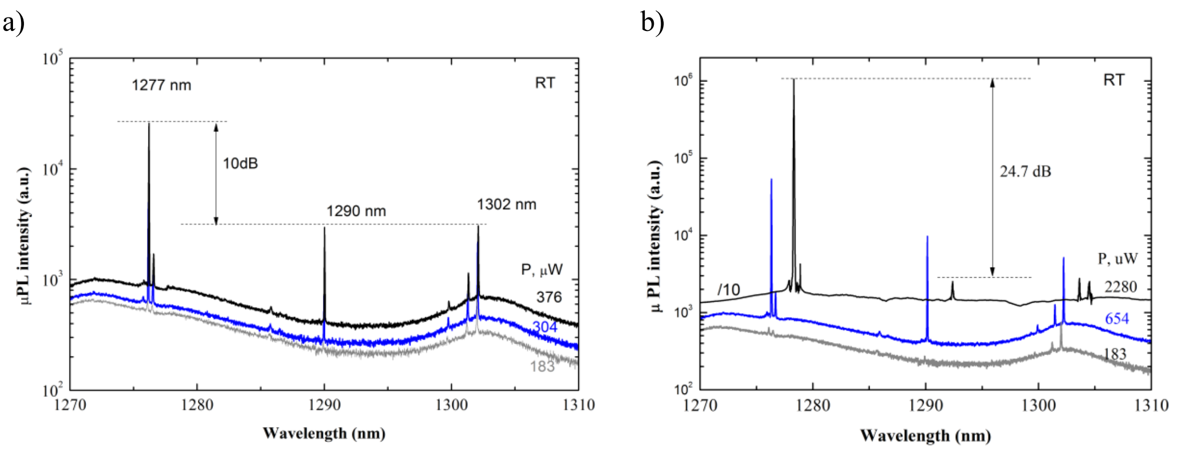

Figure 4. Lasing spectra of microdisks before (a) and after (b) nano-antenna deposition taken at room temperature at various pump power.

Figure 5(a) summarizes side mode suppression ratio (SMSR) for the microdisk lasers before and after nano-antenna deposition. It is seen that the maximal SMSR increases from only 10 dB in the microlaser without nano-antenna to 24.7 dB in the microlaser with antenna. The modified structure is also characterized by better light outcoupling from the resonator into a free space as it is demonstrated in figure 5(b), where the dominant mode intensity is shown as a function of pump power. It should be noted that the nano-antenna increases the maximal output light intensity by more than 20 times.

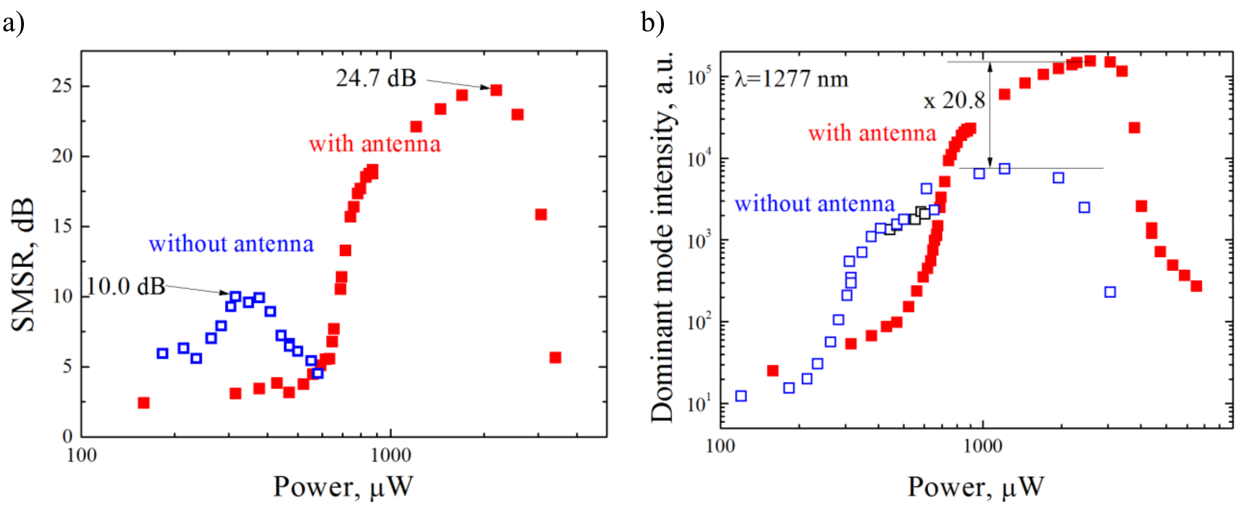

Figure 5. Side mode suppression ratio (a) and dominant mode intensity (b) as function of pump power for microdisks with and without nano-antenna.

4. Conclusions

In conclusion, lasing in a quantum dot microdisk laser at temperature as high as 100 ^{o}C has been for the first time. The threshold current density was 1.8 kA/cm^2; lasing wavelength 1.3 μm. We also proposed and realized a novel method of mode selection in microresonators with quantum dots. The method is based on an enhancement of a dominant mode intensity by means of a nano-antenna attached to the microdisk. Using Pt-C antennas formed with electron-beam assisted deposition, we achieved the maximal SMSR increment by 14 dB and the dominant mode enhancement by 20 times in room-temperature spectra of 6-μm-diameter QD microdisk lasers.

5. Acknowledgement
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