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# Room temperature lasing from microdisk laser in aqueous medium

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**Abstract.** Lasing of optically pumped semiconductor microdisks immersed in aqueous medium is demonstrated for the first time. Microlasers containing quantum dot active region were placed into the transparent polydimethylsiloxane chamber filled with distilled water at room temperature. The spectral and threshold characteristics of the lasers are compared in both air and aqueous environments. We suppose that such high- $Q$  microlasers can be used as highly sensitive biosensors.

## 1. Introduction

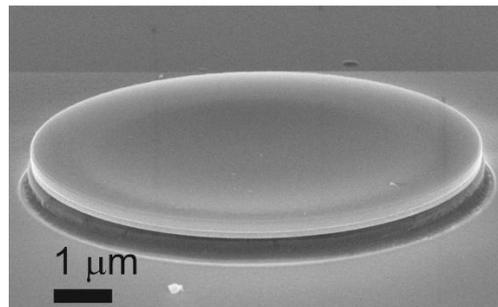
Optical whispering-gallery-mode (WGM) microresonators have unique properties, such as small mode volumes, extremely low total optical loss, which leads to ultrahigh quality factors and low lasing thresholds. WGM resonators are also prospective for biomolecular detection due to high sensitivity of the WGMs to surrounding environmental conditions. In past decades, significant results were obtained in this field of application with passive microspherical WGM resonators [1]. Biochemical samples typically require aqueous solution, and the resonator should be placed into a cuvette with water or in a microfluidic chip [2]. The dimensions of such microspherical based biosensor are typically large (several  $\text{cm}^3$ ). Recently, low-threshold lasing in optically pumped semiconductor III-V microdisk lasers with very small diameter (down to  $1\ \mu\text{m}$ ) has been demonstrated [3]. Operation at room and elevated temperatures of injection microdisk lasers were also reported in [4]. Such WGM microlasers coupled with a photodetector could be an ideal platform to realize small-sized sensors of single nano-sized particles or molecules. In this work we study lasing characteristics of microdisk lasers in air and in water environment. Room temperature lasing in optically pumped semiconductor microdisks in aqueous medium is demonstrated for the first time. The obtained results open wide prospects for use of the microlasers as building block of the high-sensitive biosensors.

## 2. Experiment details

Epitaxial structures used for fabrication of the microdisk lasers were grown by molecular beam epitaxy on n-doped GaAs substrate. An active region represents 5 layers of  $\text{InAs}/\text{In}_x\text{Ga}_{1-x}\text{As}$  quantum dots inserted into a  $0.35\text{-}\mu\text{m}$ -thick GaAs waveguiding layer cladded with  $400\text{-nm}$ -thick  $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$

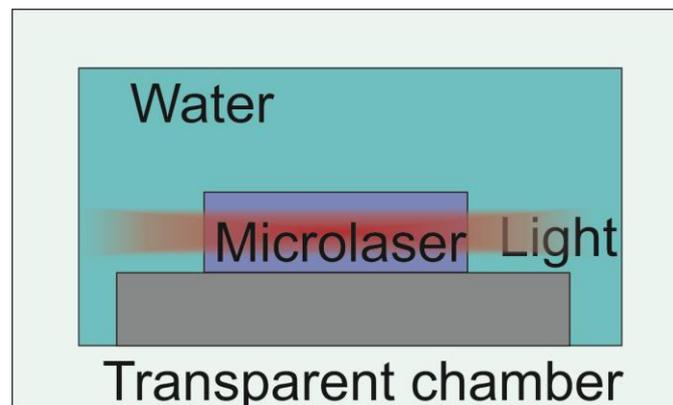


layer from the substrate side. The spectral position of quantum dot ground-state transition was located around  $1.28 \mu\text{m}$  at room temperature. Microdisk resonators were fabricated using photolithography and  $\text{Ar}^+$  ion beam etching. Outer diameter of the microdisks was  $7 \mu\text{m}$ . The  $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$  bottom cladding layer was selectively oxidized to be transformed into an  $\text{AlGaO}$  layer providing effective optical confinement from the bottom side [5].



**Figure 1.** SEM image of a microdisk laser with  $7 \mu\text{m}$  outer diameter.

Microdisks were tested in air and after that placed into a chamber made of transparent polydimethylsiloxane (PDMS) using Sylgard 184 silicone elastomer. Then the chamber was filled with distilled water (figure 2) and lasers were tested in aqueous medium. The microdisk lasers were studied at room temperature under optical pumping with cw-operating YAG: Nd laser ( $\lambda=532\text{nm}$ ). The signal was collected by microobjective  $\times 100$  and detected by ANDOR iDus multi-channel detector and confocal optical spectroscopy setup (Integra Spectra, NT MDT).

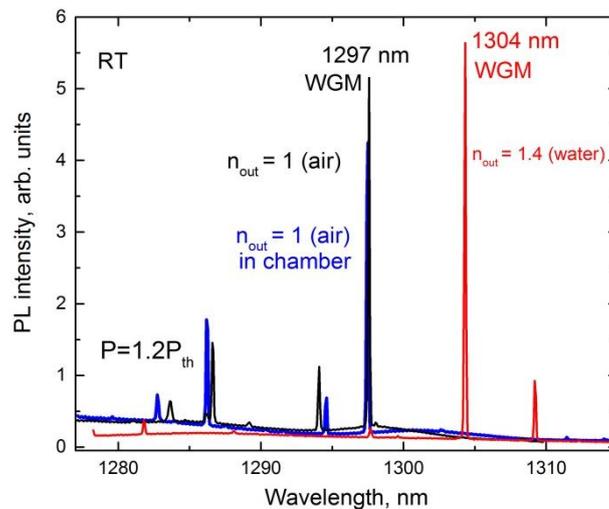


**Figure 2.** The schematics of the PDMS chamber construction with a sample and distilled water.

### 3. Results

First, microdisk lasers were characterized in air surroundings. The room temperature spectra of initial microdisks contain a series of sharp lines corresponding to WGMs of different radial and azimuthal order (Figure 3). One WGM ( $\lambda \sim 1297 \text{ nm}$ ), which spectral position is the closest to the quantum dots ground-state transition peak, demonstrates lasing behavior. The increase of pump power results in distinct knee at the light in - light out dependence for this WGM at threshold pump power  $P_{th} \sim 0.3\text{mW}$  (Figure 4). The full width at half maximum value of the line ( $\Delta\lambda \sim 30\text{pm}$ ) near the

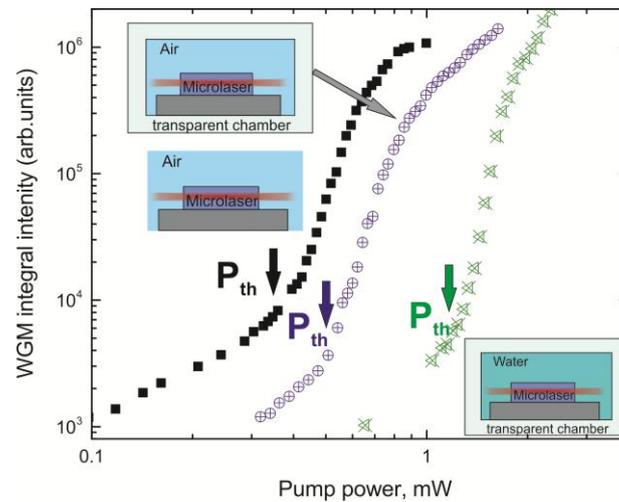
threshold gives the resonator quality factor  $Q$  ( $\lambda/\Delta\lambda$ ) as high as  $3 \times 10^4$ . Then the microlasers were inserted into the PDMS chamber without water filling and tested to estimate the influence of the chamber's walls (light absorption and reflection) on optical pump power and signal collection. Spectral positions of the WGM lines remain almost the same as in the initial microlasers (Figure 3). Due to the certain limitations in device processing, the diameters of microdisks under study were slightly varied from sample to sample. According to SEM data, the actual diameter of microdisks with nominal diameter of  $7 \mu\text{m}$  may vary from  $6.9 \mu\text{m}$  to  $7.1 \mu\text{m}$ . Thus emission wavelengths of the same WGM also may vary from disk to disk in the range of several nanometers.



**Figure 3.** The room temperature  $\mu\text{PL}$  spectra of the microdisk lasers in the air and in the water at  $P \sim 1.2 P_{th}$ .

Placing the microlasers into the empty PDMS chamber results in increase of the threshold pump power to  $P_{th} \sim 0.7 \text{ mW}$  (as measured on the chamber input window) due to the loss of the pumping laser power in PDMS (Figure 4). When the PDMS chamber was filled with deionized water we observed dramatic change in the microdisk mode spectrum. We attribute this modification to the change of the refractive index of the surrounding material (1.33 for water at  $1.3 \mu\text{m}$ ). The wavelength of lasing WGM is now shifted by  $+7 \text{ nm}$  to  $1304 \text{ nm}$  (Figure 3) and the threshold pump power increases to  $1.5 \text{ mW}$  (Figure 4). The observed two-times increase of threshold pump power cannot be caused just by light absorption in the water since the water absorption coefficient at  $\lambda \sim 0.53 \mu\text{m}$  is low ( $\alpha \sim 3 \cdot 10^{-4} \text{ cm}^{-1}$ ). The observed increase of the threshold pump power can be partially explained by worsening of the resonator quality factor. Indeed, the WGM linewidth becomes three times broader after water filling. Nevertheless, the resonator quality factor remains sufficiently high ( $Q \sim 10\,000$ ) for sensing purposes.

Spectral and threshold characteristics of the microlasers recovered to their initial state when the water evaporated from the PDMS chamber.



**Figure 4.** The dependence of the dominant WGM intensity on the pump power.

It is worth mentioning that the water ambient also results in the improvement of the thermal conduction compare to the air ambient. The thermal resistance of laser was estimated from the dependence of the spectral position of the lasing WGM line on the pump power. Considering the temperature induced shift of a WGM line  $0.075 \text{ nm}/^\circ\text{C}$ , the thermal resistance  $R_{th}$  of 10 and  $5 \text{ }^\circ\text{C}/\text{mW}$  was estimated for the  $7 \text{ }\mu\text{m}$  microdisk laser operating in the air or in the water, respectively.

To conclude, characteristics of the semiconductor microdisk lasers operating at room temperature under optical pumping in aqueous medium are studied for the first time. The obtained results (threshold, quality factor) demonstrate the possibility to use microdisk lasers for compact sensors requiring aqueous solution.

### Acknowledgments

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