Improved emission outcoupling from microdisk laser by Si nanospheres

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Abstract. Far field emission of optically pumped QD microdisk lasers with spherical Si nanoantenna placed on the top surface of microdisk is studied theoretically and experimentally. The interaction of the whispering gallery mode microdisk resonator with properly designed and positioned Si nanospheres results in improvement of light outcoupling and directed emission.

1. Introduction

Optical whispering-gallery mode (WGM) microcavities having ultrahigh Q factor (up to $10^{11}$ [1]) and small mode volumes enhance significantly the interaction between light and matter, becoming an excellent platform for achieving ultralow-threshold microlasers [2]. However, the emission of WGM microlasers is isotropic in plane due to the rotational symmetry, whereas for practical applications the directional emission is required. To increase the collection efficiency and improve the directivity of the emitted light several types of defects such as a point scatterer [3], linear defect [4], air hole [5] have been proposed but they introduce Q spoiling accompanied by essential increase of the threshold characteristics. In this work we used a subwavelength silicon scatterer placed on the top surface of the microdisk, to obtain the improved emission outcoupling due to the effect of the Si nanosphere-enhanced scattering. Optimization of the Si nanosphere size and location results in increased intensity of the outcoupled WGM and its directional far field emission without Q/threshold spoiling.

2. Experiment and calculation details

The epitaxial structures used for fabrication of the microdisk lasers were grown by molecular beam epitaxy on a n-doped GaAs substrate. An active region represents 5 layers of InAs/In$_x$Ga$_{1-x}$As quantum dots inserted into a 0.35-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.

Spectrum and field structure of the eigenmodes in the microdisk cavity were calculated by use COMSOL Multiphysics software using the approach described in [6-7]. Si nanospheres with a
different diameters were made by laser ablation of thick a-Si:H layers on quartz substrates and placed on the top surface of the microdisk by a microtip using pick-and-place technique. The scanning electron micrograph (SEM) of the microdisk laser with nanosphere is shown in figure 1. The spectra and distribution of the emitted light of the microdisk laser were studied by confocal scanning optical spectroscopy (Integra Spectra, NT MDT). The microdisk was uniformly optically pumped by YAG:Nd laser (\(\lambda = 532\text{nm}\)) using lensed fiber.

![SEM image of the 6-\(\mu\text{m}\) microdisk with a nanosphere](image1.png)

**Figure 1.** Scanning electron micrograph of the 6-\(\mu\text{m}\) microdisk with a nanosphere (the position of sphere is shown with mark).

### 3. Results
First, optimization of the Si nanosphere size and location at the microdisk surface for directional light outcoupling was done. We studied the dependence of the microdisk laser dominant modes intensities, azimuthal distributions, thresholds and widths on the size and position of the Si nanosphere. If the nanosphere diameter was less than 200nm and/or its position did not coincide with the maximum of electric field of the microdisk resonator mode we did not observe any difference in the microlaser spectra, threshold power, and quality factor of the modes. Figure 2 shows SEM image of the 6-\(\mu\text{m}\) microdisk laser with nanosphere placed at the position of the maximum of electric field of the microdisk resonator mode but with diameter 170 nm that is smaller than optimal. The room temperature spectra of the microlaser without and with 170 nm Si nanosphere are shown in figure 3. We also do not observe any difference in the threshold power, and quality factor of the modes.

![SEM image of the 6-\(\mu\text{m}\) microdisk with a 170 nm in diameter nanosphere](image2.png)

**Figure 2.** SEM of the 6-\(\mu\text{m}\) microdisk with a 170 nm in diameter nanosphere.
Figure 3. The room temperature µPL spectra of the microlaser without and with 170 nm Si nanosphere obtained at optical power $P \sim 1.5P_{th}$. The spectra are vertically shifted for clarity.

From the calculation of the coupling parameters of the Si nanosphere and 6-μm microdisk resonator optimal diameter of the single Si nanosphere was found to be 300 nm. In order to influence the high quality $TE_{39,1}$ WGM with low radial index the nanosphere was placed near the maximum of its electric field and the distance between the Si nanosphere center and the microdisk edge was 480 nm. Figure 4 demonstrates the room temperature spectra of the 6-μm microlaser without and with 300 nm Si nanosphere. After the placing of the Si nanosphere with optimal size the enhancement of the $TE_{39,1}$ WGM line at 1294 nm intensity is observed.

Figure 4. The room temperature µPL spectra of the microlaser without and with 300 nm Si nanosphere obtained at optical power $P \sim 2P_{th}$. 
We studied the dependence of the intensity of the WGM line TE$_{39,1}$ at $\lambda=1294$ nm on the pump power of the same microdisk laser without Si nanosphere and with Si nanosphere (figure 5). More than 20-times increase of the line intensity (at the pump power $\sim$2$P_\text{th}$) provided by Si microsphere-enhanced scattering is observed. The threshold pump power and line full-width remains the same $P_\text{th}$=0.3 mW, FWHM=30 pm (within the setup resolution).

![Figure 5. The dependence of the intensity of the WGM line at $\lambda=1294$ nm on the pump power.](image)

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Figure 6 (a) and (b) demonstrates the spatial distributions of the lasing WGM TE$_{39,1}$ line intensity of the initial microdisk and microdisk with nanosphere. The initial microdisk demonstrates nearly isotropic emission distribution with some modulation in azimuthal direction due to the light scattering at the microdisk surface roughness due to technology imperfections. Light distribution from the microdisk with nano-antenna is highly directional. The maximum of the intensity is observed at the Si microsphere position resulting in a highly directional far field emission ($\sim$38°). The other modes of the microdisk resonated that are not coupled to the Si microsphere demonstrate the random spatial distribution of the intensity mainly governed by the scattering on the surface roughness.

![Figure 6. The distribution of the WGM line intensity ($\lambda=1294$ nm) in microlaser without (a) and with Si nanosphere on the top surface (b).](image)
To conclude we demonstrated the method of enhancement of a dominant mode intensity by means of a Si nanosphere placed at the top of the microdisk laser. Using Si nanosphere with optimized size of 300 nm we achieved more than 20-times increase of the WGM line intensity enhancement by 20 times in room-temperature spectra of 6-µm-diameter QD microdisk. The azimuthal emission intensity distribution for microdisk cavity with Si nanosphere is built and divergence angle at half height of maximum intensity is about 38°, which corresponds to a highly directional far field emission.

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