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Directional output emission from ring microlasers with broken rotational symmetry

© *D.A. Masyutin*[1], *E.I. Moiseev*[1], *S.D. Komarov*[1], *S.A. Mintairov*[2,3], *N.A. Kalyuzhnyy*[2,3], *Yu.A. Saliy*[2], *M.M. Kulagina*[2], *F.I. Zubov*[3], *R.A. Khabibullin*[4], *R.R. Galiev*[4], *A.Yu. Pavlov*[4], *K.N. Tomosh*[4], *N.V. Kryzhanovskaya*[1], *A.E. Zhukov*[1]

[1] HSE University, St. Petersburg, Russia
[2] Ioffe Institute, St. Petersburg, Russia
[3] Alferov University, St. Petersburg, Russia
[4] National Research Center „Kurchatov Institute“, Moscow, Russia
E-mail: dmasyutin@hse.ru

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Injection semiconductor microlasers with a 15 μm-radius ring resonator and an asymmetrically positioned internal resonator aperture are studied. It is shown that the asymmetry results in the formation of two directional radiation lobes in the radiation pattern, misaligned by 50 degrees relative to the internal aperture's offset axis. The measured Q-factor of the resonators is comparable to that of disk resonators and is at a level of $\sim 10^6$.

Keywords: microlasers, ring resonator, InGaAs/GaAs quantum dots, directed emission, quality factor.

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Semiconductor disk microlasers supporting optical whispering gallery modes (WGMs) reach high Q-factors at sizes ranging from a few micrometers to several tens of micrometers and are regarded as candidate components of quantum optical communication systems [1], photonic integrated circuits [2], highly sensitive sensors [3], and optical gyroscopes [4]. However, rotational symmetry of a disk implies isotropic emission into free space, whereas a number of applications (e.g., single photon sources, photonic integrated circuits) require directional emission. Various approaches to obtaining directional emission in disk lasers (point scatterer [5], line defect [6], optical nanoantennas [7]) have been proposed. An alternative approach is to use resonators of asymmetric shapes (spiral [8], rounded triangle [9], racetrack microring [10], limacon [11]). Methods [5–7] are ill-suited for batch fabrication. Methods [8–10] are characterized by a low Q-factor (Q) and, in most cases, a high lasing threshold (due to resonator deformation). Directional emission with a high Q-factor was demonstrated for the method detailed in [11]; however, both Pascal's snail and disk geometries are characterized by the presence of an internal region in the resonator that does not contribute to WGM lasing [12]. A technique for producing asymmetric microresonators with a ring geometry and an asymmetrically positioned internal aperture, which ensures the formation of high-Q modes and directional emission, was proposed in [13,14]. In the present study, we examine experimentally the operation of continuous-wave high-Q injection microlasers with an asymmetric resonator geometry and $In_{0.4}Ga_{0.6}As$/GaAs quantum dots in the active region.

The epitaxial structure was synthesized by metalorganic vapour-phase epitaxy on an n^+-GaAs substrate misoriented by 6° relative to the (100) plane. The active medium consisted of five layers of $In_{0.4}Ga_{0.6}As$/GaAs quantum dots in a waveguide GaAs layer with a total thickness of 0.79 μm. Emitter $Al_{0.39}Ga_{0.61}As$ layers with a thickness of 1.5 μm were doped with silicon (n layer) and zinc (p layer). The contact p^+-GaAs layer was doped to a level of $10^{19}\,\mathrm{cm}^{-3}$. Microresonators 30 μm in diameter were formed by electron lithography and plasma-chemical etching of deep cylindrical mesas. An aperture $d = 10\,\mu$m in diameter was made inside the cylinder; the distance from the edge of the resonator to the aperture was 5 μm (see the inset in Fig. 1, a). Microdisk lasers without an internal aperture were also manufactured for comparison. The mesa etching depth was 4 μm. Top ohmic contacts to p^+-GaAs were formed using AgMn/Ni/Au metallization and had a ring shape. The bottom solid contact to the n^+ substrate was formed using AuGe/Ni/Au metallization. The GaAs substrate with microlasers was then divided into individual chips.

Chips with individual microlasers were soldered with their n-contact onto a copper heat sink and tested in continuous-wave operation. A Keithley 2401 power supply was used for electrical pumping. Needle probes provided electrical connections. A Mitutoyo Plan Apo NIR 20X microobjective was used to collect microlaser radiation. Electroluminescence spectra were recorded with a Yokogawa AQ6370C optical spectrum analyzer. The spectral line width was measured using a setup based on a Thorlabs SA210-8B Fabry–Pérot interferometer with a spectral resolution of 67 MHz. The absolute value of optical power was estimated using a Thorlabs S132C photodiode

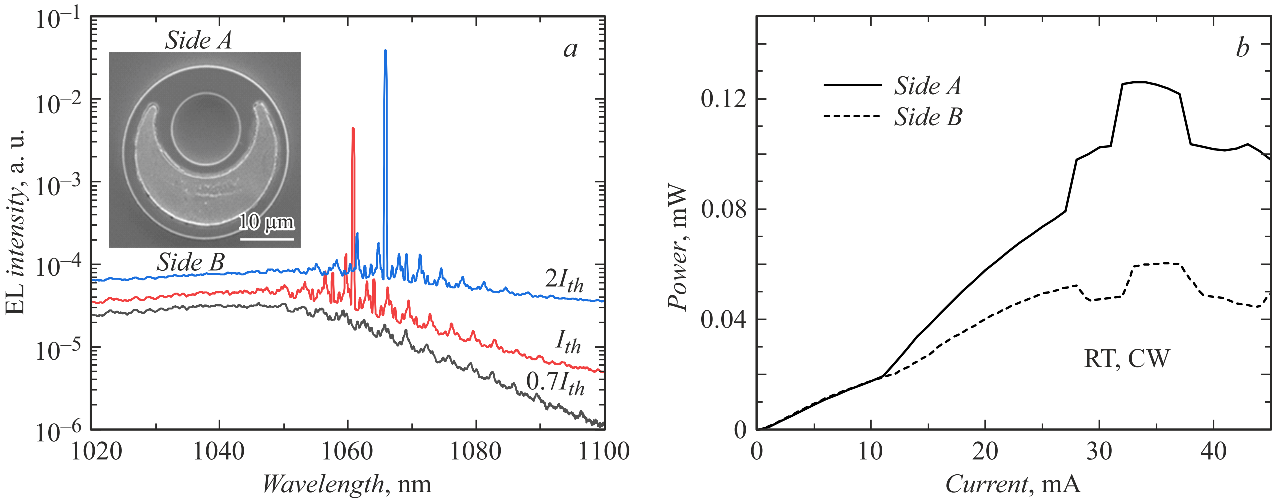

Figure 1. *a* — Electroluminescence spectra of a microring with an aperture obtained at different pump currents; *b* — watt–ampere dependence measured from the aperture side (solid line) and from the opposite side (dashed line). The scanning electron microscope image of the ring microlaser is shown in the inset.

positioned at a distance of 4 mm from the tested microlaser. The distribution of optical power over the azimuthal angle was measured by rotating the sample around the axis and recording the optical power with the photodiode; the angular resolution was set to $\sim 0.3^\circ$ by a diaphragm limiting the photodiode aperture.

Figure 1, *a* shows the electroluminescence spectra of the microlaser with an aperture. The lasing line is positioned at 1060 nm and is close to the maximum of spontaneous electroluminescence of $\mathrm{In_{0.4}Ga_{0.6}As/GaAs}$ quantum dots. The lasing threshold current was determined to be $I_{th} = 11$ mA by finding the knee of the watt–ampere dependence (Fig. 1, *b*). As the pump current increased, the lasing line shifted toward longer wavelengths due to self-heating of the laser. Owing to an increase in temperature of the active medium and narrowing of the band gap of the InGaAs/GaAs layers, an increase in pump current leads to intensification of spontaneous electroluminescence within the wavelength range of 1080–1100 nm, which is seen in Fig. 1. The optical power increases through to an injection current of 35 mA and is limited by self-heating of the laser at higher currents. The maximum value of optical power on the side of the aperture is 2.5 times greater (Fig. 1, *b*) than on the opposite side.

A more detailed study of the power distribution over the azimuthal angle of detector positioning (β) relative to the aperture offset axis was then performed for the disk laser with rotational symmetry (μ-disk) and the asymmetric ring microlaser (μ-ring) (Fig. 2, *a*). It can be seen that radiation of the ring features two intense lobes at $\pm 50^\circ$, while the radiation pattern of the disk has no preferential emission directions; its local radiation maxima are associated with scattering on the roughness of the lateral surface. The dip in laser intensity observed near -90° corresponds to the shadow of the needle probe used to connect the laser to the power supply.

The experimental dependence of the lasing line width for the asymmetric ring microlaser on pump current has two distinct sections (Fig. 2, *b*): in the first section, the emission line width decreases sharply with increasing pump current due to the transition to lasing; in the second section, the width increases slowly under the influence of various factors, which include heating, an increase in density of carriers and photons in the microresonator, etc. [15]. The dependence of spectral width of the laser line on pump current for the disk microlaser is shown for comparison. The laser line width is approximately 170–200 MHz near the threshold for both symmetric and asymmetric resonator shapes, which is close to values obtained in other high-resolution spectroscopy studies of disk microlasers of the same diameter [16]. The Q-factor of the directional ring resonator was estimated at $\sim 10^6$ as the ratio of the wavelength to its width. The obtained result demonstrates that the formation of an offset aperture of this geometry in a microresonator does not lead to broadening of the laser line and does not reduce the Q-factor.

Thus, microlasers with an active region based on InGaAs/GaAs quantum dots and a ring resonator with an aperture offset from the center were investigated. It was demonstrated that the introduction of asymmetry into the resonator geometry provides an opportunity to obtain directional emission on the side of the aperture. The directional pattern features two intense lobes at approximately $\pm 50^\circ$, and the lasing threshold and the Q-factor are not inferior to those measured for disk microlasers with a symmetric resonator; the Q-factor is at least 10^6. The obtained results verify the possibility of constructing compact microlasers with controlled emission direction and no reduction in

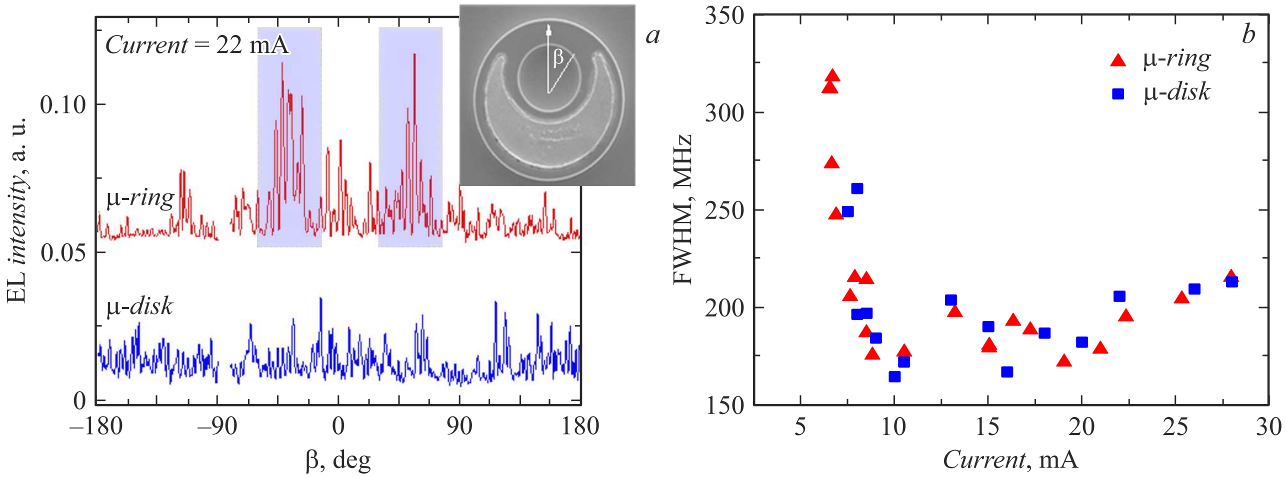

Figure 2. *a* — Far-field azimuthal profile for disk (lower curve) and ring (upper curve) microlasers (shifted along the vertical axis for clarity); *b* — dependence of the laser line width on current.

Q-factor, highlighting the potential for their application as active components of photonic integrated circuits.

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Conflict of interest

The authors declare that they have no conflict of interest.

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