

## Study of the emission from a microdisk laser monolithically integrated with an optical waveguide

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The power and spectral characteristics of the radiation of a semiconductor microdisk laser with a diameter of 40  $\mu\text{m}$ , monolithically integrated with an optical waveguide, have been studied. To reduce absorption in the waveguide, current pumping was used. In the light–current dependence, features associated with the onset of generation at a longer-wavelength resonance are observed. When this resonance falls within the region of weak waveguide absorption, an increase in output power is observed. Applying a forward bias to the waveguide makes it possible to increase the extracted power by more than 1.5 times.

**Keywords:** whispering gallery modes, microdisk laser, conjugate waveguide, mode switching.

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Recently, the implementation of photonic integrated circuits based on GaAs has attracted increasing interest, since it is possible to create efficient sources and receivers of optical signals based on this system of materials [1]. Microdisc (MD) lasers with high quality ( $\sim 10^5$ ) and small sizes up to units of microns can be used as signal sources [2]. To realize the directional transmission of MD radiation, the laser can be evanescently coupled to an optical waveguide (WG). At the same time, both the MD laser and the WG can be made from a single epitaxial heterostructure, which increases positioning accuracy and simplifies the technological process compared to heterogeneous integration (see, for example, [3]). It is worth noting that the presence of an active region in this case leads to partial absorption of the MD laser radiation propagating in it. This effect significantly affects the spectral and power characteristics of the light coming from the end of the WG, and can be compensated by additional WG pumping. The output of MD laser radiation through a conjugate WG was studied in this paper at various WG pumping currents.

The studied heterostructure was obtained by the method of metalorganic vapour-phase epitaxy on a  $n^+$ -GaAs substrate. 5 layers of  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$  quantum dots were used as the active region. An MD laser with a diameter of 40  $\mu\text{m}$  and an adjacent WG with a length of  $\sim 440 \mu\text{m}$  were formed using electron lithography and plasma reactive ion etching from the same heterostructure and thus possessed the same active region. The gap between the WG and MD was 200 nm. Isolated ohmic contacts to the  $p^+$ -GaAs layer were formed on the tops of the laser and on the waveguide

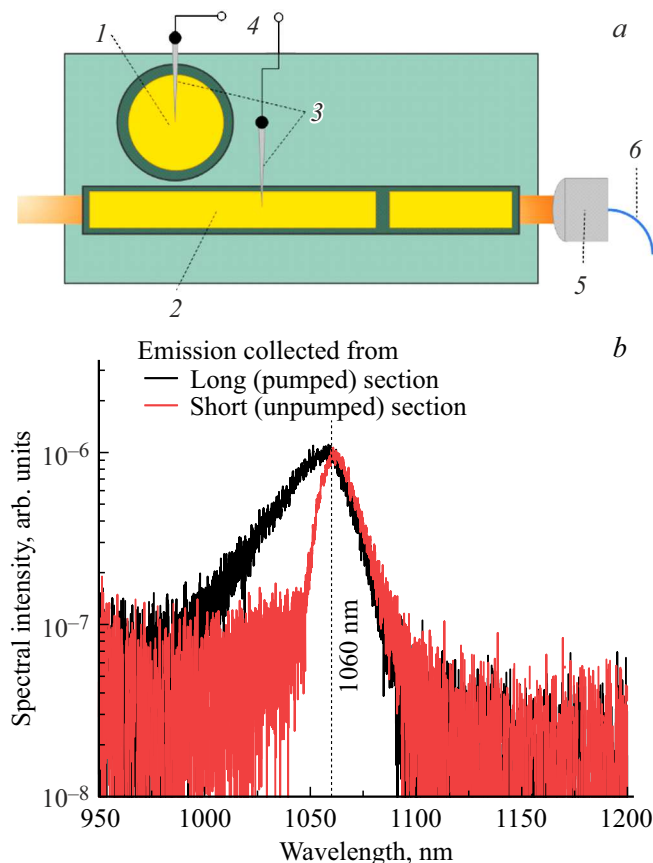
using photolithography and AgMn/Ni/Au metallization. The WG contact was divided by a focused ion beam into two sections in a ratio of 3/1: a long section near the MD laser and a short section at a distance from the MD (see Figure 1, *a*). The incision width was  $\sim 10 \mu\text{m}$ . The substrate was thinned to  $\sim 100 \mu\text{m}$ , then AuGe/Ni/Au metallization was applied to its lower face, which served as a  $n$ -contact.

During the experiment, a needle-shaped tungsten probe was connected to the  $p$ -contact of the structure to carry out electrical pumping (see Figure 1, *a*). The structure was located on the copper heat sink with  $n$ -contact down, so that it was in contact with the surface of the heat sink, to which a common wire was connected to close the circuit. All the MD lasers studied operated at room temperature in a continuous pumping mode. The optical signal was recorded directly from the MD laser, as well as from the end of the WG connected to it using a Mitutoyo x20 micro objective, after which the signal was transmitted via fiber to either the Thorlabs S155C power meter or the Yokogawa AQ 6370C optical spectrum analyzer.

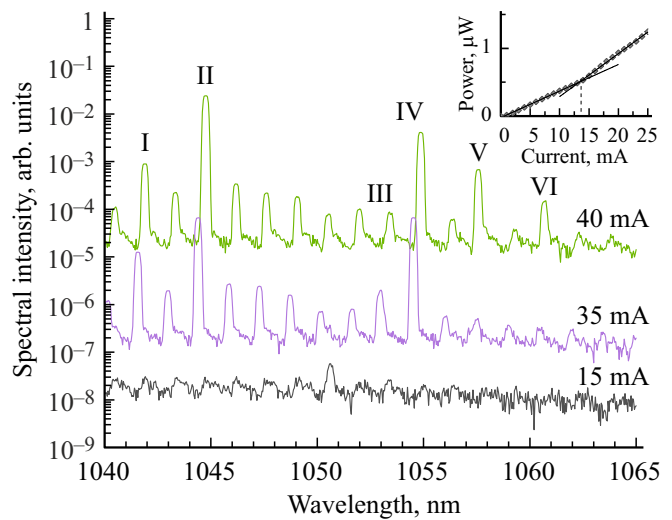
First, the radiation output of the WG itself from different ends was investigated when a pumping current was applied to its long section, while the MD remained un-pumped. In the studied current range from 0 to 75 mA, laser generation in the WG, which is a Fabry-Perot resonator, was not observed. Typical electroluminescence spectra (EL) obtained at a pumping current of 10 mA from different ends of a WG are shown in Figure 1, *b*. The EL spectra of quantum dots (QDs) are broadened due to the statistical distribution of the

size of the dots (the so-called inhomogeneous broadening), the half-width of the EL line is 32 meV for radiation collected from the end of the long section and 19.5 meV for radiation collected from the end of the short section. When detecting light from a short section, light is absorbed by the active region of this section, which manifests itself on the EL spectra in the form of a sharp decrease in intensity with an absorption edge at  $\lambda = 1060$  nm. The absorption edge does not depend on the pumping current of the WG long section. These results are consistent with previous studies of the absorption spectrum of  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$  quantum dots, presented in the Ref. [4].

Next, a study of the laser generation of an MD laser was performed. Figure 2 shows the spectra of the electron microlaser when focusing the lens collecting radiation on the side surface of the laser. The threshold current of the studied MD laser was determined to be 13.67 mA. At this current, a narrow resonance occurs on the EL spectrum, corresponding to the whispering gallery mode (WGM) with wavelength of  $\lambda \approx 1050$  nm, and an inflection is recorded on the watt-ampere characteristic (WAC), confirm-



**Figure 1.** Connection diagram for current-carrying probes and radiation collection *a*: 1 — MD, 2 — WG with two contact sections, 3 — current-carrying probes, 4 — terminals to current sources, 5 — micro objective, 6 — optical fiber. *b* — WG EL spectra from two ends obtained at a pumping current of a WG long section of 10 mA.



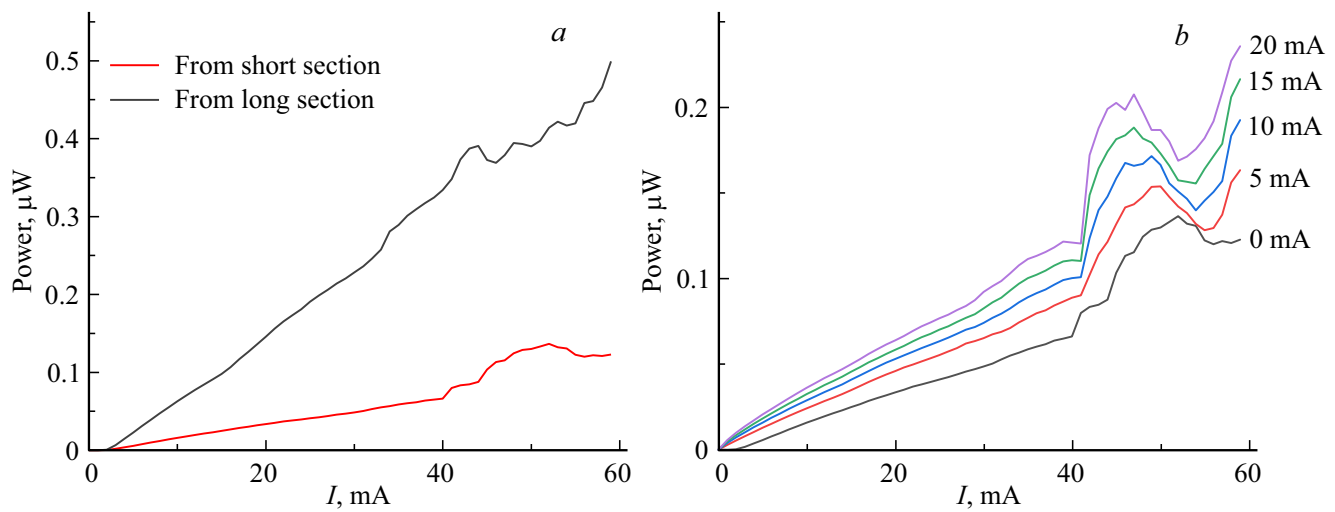
**Figure 2.** MD laser generation spectra in free space at different pumping currents. The spectra are shifted for easier reading. Roman numerals indicate the most intense modes. WAC near 15 mA is shown in the insert.

ing the transition to the laser generation mode (see insert on Figure 2). As the pump current increases, equidistant resonances occur in the spectra and the laser switches to a multimode generation regime.

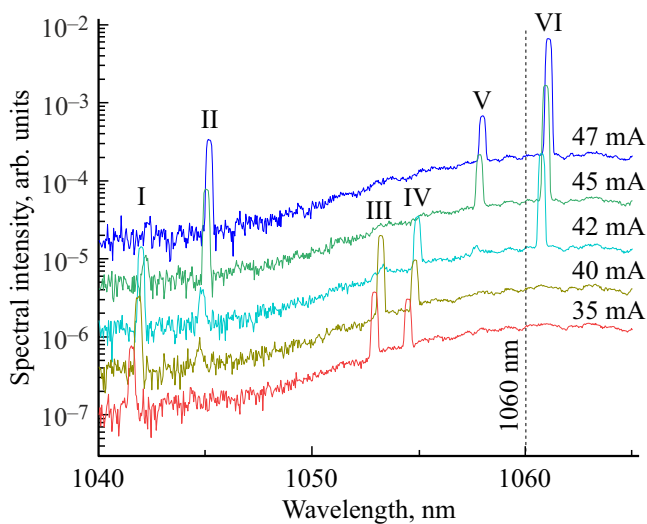
Next, the watt-ampere characteristics of the MD laser were obtained from different ends of the WG in the range of laser pump currents of 0–60 mA (Figure 3, *a*). An increase in output power is observed at the pump current of the microlaser  $\sim 40$  mA on the WAC obtained from the end of the short WG section, whereas on the opposite side this effect is less pronounced. Then, the WAC from the side of the short section of the WG was studied when an electric current was applied to the long section of the WG to reduce the absorption of the active region. The radiation level at zero pump current of the laser, due only to spontaneous emission of WG, was set as zero level for each curve. With an increase in the WG pump current (Figure 3, *b*), the magnitude of the indicated jump on the WAC increased in the same way as the total output optical power of the MD laser. To explain this effect, the spectral composition of the radiation emitted from the end of the WG was studied.

The MD laser EL spectra from the end of the WG were studied at pumping currents of the long WG section from 0 to 20 mA. The features on the WAC obtained from the short end of the WG at a current of MD slightly above 40 mA correspond to the appearance in the EL spectra of an intense laser line at a wavelength of  $> 1060$  nm (Figure 4), which is in the spectral range of weak absorption of radiation from the active region in the waveguide.

Thus, the spectral and power characteristics of MD laser radiation propagating along a monolithically integrated WG are studied in this paper. An increase in radiation intensity at the MD pumping current of 40 mA was detected on the WAC obtained from the end of the WG section without



**Figure 3.** *a* — WAC of the MD laser obtained from different sides of the WG, without pumping the WG. *b* — WAC of the MD laser minus the intensity of spontaneous emission of the WG obtained from the short section of the WG at different pumping levels of the long section (indicated to the right of the curves).



**Figure 4.** The emission spectra of an MD laser collected from the side of a short WG section at different MD pumping currents. WG pump current is 10 mA. The spectra are shifted for clarity. The mode designations correspond to the designations in Figure 2.

pumping. The detected features on the WAC are explained by the appearance of a laser mode in the optical spectrum of the microlaser at a wavelength of  $> 1060$  nm, which corresponds to the spectral region of weak absorption of QD. The application of voltage to the WG made it possible to increase the output optical power by 1.52 times.

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## Conflict of interest

The authors declare that they have no conflict of interest.

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