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Monolithic integration of InGaAs/GaAs quantum dot microdisk lasers with optical transparent waveguides

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Received May 29, 2025
Revised June 30, 2025
Accepted July 1, 2025

Directional output of microdisk laser radiation through a coupled optical waveguide made of the same heterostructure was investigated. Disks with diameters of 30 and 40 μm with an active region based on InGaAs/GaAs quantum dots were used. Forward bias was applied to the waveguide to reduce absorption losses. At a current value in the waveguide of about 60 mA, a sharp (almost an order of magnitude) increase in the output optical power of the microlaser was observed, which we associate with the achievement of the state of optical transparency of the waveguide.

Keywords: microdisk lasers, quantum dots, optical waveguide, photonic integrated circuits.

DOI: 10.61011/TPL.2025.10.62104.20390

The fabrication of photonic integrated circuits (PICs) with the use of semiconductors based on A_3B_5 compounds has recently attracted a significant amount of interest, since it provides an opportunity to combine both classical PIC components (waveguides, splitters, interferometers, etc.) and active elements (radiation sources, receivers) on a single platform [1]. Microdisk (MD) lasers with an active region based on A_3B_5 quantum dots (QDs) are compact, have a high Q factor, and offer the possibility of lateral radiation output, which makes them promising for application as radiation sources in PICs [2]. However, such microlasers have no preferred direction in the radiation pattern, since their cavities are axially symmetric. Directional output of MD laser radiation may be achieved via coupling to lateral optical waveguides (OWs) [3]. In this case, an MD laser and a waveguide may be made from a single heterostructure and form an elementary PIC unit [4]. However, since OWs and MD lasers have the same active region, radiation will be absorbed in the process of propagation along an OW. This effect reduces significantly the power of microlaser radiation output through an OW [4]. When forward bias is applied to an OW, the electron-hole states are occupied gradually and, consequently, the absorption of MD laser radiation is suppressed. With a certain pumping, the state of OW transparency at the microlaser radiation wavelength may be reached. This possibility and the potential for radiation amplification in A_3B_5-waveguides integrated with microlasers have not been investigated yet. In the present study, we examine the influence of waveguide transmission augmentation on the spectral and power characteristics of output radiation of an MD laser coupled to an OW.

Metalorganic vapor phase epitaxy was used to synthesize the heterostructure. Epitaxial growth was performed on an n^+-GaAs substrate misoriented by 6° relative to the (100) plane. The heterostructure included an n^+-GaAs buffer layer, an n-AlGaAs bottom emitter layer 1.5 μm in thickness with a doping level of $7 \cdot 10^{17}\,\mathrm{cm}^{-3}$, an undoped GaAs waveguide layer with a thickness of 0.75 μm, a p-AlGaAs ($7 \cdot 10^{17}\,\mathrm{cm}^{-3}$) top emitter layer 1.5 μm in thickness, and a p^{++}-GaAs contact layer 0.35 μm in thickness. The molar fraction of AlAs in AlGaAs layers was 40 %. The active region consisted of five InGaAs/GaAs QD layers and was located in the middle of the waveguide layer. The QD layers were formed by depositing $In_{0.4}Ga_{0.6}As$ (2 nm) layers separated by 40-nm-thick GaAs spacers. MD lasers with a diameter of 30 and 40 μm and OWs with a length of 440 μm and a width of 10 μm were formed using electron lithography (Raith Voyager) and inductively coupled plasma reactive ion etching (ICP-RIE Sentech SI500). The distance between the side faces of MD lasers and OWs was on the order of 100 nm. These processes were detailed in [5]. AgMn/Ni/Au metallization to the p^{++}-GaAs contact layer was used to form p-contacts. The contacts to OWs had the shape of 8-μm-wide strips, while the contacts to MD lasers were circular and had a diameter 2 μm smaller than the microdisk diameter. The GaAs substrate was thinned and an AuGe/Ni/Au n-contact was deposited onto its back side. To suppress OW lasing at the Fabry–Pérot modes, the OW ends were beveled at an angle of $\sim 15^\circ$ by etching with a focused ion beam.

Microchips were cut out from a wafer containing formed MD lasers and OWs and soldered with the p-contact facing up onto a copper heat sink. Needle-shaped tungsten microprobes with a diameter of 15 μm were used to establish contact with the top electrodes of MD lasers and OWs. A Keithley 2400 Series SourceMeter® served

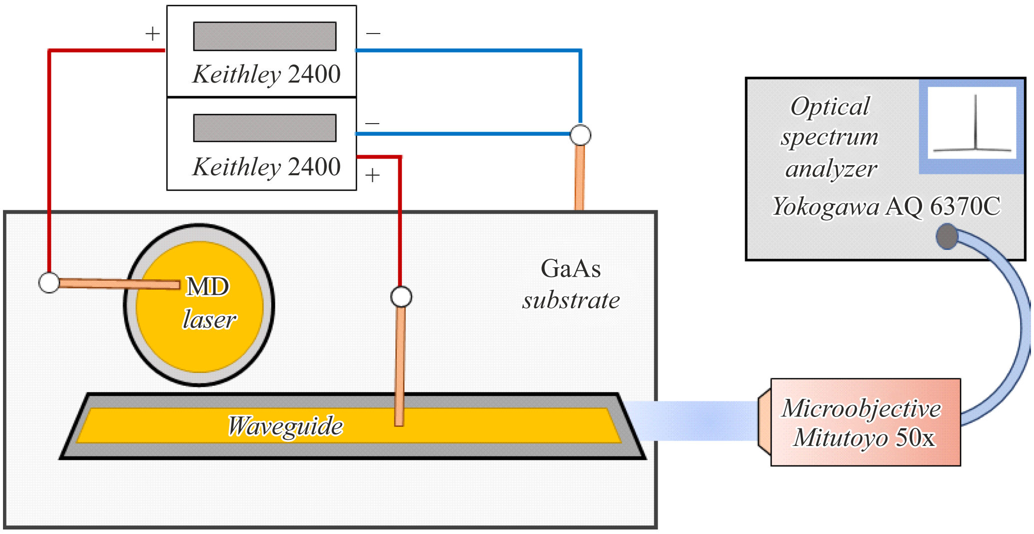

Figure 1. Diagram of the experimental setup.

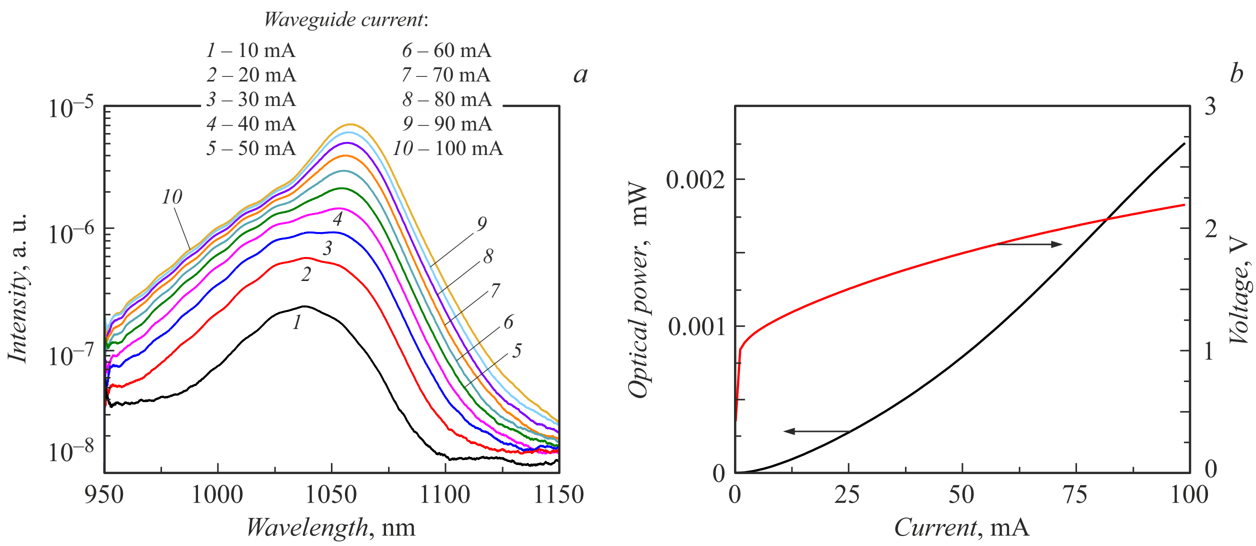

Figure 2. *a* — OW EL spectra at various pumping currents; *b* — dependence of the optical power of the OW on the pumping current and its CVC.

as a current source. Radiation was collected in the MD laser emission plane by a Mitutoyo M Plan Apo NIR HR 20× objective with focusing onto the OW end. A Yokogawa AQ 6370C optical spectrum analyzer was used to detect radiation. The optical power was measured with a Thorlabs PM100D meter to which radiation collected by the microobjective was fed through an optical fiber. The diagram of the experimental setup is shown in Fig. 1.

Electroluminescence (EL) spectra from the OW end recorded at room temperature with continuous pumping of the OW only were examined first (Fig. 2, *a*). Spontaneous emission of InGaAs/GaAs QDs is seen in the spectra. The EL intensity and optical power increase with current (Fig. 2, *b*), but beveled edges suppress the transition to lasing. The spectral maximum shifts from 1035 nm at a pumping current of 10 mA to 1055 nm at a pumping current of 100 mA, which is attributable to OW heating. The current–voltage curve (CVC) of the OW has the shape of a typical diode CVC and has no noticeable features (Fig. 2, *b*).

Radiation of microlasers from the ends of waveguides was then studied at room temperature in the continuous mode with zero OW current (Fig. 3). The threshold currents of microlasers with a diameter of 40 μm and 30 μm were close to 13 mA and 20 mA, respectively. The onset of lasing was observed at wavelengths near 1056 nm (for the MD laser with a diameter of 30 μm) or within the 1052–1057 nm range (for the MD laser 40 μm in diameter). The MD lasers 30 μm in diameter coupled with OWs provided predominantly single-mode lasing (Fig. 3, *b*), while the 40 μm microlasers had a larger number of laser modes in

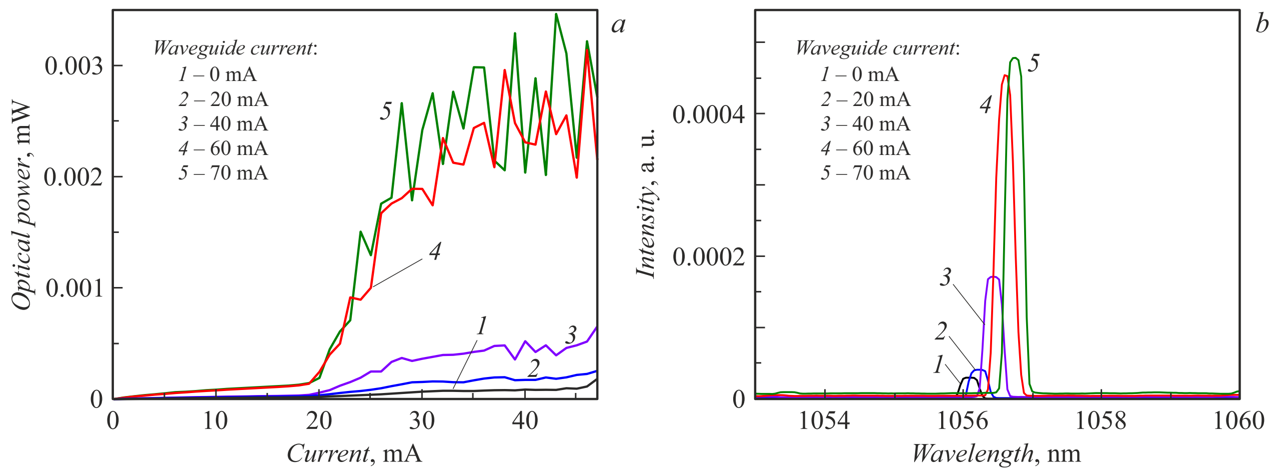

Figure 3. *a* — Dependences of the optical power of the MD laser with a diameter of 30 μm on the pumping current at various OW currents. *b* — EL spectra of the 30 μm MD laser at a pumping current of 30 mA recorded from the beveled OW ends at various OW currents.

the spectrum, which is consistent with the results of earlier spectral studies of MD lasers of a similar design [4].

This was followed by the study of MD laser power output from the ends of coupled OWs at different pumping currents of the latter (Fig. 3, *a*). When the MD laser current is zero and a non-zero forward bias is applied to the OW, the detected power is composed exclusively of the optical power of the OW itself. In order to exclude its contribution, the value of optical power determined at zero microlaser current was taken as zero.

The lasing threshold for MD lasers with a diameter of 30 μm, which was determined by the emergence of narrow laser modes in the emission spectrum, also manifests itself as a characteristic knee in the watt–ampere characteristic (WAC). An increase in OW pumping current has virtually no effect on the lasing threshold. The lasing threshold cannot be distinguished in the WAC for MD lasers with a diameter of 40 μms, which is attributable to a large contribution of spontaneous emission.

The output optical power of MD lasers of both diameters increased gradually with increasing OW pumping current. When the current applied to the OW was raised to 60 mA, the output optical power of all the examined samples increased sharply by almost an order of magnitude. A further increase in OW current did not lead to any noticeable enhancement of the output optical power of the MD laser. We attribute this effect to the state of transparency reached in the OW and the emergence of amplification in it. Thus, the current required to achieve optical transparency of the used OWs with beveled ends is on the order of 60 mA, which is comparable to the pumping current of the MD laser itself.

EL spectra of the studied MD lasers were recorded from the OW ends at different waveguide pumping currents (from 0 to 70 mA) (Fig. 3, *b*). It is evident that the spectra are dominated by laser resonance lines and the contribution of EL of the OW itself is insignificant. We believe that the wavelength shift of laser modes with an increase in current through the waveguide is associated with additional heating of microlasers. Since the distance between the side faces of MD lasers and OWs is quite small, the OW heating induced by an increase in pumping current leads also to heating of the MD laser coupled with it. This additional heating of the microlaser was evaluated based on the lasing wavelength shift, and it was found that MD lasers with a diameter of 30 and 40 μm are heated by 9 and 7 °C, respectively, as the OW pumping current increases from 0 to 70 mA. Note that the mode composition of EL spectra of microlasers remains unchanged in this case.

Directional output of radiation from MD lasers based on InGaAs/GaAs quantum dots through a coupled optical waveguide made from the same heterostructure was studied. In order to reduce absorption losses in OWs, a forward bias was applied to them. The OW lasing was suppressed by beveling their end faces at an angle of $\sim 15^\circ$ via focused ion beam etching. When a current of approximately 60 mA was applied to OWs, the output optical power of microlasers increased sharply by almost an order of magnitude, which is attributable to reaching the state of waveguide transparency.

Funding

This study was carried out as part of the Fundamental Research Program of the National Research University Higher School of Economics.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin