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Current- and light-controlled switching of lasing wavelengths in InAs/InGaAs/GaAs quantum dot lasers for application in neuromorphic photonics

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Influence of the optical pumping by light with wavelength of 1260 nm on the spectra of lasers, based on InAs/GaAs quantum dots operating on the ground state (1260 nm), the excited state (1180 nm), as well as on the both of these states simultaneously (two-state lasing) was investigated. Pumping by the ground state radiation does not change the lasing mode of the devices, which also emit on ground state, but results in a suppression of the excited state lasing. The greater lasing intensity via the excited state, the greater optical injection power is required to suppress it.

Keywords: laser, two-state lasing, quantum dots.

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The design of optical integrated circuits simulating the behavior of optical neurons is attracting considerable attention at present. Optoelectronic devices have the capacity to produce effects similar to neural excitability or periodic bursts (spikes) [1,2] under optical or electron injection. The prospects of application of quantum dot (QD) lasers in neuromorphic photonic circuits appear to be extremely optimistic [3–5]. In such lasers, switching between the ground state (GS) lasing mode with an emission wavelength of 1260−1300 nm and the excited state (ES) lasing mode with an emission wavelength of 1180−1220 nm under the influence of optical injection provides an opportunity to simulate both excitatory and inhibitory neurons. For example, one may associate pulses from the long-wave spectral range (GS of QDs) with signals of nervous excitation and pulses from the short-wave spectral range (ES of QDs) with inhibitory signals.

The feasibility of an all-optical neuromorphic circuit based on InAs/InGaAs/GaAs QD semiconductor lasers has been demonstrated recently [3]. However, the optical setup proposed by the authors of [3] is extremely hard to implement in an integrated form, since it includes optical isolators, filters, and lenses. In the present study, we investigate the switching of lasing modes in optically coupled pairs of QD lasers that were mounted end-to-end with a gap of several micrometers between the mirrors. This arrangement is simpler than the one proposed in [3] and is easily scalable for use in optical integrated circuits. Preliminary research results have already been published in [6]. Here, we perform an in-depth study of the influence of injection current and intensity of additional optical pumping on the lasing spectra of lasers operating via the GS, ES, and GS and ES simultaneously (two-level lasing).

The laser heterostructure was grown by molecular beam epitaxy on an n^+-GaAs (100) substrate. An n-type GaAs buffer layer 0.3 μm in thickness was grown first. This was followed by the synthesis of an n-type $Al_{0.35}Ga_{0.65}As$ bottom emitter 1.5 μm in thickness, a GaAs waveguide with a thickness of 450 nm, a p-type $Al_{0.35}Ga_{0.65}As$ top emitter 1.5 μm in thickness, and a p^+-doped GaAs contact layer 0.2 μm in thickness. The active region consisted of ten layers of InAs/InGaAs/GaAs QDs separated by 35-nm-thick GaAs spacers and positioned symmetrically relative to the waveguide center. InAs/InGaAs/GaAs QDs were synthesized as three-dimensional islands, which were obtained by InAs (0.8 nm) deposition in the Stranski–Krastanov growth mode, overgrown with a 5-nm-thick $In_{0.15}Ga_{0.85}As$ layer. The homogeneity of the QD ensemble was estimated by the half-width of the electroluminescence spectrum of a laser with a small cavity length (0.1 mm) at a low pumping current (20 mA), which was close to 50 meV and corresponded to the standard inhomogeneous broadening of self-organizing InAs/InGaAs/GaAs QDs. Edge lasers with a width of 50 μm were fabricated from the epitaxial heterostructure by optical lithography and dry etching and were then separated into individual chips of different lengths by cleaving. Laser pairs were mounted on heatsinks using a Finetech Lambda 2 bonder that ensures high alignment accuracy (Fig. 1). Continuous injection pumping was provided for each laser independently. The heatsink temperature in the experiments was stabilized at 20 °C. Laser radiation was collected by lensed optical fiber.

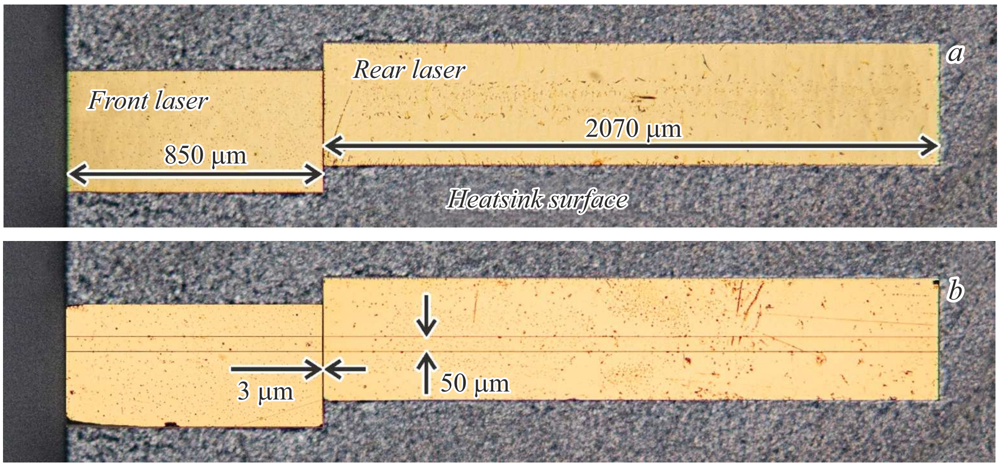

Figure 1. *a* — photographic image of optically coupled stripe lasers (top view) mounted end-to-end on a heatsink with the *p*-side down; *b* — photographic image from panel *a* with superimposed photographs of chips imaged from the *p*-side before mounting.

The lasing spectra of InAs/InGaAs/GaAs QD lasers operating in the optical range of $1.25-1.3\,\mu$m have been examined thoroughly at different cavity lengths and pumping currents in our earlier studies [7,8]. In the examined lasers with a length of more than $800\,\mu$m, lasing is initiated at GS, but ES lasing also emerges at higher currents (two-level lasing). The longer the cavity is, the higher is the two-level lasing threshold. If a laser is shorter than $800\,\mu$m, lasing is initiated via ES. In what follows, we discuss the results of experiments with three pairs of optically coupled lasers. In each pair, the laser under study is mounted at the edge of the heatsink (it is referred to as the „front laser"). The second laser is regarded as a source of optical injection (pumping) and is called the „rear laser". The length of the rear laser was $2070\,\mu$m; accordingly, its two-level lasing threshold current was high (> 4 A). In view of this, we neglect the influence of radiation of the front laser on the characteristics of the rear one and regard it as a source of stable radiation with a wavelength of 1260 nm. The threshold current of the rear laser was 190 mA, and its watt–ampere characteristic was linear up to currents above 1000 mA. Thus, the intensity of optical pumping of the front laser depended linearly on current through the rear laser.

In the first series of experiments, the length of the front laser was chosen to be $850\,\mu$m. Its thresholds of lasing via the ground and excited states were $I_{th}^{\mathrm{GS}} = 180$ mA and $I_{th}^{\mathrm{ES}} = 590$ mA, respectively. Figure 2, *a* shows the lasing spectra of the front laser (optical neuron) pumped by the rear laser. It can be seen that optical pumping of the front laser at the GS wavelength does not alter its operating mode. Only a broadening of the GS lasing line and a slight increase in its intensity are observed. Notably, the intensity of spontaneous ES emission decreases with increasing optical pumping. These effects are observed within a wide range of front laser pumping currents (from 400 to 570 mA) and optical injection powers (within the range of rear laser currents from the threshold value of 190 mA to 1000 mA) (Fig. 2, *b*). The maximum pumping current of the front laser ($I_{front} = 570$ mA) was slightly below the threshold of lasing via ES. Thus, the length of this laser and the maximum current through it were chosen so that it could switch to the two-level lasing mode under a relatively weak external influence. However, in contrast to the results reported in [3] and our previous study [6], we did not detect ES lasing at any combination of currents and optical injection intensities. It is fair to assume that lasing via ES observed at a particular current value in [3,6] is associated with overheating and/or degradation of the front laser.

In the second series of experiments, the length of the front laser was the same ($850\,\mu$m), but its current I_{front} was raised to 1500 mA, which is above the two-level lasing threshold of 590 mA. With zero optical injection ($I_{rear} = 0$), the intensities of GS and ES lasing lines are approximately equal (Fig. 3, *a*). As the optical pumping (current through the rear laser) becomes more intense, the GS intensity increases and the ES intensity decreases. In other words, lasing via ES is suppressed when the laser is pumped in the two-level mode with photons with the GS energy. This effect can be explained if we qualitatively consider the dependence of the populations of GS and ES (f_{GS} and f_{ES}, respectively) on the intensity of optical pumping. Photons injected by the rear laser raise the rate of stimulated recombination via GS in the front laser. The population of the ground state (f_{GS}) decreases as a result, enhancing the ES–GS relaxation rate that is proportional to $f_{\mathrm{ES}}(1 - f_{\mathrm{GS}})$. This leads to a reduction of f_{ES} and a corresponding reduction of the ES lasing intensity with increasing optical pumping. Figure 3, *b* illustrates the variation of intensities of the GS and ES peaks of the short laser with current through the rear laser at several values of current through the front laser. The ES lasing intensity decreases with an increase in optical injection intensity at all pumping currents through the front laser. However, the higher the current through the front laser is, the higher is the optical pumping intensity, which

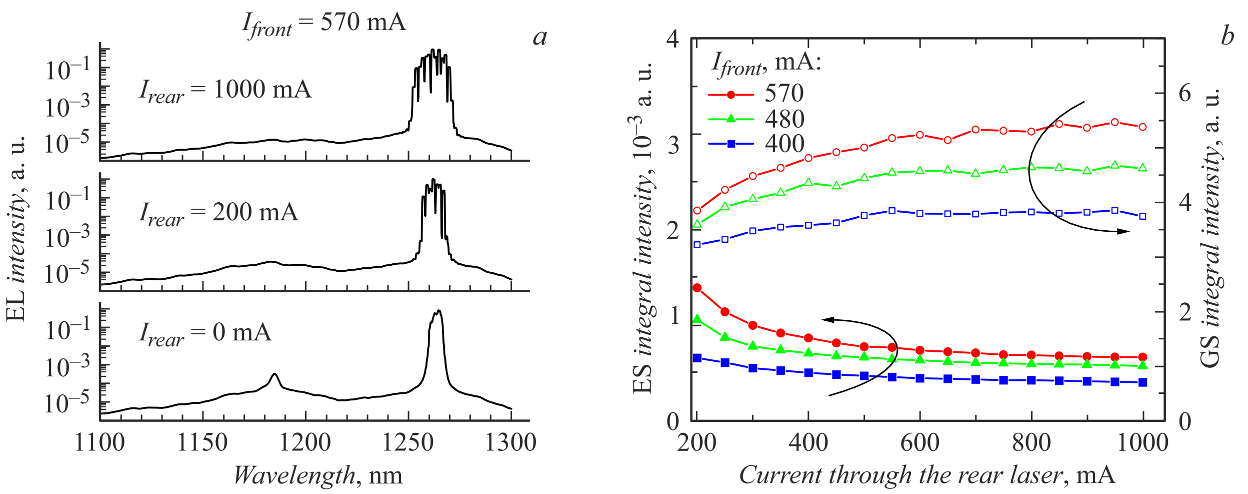

Figure 2. *a* — Lasing spectra of the front laser with a length of 850 μm at different currents through the rear laser. The front laser current (I_{front} = 570 mA) is below the two-level lasing threshold. *b* — Dependences of the GS and ES emission line intensities of the front laser on the rear laser pumping current at different currents through the front laser. I_{front} and I_{rear} are the currents through the front and rear lasers.

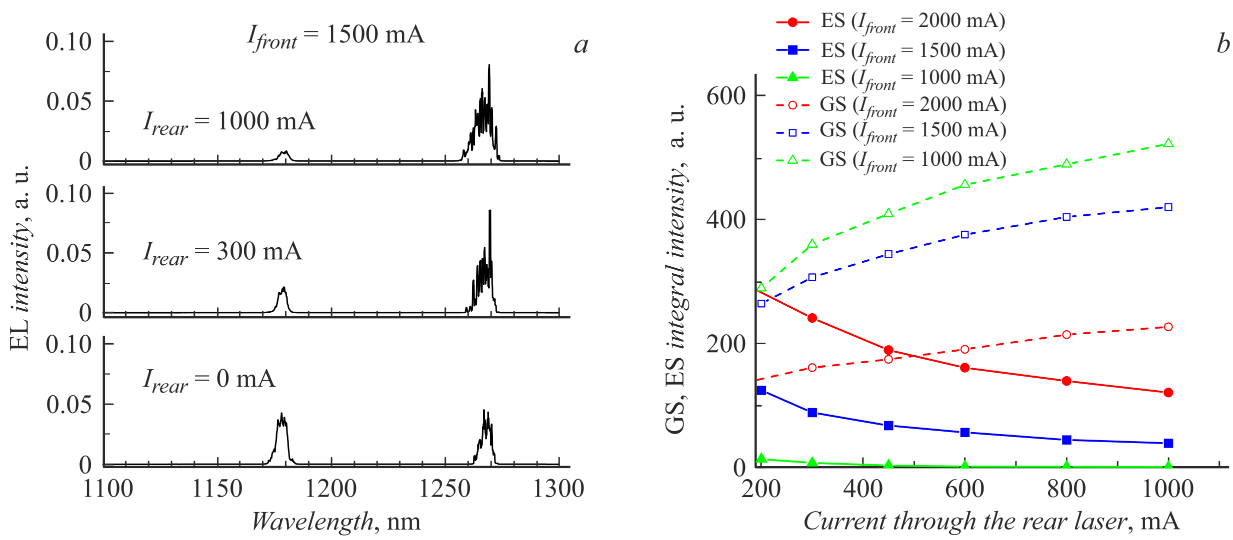

Figure 3. *a* — lasing spectra of the front laser with a length of 850 μm at different currents through the rear laser. The front laser current (I_{front} = 1500 mA) is above the two-level lasing threshold. *b* — Dependences of the GS and ES emission line intensities of the front laser on the rear laser pumping current at different currents through the front laser. I_{front} and I_{rear} are the currents through the front and rear lasers.

is specified by I_{rear}, needed to achieve the required level of ES suppression. As I_{rear} grows, the intensity of the GS peak of the front laser increases due to the transmission of radiation of the rear laser.

In the third series of experiments, the cavity length of the front laser was reduced to 750 μm. It operated in the ES lasing mode right from the start with a threshold current of 350 mA. At a current of 450 mA through the front laser, its optical pumping by the rear laser at a wavelength corresponding to GS leads first to the emergence of a GS peak in the spectrum and then to complete suppression of lasing via ES (Fig. 4, *a*). This pattern is observed at currents through the front laser ranging from 370 to 500 mA (Fig. 4, *b*). The lower the current through the front laser is, the lower are the optical injection intensities at which the ES lasing mode switches to the GS one. At a current of 370 mA, complete quenching of ES emission is observed almost immediately after switching on the rear laser. At a current of 500 mA through the short laser, the ES line does not vanish even at the maximum current through the rear laser (1000 mA). The effects seen in Fig. 4 may be explained on the same grounds as the ES intensity reduction under optical pumping in the case of two-level lasing (Fig. 3). The GS peak in the front laser emission spectrum is apparently

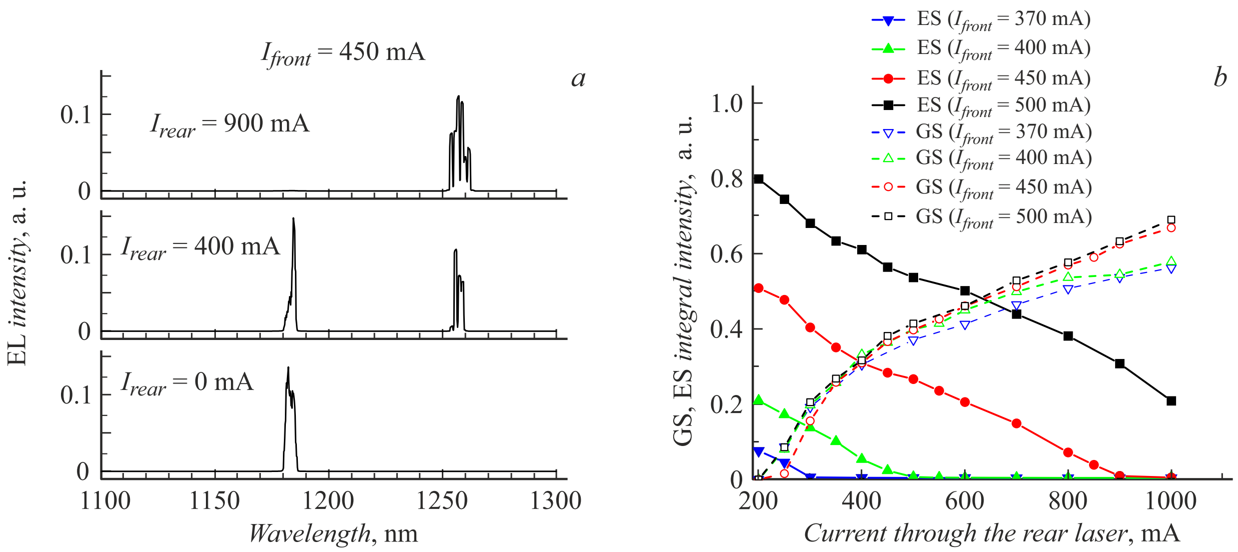

Figure 4. *a* — lasing spectra of the front laser with a length of 750 μm at different currents through the rear laser. The front laser operates in the ES lasing mode from the very start; its current is $I_{front} = 450$ mA. *b* — Dependences of the GS and ES emission line intensities of the front laser on the rear laser pumping current at different currents through the front laser. I_{front} and I_{rear} are the currents through the front and rear lasers.

associated with transmitted and amplified emission of the rear laser.

Thus, the effects of lasing mode switching in lasers based on InAs/InGaAs/GaAs quantum dots under current and additional optical pumping (with a wavelength corresponding to the ground state emission) were studied systematically. It was demonstrated that additional optical injection does not alter qualitatively the state of a laser operating in the ground state lasing mode. However, with sufficiently intense optical pumping, a laser operating in the excited-state or two-level lasing modes switches to the ground state lasing mode. The reported effects may be used to simulate biological neurons, and the simplicity of the optical circuit makes it readily applicable in integrated photonics.

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Conflict of interest

The authors declare that they have no conflict of interest.

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