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Spectral characteristics of an optically coupled pair of stripe lasers based on InAs/InGaAs/GaAs quantum dots

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Effect of an additional optical pumping on the two-state lasing in an InAs/InGaAs/GaAs quantum dot (QD) laser has been studied. Pumping has been carried out using a second QD laser mounted butt-to-butt. Additional optical injection at the wavelength of the ground state is capable of switching two-state lasing regimes, namely, starting generation at the excited state or, conversely, suppressing it, depending on the combination of currents through each of the devices.

Keywords: laser diodes, quantum dots, two-state lasing, artificial neurons.

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A method of data processing similar to that used by biological neural networks holds immense promise for solving a number of computational problems. Its advantages include an analog-digital representation of signals and combined memory and processor functions. Just like the brain, spiking neural networks encode data as events (spikes) in time rather than in bits. Since the time at which a spike occurs is analog and its amplitude is digital, a hybrid encoding scheme, where a hybrid signal has both analog and digital properties, is used to transmit such signals [1]. This encoding strategy provides an increased noise immunity [2] and potential enhancements in terms of computational efficiency [3]. Optoelectronic devices are capable of simulating effects similar to neural excitability or periodic bursts (spikes) [4] under optical or electron injection. Biological neurons come in two main types. Once activated, a neuron of the first type (excitatory) causes all connected neurons to fire. Although neurons of the second type (inhibitory) are activated by the same stimulatory pulses as excitatory ones, they emit pulses that tend to suppress the activity in all connected neurons.

Quantum dot (QD) lasers are unique in supporting lasing through the ground or excited states of QDs and both these states simultaneously [5] at relatively low levels of electron or optical injection. The feasibility of an all-optical neuromorphic circuit based on InAs/InGaAs/GaAs QD semiconductor lasers has been demonstrated recently [6]. In this study, QD lasers operating at the ground-state (GS) and excited-state (ES) lasing regimes served as inhibitory and excitatory optical neurons, respectively. Pulses at the GS wavelength of QDs were interpreted as signals of neural excitation, while pulses at the ES wavelength were regarded as inhibitory signals. It was demonstrated that switching between the regimes of lasing at GS or ES wavelengths in QD lasers under optical injection allows one to simulate both excitatory and inhibitory neurons. However, the optical circuit used in [6] was quite complex and contained a large number of elements, including an optical isolator and filters. It should also be noted that the correspondence between the lasing regimes of QD lasers and optical neurons proposed in [6] is not a priori the only possible one. Specifically, it is fair to assume that a QD laser operated in the two-state lasing regimes should also find use in neuromorphic optical networks. In the present study, we report the results of experiments on switching the lasing regimes of an injection QD laser with radiation introduced into its end directly from the end of another QD laser. The small size and relative simplicity of this setup make it promising for application in optical integrated circuits.

The aim of the study is to examine the influence of additional optical pumping (optical injection) at a wavelength of approximately 1260 nm on a laser in which lasing may proceed either through the GS (1260 nm) or through the GS and ES (1180 nm) simultaneously. The laser heterostructure was grown by molecular beam epitaxy on an n^+-GaAs (100) substrate. 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 center of a 450-nm-wide GaAs waveguide. The waveguide was bounded by *n*- and *p*-type $Al_{0.35}Ga_{0.65}As$ emitters, each with a thickness of 1.5 μm. InAs/InGaAs/GaAs QDs were synthesized by overgrowing initial three-dimensional islands, which were obtained by deposition of InAs (0.8 nm) in the Stranski–Krastanow growth mode, with a 5-nm-thick $In_{0.15}Ga_{0.85}As$ layer [7]. Standard methods of post-growth crystal processing were used to fabricate edge emitting laser chips with a stripe width of 50 μm from the heterostructure. Laser cavities were formed by cleaving, and dielectric mirrors were not deposited onto the cleaved faces. The GS and ES lasing thresholds were measured first for lasers

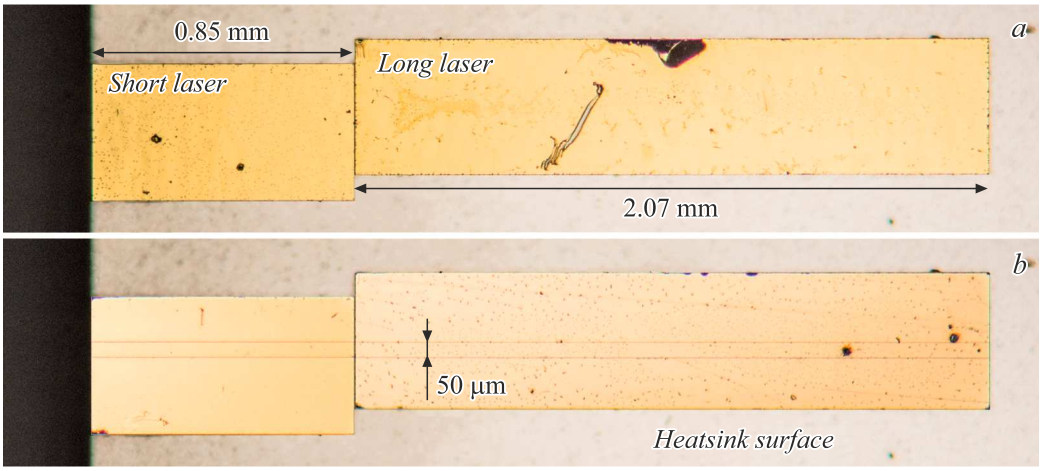

Figure 1. Images made with an optical microscope. *a* — Top view of a pair of optically coupled stripe lasers mounted on a heatsink (before wire bonding); *b* — photographs of chips taken from the *p* side before mounting are superimposed onto the image shown in the upper panel.

of different lengths, which allowed us to select the chip lengths for subsequent experiments. A 2.0-mm-long QD laser, which supported GS lasing within the entire studied range of injection currents, was used as an optical pumping source. This laser is hereinafter referred to as the „long" one. The pumped laser had a length of 0.85 mm. Its lasing was initiated through the GS, but ES lasing also emerged after a relatively small increase in injection current; i.e., two-state lasing was observed [8]. In what follows, this laser is referred to as the „short" one. These two lasers were mounted butt-to-butt with a 4 μm gap between the mirrors (Fig. 1). A Finetech Lambda 2 setup was used to position the chips and mount them onto a heatsink with a high accuracy of stripe alignment in angle and coordinate (no worse than 1 μm) in the lateral plane. A small distance between the devices and the high accuracy of their alignment ensured efficient optical coupling. CW injection pumping was provided for each laser independently. The heatsink temperature in the experiments was 20°C. Laser radiation for spectral measurements was collected by a lensed optical fiber.

Figure 2, *a* shows the spectra of the long laser at pump currents of 1 and 4 A; radiation was collected directly from its end face (on the right in Fig. 1, *a*), and current was not passed through the short laser. We believe that reflection from the end of the short laser has little effect on the characteristics of the long one; i.e., the spectra in Fig. 2, *a* are similar to the spectra of solitary long laser. The threshold current of the long laser was 140 mA, and lasing proceeded exclusively through the GS within the entire studied range of injection currents. As the CW pump current grows from 1 to 4 A, the lasing peak shifts toward longer wavelengths, which is attributable to overheating of the active region. The threshold current density of the short laser was 430 A/cm^2 and exceeded the one of the long laser (140 A/cm^2), which is due to high radiation output losses. The threshold current of two-state lasing of the short laser was close to 0.50 A (Fig. 2, *b*).

The influence of additional optical pumping from the long laser on the switching of two-state lasing regimes of the short laser was investigated. Radiation was collected in these experiments from the end face of the short laser (on the left in Fig. 1, *a*). We assume that radiation of the short laser had little effect on the operating modes of the long laser, since the threshold of two-state lasing in the long laser was very high. Two types of lasing regime switching in the short laser were discovered. An example of switching of the first type is shown in Fig. 2, *c*. Initially, the short laser was kept just below the two-state lasing threshold. And the ES radiation intensity was significantly lower than the GS radiation intensity. When the long laser was switched on, the ES radiation intensity in the short laser increased significantly; GS lasing persisted, but the center of its peak shifted approximately by 10 nm toward longer wavelengths. The long-wave shift of radiation of the short laser is apparently attributable to heat transfer from the long laser, which operates at a high continuous pump current (28 times higher than the threshold one) and is located in close proximity to the short laser. Heating of the active region of the short laser due to additional optical pumping may be a complementary factor here. This type of switching (Fig. 2, *c*) is observed only at sufficiently high intensities of radiation from the long laser (when the current passed through it exceeds 2 A). This behavior of the short laser may be used to simulate an inhibitory optical neuron.

An example of switching of the second type is shown in Fig. 2, *d*. The short laser was initially in the two-state lasing regime, and the ES peak intensity was fairly high. The ES radiation intensity of the short laser was raised compared to the previous experiment (Fig. 2, *c*) by increasing the pump current. When the long laser was switched on, ES lasing of the short laser was quenched and the ground-state peak

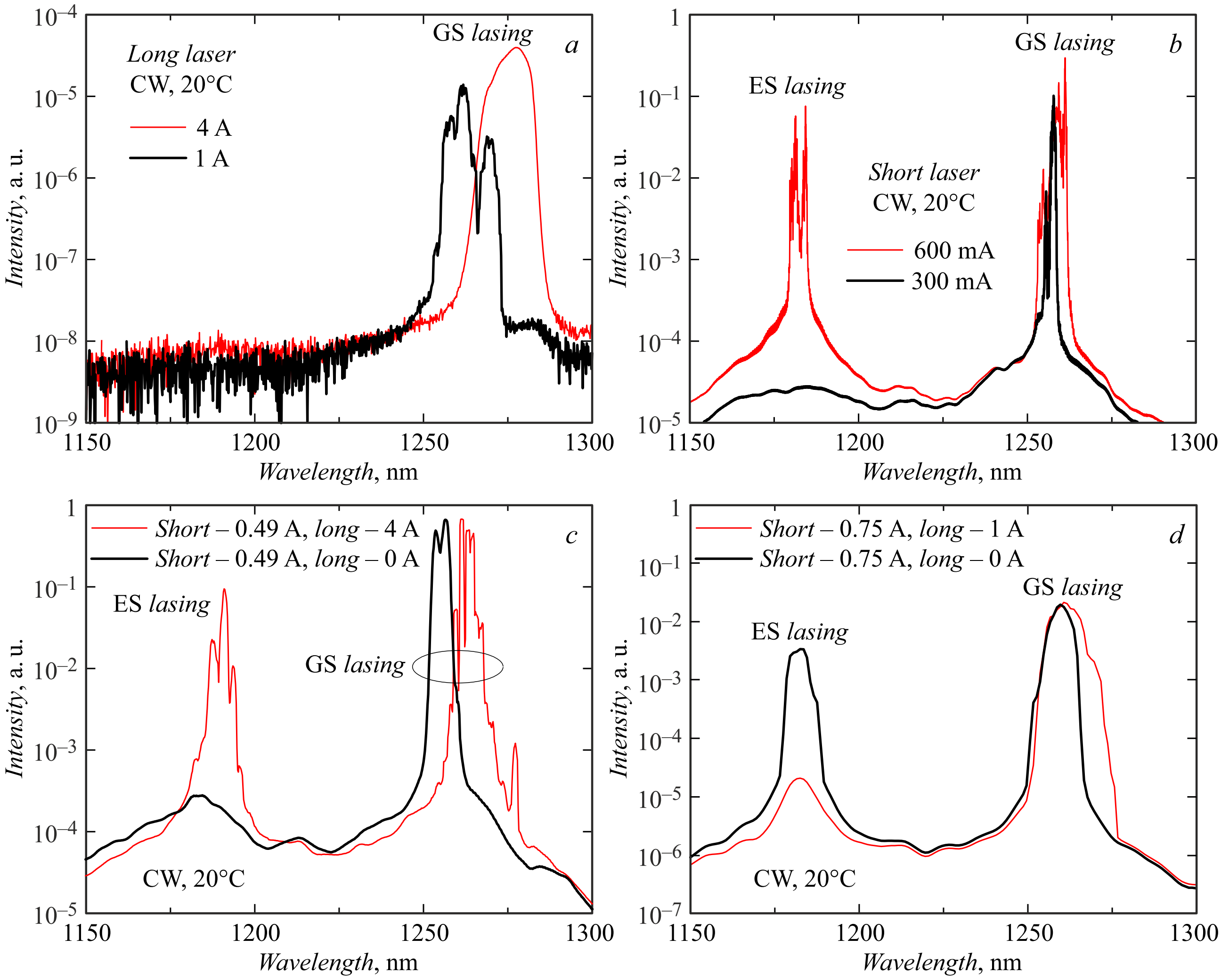

Figure 2. Electroluminescence spectra of the long laser measured with no current flowing through the short laser (*a*) and of the short laser with no current flowing through the long laser (*b*). Radiation was collected directly from the end face of the pumped laser in both cases (*a* and *b*). Emission spectra of the short laser pumped optically by the long one: *c* — onset of ES lasing; *d* — ES lasing suppression. The injection currents through long and short lasers are indicated in each plot.

FWHM increased from 7 to 10 nm, which is apparently attributable to an increase in the number of lasing QDs due to the intensification of combined (injection and optical) pumping. The suppression of ES lasing in the short laser by GS radiation of another laser may be used to simulate the behavior of an excitatory optical neuron. Therefore, depending on the current flowing through the short laser, it may serve as an optical analog of an inhibitory neuron or an excitatory one.

Thus, an optically coupled pair of stripe lasers of different lengths based on InAs/InGaAs/GaAs QDs was fabricated and studied. Depending on the currents flowing through the lasers, the effects of excitation and quenching of ES lasing in the short laser are observed due to it being pumped optically by the long one. These effects may be used to simulate the behavior of inhibitory and excitatory optical neurons, respectively. The simplicity of design and small size of the examined optical pair of lasers make it promising for the implementation of computational neuromorphic photonic integrated circuits.

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Conflict of interest

The authors declare that they have no conflict of interest.

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