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Information encoding using two-level generation in a quantum dot laser

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We propose an approach for encoding and transmitting information based on the use of a quantum dot laser, which, depending on the injection current, emits either one of two or simultaneously two spectral components, with different wavelengths. When the laser is modulated by current, each lasing line is detected by an independent photodiode, and thus the information is encoded by both the intensity of each line and its wavelength.

Keywords: quantum dot lasers, two-state lasing, multilevel signaling, wavelength- division multiplexing.

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„Two-level intensity modulation with direct detection“ is currently the most widespread format of modulation for data transmission. In a simple binary scheme, two signals (e.g., two levels of laser radiation intensity) are used to encode „1“ and „0.“Thus, the rate of bit transmission equals the signal transmission rate. However, further improvement of the bandwidth rate with this modulation pattern is impeded by the speed performance of lasers. For example, the current level of frequencies of efficient modulation for vertical-cavity surface-emitting lasers (VCSELs) is ~ 30 GHz, which is close to the limit [1,2]. Multilevel modulation [3] with more than two signal levels used for encoding was proposed in order to enhance further the information capacity of optical channels with a single transmitter. Each signal corresponds to multiple bits of data. For example, groups of two data bits („00“, „01“, „10“ and „11“) in a four-level scheme may be represented by four levels of laser radiation intensity $(0, 1, 2$, and $3)$. Thus, a distinct optical signal level corresponds to each pair of data bits, and the bit transmission rate is two times higher than the signal transmission rate. In other words, the data transmission rate increases not due to the growth of the signal transmission rate in a channel, but due to the fact that each signal carries a greater amount of information. However, the difference in intensities of optical signals in this scheme naturally becomes smaller than in the two-level one, contributing to noise and raising the probability of errors. This problem could be solved by increasing the output laser power (e.g., by a factor of 3, which is the one required for the four-level scheme). However, the proposed solution has several evident drawbacks: laser overheating, efficiency reduction, growth of the energy consumption, and loss of service life.

In the present study, we propose a new encoding scheme that combines the advantages of multilevel signal transmission and wavelength-division multiplexing by means of two-state lasing in quantum dot (QD) lasers.

An example of evolution of lasing spectra of a multimode laser, which has an active region based on InAs/InGaAs/GaAs QDs, with increasing injection current is presented in Fig. 1. It should be noted that the processes of switching of lasing from the ground state to the excited one proceed in the same manner for multimode and single-mode lasers used for data transmission. At a low pumping level, lasing is initiated at the ground state (GS) in the wavelength range of $1.25-1.3\,\mu$m. As the current increases further, a new line associated with the first excited state (ES) of QDs emerges in the lasing spectrum. This line is typically shifted by $60-80$ nm toward shorter waves relative to the GS line. The phenomenon of two-level lasing in InAs/InGaAs/GaAs semiconductor QD lasers has been examined experimentally and theoretically [4–7]. The physical basis for two-level lasing in QD lasers is that relaxation of electrons from the excited state to the ground one is a relatively slow process. When the pumping intensity grows, the stimulated recombination time may become comparable to the relaxation time. The excited state then gets filled with carriers, its gain increases and eventually reaches the threshold value. As the current grows further, the GS lasing line intensity in QDs decreases down to complete quenching (Fig. 1). This effect was attributed to a lower rate of hole capture in QDs (compared to the rate of electron capture) and to specific features of the band structure of InAs/InGaAs/GaAs QDs, where hole levels are positioned closely in the valence band [7]. It should be noted that ES lasing may also be observed in quantum well lasers, but the required injection currents are very high [8]. In contrast, the ground state in QD lasers quickly becomes saturated due to low levels of the density of states and GS gain, and ES lasing is achieved at relatively low current densities.

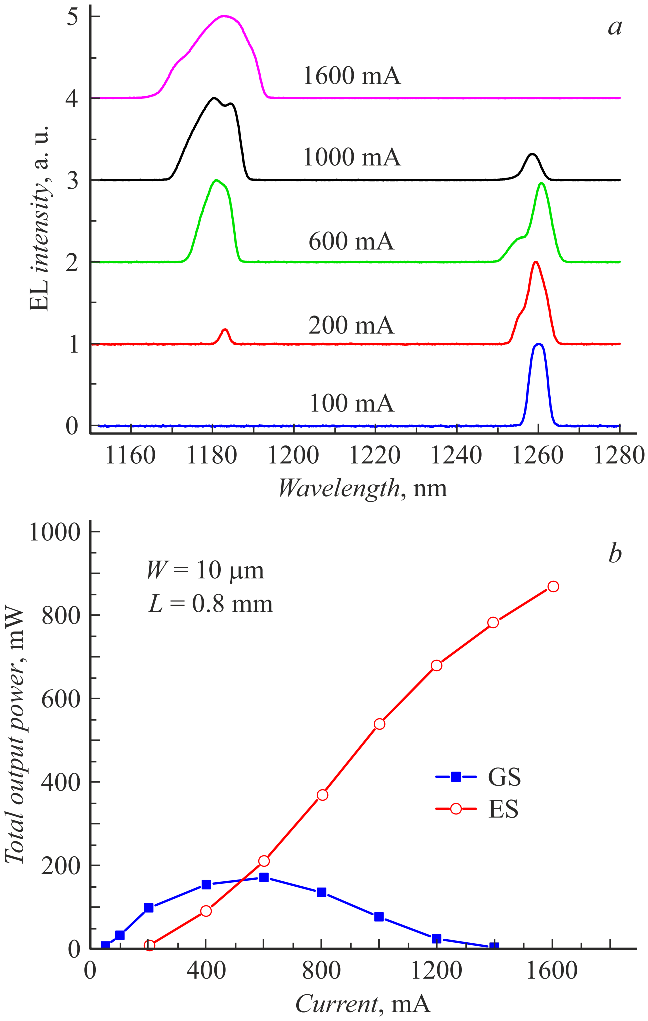

Figure 1. *a* — Lasing spectra in the pulsed mode at different pumping currents for a laser with ten InAs/InGaAs/GaAs QD layers; *b* — dependences of power of spectral components corresponding to the ground and the first excited states on the pumping current. The strip width is 10 μm, and the cavity length is 0.8 mm.

The proposed information encoding method relying on two-level lasing in QDs is illustrated in Fig. 2. Both the intensity and the wavelength of laser radiation are utilized in this method. A laser is modulated by four levels of the injection current, each of which corresponds to its own lasing spectrum. A pair of bits (0,0) corresponds to a pumping current slightly above the QD GS lasing threshold. The intensity of GS emission is low at this current (as in standard NRZ encoding). A pair of bits (0,1) corresponds to an injection current at which the GS lasing intensity reaches its maximum right before the onset of ES lasing. A pair of bits (1,1) is assumed to be represented by a current at which the ground- and excite-state intensities are approximately equal, and bits (1,0) are encoded by lasing through the excited state only. The output radiation is introduced into an optical fiber and is routed by a *Y*-shaped splitter to two photodiodes (Fig. 2, *b*). Optical filters transmitting QD GS ($\lambda \sim 1.25{-}1.3\,\mu$m) and ES ($\lambda \sim 1.18{-}1.23\,\mu$m) emission are mounted in front of the first and the second photodiode, respectively. A demultiplexer may be used instead of a *Y*-shaped splitter and filters. Since information is encoded by both intensity and wavelength, the detected signals are, in a sense, independent of each other. In contrast, the signal corresponding to „1" for level *m* in common multilevel NRZ encoding acts as „0" for level $(m+1)$, and this inevitably leads to cross-talk interference. Therefore, we expect the noise and the bit error rate in the proposed multilevel scheme to be reduced considerably compared to the ones in common multilevel encoding schemes.

It is important to emphasize that the speed performance of QD lasers is sufficient for commercial data transmission systems. For example, InAs/InGaAs/GaAs QD lasers with a GS lasing wavelength of 1.3 μm provided a data transmission rate of 25 Gbit/s with the common two-level intensity modulation scheme [9]. It was demonstrated [10] that the modulation frequency for ES lasing is higher than the one for GS lasing. This was attributed to a higher saturated gain and a shorter time of carrier injection to the excited state. It was found in [11] that the process of switching of

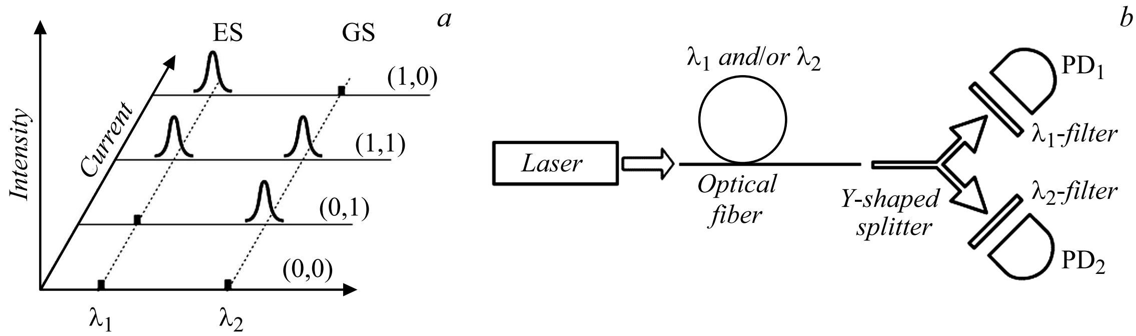

Figure 2. *a* — Schematic diagram of the proposed information encoding principle relying on two-level lasing in QD lasers; *b* — possible implementation of the optical circuit for multilevel encoding.

lasing in InAs/GaAs QD lasers from the ground state to the excited one and back under the influence of short external optical pumping pulses is very fast. The characteristic ES–GS lasing switching time is 300 ps. The fall time of GS lasing intensity measured after a pumping pulse was cut off was 700 ps. This fast dynamics of GS–ES lasing switching should help achieve high data transmission rates in the proposed encoding scheme.

Thus, a new data transmission method with information encoding by both the intensity and the wavelength of radiation of one and the same quantum dot laser with current modulation was proposed. It is evident that the current inducing two-level lasing needs to be lowered for this method to become practically viable. This may be achieved by increasing radiation outcoupling losses and/or suppressing the optical gain by, e.g., reducing the number of QDs in the active region. The proposed combined method of encoding with intensity and wavelength may be implemented using any lasers emitting at several wavelengths with reproducible and controllable (by current modulation of the emission spectrum) switching between them. This principle is scalable to a greater number of radiation intensity levels at each of the two (or more) wavelengths.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] S.A. Blokhin, N.A. Maleev, M.A. Bobrov, A.G. Kuzmenkov, A.V. Sakharov, V.M. Ustinov, Tech. Phys. Lett., **44** (1), 1 (2018). DOI: 10.1134/S1063785018010054.

[2] K. Chi, J. Yen, J. Wun, J. Jiang, I. Lu, J. Chen, Y. Yang, J. Shi, IEEE J. Sel. Top. Quant. Electron., **21** (6), 470 (2015). DOI: 10.1109/JSTQE.2015.2451015

[3] N. Kikuchi, IEICE Trans. Electron., **E102.C** (4), 316 (2019). DOI: 10.1587/transele.2018ODI0004

[4] A.E. Zhukov, A.R. Kovsh, D.A. Livshits, V.M. Ustinov, Zh.I. Alferov, Semicond. Sci. Technol., **18** (8), 774 (2003). DOI: 10.1088/0268-1242/18/8/310

[5] A. Markus, J.X. Chen, C. Paranthoën, A. Fiore, C. Platz, O. Gauthier-Lafaye, Appl. Phys. Lett., **82** (12), 1818 (2003). DOI: 10.1063/1.1563742

[6] E.A. Viktorov, P. Mandel, Y. Tanguy, J. Houlihan, G. Huyet, Appl. Phys. Lett., **87** (5), 053113 (2005). DOI: 10.1063/1.1995947

[7] V.V. Korenev, A.V. Savelyev, A.E. Zhukov, A.V. Omelchenko, M.V. Maximov, Semiconductors, **47** (10), 1397 (2013). DOI: 10.1134/S1063782613100151.

[8] D.A. Veselov, K.R. Ayusheva, N.A. Pikhtin, A.V. Lyutetskiy, S.O. Slipchenko, I.S. Tarasov, J. Appl. Phys., **121** (16), 163101 (2017). DOI: 10.1063/1.4982160

[9] M. Ishida, M. Matsuda, Y. Tanaka, K. Takada, M. Ekawa, T. Yamamoto, T. Kageyama, M. Yamaguchi, K. Nishi, M. Sugawara, Y. Arakawa, in *Conf. on lasers and electro-optics 2012* (Optica Publ. Group, 2012), paper CM1I.2. https://opg.optica.org/abstract.cfm?URI=CLEO_SI-2012-CM1I.2

[10] B.J. Stevens, D.T.D. Childs, H. Shahid, R.A. Hogg, Appl. Phys. Lett., **95** (6), 061101 (2009). DOI: 10.1063/1.3193664

[11] B. Tykalewicz, D. Goulding, S.P. Hegarty, G. Huyet, D. Byrne, R. Phelan, B. Kelleher, Opt. Lett., **39** (15), 4607 (2014). DOI: 10.1364/OL.39.004607