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New-generation vertically emitting lasers as a key factor in the computer communication era

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1. Introduction

At present, supercomputers are becoming one of the basic driving forces in the development of our civilization, providing progress in genomics, biomedical sciences, aerodynamics, mechanical engineering, predictions of natural cataclysms and technogenic impacts on the environment, and many other strategic fields of science and technology. Supercomputers play an important role in neural simulations and studies in the field of artificial intelligence. The development of high-speed telecommunications and internet technologies allows broad commercialization of high-performance computers and considerable broadening of the scope of their applications.

The continual decrease in the characteristic size of elements of the silicon integrated circuit leads to the doubling of the density of discrete elements on a crystal every two years. Correspondingly, processor efficiency and memory capacity drastically increase. To provide efficient data exchange among processors and the processors and memory or peripheral devices, it is necessary to increase the data transmission rate per channel. Communications among the elements of a system are gradually becoming its bottleneck, especially because of the necessity of constant scaling [1] of the spatial density of elements and the data transfer rate in the contacts of an individual integrated circuit (IC) and in all modules and boards. To support the scaling of the data transfer rate by preserving or reducing the size of interconnects, the data transfer rate per channel in all modern standards of electric interconnects should be approximately doubled every two to three years. For bit rates above 10 Gbit s^{-1}, the use of copper interconnects becomes complicated, and therefore the role of optical communication lines drastically increases. The modern supercomputer Blue Waters (IBM 2011) with a 10-petaflops efficiency (10^{16} flops: flops is the number of floating-point operations per second) already contains about five million optical interconnects, each of them operating at a bit rate of 10 Gbit s^{-1}. The tenfold increase in the supercomputer efficiency compared to the Roadrunner model (IBM, 5 Gbit s^{-1}) produced in 2008 resulted in an increase in the number of optical interconnects by two orders of magnitude. Supercomputers with the efficiency 20–30 times higher than that of the Blue Waters computer, which are expected in 2015, will use about a billion optical interconnects. In exaflop systems (10^{18} flops), up to 80% of the consumed power and up to 90% of the system efficiency will be determined by optical interconnects [1]. We note, however, that the manufacturing of energy-efficient, compact, and economical optical communication lines is far from a trivial problem for bit rates 50–100 Gbit s^{-1} per channel, which should be achieved in the near 3–6 years. In this brief review, we consider vertical-cavity surface-emitting lasers as the main element of modern short-range optical communication lines and discuss the outlook for a further increase in their bit rate in accordance with the requirements of computational systems in the nearest future.

[1] The term 'scaling' refers to a proportional change in physical sizes of components on a crystal. In silicon technology, the size of elements is constantly reduced with the basic geometry being preserved. This is called silicon scaling.

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2. Basic applications and standards

The development of modern data processing systems is based on silicon microelectronics. The 1.4-fold scaling of the characteristic size of the IC every two years leads to an exponential increase in the computational efficiency of processors. The increase in the efficiency is mainly achieved by increasing the number of kernels on one IC (modern Intel processors contain 80 kernels). The characteristic topological size of an element has been reduced to 22 nm, while the required bit rates of input–output devices per channel equal to 26 Gbit s^{-1} (2.6×10^{10} bit s^{-1}) approximately correspond to the number of grains of sand it would take to form a line the length of Earth's diameter. We note that IC prototypes with elements 18 mm and even 14 nm in size are already being manufactured and are in operation. The size and bit rate scaling in silicon technology will be continued, resulting in a radical increase in loading in local data communication networks.

An important strategic standard for receiving and transmitting data in highly efficient computational systems is the Infiniband standard. The bit rate per channel is doubled every 2.5 years on average. By 2014, the bit rate should exceed 50 Gbit s^{-1}, while by 2016–2017, it should achieve 100 Gbit s^{-1}.

The scaling of the other most important interfaces is occurring similarly. The most popular standard used in data storage networks is the Fibre Channel standard. Here, the standardized bit rate per channel reached 14 Gbit s^{-1} already in 2009, while by 2012, the standardization of interfaces to 28 Gbit s^{-1} is expected. The use of copper communication lines at such bit rates is limited to the cable length of about 1 m and 10 cm on a board. From the standpoint of energy consumption, interference produced during operation, and the size of cables and connectors, the use of copper is impractical even at considerably smaller distances. A new standard appears in the market the year following its adoption and begins to dominate after approximately 2–2.5 years. When the 28 Gbit s^{-1} standard is adopted, the 14 Gbit s^{-1} interface will dominate in the market.

An important feature of some interfaces, for example, the Ethernet standard that dominates data communication and processing networks, is the necessity of scaling not only the bit

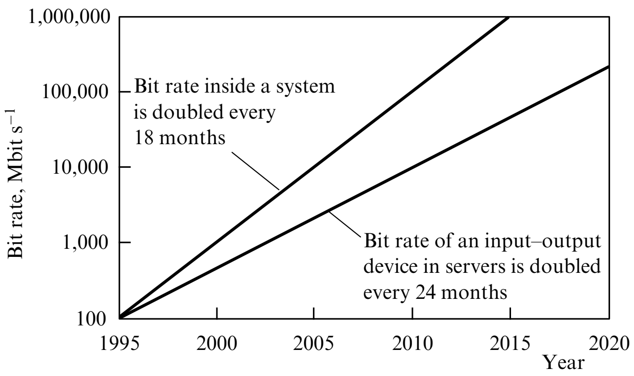

Figure 1. 'Road map' for the growth of the bit rate per channel in the Ethernet Standard (used in data processing centers) and the bit rate increase that is driven by advances in silicon integrated circuits. The number of transmission lines in the integrated system continuously increases (from 2 in 2000 to 10 in 2010), while the bit rate of an input–output device increased from 500 Mbit s^{-1} to 10 Gbit s^{-1} in the same period.

rate per channel but also the number of channels (Fig. 1). Thus, the spatial region allotted per channel on a commutation board having invariable size should decrease along with a simultaneous increase in the operational speed of the interconnect. The increase in the bit rate inevitably leads to an increase in the role of electromagnetic interference. Therefore, the trends of increasing the bit rate per channel and developing more and more compact receiver–transmitters obviously contradict each other.

In the area of interfaces in the consumer market, the Thunderbolt interface used in Apple devices (MacBook, iMac) has the highest bit rate per channel. It can be expected that electric interconnects in consumer electronics will be rapidly changed to optical interconnects (for example, using the Intel Lightpeak technology)

3. Modulated-current vertical-cavity surface-emitting lasers

At present, vertical-cavity surface-emitting lasers (VCSELs) dominate in optical data communication systems [2]. Unlike double-heterostructure stripe lasers [3], where light propagates parallel to the surface of epitaxial layers along a semiconductor waveguide with the refractive index higher than that of the layers surrounding the waveguide, the radiation of VCSELs is emitted perpendicular to the substrate surface. Individual devices of such a design and their arrays can be manufactured by using planar technology and can have a very small size in the plane of a wafer. As a result, the production of good structures has proven to be high, while the production cost of an emitter is low. In both cases, the active region is formed by the layers of a material with a smaller band gap, into which nonequilibrium charge carriers are injected. Currently, layers containing quantum wells, quantum wires, and quantum dots are used most extensively [4] because they considerably improve the properties of lasers. For example, InAs quantum dots allow the fabrication of VCSELs and stripe lasers emitting at 1.3 μm [5] by using the standard and economical arsenide–gallium technology. Stripe lasers have demonstrated the unique temperature stability of parameters, emission at temperatures above 220 °C, and bit rates upon direct current modulation higher than 25 Gbit s^{-1} per channel [6].

3.1 Laser geometry

An outline of a modulated-current VCSEL is shown in Fig. 2. The laser consists of a microresonator with a planar resonance cavity whose thickness is a multiple of half the wavelength. Inside the cavity is located the active medium into which nonequilibrium charge carriers are injected, in which population inversion is produced, and in which amplification occurs per transit of light in the vertical direction. Multilayer structures of alternating layers approximately a quarter of the wavelength in thickness of the higher and lower refractive indices (for example, made of $Al_xGa_{1-x}As$ with low and high aluminum content, respectively) are located above and below the microcavity. This sequence of layers satisfies the Bragg condition and provides the high reflectivity of mirrors, such that the light loss upon reflection from the mirrors remains lower than the gain per transit, and lasing is possible. The structure is grown on a GaAs substrate. The AlAs layers in the microcavity region are subjected to selective oxidation in water vapor to form a current aperture and restrict the optical modes of the microresonator by a region with a lower refractive index. An advantage of the gallium arsenide–aluminum arsenide system for VCSELs is the possibility of growing the layers of a Bragg reflector by using binary AlAs and GaAs compounds or quasibinary solid solutions with small amounts of gallium or aluminum. Because the heat conduction of binary solutions is an order of magnitude higher than that of the solid solution, the active medium is not overheated and the construction of the laser is simplified. In addition, because the jump of the refractive index in each aluminum arsenide–gallium arsenide interface exceeds 0.5, the total thickness of multilayer reflectors is small (about 3–3.5 μm per multilayer mirror), which also facilitates heat transfer and reduces the cost of the epitaxial growth. The large jump in the refractive index produces a broad ledge (60 nm) in the reflection spectrum of a multilayer mirror, simplifying requirements for the accuracy of the epitaxial growth control, thereby increasing the production of good wafers and reducing their cost.

The emission wavelength of the laser is determined by the photon resonance energy and, correspondingly, by the thickness of the microcavity layer, rather than by the band

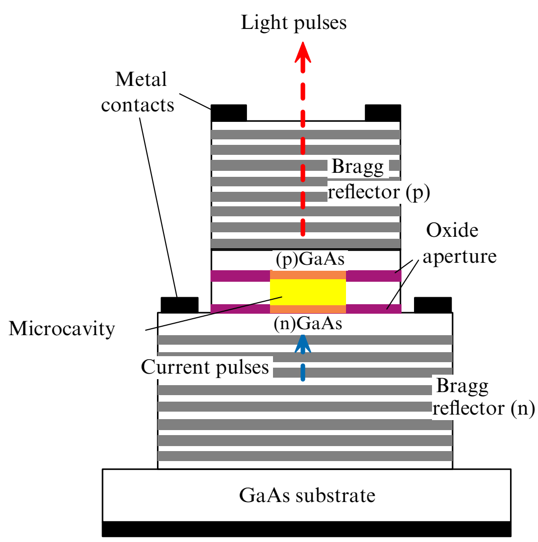

Figure 2. Schematic view of a modulated-current vertical-cavity surface-emitting laser.

gap of the active medium, as in a stripe laser. Because the band gap changes with temperature much faster than the photon resonance energy, the amplification spectrum of the active medium should be rather broad (no less than 50 nm) to provide lasing in the entire required temperature range. The optical design of VCSELs should provide:

(i) the optimization of parasitic radiation modes with the maximum enhancement of the interaction of the active medium with a vertical emission mode [7], for example, by using the antiwaveguide design of the VCSEL microcavity;

(ii) the optimization of oxide aperture layers to provide the specified mode composition of radiation in the transverse direction, for example, to obtain single-mode radiation;

(iii) the optimization of the transmission coefficient of the mirrors along with the optimization of the number of periods in the Bragg reflector or the use of several resonance cavities to provide the required photon lifetime in the microcavity.

3.2 Active medium

Figure 3a schematically shows a bulk semiconductor, a quantum well (QW), an array of quantum wires (QWs), and an array of quantum dots (QDs), and Fig. 3b schematically shows the density of states (dashed curves) and the occupation of states by charge carriers (solid curves) for active regions of different dimension.

The use of reduced-dimension heterostructures [8] in VCSELs plays a very important role for several reasons. First, the higher the differential gain of a laser is, the higher its operating speed for a similar geometry and the same operating current. The differential gain of QW lasers is mainly determined by the number of QWs and the dispersion of the subband of heavy holes, which can be controlled by stresses in the case of elastically stressed QWs. The differential gain of QD lasers is determined by the lateral density of QDs, which can be rather high for lasers emitting at 850 nm (more than 10^{12} cm^{-2} per QD layer), which allows obtaining the giant differential and modal gains.

Figure 4a shows a high-resolution transmission electron micrograph of InAs QDs produced by the molecular beam epitaxy (MBE) method in an $Al_xGa_{1-x}As$ matrix emitting at 850 nm [9]. Figure 4b presents photoluminescence spectra of InAs QD structures and GaAs QW structures at low temperature (77 K). It can be seen that luminescence spectra of QD structures at moderate pump powers are considerably broader than those of QW structures. But the situation drastically changes at high current densities, and the amplification spectra of QDs are typically considerably narrower than the structureless broad amplification spectra of QWs caused by the step density of states (see Fig. 3).

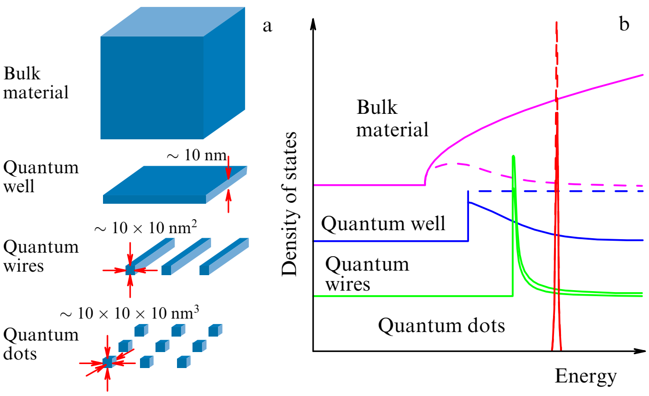

Figure 3. (a) Schematic view of a bulk semiconductor, a quantum well (QW), an array of quantum wires (QWs), and an array of quantum dots (QDs). (b) Schematic view of the density of states (dashed curves) and the occupation of the states by charge carriers (solid curves) for active regions of different dimensionalities. In real structures containing QDs and QWs, the spectrum of the density of states is broadened due to both the inhomogeneous broadening (caused by the dispersion of QWs and QWs over shape and size) and the homogeneous broadening caused, for example, by interaction with phonons.

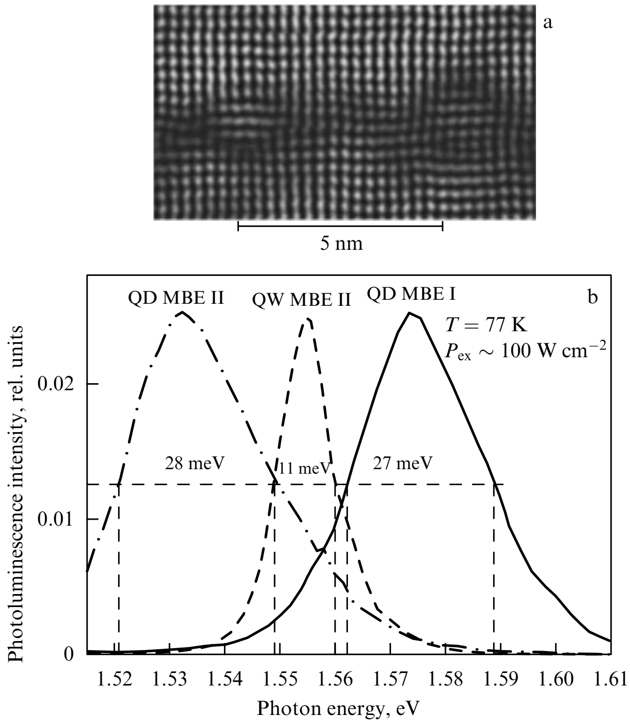

Figure 4. (a) Image of InAs QDs in an $Al_xGa_{1-x}As$ matrix emitting at 850 nm. The inverted-line-contrast regions contain InAs in amounts higher and lower than 20%. (b) Photoluminescence spectra of InAs QDs and GaAs QWs at 77 K.

3.3 Operation speed of VCSELs

In the case of stimulated emission, the radiative recombination time is inversely proportional to the optical field intensity in a resonator; for VCSELs, this means the necessity of increasing the current density for reducing the time of stimulated emission upon annihilation of the injected electrons and holes. At the same time, the decrease in the radiative recombination time leads to a sublinear dependence of the density of nonequilibrium carriers and the field intensity on the current density. The resonance frequency that characterizes the system response to a step change in the current and hence the operation speed of the laser also strongly depends on the current density. Because the period of resonance oscillations consists of positive and negative half-waves, the signal rise and decay time are approximately equal to the quarter of the period. The maximum rate of optical pulse transfer without distortions in the absence of a considerable damping is determined by the sum of the signal rise and decay times and is therefore approximately equal to the doubled resonance frequency. To double the resonance frequency and operation speed, the pump current density should be increased fourfold. However, the doubling of the pump current of a VCSEL drastically reduces its service life (by 30 – 40 times). This is related to the overheating of the active region and a high probability of nonradiative recombination (for example, Auger recombination) accompanied by energy transfer to a crystalline lattice, including the generation of defects. Because 10 Gbit s^{-1} GaAs QW VCSELs already operate near the current density at which the overheating of the laser begins and its output power and operation speed decrease, the achievement of resonance frequencies considerably exceeding 10 Gbit s^{-1} was considered unlikely. The use of QDs as the active medium can considerably reduce the generation and growth rates of defects by restricting the diffusion transport of nonequilibrium carriers to regions with the enhanced rate of nonradiative recombination.

As mentioned above, controlling stresses in the active medium and (or) changing its dimension allow drastically increasing the differential amplification of the laser and achieving the same resonance frequencies at much lower current densities. The reduction in the oxide aperture thickness of the laser can also improve the frequency characteristics due to the improvement in heat transfer at the same current density and a decrease in the optical mode volume followed by the suppression of parasitic radiation. When photonic crystals or microcavities are used that provide the concentration of the optical field in one small-volume vertical mode, a very high operation speed can be achieved by using the Purcell effect even without the population inversion [10].

Figure 5 shows the dependence of the relaxation resonance frequency on the current in a cw VCSEL [11, 12]. It follows that in the case of small apertures, resonance frequencies of the order of 30 GHz are achieved. Correspondingly, by suppressing the parasitic decay in such VCSELs (caused, for example, by the high resistance and capacitance of the laser or by the long photon lifetime in the microcavity [13]), bit rates up to 50 Gbit s^{-1} and higher can be achieved. The maximum heat-removal operation temperature of such 850 nm VCSELs at which lasing is still observed reaches 200 °C, while the operation parameters of the laser at 100 °C change within 10–20%.

The presence of the high relaxation resonance frequency for using VCSELs in receiver–transmitter systems is not a sufficient condition. The laser should not emit intensity overbursts on applying rectangular current pulses, and arbitrary trains of unit current pulses should produce an optical signal of the same amplitude. The power accumulation effect in the laser cavity or, on the contrary, the photon depletion effect in the cavity, depending on the duration of pulses or intervals between them, leads to the 'floating' of the 'zero' (minimal signal) and 'one' (maximal signal) levels. Figures 6a and 6b show experimental 'eye diagrams' at 20 and 40 Gbit s^{-1}, obtained by using control integrated circuits and microassemblies of VCSEL transmitters and PIN photodetectors (produced by VI-Systems GmbH). We see that the one and zero levels are well discriminated over the signal level for any arbitrary train of pulses (when using the 2^7–1 PRBS measurement standard). For 40 Gbit s^{-1}, the error-free transmission (less than one error in 10^{12} pulses) was realized for a 1 mW optical power in a fiber (0 dBm). In the future, a drastic reduction in the optical power is expected for achieving the same noise level and increasing the operation speed. Figure 6c shows a microassembly containing a VCSEL and a control integrated circuit, and Fig. 6d shows a complete module connected with a multimode fiber (50 μm) used in the eye diagram measurements.

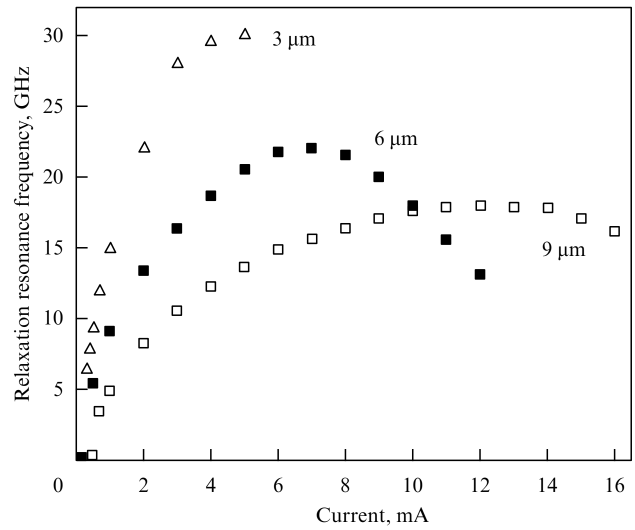

Figure 5. Dependence of the relaxation resonance frequency of a VCSEL on the pump current in the cw regime for different diameters of the oxide aperture of the laser.

3.4 Vertical-cavity surface-emitting lasers based on other $A^{III}B^{V}$ compounds

Vertical-cavity surface-emitting AlGaAs lasers emitting at 850 nm are in demand the most. First, all the most important short-range receiver–transmission standards use this wavelength. Multimode optical fibers, which also should be specially standardized, are adapted to this wavelength. The manufacturing of VCSELs based on InP, GaN, GaSb, and related solid solutions is a considerably more complicated problem, and their market is much smaller than that of GaAs VCSELs used to replace copper interconnects. The annual turnover of copper interconnects, not taking control circuits into account, was more than $130 billion in 2010. Vertical-cavity surface-emitting lasers emitting at 1.3 μm have a considerable market potential. These lasers can be used for transmitting signals over single-mode optical fibers and manufactured on GaAs [5] and InP [14] substrates. Work in this area actively continues. 1.3 μm VCSELs on GaAs substrates can be very easily manufactured by using QD technology. However, only a few groups exist in the world that possess the technological knowledge and equipment for growing QD lasers. To manufacture a QD VCSEL, it is also necessary to know the specific design of the laser for a given wavelength. The main problem in the manufacturing of lasers based on InP is the low heat conduction of solid (In, Ga, Al)As solutions and the low contrast of the refractive index of multilayer Bragg mirrors. The thickness of a multilayer mirror required to obtain the same reflectance as that of GaAs – AlAs mirrors is twice as large and the heat conduction 30 times lower than for GaAs – AlAs mirrors. The width of the reflection ledge is small (25 nm) and requires the high-precision control of epitaxial growing, while the use of InP substrates and a long growing time lead to a high cost of epitaxial VCSEL structures. In addition, because the selective oxidation technology cannot be used for these materials, the injection region is formed by the method of a local tunneling junction with selective etching, followed by epitaxial growth, which additionally complicates the technology.

3.5 Alternative approaches in VCSEL construction

To overcome the problems considered above, we proposed a solution based on the use of passive resonators. It is known

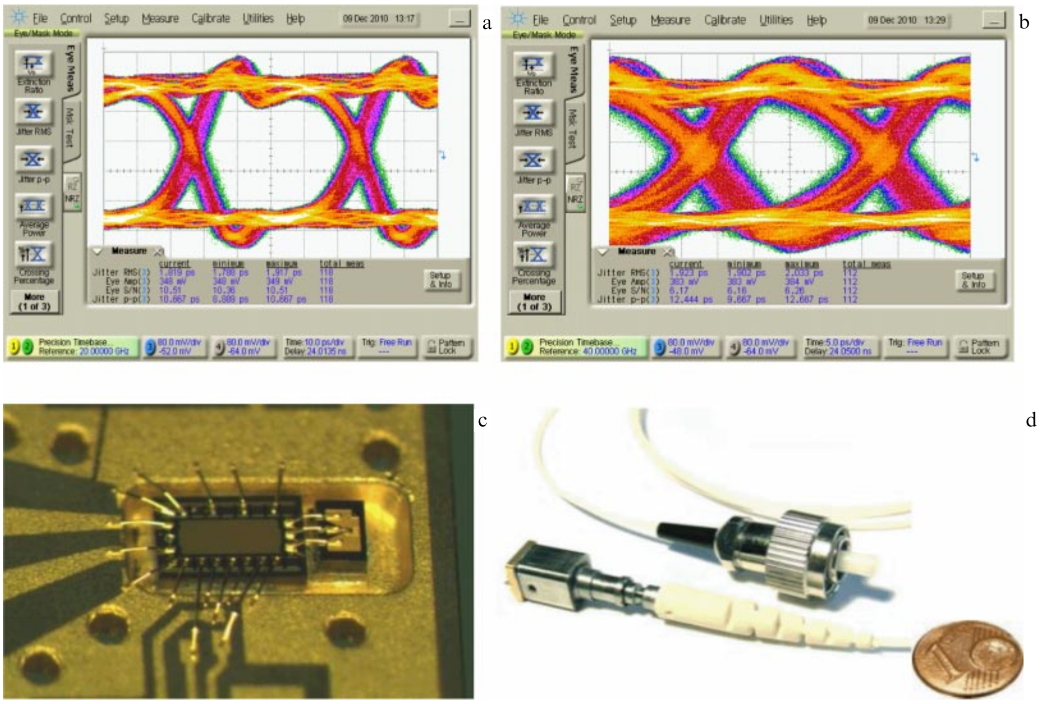

Figure 6. Experimental 'eye diagrams' obtained for bit rates (a) 20 Gbit s^{-1} and (b) 40 Gbit s^{-1} by using microassemblies of VCSEL transmitters and PIN photodetectors (VI-Systems GmbH). (c) Microassembly of a VCSEL and control integrated circuit. (d) Complete module connected with a multimode fiber (50 μm).

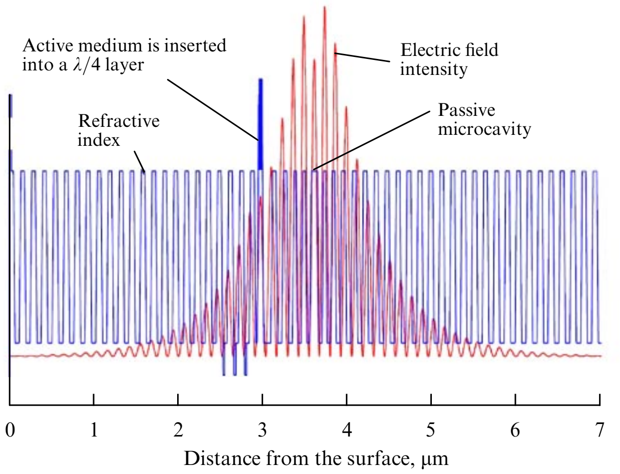

Figure 7. Design of a passive microcavity VCSEL.

that the high-Q resonator approximation can drastically change the radiation pattern and radiation lifetime of an oscillator. This led to the idea of manufacturing a VCSEL with a passive microcavity. In this case, the active medium is introduced into the Bragg reflector layer in the region of the noticeable decay of the optical field, while the microresonator remains 'empty' [15] (Fig. 7). Such a laser operates similarly to a usual VCSEL up to transition temperatures above 130 °C [15]. At first glance, such a design seems to have low efficiency because the field intensity in the active medium decreases compared to that in the passive microcavity. However, not the absolute intensity but the relative field intensity is in fact important. Therefore, for example, when a dielectric resonator is used with the giant power density of the optical mode caused by a giant jump of the refractive index (up to 2 and more) on the interfaces of dielectric Bragg reflectors, the field intensity in the active medium, even reduced several-fold, considerably exceeds the field intensity in the field maximum when Bragg mirrors are based on 'related' semiconductors with a small jump of the refractive index and, correspondingly, a broad field distribution. The dramatic reduction in the thickness of 'residual' semiconductor Bragg mirrors, if they are needed at all, provides an efficient heat conduction of the device.

The presence of a passive microcavity opens the possibility of producing photonic crystal structures in it, inserting metal nanostructures, using nanoimprint technology, applying materials with giant electrooptical or piezoelectric effects for controlling the emission wavelength, etc., without worrying about the current flow, nonradiative recombination, and heat conduction in the active medium.

4. Electrooptically modulated vertical-cavity surface-emitting lasers

Simultaneously with the development of the technology of directly modulated VCSELs, work on the development of electrooptically modulated VCSELs continues. In this case, as shown in Fig. 8, the alternating voltage is applied to the electrooptical modulator (EOM) section vertically integrated with the laser section operating in the cw regime. A change in the refractive index in the active medium of the EOM (for example, a superlattice) caused by the electric field leads to a spectral shift of the resonance in the transmission spectrum of the EOM section. Correspondingly, the light from the VCSEL section is either emitted from the laser or blocked [16]. Depending on the operation regime, the VCSEL section can operate at very low current densities, having an extremely long service life. On the other hand, the EOM

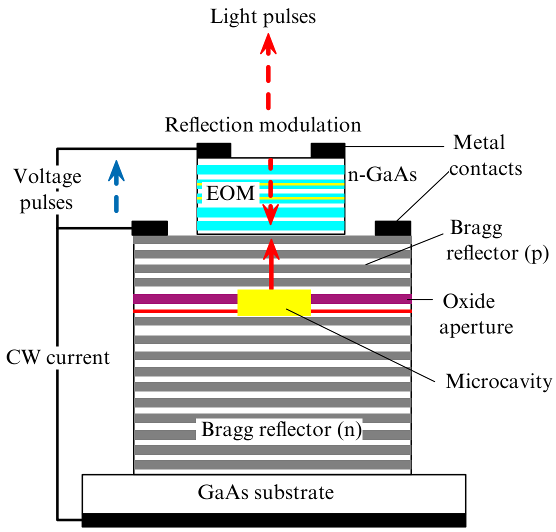

Figure 8. Electrooptically modulated VCSEL. A change in the transmission coefficient of the EOM section in the case of a reverse bias applied to the p–i–n junction in the EOM section having a low capacitance provides ultrahigh operational frequencies of the laser.

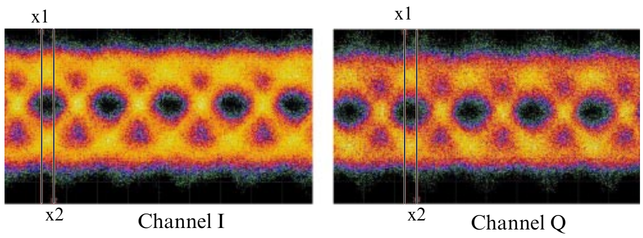

Figure 9. 'Eye diagrams' of an EOM VCSEL obtained in the QPSK multilevel coding mode for a bit rate of 10 Gbit s^{-1} per channel (the total bit rate in the line is 20 Gbit s^{-1}) at a carrier frequency of 13 GHz.

section operating in the reverse bias regime has an extremely low capacitance and can provide operation frequencies equal to 60 GHz [7] and above.

A distinct feature of EOM VCSELs is the high linearity of their characteristics [7], which allows realizing multilevel coding [17]. Figure 9 shows eye diagrams of an EOM VCSEL with the bit rate 10 Gbit s^{-1} per channel (the total bit rate is 20 Gbit s^{-1}) with the use of QPSK coding at the carrier frequency of 13 GHz.

Error-free data transfer was realized at the bit rates up to 16 Gbit s^{-1}. Rapid progress in this field of VCSEL applications can be expected in the near future.

5. Conclusions

Modern VCSELs represent a complex combination of micro- and nanotechnologies. The small size of and low power consumed by the laser in both the current and EOM versions give promise that energy-efficient optical interconnects with bit rates of 50–100 Gbit s^{-1} per channel will be realized and used in new-generation supercomputers, data storage and processing centers, and electronic devices in the consumer market.

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The photonics of self-organizing biomineral nanostructures

Yu N Kulchin

1. Introduction

The possibilities of using optical radiation for the transmission and processing of more and more increasing volumes of information are stimulating the search for principally new technologies aimed at developing the requisite components for communication systems and devices for generating and detecting radiation, and designing optoelectronic computers. Nanophotonic objects such as photonic crystals have been attracting increasing attention recently as promising systems for solving such problems [1]. It is known that Nature has already created various materials with photonic crystal properties, the diversity of these materials including noble opal, the pollen of the butterfly's wing, the beetle's chitin shell, and the mother-of pearl of a shell which grow due to self-organization — one of the most promising technologies. The basic structural components of living systems almost entirely consist of ordered arrays of protein and hydrocarbon molecules. This specific feature of living systems is due to the ability of biological macromolecules to self-organize in

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