

Advances in VCSELs for Communication and Sensing

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(Invited Paper)

Abstract—The vertical-cavity surface-emitting laser (VCSEL) has become a light source of great importance for industrial and consumer applications. This includes communication and sensing in particular, where dynamics and optical mode behavior are key performance characteristics. This tutorial treats relevant VCSEL basics, performance requirements and recent progress toward higher speed, higher single-mode power, and polarization control.

Index Terms—Communication, dynamics, optical modes, sensing, vertical-cavity surface-emitting laser (VCSEL).

I. INTRODUCTION

THE CONCEPT of the vertical-cavity surface-emitting laser (VCSEL), proposed already in 1977 by professor K. Iga at Tokyo Institute of Technology [1], is unique among semiconductor lasers in that emission normal to the surface is inherent to the design. Surface emission and a compact laser design lead to a number of advantages and possibilities in terms of performance, integration, manufacturing, and packaging [2]. The low divergence, circular, and nonastigmatic beam facilitates efficient coupling to optical fibers and other optical elements, and, in most cases, eliminates the need for beam correction optics. The small volume of the resonator and the active region enable low threshold current and efficient high-speed modulation at low currents. Properly designed VCSELs are able to operate over a wide range of temperature with minimal change in performance, allowing for unmonitored operation. Surface emission also enables dense 2-D integration of VCSELs, vertical integration with other active and/or passive elements for enhanced functionality and simplified packaging. Last, but not least, surface emission allows for wafer level fabrication, testing, and screening, which lowers the cost of manufacturing.

Data communication was the first real driver for the development of the VCSEL technology [3]. This led to significant improvements of VCSEL performance in terms of efficiency, speed, and reliability. More recently, the optical computer mouse

has emerged as another major application and has driven the development of polarization stable, single-mode VCSELs [4]. Volumes for these leading applications are presently at tens of millions per year. However, volumes are expected to “go through the roof” over the next few years as VCSELs are becoming increasingly used in computing and consumer applications, including high-speed routing of data in consumer electronics [5]. Other VCSEL applications include gas analysis [6], laser printing [7], atomic clocks [8], and a variety of sensors operating in, e.g., reflection, transmission, absorption, or scattering modes for position sensing, motion control (optical encoding), and many other measurement tasks [9]. In addition, new applications are targeted by the development of VCSELs in new material systems (e.g., antimonides for VCSELs in the mid-IR [10] and III-nitrides for VCSELs in the green-blue-ultraviolet [11]) and the development of new VCSEL technologies, such as large incoherent VCSEL arrays as high power sources for, e.g., illumination, pumping, and surface treatment [12].

This tutorial focuses on VCSELs for communication and sensing. Section II reviews VCSEL basics of importance for these applications, including optical fields and modes, and dynamics. In Section III, performance requirements are derived from a discussion on applications and future needs. Section IV deals with high-power single-mode VCSELs and techniques used for transverse and polarization mode control; as such VCSELs are of particular importance in sensing. Progress and state of the art in high-speed communication VCSELs are presented in Section V. Specific examples from work at Chalmers are highlighted in both Sections IV and V. Finally, conclusions are presented in Section VI.

II. VCSEL BASICS

The vertically oriented VCSEL resonator is created by sandwiching the active region by two highly reflective multilayer reflectors, or distributed Bragg reflectors (DBRs), composed of alternating layers (quarter wavelength thick) of high- and low-refractive index (see Fig. 1). Gain is achieved by carrier injection into the active region, through a p-n junction, and lasing commences at a current where the round trip gain balances the round trip loss. This defines the threshold current. Above threshold, coherent light produced by stimulated emission is preferentially outcoupled through the DBR with the lowest reflectivity. Top emission is always possible, while a transparent substrate (or substrate removal) is required for bottom emission.

The DBRs are based on either semiconductors or dielectric materials. Semiconductor DBRs can be doped, and, therefore,

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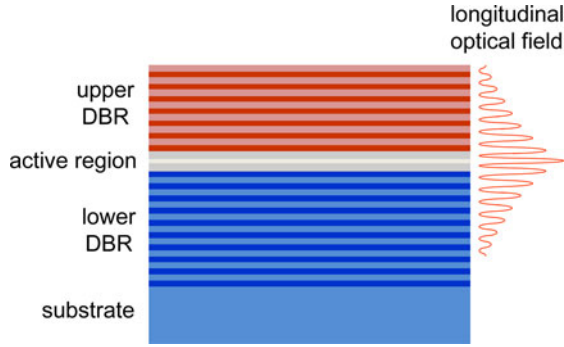


Fig. 1. Vertical VCSEL resonator and the longitudinal confinement of the optical field by the DBRs. Blue indicate n-type material and red indicate p-type.

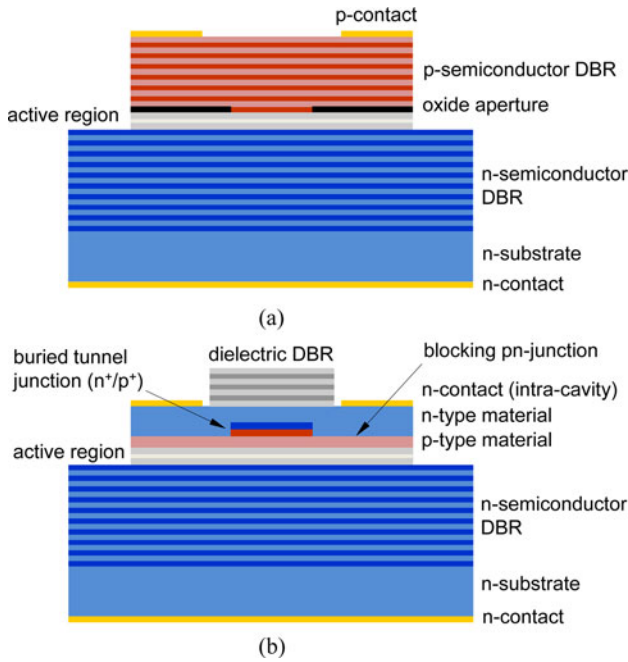


Fig. 2. (a) Basic design of an oxide-confined VCSEL and (b) a BTJ VCSEL.

allow for convenient current injection through the DBRs. Dielectric DBRs, which are used to reduce optical loss (from free-carrier absorption) and when semiconductor DBRs with sufficient index contrast are not available, are electrically nonconducting, and, therefore, require an intracavity contact for current injection. Intracavity contacts can also be used with undoped semiconductor DBRs for reduced optical loss and reduced electrical resistance, which together with the superior thermal conductivity of semiconductor DBRs can improve performance and efficiency.

Transverse optical and current confinement can be achieved by various means and the preferred technique depends on the material system. GaAs-based VCSELS (covering 0.65–1.3 μm) commonly employ oxide confinement [see Fig. 2(a)], while InP-based VCSELS (covering 1.3–2.3 μm) and GaSb-based VCSELS (covering 2–3 μm) commonly employ a buried tunnel junction (BTJ) [see Fig. 2(b)]. These are the confinement techniques that today enable the highest VCSEL performance.

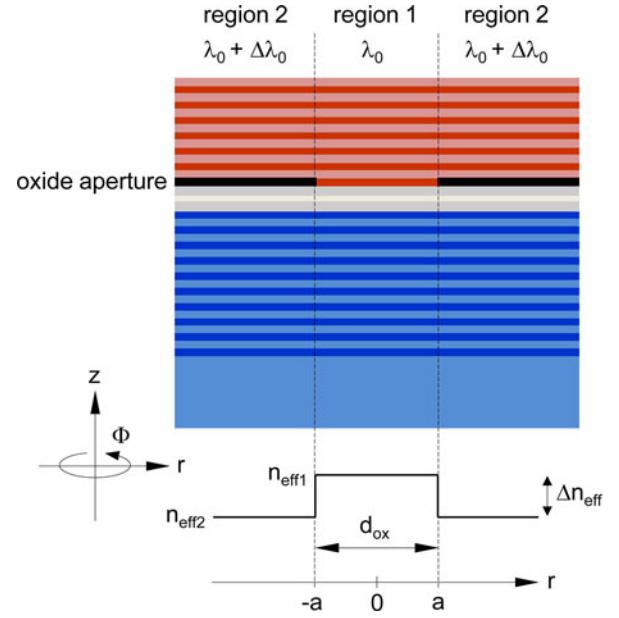


Fig. 3. Formation of a waveguide for transverse optical confinement in an oxide-confined VCSEL.

The active region of a VCSEL typically employs a number of quantum wells (QWs) positioned at an antinode of the standing wave in the vertical resonator (see Fig. 1), thus providing high-modal gain through a resonant enhancement of the longitudinal optical confinement.

A. Optical Fields and Modes

Optical field confinement in the longitudinal (vertical) direction is accomplished by the highly reflective DBRs positioned below and above the active region. Because of the short distance between the reflectors, forming a resonator with an effective length of only one or a few wavelengths, the resonator supports only one wavelength within the gain bandwidth of the active region. This corresponds to a single longitudinal mode with a field distribution as indicated in Fig. 1.

To introduce the concept of transverse modes, we consider an oxide-confined VCSEL [13] of circular symmetry, as illustrated in Fig. 3. The partially oxidized layer is electrically nonconducting, thus confining the current to the central region of the VCSEL defined by the oxide aperture of diameter d_{ox} . It also has a lower refractive index [14], thus providing transverse confinement of the optical field by forming a waveguide for light propagating in the longitudinal direction. The formation of a waveguide can be understood by applying an effective index analysis [15], which shows that any local modification of the VCSEL resonator that produces a local shift of the resonance wavelength ($\Delta\lambda_0$) produces a corresponding change of the effective index (Δn_{eff}) in that region

$$\frac{\Delta n_{\text{eff}}}{n_{\text{eff}}} \approx \frac{\Delta\lambda_0}{\lambda_0}. \quad (1)$$

Oxidation (which lowers the refractive index) produces a blue shift of the resonance wavelength ($\Delta\lambda_0 < 0$), and, therefore,

lowers the effective index in the oxidized region ($n_{\text{eff}2} < n_{\text{eff}1}$). Thus, a cylindrical waveguide is formed, having a core diameter of d_{ox} and an effective index difference between core and cladding of Δn_{eff} (see Fig. 3). Δn_{eff} is typically on the order of 0.01.

Using Maxwell's equations and the boundary conditions at the core-cladding interface, one can find the transverse electromagnetic modes supported by the waveguide, which are characterized by their propagation constants and characteristic field distributions in the transverse plane. In the weakly guiding approximation [16], where $\Delta n_{\text{eff}} \ll n_{\text{eff}}$, the modes can be expressed in terms of linearly polarized modes (polarized in the r - Φ plane), or LP_{mn} modes, where m is the azimuthal mode number and n is the radial mode number. In cylindrical coordinates, we have for the electric field amplitude of an LP_{mn} mode

$$E_{mn}(r, \Phi, z) \propto e^{jm\Phi} e^{-j\beta_{mn}z} J_m(u_{mn}r) \quad (2)$$

when $r < a$ (core), and

$$E_{mn}(r, \Phi, z) \propto e^{jm\Phi} e^{-j\beta_{mn}z} K_m(v_{mn}r) \quad (3)$$

when $r > a$ (cladding), where r , Φ , and z are the cylindrical coordinates, β_{mn} is the propagation constant, J_m is a Bessel function of the first kind and order m , and K_m is a modified Bessel function of the second kind and order m . The parameters u_{mn} and v_{mn} are given by

$$u_{mn}^2 = k_0^2 n_{\text{eff}1}^2 - \beta_{mn}^2 \quad (4)$$

$$v_{mn}^2 = \beta_{mn}^2 - k_0^2 n_{\text{eff}2}^2 \quad (5)$$

where k_0 is the propagation constant in vacuum. The modes supported by the waveguide and the corresponding values for the u and v parameters, and therefore the propagation constants, are obtained by applying the boundary conditions, which results in the following characteristic equation:

$$u \cdot \frac{J_{m-1}(ua)}{J_m(ua)} = -v \frac{K_{m-1}(va)}{K_m(va)}. \quad (6)$$

For a given waveguide with radius a (here, equal to half the diameter of the oxide aperture) and index step Δn_{eff} , a discrete and finite number of guided modes exist, which are the solutions of (6). With large radius and index step, a large number of modes exist. With sufficiently small radius and index step, only the fundamental LP_{01} mode exists.

The mode intensity, which is proportional to the square of the electric field amplitude, of some of the lowest order LP_{mn} modes are shown in Fig. 4. Note that each mode with $m \geq 1$ can be coupled with either a $\cos(m\Phi)$ or a $\sin(m\Phi)$ dependence, thus having two identical angular intensity distributions rotated with respect to each other. The LP_{01} mode is the fundamental mode of the waveguide and is the only active mode in a truly single-mode VCSEL.

The relative strength (intensity) of the various transverse modes under current injection depends on the overlap of the transverse intensity distribution with the transverse distribution of gain in the active region. Assuming that the transverse extent of gain is determined by the size of the oxide aperture (be-

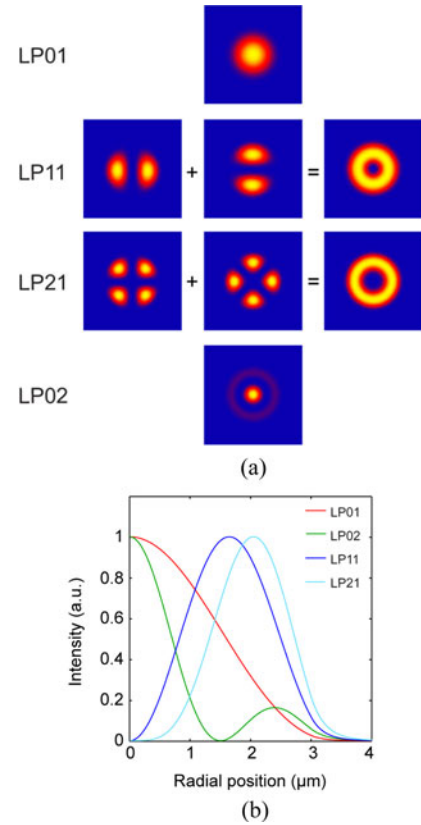


Fig. 4. (a) Intensity distributions for the four lowest order LP_{mn} modes of a cylindrical step-index waveguide in the transverse plane. (b) Transverse mode profiles in the radial direction for an oxide-confined VCSEL with $d_{\text{ox}} = 6 \mu\text{m}$.

cause of current confinement) and that gain is uniform within the aperture, one can define a transverse optical confinement factor, which determines the modal gain

$$\Gamma_{\text{trans},mn} = \frac{\int_0^a \int_0^{2\pi} E_{mn}^2 r d\Phi dr}{\int_0^\infty \int_0^{2\pi} E_{mn}^2 r d\Phi dr}. \quad (7)$$

As an example, a representative oxide-confined VCSEL emitting at 850 nm, with an aperture diameter of $6 \mu\text{m}$ [see Fig. 4(b)], has $\Gamma_{\text{trans},01} = 0.989$, $\Gamma_{\text{trans},11} = 0.971$, $\Gamma_{\text{trans},21} = 0.945$, and $\Gamma_{\text{trans},02} = 0.931$. The fundamental LP_{01} mode, which is more confined to the core of the waveguide, and, therefore, has a larger transverse optical confinement factor, has the highest modal gain, while higher order modes are less confined and therefore have less modal gain. This results in mode selectivity, favoring the fundamental mode. However, in real VCSELs any nonuniformity of current injection in the active region also introduces a certain degree of mode selectivity, e.g., favoring higher order modes in top emitting VCSELs with an annular top contact.

Under current injection, the properties of the waveguide are also affected by the presence of carriers in the active region and by self-heating. The presence of carriers within the core of the waveguide provides gain guiding which, just like index guiding, confines the optical field to the core of the waveguide [17]. However, carriers also have an effect on the real part of the refractive index, which is reduced with increasing carrier density

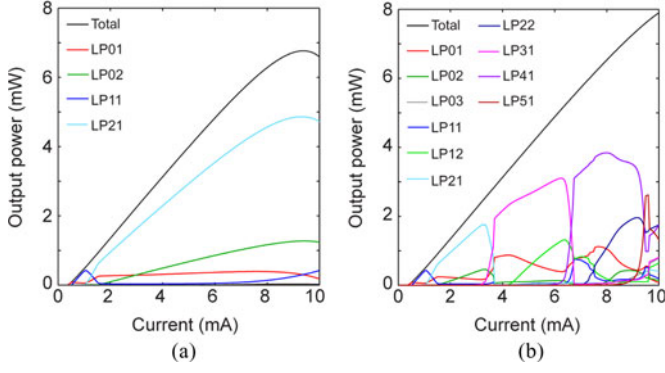


Fig. 5. Mode resolved power-current characteristics for a 7- μm oxide-confined 850-nm VCSELs without (a) and with (b) effects of carriers and temperature.

(the plasma effect). Therefore, carriers also produce an antiguiding effect. In addition, self-heating primarily due to the resistive loss in the VCSEL structure under current injection produces a convex radial temperature distribution. Through the temperature dependence of the refractive index (the thermo-optic effect), this translates into a thermal lens [18], which further confines the transverse optical fields to the core of the waveguide and allows for additional higher order modes. All these effects are superimposed on the built-in step-index waveguide and together define the modal characteristics of the VCSEL.

Above threshold, the strong stimulated emission rate in regions of high optical intensity results in a local depletion of the carrier density, an effect known as spatial hole burning [19]. This leads to further modifications of the guiding properties and strong competition between transverse modes with overlapping field distributions.

To illustrate the impact of carriers and temperature on the modal properties of VCSELs, we have applied a quasi-3-D numerical VCSEL model [20], which self-consistently treats all optical, electrical, and thermal effects, to an oxide-confined 850-nm GaAs-based VCSEL with a 7- μm oxide aperture. Fig. 5(a) shows mode-resolved power versus current characteristics when the effects of carriers and temperature on the real part of the refractive indexes are neglected, while Fig. 5(b) shows the corresponding behavior when these effects are included. Note the strikingly different behavior, and the mode competition and switching, due to spatial hole burning and thermal lensing, as the current increases.

In the weakly guiding approximation, the guided modes are transverse electromagnetic in nature with each mode having two linear and orthogonal states of polarization. If the optical properties of the VCSEL materials were isotropic, and the VCSEL geometry was perfectly cylindrical, the two polarizations of the LP_{mn} mode would propagate with the same propagation constant and have the same transverse intensity distribution. However, in a real VCSEL, due to weak anisotropies, the two polarization states have slightly different propagation constants, and therefore, the resonance wavelengths are slightly different [21]. Since there is no strong intrinsic mechanism to select one of the polarization states, VCSELs often exhibit un-

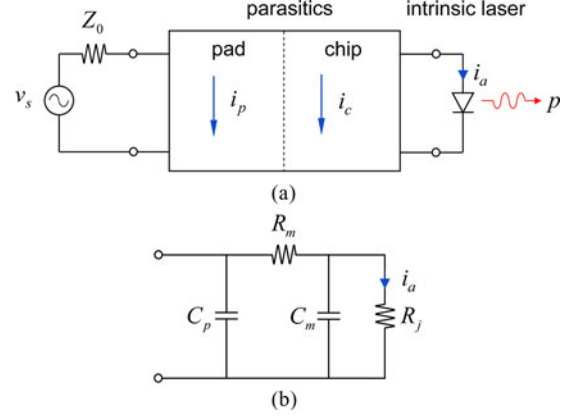


Fig. 6. (a) Two-port model for a directly modulated laser [109] showing the source voltage (v_s), source impedance (Z_0), modulation current (i_a), and modulated output power (p). Currents through pad and chip capacitances (i_p and i_c), bypassing the active region at high frequencies, are also indicated. (b) Equivalent electrical circuit used to represent the impedance characteristics and to analyze the parasitic speed limitations of a VCSEL. The circuit elements are described in the text.

controlled polarization instabilities under variations of current and temperature [22]. In a single-mode VCSEL, polarization switching causes a reduction of spectral purity and coherence.

B. Dynamics and High-Speed Modulation

The modulation speed of a VCSEL, like any other semiconductor laser, is limited by the intrinsic damping of the resonant carrier-photon interaction and by effects of self-heating and electrical parasitics. Guidelines for design can be derived from a single-mode rate equation analysis, which results in the following (intrinsic) transfer function representing the small-signal modulation response at frequency f [23]:

$$H_{\text{int}}(f) \equiv \frac{p(f)}{i_a} = A \frac{f_r^2}{f_r^2 - f^2 + j(f/2\pi)\gamma} \quad (8)$$

where p is the optical modulation amplitude, i_a is the modulation amplitude of the current through the active region [see Fig. 6(a)], and A is a constant. The resonant carrier-photon interaction (through stimulated emission) is characterized by the resonance frequency f_r and the damping rate γ . The rate at which the resonance frequency increases with current (I) above threshold (I_{th}) is quantified by the D -factor

$$f_r = D\sqrt{I - I_{\text{th}}}, \quad D = \frac{1}{2\pi} \sqrt{\frac{\eta_i \Gamma \nu_g}{q V_a} \frac{\partial g / \partial n}{\chi}} \quad (9)$$

where η_i is the internal quantum efficiency, Γ is the optical confinement factor, ν_g is the group velocity, q is the elementary charge, V_a is the volume of the active (gain) region, $\partial g / \partial n$ is the differential gain, and χ is the transport factor. The rate at which the damping rate increases with resonance frequency is quantified by the K -factor

$$\gamma = K f_r^2 + \gamma_0, \quad K = 4\pi^2 \left(\tau_p + \frac{\varepsilon \chi}{\nu_g (\partial g / \partial n)} \right) \quad (10)$$

where τ_p is the photon lifetime and ε is the gain compression factor. The damping offset γ_0 is inversely proportional to the differential carrier lifetime. Although (8)–(10) are the result of a single-mode rate equation analysis, they have proven useful also for guiding the design of high-speed multimode VCSELs [24].

The intrinsic modulation bandwidth is set by the rate at which damping increases with resonance frequency (10). Therefore, the intrinsic bandwidth benefits from a small photon lifetime, small gain compression, and large differential gain, which results in a small K -factor, and therefore, less damping at a given resonance frequency. Note, however, that these fundamental laser parameters cannot be independently optimized, since, for instance, a smaller photon lifetime leads to higher cavity loss, and therefore, a higher threshold carrier density, and consequently, a lower differential gain. This calls for tradeoffs in the design. Also, note that the commonly used expression for defining the maximum damping limited 3 dB bandwidth (derived from the rate equation analysis) [23]

$$f_{3\text{dB,damping}} = \frac{2\pi\sqrt{2}}{K} \quad (11)$$

is in most cases not valid, since it assumes that the contribution by the damping offset (γ_0) to the damping rate is negligible (10), which is typically not the case for properly designed high-speed VCSELs (with a small K -factor).

With the VCSEL having a relatively high series resistance, thermal effects caused by current induced self-heating have a more pronounced impact on speed than for edge emitting lasers. Increasing temperature leads to a reduction of gain, differential gain and internal quantum efficiency, and an increase of the threshold current, eventually causing the photon density and the output power, and therefore, the resonance frequency, to saturate at a certain current [24], referred to as the thermal rollover current [see Fig. 7(a)]. Therefore, the thermally limited bandwidth benefits from a large D -factor, which enables the VCSEL to reach a high resonance frequency before saturation. This again emphasizes the importance of large differential gain (9). In addition, smaller aperture VCSELs can reach a higher resonance frequency, since the D -factor is inversely proportional to the square root of the active region volume [25]. However, there is an optimum aperture size, since a too small aperture leads to very high resistance, and therefore, excessive self-heating. The optimum aperture size depends strongly on how resistance and thermal impedance scale with aperture size. For GaAs-based oxide-confined VCSELs, the highest resonance frequency is typically reached for an aperture size in the range 3–7 μm .

Current-induced self-heating also affects damping (the K -factor) through the temperature dependencies of photon lifetime, differential gain, and gain compression (10). In a properly designed high-speed VCSEL, with a sufficiently small photon lifetime, the K -factor is small at low currents and may increase at higher currents, primarily because of the reduction of differential gain with temperature [24]. This results in a superlinear increase of damping with resonance frequency squared [see Fig. 7(b)], and therefore, excessive damping at high currents. In addition, at very high active region temperatures, reached at high ambient temperatures and high currents, the escape rate of

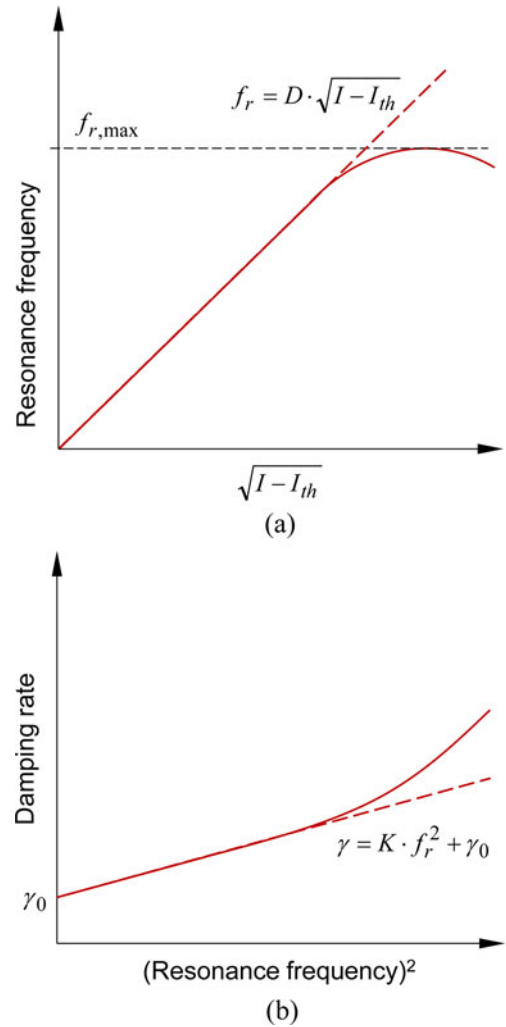


Fig. 7. (a) Dependence of resonance frequency on current and (b) dependence of damping rate on resonance frequency. The dashed lines indicate the expected linear dependencies in the absence of thermal effects, while the solid curves illustrate the effects of temperature (self-heating).

carriers out of the QWs may approach the capture rate, causing the transport factor (χ) to exceed unity [26]. This implies that effects of transport may further reduce the bandwidth through reduced resonance frequency and increased damping [see (9) and (10)].

With the strong effects of self-heating on the dynamics of VCSELs (the resonance frequency in particular), it is clear that thermal effects impose severe limitations on the achievable modulation bandwidth. High-speed VCSELs should, therefore, be designed for low heat generation (low resistance [27], low non-radiative recombination rates, low internal optical loss, etc.) and low thermal impedance (DBRs with high thermal conductivity [28], integrated metallic heat spreaders [29], mounting for efficient heat sinking [30], etc.) to minimize the current-induced temperature rise.

The modulation bandwidth is also limited by electrical parasitics (resistances and capacitances) associated with the VCSEL chip and the bond pad [see Fig. 6(a)]. This is commonly accounted for by multiplying the intrinsic transfer function (8)

by an extrinsic, single-pole transfer function representing a low-pass filter [24]

$$H_{\text{ext}}(f) \equiv \frac{i_a(f)}{v_s} = \frac{B}{1 + j(f \cdot f_p)} \quad (12)$$

where v_s is the source voltage [see Fig. 6(a)], f_p is the parasitic rolloff frequency, and B is a constant. This implies that at frequencies exceeding the parasitic rolloff frequency, the modulation current is bypassing the active region. For efficient modulation at high speed, it is therefore important to minimize both resistances and capacitances, thereby simultaneously increasing the parasitic rolloff frequency and improving the thermally limited bandwidth.

The contributions to the VCSEL capacitance depend strongly on the design and the technique used for current and optical confinement. Common to all designs are capacitances associated with the bond pad and the p-n junction used for current injection (diffusion and depletion capacitances). In an oxide-confined VCSEL [see Fig. 2(a)], there is an additional contribution from charge stored over the oxide layer (the “oxide capacitance” [31]), while in a BTJ VCSEL [see Fig. 2(b)], there is an additional contribution from charge stored over the depletion region of the reversed biased (blocking) p-n junction surrounding the BTJ [32].

An equivalent circuit commonly used for representing the impedance and analyzing the parasitic speed limitations of high-speed VCSELS is shown in Fig. 6(b). The capacitance C_p represents the pad capacitance. The resistances of DBRs, ohmic contacts, and contact/spreading layers are grouped together in R_m . The junction resistance is represented by R_j , while the capacitance C_m (the “mesa capacitance”) includes the active junction capacitance and the oxide capacitance (oxide-confined VCSELS) or the blocking junction capacitance (BTJ VCSELS). The subcircuit including R_m , R_j , and C_m represents a first-order low-pass filter and is therefore accurately described by a single-pole transfer function. When adding the pad capacitance (C_p), the single-pole transfer function (12) is an approximation. However, for a high-speed VCSEL, with a low value of C_p , the product of (8) and (12) has been found to be able to accurately represent the small-signal modulation response over a large range of currents [24]. This justifies the use of a single-pole transfer function to account for parasitic speed limitations.

The small-signal modulation bandwidth is a useful measure for assessing the high-speed capabilities of a VCSEL and for guiding the design of high-speed VCSELS. However, VCSELS used in communication links operate under large signal on-off modulation, where other measures like rise and fall times, extinction ratio, optical modulation amplitude, and jitter are of importance. While these measures are to a large extent affected by the same basic parameters as the modulation bandwidth, they also depend on, e.g., the circuitry used to drive the VCSEL. In addition, the intensity noise, which is strongly influenced by the transverse mode and polarization characteristics, is of importance. Mode competition in multimode VCSELS and polarization switching in VCSELS lacking polarization stability result in increased intensity noise, which may reduce the

signal-to-noise ratio at the optical receiver, thereby degrading link performance [33], [34].

III. VCSEL APPLICATIONS AND REQUIREMENTS

The application areas of VCSELS are mainly in sensing, measurements, and communication, with short reach communication and the optical computer mouse presently representing the largest markets in terms of VCSEL units. In what follows, requirements on VCSEL performance in selected applications are discussed and performance improvements for future developments and applications are identified.

A. Sensing and Measurements

Because of favorable beam characteristics, low power consumption, and high cost efficiency, VCSELS are increasingly used for optical navigation (position tracking) [4], [35]. This includes the optical computer mouse and optical finger navigation modules in, e.g., mobile handsets and other portable electronic devices. In position tracking, the use of laser light improves the resolution, sensitivity, and speed of tracking and enables tracking on a larger variety of surfaces. Modes of operation include analysis of interference effects, self-mixing, speckle recognition and dark field imaging, which all require an optical source with a high degree of coherence.

Gas sensing and analysis through absorption spectroscopy by means of tunable diode lasers (wavelength modulated spectroscopy), in fields ranging from medicine to monitoring and control of combustion processes, is another application area of VCSELS, where current-tuned VCSELS offer advantages over other types of diode lasers in terms of tuning range, response time, power consumption, and beam quality [6]. Since the technique is based on sweeping the laser emission line through specific gas absorption lines, high spectral purity (single emission line) of the optical source is required. The same requirement applies to VCSELS used in atomic clocks [8]. Emerging biomedical applications include, e.g., continuous blood glucose monitoring [36] and optofluidic microchip integration for chemical and biological sensing of liquid samples [37].

In other sensing and measurement applications, like optical encoding for position and motion sensing in mechanical systems [38] and the potential use of VCSELS for reading data stored on an optical disk [39], it is of importance to be able to focus the light from the VCSEL to a diffraction limited spot for the highest spatial resolution. This also includes nonsensing applications, such as laser printing, where arrays of individually addressable VCSELS are used to improve print resolution and speed [7].

It is obvious that many of the applications in sensing and measurements, where VCSELS are (or could/will be) used require coherence, spectral purity and/or the capability of focusing the beam to a diffraction-limited spot, implying that single-mode VCSELS are needed. In addition, polarization stability has to be maintained under variations of current and temperature, since polarization switching leads to reduced coherence and spectral broadening [21], [22]. Many applications would also benefit from high optical power as more power enables faster, more accurate, and more sensitive real-time measurements. High-power

single-mode VCSELs would not only benefit applications in sensing and measurements but also applications like laser printing and longer distance communication on single-mode fiber.

Although not explicitly treated in this tutorial, some sensing (and other) applications require tuning of the VCSEL emission wavelength. In, for example, gas analysis, coarse tuning is achieved by changing the VCSEL stage temperature, while fine (and faster) tuning is achieved by varying the drive current (thermally induced tuning) [6]. For a larger tuning range, a movable top mirror is integrated using microelectromechanical systems (MEMS) technology [40]–[42].

B. Communication

VCSELs can potentially be used at all levels of the optical communication network, except for very long distance transmission, where externally modulated distributed feedback lasers are used to meet requirements of high power and low chirp.

For medium distance communication, including metro and access networks, which are based on single-mode optical fiber, high-speed VCSELs emitting in the 1310 and 1550 nm bands are developed [43]. Such long wavelength VCSELs have to be single mode to enable efficient laser–fiber coupling and to prevent excessive pulse broadening over longer transmission distances caused by chromatic dispersion in the fiber. Combining high-speed modulation with array integration and/or wavelength tuning is also of interest for wavelength-division multiplexing [41], [44]. The maximum single channel (per wavelength) speed is presently at 10 Gb/s [45], but evolving FTTX and 40G/100G Ethernet solutions require a higher single channel speed (e.g., 25 Gb/s for a 4×25 Gb/s 100G solution) to meet requirements of low system cost [46].

For short reach LAN environments, including optical networks in data centers [storage area networks (SANs)] and high performance computing (HPC) systems, VCSELs have already replaced other lasers as the preferred light source to meet stringent requirements of high speed, high efficiency, and low cost [47]. Such networks are governed by standards like Ethernet, Fiber Channel, and InfiniBand [48]. The links are based on high-speed multimode fiber (MMF) (e.g., OM3 fiber) optimized for a wavelength of 850 nm. VCSELs are multimode, which relaxes fabrication tolerances and makes the link performance less sensitive to mode-selective loss and optical feedback [49]. Arrays of high-speed VCSELs are used for parallel fiber links (space division multiplexing) to achieve very high aggregate capacity (exceeding 100 Gb/s) [50]. Single channel (per fiber) speed is presently at ~ 10 Gb/s, but much higher speed is required in the near future (see Fig. 8) [48]. VCSELs at 20–25 Gb/s are under development and 40 Gb/s VCSELs are expected within an additional few years. In addition to speed enhancement, improved power efficiency is of utmost importance as the dense interconnect networks employed in, e.g., SANs and HPC systems tend to consume a substantial amount of power [51].

Optical links in computer and consumer electronics (USB, PCI Express, DisplayPort, HDMI, etc.) and very short reach optical interconnects (at board, module, and chip level) represent others areas of rapidly growing importance for communica-

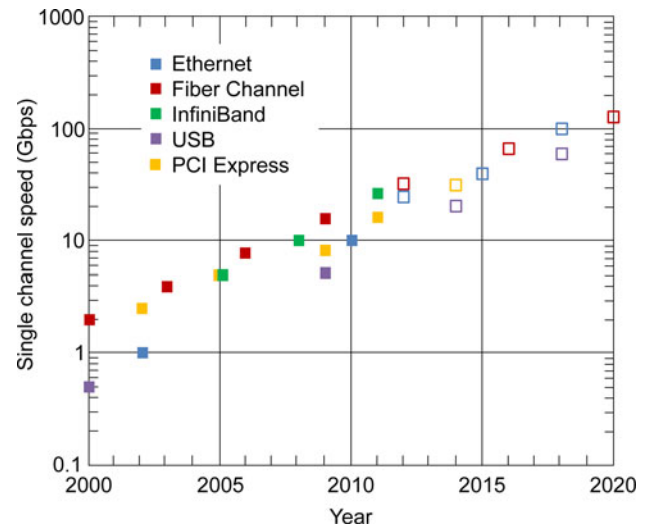


Fig. 8. Evolution of single channel speed in some LAN, SAN, HPC, and consumer standards [48]. Open symbols indicate predictions.

tion VCSELs [52], with steadily increasing speed requirements (see Fig. 8) [48]. Again, 850 nm is an important wavelength, but longer wavelength GaAs-based VCSELs (at, e.g., 980 and 1060 nm) are of increasing interest, as they offer not only high speed but also lower drive voltage, improved efficiency, and improved high temperature performance [53].

With VCSEL-based optical links becoming increasingly used for computer interconnects and with consumer electronics emerging as a new market for communication VCSELs, production volumes will soar. Developments like the Light Peak technology by Intel (a high-speed optical cable technology designed to interconnect electronic devices with the ability to run multiple protocols simultaneously over a single cable [54]) and the emergence of PetaFlop/s-ExaFlop/s capacity supercomputers, eventually requiring hundreds of millions of optical interconnects [55], will accelerate the growth.

IV. HIGH-POWER SINGLE-MODE VCSELs

A. Techniques and State of the Art

Single-mode VCSELs can be divided into those that are inherently single mode and those that are inherently multimode with single-mode emission enforced by mode selective loss. We will limit the discussion to VCSELs, where the entire VCSEL resonator is defined by the epitaxial structure. This excludes VCSELs with an external curved mirror for mode selective feedback, which can produce much higher output power under current injection [56], [57].

In its most simple form, an inherently single-mode VCSEL employs a waveguide sufficiently narrow, and with a sufficiently small effective index step, to support the fundamental LP_{01} mode only. Among the GaAs-based (short wavelength) VCSELs, the oxide-confined VCSEL [see Fig. 2(a)], with an oxide aperture diameter of only $3.5 \mu\text{m}$ and the oxide layer positioned at a field minimum for weak index guiding, has demonstrated 4.8 mW of single-mode power at 840 nm [58]. The small

aperture leads to a high series resistance, which limits the output power because of excessive current induced self-heating. A more elaborate method for transverse mode control in VCSELS is the use of a 2-D, single-defect photonic crystal (PhC) structure defined by a pattern of etched holes in the top DBR [59]. With a proper selection of hole depths, diameters, and arrangement, index confinement can be exploited to create a single-mode waveguide. GaAs-based PhC-VCSELS have reached a highest single-mode power of 5.7 mW at 990 nm [60]. A particular problem for such PhC-VCSELS is the increased optical loss and electrical resistance caused by the deep holes, leading to relatively high threshold currents and low efficiency.

Among the InP and GaSb-based (long wavelength) inherently single-mode VCSELS, the use of a BTJ has been most successful [see Fig. 2(b)]. With a small enough diameter of the BTJ, the waveguide supports the fundamental mode only. InP-based BTJ-VCSELS have produced single-mode powers exceeding 3 mW at 1.3 μm [61], [62] and as much as 6.7 mW at 1.55 μm [63] and 0.5 mW at 2.36 μm [64]. Using a somewhat different design with wafer-fused AlGaAs-based DBRs, InP-based BTJ-VCSELS have reached single-mode powers of 6 mW at 1.3 μm [65] and 6.5 mW at 1.55 μm [66]. The less mature GaSb-based BTJ-VCSEL technology has reached single-mode powers of 0.7 mW at 2.36 μm [64] and 0.3 mW at 2.6 μm [67].

A variety of techniques have been developed to enforce single-mode emission from inherently multimode VCSELS by mode selective loss. This allows for larger current apertures compared to inherently single-mode designs, and therefore, lower resistance and less self-heating, which enables higher output power. Since this is of particular importance for short wavelength VCSELS, which require small apertures for inherent single-mode emission, such techniques have been implemented primarily for oxide-confined GaAs-based VCSELS. Successful techniques include:

- 1) the use of an extended cavity, where higher order modes with larger propagation angles suffer from increased diffraction loss (5.4 mW at 980 nm [68]);
- 2) the use of a small metal aperture on the top DBR for increased loss (phase-mismatched reflection) and spatial filtering of higher order modes (4.7 mW at 850 nm [69]);
- 3) the use of selective area, impurity induced disordering of the top DBR for a mode selective increase of the cavity loss through reduced top DBR reflectivity and increased free-carrier absorption (7.3 mW at 850 nm [70]);
- 4) the use of a shallow surface relief etched in the top DBR for a spatial variation of the cavity loss through a spatial variation of the phase of the reflection at the surface (>6 mW at 850 nm [71], [72]).

The latter is described in more detail in Section IV-B. Single-mode emission can also be achieved with an antiguiding VCSEL design, where higher order modes suffer from excessive transverse radiation loss [73]. However, mode suppression is limited and the threshold current is typically high, since also the fundamental mode suffers from large radiation loss.

Table I summarizes the performance in terms of maximum single-mode power under continuous operation at room temperature for GaAs-, InP-, and GaSb-based VCSELS, covering the

TABLE I
SUMMARY OF HIGHEST POWER SINGLE-MODE VCSELS AT SHORT
AND LONG WAVELENGTHS (OC = OXIDE CONFINED)

Technology	Wavelength (nm)	Single mode power (mW)	Ref.
GaAs-OC (small aperture)	670	2.8	74
GaAs-OC (surface relief)	760	2.0	75
GaAs-OC (metal aperture)	780	3.4	76
GaAs-OC (small aperture)	840	4.8	58
GaAs-OC (surface relief)	850	6.3	72
GaAs-OC (disordering)	850	7.3	70
GaAs-OC (metal aperture)	850	4.7	69
GaAs-OC (extended cavity)	980	5.4	68
GaAs-antiguided	980	7.1	73
GaAs-OC (PhC)	990	5.7	60
InP-BTJ	1310	6.0	65
InP-BTJ	1550	6.7	63
InP-BTJ	2365	0.5	64
GaSb-BTJ	2355	0.7	64
GaSb-BTJ	2420	0.3	10
GaSb-BTJ	2600	0.3	67

short and long wavelength regions. While these are the highest single-mode powers reported, it should be noted that not all designs fulfill requirements of low threshold current, high efficiency, and sufficient mode suppression.

Because of highly symmetrical crystal properties and circularly symmetric device geometries, the single-mode VCSEL designs presented above lack strong polarization anisotropy, and therefore, unpredictable polarization switching may occur with changing current and temperature [22]. To guarantee polarization stability, thereby maintaining spectral purity and coherence, a number of techniques for polarization control, all based on the introduction of anisotropic optical gain or loss, have been proposed. This includes, for example, the use of anisotropic stress [77], asymmetric cavities [78], asymmetric current injection [79], DBRs with gratings (surface or buried) [80]–[83], high contrast grating mirrors [84], and growth on non-(1 0 0) substrate orientations for polarization-dependent optical gain [85]. Among these techniques, the use of gratings has proved most successful, enabling strong polarization pinning also under strong current modulation [86].

It is likely that with further refinements (improved efficiency and thermal management in particular) and/or the development of new schemes for transverse and polarization mode control, polarization stable single-mode all-epitaxial VCSELS will be able to routinely provide in excess of 10 mW of optical power at both short and long wavelengths.

B. Surface Structures for Transverse and Polarization Mode Control

One of the most efficient and successful techniques for transverse and polarization mode control in oxide-confined, short wavelength VCSELS is the use of a shallow surface structure etched in the top DBR [87]. The technique, which was developed at Chalmers University of Technology [71], [81], [88], [89] and Ulm University [72], [80], [90], [91], is superior to other techniques in that the electrical and thermal properties of the VCSEL are not degraded by the shallow surface structure.

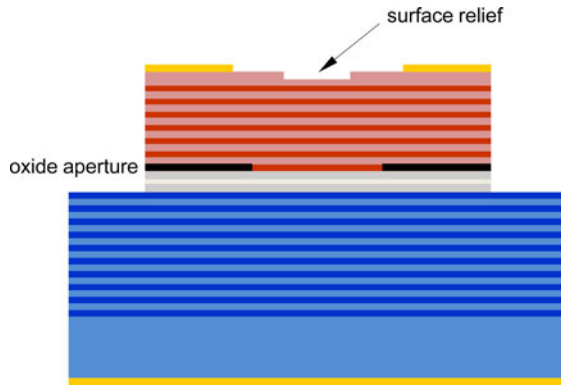


Fig. 9. Oxide-confined VCSEL with a shallow surface relief for single-mode emission (the “inverted” design).

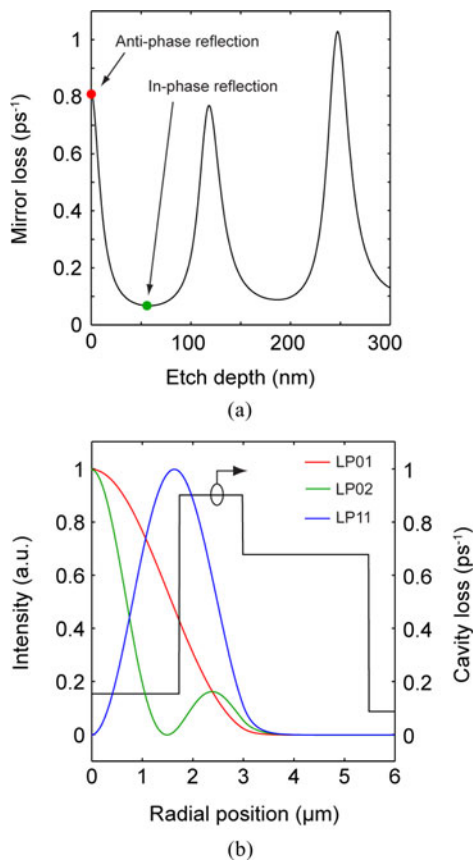


Fig. 10. (a) Dependence of top DBR loss on etch depth for an 850-nm VCSEL with a 22 pair top DBR and an added antiphase layer. (b) Cavity loss as a function of the transverse position for an oxide-confined 850 nm VCSEL with a 6- μm oxide aperture and a 3- μm surface relief (60 nm deep), illustrating the overlap of the fundamental mode with the low loss region and the overlap of the higher order modes with the high loss region.

Therefore, high single-mode power and polarization control can be achieved together with low threshold current, high efficiency, and low-series resistance. The introduction of shallow surface structures also represents a small modification to standard VCSEL fabrication procedures.

The technique is based on the fact that the reflectivity (or loss) of the top DBR is very sensitive to the phase of the reflection at

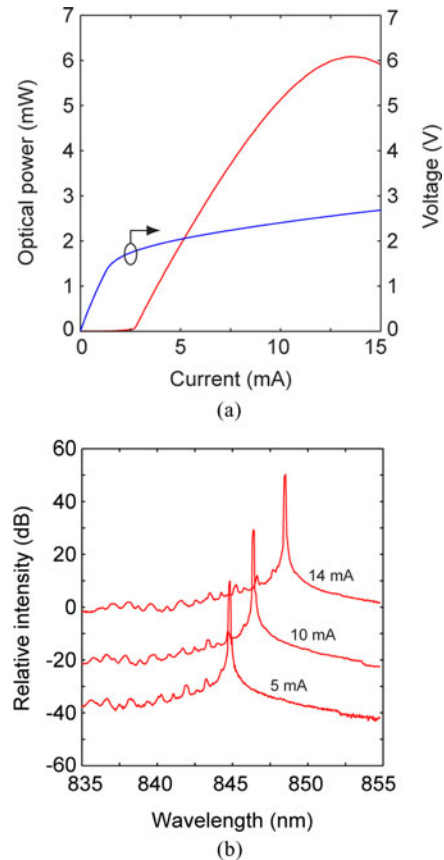


Fig. 11. (a) Output power and voltage as a function of current for an 850-nm VCSEL with a 5- μm oxide aperture and a 2.5- μm surface relief. (b) Emission spectra recorded at different drive currents.

the surface, with the phase being controlled by the thickness of the top layer. An in-phase reflection results in a high reflectivity, while an antiphase reflection results in a lower reflectivity. The large sensitivity to phase variations of the surface reflectivity is a result of the large index step at the surface.

To simplify fabrication, we use an “inverted” design (see Fig. 9) [71], [87], where the thickness of the top layer is increased by a quarter wavelength for an antiphase reflection at the surface. The added antiphase layer results in an approximately tenfold increase of the optical loss through the top DBR [see Fig. 10(a)]. Mode selective loss is then achieved by removing the antiphase layer in the central part above the oxide aperture, thereby increasing the top DBR reflectivity in this region and preferentially lowering the loss for the fundamental mode, while maintaining a higher loss for the higher order modes [see Fig. 10(b)]. The “inverted” design relaxes the requirement on precision in etch depth [71], [87], [90]. By optimizing the diameters of the oxide aperture and the surface relief, more than 6 mW of single-mode power and a 30-dB suppression of higher order transverse modes, from threshold to thermal rollover (see Fig. 11), have been achieved for VCSELs emitting at 850 nm [71], [72]. The strong mode discrimination is also proved by single-mode emission being maintained under strong RF modulation [92].

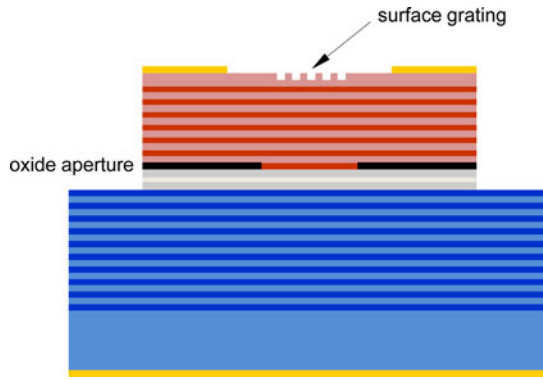


Fig. 12. Oxide-confined VCSEL with a small area surface grating for single-mode emission and polarization control.

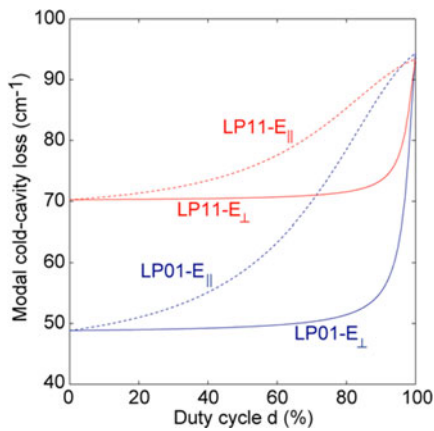


Fig. 13. Cavity loss for the lowest order transverse modes (LP_{01} and LP_{11}) and their orthogonal polarization states as a function of grating duty cycle. The diameter of the oxide aperture, the diameter of the grating region, and the grating depth are $4.5 \mu\text{m}$, $2.5 \mu\text{m}$, and 60 nm , respectively.

Polarization control of the fundamental mode has further been achieved by combining the shallow surface relief with a shallow surface grating (see Fig. 12), where the spatial extent of the grating region selects the fundamental transverse mode, while the grating lines pin the polarization state [93], [94]. A subwavelength grating has been used to prevent an increase of optical loss and a degradation of beam quality, which may occur if higher diffraction orders are allowed. To a good approximation, the grating layer can then be treated as an anisotropic effective index medium [93], with different effective indexes parallel and perpendicular to the grating lines. By optimizing the diameters of the oxide aperture and the grating region, and the depth and duty cycle of the grating, large discriminations against higher order transverse modes (20 cm^{-1}) and the orthogonal polarization mode (15 cm^{-1}) can be achieved (see Fig. 13) [89], [93]. Such a VCSEL design has produced more than 4 mW of single-mode power with 30 dB suppression of higher order transverse modes and 20 dB suppression of the orthogonal polarization state, from threshold to thermal rollover (see Fig. 14) [81].

The use of surface structures for transverse and polarization mode control is a generic technique, not limited to GaAs-based oxide-confined VCSELs emitting at 850 nm . The technique has also been applied to GaAs-based oxide-confined VCSELs

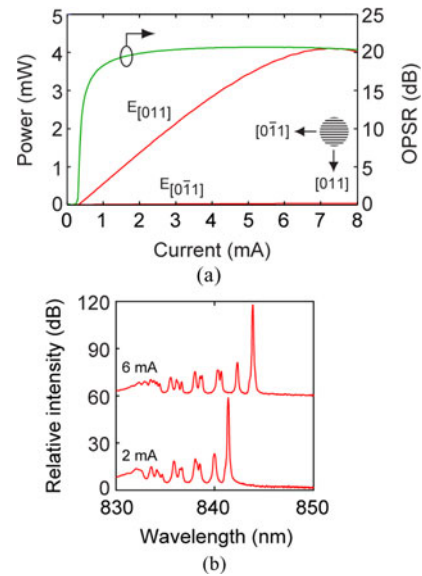


Fig. 14. (a) Polarization resolved output power as a function of current for an 850-nm VCSEL with a $4.5\text{-}\mu\text{m}$ oxide aperture and a $2.5\text{-}\mu\text{m}$ grating diameter. The orthogonal polarization suppression ratio (OPSR) is also shown. (b) Emission spectra recorded at different drive currents.

emitting at $1.3 \mu\text{m}$ [95] and more recently to GaSb-based BTJ-VCSELs emitting at $2.3 \mu\text{m}$ [96]. Subwavelength gratings have also been used to stabilize the polarization of InP-based single-mode BTJ-VCSELs emitting at $1.6 \mu\text{m}$ [83]. Finally, it should be noted that surface gratings are nowadays used in the production of polarization stable oxide-confined single-mode VCSELs for optical mice (850 nm), where the grating is defined by nanoimprint lithography for cost-efficient manufacturing [4].

V. HIGH SPEED VCSELs

A. Progress and State of the Art

During recent years, there has been significant progress in the development of high-speed VCSELs for medium- and short-reach communication, driven by the needs for much higher capacity at all levels of the communication network.

Table II summarizes the state of the art for long wavelength communication VCSELs (single mode) in the 1310 and 1550 nm bands. At $\sim 1300 \text{ nm}$, both GaAs-based oxide-confined VCSELs (with strained GaInNAs QWs [100] or heavily strained InGaAs QWs [99]) and InP-based BTJ-VCSELs [62], [97], [98] have reached a modulation bandwidth of about 10 GHz and have demonstrated error-free transmission over $\sim 10 \text{ km}$ of single-mode fiber at 10 Gb/s . The highest data rate reported is 12 Gb/s using an InP-based BTJ-VCSEL [97]. Most notable is also the development of 10 Gb/s InP-based BTJ-VCSELs operating up to a temperature as high as 100°C [98]. At $\sim 1550 \text{ nm}$, all high-speed VCSELs are InP-based BTJ-VCSELs [32], [62], [101]. A record modulation bandwidth of 17 GHz was recently achieved with a short cavity design, enabling error-free transmission at 25 Gb/s over 4.2 km of standard single-mode fiber at 25°C [101]. At higher temperatures (85°C), transmission has so far been limited at 12 Gb/s [32].

TABLE II
STATE OF THE ART FOR HIGH-SPEED LONG WAVELENGTH COMMUNICATION VCSELS
(OC = OXIDE CONFINED AND SMF = SINGLE-MODE FIBER)

Wavelength (nm)	Technology	Bandwidth @ RT (GHz)	Bit rate (Gbps)	Temp. (°C)	Link configuration	Ref.
~1310	InP – BTJ	11	12	70	10 km SMF	97
	InP – BTJ	>6	10	100	10 km SMF	98
	InP – BTJ		10	85	10 km SMF	62
	GaAs – OC	8	10	85	9 km SMF	99
	GaAs – OC		10	25	10 km SMF	100
~1550	InP – BTJ	17	25	25	4.2 km SMF	101
	InP – BTJ	12	12	85	BTB	32
	InP – BTJ		10	85	10 km SMF	62

TABLE III
STATE OF THE ART FOR HIGH-SPEED SHORT WAVELENGTH COMMUNICATION VCSELS

Wavelength (nm)	Bandwidth @ RT (GHz)	Bit rate (Gbps)	Temp. (°C)	Current density (kA/cm ²)	Efficiency (fJ/bit)	Link config.	Ref.
~850	23	40	25	21	450	BTB	102
	23	35	25	19	460	100 m MMF	102
	20	32	25	11	330	50 m MMF	103
	20	25	85	14	650	100 m MMF	103
	21	38	25	14	500	BTB	104
	19	30	25	28		100 m MMF	105
	19	25	25	21		100 m MMF	105
	16	25	25	7	800	100 m MMF	106
	14	25	25	25		BTB	107
	16	20	70	24	800	BTB	108
~980	20	35	25	60	285	BTB	109
		25	70	14		BTB	110
		20	70	10		BTB	110
	14	20	120	85		BTB	111
	14	25	85	23	800	BTB	112
~1060	24	40	25	18	240	BTB	113
	20	30	25	19		100 m MMF	114
	18	25	100	21		BTB	115
		10	25		180	100 m MMF	116

All VCSELS are GaAs-based and all are oxide-confined, except for ref. [106], which is a PhC-confined VCSEL, and ref. [113], which is a BTJ VCSEL.

Large efforts have been invested in the development of short wavelength communication VCSELS. Table III summarizes the state of the art. All VCSELS are GaAs-based (in most cases multimode) and performance has (in most cases) been verified by error-free transmission back-to-back (BTB) or over certain lengths of MMF. At 850 nm, a modulation bandwidth as high as 23 GHz has been reached by an oxide-confined VCSEL design offering high differential gain, low gain compression, small photon lifetime, low thermal impedance, and low capacitance (described in more detail in Section V-B). This has enabled transmission at 40 Gb/s BTB and at 35 Gb/s over 100 m of MMF [102]. At longer wavelengths of 980 and 1060 nm, VCSELS with modulation bandwidths of 20 and 24 GHz have enabled transmission at 35 and 40 Gb/s, respectively [109], [113]. The modulation bandwidth of 24 GHz, achieved by a GaAs-based tunnel junction VCSEL design, is the highest modulation bandwidth ever reported for a VCSEL. At data rates in the range 20–25 Gb/s, operation at high temperatures has been reported for VCSELS at both 850, 980, and 1060 nm, with a tendency of improved high-temperature performance at the longer wavelengths (20 Gb/s at 120 °C at 980 nm [111] and 25 Gb/s at 100 °C at 1060 nm [115]). The same tendency can

be observed for the efficiency of data transfer (in terms of dissipated energy per transmitted bit), with values above 300 fJ/bit at 850 nm [103] and values below 300 fJ/bit at 980 and 1060 nm at high bit rates [109], [113]. A record efficiency of 140 fJ/bit was recently demonstrated for a 1060-nm VCSELS at a lower bit rate (10 Gb/s) [116]. The improved efficiency and improved high-temperature performance at longer wavelengths are related to the use of deeper and more strained InGaAs QWs. Improvements are also partly due to the use of intracavity contacts (for low resistance and low optical loss) and binary elements in the DBRs (for low thermal impedance). Finally, it should be noted that many of the high-speed GaAs-based VCSELS operate at a current density approaching 10 kA/cm², which is close to the current density of today's very reliable 10 Gb/s VCSELS [117].

It is likely that, with further refinements, present high-speed VCSEL technologies (at both short and long wavelengths) will be capable of 40 Gb/s modulation over a wide range of temperatures and with the margins needed in real systems. However, it is also likely that 40 Gb/s is the upper limit for direct current modulation. Reaching a higher single channel speed (e.g., 100 Gb/s) will require new innovative modulation schemes [118]–[120] and/or new modulation formats [121].

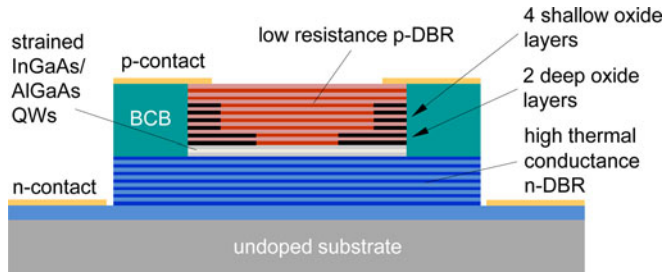


Fig. 15. Cross-sectional view of the high-speed 850-nm VCSEL indicating several of the design features for speed enhancement.

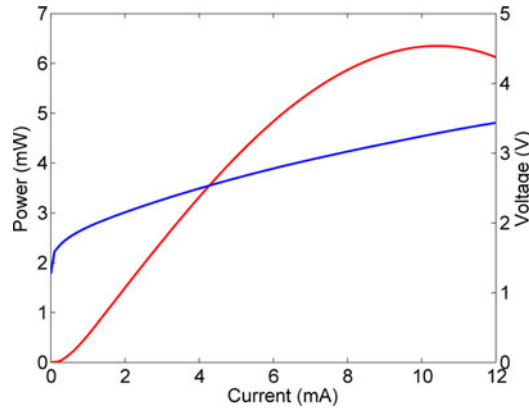


Fig. 16. Output power and voltage as a function of current for a VCSEL with a 7- μm aperture in the deep oxide layers (see Fig. 15).

B. Data Communication VCSELs at 40 Gb/s

As mentioned earlier, datacom VCSELs at 850 nm have recently reached a modulation bandwidth of 23 GHz, enabling for the first time error-free transmission at 40 Gb/s at this wavelength [102]. The design is shown in Fig. 15. The active region employs five strained InGaAs/AlGaAs QWs for improved differential gain and a separate confinement heterostructure designed for fast carrier capture and reduced gain compression [122]. For low resistance, we use graded interfaces and modulation doping in the AlGaAs-based DBRs, and to lower the thermal impedance, we use a binary compound (AlAs) in most of the bottom DBR [28]. For low capacitance, we use a multioxide layer design [109], [123] with two deep oxide layers defining the aperture for current and optical confinement, and an additional four shallow oxide layers for capacitance reduction [124]. The Al-contents in the two sets of oxide layers (98% and 96%, respectively) result in an oxidation rate for the higher Al-content layers twice that of the lower Al-content layers, thus creating an aperture size in the lower Al-content layers twice as large as that in the higher Al-content layers. Transport simulations have shown that this causes a negligible increase of resistance, while reducing the oxide capacitance by 50%. The bond pad capacitance is kept at a minimum by a thick layer of benzocyclobutene under the pad and a small pad size. A reduction of the photon lifetime is achieved by shallow etching of the topmost layer in the top DBR (which is initially a quarter wavelength thick), thus again controlling the reflectivity of the top DBR by the phase of the reflection at the surface [125].

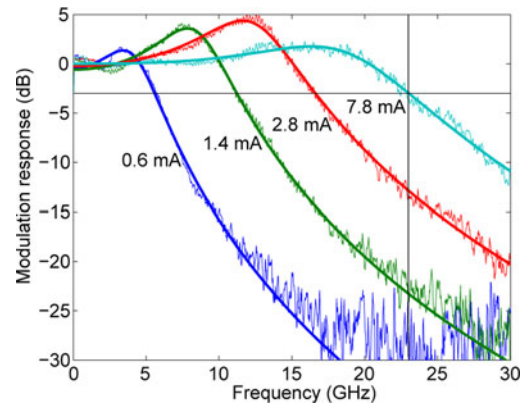


Fig. 17. Small-signal modulation response at different bias currents.

The optimum photon lifetime, for maximum modulation bandwidth, was found to be ~ 3 ps for this particular VCSEL design (achieved by a 40-nm surface etch).

Output power and voltage versus current characteristics for a VCSEL with a 7- μm aperture in the deep oxide layers are shown in Fig. 16. The threshold current is 0.43 mA, the slope efficiency is 0.95 W/A, and a maximum output power of 6.2 mW is reached at the thermal rollover current of 10.5 mA. The high slope efficiency, which improves the optical modulation amplitude, is a result of the reduced top DBR reflectivity. The small increase of damping with resonance frequency (current), achieved by a small photon lifetime, large differential gain and small gain compression, is seen in the small-signal modulation response shown in Fig. 17. The maximum modulation bandwidth of 23 GHz is the highest ever achieved for an 850 nm datacom VCSEL [125]. Finally, results from transmission experiments using an OM3 MMF and a 30-GHz optical receiver are shown in Fig. 18 [102]. In a BTB configuration, error-free transmission at 40 Gb/s was achieved with less than 0 dBm of received optical power. At 35 Gb/s, error-free transmission over 100 m of fiber was achieved at a similar power level.

VI. CONCLUSION

Significant progress in the development of VCSELs toward higher speed, higher single-mode power, and polarization control has occurred during recent years, driven by real needs in communication and sensing systems. Further progress is anticipated by engineering refinements of present VCSEL designs (thermal engineering and management in particular) and by the development of new VCSEL concepts. Production volumes will soar as VCSELs are becoming increasingly used in optical interconnects and consumer applications. New areas of application will likely emerge as a result of an extended wavelength coverage (by VCSELs in new materials), enhanced functionality through integration (horizontal as well as vertical), and new VCSEL technologies (such as high-power VCSELs and VCSEL arrays). Finally, for the commercial success of new VCSEL technologies, stringent requirements on reliability and manufacturability have to be met.

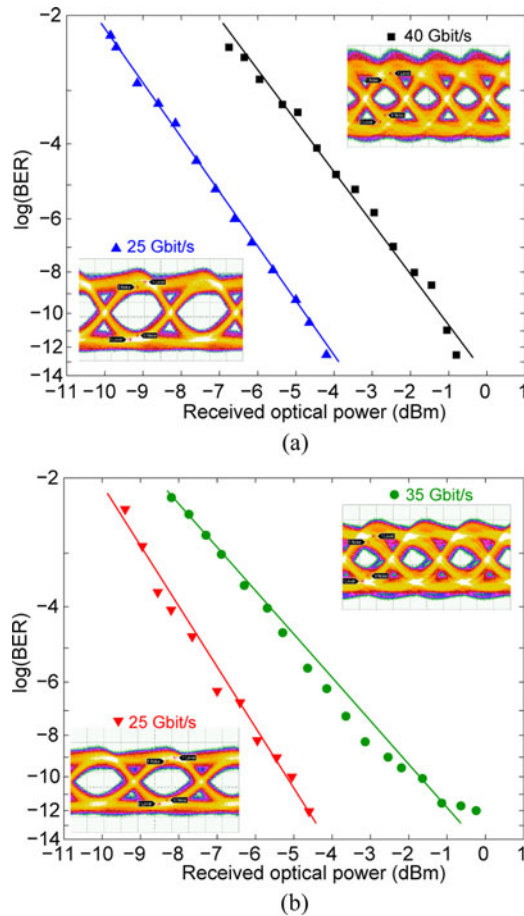


Fig. 18. Bit error rate as a function of received optical power at bit rates of (a) 40 and 25 Gb/s in a BTB configuration and (b) 35 and 25 Gb/s when transmitting over 100 m OM3 fiber. The insets show the received eyes.

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