

Article

VCSELs: Influence of Design on Performance and Data Transmission over Multi-Mode and Single-Mode Fibers

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Abstract

Substantial improvements in the performance of optical interconnects based on multi-mode fibers are required to support emerging single-channel data transmission rates of 200 Gb/s and 400 Gb/s. Future optical components must combine very high modulation bandwidths—supporting signaling at 100 Gbaud and 200 Gbaud—with reduced spectral width to mitigate chromatic-dispersion-induced pulse broadening and increased brightness to further restrict flux-confining area in multi-mode fibers and thereby increase the effective modal bandwidth (EMB). A particularly promising route to improved performance within standard oxide-confined VCSEL technology is the introduction of multiple isolated or optically coupled oxide-confined apertures, which we refer to collectively as multi-aperture (MA) VCSEL arrays. We show that properly designed MA VCSELs exhibit narrow emission spectra, narrow far-field profiles and extended intrinsic modulation bandwidths, enabling longer-reach data transmission over both multi-mode (MMF) and single-mode fibers (SMF). One approach uses optically isolated apertures with lateral dimensions of approximately 2–3 μm arranged with a pitch of 10–12 μm or less. Such devices demonstrate relaxation oscillation frequencies of around 30 GHz in continuous-wave operation and intrinsic modulation bandwidths approaching 50 GHz. Compared with a conventional single-aperture VCSELs of equivalent oxide-confined area, MA designs can reduce the spectral width (root mean square values < 0.15 nm), lower series resistance ($\approx 50 \Omega$) and limit junction overheating through more efficient multi-spot heat dissipation at the same total current. As each aperture lases in a single transverse mode, these devices exhibit narrow far-field patterns. In combination with well-defined spacing between emitting spots, they permit tailored restricted launch conditions in MMFs, enhancing effective modal bandwidth. In another MA approach, the apertures are optically coupled such that self-injection locking (SIL) leads to lasing in a single supermode. One may regard one of the supermodes as acting as a master mode controlling the other one. Streak-camera studies reveal post-pulse oscillations in the SIL regime at frequencies up to 100 GHz. MA VCSELs enable a favorable combination of wavelength chirp and chromatic dispersion, extending transmission distances over MMFs beyond those expected for zero-chirp sources and supporting transfer bandwidths up to 60 GHz over kilometer-length SMF links.



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1. Introduction

Modern computing systems continue to increase their processing capabilities, roughly doubling every year. This growth drives an exploding demand for energy efficient data transmission links at continuously higher single-channel data rates and larger channel counts per link. Copper cables have historically seen their usable distance shrink by a factor of four every 10 years, and they struggle to accommodate more channels within the same cross-section at elevated data rates. Optical interconnects are therefore steadily increasing their share of the overall cable-assembly market. Vertical-cavity surface-emitting lasers (VCSELs) are the principal building blocks for compact, energy-efficient optical interconnects. Because of their very small device dimensions—mesa diameters in the 15–30 μm range—VCSELs can be hybrid-integrated with CMOS integrated circuits or chiplets, and they remain compatible with the installed base of multi-mode fibers. VCSEL manufacturing relies on well-established, foundry-based processes; development and equipment costs are further supported by applications in sensing, optical pumping and free-space optical communications. This combination facilitates cost-efficient, scalable manufacturing: the same technology platform can be used while only the chip design or emission wavelength is modified to meet specific standards or applications. In the past, VCSELs have consistently met or exceeded required data-communication targets at the lowest possible cost, form factor and energy consumption. New physical effects now offer the possibility of further increasing the intrinsic modulation bandwidth of these devices.

2. VCSEL Design Development

Initially VCSELs [1] were fabricated with a semiconductor active region sandwiched between dielectric or metal reflectors. GaInAsP–InP was used for the active region. GaAs-based VCSELs and VCSEL arrays, including individually addressable arrays [2], were fabricated during the early stages of development. The basic design typically consisted of a vertical cavity made of a material with a high refractive index confined by distributed Bragg reflectors (DBRs) of a lower average refractive index.

Optical properties of AlAs–GaAs planar vertical cavities [3] intended for VCSELs were evaluated. Maximum overlap of the optical field with the gain medium is achieved in a half-wavelength ($\lambda/2$) cavity. Such cavities can be implemented in either a guiding (the cavity has a higher refractive index than the average one for DBRs) or an anti-guiding configuration (the cavity layer has a lower refractive index). In a guiding design the gain region is placed at the antinode at the cavity edges and is clad by DBR layers with a lower refractive index; here the gain medium has a higher index than the cavity layer. Once the $\lambda/2$ cavity is largely formed of lower-refractive-index materials, the field antinode lies at the center of the cavity. As the gain medium has a higher refractive index than the AlAs-rich layers of the DBRs, the overall refractive-index profile is complex and does not correspond to a pure $\lambda/2$ design [4]. In early $\lambda/2$ VCSEL prototypes [5], dielectric top DBRs were used, further complicating the refractive-index profile and limiting the field enhancement in the gain region. Hybrid semiconductor–dielectric DBR structures allow a DBR-confined oscillating mode with a maximum confined at the semiconductor/dielectric interface. Additional interface-bound transverse-electric (TE) and transverse-magnetic (TM) modes with strong field enhancement in the gain region exist [6]. These modes form

additional in-plane light propagation channels toward the mesa edges, contributing to gain depletion and defect formation.

An all-semiconductor VCSEL design with a low refractive index in the cavity offers fundamental advantages [7]. In an in-plane guiding configuration, a substantial fraction of the optical power can be channeled outside the aperture. This can lead to a high concentration of nonequilibrium carriers in passive regions, stimulating defect generation at the mesa sidewall and growth of point defects and dislocations along the boundary with the oxide-confining region that forms the aperture [8]. Guided-mode effects can be suppressed by minimizing the refractive-index contrast at the gain region through appropriate cladding with low-index layers. This is characteristic of anti-waveguiding designs applied to wavelength-stabilized tilted-cavity lasers (TCLs [7]) in edge geometry and to anti-waveguiding VCSELs (A-VCSELs) [7,9]. The advantage of the A-VCSEL design is most clearly revealed when the simplest processing approach is applied (metal grid placed on top of the surface of the VCSEL wafer). For a proper A-VCSEL design, vertical cavity lasing occurs at a low threshold current density without any complex processing steps such as mesa etch, oxidation or ion implantation. The same approach applied to VCSELs in edge geometry results in in-plane lasing, and vertical cavity lasing starts only at very short cavity lengths ($\sim 100\ \mu\text{m}$) and at much higher current densities. TCL designs allow wavelength-stabilized lasing solely through the layered structure. The mode in the anti-guiding cavity layer is supported by the bottom DBR only at a certain wavelength matching the related effective leakage angle of the cavity mode in the anti-guiding geometry. The anti-guiding principle is thus applied in edge-emitting geometry, as leakage-induced wavelength selection is not possible for edge emitters in a conventional guided design. All-semiconductor A-VCSELs with ultrahigh temperature stability of output power and threshold current were realized in 2006–2008 [10], demonstrating improved modulation bandwidth over the guiding VCSELs based on λ thick GaAs-rich cavities. A jump in the modulation frequencies from 10–20 Gbaud to 40–50 Gbaud and above occurred.

Ideal anti-guiding $\lambda/2$ GaAs–AlAs A-VCSEL designs offer a 37% improvement in the oscillator strength of the vertical transition relative to guiding λ designs and to anti-guiding $3\lambda/2$ designs [11]. Introducing a GaAs–InGaAs gain region reduces the oscillator strength of the vertical cavity transition [4] and can negate the benefits of the anti-waveguiding design, even leading to a guiding effect. The first all-semiconductor $\lambda/2$ VCSELs were realized in 2011–2012 [12,13], although a full analysis of their anti-waveguiding properties was not yet available by that time [9].

Many developments have been pursued to improve VCSEL performance. A persistent challenge is achieving single-transverse-mode lasing while maintaining a relatively large oxide-confined aperture to provide sufficient output power. One strategy minimizes the overlap between the aperture layer and the optical field [14]; another uses a leaky-cavity approach in which the layered structure near the aperture boundary allows higher-order modes to leak away from the aperture for optimized design, as the optical modes in the oxidized and unoxidized regions are non-orthogonal [15]. In both cases, the goal is reached without application of surface processing.

3. Epitaxial Growth of VCSELs

VCSEL structures can be grown successfully by either molecular beam epitaxy (MBE) or metal–organic chemical-vapor deposition (MOCVD). A variety of substrate orientations can be employed. VCSELs emitting in the red spectral range are typically grown on substrates that are significantly misoriented toward the $\langle 111 \rangle$ direction, as is common for light-emitting diodes and edge-emitting lasers in this wavelength range [16]. Growth on non-(100)-oriented substrates has multiple impacts on the symmetry of electron and hole

states, on interface properties and on the formation of self-organized quantum wires and dots. For MOCVD growth at small misorientations from (100) surfaces ($\approx 0.2^\circ$), periodic ripples with a height of ~ 1 nm and a periodicity of ~ 90 nm develop. As the misorientation angle increases to $\sim 2^\circ$, the periodicity of the surface structure is not changed but the height of the steps at the ripple edges increases to 3–4 nm. Locally ordered periodic surface domains have an extension of 2–3 μm and are separated from each other by 18 nm high steps at the domain boundaries. The influence of substrate orientation on nanofaceting, composition and interface modulation was investigated for (811) surfaces [17], where the step height was very uniform (5 nm), with a periodicity of 35 nm. Growth of InGaAlP alloys on such surfaces led to strain-relaxation-driven formation of natural superlattices and formation of thickness-modulated wire-like structures in the gain region [17]. Studies of MBE growth of GaAs–AlAs structures on (211), (311), (111) [18] and (110) [19] substrates revealed transitions from stepped surfaces to one- or two-dimensional periodic nanofaceting; mirror-smooth morphology can be obtained in all cases.

AlAs–GaAs structures on (311)A substrates were investigated using high-resolution electron microscopy and image processing [20]. Plan-view TEM observations revealed vertically stacked, correlated GaAs–AlAs quantum wires with a lateral periodicity of 3.2 nm, indicating the possibility of highly ordered nanostructures [21]. Formation of such quantum wires may be important for polarization-selective lasers with high gain, as well as for top-illuminated infrared emitters and detectors. Deposition of InGaAs on surfaces with high Miller indices strongly modifies the surface reconstruction/nanofaceting, producing larger periodicities. This may lead to ordered arrays of InGaAs nano-domains once low-lattice-mismatch insertions are used. For example, InGaAs quantum-disk lasers have been realized on (311)B substrates [22]. A transition from two-dimensional to three-dimensional islands was reported for high-quality 850 nm GaAs VCSELs on (211)A substrates [23]. High-performance VCSELs have also been realized on (110)-oriented substrates [24,25].

A comparison of the threshold current density in AlGaAs 850 nm VCSELs grown side by side on differently oriented substrates is presented in Figure 1a. The devices were grown with the same MOCVD process on differently oriented substrates. Large-mesa VCSELs grown in anti-guiding design were fabricated with metal grid top contact and compared. All devices exhibited similar temperature coefficients of the lasing wavelength in pulsed mode (200 ns pulses, 5 μs period) of ≈ 0.06 nm/K, but the dependence of threshold current density on temperature differed significantly. The best performance was realized on (211)-oriented substrates. Detailed studies show that this orientation favors formation of periodically modulated (In,Ga)As structures (quantum-disk or quantum-dot-like) even if thin InGaAs insertions contain only $\sim 12\%$ indium (Figure 1b).

Substrate orientation also affects the oxidation process. For surface orientations near (100), the apertures have round, octagonal or elongated shapes depending on oxidation conditions. The degree of anisotropy is higher at higher oxidation rates [26]. In AlAs aperture layers, square apertures can form from round mesas. Oxidation of VCSELs grown on (211) substrates results in triangular apertures, which become more rounded at lower oxidation rates.

Dense arrays of QDs are promising for lasers because they enable O-band wavelengths on GaAs substrates. On (100) surfaces at small inclination angles, a substantial lattice mismatch is required for three-dimensional island formation; at high deposition thicknesses, the islands become dislocated. There is a trade-off between the critical strain required for QD formation and a need to achieve high gain or reach longer wavelengths (~ 1300 nm). Lasing from self-organized QDs was reported as early as 1993 [27]. In 1994 it was shown that such structures have truly zero-dimensional density of states [28,29]. The demonstration of 1300 nm GaAs VCSELs in 2000 [30] and subsequent performance improvements at

NL-Nanosemiconductor [31] have opened new prospects for 1300 nm VCSEL engineering. Meanwhile the commercialization of reliable, high-power QD edge-emitting lasers have created multiple opportunities in silicon photonics, optical coherence tomography (OCT) and frequency conversion.

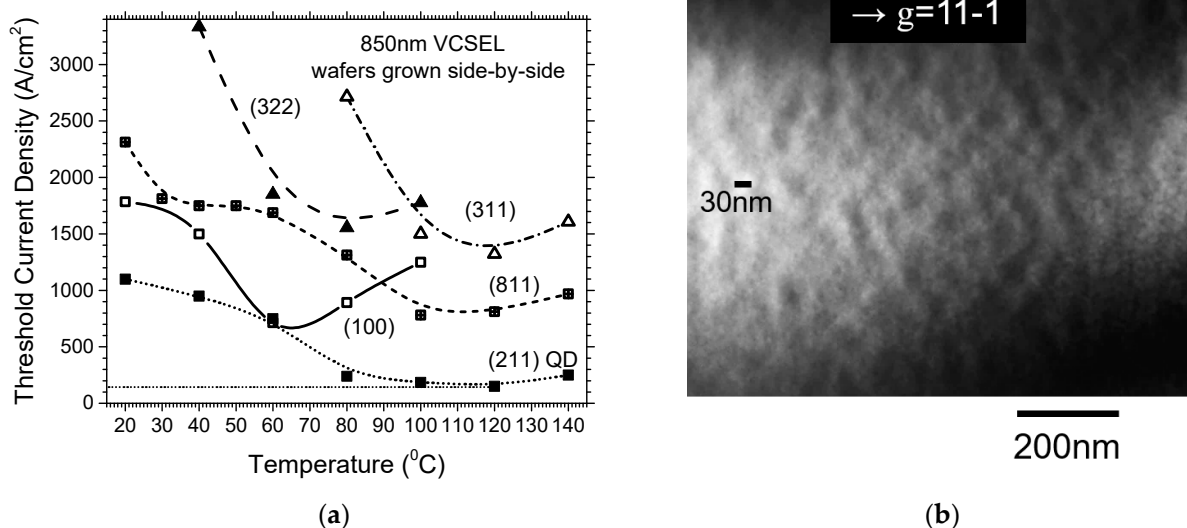


Figure 1. (a) Dependence of threshold current density on heat sink temperature for VCSELs grown side by side in the same MOCVD reactor. Low substrate inclinations from (100) produce step-bunched surfaces and quantum-wire-like structures in the active region [17]. Large inclinations such as (211) lead to three-dimensional quantum-dot-like structures [23]. (b) Plan-view transmission electron microscopy image of a five-fold stack of InGaAs-AlGaAs insertions taken from the cavity region of an 850 nm VCSEL grown on a (211) substrate. A two-dimensional network of strained InGaAs composition domains is observed, making this orientation suitable for low-strain quantum-dot lasers.

In 2005, 130 mW single-mode lasing in continuous mode was achieved in a 1.3 μm GaAs VCSEL based on a stack of 17 InAs/InGaAs QD layers arranged in a resonant periodic-gain sequence. Optical pumping was used to uniformly excite the QD layers [32]. Later, optically pumped QD vertical external-cavity surface-emitting lasers were used for intracavity frequency conversion, generating multi-watt output at 590 nm [33]. To enable gain cascading under electrical injection, tunnel-junction QD VCSELs were proposed and realized in 2005. Figure 2 shows the light-current-voltage (LIV) characteristics of a 1300 nm VCSEL with two tunnel junctions and 27 QD stacks distributed over three regions connected by tunnel junctions [34]. Reducing the number of periods in the top DBR mirror to just 19 allowed for a high differential quantum efficiency (>120%) in continuous-wave operation [34], resolving the problem of free-carrier absorption in heavily p-doped top DBRs at long wavelengths. GaAs VCSELs and arrays based on this technology can be used for 1300 nm range sensing, OCT and as pumps or gain chips for silicon photonics, for example, when directly attached to silicon photonics waveguides.

The gain spectrum of GaAs QD lasers can be shifted anywhere within the 1300 nm range. High modal gains of 46 cm^{-1} at 1330 nm and 20 cm^{-1} at 1350 nm have been demonstrated [35]. Such a modal gain at 1350 nm, combined with multi-cascaded QD layers using tunnel junctions, could enable VCSELs for next-generation automotive LiDAR and under-OLED display sensors. Detuning a 1350 nm gain peak from a 1380 nm cavity wavelength corresponds to a 20 meV bandgap shift typical for industrial VCSELs. Emission at 1380 nm coincides with a local maximum in atmospheric absorption, reducing background solar scattering by four orders of magnitude and raising the eye-safety limit by five orders of magnitude relative to current 940 nm VCSELs.

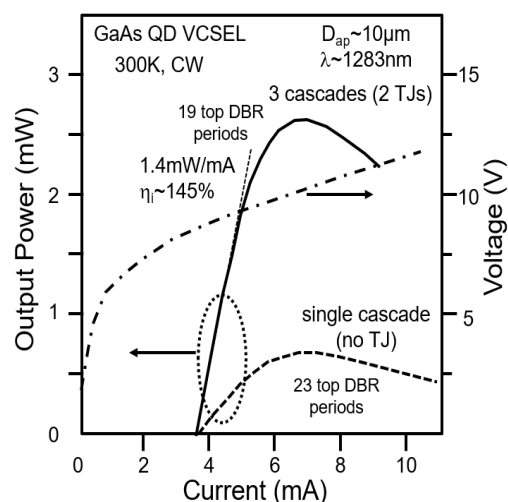


Figure 2. Light–current–voltage curves of a long-wavelength VCSEL with three cascaded QD gain regions containing three sheets of stacked QDs in each cascade and connected by two tunnel junctions (adapted from [34]).

For direct-modulated datacom applications, the bandwidth of single-cavity 1300 nm QD VCSELs is limited to a few gigahertz. Cascading QD gain regions increases the modal gain, enabling higher intrinsic bandwidth, while series connections of p–n junctions reduce the total junction capacitance, significantly increasing the modulation bandwidth [36]. This makes such devices attractive for high-speed operation. However, 1300 nm QD GaAs VCSEL technology requires MBE growth and expertise in growing uniform nano-island arrays while avoiding defects. Work on 1300 nm QD VCSELs at NL-Nanosemiconductor was discontinued when the company shifted focus, even though key building blocks for high-power, high-speed devices—low threshold current, scalable power via tunnel-junction cascading and reliability—were available by 2006. Subsequent work on OCT and silicon photonics benefited from the change in focus towards high-performance gain chips and lasers developed by NL-Nanosemiconductor (Innolume) during the subsequent period.

Increasing the lateral density of QDs by depositing at lower temperatures boosts the modal gain in single-junction, single-cavity QD VCSELs. High modulation bandwidths comparable to those of quantum-well VCSELs have been demonstrated [37]. The emission wavelength of such QD VCSELs is limited to 1240–1250 nm [10]. Attempts to shift the wavelength farther result in performance degradation due to dislocations caused by high accumulated strain in the QD plane. Tunnel-junction cascading can support performance in this case. Further wavelength extension is possible via metamorphic growth of InAs QDs on InGaAs using defect-free plastically relaxed InGaAs buffers on GaAs [38], enabled by defect-reduction techniques [39]. Degradation-free continuous wave operation has been demonstrated in metamorphic 1.46 μm GaAs QD laser diodes [38].

4. Reliability of VCSELs

Degradation stability of oxide-confined VCSELs depends on multiple parameters. First, the gain medium should be free from defects formed during epitaxial growth, such as misfit dislocations or defects propagating from the substrate. Strain compensation must be applied for gain media composed of multiple sheets of $\text{In}_x\text{Ga}_{1-x}\text{As}$ quantum wells (QWs) or long-wavelength QDs of high lateral density. The optimizing growth regimes and sequences are similar to those applied for GaAs-based edge-emitting lasers and light-emitting diodes (LEDs).

VCSEL reliability is crucially dependent on the oxidation process [8,40,41]: high-purity carrier gases must be used, the reactor must be carefully purged, and the oxidation temper-

ature must be kept optimal to favor a selective H_2O –AlAs oxidation mechanism in which all arsenic atoms leave the crystal in volatile form (AsH_3). High levels of oxygen may completely block AlAs oxidation or result in non-selective oxidation of GaAs-rich regions, forming unstable or porous GaO_x -rich phases. AsO_x precipitates formed under H_2O deficiency compete with O_2 and introduce mechanical stress which, together with unstable GaO_x at the aperture interface, can cause delamination of the VCSEL mesa. Vacuum-grade equipment with leak detection and gas purity control is therefore preferable. Mesa edges are exposed to the oxidation process for the longest time, and imperfections are most pronounced there. In early VCSELs the mesa edge was identified as the main source of defect generation, leading to rapid dislocation propagation toward the current-injection aperture [8]. This process can be further activated by high photon densities and photogenerated carriers. Techniques such as etching away the damaged mesa sidewall, passivating the sidewall, implanting ions to block current flow and quenching nonequilibrium carriers via non-radiative recombination have been applied. Defects generated at the mesa sidewall propagate toward the aperture and multiply near that region. The [110] direction is the dominant direction for defect growth [40]. If defects do not originate at the mesa edge, they may form directly at the aperture edge due to in-plane current crowding and oxygen electromigration. Post-oxidation current-induced aperture shrinkage can occur. Extended defects generated near the aperture tip propagate into the gain region [41], triggering rapid degradation.

For high-quality oxidation, proper composition of the oxide aperture, standard VCSEL designs [9] and appropriate low-stress processing, electromigration of oxygen species along the aperture with further flow of oxygen into the active region can be the major factor for power degradation. Applying designs with reduced in-plane and vertical current crowding in the aperture region can minimize the problem for otherwise similar growth and processing technology.

VCSEL degradation can also arise from manufacturing errors. Local voids caused by non-optimal cleaning procedures in the aperture layers can serve as defect sources, while high stress in dielectric layers used to passivate the mesa sidewall may cause cracks in the DBRs and rapid device failure.

Significant substrate misorientation from the (100) direction may favor higher reliability. However, high-index surfaces have higher surface energy as compared to (100) surfaces and surface reconstruction (atomic-scale, periodic step-bunching or nanofaceting) may be easily affected by minor strain [42] or wetting- and non-wetting effects. This can result in evolution of macro-faceting and a loss of a mirror-like surface morphology. For example, the same surface instability allows formation of low-strain self-organized QDs on high-index surfaces [22] and, consequently, this instability may play a negative role in VCSELs at longer wavelengths. While excellent degradation-robust 850 nm VCSELs can be realized on (211)A GaAs substrates (Figure 3 and Ref. [23]), the same substrate orientation results in formation of mesoscopic InGaAs dislocated clusters when spectral ranges beyond 900 nm are targeted, despite the fairly low strain applied in the active region.

Another feature related to growth on GaAs substrates strongly tilted with respect to the (100) direction is a strong anisotropy in the oxidation process [43,44]. Such anisotropy can result, for example, in asymmetric and triangular-type apertures for VCSELs (e.g., (211) and (311) substrates) and strongly affect mode structure, noise pattern and modal composition in the lasing spectra. Careful optimization of mesa shape may be needed. Yet another problem is the availability of such substrates. For inclination angles of $\sim 18^\circ$ and above, 4" and 6" GaAs substrates with qualified epi-ready surfaces are hardly available and formation of growth-related defects at significant concentrations may occur.

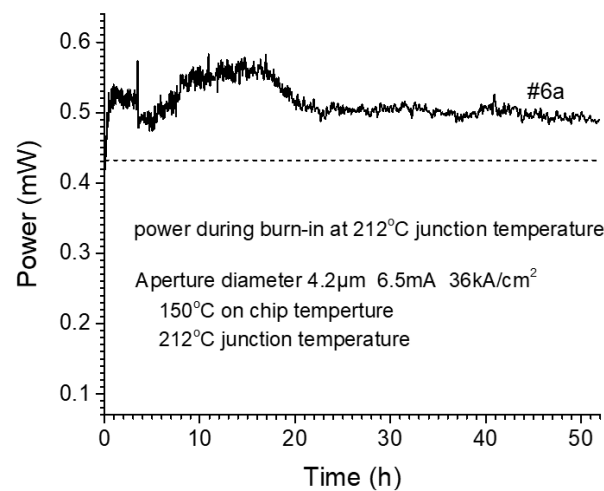


Figure 3. Output power of an oxide-confined 850 nm $\lambda/2$ VCSEL (211) operated at 36 kA/cm² and monitored at 150 °C chip temperature and 212 °C junction temperature. The power initially increases due to contact burn-in and then remains stable for around 40 h. The oxide aperture is located at the first node of the optical field, enabling compatibility with 200 Gb/s applications.

Despite these challenges, properly designed and oxidized oxide-confined VCSELs can be highly reliable. Qualification typically includes at least three independent epitaxial growth runs of multiple wafers per targeted wavelength. At least two processing lots are applied. The first processing lot includes three wafers grown in three different runs. An additional processing lot with at least one wafer grown in the same set is applied to check processing reproducibility. All material is mapped to meet low- and high-temperature specifications such as spectral width (root mean square), output power, operating voltage at specified drive currents and threshold current. Each chip is assigned a unique ID linked to the mapping data. The material is diced, mixed and then subjected to qualification, including accelerated lifetime tests at three elevated temperatures (for example 120 °C, 135 °C and 150 °C) and high currents to extract the activation energy for power degradation (≈ -1.3 eV). The failure criterion is typically a 20% drop in output power at 1% probability (time to 1% failure, $TT_1\%F$). The current degradation coefficient k characterizes the decrease in $TT_1\%F$ with current, following $TT_1\%F \propto I^{-k}$ (with $k \approx 4-8$ depending on design and current density). Increasing current accelerates impurity and defect electromigration (slow degradation) and raises the junction temperature via Joule heating and free-carrier absorption. Monitoring junction temperature at the same heat sink temperature at different currents provides a systematic picture. Junction temperature can be estimated from the lasing-wavelength shift with current due to the temperature dependence of the refractive index. Lifetime is extrapolated from $TT_1\%F$ versus inverse temperature and versus current plots. For datacom applications, the extrapolated lifetime at a 75 °C heat sink should exceed 10 years at the specified operating current. Additionally, ~40 processed chips from three wafers and two processing lots must be aged at 95 °C for at least 7000 h without failures to exclude different degradation mechanisms, which may be present at lower temperatures of operation.

Devices must also withstand powered and unpowered damp-heat tests for 2000 h at 85 °C and 85% relative humidity to verify passivation. They must pass thermal cycling and low-temperature storage tests, as well as wire-pull and ball-shear tests to ensure contact reliability. Before full qualification preliminary burn-in trials may be performed at chip level under extreme current densities and junction temperatures.

Figure 3 shows burn-in data for an 850 nm AlGaAs (211) VCSEL with a single oxide aperture placed at $\lambda/4$ distance from the InGaAs QW gain region. No ion implantation was used for sidewall passivation. The chip temperature was controlled via the wavelength

shift in the fundamental mode measured at room temperature at 0.5 mA and at 150 °C chip temperature. At 6.5 mA, an additional wavelength shift was observed, and the corresponding junction temperature was defined as 212 °C. No significant degradation of output power was observed over 50 h of burn-in at 36 kA/cm².

Such degradation stability meets datacom requirements with a substantial margin.

5. Parameters Affecting the Modulation Response of VCSELs

VCSELs used in datacom must simultaneously meet multiple requirements [45]: high modulation bandwidth, narrow spectral width, low threshold current, adequate output power, low noise and minimal overshoot in the modulation response. These parameters must remain stable across a wide temperature range. The time response of a VCSEL is determined by its intrinsic response and by electrical parasitic (RC) bandwidth. The intrinsic bandwidth corresponds to the device's response to optical pulse excitation and is of fundamental importance. High-speed operation is impossible beyond this intrinsic bandwidth, which is typically studied with a streak camera using pulsed optical excitation (e.g., from a Ti: sapphire laser). Intrinsic modulation response can also be deconvoluted from the measured modulation response S_{21} through a lump circuit model of the VCSEL based on measurements of electrical reflectance S_{11} . The primary goal is therefore to increase the intrinsic modulation bandwidth, while RC effects represent more a technical challenge. Furthermore, RC bandwidth can be equalized without introducing excessive noise, as performed for copper interconnects.

Intrinsic response of single-aperture VCSELs. The intrinsic modulation response of a single-aperture VCSEL is governed by the relaxation oscillation frequency (ROF). ROF is analogous to the resonance frequency of a mechanical oscillator: it is proportional to the square root of the restoring force. In a VCSEL, the restoring force is determined by the electron–hole pair lifetime, which is inversely proportional (in the lasing regime) to the optical-field intensity in the cavity. As the concentration of injected nonequilibrium carriers is fixed in the lasing regime, the electron-hole pair lifetime is inversely proportional to currents above the threshold. Consequently, ROF increases as the square root of the current increases above the threshold until gain saturation, which is typically caused by junction overheating and carrier leakage. Under pulsed current excitation, which prevents overheating, ROF values of up to 90 GHz have been recorded in streak-camera studies [46]. In practical devices, ROF saturates once the active region overheats due to Joule heating and free-carrier absorption. Carrier escape from the active region is strongly enhanced at high temperatures, reducing gain and requiring higher currents above threshold, which further increases overheating. Eventually the VCSEL reaches a thermal roll-over regime. High potential barriers in the cladding layers and appropriate doping profiles help extend the temperature stability range and push ROF to higher values. At small and moderate currents, the modulation bandwidth (f_{-3dB}) for optimal photon damping scales with ROF as $f_{-3dB} \approx 1.4\text{--}1.6 \times f_{ROF}$ [47–50]; intrinsic modulation bandwidths exceeding 50 GHz are feasible for small-aperture VCSELs [48]. At higher currents, photon-damping broadening may smear the ROF resonance and reduce the intrinsic bandwidth. This occurs in VCSELs with high DBR reflectivity and low internal losses, which yield long photon lifetimes. Conversely, a low reflectivity of the top DBR shortens photon lifetime and can produce a strong ROF feature in the modulation response, leading to unacceptable overshoot and undershoot for data transmission. Increasing the modulation response near ROF leads to a small positive 3 dB bandwidth and excessive peaking for long sequences of zeros and ones. With high external losses, the ROF resonance in the modulation response curve increases but gain saturation occurs at lower current densities, limiting ROF. In practice,

the modulation response should be flat from low to high frequencies; careful optimization is needed to achieve adequate performance at operating currents.

The junction temperature rises with current and current density. VCSELs with large apertures experience more heating at the same current density than small-aperture devices due to higher total power dissipation and less efficient cooling. Heat removal is more efficient for elongated apertures at the same total current and aperture area.

Small oxide-confined apertures ($\sim 2\text{--}3\ \mu\text{m}$) show ROF $\approx 30\ \text{GHz}$ [47,49], which is sufficient for intrinsic modulation bandwidths $> 50\ \text{GHz}$ [48,50]. It can be concluded that 200 Gb/s PAM4 data transmission is possible if RC parasitic effects are minimized. Very small apertures ($\sim 1\ \mu\text{m}$) may provide intrinsic optical bandwidths of $\sim 80\ \text{GHz}$ in continuous-wave operation [51] and beyond.

6. Noise Characteristics of VCSELs

High-speed VCSELs must exhibit very low intensity noise across the operating frequency band. Relative intensity noise (RIN) at levels below $-155\ \text{dB/Hz}$ is routinely achieved in modern devices and must be maintained under modulation. Several physical mechanisms can add excess noise:

- Mode partition noise (MPN). MPN arises from random mode hopping between transverse or longitudinal modes [52]. Although the total optical power in a current pulse remains constant, individual modes can exhibit sudden power jumps that partially compensate each other in the total power. Because the rise and fall times for different modes may differ from the overall power rise time, these transients can close the eye diagram in case some of the existing modes are not coupled. To suppress MPN, the coupling efficiencies to all modes in multi-mode fibers should be as equal as possible. This requires narrow beam, low beam-parameter product and high beam quality, which modern multi-mode VCSELs deliver with a substantial margin. Multi-mode VCSELs with far-field widths below 30° at the $1/e^2$ intensity level have aperture diameters of $5\ \mu\text{m}$ or less ($M^2 < 4$). Therefore, the device meets the encircled flux requirements of the launch conditioner ($M^2 < 9$). Single-mode (SM) VCSELs do not exhibit MPN because only one transverse mode is present.
- Mode beating noise (MBN). Once several VCSEL modes have closely spaced photon energies, their optical fields interfere and locally enhance the gain at beat frequencies equal to the differences in the mode frequencies. In devices with a small number of interacting modes, this noise appears as narrow spikes of only $1\text{--}3\ \text{GHz}$ width in the RIN spectrum [53–55]. Multi-mode VCSELs emitting in a large number of modes may exhibit multiple beating features that increase RIN to values above $-140\ \text{dB/Hz}$, which is unacceptable for high-performance links. Intrinsic and strain-induced birefringence in GaAs produces beating features between modes of identical symmetry but orthogonal polarization, typically at low frequencies ($1\text{--}5\ \text{GHz}$). Randomly, modes of different symmetry may lie close in frequency, producing beat notes in the $15\text{--}50\ \text{GHz}$ range that strongly limit data transmission performance. Engineering the aperture shape to deviate from circular symmetry suppresses these modes. Otherwise, modes with enhanced frequency splitting can be applied intentionally, allowing the realization of spin lasers [56]. Single-mode VCSELs and multi-aperture VCSELs with isolated apertures inherently avoid MBN because only one mode per aperture exists. Optical reflections must still be minimized to prevent injection of additional modes that could enhance RIN [53].
- Noise due to optical feedback. Reflections from the coupling optics, fiber facets or the detector can feed back into the VCSEL cavity and excite unwanted modes or increase noise. Unlike distributed feedback lasers, VCSELs rely on a high-reflectivity

top DBR stack that also acts as an optical isolator [57]. Additional measures include antireflection-coated optics, diffusers or vortex structures [58] to scatter returning light, and thin absorber layers such as GaAs or amorphous Ge deposited on the VCSEL surface to absorb wavelength- and angle-mismatched light reflected to the cavity. These features reduce feedback without significantly lowering the lasing power. Proper optical design is therefore essential to maintain low noise. Because MA VCSELs and SM VCSELs have narrow far-field patterns, they can achieve low feedback reflection for MMF coupling by tilting the coupling angle.

7. Multi-Aperture VCSELs

Extremely small oxide-confined apertures ($<3\ \mu\text{m}$) can deliver intrinsic bandwidths of 50–80 GHz but provide only a few milliamps of current before thermal roll-over, limiting the output power and raising the series resistance. A simple way to increase power is to place several small VCSEL mesas in parallel [59], but this approach increases capacitance proportionally to the number of VCSEL mesas and yields no net benefit in RC parasitic bandwidth. Moreover, arranging multiple isolated mesas with the minimum allowable spacing complicates optical coupling to standard multi-mode fibers: the beam-quality factor M^2 exceeds the limit of the mode conditioner (≈ 9) required to match the encircled flux requirement for multi-mode fibers.

A more effective strategy is to create several oxide-confined apertures within a single compact mesa. Since all apertures share the same large top contact, the truncated-cone law holds, and the total series resistance decreases more than linearly versus the number of apertures. Closely spaced apertures also reduce the total junction capacitance, while allowing efficient coupling to multi-mode fiber by maintaining $M^2 < 5\text{--}9$. Multi-aperture (MA) VCSELs can thus simultaneously provide high output power and low electric parasitics [45,50] and reach the intrinsic modulation bandwidth ~ 50 GHz. The apertures may be optically isolated or weakly coupled. Weak coupling introduces supermodes which allow self-injection locking phenomena, as discussed below.

Figure 4 shows optical microscopy images of MA VCSELs. Under red-light illumination the shapes of the oxide-confined apertures are clearly visible (a). The chip layouts for devices with four (b) and two (c) coupled apertures demonstrate that the total chip size remains compact ($\approx 220\ \mu\text{m} \times 220\ \mu\text{m}$), allowing integration in dense arrays. The center-to-center pitch is $10 \times 12\ \mu\text{m}$ for the four-aperture array and $7\ \mu\text{m}$ for the two-aperture array. The MA concept therefore meets standards for $250\ \mu\text{m}$ pitches in VCSEL arrays.

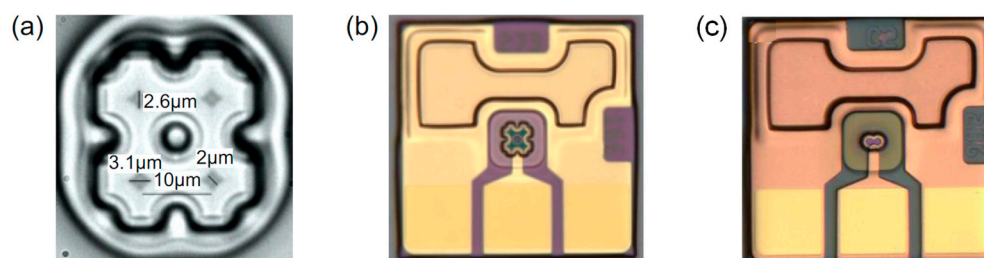


Figure 4. (a) Optical micrograph showing the oxide-confined apertures of an MA VCSEL revealed under red-light illumination. (b,c) Chip layouts for four and two coupled apertures, respectively; both chips measure $220\ \mu\text{m} \times 220\ \mu\text{m}$. The pitch between apertures is $10 \times 12\ \mu\text{m}$ for the four-aperture design and $7\ \mu\text{m}$ for the two-aperture design.

The far-field (FF) and near-field (NF) patterns of an MA VCSEL provide insight into its modal behavior. Figure 5a presents a two-dimensional FF intensity map of a four-aperture device driven at 7 mA. Figure 5b shows the FF cross-section along the horizontal axis. The NF images (Figure 5c–e) illustrate how the emission from each aperture evolves with

current: below the threshold (0.1 mA), the emission is weak and less confined, whereas above the threshold (1 mA and 9 mA), each aperture supports single-mode lasing up to at least 15 mA. The pitch between apertures is $10 \times 12 \mu\text{m}$, ensuring independent operation while permitting compact coupling optics. More detailed studies of MA VCSEL demonstrated that, in a non-coherent regime, each aperture allows a beam-quality factor of $M^2 \sim 1$. However, assuming a 3–4-fold larger pitch size between the apertures, M^2 of the MA VCSEL is within the range ~ 4 – 5 . Such an M^2 still allows coupling efficiency of the Hi780 nm single-mode fiber to be $\sim 30\%$ and allows a 90% coupling efficiency for the multi-mode fiber, which is superior to the M^2 for the standard mode conditioner used for MMF fiber evaluation ($M^2 \sim 9$). Most importantly, the spot intensity distribution, in combination with the narrow far field of each emitter, allows for well-defined launch conditions for MMFs which are needed for longer distance transmission, with further restricted launch exciting the modes in a narrower fiber volume, advancing the effective modal bandwidth (EMB) but matching the encircled flux (EF) requirement. Coupling to lensed fibers or industrial couplers [60] is possible.

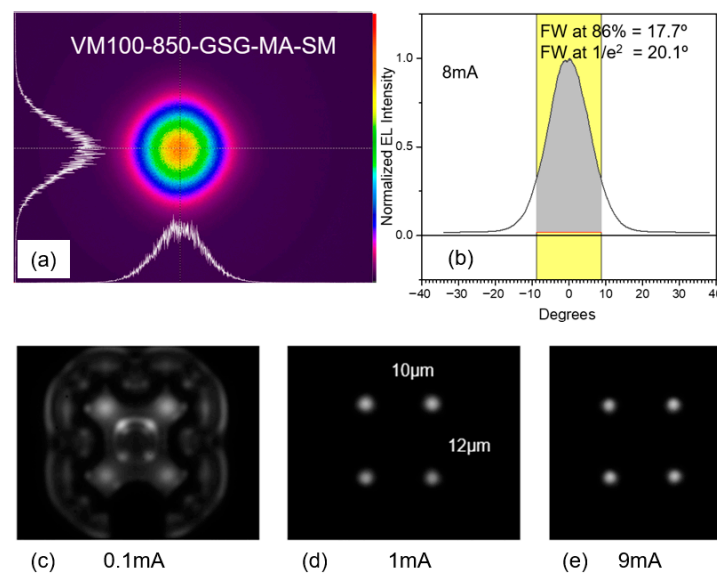


Figure 5. (a) Two-dimensional far-field map and (b) horizontal cross-section of a four-aperture MA VCSEL at 7 mA total current. (c–e) Near-field images at currents of 0.1 mA (below threshold), 1 mA and 9 mA (above threshold). Each aperture maintains single-mode lasing up to 15 mA. The apertures are spaced $10 \mu\text{m} \times 12 \mu\text{m}$ apart.

The emission spectra and light–current–voltage (LIV) characteristics of an MA VCSEL are shown in Figure 6. Over the 6–13 mA current range, the spectra remain narrow, and small differences in aperture size or mesa geometry become distinguishable only at high drive currents, where slightly different levels of current-induced heating cause slight wavelength shifts. Industrial four-inch wafer processing achieves root-mean-square spectral widths below 0.2 nm across multiple wafers at the same wavelength and for different wavelengths (850 nm, 880 nm, 910 nm and 940 nm) [50]. At currents of operation of ~ 6 – 8 mA, spectral broadening is moderate. Thus, neither transmission distance, nor eye diagrams, nor TDECQ for PAM4 107 Gb/s transmission over 200–300 m of minimum EMB OM4 fiber (~ 2.4 dB) are affected. Once the apertures are weakly optically coupled, a pure single-mode regime is possible under built-in injection, as evidenced by a spectral single-mode emission and a characteristic multilobe far-field pattern superimposed over the same envelope intensity distribution characteristic to single-aperture emission [45]. The differential efficiency remains high and the threshold current shows strong temperature stability between 25°C and 85°C .

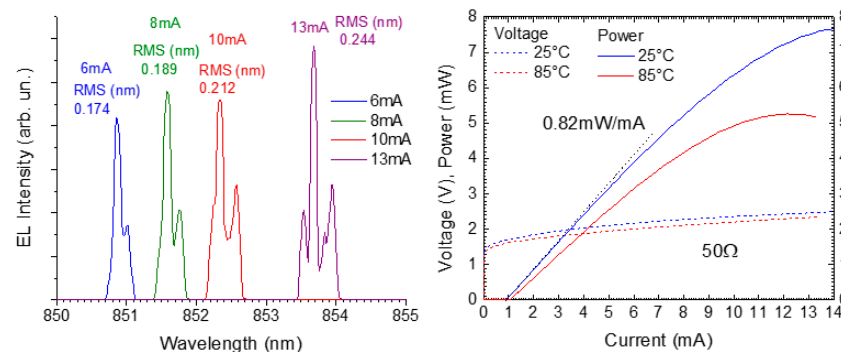


Figure 6. (a) Emission spectra of an MA single-mode VCSEL measured at drive currents from 6 mA to 13 mA. (b) Light–current–voltage characteristics at 25 °C and 85 °C, demonstrating high differential efficiency and strong temperature stability.

Figure 7 presents the modulation response of a four-aperture MA VCSEL driven at 13 mA (3.2 mA per aperture). The -3 dB optical modulation bandwidth reaches 33 GHz; analysis of the S_{11} reflection spectrum with extraction of a lumped-circuit model yields an intrinsic bandwidth up to 50 GHz [61]. Details of the lumped-circuit model applied to MA VCSELs are presented in Ref. [61] and analysis of diffusion and depletion capacitance is presented in Ref. [62]. In the lasing regime the concentration of electron–hole plasma is fixed, and the diffusion capacitance vanishes. Optically isolated apertures thus provide a large intrinsic bandwidth while reducing series resistance. In Figure 7, extracted intrinsic bandwidths of 45 GHz are reported according to similar modeling [61] and are comparable to the 50 GHz obtained from the damping parameter [61] and similar to the value derived from the analysis of Broadcom’s 200 Gb/s VCSELs with the related lumped-circuit model presented [52].

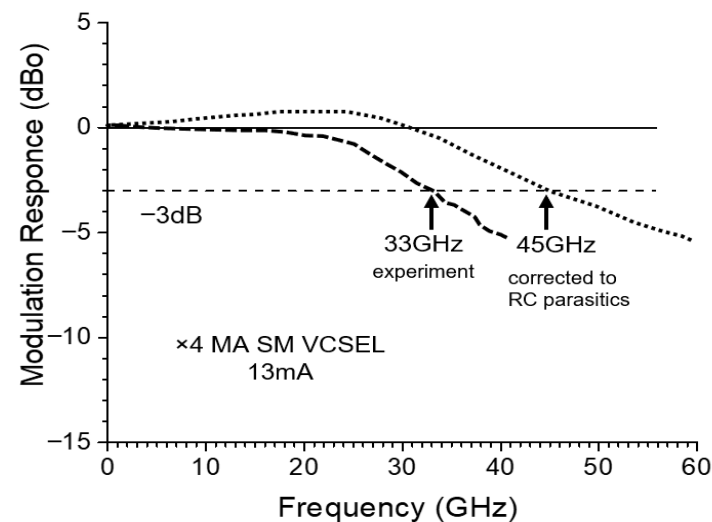


Figure 7. Frequency response of a four-aperture MA VCSEL at 13 mA total current. The dashed line shows the intrinsic modulation response extracted from an S_{11} lumped-circuit model.

Multi-aperture VCSELs with optically isolated apertures exhibit extremely low RIN (< -150 dB/Hz) because the apertures interact only weakly. Figure 8 compares the RIN spectra of a conventional single-aperture VCSEL with a $6.3 \mu\text{m}$ circular aperture (a) and an MA VCSEL with four $2\text{--}3 \mu\text{m}$ apertures spaced $10 \times 12 \mu\text{m}$ apart (b). The MA device shows a remarkably flat RIN spectrum free of beating features, demonstrating the absence of ROF, MPN and MBN features. The primary remaining noise mechanism is optical feedback, which can be mitigated through diffusers, attenuators or intentional tilt in the coupling optics to suppress back reflections.

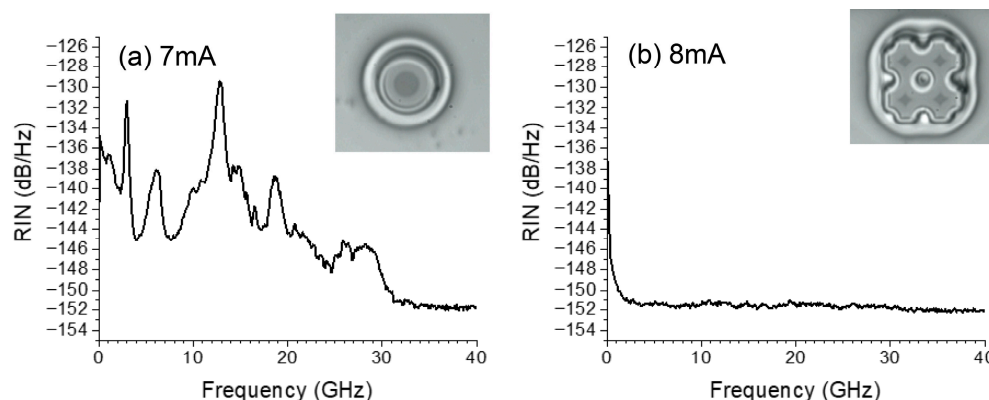


Figure 8. Relative intensity noise (RIN) spectra measured with identical optical coupling for (a) a conventional VCSEL with a circular 6.3 μm aperture designed for 25 Gbaud operation and (b) a multi-aperture single-mode VCSEL with 10 $\mu\text{m} \times 12 \mu\text{m}$ aperture spacing. The MA VCSEL exhibits significantly lower RIN, enabling high-speed transmission.

8. Data Transmission Using Single-Mode MA VCSELs: Chirp and Launch Conditions

Single-mode MA VCSELs with optically isolated apertures are attractive for long-distance data transmission over both multi-mode (MMF) and single-mode fibers (SMF) [63]. Their behavior is similar to that of single-aperture SM VCSELs [64]: a favorable combination of device chirp and fiber chromatic dispersion can extend their reach well beyond the value expected for zero-chirp sources [65–67]. The chirp arises from refractive-index changes induced by carrier density modulation; negative chirp ($\alpha < 0$) partially compensates the positive chromatic dispersion of silica fibers. We note that, under restricted central launch conditions applying an externally modulated single-mode narrow linewidth source, 112 Gb/s PAM4 transmission over 1 km of OM2 MMF is realized [68]. Bending of the OM2 fiber, shaking and vibrations do not distort data transmission [68]. Consequently, with proper coupling SM VCSELs at any wavelength, also below the onset of the second mode of the standard SMF ($\sim 1250 \text{ nm}$) can be used for long distance SMF transmission in datacenters [69,70] reaching 500 m transmission over standard SMF at 240 Gb/s PAM4 modulation [71]. The effect of bit error ratio (BER) improvement after long-distance transmission over SM and MM fibers was explained [67] by a favorable combination of 850 nm VCSEL chirp with chromatic dispersion of glass fiber enabling the pulse compression effect. 25 Gb/s transmission over 1 km-long two-mode 850 nm-optimized fiber reduced BER by 4 orders of magnitude as compared to back-to-back (BTB) configuration due to chirp-induced pulse compression in glass fiber. The effect is similar to the one observed for the shorter wavelength segment of the O-Band using DFB lasers [72].

Figure 9a compares measured and modeled link transfer functions for an 850 nm SM MA VCSEL transmitting through 10.099 km of Hi780 single-mode fiber. Fitting the data yields a chirp parameter $\alpha \approx -3.81$. For comparison, the modeled zero-chirp transfer function exhibits a null value at 14.5 GHz, whereas the measured curve shows the null value at a higher frequency because negative chirp delays the onset of dispersion-induced roll-off. Figure 9b presents modeled transfer functions for 1 km, 2 km and 3 km of SMF using the same extracted chirp value. Therefore, 850 nm MA VCSELs can support SMF transmission across up to $\approx 1 \text{ km}$ at modulation bandwidths approaching 60 GHz. This performance is comparable to that of quantum-well VCSELs operating at longer wavelengths and highlights the potential of MA designs for short-reach data centers.

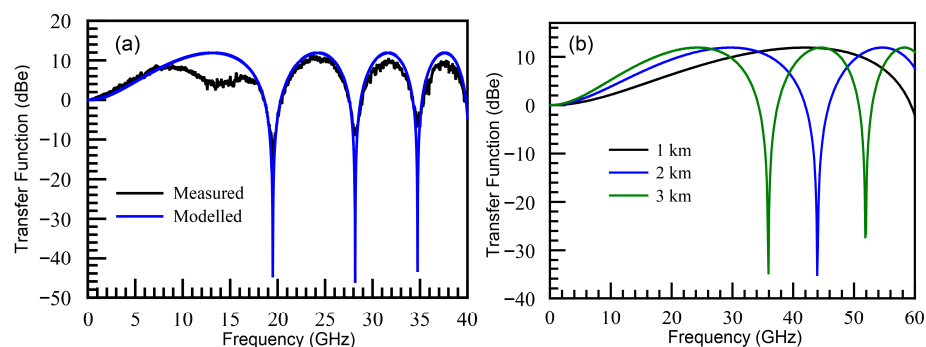


Figure 9. (a) Measured (points) and modeled (solid line) transfer functions of an 850 nm SM MA VCSEL transmitted through 10.099 km of Hi780 single-mode fiber. The extracted chirp parameter is $\alpha \approx -3.81$. The zero-chirp model exhibits a sharp minimum at 14.5 GHz. (b) Modeled transfer functions for 1 km, 2 km and 3 km of SMF using the experimentally derived chirp value.

In multi-mode fibers, chromatic dispersion is not the primary limitation; instead, the effective modal bandwidth (EMB) defines the usable data rate. The EMB (4700 GHz/km at 850 nm for OM3 and OM4 fibers) is derived under restricted-mode launch conditions designed to emulate typical VCSEL sources: the encircled flux specification requires < 25% of the launched power within a $4.5 \mu\text{m}$ radius and >75% within $15 \mu\text{m}$ [73]. These conditions were established around the year 2000 using 1 Gbit/s VCSELs with a beam-quality factor of $M^2 \approx 9$. To support 10 Gbit/s transmission, higher-bandwidth $50 \mu\text{m}$ fibers (OM3/OM4) were introduced along with differential mode delay (DMD) testing. The calculation of minimum EMB applies 10 weighting coefficients derived from the encircled fluxes of a set of industrial VCSEL sources, which existed at that time, to the fiber's DMD data.

Modern industrial VCSELs have aperture diameters around $5 \mu\text{m}$ and numerical apertures near 0.25, yielding beam-quality factors of $M^2 < 4$ —substantially better than those assumed when the standards were defined. Restricted-launch conditions can therefore be optimized to maximize EMB even for standard MM VCSELs (RMS spectral widths $\approx 0.6 \text{ nm}$) [74]. MA VCSELs with isolated single-mode apertures spaced at $\approx 10 \mu\text{m}$ exhibit nearly the same far-field divergence because the individual apertures emit single-mode beams. However, the combined emission area is twice as large and the numerical aperture is roughly half of those in conventional MM VCSELs. As a result, M^2 remains comparable and EMB can be strongly improved under optimized launch conditions. Restricted launch at lower overfill also benefits photodetectors by concentrating the beam onto a smaller active area, enabling higher-bandwidth receivers.

As the installed base of multi-mode fibers supports a reach of only 100 m at 850 nm (OM4 and OM5 fibers), this wavelength remains critical for 200 Gb/s applications. The first demonstration of 200 Gb/s transmission over 100 m of OM4 fiber using an 850 nm VCSEL module appeared in 2020 [75,76]. More recent experiments using a quasi-single-mode 35 GHz VCSEL-based module have achieved transmission of beyond 200 Gb/s: gross bit rates of 245 Gb/s (PAM-6) back-to-back and 214 Gb/s (PAM-4) over 60 m OM4 fiber have been reported, assuming standard KP4 forward-error correction [77]. Extending the link length to 100 m introduces penalties that slightly exceed the KP4 threshold if only linear equalization is applied. Combining MA VCSELs with advanced nonlinear equalization and novel low-impedance MMF photodiode modules (-3 dB bandwidths $> 40 \text{ GHz}$) will further improve performance.

9. Mode Evolution in MA VCSELs with Coherently Coupled Apertures

Multi-aperture VCSELs can also be designed such that adjacent apertures are optically coupled via unoxidized bridges. Coherent coupling of optical modes in VC-

SEL arrays has long been studied for high beam brightness and spectral-narrowing applications [78–80]. Once two cavities are coupled, two supermodes form: a symmetric (S) mode and an antisymmetric (AS) mode. Depending on the relative polarization of these supermodes—parallel or perpendicular to the coupling axis—different dynamical behaviors are observed. Optical injection locking has previously been used to enhance modulation bandwidth via master–slave mode interactions [81], but external injection is impractical for datacom VCSELs. Instead, self-injection locking (SIL) occurs when coupled cavities lock to a single supermode without external feedback; this effect can both narrow the linewidth and increase the modulation bandwidth [82–84]. Notably, SIL can be achieved using standard oxide-confined VCSEL technology without exotic processing such as photonic crystals, proton implantation or dielectric isolation [45,85–88].

Figure 10 illustrates two coupled-aperture MA VCSEL designs (types A and B) in which the oxide apertures are connected by unoxidized bridges of different widths. The shape of the apertures is revealed by illuminating the devices with light at a wavelength close to the DBR stop-band edge (~ 790 nm). In design A (Figure 10a), the bridge is relatively wide, whereas in design B (Figure 10b), it is narrower. The bridge width strongly influences the coupling strength and hence the modal behavior of the devices.

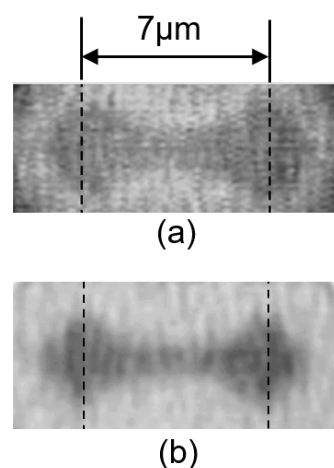


Figure 10. Optical microscopy images of two-aperture MA VCSELs under red-light illumination. Dark regions correspond to unoxidized areas. (a) Design A, with a relatively wide non-oxidized bridge connecting the apertures; (b) design B, with a narrower bridge. The bridge width strongly affects the coupling and dynamic behavior.

In single-aperture VCSELs, each mode can exist in two orthogonal polarizations aligned along (011)-like directions [54,55]. In two-aperture devices, the S and AS supermodes can be either co-polarized or cross-polarized relative to the coupling axis. It is known from VCSELs having a single circular aperture that, once birefringence is introduced into the system, e.g., by external mechanical stress, modes with different polarization have different optical frequencies, and the beating between the two modes occurs. Such beating causes periodic changes in polarization state and temporal intensity fluctuations. Same effect is observed in two-aperture devices, where the aperture geometry renders the two in-plane directions non-equivalent. The polarization mode beating manifests as RIN enhancement and can flatten or shift the relaxation oscillation peak to higher frequencies. In design A, the S mode is polarized parallel to the bridge, and the AS mode is polarized perpendicular to it, leading to cross-polarized supermodes that can interact strongly and synchronize frequencies. We note that both the S and AS modes can exist in two polarizations and altogether four modes at different frequencies exist in systems with two coupled cavities (eight modes in four coupled cavities). The existence of only two supermodes instead of

four already indicates a partial SIL effect. In design A, polarization control is a function of crystal birefringence, shape and oxidation-induced stress. The antisymmetric mode is more equally distributed between the apertures and is most affected by the shape. Polarization is aligned to the coupling axis. Due to technological tolerances, the two apertures may have slightly different shapes and/or sizes. Then the two supermodes are not perfectly symmetric or antisymmetric. The initially symmetric mode is more confined to one of two apertures. The relative polarization of two supermodes is unstable, with a preference for a cross-polarized state. In the SIL regime, only one mode (AS) at one polarization is present but the interaction with the second cross-polarized and non-lasing mode persists resulting in broadening of the modulation curve. In design B, with a stronger elongation of the aperture shape and a narrower bridge, both supermodes are polarized parallel to the alignment axis. No beating below the SIL threshold is observed.

Figure 11 presents spectrally demultiplexed near-field images of design A at different currents. At low currents, the supermodes are confined mostly to individual apertures because of slight differences in the aperture shape break symmetry. Higher-order modes with three or five intensity maxima are also visible and show alternating polarization. The spectral splitting between the S and AS modes increases with the current, suggesting interactions between electron–hole plasma and the optical modes. Based on basic considerations one can expect that for small apertures and the reduced number of modes in the SIL regime, the impacts of exciton polaritons and polariton condensation may play a significant role [89].

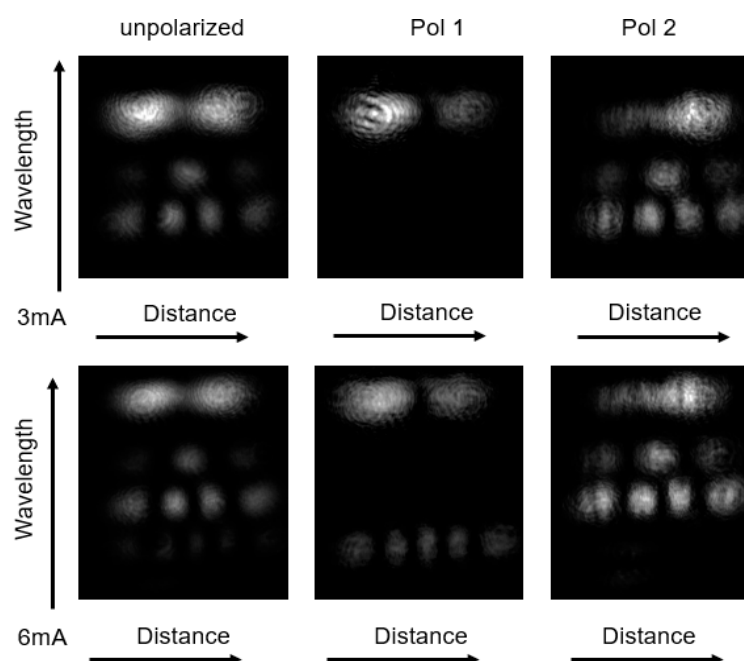


Figure 11. Spectrally demultiplexed near-field images of design A at increasing current. Polarization filters select emissions perpendicular to the alignment axis (Pol 2) and parallel to the axis (Pol 1). The S mode has a finite intensity in the bridge region. Higher-order modes with multiple intensity maxima exhibit alternating polarization.

Figure 12 compares the emissions of design A at 9 mA and 13 mA. At 9 mA, the S and AS modes have comparable intensities and both apertures lase in both modes. At 13 mA, the emission from the bridge region disappears, indicating that only the AS supermode remains. This transition to single-supermode lasing corresponds to self-injection locking: the master mode forces the slave mode to vanish. SIL thus enables single-mode operation with enhanced modulation bandwidth.

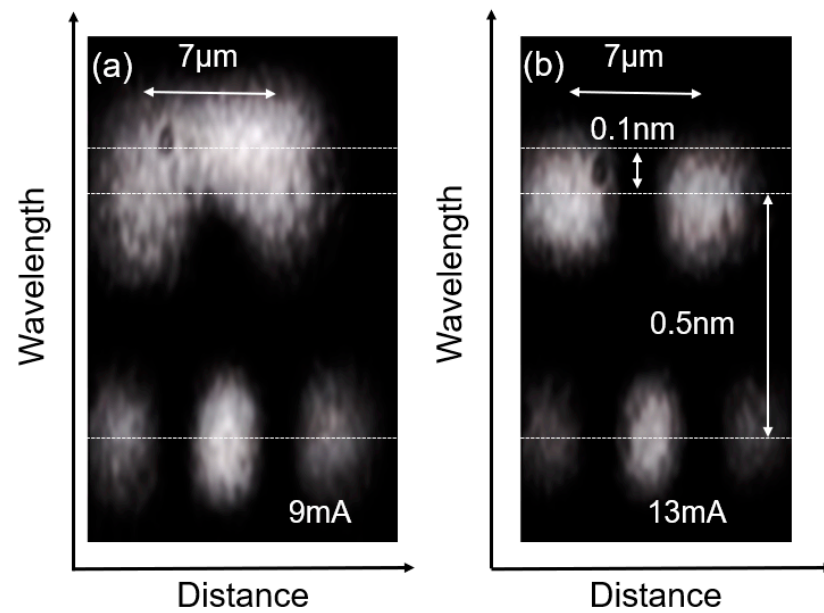


Figure 12. Unpolarized near-field images of design A. (a) 9 mA, both cross-polarized supermodes lase. (b) 13 mA, only the AS supermode remains. This transition represents self-injection locking to a single supermode.

Figure 13 shows near-field images of design B at 6 mA and 6.2 mA with polarization parallel to the alignment axis. The bridge is narrower and both the S and AS supermodes are polarized along the same axis. At 6 mA, both modes lase, whereas at 6.2 mA, the device transits to SIL and only the AS supermode remains. A reduced bridge width thus favors earlier SIL at lower current, albeit without polarization beating.

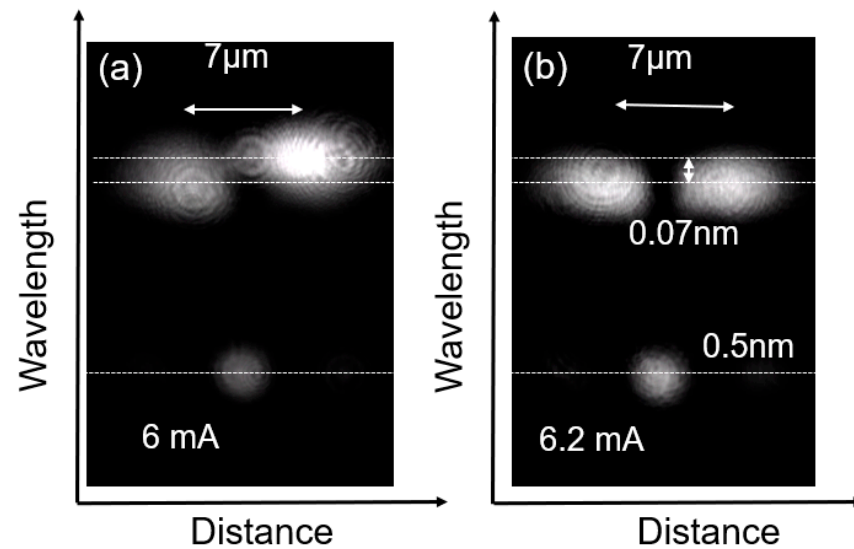


Figure 13. Unpolarized near-field images of design B. (a) 6 mA, both S and AS mode lase. (b) 6.2 mA, only AS mode remains. This transition represents self-injection locking to a single supermode.

The far-field patterns below and above the SIL transition illustrate how mode symmetry affects beam shape. Figure 14 compares far-field and near-field patterns of design B at 7 mA (before SIL) and at 9 mA and 11 mA (after SIL). The far field shows a two-lobed pattern characteristic of the antisymmetric mode and shows evidence of single-mode lasing. Similar transitions to SIL and dominance of the AS mode occur in both design A (cross-polarized) and design B (co-polarized), although only design A exhibits strong mode beating effects, which we attribute to a strong interaction between cross-polarized modes.

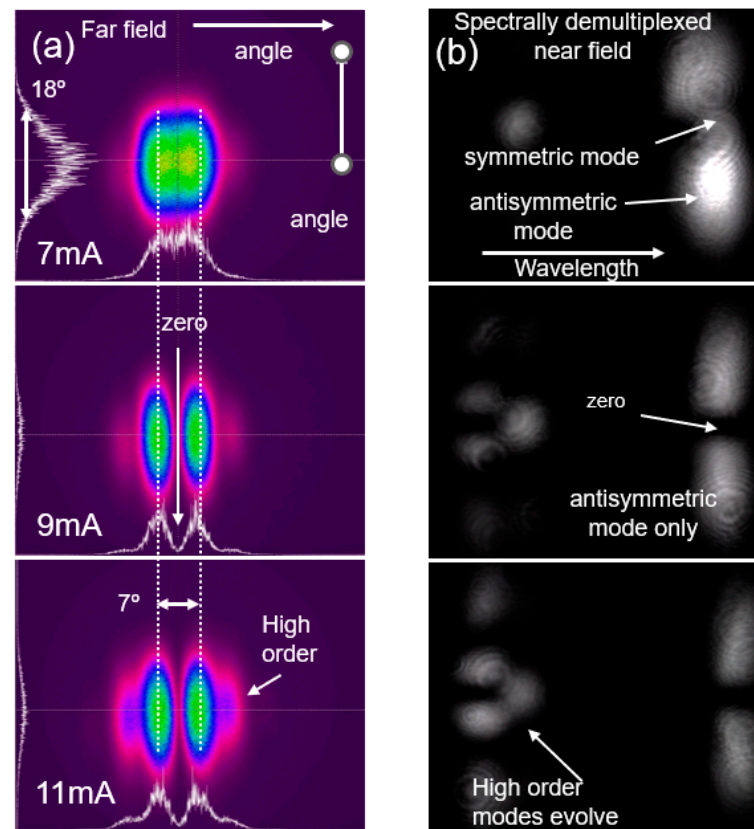


Figure 14. Far-field (a) and near-field (b) patterns of design B at 7 mA (below SIL threshold), 9 mA and 11 mA (above SIL threshold). The far field shows a two-lobed pattern characteristic of the antisymmetric P mode. Transition to SIL and dominance of the AS mode occur in both co-polarized and cross-polarized designs.

The differences between the designs depend on the aperture size and the bridge width controlled by the oxidation length. For deeper oxidation, design A shows unstable polarization of the supermodes; when in different regimes, both co-polarized and cross-polarized supermodes may exist. The beating effect remains in both cases.

10. Impact of Self-Injection Locking on VCSEL Dynamics

The dynamic impact of SIL on MA VCSELs has been investigated using streak-camera measurements with picosecond optical excitation [86,87]. In design A, short pulses from a Ti:Sapphire laser triggered antiphase intensity oscillations in the two cavities. These oscillations persisted for at least 10 ns after the excitation pulse and were attributed to constructive and destructive interference between the S and AS supermodes, each oscillating at a frequency defined by its photon energy. The oscillation frequency matched the spectral separation of the modes and followed the current dependence of that separation.

Figure 15 (renumbered here to avoid confusion) shows the Fourier transform of the modulation response signal after pulse excitation for design A at currents below and above the SIL threshold. Below the threshold (<6 mA), the luminescence spectra represent two narrow peaks with frequency spacing increasing linearly with drive current. The intensity of each of the apertures oscillates in antiphase, providing an option for generation of a coherent THz signal [88]. However, the combined signal from both apertures shows no enhancement in the modulation response because the oscillations occur in antiphase. Above the SIL threshold (>6 mA), only the AS supermode lases. A strong resonance evolves in the modulation response for the signal coming from both cavities. The resonance feature in electrical modulation spectrum shifts to lower frequencies by ~25 GHz at the onset

of SIL. With the following increase in current, the SIL relaxation oscillation frequency increases linearly with the current, reaching ~ 60 GHz. The frequency resonance broadens by 2–3 GHz, and additional weaker frequency components become resolved.

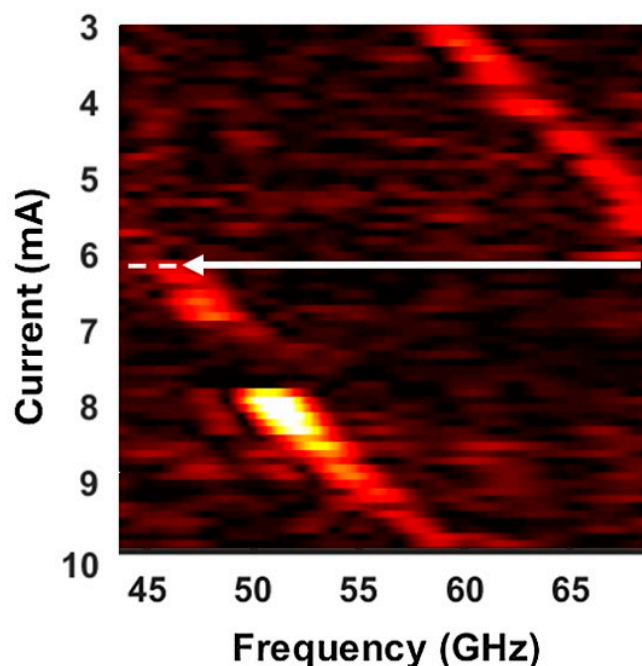


Figure 15. Fourier transform of the modulation response signal after pulse excitation for design A at currents below and above the SIL threshold. Below 6 mA, only antiphase oscillations in individual apertures are observed, while no overall intensity modulation of the integrated signal is detected; above 6 mA, a strong resonance appears in the modulation response measured from both cavities. This resonance shifts to higher frequencies linearly with the current. We note that the resonance frequency dependence vs. current has the same slope below and above SIL threshold. The frequency in the antiphase modulation regime is defined by the mode splitting of the S and AS modes, while the frequencies of the modes decrease with the current due to current-induced heating effects (see Figure 7).

In design B, electroluminescence spectra show that the frequency splitting between the S and AS modes decreases slightly with currents above the SIL threshold, and no significant antiphase oscillations are detected. Figure 16 plots the electroluminescence spectrum as a function of current; the inverse frequency difference relative to the S mode frequency is indicated. Sidebands separated by ≈ 72 GHz may originate from four-wave mixing. Dynamic studies in which one aperture is excited via a single-mode fiber reveal intense periodic oscillations only at currents just above the SIL threshold (≈ 3 mA). The oscillation frequency matches the supermode splitting only at threshold (~ 20 GHz). At higher currents the splitting increases linearly with the current, reaching about 100 GHz. At high currents, the oscillations become aperiodic, with multiple frequency components. This is similar to the behavior observed under optical injection locking [89]. Time-resolved measurements show that the oscillation period shrinks to a few picoseconds, near the resolution limit of the streak-camera system; the oscillation period then lengthens to 100–150 ps over ~ 0.5 ns as all frequency harmonics contribute to the response signal.

Figure 17 presents a color-coded map of the temporal evolution of electroluminescence intensity after pulse excitation at different currents. Above the SIL threshold, strong aperiodic oscillations are observed; at higher currents, the first oscillation period decreases to a few picoseconds. The second and subsequent oscillation periods reach hundreds of picoseconds. Figure 18 plots the equivalent frequencies of the first and subsequent

oscillations as a function of the current. Beyond the SIL threshold, the frequency increases linearly with current. The slope for the first oscillation is three times larger than that for later oscillations, suggesting that the restoring force for the electron–hole plasma concentration is proportional to the product of the optical-field intensity and the intensity of the effective master mode. Because this restoring force scales with the square of the current, the oscillation frequency—proportional to the square root of the restoring force—scales linearly with current.

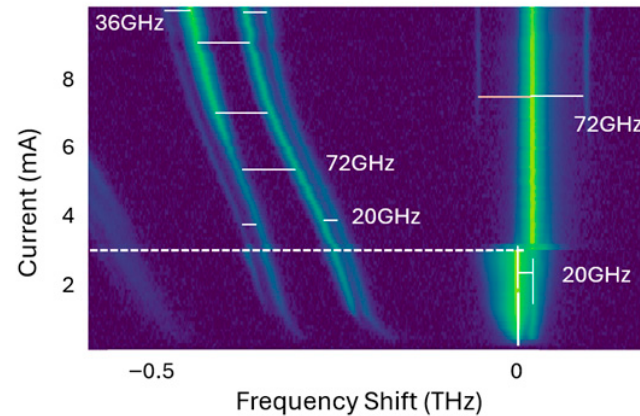


Figure 16. Electroluminescence spectrum of design B versus current, relative to the S mode frequency to underline the value of the frequency spacing between the AS and S modes (20 GHz). Sideband satellites separated by ≈ 72 GHz may originate from four-wave mixing. White dotted line indicates the SIL threshold. Dynamic measurements show the onset of post-pulse oscillations only above the SIL threshold and increase in frequency with the current.

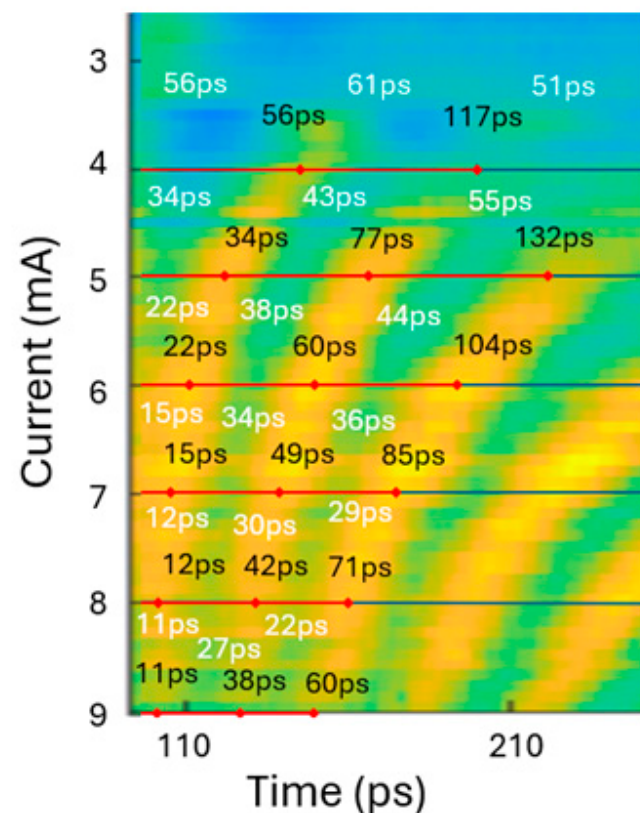


Figure 17. Color-coded map of the post-excitation temporal evolution of the electroluminescence intensity at different drive currents for design B. Aperiodic oscillations appear only above the SIL threshold and evolve toward shorter periods at higher currents. The time window is arbitrary, and the triggering pulse generating the oscillations is provided at 90 ps spot.

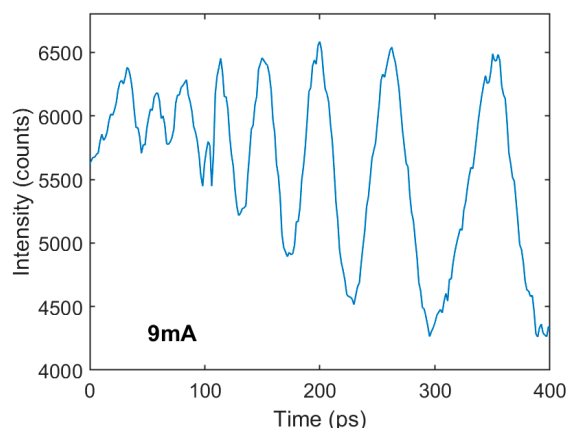


Figure 18. Temporal evolution of the EL spectrum after the excitation pulse at 9 mA CW current. The pulse train generated is strongly aperiodic. The peak intensities of the first oscillations are strongly suppressed by the limited streak-camera bandwidth caused by an excitation pulse broadening in the fiber of ~3–5 ps.

To illustrate the aperiodic nature of the oscillations in Figure 18, we show the evolution of the EL signal over time after the excitation pulse at 9 mA CW current. Post-pulse periodicity and the width of the first (“period one” [90]) oscillation are at the limit of the post-fiber resolution (~3 ps) and may not be resolved at currents above 9 mA. The oscillation period changes with time after the excitation pulse, and the traces of different oscillation periods overlap, making frequency analysis difficult. The resolved period of the oscillations increases to 100–150 ps within ~0.5 ns after the excitation pulse, indicating that all the frequency harmonics contribute to the pulse response.

In Figure 19, we show the equivalent frequencies of the first oscillation and the two subsequent oscillations in the time response plots. The frequencies of the oscillations increase linearly with currents above the SIL threshold. The frequency slope for the first period oscillation is 3-fold larger than those of the two following oscillation periods. The linear trend in the frequency response may be related to the nature of restoring force for the electron–hole plasma concentration after the pulse, which is proportional to the product of field intensity in the cavity and the intensity of the master mode. The restoring force becomes proportional to the square of the current above the SIL threshold, and the frequency of the oscillations, being proportional to the square root of the restoring force, seems to linearly scale with currents above the SIL threshold. Further studies are needed to fully understand this phenomenon.

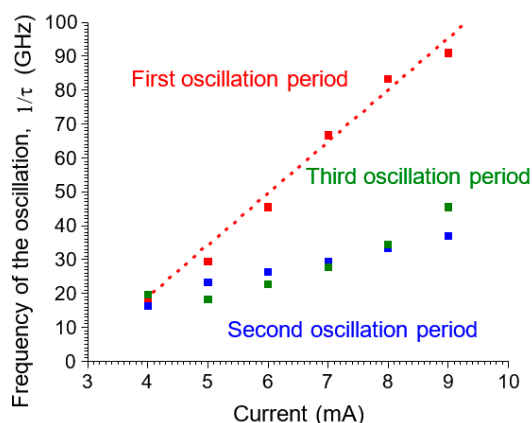


Figure 19. Equivalent frequencies of the first oscillation and the two subsequent oscillations observed in Figure 14. Above the threshold current for the SIL regime, the characteristic oscillation frequencies linearly increase with the current.

The modulation response of the device to electric signals was limited by electric parasitic effects. The damping mechanism is important for digital data transmission, enabling broadband frequency modulation response. Small signals with low electrical modulation bandwidths sent to the device are limited by electric parasitics at $f_{-3\text{dB}} \sim 27\text{--}30\text{ GHz}$. Such a bandwidth enables high-quality PAM4 signaling at 107 Gb/s [50]. It is expected that, with reductions in series resistance and capacitance, devices can reach electric modulation bandwidths in the range 60–70 GHz while keeping a smooth modulation response curve.

11. Conclusions

Vertical-cavity surface-emitting lasers will continue serving high-performance optical interconnects at further increased data rates. Innovative design strategies enable VCSEL performance of up to 200 Gb/s and beyond while maintaining low costs, low power consumption, small sizes and compatibility with installed bases of multi-mode fibers. The multi-aperture approach presented here introduces multiple isolated or coupled oxide-confined apertures into a single VCSEL mesa. Properly designed MA VCSELs provide narrow emission spectra, narrow far-field profiles, reduced series resistance, increased output power and extended intrinsic modulation bandwidths. Optically isolated apertures provide low noise and high coupling efficiency to both MMF and SMF. With SMF 200 Gb/s-class transmission over kilometer-scale distances becomes possible. Optically coupled apertures exhibit built-in self-injection locking, allowing single-supermode operation with enhanced modulation bandwidth. Injection locking may further advance transmission distance via wavelength chirp optimization [89]. Understanding the interplay between electron–hole plasma dynamics, mode coupling and polariton-condensation phenomena is essential for further performance improvements. Due to small apertures, high optical confinement and inherent SIL effects of at least two modes, coupled aperture VCSELs could be ideal candidates for room-temperature lasers based on Bose–Einstein condensation of polaritons [91,92]. The main limiting factor for VCSEL modulation bandwidth is presently RC parasitic effects. RC reduction is a challenging but predominately a technical task. With continued development, shaped apertures and MA VCSELs could support single-channel data rates of up to at least 400 Gb/s, opening new possibilities for data-center, optical wireless and radio-over-fiber applications.

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