VCSELs...

*Go the Distance*

P. KNER, D. SUN, J. BOUCART, P. FLOYD, R. NABIEV, D. DAVIS,
W. YUEN, M. JANSEN, and C. J. CHANG-HASNAIN
Vertical-cavity surface-emitting lasers (VCSELs) have come a long way in the past decade, evolving from a laboratory curiosity to a key component in fiber-optic communications in local area networks (LANs). Rapid advances are reported in 1.5-1.6-µm wavelength VCSELs with tunability and long-reach single-mode fiber transmission. With proven cost benefits in LAN applications, VCSELs are poised to meet the rising market demands of metropolitan area applications.

A vertical-cavity surface-emitting laser is a type of semiconductor diode laser whose cavity is perpendicular to the wafer plane, a design which allows it to emit an output optical beam in the vertical direction. A VCSEL cavity consists of two distributed Bragg reflectors (DBRs) with an active region sandwiched in between. Typically, the entire cavity is grown in one single-step epitaxy. Subsequent processing is used to create the necessary current and optical confinements.

The major advantages of VCSELs are low-cost manufacturing and high spectral performance. It is well known that testing and packaging constitute a large portion of the manufacturing cost of optoelectronic devices. Since their topology is equivalent to that of top-emitting diodes (LEDs), VCSELs can be tested and packaged in volume for Gigabit Ethernet and other low-cost LAN applications. The spectral performance advantage arises from the fact that a VCSEL has an ultra-wide emission wavelength range compared to a conventional 850-nm top-emitting VCSEL.

The search for 1550-nm VCSELs
VCSELs emitting in the 1550-nm wavelength range can be key to the success of single-mode fiber applications. The most challenging problem remains the fabrication of high reflectivity DBRs. The main reason is the small refractive index difference available in typical III-V compound materials lattice-matched to an InP substrate. The smaller index difference dictates use of a large number of pairs, and hence a higher diffraction loss and dopant-related loss. In the mid-1990s, progress in 1550-nm VCSELs was achieved using a wafer-bonding technique. Complicated processing and a higher junction voltage at the heterobonding interface make this approach undesirable. The search for a monolithic, electrically pumped, directly modulated 1550-nm VCSEL continued. Recently, there have been rapid advances in this area. Here we will discuss the only top-emitting structure which facilitates wafer-scale testing and the integration of a micro-electro-mechanical (MEM) tuning structure.

Single-step epitaxy makes low-cost manufacturing possible. Because most well-characterized 1550-nm active regions are InP based, the bottom DBR must be lattice-matched to an InP substrate. On the other hand, the top DBR, grown after the active region, is not constrained by the same lattice-matching requirement. In the design shown in Fig. 1(a), an InGaAlAs/InGaAs bottom DBR and a metamorphic GaAs/AlGaAs top DBR were used. The metamorphic GaAs/AlGaAs layers have a large refractive index difference and high thermal conductivities, are optically flat and electrically conductive. Processing of a metamorphic top-emitting VCSEL follows that of a conventional 850-nm top-emitting VCSEL on wafer scale. Selective oxidation is used to provide electrical and optical confinement.

Figure 1(a). Schematic of Bandwidth9’s top-emitting oxide-confined VCSEL. The heterostructure is grown in one single-step epilaxy. It consists of an InGaAlAs/InGaAs bottom DBR, an active region, and a metamorphic GaAs/AlGaAs top DBR, grown on an InP substrate. The processing is identical to that of a conventional 850-nm top-emitting VCSEL on wafer scale. Selective oxidation is used to provide electrical and optical confinement.

Figure 1(b). CW output power as a function of drive current for an electrically pumped top-emitting 1550-nm VCSEL at 15 °C heat-sink temperature. The VCSEL remains single mode throughout operation, with side-mode suppression ratio > 45 dB and output power > 0.9 mW.

Confined VCSELs are fabricated with 1–2 mA threshold currents and 0.9 mW output power under room temperature continuous wave (CW) operation [Fig. 1(b)]. The devices operate up to 75 °C. A wide range of emission wavelengths from 1.53–1.62 µm was achieved with greater than 45 dB side-mode suppression ratio.

Tunable 1550-nm VCSELs
Tunable lasers are recognized as highly desirable components for wavelength-division multiplexed (WDM) systems. Applications include sparing, hot backup, and fixed-wavelength laser replacement, with the motivating factors being cost savings and higher system reliabilities. Tunable lasers are also vital in enabling dynamical...
Figure 2(a). Schematic of a tunable c-VCSEL. The device consists of a bottom n-DBR, a cavity layer with an active region, and a top mirror. The top mirror, in turn, consists of three parts (starting from the substrate side): a p-DBR, an air gap, and a top n-DBR, which is suspended above the laser cavity and supported via a cantilever structure. Laser drive current is injected through the middle contact via the p-DBR. An oxide aperture is formed in the p-DBR section above the cavity layer to provide simultaneous current and optical confinements. Tuning is achieved by biasing the tuning contact on the top n-DBR and the middle p-DBR contact.

Figure 2(b). SEM photograph of a completed c-VCSEL. The entire heterostructure is grown in a single step, yielding an accurate wavelength-tuning range and predictable tuning characteristics.

Figure 3(a) shows a typical c-VCSEL wavelength as a function of tuning voltage. The continuous, repeatable, and hysteresis-free tuning curve enables the transmission system to lock onto a channel well ahead of its data transmission, a process known as dark tuning. Dark tuning is crucial for reconfigurable metro networks when activation and redirection of broadband optical signals must be accomplished without interference with other operating channels. A 22-nm tuning range is shown in Fig. 3(a). With variations in design, we expect to be able to tune over the entire C- and L-bands. Figure 3(b) shows the emission spectra of a c-VCSEL tuned across 20 channels of C-band at 100 GHz ITU spacing. Single mode with greater than 45-dB side-mode suppression ratio (SMSR) was obtained throughout tuning.

**Single-mode fiber transmission**

One of the most important cost-effective attributes of diode lasers used in LANs and metro applications is the fact that they can be modulated directly by a current source at the appropriate high-speed data rates (e.g., 622 Mbit/s, 1 Gbit/s, and 2.5 Gbit/s). This eliminates the need for an external modulator, which is bulky and expensive.

Figure 4 shows typical bit-error-rate (BER) data as a function of minimum receiver power for a cantilever vertical-cavity surface-emitting laser (VCSEL) under direct modulation at 2.5 Gbit/s (OC-48) transmitted through various lengths of standard single-mode fiber (Corning SMF-28). Without the insertion of fiber, the minimum receiver power at 10^-10 BER is ~31.5 dBm, determined by the avalanche photodiode used. As the propagation distance increases, so does the minimum required receiver power at 10^-10 BER; this indicates a power penalty attributable to laser chirp and fiber dispersion. However, no BER floor (or saturation) was observed for all the fiber lengths tested. Power penalties of 1.4 and 2.3 dB were obtained for transmission through 75 and 100 km of standard single-mode fiber, respectively, with a greater than 8.2-dB extinction ratio. We interpolate a power penalty of less than 2 dB for 85 km of single-mode fiber, fulfilling one important Synchronous Optical Network (SONET) long-reach requirement.

**Reliability**

The c-VCSELS are tested under elevated temperatures with CW operation. The initial reliability data for 16 devices, burned-in prior to experiment and subjected to life-test at 70 °C, is shown in Fig. 5. One device degraded within the first 200 hours, while the rest did not demonstrate any degradation after 1500 hours. One of the important reliability parameters is the so-called activation energy, E_a, which reflects how much faster devices degrade at elevated temperatures. From experiments at different temperatures, we estimate the activation energy for gradual degradation to be 0.45 ± 0.12 eV. This is comparable to standard distributed feedback (DFB)
lasers emitting in the 1550-nm region and having activation energies between 0.35 and 1 eV.\(^9\)

**Conclusion**

The monolithic integration of MEMS and VCSELs has successfully combined the best of both worlds: high performance and cost-effective manufacturing. Electrically pumped c-VCSELs can be directly modulated at 2.5 Gbit/s and transmitted over 100 km of standard single-mode fiber. They have a simple monotonic tuning curve controlled by a single electrode. Tuning speed as fast as microseconds has been reported. The tuning range can be designed to cover the C- or L-band or any part of the 1500-1620-nm wavelength regime. The c-VCSELs can be batch-processed and tested, an essential characteristic as far as mass production is concerned. For all of these reasons, tunable VCSELs are expected to shape the horizon of metropolitan WDM networks.

**References**


P. Kner, D. Sun, J. Boucart, P. Floyd, R. Nabiev, D. Davis, W. Tian, M. Jensen, and C. J. Chang-Hasnain are with Bandwidth9 Inc., Fremont, California. The company’s e-mail address is info@bw9.com.