

Analysis of On Chip Optical Source Vertical Cavity Surface Emitting Laser (VCSEL)

Sandeep Dahiya, Suresh Kumar and B. K. Kaushik

Abstract The major developments in semiconductor laser technology, i.e., Vertical Cavity Surface Emitting Lasers (VCSELs), really revolutionized the field of semiconductor lasers and play a pivotal role in every walk of life such as science and technology, research and development, consumer and industrial environment, medical, military, surveillance, telecommunication, and a host of other applications. Although the development of lasers is pertinent to each other because of dependence on Distributed Bragg Reflector (DBR) mirrors, the devices under reference are normally supposed to be the most appropriate semiconductor lasers for their evident plentiful significances and applications. In modern age, the importance of VCSELs is reflected in fact that they have become the second largest production among all types of semiconductor lasers due to intrinsic structure features of array formation, coherent emission with small beam divergence, large output power, low-threshold operations, high modulation bandwidths, etc., tuned by electrical and temperature variations. In the present investigation, the electrical and optical characteristics of the state-of-the-art long-wavelength VCSEL at 1310 nm emission is analyzed with different apertures such as 20 and 12 μm . The authors observed that if the oxide aperture of the same device is reduced 20 to 12 μm , it obtained the incremental in the carrier and photon density rates and subsequently reduces the emitted power, threshold current, and gain of the devices. The present communication discusses the history, present status, and an exposure of some state-of-the-art performances with optimized results of VCSELs.

S. Dahiya (✉)

Department of Electronics and Communication Engineering,
BPSMV, Khanpur-Kalan, Sonipat, India
e-mail: sandy_dahiya2001@yahoo.com

S. Kumar

Department of Electronics and Communication Engineering,
UIET, MDU, Rohtak, India
e-mail: skvashist_16@yahoo.com

B. K. Kaushik

Department of Electronics and Communication Engineering, IIT, Roorkee, India
e-mail: bkkaushikiitr@gmail.com

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Characterization and results

1 Introduction

Lasers are one of the most significant inventions developed during the mid-twentieth century and play a pivotal role in tremendous aspects of uses in electronics, computer hardware, science, and technology. The first semiconductor p–n junction laser was reported in 1962 [1] and constant developments have been achieved which appreciably increasing the performances of the lasers. But due to the lack of optical and electrical confinement amongst the semiconductor p–n junction lasers, the major advance was recognized for the first time in 1968–1969 with the development of the double-heterojunction laser allowing to reach room-temperature operation. Further, by the impact of optical attenuation and scattering effects in long-haul fibers, there was a dire need for high-intensity transmitters. In optics, the physics is determined by the nature of light and the data is modulated on to optical signals to increase the bandwidth at low power dissipation. The right candidate of optical source is VCSEL which can operate at 850–1550 nm wavelength with single-mode or multimode emission. VCSEL is a type of semiconductor laser with the cavity perpendicular to the wafer plane; its structure allows the emission of light or optical beam in vertical direction either to top (top-emitting devices) or to downward (bottom-emitting devices) direction.

The concept of the VCSEL was first proposed by the elite group of Professor K. Iga of Tokyo Institute of Technology in 1977 and the first working VCSEL devices were accordingly reported in a while by the same group [2]. The preliminary VCSELs with pulsed operation had metallic mirrors and operated at very high threshold currents app. 1000 mA at temperatures 77 K as reported by Soda et al. in 1979 for VCSELs emitting at 1310 nm with GaInAsP/InP for active region and 6 mA threshold device was reported by the same group in 1986 and later Chow et al. presented the fabrication and performance of infrared and visible VCSELs in 1997 [3, 4]. But in next decade, some improvements have been made by the same group of Professor Iga about the prospects of VCSEL devices in the GaInAsP/InP and AlGaAs/GaAs materials. Subsequently, the first room-temperature VCSEL came into existence with two dielectric mirrors [5], and in 1989 Jewell et al. presented 850 nm VCSELs with continuous wave operation which came into existence in 1991 [6]. VCSEL really shows the presence of advances in epitaxial growth techniques of molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD). To make the device companionable with an industrial fabrication, the researchers used double-fused GaAs/GaAlAs mirror for 1550 nm [7, 8] and 1300 nm wavelength [9, 10] or by the combination of one dielectric mirror and one wafer fusion to obtain the good results. Moreover, in 1989, Lee et al. presented 2 mA threshold QW VCSEL [11], Baba et al. demonstrated CW operation for 1310 nm device in 1993 [12], and

20 mW high power was reported by Grabherr et al. in 1996 for the VCSEL emitting at 960 nm [13]. The better results provided by the high thermal conductivity and reflectivity intrinsic to the GaAs-based material is widely optimistic for short wavelength, i.e., 850 and 980 nm wavelength VCSELs. Although edge-emitting traditional lasers are competent of watt-level output power, their asymmetric optical confinement causes very low coupling efficiency into optical fibers. VCSELs possess higher coupling efficiency into fibers due to low-divergence circular output beams, low-threshold currents continuous wave operation, etc. [3, 14, 15]. The techniques MBE and MOCVD significantly improved the characteristics of the mirrors due to the DBRs [16] providing high reflectivity and low losses at low-threshold currents. The rapid progress by Coldren's team in 1991 by introducing new gain materials InGaAs quantum wells (QW) for the cavity of VCSEL was undertaken [17]. Further, the introduction of Al oxide confinement in VCSELs' technology such as [18] has led to even lower threshold values [19] and high-frequency modulation [20]. The research was accelerated to plunge the device in commercial market in the late 90s to meet the third generation of development in 1999 [2].

VCSELs have been of enormous outcome over recent years with their remarkable features such as single-longitudinal-mode operation, circular output beams with low-divergence, low-threshold currents CW operation, ability to be modulated at very high frequencies, and a significance progress that has been made in many diverse current technology applications. The device is considered one of the most vital companions for the performance of the optical interconnects and facilitating ultra-parallel information broadcasted in lightwave and computer systems. Generally, there are two types of VCSELs in existence emitting at short-wavelength spectral range, i.e., wavelength in between 800 and 1000 nm and long-wavelength VCSELs emitting greater than 1000 nm. In past decade, almost all commercial VCSELs were designed for multimode emission but nowadays single-mode emission devices have captured half of the market volume [21–24].

The present investigation will provide an overview of historical path and present status to give an exposure of some state-of-the-art VCSELs performances with optimized results for long-wavelength 1310 nm emission. The manuscript is organized as follows: Sect. 2 presents the device structure and operation; in Sect. 3, the advantages and applications of devices are presented; and Sect. 4 is devoted to the characterization and results of VCSEL summarized the concluding remarks. The succeeding section of study will present the VCSEL structure and its operation.

2 Device Structure and Operation

Nowadays, significant research and development efforts have been reported by researchers and scientists toward VCSELs due to their remarkable features. The VCSEL structure is unique than the conventional edge-emitting lasers or stripe lasers because it emits light perpendicular to the surface of semiconductor wafer by

making more features available on it. The device structure comprised of a top p-type DBR mirror, an active region (cavity), and a bottom n-type DBR mirror to provide the essential optical feedback.

The active layer thickness based on quantum wells or quantum dots is much shorter than cavity length formed by epitaxial layers. Since they gain path along the emission, i.e., in vertical direction, the cavity length of VCSEL is of few tens of nanometers, i.e., hundred times lesser than that of traditional lasers because very high reflectivity required for optical feedback. The transverse symmetry of the cavity causes a low-divergence angle circular output beam [25]. This optical confinement has been obtained through the current confinement schemes such as index guiding via selectively oxidized apertures [19], gain guiding via proton implantation [26], as well as two-dimensional photonic crystals for endless single-mode operation [27]. The properties of VCSEL make it advantageous over traditional edge-emitting lasers because reflectivity of mirror has to be nearly 99–99.9%, whereas it is merely 3% in case of edge-emitting lasers. The emission of light or power is from the top mirror of the device as demonstrated in Fig. 1 [2].

Figure 2 shows the device structure at 1310 nm wavelength emission with 20 μm oxide aperture generated by simulation package. The DBR mirrors as shown in Fig. 3 comprised of alternating sequence of high and low refractive index layer material represented by n with quarter wavelength thickness, where λ is the free space wavelength [28]. Generally, to achieve the better reflectivity and electrical conductivity, more than 20 pairs of each top and bottom mirror are required. The

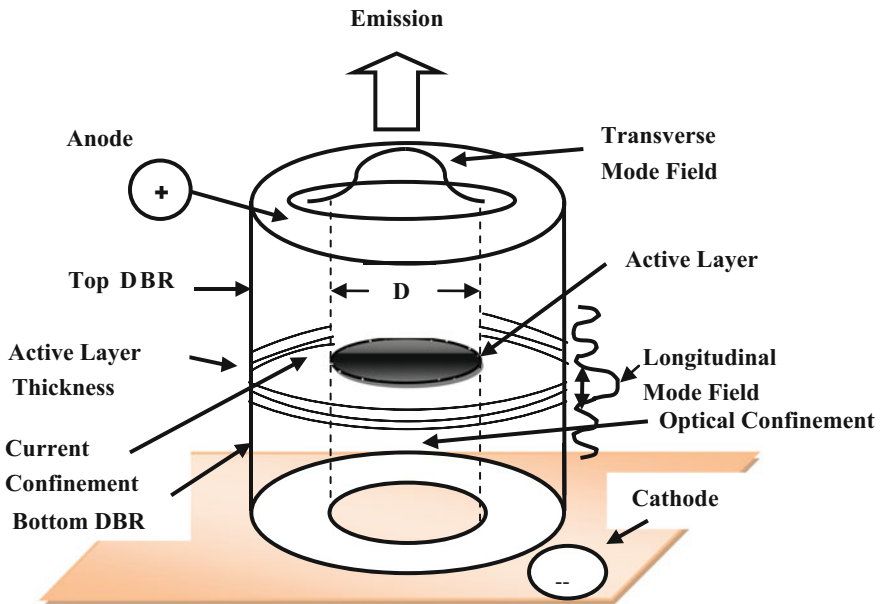


Fig. 1 Layout structure of vertical cavity surface emitting laser

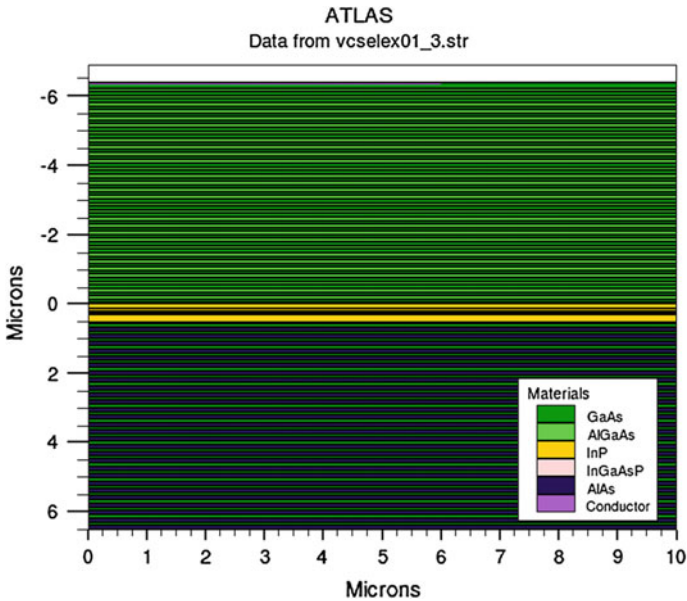
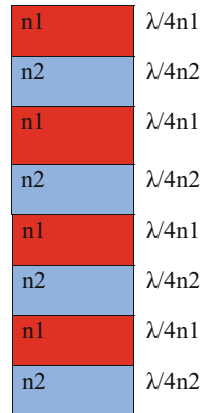


Fig. 2 VCSEL structure created by simulation package

Fig. 3 DBR structure



two top and bottom DBRs in the VCSEL are oppositely doped, i.e., n-type DBR and p-type DBR. The active region emitting light, generally including undoped single or numerous quantum wells, receives current through a current conducting structure which results in high optical power, low divergent angle, and circular symmetric beam in a superior quality [29–31]. Most common quantum well materials assisting direct transitions comprise GaAs for 850-nm-short-wavelength emission and GaInNAs for 1310-nm-long-wavelength emission [32–34].

Moreover, for integration in three-dimensional micro-optical systems, the vertical emission of light sources (VCSELs) is desirable. The structure of VCSEL is optimized for the lithographic fabrication of densely packed two-dimensional arrays. Therefore, VCSELs are perfect light sources for three-dimensional micro-optic, where two-dimensional data are processed in parallel. Finally, the device layout structure and small mode size enable fabrication of extremely consistent and compactly packed lasers with nominal crosstalk for use in parallel optical interconnects [35–37]. The succeeding section will discuss a few among the numerous advantages of VCSELs including optical interconnects, parallel fiber optic systems, medical, data communication, signal processing, etc.

3 Significance and Applications of VCSEL

VCSELs have turned out to be long strides in the short duration of its existence due to its enormous progress of VCSELs performance and applications. Although the first lasing operation on VCSEL was experimental in 1979 in modern information and technology era, they have various advantages over edge-emitting lasers such as low-threshold operations, low cost which makes it commercially viable, single-mode operations, high-speed operations, efficient sources for coherent radiation [2, 21, 38, 39], temperature sensitivity of wavelength, high modulation bandwidth [40], low-divergence circular output beams, low power consumption, compactness [21, 41], high-speed data transfer [42], optical data interconnects [43], efficient coupling to optical fibers, two-dimensional array fabrication by entirely monolithic processes, packaging and heat sinking [44], optical information processing functions [21], pumping for solid-state lasers [45], device structure allowing wafer-level testing, thereby low-cost chip production [2], high power adaptation efficiency, i.e., more than 50%, suitable for optical storage and telecom appliances, due to which embedded active region lifetime is longer, index-guided structure with an oxide aperture and multiple quantum wells in active region, increase in the system throughput, probable sources for plastic fiber communication, free space optoelectronic processing [2, 38, 39], and a host of other significant applications of VCSELs. Long-wavelength VCSELs have also been used in some emerging areas such as Si-related technologies and sensor system [46, 47].

Apart from the above, VCSEL became useful for a diversity of consumer and industrial environment, medical, and military applications requiring high power and energy, such as medical and cosmetics, infrared illuminators for military and surveillance, pumping of solid-state lasers and fiber lasers and also applicable in biological tissue analysis, gas sensing, laser printers, biophotonic chips, etc. [33, 34, 48–50]. In past several years, the commercialization of VCSELs with above-discussed performances and applications make it a strong contender over conventional lasers.

This section deliberates on few significances and applications of VCSELs; the next section of the investigation reports the characterization and optimized results of VCSELs.

4 Characterization and Results

Optical interconnects are promising technology to fulfill the high-speed requirements of next generation. Optical interconnects exhibit a variety of advantages over copper and electrical interconnects such as higher bandwidth, low crosstalk between channels, and low power consumption. Moreover, it is vital to decrease the volume of active region (cavity) in order to reduce the threshold current in case of VCSELs. Ikechi et al. in 2013 demonstrated the performance comparison of the high-speed characteristics of VCSELs for the short wavelength (850 nm emission) and long wavelength (1310 nm emission) for top- and bottom-emitting surface for use in modern high-bandwidth fiber optic networks [51]. The VCSEL's exceptional characteristics such as parallel operation, high modulation rate, and circularly symmetric emitted beam make them very gorgeous light sources for the next generation of LAN, ethernet, and optical interconnects. The long-wavelength VCSELs are advantageous for parallel light wave structures to assemble speedy enhancement of information transmission capability in local area networks. Semiconductor VCSEL layouts are appropriate for exploring the characteristics of the spontaneous emission since the device structures are fabricated by MBE and MOCVD technologies. The reflectivity of the spontaneous emission can be simply deliberated by varying AlAs/GaAs pairs of DBR mirrors. The communication between excitonic energy and active region (cavity mode) can be analytically changed by employing thermal characteristics of VCSEL layout structures [52, 53].

In present analysis, the characteristics of 1310-nm-long-wavelength VCSEL of oxide aperture 20 μm is demonstrated. The VCSEL under reference utilize strain-compensated InGaAsP six MQ wells optical cavity sandwiched between GaAs/AlGaAs mirrors, those are double-fused on the InP space layers in active region at both sides. The top mirror consists of 30 pairs of materials GaAs and AlGaAs and is covered by GaAs layer to enhance the reflectivity with 28 pairs of bottom mirror of material GaAs and AlAs quarter-wave layers. The simulated waveforms obtained by commercial software tool for laser power, gain, photon density, optical wavelength, and mirror loss versus applied voltage are shown in Fig. 4. On analyzing the obtained results for 1310-nm-long-wavelength emission, the laser or emitted power achieved is 98.6 mW, gain is 30 cm^{-1} , photon density is $2.88 \times 10^6/\text{cm}^3$, and mirror loss is 30.7 W/cm with reflectivity of DBR mirrors greater than 99%. The amplification must be able to offset all the losses to obtain lasing operation to maintain the reflectivity of mirrors very high. The authors analyzed that if the oxide aperture of the same long-wavelength VCSEL under reference is reduced from 20 μm to 12 μm , then the incrementation in the carrier

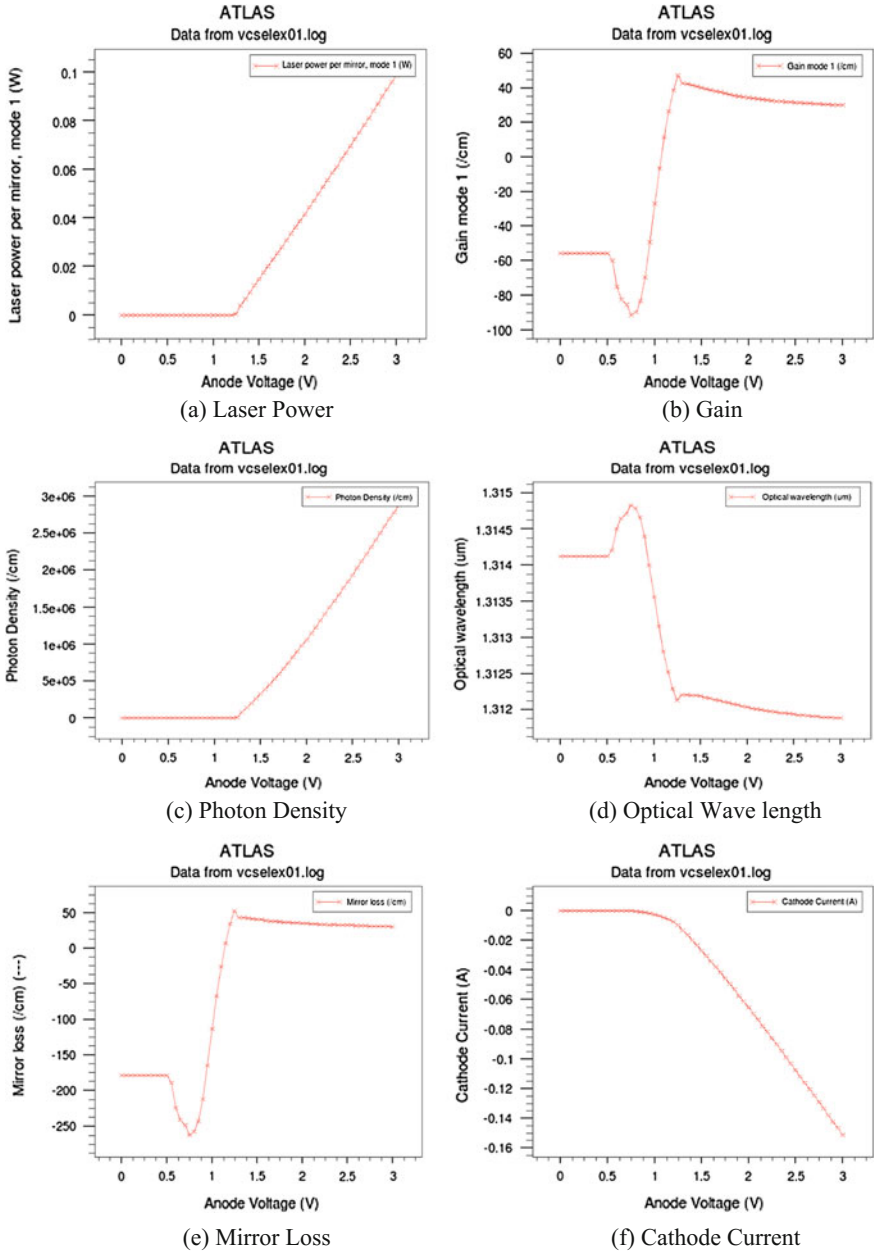


Fig. 4 Laser power, gain, photon density, optical wavelength, mirror loss, cathode current versus applied bias

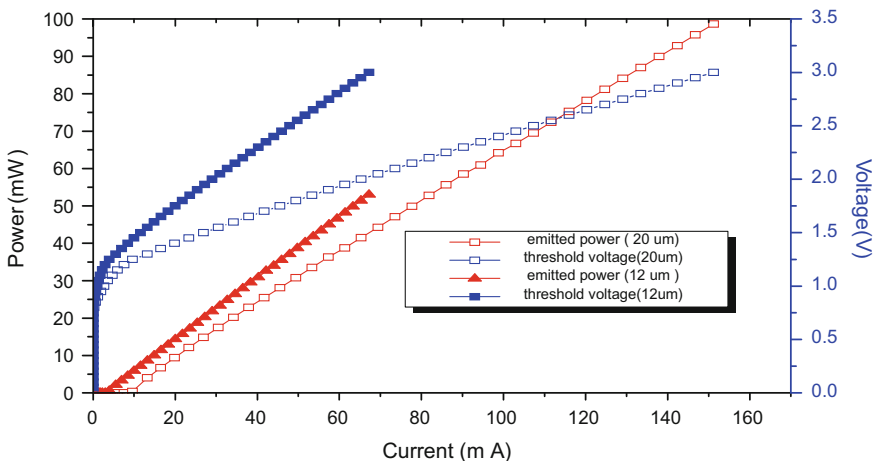


Fig. 5 Laser power, voltage versus current (LIV) characteristics of 1310 nm VCSEL

and photon density rates and subsequently reduction in the power, threshold current, and gain have been observed, as discussed in next para, in Fig. 5 [8, 54–57].

Moreover, the comparative light–current–voltage characteristics of 1310 nm emitting devices with different oxide apertures, i.e., 12 and 20 μm, is shown in Fig. 5. In this analysis, a comparison of electrical and optical characteristics of 1310-nm-long-wavelength emission of VCSEL using simulation tool is presented. The single-mode optical powers of 53 mW at 12 μm and 98.6 mW at 20 μm oxide aperture of 1310 nm emitting device have been obtained with a maximum diode voltage of 3 V. The obtained results demonstrate that by increasing the oxide aperture of the device under reference provides the better emitted or laser power.

The next section of present communication focuses on future direction of VCSELs summarized with concluding remarks.

5 Conclusion and Future Prospects

Presently, VCSEL play a essential role in every walk of life such as science and technology, research and development, consumer and industrial, medical, military/surveillance, telecommunication, etc. due to intrinsic structure of array formation, circular beam emission with small divergence, large output power, low- threshold operations, high modulation bandwidths, etc. Nowadays, the commercialization of VCSELs with above-discussed performances and numerous applications make it a strong contender over conventional edge-emitting lasers. In the present paper, the electrical and optical characteristics of 1310-nm-long-wavelength VCSEL of oxide aperture 20 and 12 μm are analyzed in industrial-specific commercial software package. The single-mode optical powers of 53 mW at 12 μm and 98.6 mW at

20 μm oxide aperture of 1310 nm emitting device have been obtained with a maximum diode voltage of 3 V and reflectivity of DBR mirrors greater than 99%. The obtained results confirm that numerical simulation presents a suitable platform to calculate and optimize diverse design parameters of VCSELs without increasing fabrication cost and time. The authors observed that if the oxide aperture of the same VCSEL is reduced from 20 to 12 μm , it obtains the increased carrier and photon density rates and subsequently reduces the threshold current and gain as shown in Fig. 5.

After deliberation on past, present of short- and long-wavelength VCSELs, it is evident that predictions are not easy to make when the things are concerned with future. The Si-based memory technology should be used for optical storage in future because from its existence, optical data storage has been listed as a future VCSEL application. High-speed and high capacity data transmission are in great demand for future optical telecommunication, computer memory systems, and mobile communications. Moreover, future paths are integration of VCSEL, PD, and actuator with MEMS technology and used for the development and manufacture of portable, cost-effective biomedical diagnostic tools.

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