Optical Interconnects Using Single-Mode and Multi-Mode VCSEL and Multi-Mode Fiber

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Abstract: Single mode (SM) VCSELs, produced in industrial 4” technology, are suitable for 100Gb/s PAM2 and >160Gb/s PAM4 data transmission. >107Gb/s transmission over 1km of multimode (MM) fiber at 850nm and 910nm is realized.

OCIS codes: (140.5960) Semiconductor lasers, (140.7260) Vertical cavity surface emitting lasers

1. Introduction

Upgrades in technology and architecture of modern processors drive their computational power. To match the demand of ever-increasing productivity of processors and the related computational systems, the data rates of the input-output devices must double approximately each two years and the bandwidth density should double each 18 months via additions of new channels. The copper interconnects have already met difficulties for data rates above 25Gb/s in on-off keying (OOK). A transition to multi-level coding such as pulse-amplitude modulation at 4 levels (PAM4) became necessary, even at the expense of increased complexity and latency. As the technology scaling continues, electrical interfaces at 56Gbuad and data rates at 112Gb/s are needed, while further upgrades in data rates are being actively discussed. Vertical cavity surface emitting lasers (VCSELs) dominate optical data transmission over multimode fiber at distances <300m and serve as extensions of copper interfaces and interconnects. VCSELs can be made very small, with a device mesa diameter of only ~20-30µm and 5-7µm current injection aperture. To match future applications VCSEL however must comply with the data rate scaling at required distances and tolerate temperatures of at least 105°C to penetrate on board and on-chip applications. New developments in the device design are necessary to match the demand.

2. Advancements in VCSEL design

(i) *Cavity design.* Until 2006 it was believed that VCSELs will not be able to operate reliably at data rates well above 10Gb/s [1]. At that time in standard VCSELs the cavity region was typically composed of a material having a higher refractive index, as compared to the average refractive index of the surrounding distributed Bragg reflectors (DBRs). This design representing thus a waveguiding cavity concept, which is characteristic also to conventional in-plane injection lasers. The in–plane waveguide mode in such design had the highest overlap integral and the highest oscillator strength of the related optical transmission, while the oscillation strength of the vertical cavity transition was reduced. In the normal VCSEL design with a relatively small top mesa diameter, under generation of light in the device, high quality factor (Q) whispering gallery modes (WGM) are excited [2], causing the gain depletion, or even WGM lasing. In an anti-guiding design (A-VCSEL) [2], the waveguiding modes are suppressed and the gain is not depleted. Furthermore, the oscillator strength of the vertical transition is strongly increased, and in 3/2λ A-VCSEL geometry it the same as in a λ-thick guiding cavity VCSEL design, in spite of the optical overlap with the gain medium being significantly higher in the latter case. It is also feasible to apply λ/2 vertical cavity in the A-VCSEL design and increase the oscillator strength for the vertical transition by further 37%. As opposite in the guiding 1/2λ cavity design the field intensity for the vertical mode is zero in the center of the 1/2λ cavity, and a proper placement of the active region is thus challenging. A 1/2 λ design with a cavity composed of AlAs was applied [3] to oxidize the cavity region by half and reduce the oxide aperture-to-QW distance and reach lower current density. In industrial VCSELs, however, the aperture layer is usually shifted from the gain medium into the DBR section (for example into the third DBR period [4]) to slow down the wear-off degradation. The A-VCSEL design must thus comply with reliability requirement and a proper design of the aperture region is necessary.

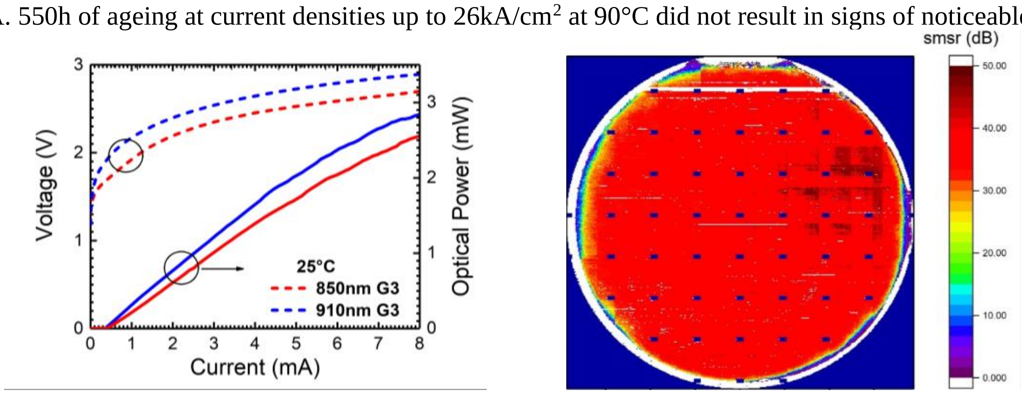
(ii) *Spectral width and modal composition*. Transverse modes excited in VCSEL cause spectral broadening. As the chromatic dispersion in glass is significant at MMF datacom wavelengths, the reduction of the spectral width is of critical importance to increase the transmission distance. Single mode (SM) VCSEL has an advantage of ultranarrow spectrum eliminating the impact of the chromatic dispersion in MMF. A single lobe emission in the far field makes optical coupling more reliable, reducing optical feedback from poorly controlled back reflections of high order modes and preventing the mode partition noise characteristic of multimode devices. Single mode emission can be realized by choosing a very small aperture size, however, in such approach the resistance of the device becomes not compatible to energy-efficient drivers. Also, the power at current densities matching reliable operation may become insufficient, particularly at high temperatures. Surface patterning was proposed [5] to stabilize single mode operation, even the impact of the surface relief may be too sensitive in respect to the particular shape of the etched pattern and the oxide-confined aperture diameter. Thin apertures may result in higher stability of the single mode operation at small currents. However, at practical current densities Joule- and free-carrier absorption-induced heating strongly affects the refractive index profile confining high order modes [6]. All-epitaxial design approach was proposed to generate leakage of the high order transverse modes into the surrounding oxidized sections [7]. With combination of the approaches stable SM operation in low resistance VCSELs was realized.

(iii) *Photon lifetime.* Removal of DBR pairs or etching of top layer [8] of the DBR sequence can affect DBR reflectivity and, thus, the photon lifetime in the cavity. Reduced photon lifetime reduces the damping and can enhance the modulation bandwidth. Alternative approaches to modify the post-epitaxy photon lifetime are: replacement of a semiconductor DBR with a dielectric DBRs [9] and the deposition of a dielectric layer to match the required phase of the optical wave at the semiconductor- air interface [10, 11].

(iv) *Active region*. 850nm VCSELs fabricated with industrial processing are based on quantum wells (QWs) and quantum dots (QDs). QD VCSEL show a drastically improved temperature stability of operation. Data transmission at 40Gb/s at 150°C and 25Gb/s at 180°C is demonstrated [12].

3. Experimental

In this work we report results realized with the latest generation of the SM VCSEL chips. Epitaxial wafers were grown by metal-organic chemical vapor deposition (MOCVD) using multi-wafer industrial reactor. 4” industrial technology was applied for processing of epitaxial wafers to VCSELs. We concentrate on 850nm and 910nm oxide-confined VCSEL which demonstrated similar high-frequency and light-current-voltage characteristics. The oxide confined aperture diameter was ~3µm. Roll over power of ~4-5mW was reached at ~8-10mA drive current. Differential series resistance of the chips was ~80Ω at ~4mA. The power decrease at 85°C constituted ~15% at 3mA. 550h of ageing at current densities up to 26kA/cm^2 at 90°C did not result in signs of noticeable degradation.



(a) (b)

Figure 1. (a) Fiber-coupled light-current-voltage (LIV) curves of the VCSELs studied in this work. (b) Side mode suppression ratio (SMSR) across 4” VCSEL wafer at 3mA current (910 nm VCSEL wafer).

3. Data transmission

Back-to-back and long-distance transmission over OM5 fiber was studied. For up to 100Gbit/s NRZ experiments the input electrical signal was generated with a 45GHz 120 Gsamples/s arbitrary waveform generator (AWG) and was subsequently amplified with a 55GHz electrical amplifier with 22dB gain. The connection between the amplifier and the VCSEL was made with a 10 cm-long coax cable. The output of the VCSEL was coupled into a short OM3 fiber and detected with a 32GHz optical receiver. Following pre-emphasis at the transmitter side was used in the experiments: (i) for PAM2 transmission the signal pre-emphasis consisted of compensations for the AWG channel characteristics, electrical amplifier and the optical link response. The signal was additionally shaped with root raised cosine filter with 0.1 roll off. (ii) for PAM4 transmission, a static 6-tap FFE filter and at the receiver a static 5-tap FFE filter were applied for equalization of the channel. A raised cosine filter (9-tap 0.3 roll off) was added for

deliberate shaping of the drive signal to match the equalized channel. The performance of 850nm and 910nm VCSELs was very similar both in achieved data rates, as well as in the amount of required equalization.
The eye diagrams are presented in Fig. 2 show good performance both for PAM2 and PAM4 data transmission. Error free transmission up to 90 Gbit/s was realized, while at 100Gbit/s degradation of the eye diagram due to the required link gain is observed and equalization had to be applied to reach FEC error levels. Up to 70Gb/s error free transmission could be realized without pre-emphasis and equalization.

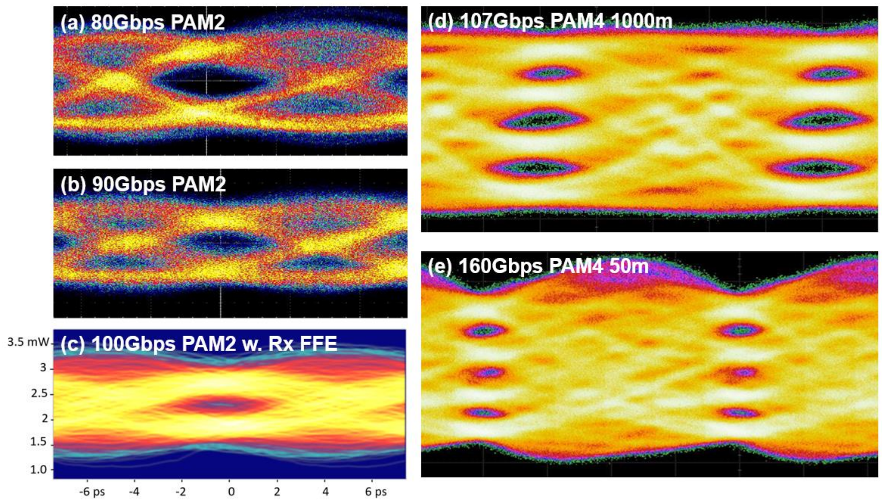


Figure 2. Eye diagrams of MMF data transmission with the 850nm VCSEL at (a-b) 80Gb/s, 90Gb/s PAM2 w. pre-emphasis only, (c) 100Gb/s PAM2 w. pre-emphasis and 5-tap receiver FFE equalization. (d) SM VCSEL 107 Gb/s PAM4 data transmission over 1000m of OM5 MMF and (e) 160Gb/s over 50m of OM5 fiber.

With a new generation of VCSELs data transmission at 100Gb/s in PAM2 and 160Gb/s in PAM4 is reached. Data transmission over 1km OM5 fiber is realized with SM VCSEL at both 850nm and 910nm wavelengths at 107Gb/s.

4. Conclusion

SM VCSELs are suitable for signaling up to 100Gbaud and for SWDM data transmission at 100Gbaud over 1km-long distances of MMF. Technology upgrade to QDs improves temperature stability allowing 40Gb/s PAM2 transmission up to 150°C. This opens a range of applications from automotive data links to on-board signaling. Further SM VCSEL design concepts will enable strongly reduced series resistance and enhanced electrical modulation bandwidth, which are presently the main limiting factors to exceed 100Gbaud signaling and reach data rates well above 200Gb/s.

5. References

[1]. Tatum J. “Optical components for 100 Gbps. IEEE 802.3 Higher Speed Study Group Meeting, 2006.
[2]. N.N. Ledentsov et al "Novel concepts for ultrahigh-speed quantum-dot VCSELs and edge-emitters" Proceedings SPIE 6468, 6468–47 (2007); N.N. Ledentsov “High-speed modulation, wavelength, and mode control in vertical-cavity surface-emitting lasers” Proc. SPIE 9381, 93810F-10 (2015); Ledentsov NN, Shchukin VA. “Optoelectronic device based on an antiwaveguiding cavity”. US Patent 7,339,965 (2004).
[3]. D.L. Huffaker, J. Shin and D.G. Deppe “Low threshold half-wave vertical-cavity lasers” Electronics Letters 30 (1994) 1946-1947
[4]. B. M. Hawkins et al, “Reliability of various size oxide aperture VCSELs” Electronic Components and Technology Conference. Proc. 52, 540–550 (2002).
[5]. A. Larsson at al. “VCSEL modulation speed: status and prospects” Proceedings SPIE 10938, 1093802 (2019).
[6]. N. N. Ledentsov et al, "Anti–waveguiding vertical–cavity surface–emitting laser at 850 nm: From concept to advances in high–speed data transmission" Opt. Express 26, 445-453 (2018)
[7]. N. Ledentsov Jr, et al “Direct Evidence of the Leaky Emission in Oxide-Confined Vertical Cavity Lasers” IEEE Journal of Quantum Electronics 52 (3), 2400207 (2016).
[8] P. Westbergh, et al “Impact of photon lifetime on high-speed VCSEL performance,” IEEE J. Select. Topics Quantum Electronics 17, 1603-1613 (2011).
[9]. M. Ortsiefer et al “Recent Progress of InP-based Long-Wavelength VCSELs for Communications Applications” Extended Abstracts. VCSEL Day 2013 May 31st-June 1st, 2013, Lausanne, Switzerland.
[10]. A. N. AL-Omari, et al “Improved performance of top-emitting oxide-confined polyimide-planarized 980nm VCSELs with copper-plated heat sinks” J. Phys. D: Appl. Phys. 45, 505101 (8pp) (2012)
[11]. G. Larisch, et al, “Impact of Photon Lifetime on the Temperature Stability of 50 Gb/s 980 nm VCSELs” IEEE Photonics Technology Letters 28, 2327-2329 (2016).
[12]. N. Ledentsov Jr., et al “Quantum-dot oxide-confined 850-nm VCSELs with extreme temperature stability operating at 25 Gbit/s up to 180°C” Proc. SPIE 11300, 11300-15 (2020).