850 nm VCSEL and PD for Ultra High Speed Data Communication over Multimode Fiber

Chuan XIE*, Jiaxi KAN, Shenghong HUANG, Li WANG, Neinyi LI, Chan Chih CHEN
and Shigeru INANO

With the advent of cloud computing, the proliferation of smart phones and tablets, and the omnipresence of social networking, the bandwidth need for data communication continues its phenomenal growth. Less than two years after the high data rate of 14Gbit/s was finalized in 2011, the new high data rate of 25Gbit/s to 28Gbit/s is already upon us. In this paper, we report the development of the 850nm vertical-cavity surface-emitting laser (VCSEL) and photodiode (PD) at Sumitomo Electric Device Innovations USA (SEDU) to operate at this new data rate. These devices are targeted to use in active optical cables (AOC) and transceivers over multimode fiber for optical interconnect and short reach applications. We have successfully demonstrated their operation in an EDR AOC running at 25.8Gbit/s over 50 meters of OM3 fiber at Optical Fiber Communication Conference and Exposition (OFC) 2013.

Keywords: 25Gbit/s, 28Gbit/s, 850nm, VCSEL, PIN photodiode, AOC

1. Introduction

The gigantic modern infrastructure referred to as the Internet continues its most phenomenal growth in human history. While the number of users is still growing rapidly, the usage per user is growing much faster. The variety of devices people use to access the Internet has grown way beyond PCs and laptops in recent years. The type of services people rely on the Internet to provide and the amount of data people store on the Internet are both growing at a dazzling pace. All this growth pushes for a steep increase in communication bandwidth and data rate. On the InfiniBand road map(1), the data rate was anticipated to reach 14 Gbit/s per channel (Fourteen Data Rate or FDR) in 2011 (and it did); the next data rate of 26 Gbit/s (Enhanced Data Rate or EDR) will arrive before 2014.

In anticipation of such a market demand, we have developed the next generation 850 nm VCSEL and photodiode (PD) (3),(4),(6). These next generation devices are targeted to operate at data rates from 25 Gbit/s to 28 Gbit/s. In this paper, we shall report the status of this development effort. The characterization data of the new devices and their preliminary validation results in the EDR active optical cables AOC will be presented.

2. Device Design Considerations

2-1 Design the VCSEL for higher speed

Since the vertical-cavity surface-emitting laser (VCSEL) is smaller and has higher thermal impedance than an edge emitting laser, it is more critical for the VCSEL to have a relaxation oscillation frequency (ROF) that increases rapidly with bias current to attain high speed. Thermal restriction aside, the desire for low power consumption and longevity of the device also demands low operation current(2),(3),(5).

To achieve a high ROF at low bias, we need to design the VCSEL with high differential gain, high internal efficiency, and small optical mode volume.

We use compressively strained quantum wells (QWs) for the new VCSEL to significantly boost its differential gain. The material composition of both the QW and the barrier is carefully chosen. The number of wells is also optimized based on cavity loss.

For high internal efficiency, the laser's cavity and active region are redesigned for enhanced carrier confinement and lower carrier leakage. Low carrier leakage is especially beneficial to both DC and AC characteristics at high temperatures. Thus, the new design has less performance variation over temperature.

High quality epitaxial growth is of paramount importance. The laser's active region, especially the QW and barrier interface, needs to have low defect density. Defects cause carriers to non-radiatively recombine, hence decrease internal efficiency and increase laser threshold. More importantly, the energy released in non-radiative recombination generates new defects and promotes defect migration. Such defect generation and migration are a major reliability concern.

When the oxide aperture is relatively large, reducing its size effectively lowers mode volume. When the aperture is sufficiently small, however, further size reduction only hinders laser speed, because the increased resistance sets a low bandwidth limit due to a combination of thermal rollover and the RC effect. Moreover, when the aperture is very small, the (lateral) optical confinement becomes worse, negatively impacting speed as well. Based on these considerations, our new VCSEL uses an aperture size similar to that of our 10 Gbit/s VCSEL, which appears to be near optimal. Unlike the 10 Gbit/s VCSEL, however, the new design has improved vertical optical confinement, improving the overlap between the optical field and the QWs.

In addition to reaching a high ROF at low bias, proper damping is also critical to getting a high quality optical eye. Damping is largely controlled by photon lifetime. As shown by simulation in **Fig. 1**, shorter photon lifetime (lower damping) offers higher bandwidth at operation bias, but the electro-optical (EO) response has more peaking and the optical eye can have higher overshoot and data dependent jitter (DJ). Lengthening photo lifetime can reduce overshoot and DJ, but excessively long photo lifetime results in insufficient bandwidth and vertical eye closing.

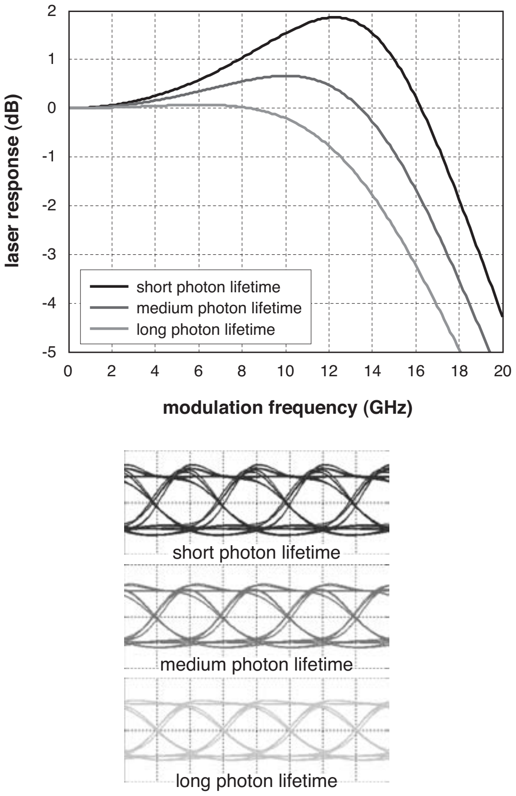


Fig. 1. Simulated laser EO response (top) and (filtered) eye diagrams at 25 Gbit/s

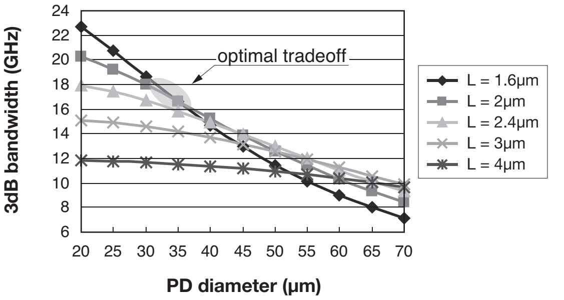
Last but not least, the VCSEL's parasitic elements need to be carefully controlled when designing the structure of the device. The parasitic bandwidth is largely limited by the RC constant of the aperture defined resistance (R) and the oxide capacitance (C). This RC constant needs to be minimized. To this end, we should not make the aperture too small, and we need to design for an effectively lower oxide capacitance.

2-2 Make design trade-offs for the PD

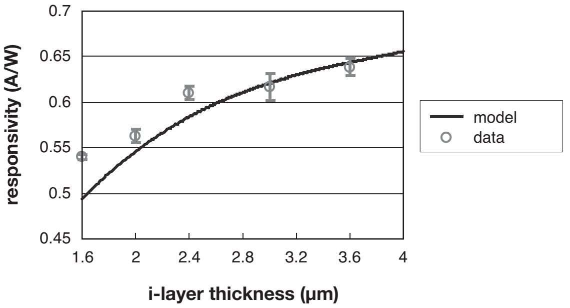
The PD's bandwidth is limited by two factors: its capacitance and the carrier transit time. For multimode applications, especially when passive alignment is preferred for lower cost, a large aperture PD is desirable. Unfortunately, a PD's capacitance is proportional to its area. To lower the capacitance of a large detector, its intrinsic layer (i-layer) needs to be thick. When the i-layer is too thick, however, long carrier transit time will limit speed. **Figure 2 (a)** shows the simulated bandwidth$^{(7)}$ (assuming a 50 Ω load and saturated carrier velocities). Bandwidth of a PD with a thick i-layer is limited by the transit time; it does not increase much with reduced size. When a small PD can be tolerated, a thinner i-layer can be chosen for higher bandwidth.

The PD's responsivity depends on its i-layer thickness. However, **Fig. 2 (b)** shows that the responsivity is still acceptable with a relatively thin i-layer.

For our applications, the best trade-off is likely in or near the area marked by the shaded oval.



(a) Simulated PD bandwidth



(b) PD responsivity, simulation versus data

Fig. 2. PD bandwidth (a) and responsivity (b)

3. Device Performance Characterization

3-1 VCSEL bandwidth and ROF versus bias

Based on the design considerations outlined in Section 2-1, we produced a VCSEL that significantly outperforms the current 10 Gbit/s VCSEL in production in speed. This new VCSEL's ROF increases substantially faster with bias current over temperature (**Fig. 3 (b)**). The bandwidth is also much wider, and with much reduced difference between 25˚C and 85˚C (**Fig. 3 (a)**). **Figure 4** shows the typical electro-optic (EO) response of this laser at 25˚C and 85˚C.

3-2 VCSEL eye diagram

The new VCSEL was evaluated at data rates of up to 28 Gbit/s, using a pattern generator to drive it through a 40 GHz bias-tee and a 40 GHz RF probe. The output of the VCSEL was coupled into the fiber via a lensed fiber probe. The optical eye diagrams were captured by a high speed sampling scope with a 20 GHz opto-electronic (OE) conversion bandwidth. The scope's response is not de-embedded.

Figure 5 shows the eye diagrams at 25 Gbit/s and 28

Gbit/s for the Pseudorandom Binary Sequence 31 (PRBS31) pattern at 25°C and 85°C. The bias was 8 mA for 25°C and 9 mA for 85°C.

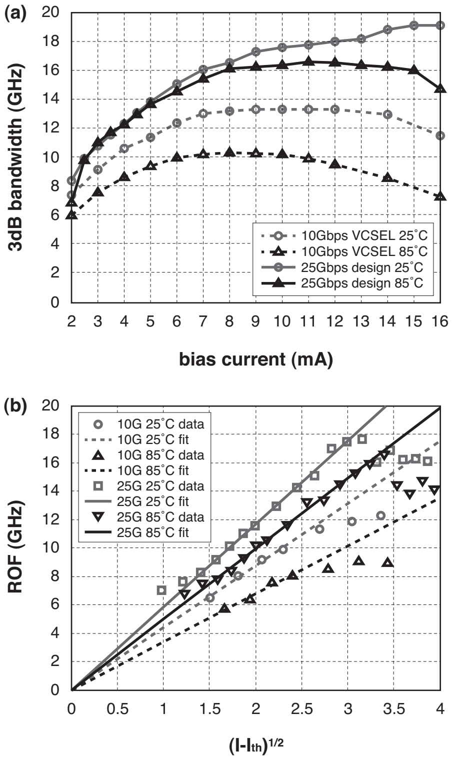


Fig. 3. Bandwidth (a) ROF (b)

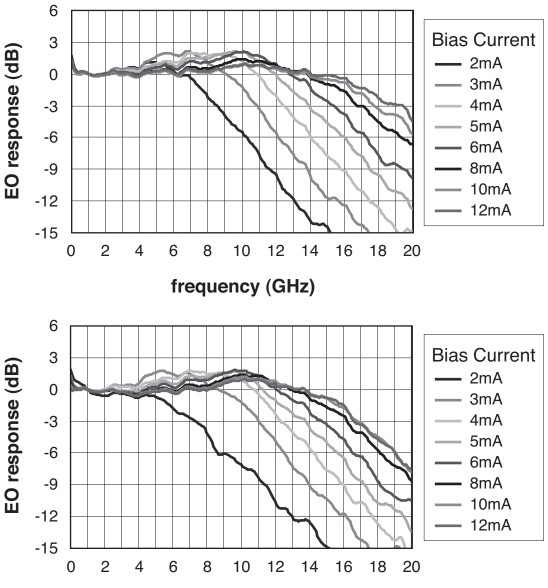
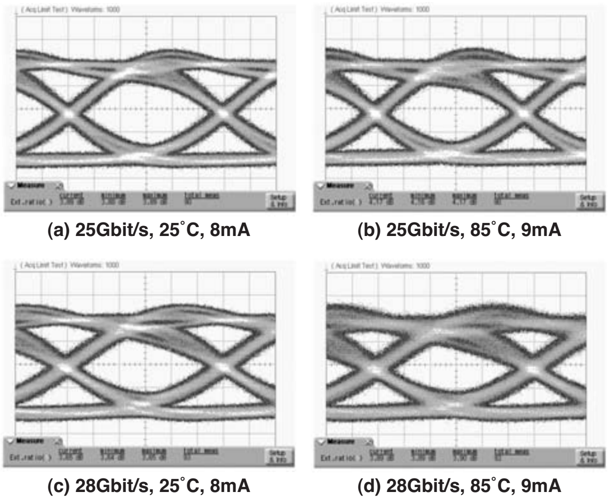


Fig. 4. EO response of the new VCSEL at 25°C (top) and 85°C (bottom)


(a) 25Gbit/s, 25°C, 8mA

(b) 25Gbit/s, 85°C, 9mA

(c) 28Gbit/s, 25°C, 8mA

(d) 28Gbit/s, 85°C, 9mA

Fig. 5. 25 Gbit/s and 28 Gbit/s VCSEL eye diagrams

3-3 VCSEL spectral width

Since the new VCSEL has the same aperture size and oxidation layer design as the 10 Gbit/s VCSEL, the spectrum and spectral width are the same as well.

Figure 6 is the spectral width data from two 1 x 4 arrays (sample A and B) at 25°C and 85°C under various bias currents. The approximate range of operation bias over temperature is between the two vertical dash lines.

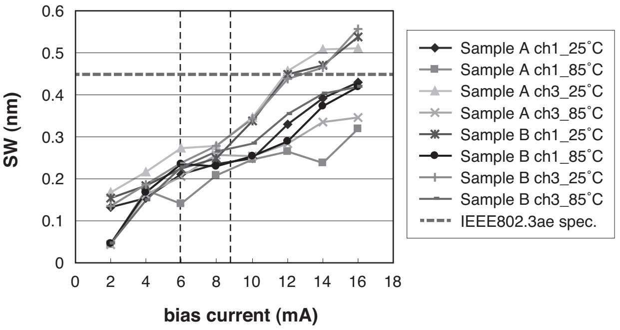


Fig. 6. Spectral width of the new VCSEL

3-4 PD performance validation

We checked the PD's capability to operate at 25 Gbit/s by directly measuring its OE eye diagrams in conjunction with a trans-impedance amplifier (TIA). **Figure 7** shows the 25 Gbit/s, PRBS31 electrical output eye diagrams of two commercially available TIAs with our PD connected to them through wire bonds. The optical input to the PD is from our new VCSEL driven by the pattern generator.

3-5 Sensitivity and performance over fiber

To assess the link budget at 25 Gbit/s with the new VCSEL and PD, we built a transmitter using a pattern generator driving a VCSEL, and a receiver using PD of two different sizes (25 μm and 35 μm) on a commercial TIA

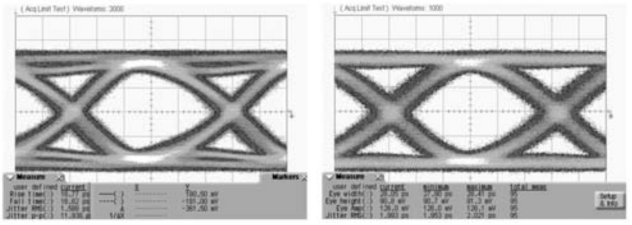

(a) Vendor A's TIA
(b) Vendor B's TIA

Fig. 7. TIA output eye diagrams measured with a 35 μm PD

evaluation board (from vendor A). Light was coupled out of the VCSEL and onto the PD with lensed fibers. We measured back to back (B2B) sensitivity as well as sensitivity over various lengths of OM3 fiber. We used two different patterns (PRBS7 and PRBS31) to check for pattern dependency. The results are presented in **Fig. 8**.

Comparing the bit error ratio (BER) curves in **Fig. 8 (a) and Fig. 8 (b)**, we see comparable performance between the 25 μm PD and the 35 μm PD. The B2B sensitivity (BER = 10^{-12}) is better than -8 dBm in optical modulation amplitude (OMA) for both detectors. The link penalty (from modal and chromatic dispersion) is almost negligible over 50 meters of OM3 fiber. Error-free operation is still achieved over a 200 meter OM3 link with approximately -5 dBm OMA sensitivity for PRBS31. The worst case pattern dependency is about 1 dB.

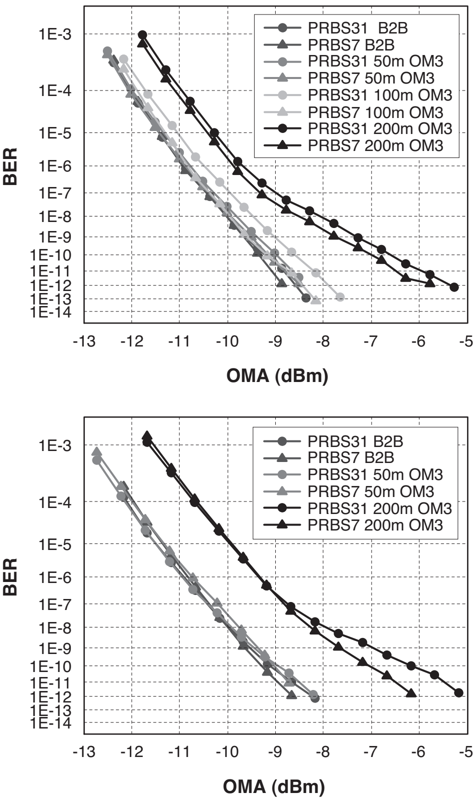


Fig. 8. 25 Gbit/s BER curves with a 25 μm PD (top) and a 35 μm PD (bottom)

4. Performance Demonstration in EDR

To further validate this new technology in a more realistic use case, we made EDR cables (**Fig. 9**) using commercial VCSEL drivers and TIAs on transceiver printed circuit boards (PCBs). To enhance high frequency performance, we used a combination of Panasonic MEGTRON 6-5775 and FR4 as the PCB's dielectric materials (the FDR PCB uses FR408 HR). The devices were wire-bonded to the driver/TIA ICs. Error-free operation for PRBS31 (BER < 10^{-15}) at 25.8 Gbit/s

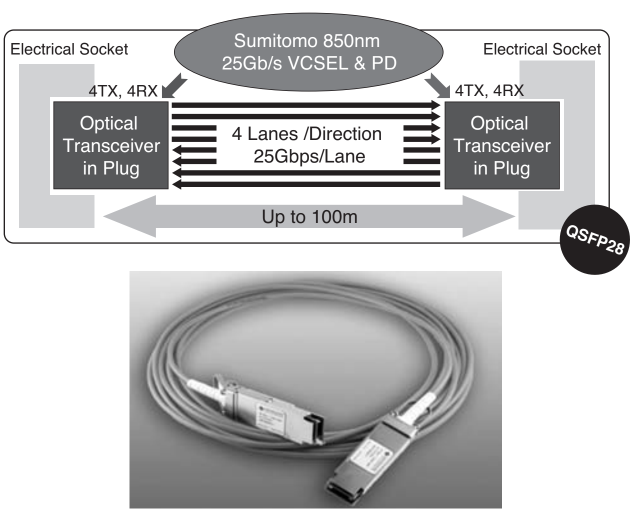
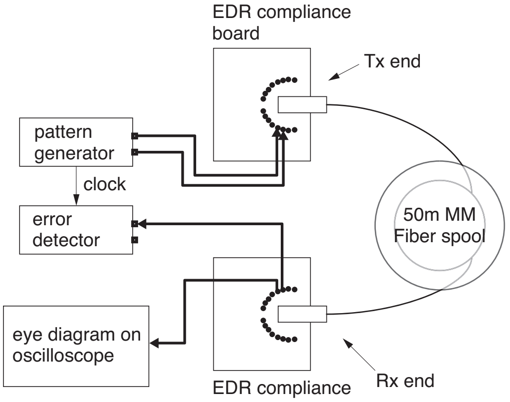


Fig. 9. EDR cable block diagram (top); image of InfiniBand AOC (bottom)



(a) EDR cable test setup

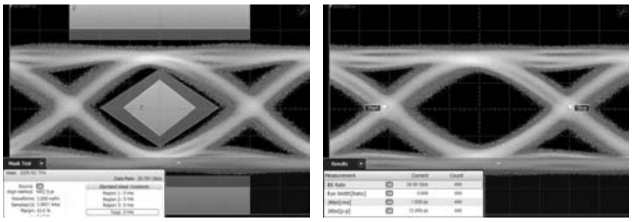

(b) 25.8Gbit/s Rx output eye
(c) 28.05Gbit/s Rx output eye

Fig. 10. Electrical eye diagrams from an EDR cable

was achieved over a 50-meter OM3 multimode fiber cable with different driver/TIA IC combinations from two vendors. **Figure 10 (a)** illustrates the EDR cable test setup. The receiver's output eye diagram (PRBS31) has more than 40% mask margin on the InfiniBand mask (**Fig. 10 (b)**). Its J9 jitter is 0.51 mUI. Pushing the data rate up to 28.05 Gbit/s (32 GFC rate), the PRBS31 eye still looks extremely clean and with low jitter (**Fig. 10 (c)**). Error-free operation at 28.05 Gbit/s has also been achieved for PRBS31.

We demonstrated consistent performance of such an EDR cable at Optical Fiber Communication Conference and Exposition (OFC) 2013 (**Photo 1**).

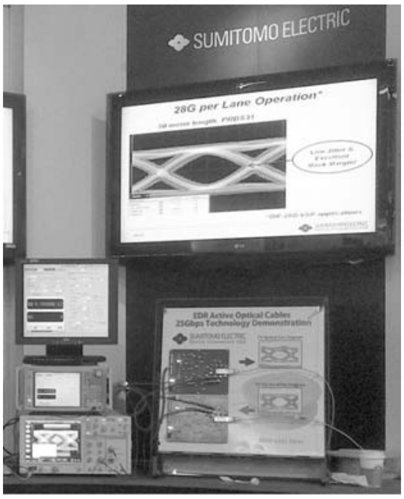


Photo 1. Live demonstration at OFC

5. Conclusion

In this paper, we reported the progress of the next generation high speed VCSEL and PD development. What we have achieved clearly demonstrates that both the VCSEL and the PD are not only capable of operating at high transmission rates from 25 Gbit/s to 28 Gbit/s using commercial drivers and trans-impedance amplifiers, but also capable of communicating at such data rates over reasonably long fiber links.

The VCSEL FAB of Sumitomo Electric Device Innovations USA (SEDU) in Albuquerque, New Mexico contributed to producing the devices for this work, and SEDU's transceiver design group in San Jose, California contributed to putting the demonstration together. Contribution from Sanh Luong for preparing the PD samples and it from Edwin Loy for assembling the EDR cables were particularly necessary for this work.

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Contributors (The lead author is indicated by an asterisk (*).)

C. XIE*

- Ph. D, Senior Staff Scientist, R&D, Sumitomo Electric Device Innovations U.S.A., Inc.

J. KAN

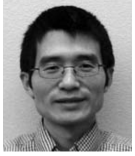
- Ph. D, Senior Staff Scientist, R&D, Sumitomo Electric Device Innovations U.S.A., Inc.

S. HUANG

- Ph. D, Staff Scientist, Sumitomo Electric Device Innovations U.S.A., Inc.

L. WANG

- Ph. D, Staff Scientist R&D, Sumitomo Electric Device Innovations U.S.A., Inc.



N. LI

- Ph. D, Senior Director, VCSEL FAB & Development, Sumitomo Electric Device Innovations U.S.A., Inc.

C. C. CHEN

- Senior Director, Module Design, Sumitomo Electric Device Innovations U.S.A., Inc.

S. INANO

- Vice President, VCSEL Technology, Sumitomo Electric Device Innovations U.S.A., Inc.