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Abstract *We demonstrate a 1530 nm VCSEL that can operate error-free without DSP or FEC to 56 Gb/s. At 50 Gb/s, error-free operation is attained up to 2 km of SMF. A 2-tap FFE driver is used to pre-compensate the VCSEL.*

Introduction

Today's datacenters are mainly using 25 Gb/s optical links which are based on 850nm VCSELs and multimode fiber. The next generation datacenters are likely to use optical links based on singlemode fiber with longer transmission distances that operate up to 50 Gb/s. High-performance computing systems have a need for low latency optical links, which implies NRZ modulation instead of PAM4 which generally requires FEC and DSP. Directly modulated C-band VCSELs have the potential to satisfy both of these large system requirements simultaneously. Additionally, NRZ modulation is likely to result in less power consumption than PAM4 and VCSELs are likely to be less expensive than alternative technologies such as DFB lasers and Si Photonics. In the literature for C-band VCSELs we find demonstrations of directly modulated VCSELs using NRZ[1], PAM3[2], PAM4[3,4,5], QPSK[6], and DMT[7] and either direct[1,3,4,7] or coherent detection[2,5,6]. For NRZ, the highest error-free data rate to date is 35 Gb/s, back-to-back (BTB)[1]. Here we demonstrate a directly NRZ modulated 1530 nm VCSEL link operating error-free to 56 Gb/s BTB and 50 Gb/s to 2 km using direct detection without FEC or DSP.

1530 nm Single mode VCSEL Properties

A high speed, long wavelength VCSEL based on InP with a buried tunnel junction (BTJ) design is used as the directly modulated optical source[8]. The BTJ aperture provides self-aligned optical and current confinement and is lithographically defined. In conjunction with the use of electrically and thermally advantageous regrown *n*-InP on the *p*-side of the multiple quantum well active region, this enables a significantly reduced electrical resistance, whereas excess heat can be efficiently transferred to the integrated electroplated gold heat sink. The strong focus on thermal management results in high output powers both at room and elevated temperatures. Dielectric Distributed Bragg Reflector (DBR) mirrors with layers featuring a large refractive index difference are employed as back and front mirror. In contrast to the conventional design with a semiconductor front DBR, the fast decay of the optical field intensity in this VCSEL leads to a shorter effective cavity length with consequently reduced photon lifetime and increased resonance frequency[9]. A schematic of the device structure and contact pad design are presented in Fig. 1. Low-k layers of benzocyclobutene (BCB) are used to minimize parasitic capacitances and coplanar contact pads facilitate flip chip bonding and testing. With the metallic vias from the top to the bottom side, the gold substrate can also be used as the *p*-contact.

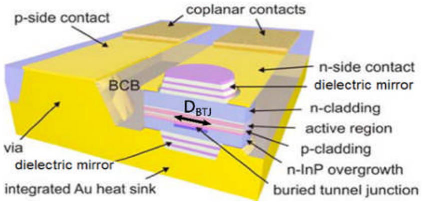

Fig. 1: Schematic cross section of the short cavity VCSEL structure.

The stationary room temperature characteristics in Fig. 2 exhibits a low threshold current of approximately 1 mA and an output power of nearly 4 mW. The inset plot in Fig. 2 shows the optical emission spectrum measured at a rollover current of 17 mA. As can be seen, a high side mode suppression ratio of 50 dB is achieved.

The differential series resistance is below 50 Ω and even at rollover current the operating voltage is still less than 2 V. In addition to the low-capacitance BCB structure, several parameters such as the semiconductor mesa diameter, the bond pad area and the epitaxial structure were optimized to aid achieving a 3 dB modulation bandwidth of almost 18 GHz at room temperature as shown in Fig. 3. Comparing both plots in Fig. 2 and 3, it can be determined that this large bandwidth can be achieved for bias currents in the 8.5 mA to 11.5 mA range.

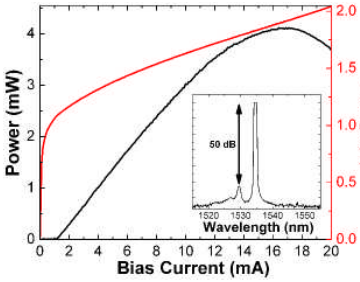

Fig. 2: Room temperature characteristics showing low threshold current of 1 mA and high optical output power of 4 mW. Inset: single mode 1535 nm optical spectrum

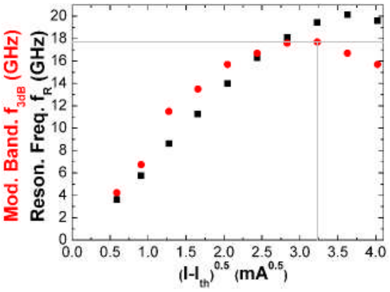

Fig. 3: Room temperature small signal characterization showing a 3 dB modulation bandwidth of nearly 18 GHz.

56 Gb/s VCSEL Transmitter

The transmitter used in this experiment consists of a 2-tap Feed Forward Equalizer (FFE) driver IC directly wirebonded to the VCSEL and is shown in Fig. 4. The driver IC is implemented in a 130 nm BiCMOS process. This driver IC combined with a high-bandwidth 850 nm VCSEL has been shown to operate error-free to 71 Gb/s[10]. One key difference in this transmitter configuration is that the Au-terminated anode substrate contact allows the 1530nm VCSEL to be placed directly on top of the VCSEL power supply decoupling capacitor, which helps to reduce the inductance in this path. The VCSEL bias current is 10.6mA and the transmitter is held at 30 °C for all measurements.

Link Measurements

Fig. 5 shows eye diagrams using NRZ modulation for several different data rates. The data pattern is PRBS7 due to the ac-coupling in both the transmitter and receiver. The left column of Fig. 5 shows the transmitter optical eyes using a Tektronix 80C02 linear 30 GHz photodiode. The right side of Fig. 5 shows the received link eyes using a commercially available 31 GHz receiver, Finisar model MPRV 1331A. The eyes can be seen to degrade as the data rate is increased. This is due primarily to the bandwidth of the VCSEL and secondarily to the bandwidth of the receiver, which is rated for 43 Gb/s operation. The MPRV 1331A receiver was used for all link measurements.

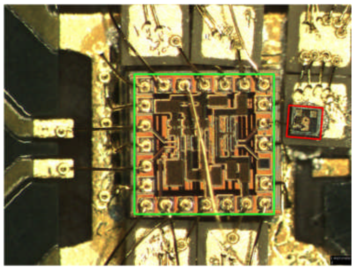

Fig. 4:VCSEL transmitter picture showing 2-tap FFE Driver IC in the center wirebonded to the 1530nm VCSEL shown on the right. The IC is 1mm x 1mm.

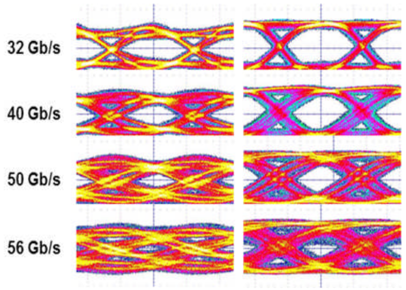

Fig. 5: (left) Optical transmit eye diagrams and (right) Electrical received eye diagrams from 32-56 Gb/s

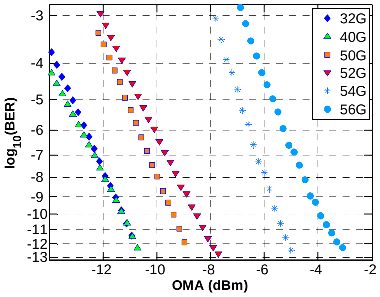

Fig. 6: BER vs. OMA for data rates from 32 to 56 Gb/s

Fig. 6 shows BER versus Optical Modulation Amplitude (OMA) for six data rates from 32 to 56 Gb/s. All data rates are able to reach error-free operation, which is defined as a BER < 1E-12 for > 200 s. 56 Gb/s is the highest error free data rate demonstrated to date for a C-band VCSEL. The curves for 32 and 40 Gb/s lay on top of each other, indicating the sensistivity limit of the receiver. At 52 Gb/s, a penalty of 2.8 dB is incurred, and at 56 Gb/s the penalty is 7.5 dB. At 50 Gb/s, there is 5.7 dB of link margin (defined as the amount of attenuation on the optical attenuator for BER < 1E-12) and at 56Gb/s there is only 0.25dB of margin. From bathtub curve measurements, the eye opening at BER =1E-12 is 0.33, 0.24, and 0.06UI for 50, 52, and 56 Gb/s, respectively.

Since there is margin available at 50 Gb/s, measurement over distance were conducted. Using standard SMF-28 fiber, which has a chromatic dispersion coefficient of ~17 ps/nm*km, at 500 m the link was not error-free with a BER of 3E-6. The eye closure is due to the spectral broadening of the 50 Gb/s NRZ modulation and the fiber's chromatic dispersion. Using a low dispersion SMF, Corning LEAF™ , which has a dispersion coefficient of ~4ps/nm*km, error-free operation out to 2 km was realized at 50 Gb/s. Fig. 7 shows the BER vs. OMA for four lengths of this fiber. At 1 km, there is a 1.7 dB penalty leaving about 4 dB of margin, and at 2 km there is a 3.8 dB penalty. Fig. 8 shows the bathtub curves at 50 Gb/s versus fiber length. The eye opening decreases linearly with distance from 0.33UI BTB to 0.15UI at 2km.

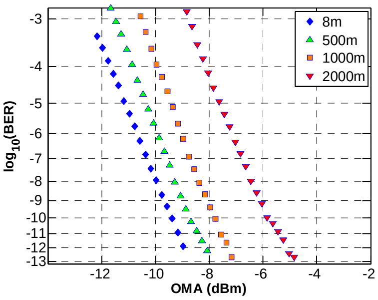

Fig. 7: Bit Error Ratio vs. OMA at 50Gb/s for distances from 8m to 2km

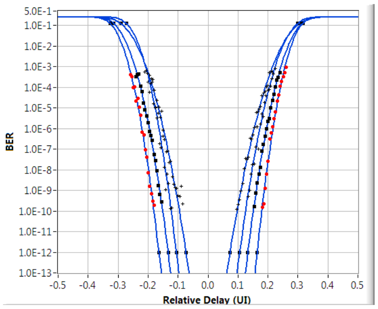

Fig. 8: Bathtub curves at 50Gb/s for fiber distances of BTB (outermost), 500m, 1km and 2km (innermost)

Conclusions

We demonstrated a single-mode VCSEL link operating error-free at 56 Gb/s BTB, while at 50 Gb/s the error-free distance is 2 km using low-dispersion SMF. These results are obtained with NRZ modulation and direct detection without the use of FEC or DSP. This is the highest data rate demonstrated for a C-band VCSEL and the 2 km range satisfies the requirements for modern datacenters. The low cost and ease of packaging LW VCSELs make them an attractive alternative to competing technologies such as Si Photonics.

Acknowledgements

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