4×112 Gbps/fiber CWDM VCSEL Arrays for Co-Packaged Interconnects

Binhao Wang, Wayne V. Sorin, Paul Rosenberg, Lennie Kiyama, Sagi Mathai, and Michael R.T. Tan
Hewlett Packard Labs, Hewlett Packard Enterprise, Palo Alto, CA 94304, USA
Email-address: binhao.wang@hpe.com

Abstract: We demonstrate a 4×112 Gbps/fiber VCSEL link using a co-packaged coarse wavelength division multiplexing (CWDM) optical module. A complete co-packaged CWDM module can achieve a 2.668 Tb/s aggregated bandwidth by assembling four 1×6 VCSEL arrays.
OCIS codes: (140.7260) Vertical cavity surface emitting lasers; (200.4650) Optical interconnects; (060.4230) Multiplexing

1. Introduction

The volume of data has grown exponentially due to applications in video streaming, Artificial Intelligence (AI), and Internet of Things (IoT). The large amount of data demands mega-data centers and high performance computing (HPC) systems with high bandwidth and energy efficient optical interconnects. VCSEL based interconnects are commonly deployed in data centers and HPC due to their simplicity, low cost, and low power consumption. To increase the aggregated data rates per fiber, 4×50 Gb/s shortwave division multiplexing (SWDM) VCSEL links with four wavelengths (850 nm, 880 nm, 910 nm, and 940 nm) per fiber have been demonstrated [1]. Multimode fiber (MMF) manufacturers have developed OM5 MMFs to provide sufficient bandwidth from 850 nm to 950 nm for SWDM VCSEL interconnection. It has been shown that 100 Gb/s VCSEL PAM4 transmission across four wavelengths (850 nm, 880 nm, 910 nm, 940 nm) is feasible over 100 m of OM5 MMFs [2]. To meet the demand of continual growth of datacom, more wavelengths are needed to increase the VCSEL link capacity. Eight wavelengths from 850 nm to 1060 nm with a 30 nm channel spacing over OM5 MMF are being investigated. Error-free 100 Gb/s PAM4 transmission over 100 m OM5 MMF using two-end wavelength (850 nm and 1060 nm) VCSELs has been successfully demonstrated [3].

To meet the requirements of high bandwidth and energy efficient data communication in mega-data centers and HPC, optics has to be brought closer to switch ASICs. The current pluggable optical modules will limit the bandwidth scaling of switch ASICs when the aggregated bandwidth of the switch ASICs reach about 50 Tb/s and beyond due to their limited bandwidth density. Co-packaging optical modules with switch ASICs is one solution to keep the bandwidth scalable as well as maintain low cost and energy efficiency [4]. Co-packaged VCSEL modules have been investigated in the SWDM spectrum [1] and around 1 µm range [4]. Both wavelength ranges are promising to address the bandwidth, energy, and cost challenges. Particularly, VCSELs around 1 µm can emit through the device substrate due to its transparency for wavelengths longer than 900 nm, enabling flip-chip bonding and solder reflowable assembly, allowing for 2D VCSEL array implementation [4]. This technology is feasible to achieve extremely high aggregated bandwidth throughput.

Here, for the first time to our knowledge we demonstrate a 4×112 Gbps/fiber VCSEL link using a co-packaged high-density CWDM optical module. VCSELs were designed and characterized at 990 nm, 1015 nm, 1040 nm, 1065 nm, and 1090 nm. Currently only four wavelengths are used in our module. All four wavelengths (990 nm, 1015 nm, 1040 nm, and 1065 nm) are combined into the single multi-mode fiber using a test board and our CWDM optical module to achieve 112 Gb/s data rates with BERs of around 10^{-6} demonstrating a 448 Gbps/fiber VCSEL link. A complete co-packaged CWDM optical module using 6 input and output fibers can achieve a 2.668 Tb/s aggregated bandwidth by assembling four 1×6 VCSEL arrays using flip-chip bonding and solder reflow.

2. VCSEL Design and Characterization

A hybrid-mirror bottom-emitting VCSEL is illustrated in Fig. 1(a). By using a hybrid metal/Si_3N_4/p-distributed Bragg reflector (DBR) top mirror, the number of required p-DBR pairs is reduced from 34 pairs to 16 pairs. Fabrication of the hybrid-mirror oxide-confined VCSEL is performed in the usual manner, except a ring or annular p-contact is used instead of a solid circular contact. The aperture of the ring p-contact is chosen to be larger than the oxide aperture diameter to prevent optical loss within the VCSEL cavity. After the ring contact is deposited, a quarter wave thick layer of silicon nitride and a 200 nm thick layer of Au are deposited on the top 16 pair p-DBR to enhance the top mirror reflectivity. The hybrid metal/Si_3N_4/p-DBR mirror results in a peak reflectivity of around 99.9%. This enhanced reflectivity is only within the area defined by the ring contact opening. This hybrid-mirror VCSEL can be easily modified to be single-mode by making the ring p-contact opening smaller or equal to oxdie aperture diameter since the mirror loss is high outside the ring contact opening which prevents the lasing of higher order modes [5]. The different wavelength VCSELs are nominally of the same design with slight modifications to the DBR, oxide and

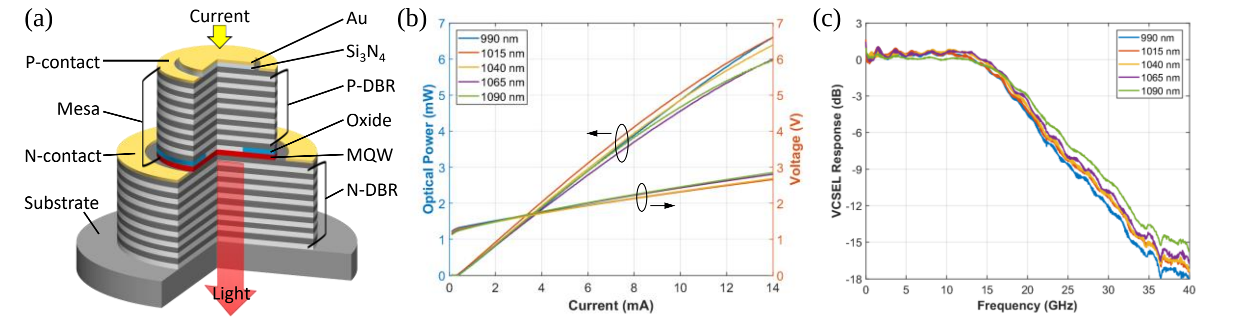

Fig. 1(a) Schematic of a hybrid-mirror bottom-emitting VCSEL; (b) Five-wavelength 7-µm oxide-aperture VCSEL Light-Current-Voltage (LIV) characteristics; (c) Small signal S21 characteristics measured for all five-wavelengths. Bias currents are 7 mA and oxide diameters are 7-µm.

quantum well layers to adjust for the emission wavelength range of over 100 nm. Strain compensation allows the use of highly strained InGaAs quantum wells resulting in higher differential gain and better over-temperature performance.

The Light-Current-Voltage (LIV) characteristics for 7-µm oxide-aperture VCSELs at 990 nm, 1015 nm, 1040 nm, 1065 nm, and 1090 nm are shown in Fig. 1(b). VCSELs with high slope efficiency and low differential resistance are required to provide sufficient optical modulation amplitude (OMA) to support PAM4 signaling due to the one third eye opening penalty compared to on-off signaling. As shown in Fig. 1(b), the slope efficiency for all five wavelength VCSELs is above 0.5 W/A. The differential resistance of all five wavelengths at 7 mA bias is around 100 Ω thanks to the hybrid mirror design and modulation doping optimization. Fig. 1(c) shows the small signal frequency responses for all five VCSEL wavelengths, each with a 7-µm oxide-aperture and a 7 mA bias. VCSELs with sufficient damping and high linearity are desired for PAM4 modulation. This can be achieved by increasing the photon lifetime and the gain compression. The 3 dB bandwidths of all five wavelength VCSELs are >18 GHz. The 1090 nm VCSEL achieves a slightly higher 3 dB bandwidth of 20 GHz due to the higher strain (indium content) in the quantum wells which results in a higher differential gain.

3. Experimental Results

A schematic of the co-packaged CWDM optical module is shown in Fig. 2(a) [6]. The VCSEL and photodiode arrays are flip chipped onto precisely defined solder pads on a high speed organic substrate. During solder reflow, the arrays self-align to one another. A connectorized injection molded optical ferrule that contains a reflective zig-zag slab with integrated wavelength filters acts as both multiplexer and de-multiplexer. The Tx module is comprised of four independent bottom-emitting 1×6 VCSEL arrays, each at a different wavelength, and each with integrated lenses fabricated directly on the back of the GaAs substrate. The integrated lenses on the VCSELs provide for improved misalignment tolerance to the Mux/DeMux assembly. A turning lens at the output of the zig-zag focuses the light from the multiplexed four wavelength VCSELs into a multimode fiber yielding an aggregated bandwidth of >400 Gbps/fiber. The integration of collimating lenses on the VCSELs eliminates the need for a separate optical element along with the additional serial alignment process step. The magnified output beam from the lensed VCSEL improves the x-y alignment tolerance to the zig-zag assembly. A 25 nm channel spacing was chosen to allow for manufacturing variations of the VCSELs and filters while removing the need for temperature control of the VCSEL wavelengths, improving yield and reducing cost. The receiver consists of a 2D lensed array of bottom entry InGaAs PIN photodiodes placed next to the VCSEL arrays. For the results in this paper our test board did not include the detector array since it

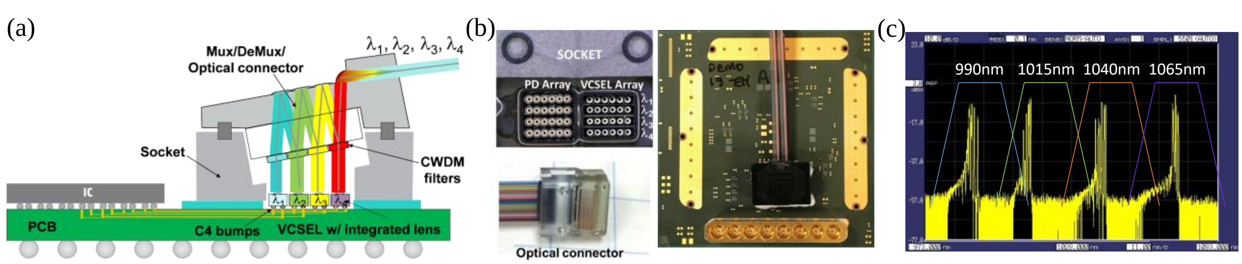

Fig. 2(a) Schematic of the co-packaged CWDM optical Tx/Rx module showing Mux/DeMux, OE array, filters and output fiber; (b) PD, VCSEL arrays on organic substrate with socket (top left), optical connector housing Mux/DeMux (bottom left), and assembled CWDM Tx/Rx module on a PCB (right); (c) Four wavelength VCSEL spectra from a single multimode fiber.

was not designed to support an appropriate transimpedance amplifier IC chip. Instead we used a Thorlabs (DXM30BF) photodetector followed by a 22 dB RF amplifier.

Fig. 2(b) shows an assembled CWDM optical module on a PCB with a Huber Suhner MXP50 electrical connector for delivering the external driving signals. Four (1×6) VCSEL arrays at each of the four wavelengths were flip-chip reflowed onto the organic substrate. After solder reflow, the PD and VCSELs self-align with respect to one another to well within the tolerance limit of ±15 µm. The optical socket is designed to receive alignment pins located on the optical connector assembly. The optical connector which houses the Mux/DeMux is assembled into a separate injection molded piece which latches into the optical socket. This allows the socket to be soldered onto the PCB without the optical connector attached. By using a standard 1×12 MT fiber ribbon (6 Tx and 6 Rx), the optical module has a potential capacity of >2.5 Tb/s in a volume of about 1 cm^3. Multiple optical modules can be tiled horizontally around a large ASIC switch chip to provide for a very high density multi-Terabit per second optical I/O. After reflowing the four 1x6 VCSEL arrays onto our test board the optical losses from the VCSELs through the Mux were measured. A maximum insertion loss of 3 dB was measured on the channel with the most bounces and about 1.4 dB for the channel with no bounce. Fig. 2(c) shows simultaneously all four wavelengths after being multiplexed into a single output fiber. With all four VCSEL wavelengths lit, we observe that there is good spectral alignment between the VCSELs and bandpass filters, resulting in a low optical crosstalk of better than 35 dB between channels.

To perform the eye diagram measurement, a 120 GS/s Keysight M8194A arbitrary waveform generator (AWG) was used to produce a PRBS9 PAM4 data pattern. The mounted VCSELs were driven through a six inch coax cable and then into a Huber Suhner MXP50 electrical connector (Fig. 2(b)) and then finally through about 20 mm of transmission line on the test board. The output of each VCSEL was multiplexed into a single fiber via the CWDM optical connector. The fiber output was converted to an electrical signal with a 35 GHz Thorlabs DXM30BF photodiode followed by a 22 dB SHF RF amplifier and then connected to a Keysight 60 GHz digital communication analyzer (DCA) sampling oscilloscope to record eye diagrams.

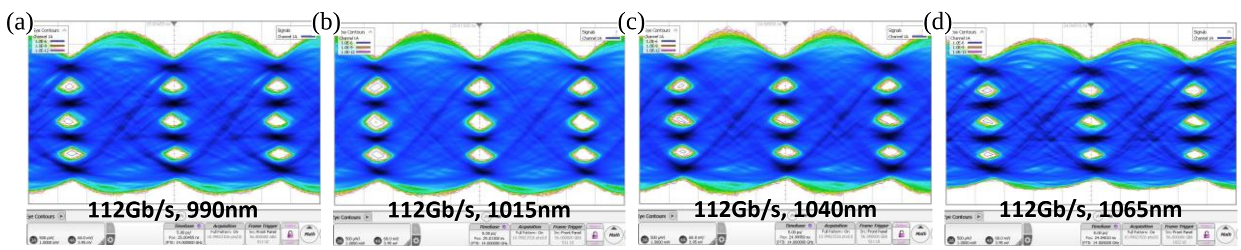

Fig. 3 VCSEL 112 Gb/s PAM4 eye diagrams through co-packaged CWDM optical module. Eye contours estimate BERs $<10^{-6}$.

The transmission link was calibrated using the calibration functionality provided by our Keysight AWG pattern generator, which is able to measure the system transfer function and pre-distort the output bit pattern to produce the best eye performance. A time-domain raised cosine filter with 0.5 roll off factor was applied to the calibrated driving signal to optimize the signal-to-noise ratio (SNR) at high frequencies. The AWG needed to equalize a loss of about 12-14 dB at the fundamental data rate frequency of 28 GHz based on the system transfer function from the six inch coax cable to the output of the optical receiver. Using the VCSEL responses in Fig. 1(c), the electrical RF transmission loss was estimated to be about 3-4 dB at the Nyquist frequency of 28 GHz for the 112 Gb/s PAM4 signal. Fig. 3 shows VCSEL eye diagrams at a data rate of 112 Gb/s PAM4 through our test board and CWDM optical module after being detected by the Thorlabs receiver. This corresponds to an aggregate bandwidth of 448 Gbps/fiber. Eye diagram contours in Fig. 3 with BERs of 10^{-6} were successfully achieved at all four wavelengths through our test board set-up.

4. Conclusion

We have demonstrated a 4×112 Gbps/fiber VCSEL link using a co-packaged CWDM optical module. To achieve high bandwidth density, a low cost, solder reflowable, optically connectorized CWDM optical engine was developed. Our solution is capable of providing 2.668 Tb/s in a 1 cm^3 footprint and will be able to achieve a low cost target when scaled to high volume manufacturing.

References

[1] T. Huynh, et al. “4×50Gb/s NRZ Shortwave-Wavelength Division Multiplexing VCSEL Link over 50m Multimode Fiber,” OFC, Tu2B.5 (2017).
[2] J. Lavrencik, et al. “Scaling VCSEL-MMF Links to 1 Tb/s Using Short Wavelength Division Multiplexing,” IEEE JLT, 36, 4138-4145 (2018).
[3] S. E. Ralph, et al. “High Capacity VCSEL Links,” OFC, Tu3A.1 (2019).
[4] M. R.T. Tan, et al. “Universal Photonic Interconnect for Data Centers,” IEEE JLT, 36, 175-180 (2018).
[5] M. R. Tan, et al. “50Gb/s PAM4 Modulated 1065nm Single-Mode VCSELs Using SMF-28 for Mega-Data Centers,” IEEE PTL, 29, 1128-1131 (2017).
[6] P. Rosenberg, et al. “CWDM Transceiver for Midboard Optics,” Proc. SPIE, 10109 (2017).