VCSEL-Based Interconnects for Current and Future Data Centers

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***Abstract*—The vast majority of optical links within the data center are based on vertical cavity surface emitting lasers (VCSELs) operating at 850 nm over multimode optical fiber. Deployable links have evolved in speed from 1 Gb/s in 1996 to 28 Gb/s in 2014. Serial data links at 40 and 56 Gb/s are now under development and place even more demand on the VCSEL and photodiodes. In this paper, we present the characteristics of VCSELs and photodiodes used in current generation 28 Gb/s links and present several methods to extend link distances using more advanced data encoding schemes. Finally, we will present results on wavelength division multiplexing on multimode optical fiber that demonstrate 40 Gb/s Ethernet connections up to 300 m on duplex OM3 optical fiber, and present results on fiber optimized for modal bandwidth in the 850 to 980 nm range.**

***Index Terms*—Data center, fiber optics, interconnects, vertical cavity surface emitting laser (VCSEL).**

I. Introduction

SINCE the commercial introduction of Vertical Cavity Surface Emitting Lasers (VCSELs) in 1996, there have been more than 300 Million devices deployed in data communication systems [1]. They have proven to be very reliable and have been a key component in low cost multimode fiber optic interconnects. To date, the speeds have been up to 14 Gb/s, with the majority operating at less than 10 Gb/s. Recent activity in the several networking standards bodies (IEEE Ethernet, ANSI X3.T11 Fibre Channel, etc) has focused on standardization of links operating at 25 Gb/s (Ethernet) and 28 Gb/s (Fibre Channel). This has driven the need to commercialize VCSELs and photodiodes (PDs) with operating characteristics capable of these higher operating speeds. One disadvantage to the continued increase in the data rate has been the decrease in link reach length. While this has been mitigated to some extent with the introduction of higher bandwidth optical fibers (OM4) and the use of Forward Error Correction (FEC) techniques, at 28 Gb/s the standards compliant links are limited in the worst case conditions to 100 meters. The use of even more advanced modulation schemes such as Pulse Amplitude Modulation (PAM) and Discrete Multitone are two methods that have been investigated to demonstrate link lengths over 300 m [2]. It has also been suggested that reduction of the VCSEL spectral bandwidth can also lead to increased link distances [3]. However we find this to be insufficient by itself to achieve robust 300 m operation. These advanced schemes can also be used to increase the data line rate, and links operating to more than 80 Gb/s have been demonstrated [2]. Current standards activities are also concentrated on increasing the total bandwidth of a single optical interconnect. The focus of this activity has been on 40 Gb/s, 100 Gb/s, and 400 Gb/s optical links on parallel multimode fiber. Parallel interconnects are now widely deployed; achieving volume shipments similar to single channel interconnects and have proven to be highly manufacturable [1]. An alternative approach to the spatial division multiplexing of parallel devices is wavelength division multiplexing at short wavelength (SWDM). This method can provide the desired link data rate on a single duplex multimode optical fiber. Adding the SWDM capability will increase the lifetime utility of deployed fiber optic cabling systems. VCSEL based SWDM combined with parallel ribbon multimode fiber offers a clear path to connectivity at 400 Gb/s and possibly 1 Tb/s.

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II. VCSEL and PD Characteristics

The active devices used in this work were grown by Metal Organic Chemical Vapor Deposition and fabricated in a production fabrication facility using standard processing cells. The VCSEL design is based on N and P type mirror designs from lower speed devices [4], with the primary differences in the quantum wells being the amount of indium. Previous optimization analysis of the active region has shown that 5 quantum wells with $In_{0.1}Ga_{0.9}As$ is reasonable to achieve high speed operation [5]. Our device is similar to this design. The emission diameter is approximately 7 microns. This diameter was chosen as a tradeoff between reliability, optical power output, relative intensity noise, spectral bandwidth, and modulation bandwidth for our design. The reliability of this VCSEL has been previously presented and is more than sufficient for data center applications [6]. Fig. 1 is a plot of the optical power output and the forward voltage for a typical 28 Gb/s VCSEL at temperatures from 10 to 95 C. Typical operating bias current is about 7.5 mA over the entire operating temperature range. The 25 C threshold current, slope efficiency and series resistance are 0.65 mA, 0.47 W/A,

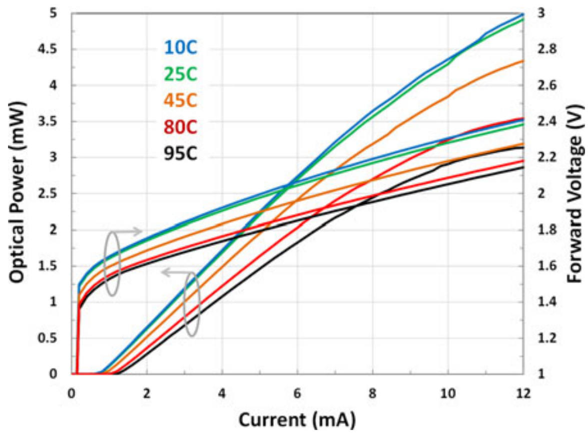

Fig. 1. Optical power output (left axis) and forward voltage (right axis) as a function of current for a typical 28 Gb/s VCSEL at temperatures ranging from 10 to 95 C.

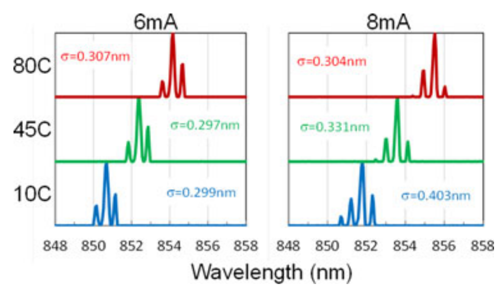

Fig. 2. Optical spectrum measured at 10, 45 and 80 C and bias currents of 6 and 8 mA. Also shown is the calculated RMS spectral bandwidth (σ).

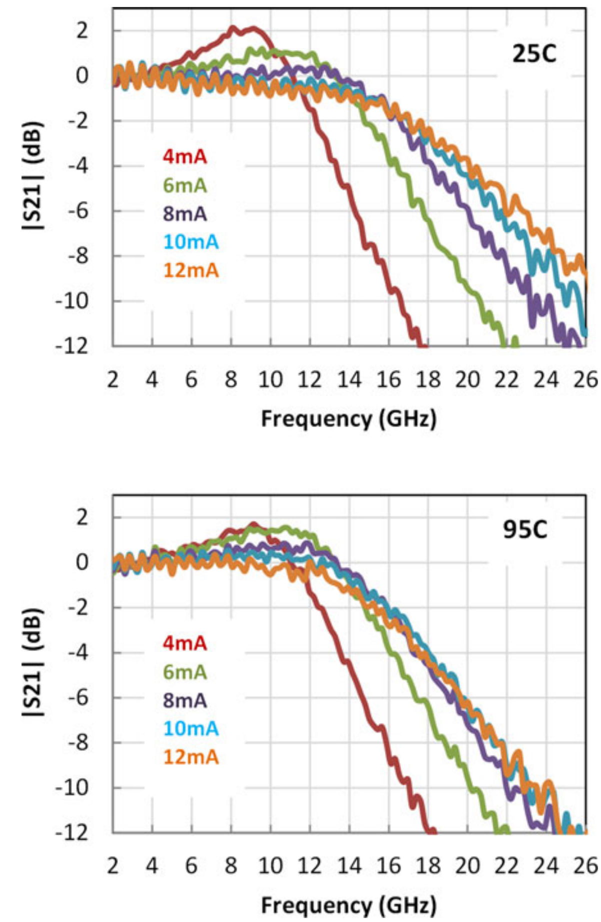

Fig. 3. Normalized |S21| response of the 25 Gb/s VCSEL at bias currents from 4 to 12 mA and at temperatures of 25 and 95 C. Nominal operating current is 7.5mA.

and 61 Ω respectively. Fig. 2 shows the optical spectrum of the VCSEL at 10, 45, and 80 C and at operating currents of 6 and 8 mA. The RMS spectral bandwidth (σ) is calculated at each of the bias currents. The existing 28 Gb/s Fibre Channel optical standard requirement is $\sigma < 0.59$ nm.

The VCSEL optical modulation response (S_{21}) and electrical reflectance (S_{11}) was measured using an Agilent Lightwave Component Analyzer (LCA). The normalized S_{21} measurements as a function of bias current and temperature are shown in Fig. 3. The data is not corrected for the VCSEL impedance. Note that the VCSEL frequency response has been engineered to be critically to slightly overdamped. This operating point has been determined to best interface to the transceiver drive electronics [7]. The drive current pulse shape can be tailored to compensate for the lower bandwidth of the VCSEL but it is less successful for driver electronics to compensate for overshoot or ringing in the optical response.

The GaAs PD fabricated for 28 Gb/s was based on standard design principles of lower speed PDs. At this speed level, the PD design is a trade-off between the desire for a thick active region to keep the capacitance low and responsivity high, and a thin active region to decrease the carrier transit time. The active area diameter also affects the capacitance of the PD, but conflicts with the desire for a large active area to increase alignment tolerances, particularly in parallel optical transceivers [8]. In this design, the PD active area diameter is 30 μm, and the undoped GaAs active region is approximately 1.2 μm thick. The series resistance of the PD is 15 Ω, the total capacitance is approximately 150 fF, and the responsivity is greater than 0.55 A/W. The small signal optical response (S_{21}) and electrical impedance (S_{22}) were measured at 25 C and 110 C with the LCA and the optical response of the PD was extracted using a simple R-C model and the result is shown in Fig. 4. The intrinsic transit time (non-parasitic limited) optical bandwidth is over 30 GHz over the entire operation temperature range.

III. Transceiver Results

The VCSEL and PD described in the previous section are used in both single and multichannel optical transceivers. The transceivers include custom-designed integrated circuits to drive the VCSELs. The ICs include electrical waveform shaping capability that is used to improve the large signal response of the VCSEL. This functionality allows for a laser design that is more manufacturable and tolerant of device to device variation. As previously mentioned, the optimal VCSEL design to match with the driver is not necessarily the device with the largest 3 dB optical bandwidth, but instead is one that has a slightly

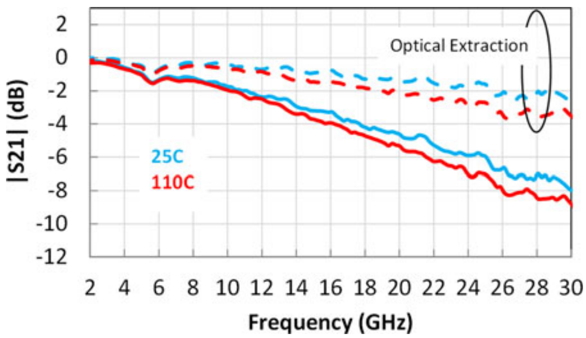

Fig. 4. Measured |S21| (solid) and extracted optical response (dashed) responses for the 25 Gb/s photodiode at 25 C (blue) and 110C (red). The total capacitance is 0.115 pF. The bias voltage is 2.05 V.

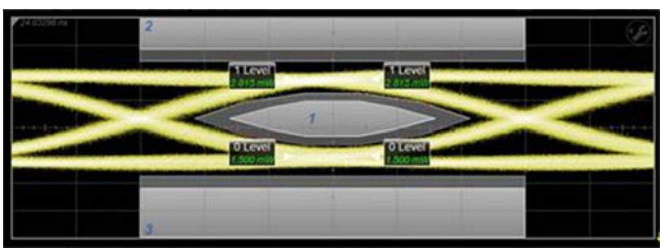

Fig. 5. Typical eye diagram from a 28 Gb/s transceiver demonstrating more than 30% margin the standard defined mask.

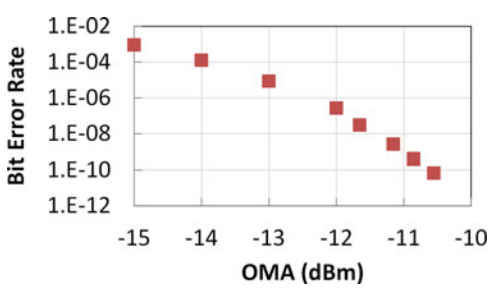

Fig. 6. Typical receiver BER sensitivity measured in the optical transceiver without FEC.

overdamped frequency response. The high damping limits the amount of optical overshoot in the eye diagram and can be effectively controlled with electrical pre-emphasis.

A typical eye diagram from a 28 Gb/s (Fibre Channel) transceiver is shown in Fig. 5. The margin to the standard defined mask is greater than 30%. The bit error rate of the transceiver was measured with results shown in Fig. 6, which demonstrates sensitivity levels better than −10 dBm at the 1E-12 BER point, and about −14 dBm at the FEC limit of 5E-5, corresponding to RS(528,514) code specified for IEEE 100GBASE-SR4 standard. The single channel transceiver is the technology basis for the parallel transceiver in terms of integrated circuits and active components. The packaging of the parallel transceiver is quite different, but results are similar. Fig. 7 shows optical eye diagrams at 25 G from a 12 channel transmitter at room temperature. All channels exhibit mask margin in excess of 25%. The reduction in eye margin from the single channel case to the parallel transceiver is due to increased electrical parasitics in the module.

Fig. 7. Optical eye diagrams from a 12 × 25 Gb/s transceiver demonstrating more than 25% mask margin on every channel with all channels running.

IV. Extending the Operating Distance

Data centers have continued to evolve into larger and larger structures. Today, links in excess of 1 km are a requirement to fully cover the entire footprint, and some VCSEL based links have been demonstrated to cover this distance [9]. This has put pressure on maintaining link operating distances on multimode fiber, and has precipitated the release of higher bandwidth cabling such as OM3 and OM4 fibers. At 25 and 28 Gb/s, link lengths at 850 nm are again challenged and are currently standardized to operating distance up to 100 m on OM4 multimode fiber. The link distances are generally limited by a combination of laser performance requirements and fiber capability. Surveys have indicated that the vast majority (>80%) of the deployed multimode links are less than 100 m [10]. As more short reach data connections migrate from copper to optical, that percentage will likely continue to increase. Still there are both deployed and planned links that are up to 300 m in length. To address this distance, certain laser parameters can be tightened, in particular relative intensity noise (RIN), rise/fall times and spectral bandwidth. However even taking these well beyond current manufacturing capability does not necessarily yield a suitable link budget.

A perhaps more straightforward method of increasing the optical link length is to add equalization to the optical receiver to compensate the channel effective bandwidth. This technology has been previously deployed in IEEE standards in the 10 GBASE-LRM transceivers operating at 1310 nm on multimode fiber. In this case, the minimum fiber bandwidth specification was 500 MHz* km. We have used the VCSELs and PDs described in Section II to achieve 300 m transmission distance on standard OM3 fiber at 25 Gb/s. The experiment was done by directly modulating a VCSEL with a pattern generator and a commercial MMF PD with 22 GHz bandwidth. The received waveform was captured using a real time scope with sampling rate of 80 Gs/s, and then processed offline in Matlab to emulate a Feed Forward Equalizer (FFE) and Distributed Feedback Equalizer (DFE) and estimate the Q-factor from the samples at the center of the eye. Fig. 8(a) is a plot of the Q factor as a function of the average received optical power. The eye diagram insets are the recovered signal at 2 m and 300 m respectively. Note equalization is only applied for the 300 m channel. The laser in this test was run with an extinction ratio of

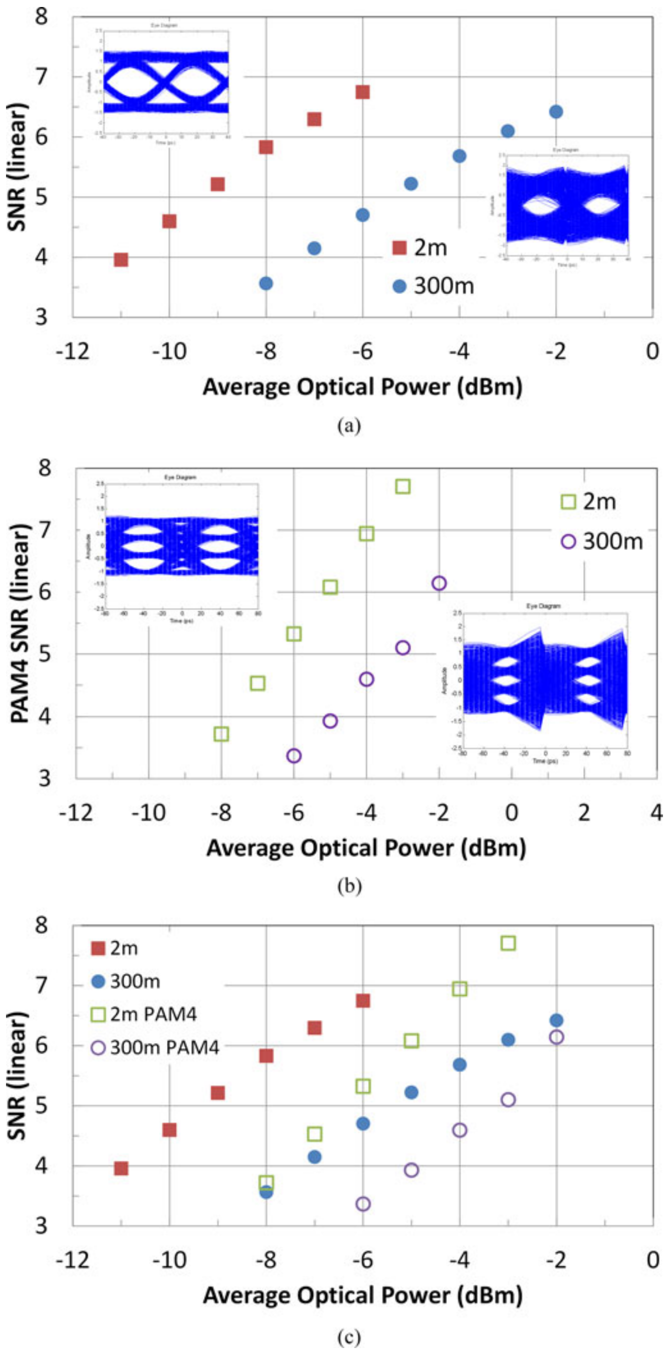

Fig. 8. Signal to Noise Ration as a function of average received optical power for a link with dispersion compensation (a), PAM4 modulation (b) and comparison of the two techniques (c). The inset eye diagrams are the recovered signal at 2 m and 300 m.

approximately 3.5 dB. A very robust link can be obtained using a small number of FFE and DFE taps with about a 4 dB optical power penalty at $Q = 4$ to transmit 300 m. To achieve a system BER of 1E-12, the Q must be greater than 3.9 when FEC is used, corresponding to a pre-FEC BER of 5E-5. We further conducted the test with lasers of varying spectral bandwidth and we find that once equalization is employed in the link, further tightening of laser and fiber requirements beyond the current communications standards may not be necessary. The implementation of the receive side equalization does not interfere with the transceiver interoperability on standards complaint components but does open up a viable method to achieve 300 m link lengths on existing OM3 fiber. Equalization techniques have long been used in copper based interconnects and has extended the life of installed cabling infrastructure and similar techniques can and have been deployed to extend the life of installed multimode cable plants.

Equalization as described in the previous section can also be used to increase the data rate of a link by using it to compensate the limited bandwidth of the VCSEL. In conjunction with transmitter waveform optimization, data links at 56 Gb/s have been demonstrated [11], and more recently up to 64 Gb/s [12]. This technique is very promising for short distance optical interconnects and can be readily adopted using existing fiber cabling infrastructure.

Recently, effort has focused on the addition of data encoding algorithms beyond traditional NRZ signaling. One example is PAM. In a PAM system, each bit can be encoded with an amplitude modulation and thus have multiple bits per bit period. NRZ signals can be thought of as a two level PAM signal, with each bit either having a “0” and a “1” level. In a PAM-4 scheme, each bit can be one of four analog levels, “00”, “01”, “10”, and “11” depending on the amplitude. Thus the amount of data transmitted is doubled per bit period. This can be used to extend the operating distance of a 25 Gb/s link by effectively cutting the baud rate by log2 of the number of amplitude levels. We conducted transmission experiments using the same VCSEL as previously described with PAM4 modulation at 12.5 Gbaud. The results are shown in Fig. 8(b) which plots the Q factor (minimum of the 3 PAM4 eyes) as a function of the average optical power for a 2 m and 300 m OM3 optical link. The eye diagram insets are the recovered signal at 2 m and 300 m respectively. We observe a smaller dispersion power penalty for PAM4 compared with NRZ due to the reduced baud rate. Fig. 8(c) is a comparison of the two optical links. Note there is a theoretical 3 dB power penalty in the PAM4 link due to the reduced amplitude of the signal. In all cases NRZ signaling plus equalization performs better than PAM4 modulation with very similar electrical power consumption. We anticipate PAM4 modulation may play a more important role in enabling 50 Gb/s links where the bandwidth limitation of a VCSEL under NRZ modulation may have more of a link power penalty than the 3 dB loss due to PAM4.

V. Short Wavelength Division Multiplexing

Wavelength Division Multiplexing is a commonly deployed technique to increase the carrying capacity of single mode optical fiber in telecommunications networks. The same approach can be applied to multimode optical fiber, and previous attempts have used VCSELs in the 980 to 1080 nm range [13]. However, unlike single mode fiber, the bandwidth of the optical fiber, and therefore the achievable link length is a function of the wavelength [14]. The design objective is to achieve similar link lengths in a single pair of multimode fiber to those obtained with parallel optical connections. OM3 supports 300 m for 10 G lanes (40 G using four parallel fibers) and 70 m for 25 G lanes (100 G using four parallel fibers). We have determined that

TABLE I
COMPARISON OF IEEE 802.3AE AND POSSIBLE SWDM LINK BUDGET PARAMETERS TO ACHIEVE 300 M ON TYPICAL OM3 OPTICAL FIBER AT 10 GB/S

Parameter	Units	10GbE	SWDM
Wavelength	nm	840 to 860	840 to 860 870 to 890 900 to 920 930 to 950
RMS Spectral width	nm	0.45	0.4
OMA (min)	dBm	−7.5	−7
Extinction Ratio (min)	dB	3	
RIN12OMA (max)	dB/Hz	−128	
Optical return loss	dB	12	
Sensitivity (OMA, max)	dBm	−11.1	−12.1
Stressed Sensitivity (OMA, max)	dBm	−7.5	−8

Note that the loss associated with multiplexing and demultiplexing are not included in this analysis as that is implementation specific

nominal OM3 optical fiber can support these link distances with VCSELs that are manufacturable at wavelengths up to 940 nm. The standard link budget calculations used in the 10 Gb/s Ethernet model were applied with modified fiber modal bandwidth and chromatic dispersion values [15]. The main differences in the longer wavelength devices are the assumption of an improved receiver sensitivity of 1 dB, a slight reduction of spectral bandwidth specification, a slight reduction of the laser rise and fall times, and an increase the minimum transmitter OMA. The comparison of the normal laser and receiver specifications is summarized in Table I [16].

We have designed and fabricated VCSELs at 850, 880, 910, and 940 nm and 980 nm that have characteristic similar to those described in Section II. The design is a scaled version of the 850 nm version described previously with the primary difference being mirror thickness changes to account for the longer wavelength, and an increase in the amount of indium in the quantum wells to achieve the desired operating wavelength. Initial reliability work has begun on these longer wavelength devices with results similar to results at 850 nm [6]. It is too early in the study to accurately determine the activation energy and current acceleration factors for these devices. The 980 nm VCSELs were used to assess margin to the specifications. Each of the VCSELs was assembled into an optical transceiver with standard components used in 850 nm transceivers in volume production. Transmission experiments using standard OM3 fiber were conducted back to back (2 m) and 300 m operation was verified at 10.3125Gb/s per wavelength for an aggregate bandwidth of 40 Gb/s. Fig. 9 shows the measured optical eye diagrams at each of the laser wavelengths over several fiber types tested. The first column shows the transmitter optical eye diagrams through a 2 m jumper. The transmission through several optical fiber types was then tested using a commercial 10GBASE-LR receiver that contains an InP based PIN PD with 36 mm active area diameter. Optical fiber specified to meet OM3 requirements of 2000 MHz* km at 850 nm can have the maximum modal bandwidth at a range of wavelengths around 850 nm [14]. Fiber type A is an example of a fiber with the maximum effective modal bandwidth (EMBW) less than 850 nm as evidenced by the increase in the Vertical Eye Closure Penalty (VECP) as the

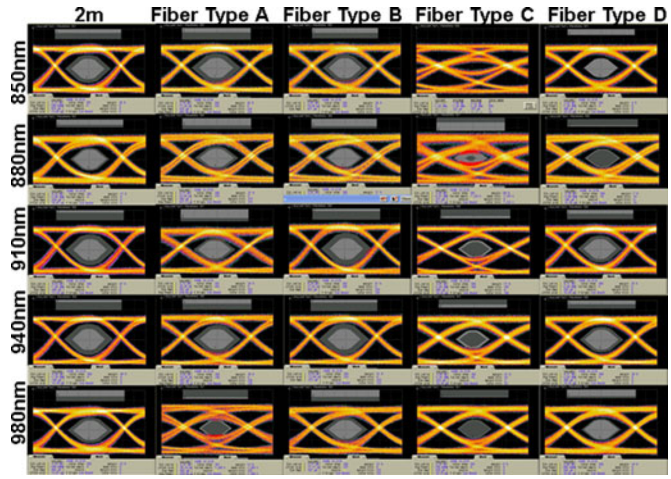

Fig. 9. Optical eye diagrams at 10 Gb/s for VCSELs operating at 850, 880, 910, 940 and 980 nm over 2 m and 300 m for several fiber types. Note that the fiber type A and fiber type C were chosen as near worst case examples of fibers with peak EMBW on the short and long wavelength side of 850 nm respectively. The specific fiber used to demonstrate type C fails the minimum OM3 specification and is for demonstration only.

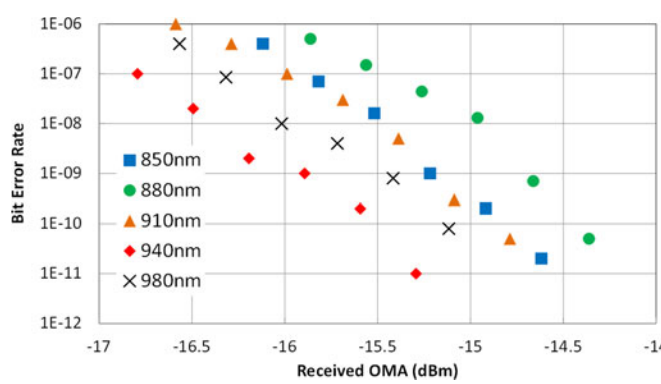

Fig. 10. Measured receiver sensitivity at 10 Gb/s in OMA (dBm) for 300 m on the SWDM optimized fibers.

wavelength is increased from 850 nm. Fiber type B in Fig. 9 demonstrates relatively flat VECP across wavelength and has maximum EMBW near 850 nm. Fiber type C is an example of a fiber with the peak EMBW at a wavelength longer than 850 nm. The particular fiber used here actually fails the 2000 MHz* km specification for OM3, having an 850 nm EMBW near 1000 MHZ* km. It is shown for demonstration purposes only. Fiber type D is a prototype fiber that is designed to provide a minimum EMBW of 2000 MHz* km for transmission across the entire wavelength band presented here. Such fiber has the potential to extend the operating capacity of multimode fiber in the data center by allowing WDM transmission from 850 to 980 nm. The core diameter is 50 μm and is therefore fully backward compatible with existing multimode fiber cable plants. The so-called α profile of the refractive index was modified to operate over a broad wavelength range while still providing the required EMBW [14], and fiber optimized for the 1060 nm range has been previously reported [17], [18]. Fig. 10 is a plot of the bit error rate measured over 300 m of fiber type D. The power penalty for this fiber at 300 m length for any of the wavelengths is less than 1 dB compared to measurements on a 2 m patch chord. It should be noted that all of the links tested on all fiber types were able to achieve BER < 1E-12 even with the large amount of VECP in some of the test cases.

The experiments described in this section demonstrate the feasibility of SWDM links to provide 40 Gb/s connectivity across 300 m of installed duplex multimode fiber. While fiber types A and B in Fig. 9 support SWDM operation over the 850 to 940 nm window, it has not been determined what fraction of the installed base of OM3 links will exhibit similar performance. The manufacturing variances within the allowed range of MMF will limit the worst case modal bandwidth at the longest wavelength. To guarantee the link distance, a linear equalizer like that incorporated in 10GBASE-LRM can be used to compensate the bandwidth limitations of the installed base of fiber. However it does not come for free in terms of circuit complexity and power dissipation so it would be likely be used only in those cases where normal receiver functionality is not sufficient. The transceiver form factor, with or without an equalizer, can be the same as existing parallel devices and share the same electrical interface which would allow for interoperability with existing networking equipment. Additionally, single wavelength transceivers could be made that would add breakout functionality. Proliferation of the new SWDM optimized OM3 fiber (fiber type D) would alleviate the bandwidth limitations and reduce both circuit complexity and transceiver power consumption.

One of the concerns with SWDM links in the past was the ability to meet class 1 eye safety standards as defined by the IEC 60825. Recent modifications to the standard now define the measurement as the maximum power in a 70 mm diameter aperture placed 100 mm from the source point. With the class 1 limit for the four wavelengths in aggregate, reasonable manufacturing limits can be applied.

VI. Summary

VCSELs and multimode fiber will continue to be an integral part of data centers in the future. With the deployable data rates now at 28 Gb/s and serial data rates demonstrated in excess of 56 Gb/s an ever increasing portion of copper based links will convert to fiber optics. Parallel optical interconnects have also become commonplace in today's data centers and supercomputer connections. With the addition of SWDM to the available transceivers, a broader coverage of installed and future links can be provided. SWDM optimized MMF will support broadband operation of 10 and 28 G lanes over distances of 300 m and 70 m respectively in the future.

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