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Reach Extension and Capacity Enhancement of VCSEL-based Transmission over Single Lane MMF Links

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***Abstract* — This paper reviews and examines several techniques for expanding the carrying capacity of multimode fiber (MMF) using vertical cavity surface emitting lasers (VCSELs). The first approach utilizes short wavelength division multiplexing (SWDM) in combination with MMF optimized for operation between 850 and 950 nm. Both non-return to zero (NRZ) and four level pulse amplitude modulation (PAM4) signaling are measured and demonstrate up to 170 Gbps post-forward error correction (FEC) transmission over 300 m. For single wavelength transmission the use of selective modal launch to increase the optical bandwidth of a standard OM3 MMF to more than 2.1 GHz•km for standard MMF is presented. A statistical model is used to predict the bandwidth enhancement of installed MMF and indicates that significant link extension can be achieved using selective modal launch techniques. These results demonstrate the continued effectiveness of VCSEL based MMF links in current and future data center environments.**

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

I. INTRODUCTION

OPTICAL data links based on an 850 nm VCSELs and MMF have served as cost-effective data center interconnects for more than two decades. It is estimated that more than 500M VCSEL based links have been deployed. Over this time, the signaling rate defined by standards such as IEEE 802.3 (Ethernet) and ANSI X3.T11 (Fibre Channel) has increased from 1 Gbps to more than 25 Gbps today. To support higher speed operation, MMF has been standardized by the Telecommunications Industry Association (TIA) by effective modal bandwidth (EMB) at 850 nm, including OM3 (2000 MHz•km) and OM4 (4700 MHz•km) [1]. To address the need for higher density interconnects, multilane parallel optical transceivers and fibers have been developed. However, this represents additional fiber and transceiver costs, has limited scalability, and does not address the installed base of single channel OM3 and OM4 fiber. The need for higher bandwidth density has led to investigation of the limits of current VCSEL and MMF technologies. For example, a 43 Gbps link operating error-free without FEC up to 100 m on OM4 fiber (57 Gbps at 1 m) has recently been demonstrated using NRZ signaling [2]. To further push the VCSEL capacity, other signaling protocols such as PAM4, signal processing such as Forward Error Correction (FEC), and other digital signal processing techniques are being investigated [3,4,5]. For example, a two-tap feed-forward equalizer (FFE) on the transmitter (TX) side enabled error-free NRZ transmission without FEC up to 71 Gbps over 7 m OM4 [6], and 60 Gbps over 107 m OM4 [7]. With the addition of PAM4 signaling, a 148.6 Gbps transmission over 5 m MMF was reported in [8] and 100 Gbps PAM4 transmission over 100 m OM4 fibers was reported in [9]. In these measurements, the equalization was implemented in the receiver and the reported rates are after removal of the FEC overhead. Using an optimized OM4 a 200 m 48.7 Gbps link was achieved in [10] and a 150 m 50 Gbps link in [11]. Using OM3 and discrete multitone (DMT) signaling, links operating up to 66 Gbps at 100 m and up to 42 Gbps at 300 m have been reported [4].

Another method to increase the capacity of a single MMF is to utilize SWDM [12]. In this approach, the capacity of a single MMF scales with the number of wavelengths. Using a combination of signaling, equalization and SWDM, 200 m OM4 links operating at 42.5 Gbps [13], and 48.8 Gbps [14] per wavelength have been reported. SWDM technology is currently under IEEE 802.3 standardization process [15]. One limitation to its deployment is that traditional MMF has not been specified for operation outside of the 840 to 860 nm range. In response, the TIA has recently developed a new fiber standard TR-42.12 for MMF to include operation up to 950 nm. This MMF is referred to as wide band OM4 (WB-OM4) in this paper. To achieve operation over the wider wavelength the minimum effective bandwidth (the combination of modal and chromatic dispersion) is specified

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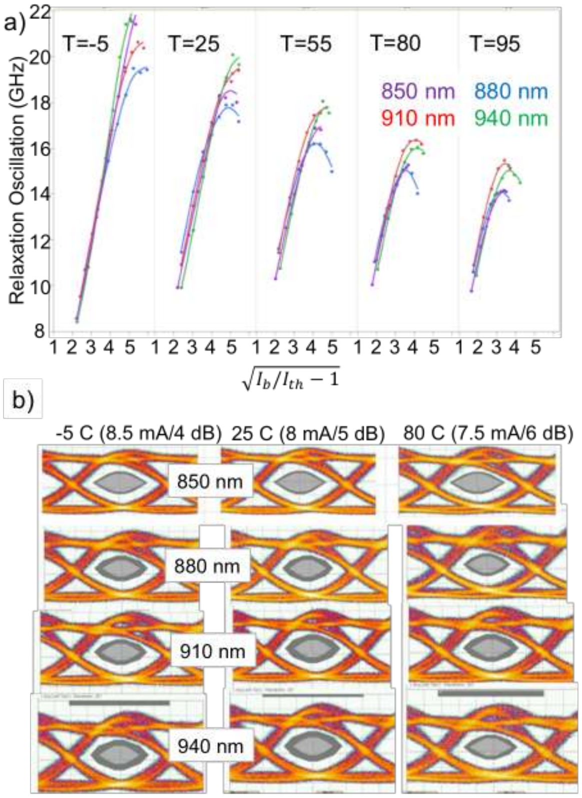

Fig. 1. (a) Relaxation oscillation as a function of normalized current for the SWDM VCSELs at temperatures of -5, 25, 55, 80 and 95 C. (b) Optical eye diagrams at 25 Gbps for each of the SWDM VCSELs at -5, 25 and 80 C. The bias current and the measured extinction ratio are given in the parenthesis for each temperature.

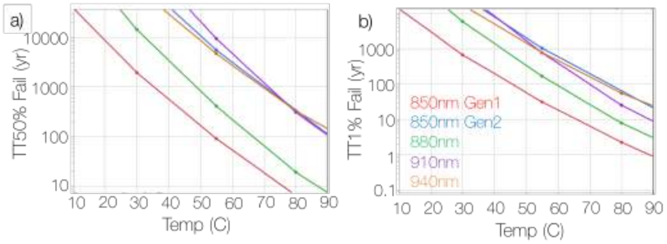

Fig. 2. (a) Years to 50% fail and (b) 1% fail as a function of VCSEL heat sink temperature.

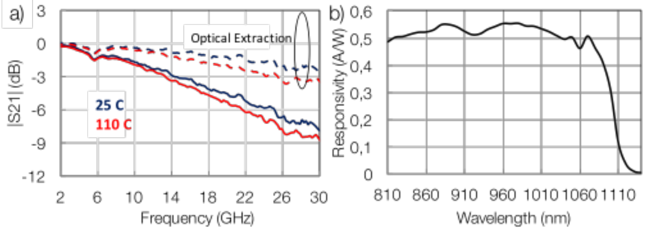

Fig. 3. (a) Frequency response (S21) of the SWDM photodiode as measured and with the electrical parasitics extracted (b) Responsivity of the SWDM PD as a function of wavelength.

as 2000 MHz•km from 840 to 950 nm. A performance comparison for OM4 and WB-OM4 for this range of wavelengths was presented in [16]. In this paper we will expand on the previous set of results and combine the several techniques described earlier to achieve 170 Gbps on a single optical fiber at distances up to 300 m. Carrying capacity of MMF is limited by both the effective bandwidth (EB) and the total fiber link length. As the speed of optical communication standards has increased, the operating length has been reduced. For example, 10 Gbps lengths could be deployed up to 300 m and this was sufficient for many data centers. As the speed increased to 25 Gbps, the specified link length has been reduced to 100 m. This has limited the infrastructure cabling deployment in some data centers and has not allowed full utilization of the installed base of OM3 and OM4 at 25 Gbps. Selective modal launch (SML) is one technique that can be used to increase the bandwidth of MMF, and has been demonstrated at 1550 nm [17], 1310 nm [18] and 664 nm [19]. These schemes employed a single-mode source and a spatial light modulator (SLM) to selectively launch light into to the MMF. In this paper we utilize a simple phase plate to increase the measured effective bandwidth of an OM3 fiber from 1800 MHz•km to 2100 MHz•km and demonstrate 25 Gbps transmission over 300 m.

II. VCSELs and PDs for SWDM Technology

The basic SWDM VCSEL structure is derived from the commercialized 850 nm 25 Gbps design which was previously discussed in [20]. A 30 nm wavelength grid (850, 880, 910 and 940 nm) was chosen to fit into the WB-OM4 specifications defined in TIA TR-42.12 standard and allows for uncooled operation over the anticipated temperature range with the use of relatively low cost optical filters. The longer wavelengths are designed by scaling the mirror thickness and active region composition. Extending the SWDM grid towards longer wavelengths (970, 1000, 1030 and 1060 nm for example) is relatively simple in terms of epitaxial growth and device fabrication, allowing for future bandwidth expansion on a single MMF. Fig. 1(a) is a plot of the relaxation oscillation as a function of current normalized to threshold at temperatures from -5 to 95 C. At 25 C all four wavelengths achieve ROF>18 GHz, and more than 14 GHz at 95 C. Fig. 1(b) depicts eye diagrams captured for each SWDM wavelength at three different temperatures. Almost identical eye openings were captured using the same NRZ electrical drive signal. The uniformity of device performance greatly simplifies the laser driver design. Fig 2 shows the reliability prediction (time to 50% fail, TT50%, and time to 1% fail, TT1%) for each of the VCSELs based on extrapolation from accelerated aging tests similar to those described in [21]. The time to 1% failure is more than 10 years of continuous operation at 80 C. These VCSELs are currently used in production transceivers. Note the 10x reliability improvement realized in the 850 nm VCSEL (GEN2) from previous reports of GEN 1 devices [21].

A single photodiode (PD) was designed to operate over the entire SWDM band. The InGaAs active region is grown on a GaAs substrate. Fig 3(a) shows the PD frequency response

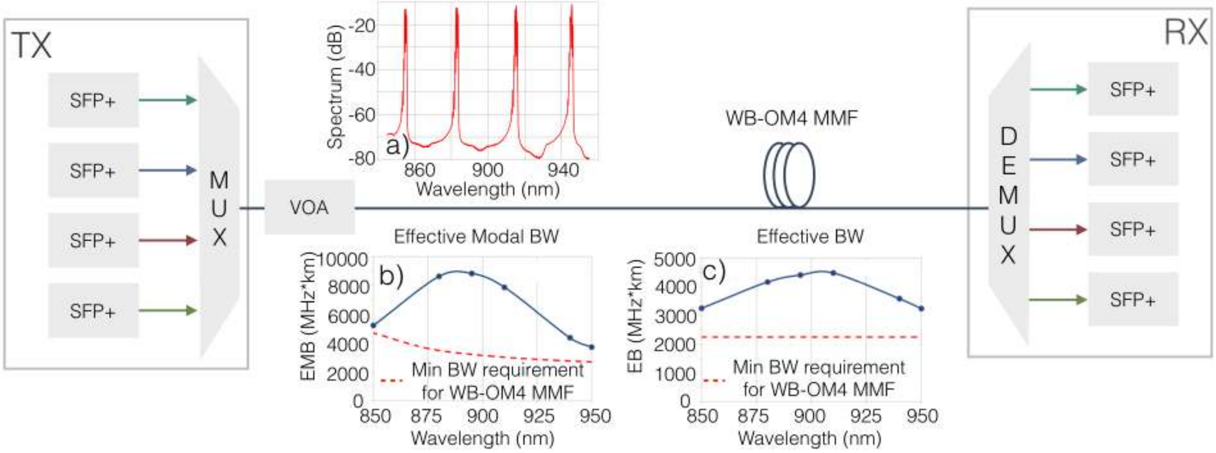

Fig. 4. SWDM experimental setup, each of the VCSELs is packaged in an SFP+ transceiver. The optical signal is combined in a MUX and then passes through a VOA, the WB-OM4 MMF (supplied by Prysmian), a DEMUX, and is received by a PD packaged in an SFP+ transceiver. Inset (a) shows the measured optical spectra measured after the MUX, inset (b) is the measured EMB WB-OM4 (solid dark blue line) and WB-OM4 minimum EMB requirement (red dashed line) as a function of wavelength. Inset (c) is the measured EB of the WB-OM4 (solid dark blue line) and a minimum WB-OM4 EB requirement (red dashed line) as a function of wavelength.

and Fig. 3(b) is the responsivity as a function of wavelength. Responsivity >0.5 A/W was achieved for wavelengths from 820 nm to 1060 nm. The series resistance of the PD is 11 Ω, total capacitance is approximately 160 fF. When the electrical parasitic is removed, the optical bandwidth of the device is >25 GHz. The optical bandwidth is determined to be limited by the transit time of photo-excited carriers in the active region by studying several active region thicknesses. Further increases in the total bandwidth of the PD can be increased by reducing the device pad capacitance and reducing the active region diameter. For this PD, the active region diameter was chosen to be 35 μm and represents the tradeoffs between total PD bandwidth and ease of optical alignment.

III. SWDM TRANSMISSION OVER WB-OM4

In this section we present measured results of a NRZ 100 Gbps and a PAM4 170 Gbps SWDM link on WB-OM4. The VCSELs and PDs described in section II are used in these measurements.

A. NRZ transmission

Fig. 4 is a schematic diagram of the experimental setup used in the NRZ transmission experiments. Each of the lasers was packaged in a small form factor pluggable (SFP+) transceiver. Inside each SFP+ is a laser driver and a clock and data recovery (CDR) circuit. There is no dispersion compensation included in the laser drive circuitry. The SFP+ transceivers were driven with a 2^{31}-1 pseudorandom binary sequence (PRBS) at 25.78 Gbps. The four wavelengths (855 nm, 883 nm, 915 nm, and 945 nm) were combined using an external optical multiplexer (MUX). The external MUX has a 2 dB insertion loss and 20 nm pass band to account for wavelength fluctuations over temperature (the VCSELs and transceivers are uncooled). The measured optical spectrum after MUX is presented in the inset (a) of Fig. 4. The root mean square (RMS) spectral bandwidths of the sources range from 0.34 nm to 0.41 nm. The optical signal was passed through a variable optical attenuator (VOA) and then coupled to a WB-OM4 fiber provided by Prysmian. The solid dark blue line in the inset (b) of Fig. 4 displays the measured EMB of the WB-OM4 fiber as a function of wavelength. The red curve presents the minimum bandwidth requirement of a WB-OM4 fiber, which was defined for wavelength window of 850 nm to 950 nm in [22]. The EMB of the WB-OM4 fiber measured at 850 nm is above the minimum OM4 requirement and increases for higher wavelengths, peaking at 880 nm. Since the chromatic dispersion for longer wavelengths is lower, the combined effect of the modal and chromatic dispersion results in the shift of the EB peak towards longer wavelengths [23]. The inset (c) of Fig. 4 displays the peak shifted towards 905 nm. At the end of the fiber, the optical wavelengths are separated with an external de-multiplexer (DEMUX) with an insertion loss of 1.5 dB. The receivers were also assembled into SFP+ transceivers using the PD described earlier, a transimpedance amplifier (TIA) and a CDR.

The experimental results are summarized in Fig. 5 and described in further detail in [24]. Fig. 5(a) shows the average optical power (AOP) received at a bit error rate (BER) of 1e-12 for each of the wavelengths for three transmission cases; a 2 m patch cord, 200 m of WB-OM4 and 300 m of WB-OM4. The optical extinction ratio was approximately 3.3 to 3.5 dB for each of the wavelengths. In this experiment error-free transmission (BER<1e-12) was achieved up to 200 m for all four wavelengths. At 300 m, the 940 nm channel was able to achieve BER<1e-9. There are a few options to improve the 940 nm channel performance, such as a lower spectral width VCSEL, higher bandwidth MMF, transmitter equalization or FEC. The Ethernet standards 100GBASE-KP4 and 100GBASE-SR4 adopted Reed Solomon (RS) code RS (528,514) for FEC. By applying this coding scheme, a signal can be recovered to a BER less than 1e-12 from an input signal with BER less than 2e-4 (KP4 FEC threshold) [25]. The KP4 level was used to allow straightforward comparison of

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AOP receiver sensitivities for NRZ and PAM4 signaling to be presented in subsection IIIB.

Figure 5(b) shows the received AOP at the KP4 FEC threshold for each of the wavelengths. For the 2 m patch cord, the AOP was approximately -13.7 dBm for all four wavelengths. The AOP penalty increased from 0.65 dB at 850 nm to 1.6 dB at 940 nm for 200 m transmission. For the 300 m link, the power penalty increased to 2.2 dB and 4.25 dB for the 850 nm and 940 nm channel respectively. With the KP4 FEC, a recovered BER<1e-12 was achieved for all four channels up to 300 m on the WB-OM4 fiber. Fig. 7(a) and (c) present the NRZ optical eye diagrams received after propagating through 200 m and 300 m of WB-OM4 fibers, respectively, for each of the wavelengths.

The results presented here demonstrate that SWDM transceivers operating on WB-OM4 optical fiber can achieve BER<1e-12 up to 200 m without FEC, and up to 300 m using KP4 FEC. This further indicates that these transceivers could be used with existing 25GBASE-SR and 100GBASE-SR4 (parallel fiber) channels.

The results demonstrate a) an error-free 103.12 Gbps transmission through a 200 m WB-OM4 fiber on an SWDM grid and b) 100 Gbps SWDM realization over a 300 m WB-OM4 fiber requires using FEC. Thus, the SWDM solution is applicable for 100 Gbps Ethernet utilizing the same multiplexing and demultiplexing technologies used in the existing 40 G SR SWDM product [20].

B. *PAM4 transmission*

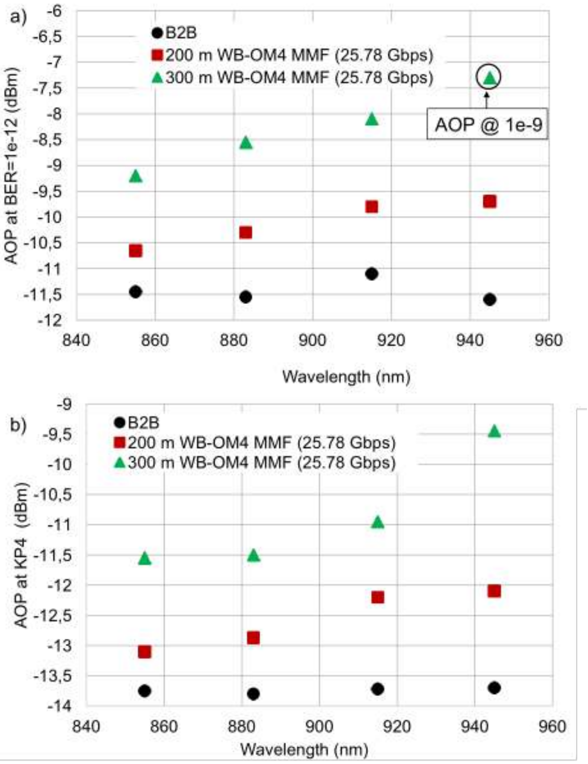

Fig. 5. AOP receiver sensitivities at (a) BER of 1e-12, and (b) KP4 BER threshold of 2e-4 for the four NRZ SWDM channels transmitted over WB-OM4 supplied by Prysmian. The black arrow in Fig. 5 a) shows the receiver sensitivity at 1e-9 for 945 nm NRZ channel over 300 m WB-OM4 fiber. The measured ER for each wavelength is approximately 3.3 to 3.5 dB.

Advanced modulation formats can be coupled with the SWDM technology to further increase the capacity of the VCSEL MMF link. A combination of SWDM and PAM4 provides a promising solution for 200 Gbps transmission through a single optical lane. Fig. 6 summaries the experimental results described in further detail in [13]. AOP receiver sensitivities at the KP4 BER threshold of 2e-4 are plotted for all four wavelengths (851.9 nm, 888.0 nm, 912.1 nm, and 942.4 nm) and two edge wavelengths through WB-OM4 fibers and/or OM4 fibers at 45 Gbps and 51.6 Gbps, respectively. Two experiments were performed with different commercially available PAM4 physical layer integrated circuits (PHY), two WB-OM4 fiber types from separate vendors and an OM4 MMF. The availability of PHYs limited our study of different fiber types and lengths. The first PHY chip had a symbol rate of 22.5 Gbaud, provided pulse shaping and CDR functionalities, and enabled equalization for chromatic and modal dispersion compensation. In the first experiment, a 45 Gbps PAM4 signal was transmitted over 100 m and 300 m of the WB-OM4 supplied by Prysmian (the same fiber type as in the NRZ experiment), as well as 200 m of the OM4 fiber. For a 2 m patch cord, the AOP receiver sensitivity at the KP4 BER threshold ranged from -9.6 dBm to -9.3 dBm for all four SWDM wavelengths. An AOP penalty of 0.2 dB was measured for PAM4 transmission over a 100 m WB-OM4 fiber for all four channels. PAM4 transmission over 200 m of the OM4 fiber resulted in AOP penalties ranging from 0.7 dB at 851.9 nm to 2.7 dB at 942.4 nm. Lower AOP penalties were captured for two long wavelengths (912.1 nm and 942.4 nm) at a 300 m WB-OM4 versus a 200 m standard OM4 fiber, indicating that an OM4 fiber is optimized for 850 nm wavelength while a WB-OM4 fiber covers a wider

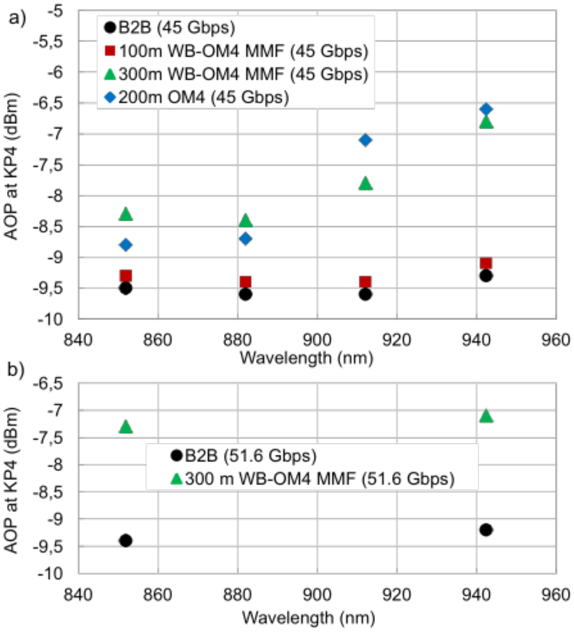

Fig. 6. (a) AOP receiver sensitivities at KP4 BER threshold of 2e-4 for PAM4 SWDM channels transmitted through WB-OM4 fibers using the 45 Gbps PHY and WB-OM4 supplied by Prysmian. (b) AOP sensitivity at KP4 FEC threshold for the 51.6 Gbps PHY and the WB-OM4 fiber supplied by OFS. The measured ER for each of the wavelengths was 3.0 dB and 4.0 dB for a) 45 and b) 51.6 Gbps PAM4 signals respectively.

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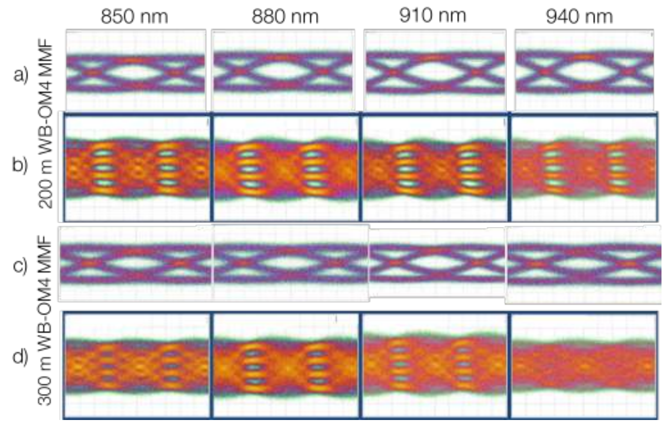

Fig. 7. Received optical eye diagrams for the SWDM wavelengths (a) 25.78 Gbps NRZ over 200 m WB-OM4, (b) 45 Gbps PAM4 over 200 m WB-OM4, (c) 25.78 Gbps NRZ over 300 m WB-OM4, and (d) 45 Gbps PAM4 over 300 m WB-OM4. WB-OM4 fiber was supplied by Prysmian.

wavelength range and is more suitable for SWDM systems. The same experiment was repeated with another PAM4 PHY chip, which had a 25.8 Gbaud data rate and capabilities equivalent to the first PHY chip. Two 51.6 Gbps PAM4 signals were transmitted at the shortest and longest SWDM grid wavelengths (851.9 nm and 942.4 nm) over a 300 m WB-OM4 fiber supplied by OFS. AOP penalties (2.2 dB) were captured for both wavelengths, which imply that the transmission at net rate 195.2 Gbps is possible over 300 m of this WB-OM4 fiber. The results for this measurement are summarized in Fig. 6(b).

Fig. 7(b) and (d) show the received eye diagrams for 45 Gbps PAM4 signaling over 200 m and 300 m WB-OM4 MMFs at four SWDM wavelengths. The columns and rows correspond to four different wavelengths and two fiber lengths, respectively.

C. *Discussion*

The results presented show that the combination of SWDM and WB-OM4 fiber technologies may provide a promising solution for improving both link capacity and reach. The WB-OM4 fiber type may also serve as a suitable option for extending the reach in the newly built data centers. Our results show that a) the specified reach using the IEEE KP4 standard (100 m OM4 at 25 Gbps) is extended to 300 m OM4 and b) 100 Gbps transmission is possible by combining either four wavelengths carrying NRZ signals or two wavelengths carrying PAM4 signals.

NRZ signaling allows for simple and energy-efficient implementation. In scenarios where an additional parallel lane can be added, NRZ transmission is a cost-effective option that provides the same capacity as PAM4 in two parallel lanes instead of one. No equalization is required to enable a net rate after FEC of 25 Gbps per wavelength in transmission over 300 m WB-OM4 fiber, as presented in Section III.A. Standard NRZ off-the-shelf electronic solutions, such as CDR circuits, may be used. On the contrary, commercially available PAM4 solutions are equipped with the energy-consuming equalizers in the TX for signal shaping and in the RX for the dispersion compensation. The PHY chips used in our experiments also include CDR. Combination of these functionalities allows for a high-capacity density of 50 Gbps per wavelength transmission over a 300 m WB-OM4 fiber. Another aspect is FEC, which has been standardized at the IEEE KP4 BER threshold of 2e-4. While FEC is required for PAM4 signaling, it is not necessary for NRZ signaling over shorter transmission distances. As presented in Section III.A, the 200 m transmission over a WB-OM4 fiber was error-free at 25.78 Gbps for all four NRZ SWDM channels with margin of approximately 3 dB. For this reason, there was no need to account for the FEC overhead. Currently, PAM4 electronics are improving in power consumption, but they will always exceed that of NRZ links. The presented results also show that AOP receiver sensitivity (at KP4 BER threshold) for the un-equalized 25.78 Gbps NRZ scheme is 4.5 dB lower than the one required in the equalized 51.6 Gbps PAM4 scheme. Due to this inherent penalty resulting from the lower optical modulation amplitude, the NRZ scheme supports applications that require higher link power budgets. The transmission penalties cannot be directly compared because the PAM4 PHY chip uses an equalizer for dispersion compensation and the NRZ module does not.

IV. REACH EXTENSION FOR STANDARD MMF

The previous results indicate that WB-OM4 MMF is a good choice for the new data center fiber infrastructure. However, new data centers are just a portion of the market. In existing data centers the fiber infrastructure cabling is rarely exchanged due to the high cost of replacement. In this section, we discuss solutions for improving the reach of the standard MMF links, such as those using OM3.

A. *Selective mode launch*

One way to improve the bandwidth of the existing OM3 MMF links is to use a selective modal launch. Utilizing the selective launch and an offset launch was proposed in order to improve bandwidth and fiber characterization in the 1550 nm [17], 1310 nm [18] and 664 nm [19] regimes. These schemes employed a single-mode source and a spatial light modulator (SLM) to selectively launch light into specific mode groups of the MMF. In this section, we present the experimental and simulation results for a selective launch in the 850 nm wavelength regime. The experiment was performed using an optical phase mask designed for 850 nm. The transmitter includes the multimode VCSEL structure described in Section II and an optical phase mask to enable SML into a MMF. The SML excites fewer mode groups in the MMF and the modal dispersion effect is mitigated as a result.

Fig. 8(a) shows the measured frequency responses of a 300 m OM3 MMF with a selective modal launch (blue line) and a standard central launch (black line). The fiber frequency response of the 305 m OM3 spool was measured by subtracting the optical response measured with a 2 m patch cord from the full-system response. In the standard central laser launch configuration the fiber bandwidth is 1800 MHz•km at 6 dB. With the optical phase plate in place for the SML, the fiber bandwidth is increased to

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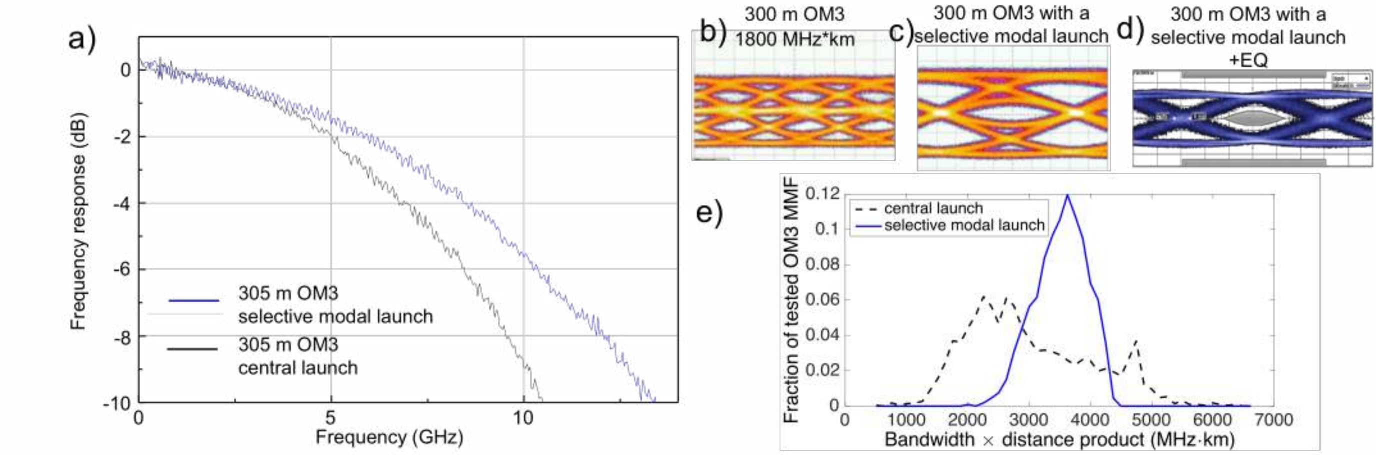

Fig. 8. (a) Bandwidth measured with and without selective modal launch in a 300m OM3 fiber (b) optical eye diagrams captured after 300 m OM3 fiber transmission without SML, (c) optical eye diagrams captured after the 300 m OM3 with SML, d) electrical eye diagrams after the 300 m OM3 fiber with SML and equalization, (e) Histogram of the calculated bandwidth-distance product of the TIA sample of OM3 fiber with (solid line) and without (dashed line) SML.

2100 MHz•km. The NRZ eye diagrams at 25.78 Gbps shown in Fig.s 8 (b)-(d) were captured after propagating through 300 m of the OM3 MMF. Fig. 8(b) is the optical eye diagram without SML, and Fig. 8(c) is with the SML. Clear improvement in the optical eye diagram is demonstrated. Fig. 8(d) is the analog electrical output from the receiver which does include equalization. With the SML and equalization, error-free transmission over 300 m of OM3 fiber was obtained.

To determine if an SML could be used with a wide range of OM3 fibers, we have calculated the EMB of a statistically representative sample of fiber bandwidths. The OM3 fiber set used was a subset of the TIA 5000 fiber set described in [26], which lists modal delays for 19 mode groups of 5000 multimode fibers without specifically describing index profile perturbations. The OM3 subset was chosen by simulating offset SMF launch procedure, using differential mode delay (DMD) weightings from TIA-455-220A to calculate impulse response, frequency responses and minimum modal bandwidth, which were filtered to >2000 MHz·km and <4700 MHz·km. This filtering left 2300 fiber profiles in the data set. Because there is a large variance within OM3 fiber group, we use the bandwidth criterion to assess if the specific fiber sample can support a 300 m 25 Gbps transmission. Fig. 8(e) is a histogram of the bandwidth-distance product of the 300 m OM3 links from the data set using a central laser launch (dashed line) and the SML profile (solid line). The phase plate design has been optimized to improve the worse tail of the OM3 fiber distribution. The simulation results indicate that by using an SML the variance of the bandwidth-distance product distribution of OM3 MMF is reduced, and the bandwidth improvement is possible for more than 80 percent of OM3 fiber samples. More importantly, the minimum bandwidth of a 300 m OM3 MMF link can be improved to more than 2000 MHz·km.

B. *Quasi-single mode VCSELs*

The previous results relied on addressing the modal dispersion in the MMF. Another method to increase the MMF bandwidth is to reduce the contribution of chromatic dispersion to the total bandwidth. In one example, an 850 nm VCSEL with an integrated mode filter supported 25 Gbps NRZ transmission over 1.3 km of MMF [27], and in another example a NRZ net rate after FEC of 50 Gbps was transmitted over 2.4 km of MMF [28]. In a third example, an equalized 25 Gbps transmission over 1 km OM4 was shown by utilizing a Zn-diffusion and oxide-relief VCSEL structure [29]. In addition, the Zn-diffusion VCSEL structure enabled a 72 Gbps DMT transmission over 300 m of OM4 fiber [30]. The disadvantage of using single mode lasers is that they are often limited in optical power and may require more complex optical alignment to minimize feedback to the laser. Still this is a promising approach to increasing the optical link length in some installed fiber. However, if the modal bandwidth of the fiber is low, a SML may also be needed to realize the full benefit.

C. *Discussion*

The experimental results presented in this section indicate the possibility of enhanced performance of an existing MMF infrastructure when SML is used to improve the modal bandwidth and/or a low SBW source is used to minimize the chromatic dispersion. The link capacity may be further increased if both strategies are combined with SWDM and advanced modulation formats. More experimental confirmation of the bandwidth improvement from the SML across a broad sample of OM3 is required before this technique could be widely deployed. SML techniques have been previously standardized using an offset launch from a single mode fiber for 1310 nm links operating on MMF in IEEE 10GGASE-LR. The proposed SML solution can be applied to the other SWDM VCSELs by adjusting the phase mask design to the specific wavelength.

V. CONCLUSION

We reviewed and suggested several methods for enhancing the capacity and extending the reach for VCSEL based MMF links. We showed that four wavelength SWDM can support 100 Gbps NRZ and 200 Gbps PAM4 transmissions. Our results demonstrated that an error-free transmission at

100 Gbps is possible for all four wavelengths with NRZ signaling over a 200 m WB-OM4 fiber, and with the addition of KP4 FEC 300 m links are possible. With PAM4 signaling and FEC the SWDM link on WB-OM4 fiber achieved 170 Gbps. Further improvements to these link speeds and distance could be realized with the addition of SML or possibly quasi-single mode VCSELs.

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