SWDM Strategies to Extend Performance of VCSELs over MMF

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Abstract: Experimental data is presented demonstrating 100GbE (4x25.8 Gbps) SWDM4 VCSEL technology, and SWDM4 transmission over 200m and 300m of wideband OM4 fibers. All NRZ SWDM4 channels achieved error-free transmission at 200m, and BER < 1e-9 at 300m. In addition, successful 180 (4x45) Gbps transmission is demonstrated over 300m wideband OM4 fibers using a 45-Gbps-PAM4 chip. Real time BERs < 2e-4 were achieved for all four SWDM grid channels in the 850-950nm wavelength range. Precise modal excitation in MMF fibers for improving the fiber bandwidth by minimizing modal dispersion is also discussed. Using our novel modal excitation method, 25 Gbps NRZ transmission over 300m OM3 is shown.

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1. Introduction

Multimode fiber (MMF) optical modules based on vertical cavity surface emitting laser (VCSEL) technology provide a low cost and power efficient solution for 100 Gbps data center networks based on parallel multimode fiber [1]. The IEEE recently standardized these systems as 100GBASE-SR4 (100GbE), providing a maximum reach of 100m on OM4 fiber. It would be desirable to extend the reach to 300m OM4, while also saving on fiber plant costs by reducing or eliminating the need for parallel fiber. In addition, 300m OM3 reach is attractive for data center networks. Higher transmission rates and longer reach can be achieved for data center networks by leveraging of electronic and/or optical technologies such as four-level Pulse Amplitude Modulation (PAM4) [2] and electronic equalizers [3] as well as short wavelength division multiplexing (SWDM) and novel wideband MMFs [4]. However, powerful DSP based modulation and equalization techniques suffer from high power consumption.

In this paper, we describe SWDM4 transmission over wideband OM4 fiber as well as selective mode excitation in OM3 fiber to increase data rate and extend reach without using DSP based modulation and/or equalization techniques. We demonstrate that the extended reach, high capacity, fiber efficiency, and low power consumption are achievable by simultaneous use of 4 x 25.8 Gbps SWDM (SWDM4) VCSEL technology and novel wideband OM4 fiber. Successful 100 GbE SWDM4 transmission is shown over 300m wideband OM4 by utilizing only conventional low-power NRZ electronics and low-cost SWDM optics. We also show that the selective mode excitation enables us to increase the 3 dB transmission bandwidth of MMF. In conjunction with simple equalization, this method extends the reach of OM3 fiber to over 300m at 25.8 Gbps; a distance objective for the extended reach data center applications. By combining optical and electronic technologies, we experimentally demonstrate the potential application of 200GBASE-SWDM4 over wideband OM4 fiber using a single chip PAM4 generator and equalizer.

The measured average optical powers (AOPs) are shown at IEEE standard KP4 FEC with a BER threshold of 2e-4 for 180/204 Gbps PAM4-SWDM transmission over 100m and 300m wideband OM4 fiber as well as 200m conventional OM4 fiber.

Fig. 1 (a) Measured SWDM4 spectrum, (b) measured effective modal bandwidth (EMB) and (c) effective bandwidth (EB) of the wideband OM4 (blue) and OM4 bandwidth requirement (red).
2. Experimental Setups and Results

A set of four 25G VCSELs and photodetectors (PDs) are designed and fabricated for SWDM application in the 850-950nm band. The VCSELs and PDs are assembled into conventional 25.8 Gbps TOSA and ROSA packages. For this initial demonstration, we employ separate SFP+ modules for each channel. The modules include conventional 25G NRZ CDR, and there is no DSP or adaptive technology, the channel spacing is 30nm, the external wavelength multiplexer has passbands of ~20nm to accommodate the wavelength accuracy specifications for uncooled VCSEL operation. The four-channel SWDM spectrum measured at output of the multiplexer is shown in Fig. 1 (a). The VCSEL center wavelengths are measured at 855, 883, 915, and 945nm, and RMS spectral bandwidths (SBWs) are in the range 0.34 to 0.41. The link includes a mode preserving VOA to adjust the optical power, and various lengths of wideband OM4 fiber. The measured effective modal bandwidth (EMB) is shown in Fig. 1 (b). This fiber is designed for peak EMB at ~ 890nm. Note that chromatic dispersion bandwidth tends to shift the peak of net effective bandwidth (EB) to slightly longer wavelengths at ~ 905nm. The EB shown in Fig. 1 (c) is calculated from the EMB data (Fig. 1 (b)) and chromatic dispersion bandwidth, assuming a VCSEL SBW of 0.4 nm, without taking into account modal and chromatic dispersion interaction.

Figure 2 shows the measured BER curves for 4 x 25.8 Gbps NRZ-SWDM (SWDM4) over the link with wideband OM4 fiber as a function of the received AOP measured at the receiver. The BER was measured simultaneously on the SWDM4 channels using a four-channel BERT. We used pseudo-random bit sequences (PRBS) of length $2^{31}-1$ in all tests. For clarity, the BER data is organized into four separate plots, one for each wavelength channel. We show BER waterfall curves measured B2B (black squares), after 200m (blue triangles), and after 300m (red diamonds) for each wavelength channel. The B2B receiver sensitivities at BER=1.e-12 are approximately in the range of -10 to -10.5 dBm. At 200m, we achieve error-free transmission on all channels when the received power is > - 8 dBm. The 200m power penalties relative to B2B are modest, approximately ranging from 1 to 2 dB at BER=1.e-12. We believe this SWDM transmission result demonstrates acceptable performance over 200m wideband OM4 without the need for FEC. At 300m, the penalties increase significantly as expected from the measured eye diagrams. Nevertheless, all channels achieve BER < 1.e-9. This BER performance provides adequate margin to achieve error-free transmission in data center systems employing IEEE standard KR4 FEC with a BER threshold at 5.e-5.
To improve 3dB MMF bandwidth and extend the reach, a selective mode VCSEL beam launcher was used at the output of a 25.8 Gbps NRZ TOSA at 850nm. Figures 3 (a-b) show the received NRZ eye diagrams at 25.8 Gbps after transmission over OM3 fiber. The eye diagram (Fig. 3 (a)) was measured using a standard launch and no equalization. In this case, the eye at the output of a 300m link of OM3 fiber is completely closed. The eye in Fig. 3 (b) was measured using a selective mode launcher and simple Feed-Forward Equalization (FFE). This eye demonstrates enhanced data transmission through a 300m OM3 fiber link at 25.8 Gbps.

Fig. 3 Received optical eye diagrams after transmission over 300m OM3 fiber (a) using standard launch and no equalization and (b) using selective mode launch with simple FFE equalization. (c) AOPs at IEEE standard KP4 FEC with a BER threshold of 2e-4 for four 45 Gbps PAM4 channels at 851.9, 882.0, 912.1, and 942.4nm and two 51.6 Gbps PAM4 channels at 851.9 and 942.4nm.

To study PAM4 SWDM4 receiver sensitivities, a single chip was used to generate 45 (or 51.6) Gbps PAM4 optical data stream. The 25G VCSELs were directly and differentially driven by 22.5-Gbaud (or 25.8-Gbaud) PAM4 PRBS of length $2^{31}-1$ produced by integrated DACs, with ~0.8 Vpp electrical signal. The chip also performed the main functions, such as 45 Gbps PAM4 clock and data recovery, pulse shaping at the transmitter, adaptive modal and chromatic dispersion equalization at the receiver, and real-time BER measurement. Two sets of MMF types and various fiber lengths were used for this experiment including: 200m conventional OM4 fiber and wideband OM4 fibers (100m/300m). The wideband OM4 fibers are manufactured by Prysmian Group and OFS Corporation. The 25G VCSELs used in this experiment were production-grade Finisar VCSELs. The measured VCSEL center wavelengths were 851.9, 882.0, 912.1, and 942.4nm. RMS SBWs were 0.558, 0.370, 0.5011, and 0.527nm from the short wavelength to the long wavelength, respectively. The measured average RINs were ~141 dB/Hz. In this study, a Finisar ROSA operating over the SWDM grid was used. The chip DSP provided functionality for digital pre-emphasis compensation. Using 22.5-Gbaud and 25.8-Gbaud PAM4 chips, the measured transmitter ERs were around 3.1 dB and 4.5 dB at four wavelengths, respectively. Figure 3 (c) shows the measured AOPs at IEEE standard KP4 FEC with a BER threshold of 2e-4 for four SWDM 45 Gbps channels over 200m conventional OM4 as well as 100m and 300m Prysmian and OFS wideband OM4 fibers. The measured AOPs were ~9.5 dBm for back-to-back over all SWDM 45 Gbps and 51.6 Gbps PAM4 channels at BER of 2e-4. Negligible AOP penalty (<0.2 dB) was captured over 100m Prysmian wideband OM4 fiber for all SWDM 45 Gbps PAM4 channels at KP4 level. Less than 0.5 dB AOP penalty was observed over 300m Prysmian wideband OM4 fiber in comparison with 200m conventional OM4 fiber for two short wavelength 45 Gbps PAM4 channels (850 nm and 880 nm). Long wavelength PAM4 channels (910 nm and 940 nm) over 300m Prysmian wideband OM4 fiber showed better receiver sensitivities at KP4 BER threshold compared to 200m conventional OM4 fiber. The required AOPs were ~7.2 dBm over 300m OFS wideband fibers at 51.6 Gbps PAM4 channels at 850 nm and 940 nm.

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4. References