Characterization of modal-chromatic dispersion compensation in 400GBASE-SR8 channels

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Abstract: We evaluate the impact of OM4 dispersion compensated fiber on 8x50Gbps transmission for reaches up to 550m. Bit error rates and eye diagrams before and after equalization are evaluated.

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1. Introduction

Multimode fiber (MMF) channels using VCSEL-based transceivers are still predominant in data centers for high-speed short-reach interconnects due to the cost advantage of transceivers and resiliency to contamination. However, due to inter-symbol interference (ISI), the reaches for higher-speed communications have been decreasing from ~400 m over OM4 fiber for 10 Gb/s (10GBASE-SR) to 100 m for 100GBASE-SR4. Currently, the Standardization of Ethernet using 50G PAM-4 per lane over MMF, scheduled for completion by the end of 2019 [1] specifies 100 m for the 400GBASE-SR8 variant.

ISI is caused primary by the VCSEL bandwidth and modal and chromatic dispersion in the fiber channel. Modal dispersion arises due to a difference in propagation speeds between supported optical modes within the MMF. The effective modal bandwidth (EMB) of the fiber is characterized using a differential mode delay (DMD) measurement. Depending on the EMB value, fibers are graded as OM3 (EMB >2000 MHz·km) and OM4 (EMB >4700 MHz·km). Chromatic dispersion (CD) is due to the difference in propagation speeds of the spectral components of the transmitted signal. CD penalties depend on the fiber dispersion parameters and the spectral width (SW) of the VCSEL. The smaller the SW, the lower the CD penalties. The SW depends on the bias current and on the laser cavity design. A large bias, which tends to enhance the VCSEL frequency response, also excites more transverse optical modes in the cavity, which in turn broadens the SW.

To increase the reaches of MMF, the modal chromatic dispersion interaction (MCDI) [2-4] for a specified type of fiber L-MMF has been previously used. Those fibers produce partial modal-chromatic dispersion compensation (MCDC) as shown in multiple experiments for 10G or 25G signals [5].

For 50G signals, although there was a significant amount of research and experimental link reach demonstrations in academia and industry [6-7], the impact of MCDI over longer reaches (500 m) over commercially available (pre-standard) transceivers have not been evaluated.

In this paper, we characterize the BER performance of OM4 fibers with and without modal-chromatic compensation. We study the effect of the MCDI on the eye diagrams before and after equalization. The result of this experiment can be used to estimate transceiver and fiber requirements for future extended reach such as 400Gbps solutions in data center networks. Also, margins observed in PAM-4 VCSELs can help to evaluate the feasibility of 100Gbs per lane for future IEEE and Fibre Channel PI-8 variants.

2. Theoretical background and experiments

As shown in Fig. 1, two fibers can have almost identical EMB but different DMD tilt. Based on the sign of the DMD tilt, the fibers can be classified as Left-tilted-MMF (L-MMF) or Right-tilted MMF (R-MMF) [2-3]. In those fibers the relative speed difference between high order modes (HOMs) and low order modes (LOMs) is different. For L-MMF the HOMs (in which energy is concentrated at larger radial offset inside the MMF core), travel faster than the LOMs (in which energy is concentrated at the lower radial offset). For R-MMF, HOMs travel slower than LOMs.

VCSELs have transverse modes that produce significant spectral dependence during VCSEL-MMF coupling given that the HOMs of the VCSEL tend to couple more efficiently to the HOMs of the fiber [3]. Since each VCSEL mode has associated a specific resonant wavelength, a spectral dependent coupling is produced.

The combined effect of the spectrally dependent coupling and the type of MMF, either increases or decreases the total dispersion in the fiber depending on the type of fiber is used.

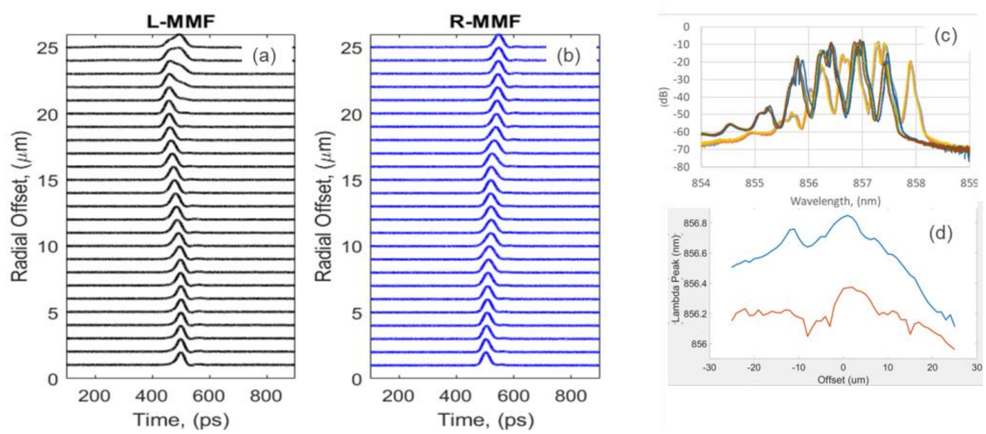

Fig. 1. (a) L-MMF, (b) R-MMF (c) 8 VCSEL spectrum for one transceiver (d) Spectral coupling characterization, max. in color blue, min in color red

Experiments to validate MCDC were performed using two MMF fibers of EMB at 5000 MHz-km as shown in Fig. 1(a) and 1(b) and three 400G BASE-SR8 transceivers from two manufacturers. The optical spectra of some of the VCSELs are shown in Fig. 1(c). The RMS spectral width of the transceivers range from 0.32 nm to 0.41 nm, the OMA ranged from 2 to 4 dBm. The spectral coupling was characterized by launching the light of the transceivers into the fiber and measuring the optical spectrum after propagation using a scanning SMF probe. The probe was moved in steps of one-micron across the MMF core. The other end of the probe fiber was connected to an optical spectrum analyzer. Some transceivers exhibit high spectral dependent coupling, e.g. 0.3 nm difference in peak wavelength spectrum between the center of the core and the radial offset 18.

Fig. 2 shows the BER results comparing the performance of three transceivers, 24 VCSELs, operating at nominal 50Gbps using PAM-4 modulation. The test was performed using a 400G VIAVI traffic analyzer (ONT 804) and a variable attenuator. In almost all cases, the BER of L-MMF was significantly better than the R-MMF. Fig. 2 shows significant margins for L-MMF compared with R-MMF despite that both fibers have similar EMB and DMD with similar shape but opposing tilt.

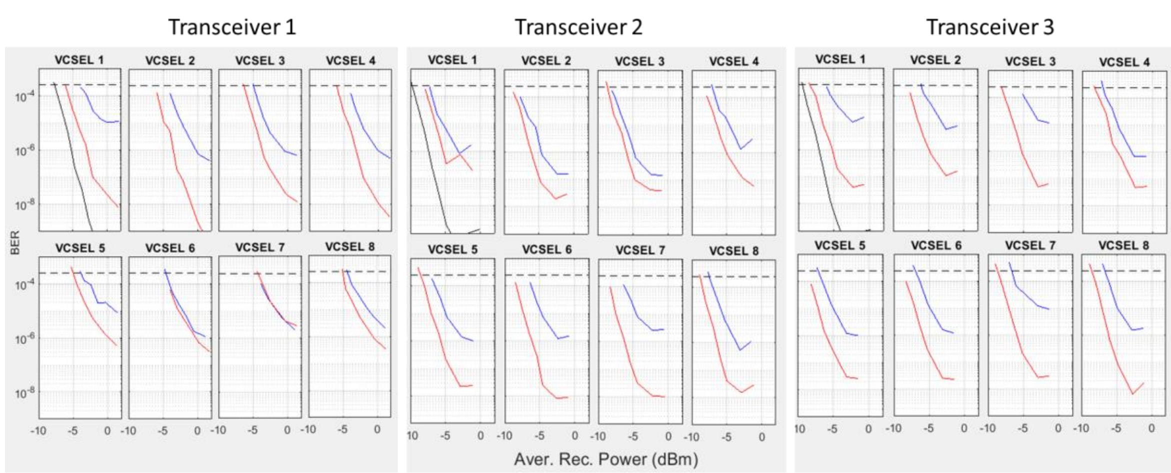

Fig. 2, BER results for 24 VCSELs, (red) L-MMF, (blue) R-MMF. Pre-FEC BER limits for 802.3 cm 400GBASE-SR8 shown as dash lines. Back to back BERs shown in black for VCSELs 1 from each transceiver.

To better understand the causes of this difference, we captured eye diagrams of the transmitted signals using a real-time 100GSa/s Tektronix scope. Fig. 3 shows the eye diagrams for 300 m for one of the transceivers. It can clearly be seen that the eye for the R-MMF is closed and requires equalization, while the eye for the L-MMF is still open after 300m transmission. Equalization using a five-tap symbol spaced equalizer was applied to both the L-MMF and R-MMF channels. At 300m the equalizer opened the eyes of the R-MMF in most cases. However, eye height for the L-MMF was significantly better since less equalization produces lower noise enhancement.

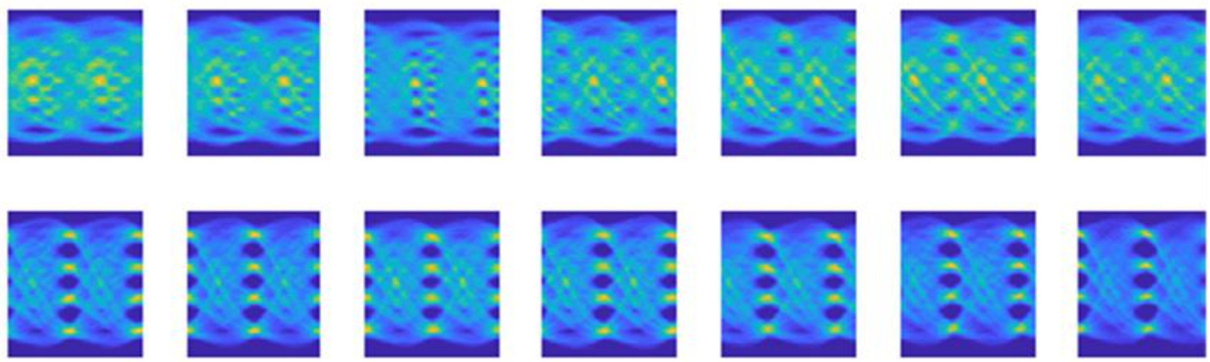

Fig. 3, PAM-4 Eye diagrams before equalization: R-MMF (top) and L-MMF (bottom)

The observed margins for 300 m L-MMF indicate that longer reaches are possible. In addition to the 300m left and right tilt MMFs, a 550m 12-fiber cable with right and left tilted OM4 fibers was also tested. Only two left tilted high EMB (EMB around 8000 MHz.km) fibers could establish link. All other fibers, including a 4700 MHz.km right tilted fiber, had completely closed eyes even after equalization. However, a L-MMF with equalization operated with BER around 3e-6 which is lower than the pre-FEC limit for the applications ((it had to be attenuated 5.5 dBs to reach 1e-4 BER). The eye diagram for one of the 550m L-MMF channels is shown in Fig. (4).

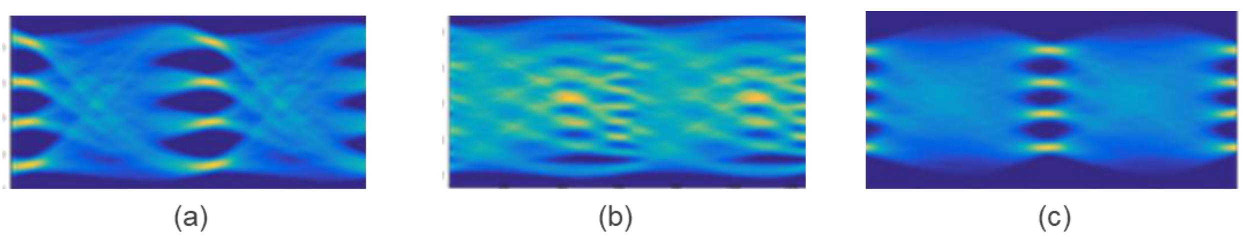

Fig. 4, Eye diagrams for 550 m channels (a) B2B, (b) after propagation without equalization (c) after propagation with 5-tap symbol space equalizer

3. Summary and Conclusions

We compare the performance of L-MMF and R-MMF using 400GBASE-SR8 transceivers. The presented results indicate that for the tested 400GBASE-SR8 transceivers all VCSEL lanes consistently showed a performance advantage on dispersion compensating, left-shifted, multimode fiber relative to non-dispersion compensating, right-shifted, multimode fiber. For 300 m, there is up to 3 dBs of margin of using L-MMF at a BER of 1e-12. The advantages shown using BER metrics were also observed in the eye diagram evaluation. The additional margins provided by L-MMF are a consequence of the reduction of channel ISI as was observed in the eye diagrams. At 300 m, L-MMF requires virtually no equalization. This advantage was shown to be sustained previously for 10GBASE-SR to 100GBASE-SR4 transceivers as well as 100G-SWDM4 transceivers.

4. References

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