Concept of BiDi Optimized OM4 Multimode Fiber for High Date Rate Short Reach VCSEL Transmission

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Abstract— **We propose the concept of BiDi optimized OM4 fiber having same reach capability as OM5 fiber for 50Gb/s and 100Gb/s BiDi PAM4 transmission. Successful experimental verifications have been conducted using 100G and 800G BiDi transceivers.**

Keywords—short reach communications, BiDi transceiver, multimode fiber, modal bandwidth, SWDM transceiver, OM5 fiber

I. INTRODUCTION

Multimode fibers (MMFs) have been widely used for short distance communications, such as within a building, on a campus, or in a data center [1-2]. MMFs and vertical-cavity surface-emitting laser (VCSEL) work together to form a system for short reach applications with distances up to 100 m. VCSELs are less expensive to manufacture and consume less power than traditional single mode lasers, making them a cost-effective and an energy-efficient option for short reach communications. Compared to single-mode fibers, MMF has a large core diameter and a high numerical aperture, which allows the use of lower-cost VCSEL light sources and connectors between fibers.

Driven by the explosive increase in data traffic and demand for cloud computing in data centers [3], optical transmission technology has advanced quickly in the past decade. Traditionally, to get to higher data rates, parallel optics with multiple lanes of MMFs in one cable is used. For example, for 100Gbase SR4 applications, eight fibers are used to transmit and receive 4×25G data. With the need to migrate to higher density, newer transceiver technology based on wavelength division multiplexing (WDM) has emerged in the past decade. One such transceiver is the BiDi transceiver, named for its bidirectional transmission. It started as 40G BiDi [4] with a QSFP form factor that transmits VCSEL light at 20 Gb/s optically at ~850 nm in one direction and at ~910 nm in the other direction. With the development of the 100G BiDi transceiver and 400G SR4.2 transceiver standardized by IEEE 802.cm, BiDi technology has advanced to higher data rates. Another competing technology is short wavelength division multiplexing (SWDM) [5-6], which utilizes four wavelengths, nominally around 850 nm, 880 nm, 910 nm and 940 nm. To date, SWDM transceivers have been offered with 40G and 100G data rates with each wavelength operating at 10Gb/s and 25Gb/s respectively [7]. Besides using existing MMFs like OM3 and OM4, SWDM also takes advantage of a new grade of MMF, OM5, standardized alongside the new SWDM transceivers in 2016 [8].

The 50-micron core MMFs have been dominantly employed and are also categorized as OM2, OM3 and OM4 based on the effective modal bandwidth (EMB) at 850 nm. The EMB of OM3 fiber at 850 nm is 2000 MHz·km while the EMB for OM4 is 4700 MHz·km. OM5 is a sub-category of OM4 with the same EMB at 850 nm, but with an added EMB requirement of 2470 MHz·km at 953 nm, the longest wavelength that can be used by SWDM technology. The data transmission rate of VCSEL-based transceivers reached 25Gbaud a few years ago. Among them, 100G transceivers such as 100G SR4, 100G BiDi, and 100G SWDM transceivers use 25G non-return-to-zero (NRZ) modulation format and 400G transceivers such as 400G SR8 and 400G SR4.2 use 50G 4-level pulse-amplitude-modulation format, referred to as PAM4 [4]. The system reaches have been specified as 70 m for OM3 fiber and 100 m for OM4 fiber.

Very recently, the data rate for emerging VCSEL technology has approached 100 Gbps per lane at 850 nm, as standardized by IEEE 802.3db. BiDi technology using 850 nm and 910 nm is also advancing towards 100 Gbps per lane. The Terabit BiDi multi-source alliance (MSA) was formed in early 2022 to push the transceiver data rate to 800G with 1.6 T in sight [9]. With the combination of using 8-fibers and two wavelengths at 100G/wavelength, the 800G BiDi transceiver uses the same fiber counts as many existing transceivers. One limitation that has emerged is its reach capability. Specified in MSA 1.0 for 800G SR4.2 applications, the transceiver supports system reaches of 45 m over OM3, and 70 m over OM4 fiber [9]. A 100 m reach could be achieved with OM5 fiber. With the highest operating wavelength of 953 nm, OM5 fiber is a sub-category of OM4 that is optimized for SWDM transceivers. While the BiDi technology is approaching 100G/lane speed for 800G and 1.6 Terabit data rate at the transceiver level, the SWDM technology seems to have stalled with the highest data rate available at 100G to date. This observation leads to the proposal in the current paper for a new sub-category of OM4 fiber that is optimized for BiDi technology. Since the highest wavelength for BiDi transmission is 916 m, which is much closer to 850 nm than 953 nm. Therefore, a much larger quantity of OM4 fibers is available to meet the modal bandwidth needs at 916 nm. In Section II, we study the wavelength dependence of modal bandwidth for MMFs and present the new MMF concept optimized for BiDi transmission. In Section III we illustrate the results of using such fiber with comparison to OM5 fiber in 100G BiDi transmission and 800G BiDi transmission results using a BiDi optimized OM4 fiber over 100 m.

II. WAVELENGTH DEPENDENCE OF MODAL BANDWIDTH AND BIDI OPTIMIZED MMF CONCEPT

A. Wavelength Dependence of Modal Bandwidth

OM3 and OM4 fibers have been widely used with VCSEL transceivers for short reach communications. When the 40G BiDi transceivers emerged around 2014, only the EMB at 850 nm was specified for OM3 and OM4 fibers. It was not possible to define the transmission reaches without the knowledge of the EMBs of OM3 and OM4 fibers around 910 nm.

The modal bandwidth of an MMF is wavelength dependent and is generally peaked at certain wavelength λ_p, and falls off on either side. As is the nature of MMF making, each individual MMF can have its peak bandwidth different from others and the λ_p can spread out over a range. OM3 and OM4 fibers are required to meet the specified EMB values at 850 nm. However, this can occur when λ_p is located at a wavelength other than 850 nm while the peak bandwidth value can also vary from one fiber to another. Fig. 1 schematically illustrates the variation of the modal bandwidth in several different situations for OM4. To meet the EMB requirement of 4700 MHz·km at 850 nm, $\lambda_p$of OM4 fibers can be as low as about 810 nm and as high as around 890 nm. For OM3 fiber, the EMB at 850 nm is much smaller than OM4 so that it can have a much wider range of λ_p than OM4. One interesting aspect is that 50-µm core MMFs are required to meet the overfill bandwidth of 500 MHz·km at 1300 nm for legacy applications using LED. The 1300 nm requirement limits how low λ_p can go as compared to the case without such a requirement. In the examples within Fig.1, the OM4 with the low λ_p value yields a lower modal bandwidth at a longer wavelength (e.g., 910 nm) than the OM4 example with a high λ_p value. In addition, it is easier to reach higher bandwidth at a wavelength closer to 850 nm than at a wavelength far away from 850 nm. This is an intuitive picture to explain why different MMFs can have different EMBs at long wavelengths.

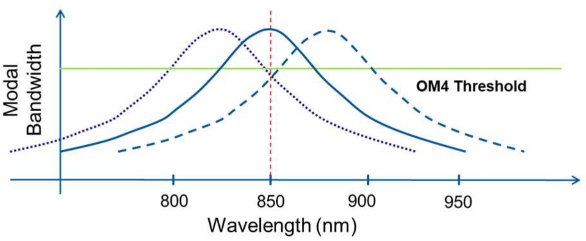

Fig. 1 The schematic illustration of OM4 with different peak wavelengths.

To gain such knowledge, a study was conducted at Corning in 2013 in response to the need for modal bandwidth information around 910 nm. With the understanding of the wavelength dependence of MMF shown above, we have developed a method to obtain the worst case EMB as a function of wavelength for OM3 and OM4 fibers. Out of a pool of available fibers, we have selected an OM3 and an OM4 with the lowest λ_p. We further measured the modal bandwidth of the fiber using a multi-wavelength bandwidth measurement setup as shown in Fig. 2. A tunable single mode light source is used, and the light is modulated by an intensity modulator with RF signals coming from a vector network analyzer (VNA). A modal conditioner was used to generate encircled flux launch condition, a typical VCSEL launch condition into the MMF under test. The transfer function of the fiber was measured, and the 3-dB bandwidth was retrieved over several wavelength points. The results are shown in Fig. 3 for both the OM3 and OM4 fiber. Although the measurements were done on a single OM3 and a single OM4 fiber, since toward longer wavelengths the modal bandwidth is mostly driven by material properties, the results are representative for the OM3 and OM4 in the worst case. Around 850 nm, the bandwidth values are more reflective of the bandwidth quality of the individual fibers we used for the measurements. In this case, they have values slightly above the OM3 and OM4 thresholds. The wavelength dependence of the OM3 and OM4 here is consistent with the IEC guidance released later in 2019 [10].

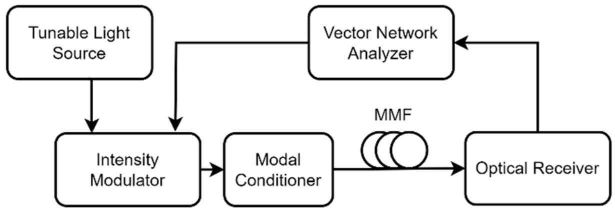

Fig. 2 The experimental setup for measuring

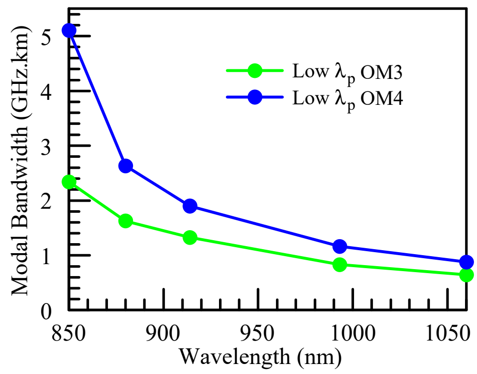

Fig. 3 Modal bandwidth vs. wavelength for a low λ_p OM3 and a low λ_p OM4.

B. Concept of BiDi Optimized MMF

The study in Section II.A shows the lower end of modal bandwidth that an OM3 and an OM4 can achieve. With such information, the system reach capability can be defined for all OM3 and OM4. It can also be learned that for the whole population of the OM3 and OM4 that a substantial portion of them can perform better than the worst case and be capable of longer system reaches. Ref. [11] illustrated the benefits for such fibers for the purpose of extended reach applications with system reach beyond those specified for OM3 and OM4 in general. This is the precursor of the BiDi optimized MMF concept proposed in the current paper.

As noted in the introduction, for 800G SR4.2 applications [9], the reach of OM4 is limited to 70 m while OM5 is specified to have a reach of 100 m. While both OM4 and OM5 meet the same EMB of 4700 MHz·km at 850 nm, it is the EMB at 910 nm that makes the difference as shown in Table 1. OM5 has an EMB of 3100 MHz·km at 910 nm in contrast of 1980 MHz·km for OM4 fiber. For comparison, the standard defined EMB values that OM4 and OM5 meet over the wavelengths from 840 nm to 953 nm are shown in Fig. 4. At 953 nm, OM5 has an EMB of 2470 MHz·km while at BiDi wavelength of 910 nm, its value is 3100 MHz·km. The EMB curve for OM4 agrees well with Fig. 3 for the overlapping wavelengths. The EMB curve for OM5 between 850 nm and 953 nm is broken into two segments, 850-930 nm and 930-

953 nm. The 930-953 nm corresponds to the highest wavelength window for SWDM transmission around the nominal wavelength of 940 nm. EMB in this wavelength window is maintained to have roughly the same total bandwidth when both the modal bandwidth and chromatic dispersion contributed bandwidth are included. On the other hand, the EMB values from 850 nm to 930 nm wavelengths were connected by a straight line. In this window the total bandwidth is higher than those in 930-953 nm window. While OM5 is capable of handling long wavelength operations, the definition focuses on its EMB at 953 nm, whereas the EMB between 850 nm and 930 nm has been specified to be functionally adequate in comparison to the 930-953 nm window. It has led to the omission of a large portion of OM4, which is equally capable in BiDi wavelength around 910 nm as OM5. Therefore, OM5 is more optimized for SWDM, and not required at 910 nm to meet bandwidth demands.

The concept of BiDi optimized OM4 fiber as listed in Table 1 is based on setting its EMB 3100 MHz km at 910 nm without regard to its EMB at 953 nm, other than meeting the value of general OM4. Even though this fiber has the same EMB at 910 nm as OM5, a larger quantity of OM4 meets the requirements, so this concept of BiDi optimized OM4 can enable a potentially large volume use of OM4 to meet the 100 m reach requirements for 800G BiDi transceivers, not limited to using OM5.

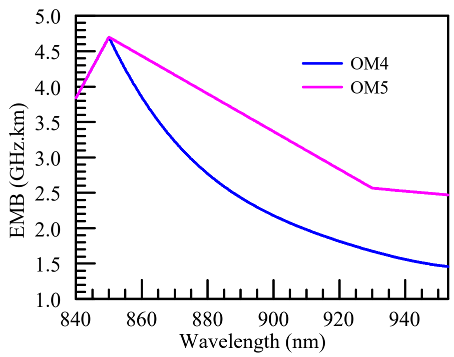

Fig. 4. The EMB guidance used by IEC 60793-2-10 for OM4 and OM5.

Table 1. The EMBs of several types of fibers at 850 nm and 910 nm wavelengths.

Fiber Type	EMB at 850nm (MHz·km)	EMB at 910 nm (MHz·km)
OM4	4700	1980
OM5	4700	3100
BiDi Optimized OM4	4700	3100

III. Transmisson Experiments and Implications to 800G BiDi Transmission

With the BiDi optimized OM4 concept proposed and defined in Section II.B, we now proceed to conduct transmission experiments to illustrate the performance of such fiber using a 100G BiDi transceiver and an 800G BiDi transceiver. A BiDi optimized OM4 has been identified meeting the definition in Table 1. It meets the 850 nm EMB requirement as an OM4 fiber. At 910 nm, it has EMB around 4 GHz.km, exceeding the 3100 MHz.km value listed in Table 1. It doesn't meet the OM5 EMB requirement at 953 nm. For the experiment in Section III.A, 150 m of such fiber was prepared along with 150 m of OM5 fiber with the fiber ends terminated with LC connectors, matching the connector interface for 100G BiDi transceiver. For the experiment in Section III.B, 100 m of 8-fiber cable based on the same BiDi optimized OM4 was prepared with LC connectors. It was used with short cables with a proper connector interface to connect to an 800G BiDi transceiver.

A. 100G BiDi Experiment.

In the past few years, VCSELs capable of PAM4 at 25-28 Gbaud/s (denoted as 50 Gb/s PAM4) per channel have been in volume production as used for 100G and 400G BiDi transceivers [12]. A 100G BiDi transceiver utilizes duplex LC connectivity and VCSELs at two wavelengths (850 nm/910 nm). 100G BiDi transceiver has the QSFP form factor and supports up to 70/100/150 m over OM3/OM4/OM5 fibers. Based on the same BiDi technology and 50G PAM4 optical modulation, 400G BiDi transceivers have been standardized by IEEE 802.3cm and have become commercially available. The 400G BiDi transceivers use an 8-fiber cable and have the same reach capability. Here we choose a 100G BiDi transceiver to conduct the experiment to simplify the fiber preparations. With 100G BiDi transceivers and 50G PAM4 optical data rate, OM5 offers 150 m reach, longer than OM4's 100 m reach. The BiDi optimized OM4 is expected to achieve the same system reach as it has the same EMB at 910 nm. Therefore, we use this as an example to illustrate the transmission capability of the BiDi optimized OM4 as compared to OM5 fiber.

In our experiment, we have used a 100G BiDi transceiver (AFBR-89BDDZ) made by FIT. We used a Viavi 100G optical network tester (ONT) (model number: ONT-603) with network traffic involved for the performance testing. The transmission testing over both fibers: a 150 m BiDi optimized OM4 and a 150 m OM5, passed with no error detected over 18 hours, the time we ran the tests.

We also obtained the eye diagrams to check the quality of the transmission in more intuitive way. Since by default the 100G BiDi transceiver does not work in a mode suitable for traditional bit error rate (BER) testing with PRBS bit sequence, we cannot use a sampling scope or a digital communication analyzer (DCA) to acquire the eye diagram as has been a common practice. Due to the lack of a clock recovery device, we cannot properly trigger the bit pattern. Instead, we have resorted to an alternative method using a real-time scope with the experimental setup shown in Fig. 5. The real-time scope is Tektronix DPO73304D. The optical receiver used is Discovery Semiconductor's Lab Buddy optical receiver (R409) for 25G transmission. By using a real-time scope, we can acquire a sequence of output signals. The optical data baud rate is 26.5625 Gb/s corresponding to an optical data rate at 56.125 Gb/s. We have used 100 GS/s for the data sampling. Using the tools in the communications toolbox of MATLAB, we have constructed the eye diagrams from the acquired data. The benefit of using a real-time scope is that we don't need the triggering signals or requiring PRBS bit pattern to obtain the eye diagrams.

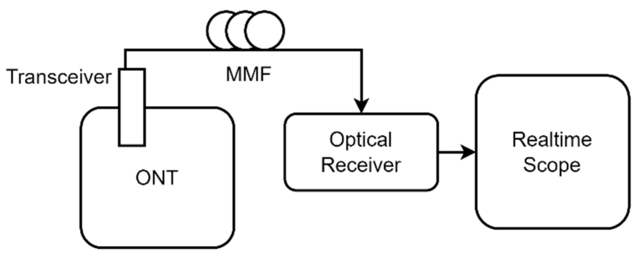

Fig. 5 The experimental setup of using a real-time scope to acquire received signals to reconstruct eye diagrams.

The eye diagrams as obtained from back-to-back (BtB) condition, with 150 m BiDi optimized OM4 and with 150 m of OM5 were shown in Fig. 6. The BtB condition is defined as using only 1 m long MMF jumper. It can be found that both BiDi optimized OM4 and OM5 show similar quality of eye diagrams as we have expected and these eye diagrams were not significantly degraded from the BtB condition.

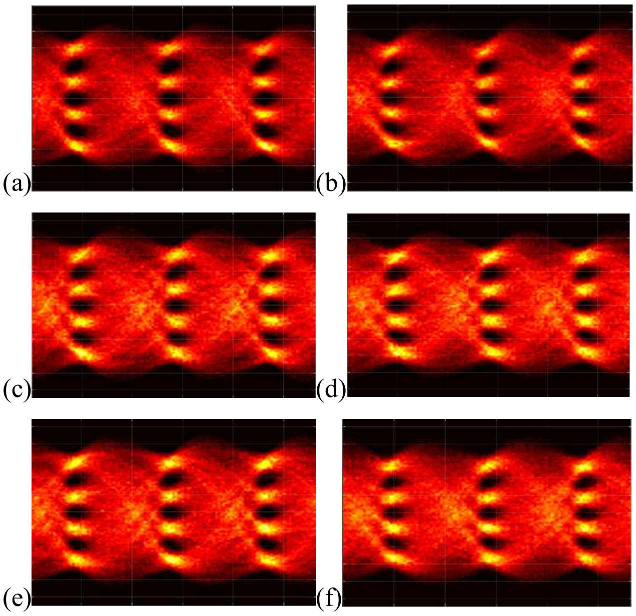

Fig 6 (a) 850 nm eye diagram in BtB condition; (b) 910 nm eye diagram in BtB condition; (c) 850 nm eye diagram with 150 m BiDi optimized OM4; (d) 910 nm eye diagram with 150 m BiDi optimized OM4; (e) 850 nm eye diagram with 150 m OM5; (f) 910 nm eye diagram with 150 m OM5.

B. *800G BiDi Transmission Experiment Using BiDi optimized OM4*

VCSELs capable of operation at 53-56 Gbaud/s (denoted as 100 Gb/s PAM4) have been actively developed to support another generation of enterprise and storage networks, switch-to-server and switch-to-switch connections in data centers as well as high performance computing and dedicated networks for machine learning applications [13]. The first transceiver to use 100 Gb/s PAM4 VCSEL is a 400G SR4 transceiver using 8-fibers operating at the wavelength of 850 nm. The Terabit BiDi MSA further specified and developed 100Gb/s PAM4 based 800G BiDi transceiver (referred to as 800G SR4.2) that utilizes both 850 nm and 910 nm with 8-fiber cables. It supports 45/70/100 m over OM3/OM4/OM5 fibers respectively [9]. Most recently, 800G BiDi SR4.2 transceivers have been announced utilizing Broadcom chip sets (DSP BCM87800, VCSEL AFCD-V84LP (850nm), AFCD-V84LQ (908nm) & PIN BPD3058-4) [14].

For 800G BiDi transceivers, the required link bandwidth from the fiber is 18 GHz. OM5 meets this requirement at 100 m. With BiDi optimized OM4 having an EMB of 3100 MHz·km at 910 nm, it should have the transmission reach as OM5. Using an 800G BiDi transceiver [14], we show the transmission test results below.

As a first step, we show the BtB optical eye diagrams at 850 nm and 910 nm. The experimental setup is shown in Fig. 7. An EXFO 800G bit error rate tester (BERT) (BA-4000) was used to drive the 800G BiDi transceiver mounted on an evaluation board (EVB). The optical signals from one fiber with either 850 nm light or 910 nm light are fed into a clock and data recovery (CDR) unit (Keysight N1077B), which is further connected with a DCA (Keysight N1092C) to obtain the optical eye diagrams. Fig. 8 shows the 100G PAM4 optical eye diagrams obtained from an 800G BiDi SR4.2 transceiver at the two BiDi wavelengths in BtB condition. The optical eye diagrams illustrate the baseline quality of the optical transmission. The transmitter and dispersion eye closure quaternary (TDECQ) was also measured, which gauges the quality of the optical transmitter with its optical link. TDECQ is the optical power penalty of the measured optical transmitter compared to an ideal transmitter. The lower the TDECQ value, the higher the quality of the measured transmitter. The TDECQ measurement uses SSPRQ 53GBd PAM4 pattern. The results show that with an extinction ratio (ER) set to 3.0 dB, both the 850 nm VCSEL and the 910 nm VCSEL show good TDECQs of 1.67 dB and 1.73 dB respectively.

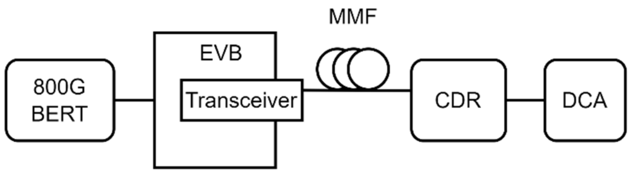

Fig. 7 The experimental setup for obtaining optical eye diagrams from an 800G BiDi transceiver.

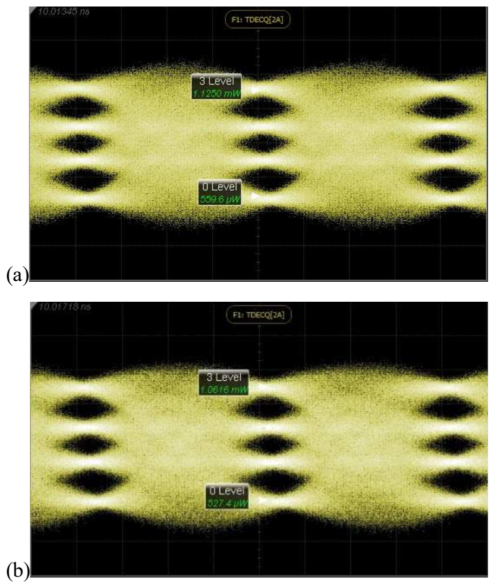

Fig. 8 (a) BtB 850 nm optical eye diagram obtained at room temperature; (b) BtB 910 nm eye diagram obtained at room temperature.

In the next step, we conducted the bit error rate (BER) testing to show the sensitivity over different received optical powers. The experimental setup is shown in Fig. 9. The 800G BERT provides the pattern signals (PRBS31Q 53GBd PAM4 pattern) to the transceiver through an EVB and received the returned signals for error detection. The optical signals from one lane of the transmitters either at 850 nm or 910 nm are fed into a variable optical attenuator (VOA). The attenuated signals are further fed into the receiver of the transceiver. Two fiber testing configurations were adopted. One is the BtB configuration and another one used a 100-m BiDi optimized OM4 fiber as described in Section II. By changing the amount of attenuation at VOA, we can obtain the BER vs. received optical power shown in Fig. 10. In BtB conditions, the transmission can reach BER below 1.5×10^{-8} and 7.0×10^{-9} at 850 nm and 910 nm respectively. With the 100 m BiDi optimized OM4, the transceiver can still achieve BER better than 6.4×10^{-8} and 3.2×10^{-8} at 850 nm and 910 nm respectively. In addition, BERs from both wavelengths are very close in terms of transmission performance after 100 BiDi optimized OM4, which is what we expected based on the EMB of the fibers. By further using forward error correction (FEC), the BER is reduced to zero.

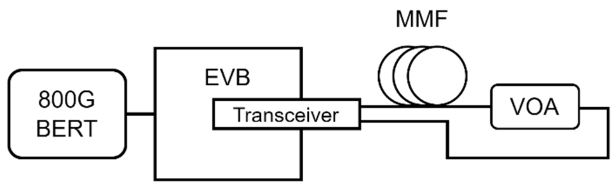

Fig. 9 The experimental setup for BER testing.

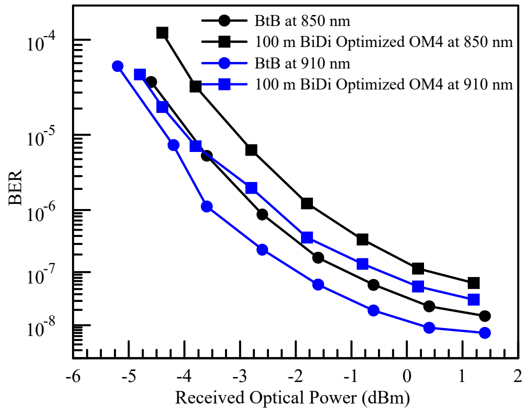

Fig 10. BER vs. received optical power measured at two fiber configurations at 850 nm and 910 nm wavelengths.

IV. Conclusions

BiDi-based VCSEL transceiver technology has advanced significantly in the past decade. It has moved from 40G, 100G, to 400G and now toward 800G and higher data rates. The underlying data rate per wavelength has moved from 20 Gb/s using NRZ modulation to 50Gb/s and now toward 100 Gb/s using PAM4 modulation. The system reach capability becomes limited with higher data rates due to the worst-case modal bandwidth of the MMFs at 910 nm. Even though OM5 can handle long wavelength operations, the EMB is optimized at what is needed at 953 nm, whereas the EMBs between 850 nm and 930 nm have been specified to be functionally adequate compared to the bandwidth in 930-953 nm. As a result, a large portion of OM4 that are equally capable at BiDi wavelength around 910 nm as OM5 has been left out. OM5 is more defined for SWDM transmission, but not required at 910 nm to meet bandwidth demands. Based on this observation, we propose the concept of BiDi optimized OM4 fiber to have the same EMB as OM5 at 910 nm. This would include a much larger portion of fibers from the OM4 population. The BiDi optimized OM4 in general does not meet the OM5 EMB threshold at 953 nm.

Using 100G BiDi transmission as an example, we showed that the BiDi optimized OM4 can transmit over 150 m, same as OM5 fiber. Using the newest developed 800G BiDi SR4.2 transceiver, we have shown that the BiDi optimized OM4 fiber performs well over 100 m transmission with BER better than 6.4×10^{-8} and 3.2×10^{-8} at 850 nm and 910 nm respectively. There is plenty of margin for FEC to further improve the transmission performant to bring the BER to essentially zero.

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