400G Coherent and IMDD Transmission over OM1 Multimode Fiber Links with Multiple Connector Junctions Using LP01 Mode-Matching Adapters

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***Abstract*—We studied and demonstrated the fundamental mode transmission over OM1 multimode fiber over several connector junctions enabled by LP_{01} mode matching adapters using 400G coherent and IMDD transceivers, i.e., 400G ZR and LR4 transceivers.**

Keywords— single-mode transmission; fundamental mode transmission; multimode fiber; high data rate; mode matching adapter; OM1 fiber

I. Introduction

Multimode fibers (MMFs) have been widely used with vertical cavity surface-emitting laser (VCSEL) based transceivers for short-range communications in various settings, from data centers to in-building networks. However, as data traffic continues to grow, there is a need to increase transmission data rates. Unfortunately, MMF links with lower bandwidth, such as OM1 and OM2 fibers, can be challenging to upgrade to higher data rates, leading to an increasing adoption of single-mode fibers for short-range communications, especially in hyperscale data centers. Nevertheless, it is still desirable to upgrade to higher data rates over legacy MMF links where the fibers are buried inside buildings and are difficult to replace. To address this need, various approaches have been proposed, including using offset launch [1,2], center launch [3,4], and mode matching fundamental mode transmission [5-9].

Mode matching fundamental mode transmission is considered the most robust approach, as it provides the highest modal bandwidth for data transmission. In Ref. [8], a modal conditioning single mode fiber (MCSMF) was designed, fabricated, and packaged into a compact adapter, with the mode field diameter (MFD) matching that of the fundamental mode of 50-µm core OM2 MMF. The mode-matching adapter (MMA) functions as an LP_{01} mode launch fiber at the transmitter side and as a mode filter at the receiver side to receive only light from the LP_{01} mode of the MMF. Using 100G CWDM4 transceivers, successful 100G transmission over 1-km of OM2 fiber was demonstrated with such adapters. In [9], the research was extended to consider the tolerance of various parameters for practical use of such modal adapters in real-world applications. The key parameters include the tolerances of the MFD mismatch and the connector offset between the MCSMF and the MMF, with both tolerances found to be around 2µm. As a result, the same adapter fiber can enable fundamental mode transmission over both OM2 and an earlier MMF, OM1 fiber. It has been demonstrated that the use of an MMA can achieve fundamental mode transmission not only at 100G using a 100G CWDM transceiver but also at 400G using a 400G LR4 transceiver [9].

In a very recent work, the study has been extended to the situation when the MMF link includes multiple connector junctions for OM2 MMF [10]. For fundamental transmission over MMF, the connector junctions can introduce coupling from the fundamental modes to higher order modes and vice versa, resulting in degraded transmission performance. MMF links are often deployed with connectors in the middle with less than 3 pairs in most cases. The work in the current paper is closely related to that in [10]. Instead of using OM2 fiber, we study the effect of multiple connector junctions on LP_{01} transmission over OM1 fiber.

An OM1 fiber has a 2% core delta and a 62.5-µm core diameter. OM1 fiber has been largely superseded by newer fiber types such as OM2, OM3, and OM4, which have higher bandwidth and longer transmission distances. However, OM1 fiber is still used in some legacy installations. Similar to the work done for OM2 with multiple connector junctions in [10], we have used a set of OM1 cables that were commercially purchased. We have used a 200 m long OM1 cable with up to six 20 m long OM1 jumpers. We measured and analyzed various aspects including the connector offset distribution of commercially available OM1 cables, multi-path interference (MPI) and transfer functions. We also conducted experiments on fundamental mode transmission with up to six connector junctions or seven spans enabled by LP_{01} mode matching adapters using 400G coherent and IMDD transceivers, i.e., 400G ZR and LR4 transceivers.

II. Mode Matching adapter for Both O-band and C-band Transmission

In [8], a simple, low-cost fiber-based approach was presented to realize fundamental mode transmission in MMFs through a compact adapter with a connector form factor. Since most single-mode transceivers for 10 km reach or less operate in the O-band, or between 1260 nm and 1360 nm, the design was optimized around 1310 nm wavelength. At 1310 nm the MFD of the LP_{01} mode of a typical OM1 MMF is around 13.6 µm, while the MFD of a typical standard single-mode fiber (SSMF) is around 9.2 µm. The mismatch of MFDs between the two fibers is significant and can cause high insertion loss, as well as significant MPI [11]. An MCSMF was designed to have its MFD matching that of the LP_{01} mode of 50 µm core MMF and packaged in a pass-through adapter illustrated in Fig. 1(a). The adapters are then used in both transmitter side and the receiver side to serve as a mode launcher and a receiving filter respectively as illustrated in Fig. 1(b).

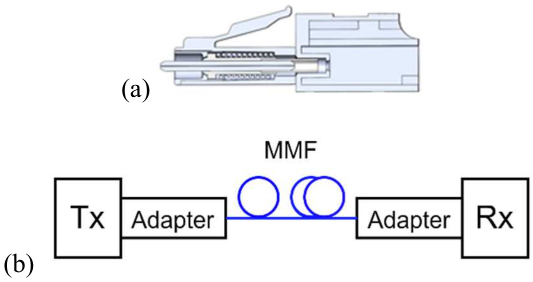


Figure 1. (a) Cross section view of the MMA in LC connector formats; (b) The schematic diagram of the optical transmission configuration involving an MMF sandwiched between two MMA.

In the current work, we also conduct coherent transmission, in which case the operating wavelength is in the C-band, or between 1535 nm and 1565 nm. Due to the intrinsic property of MCSMF, if it matches the LP_{01} MFD of MMF around 1310 nm, it also matches approximately the LP_{01} MFD of MMF around 1550 nm well as shown in Table I. The LP_{01} MFD of OM1 fiber at 1550 nm is 14.7 µm. The MFD of MCSMF we use has MFD of 16.0 µm, reasonably close to that of MMF. Note that the MFD of MCSMF can have around 2 µm tolerance as found in [9]. On the other hand, SSMF has been used to form SMF-MMF-SMF links despite that its MFD is highly mis-matched with the MFD of MMFs. Therefore, we also include the use of SSMF for fundamental mode transmission for comparison.

TABLE I. MFD OF SEVERAL TYPES OF FIBERS

	LP01 MFD @1310 nm (µm)	LP01 MFD @1550 nm (µm)
OM1	13.6	14.7
OM2	14.5	15.8
MCSMF	14.0	16.0
SSMF	9.2	10.3

III. CONNECTOR CORE OFFSET DISTRIBUTION

The current study is based on using OM1 cables commercially available today. The connector quality has improved over the years although the standard (IEC 61753-1) allows even a few microns of offset based on the technology available in earlier times. We purchased a set of OM1 cables with 20 m length and cables with 200 m length for the current study. The connector type used is the LC connector. We measured a total of 36 LC connectors using a commercial system (Data-Pixel, Koncentrik-V2). The measured fiber core center positions are illustrated in Fig. 2(a), which has the information of core center offset relative to the ferrule center and orientation. Using this information and assuming for a connector pair the relative orientation can take a random value, we can generate the connector core offset distribution for a very large set of cases through Monte Carlo simulations shown in Fig. 2(b). The histogram of the simulated core offsets is shown in Fig. 3(a). The cumulative probability is shown in Fig. 3(b). It can be found that the distribution is peaked at 0.3 µm and 90% of the cases have the core offset less than 1.6 µm. The results here are slightly better than the batch of connectors for OM2 cables used in [10]. Since the underlining technology to make the connectors is the same, we interpret here that the difference is only indicating the fluctuation from one batch to another batch, not a fundamental difference between the OM1 and OM2 cables.

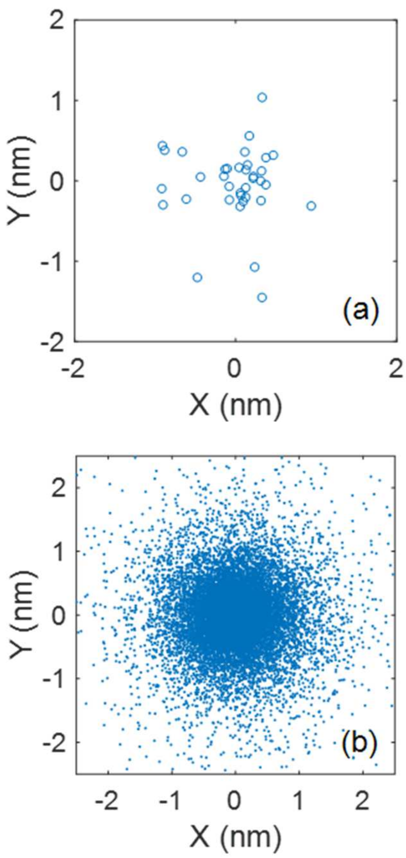


Figure 2. (a) Measured core center positions of 36 OM1 fiber connectors; (b) Simulated core position distribution of OM1 fiber connectors.

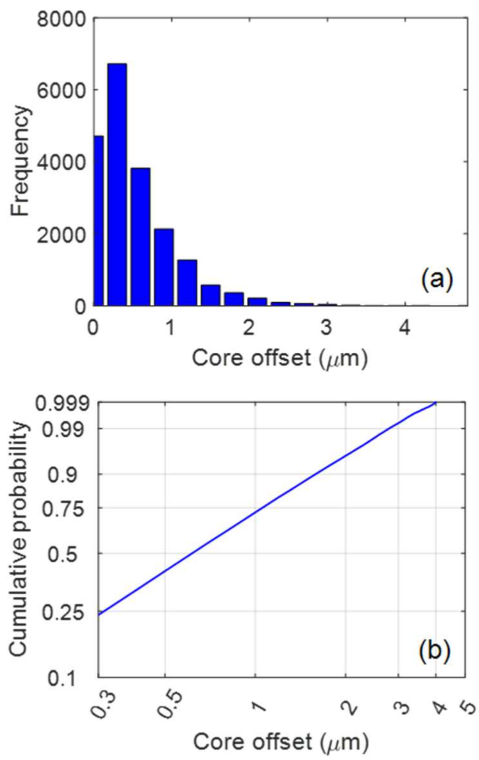


Figure 3. (a) Histogram of the simulated core offsets in connector junctions; (b) Simulated cumulative probability distribution random mated core offset based on the measurements of the OM1 fiber connectors.

IV. CHARACTERIZATION OF MPI AND TRANSFER FUNCTION OF THE MMF LINKS

In this section, we present key link characteristics, such as MPI, and the transfer function, which indicates the bandwidth of the link. The link is formed by multiple 20 m OM1 cables with one 200 m OM1 cable. The number of OM1 cables varies from 1 to 7 so that the number of connector pairs varies from 1 to 6 and the fiber length is: N × 20m + 200 m, N= 0, 1, … 6. The link configurations vs. number of spans are shown in Table II. The study focuses on distances between 200 m and 320 m since they cover the majority of MMF transmission applications. However, the fundamental mode transmission is capable of much longer distances.

TABLE II. MMF LINK CONFIGURATION VS. NUMBER OF SPANS

Number of Spans	Link Configuration
1	200 m OM1
2	1×20 m OM1 + 200 m OM1
3	2×20 m OM1 + 200 m OM1
4	3×20 m OM1 + 200 m OM1
5	4×20 m OM1 + 200 m OM1
6	5×20 m OM1 + 200 m OM1
7	6×20 m OM1 + 200 m OM1

A. MPI Measurements and Results

MPI is one key impairment that can happen in the fundamental mode transmission over MMF involving multiple connector junctions. With a small amount of light from the fundamental mode launched into higher order modes (HOMs) at the first connector junction and coupled back to the fundamental mode at the second connector junction, power fluctuations due to MPI occur leading to a transmission power penalty [8, 9]. Adding more connector junctions for the MMF allows for more back and forth coupling between the fundamental mode and HOMs. The factor affecting the MPI is MFD mismatch between the modal adapter fiber and the MMF and connector offsets at connector junctions. When more connector junctions are introduced, the MPI penalty is expected to increase in general. We followed the experimental scheme in Ref. [8] to conduct the MPI measurement for the link. Narrow linewidth CW laser sources with wavelengths at 1310 nm and 1550 nm were used respectively for the MPI measurements at the two wavelengths. The MMF under test was sandwiched between two MMAs. To capture maximum MPI information allowed by the system in a relatively short period of time, we emulated the environmental changes by introducing perturbations to the fiber such as scrambling the state of polarization at the input and shaking several segments of the cables. The optical power over time was measured. The ratio of the lowest received power P_{low} detected from the distribution to the average received power P_{avg}, defines the MPI loss for a given link, which gauges the loss of optical power from the MPI effect,

$$MPI\ \ Loss = -10 \cdot \log_{10}(P_{low} / P_{avg}) \qquad (1)$$

MPI causes optical power variations over time due to slow environmental changes, such as temperature changes, or mechanical perturbations to the fiber, resulting in a power penalty and reduced optical signal-to-noise ratio at the receiver. For a large number of interference terms, or when the mode coupling occurs in the MMF in a distributed fashion, the MPI may also be manifested more as a noise term that can degrade signal quality.

We have measured the links illustrated in Table II. The modal adapter can either be MMA or SSMF. The MPI losses are shown in Fig.4. It can be observed that MPI losses with the MMA are in general smaller than those with SSMF, with one exception at 1550 nm with 2 spans. However, compared to the study in [10] for OM2 fiber, the MPI loss difference between the configurations with MMA and SSMF here with OM1 fiber is significantly smaller. The maximum MPI loss for all number of spans is 1.2 dB, compared to maximum values around 2.6 dB and 4 dB at 1310 nm and 1550 nm, respectively, for the OM2 study [10]. The difference in MPI behavior between OM1 and OM2 fibers may be due to several factors. This batch of OM1 connectors has a smaller connector offset distribution than the OM2 connectors used in the previous study [10]. In addition, OM1 fiber has a higher core delta at 2% vs. 1% for OM2 fiber, and the core diameter is also larger at 62.5 µm as compared to 50 µm for OM2 fiber. Therefore, OM1 fibers support a greater number of modes than OM2 fibers or MMFs with 50 µm core. The higher number of modes in OM1 with different group delays may induce more beating in MPI between different modes. This may wash out the interference more than in the case of OM2, which has a lower number of modes [11].

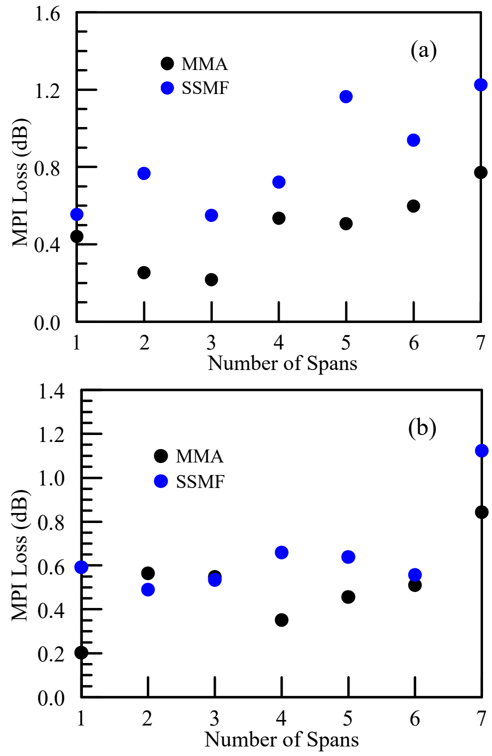


Figure 4. MPI Losses measured at 1310 nm in (a) and 1550 m in (b).

B. Transfer Functions of the MMF Links

Experiments were conducted to demonstrate the bandwidth performance for fundamental mode transmission in MMFs by measuring the transfer functions of the fibers under test at 1310 nm and 1550 nm, with and without the modal adapters. The experimental setup is shown in Fig. 5. A narrow linewidth continuous-wave laser at 1310 nm or 1550 nm wavelength is intensity modulated with the modulation frequency swept by a vector network analyzer (VNA). The device under test (DUT) is the MMF link under several conditions. They include the OM1 cables with modal adapters at both ends. The modal adapters can either be MMA or SSMF jumpers. We measured the transfer functions with both types of modal adapter. In another testing configuration, we measured the transfer functions of the MMF link with a typical multimode launch condition, i.e., encircled flux (EF) condition using a modal conditioning device called ModCon from Ardent Photonics. With the typical multimode launch, the modal bandwidths determined at 6 dBe or 3 dBo level are 10.4 GHz at 1310 nm and 2.7 GHz at 1550 nm, respectively with MMF length of 320 m. Note that the bandwidth is defined at the drop of 6 dBe (defined by 20·log operator) or 3 dBo (defined by 10·log operator) from the level at zero frequency. The bandwidths scaled to 1 km are 3330 MHz·km and 874 MHz·km at 1310 nm and 1550 nm, respectively. At 1300 nm, the overfill bandwidth is only expected to reach 500 MHz·km, which means the measured bandwidth is much higher than what is normally expected. Note that the OM1 cables used here were commercially purchased. As illustrated by Fig. 6, with either type of modal adapters, the transfer functions remain flat for all measured configurations including the highest number of spans of 7, suggesting that the modal bandwidths are very high. Over the 12 GHz frequency range we conducted the measurements, the transfer functions only dropped by less than 1.3 dBe from the zero frequency. The bandwidths of the link with the modal adapters would easily be more than 20-30 GHz, sufficient for 50 Gbaud transmission.

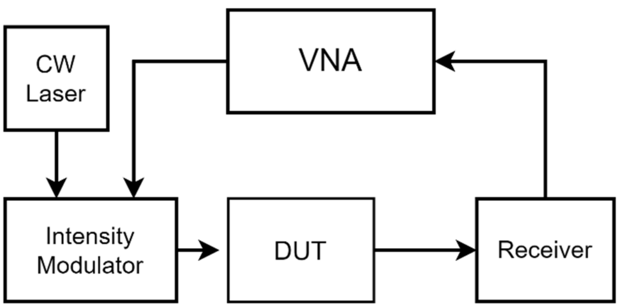


Figure 5. Experimental setup for the transfer function measurements.

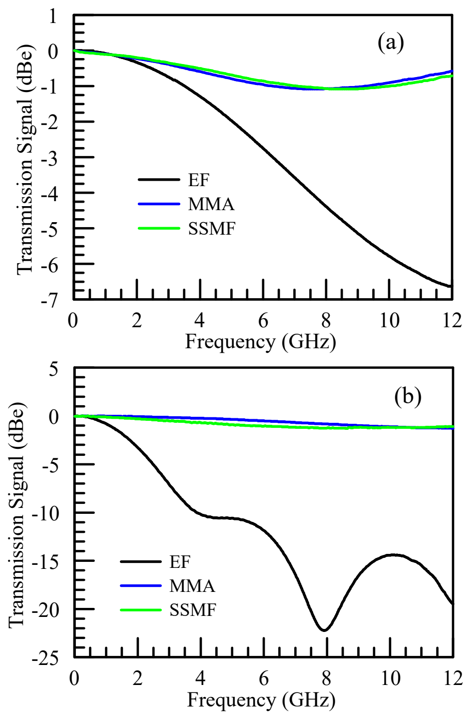


Figure 6. The measured transfer functions at 1310 nm in (a) and at 1550 nm in (b) for MMF link with 7 spans.

V. Transmission Experiments

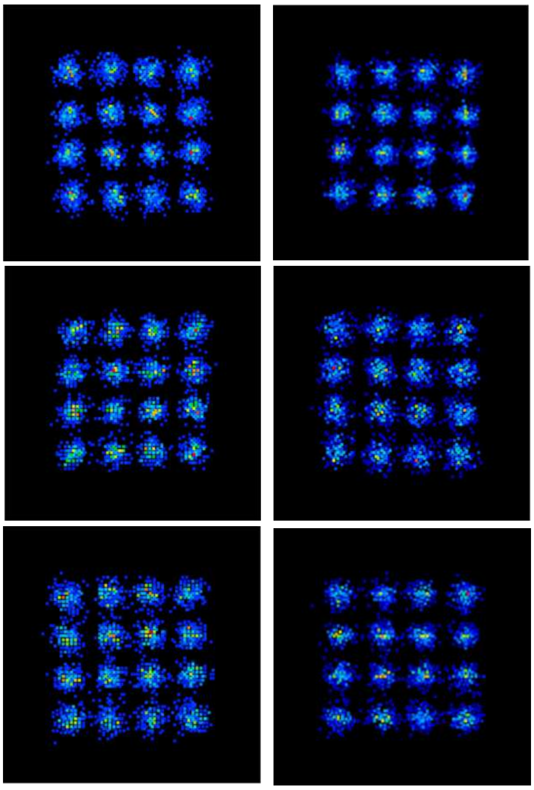
We further conducted transmission experiments with both IMDD and coherent detection to verify the system level performance of the MMF links with the modal adapters. For the IMDD transmission, we used a 400G LR4 transceiver (LMQ3928-PC+ from Hisense) rated for 10 km transmission over standard single mode fiber. It has the QSFP-DD form factor transmitting 4×100G signals with each wavelength carrying 106G PAM4 signals. For the coherent transmission, we used a 400G ZR transceiver (LCQ6380S-PC+ from Hisense) for the current experiment. The optical signal is based on the dual polarization 16-quadrature amplitude modulation (DP-16QAM) format with a symbol rate of 59.84375 Gbaud (478.750 Gbps) per polarization. Both types of transceivers have the QSFP-DD form factor and use LC connectors. 400G ZR is specified by OIF for distances up to 120 km [12]. The 400G transmission performance was evaluated using a Viavi Optical Network Tester (ONT-804). We used the 7 MMF link configurations in Table II with modal adapters. During the testing, several portions of MMF cable were shaken by hand to introduce external perturbations and therefore MPI penalties.

TABLE III. Transmission Testing Results

Spans	ZR w/SSMF	ZR w/MMA	LR4 w/SSMF	LR4 w/MMA
1	pass	pass	pass	pass
2	pass	pass	pass	pass
3	pass	pass	pass	pass
4	pass	pass	pass	pass
5	pass	pass	pass	pass
6	pass	pass	fail	fail
7	pass	pass	fail	fail

The transmission results are shown in Table III. For the IMDD transmission, using either MMA or SSMF type of modal adapter, the transmission passed with up to five spans of the cable or with four connector pairs. For 400G ZR transmission, all tests passed with up to 7 spans. Here we observed that the performance of using either MMA or SSMF type of modal adapters is very similar. We attribute this to several reasons. As found in Section IV, both the MPI loss level and the difference between using either modal adapter are relatively small compared to the case in [10] so that MPI loss penalties are not dramatic when the number of spans is increased. Another observation in Section IV is that the bandwidth of OM1 fibers used at 1310 nm shows much higher value than they are usually expected at around 500 MHz.km, which can explain better than expected performance.

On the other hand, the 400G coherent transmission using 400G ZR transceiver shows robust performance over all spans, consistent with the observations in [10] when using OM2 cables. The transmission performance using coherent transceiver was robust. This is not a surprise considering that the system was designed for long distance transmission with robust digital signal processing capabilities. The work here extends previous work on using coherent transceivers over MMF to OM1 fiber and with multiple connector junctions. Note that one recent work conducted 400G coherent transmission over a short MMF link of 300 m using SSMF as modal adapters with up to 3-6 μm offset from one front-end connector junctions [13]. Coherent transmission over MMF was also demonstrated more than a decade ago through SSMF launching over several hundred kilometers of MMFs [14-16]. Such coherent transceivers were not designed for such short distance transmission. However, working toward 800G, OIF has established a task force developing a pluggable coherent transceiver for up to 10 km transmission with lower cost [17]. Such transceivers are also referred to as coherent-lite transceivers that have margin less than coherent transceivers for long-haul transmission but adequate for such short reach transmission.



(a)

(b)

(c)

Figure 7. X- and Y-polarization constellation diagrams obtained from (a) B2B condition; (b) 2 ×20 m OM1+ 200 m OM1 with MMA in both ends; (c) 2 × 20 m + 200 m OM1 with SSMF in both ends.

We also obtained the constellation diagrams for the coherent transmission to gain insights on the details of the transmission performance. We used a ZR transceiver from another vendor from which we can acquire the constellation diagrams through an evaluation board. As examples, we show three sets of constellation diagrams for both the x-polarization and y-polarization 16QAM signals obtained from back-to-back (B2B), 2 × 20 m + 200 m of OM1 fiber with MMA in each end, and 2 × 20 m + 200 m OM1 fiber with SSMF at each end. We observe little difference in the constellation diagrams for all cases, which is in contrast of the case in [10] where slight degradation of constellation diagrams was observed for the case with SSMF as modal adapters. We attribute this to the similar MPI penalty observed for MMA and SSMF type of adapter in Section IV.

VI. Conclusions

We have studied fundamental mode transmission over 62.5-µm core diameter OM1 MMF with up to six connector junctions or 7 spans as enabled by LP_{01} MMA using 400G coherent and IMDD transceivers, i.e., 400G ZR and LR4 transceivers respectively.

The connector offset distribution of commercially available OM1 cables was measured and analyzed. The majority of connector offsets are within 2 µm, and the distribution is peaked at around 0.3 µm, which provides a baseline for the current analysis. The connector offset distribution for OM1 connectors studied in the current work is slightly better than those used in [10].

The link level performance as dictated by MPI and transfer functions was studied. MPI losses with the MMA were in general smaller than those using the SSMF type of modal adapter. The maximum MPI loss for all number of spans was 1.2 dB, compared to the maximum values around 2.6 dB and 4 dB at 1310 nm and 1550 nm, respectively, for the earlier OM2 study [10].

We also measured the transfer functions in several different configurations. We found that with either modal adapter, the bandwidth of the link is very high, sufficient to support the 400G transmission based on IMDD or coherent transmission. On the other hand, the OM1 fiber used for this study showed unusually high modal bandwidth at 1310 nm, which is not representative of general OM1.

Transmission experiments over multiple spans formed by concatenating 20 m cables and a 200 m cable were demonstrated. We found that the connector quality from this batch of commercial cables can support up to 5 spans for 400G LR4 transmission using either MMA or SSMF type of modal adapters. Coherent transmission using a 400G ZR transceiver was very robust passing the test even with 7 spans OM1 cables for both types of modal adapters.

Based on the study in this paper using MMA and SSMF types of model adapters for OM1 cables, as well as the study in [10] for OM2 cables, MMA adapters overall demonstrated better MPI and transmission performance. Some more subtle differences between OM1 and OM2 links may be explained by connector offset distributions and fiber modal bandwidth values.

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