Low-loss Mode Field Adapter Using Reverse Tapering for Fundamental Mode Transmission over MMFs

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Abstract: We demonstrate a low-loss mode field adapter based on reverse tapering for fundamental mode transmission in MMFs, which enables 7-dB MPI reduction and 2-dB Q factor improvement, compared with the center-launching situation. © 2022

1. Introduction

Multimode fibers (MMFs) are widely used in data center interconnection. Vertical-cavity surface-emitting laser (VCSEL)-based transmission systems over MMFs have been a low-cost solution for short-reach communications. As traffic grows, so does the transmission data rate, posing additional issues for short-reach systems utilizing VCSELs. Severe intermodal dispersion is the main reason for the limited transmission distance of MMF links, thus limiting the number of modes propagating in MMFs can improve the transmission capacity and distance of the MMF communication systems to some extent. To do so, fundamental mode (FM) transmission over MMFs has been studied by using a single-mode laser.

Several approaches are proposed to realize FM transmission. One approach is to use universal fibers [1]. Modal conditioning single-mode fiber with a mode field diameter (MFD) of the FM roughly matching that of MMF for FM transmission, acting as a bridge between single-mode fiber (SMF) and MMF when the FM mode is launched using a single-mode transceiver. Another is known as center-launching [2], where an SMF is axially aligned spliced to MMF at the input to excite the FM of the MMF and an SMF at the output to filter out higher-order modes (HOMs). In addition to insertion loss at the spliced point, another aspect of interest for FM transmission is multi-path interference (MPI) [3]. Different from that in SMF links, the MPI can also appear in MMF links due to the signal power coupling from the FM to HOMs, and back. The small amount of the excited HOMs can cause power fluctuation due to coherent interference with the FM and therefore leads to power penalty. The difference in delay between different paths can also cause inter-symbol interference (ISI) related penalty.

In this paper, we demonstrate a low-loss mode field adapter (MFA) to match the FM at the interface of an SMF and an MMF, by reverse tapering the SMF and thermally expanding its core [4]. Compared to center-launching, the MMF transmission system using the low-loss MFA is significantly improved with an average 7-dB MPI reduction and 2-dB Q factor increment. This exhibits great potential to provide a practical and cost-effective solution for data center applications.

2. Principle and Fabrication

Insertion loss and HOM excitation are mainly caused by MF mismatch between two different fibers. Regular MMFs used in data centers are OM3-type with an MFD of 14.5 μm at 1310 nm, while regular SMFs have an MFD of 9.2 μm at the same band [2]. The SMF pigtail of a transmitter serves as a launch fiber to excite the LP_{01} mode of the MMF. To reduce coupling loss and the HOM excitation, we need to not only enlarge SMF MF but also expand its core to match the MMF. Firstly, an SMF is adiabatically thickened by reversely tapering. Then, by heating the fattening part of the fiber, the dopants in the core diffuse into the cladding, forming a Gaussian shape graded-index distribution, which further expands the MF of the FM in this SMF. According to the diffusion characteristics of the dopants, the thermally expanded core (TEC) fiber can be regarded as a graded-index fiber. The reflective index profile of the TEC fiber can be found in [5].

We use a commercial optical fiber splicer (Fujikura, LZM-100) to perform these two operations on an SMF to fabricate the MFA. A CO_2 laser is employed in this fusion splicer, which enables highly repeatable and smooth heating processes. All the parameters of the reverse tapering process are programmable to taper any fiber with micron-level accuracy. The cladding diameter of the SMF is increased to 180 μm, and its MFD is enlarged to 13.3 μm in the same ratio. The width of the heating zone provided by the CO_2 laser is about 4.5 mm on the fiber, which is ideal for the TEC process. We heat the reversely tapering part of the fiber for a few minutes until the MFD matches that of the MMF. After that, the fiber is cut at the thickest point to fabricate an MFA. Its end view and side view are shown in Fig. 1. The MFD of the MFA is measured to be 14.5 μm at 1310 nm, and the total loss introduced by the above heating process is 0.02 dB, which means the tapering and heating process of MFA fabrication is adiabatic.

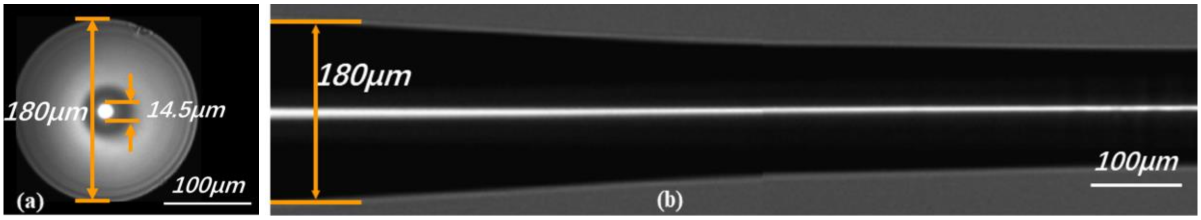

Fig. 1. (a) The end view and (b) the side view of the MFA.

3. Test and Measurement

Apart from insertion loss, the MPI effect due to HOMs is the main limitation in FM transmission over MMFs. We use spatially and spectrally resolved imaging (S^2) as the approach to visualize the mode content and qualify MPI levels in MMFs. S^2 technique uses both the spatial and the spectral interference produced by all the guided modes in MMFs to simultaneously image all the supported modes and return their MPI levels by processing the Fourier transform amplitude [6].

Based on the S^2 system [7], we conducted a detailed measurement of the MPI in two configurations, MFA-MMF and SMF-MMF (center-launching). The tunable laser terminates with an MFA at the end of an SMF pigtail. The MFA is spliced to a 10-m OM3-type MMF with an axially aligned splice to ensure MF matching at the connection. The S^2 system can provide a 12.5 ps/m differential modal group delay (DMGD) measurement range, enough to characterize the MPI levels of mainly HOMs in the 10-m MMF. As a comparison, the SMF pigtail is cleaved at the unprocessed part and reconnected to the MMF fiber with an axially aligned splice, which is the so-called center-launching [2].

The result is shown as a Fourier transform (FT) amplitude diagram concerning DMGD in Fig. 2(a). The peaks in the line graph represent the HOMs of interest and relate to the MPI [6]. MPI here is defined as the intensity ratio of the HOMs to the FM. Because the powers of the HOMs are much smaller than that of the FM, we use a band-pass filter to obtain the MPI of the HOMs. The center values of these band-pass filters are set as the abscissa corresponding to the peaks, which are the DMGDs of HOMs. The bandwidth of the band-pass filters can be set to a small range on both sides of the peaks. By integrating the relative power within filter bandwidth around each peak, the MPI and the mode distribution of each HOMs in two configurations are calculated in Fig. 2(b-d). The decreased MPI values of LP_{11}, LP_{21}, and LP_{02} are 7.14 dB, 7.15 dB, and 7.45 dB respectively, indicating that much less power of HOMs is excited at the splice. Compared to the center-launching situation, the power distributions of LP_{11} and LP_{21} in MFA-MMF are more concentrated, which means more launched power is coupled into LP_{01} mode. The insertion loss of MFA is less than 0.2 dB, much lower than that using center-launching with an insertion loss of 1 dB, which further emphasizes the benefits of MFAs in lowering mode mismatching.

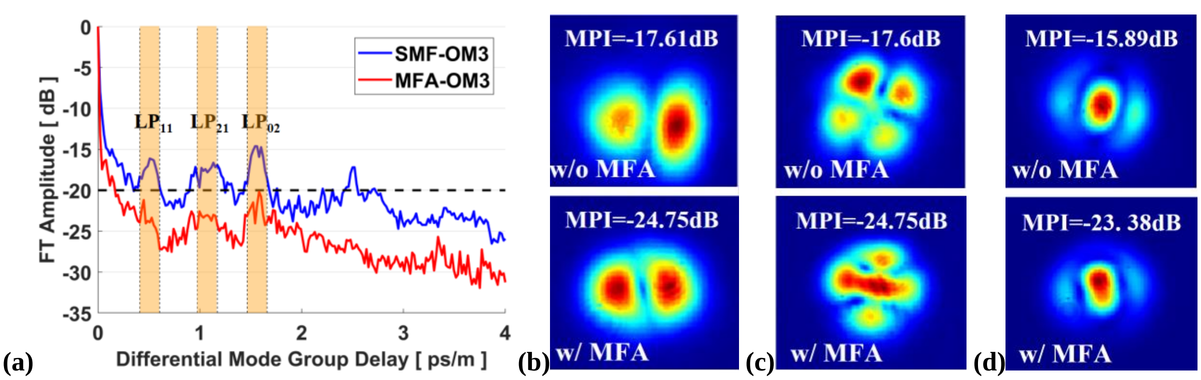

Fig. 2. (a) FT Amplitude vs. Differential Mode Group Delay for the S^2 measurement over a 10-m OM3-type MMF, with 3 labeled areas standing for LP_{11}, LP_{21}, and LP_{02}. Their MPI and mode distributions are illustrated in (b-d).

4. Transmission Results

To validate the performance of MFA in FM transmission, eye diagrams are measured over 1-km MMF at 1310 nm. As illustrated in Fig. 3(a), 10-Gbaud OOK signal is transmitted using either MFA or 1-m SMF pigtail spliced to the input of the MMF to excite FM in MMF, while another 1-m SMF pigtail is spliced to the output of the MMF to filter the HOMs and ensure that only the FM can pass through. The MMF used here is OM3 but it can be any MMF with a 50-μm core diameter. The system with SMF pigtail shows a worse eye diagram (Fig. 3(b)) with 6.17-dB Q factor and suffers significant penalties due to the insertion loss and MPI, while the system with MFA spliced to MMF shows a 9.12-dB Q factor (Fig. 3(c)), indicating that the MFA can improve the transmission efficiency of FM and reduce the power loss caused by mode field mismatch.

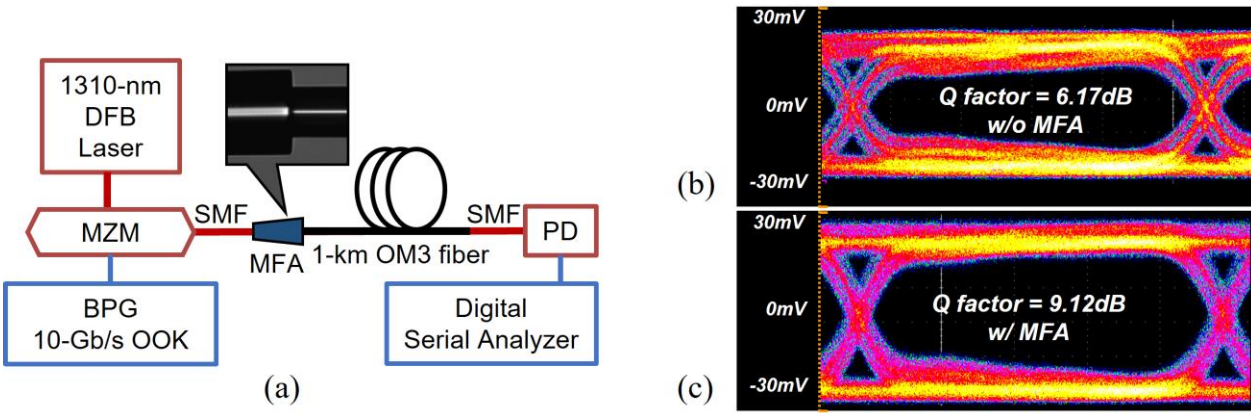

Fig. 3. (a) FM transmission over 1-km OM3-type MMF fiber at 1310 nm and the measured eye diagrams for (b) SMF-MMF and (c) MFA-MMF.

5. Conclusion

We have demonstrated a new approach to improve the mode field matching in FM transmission over MMFs, using reverse tapering and thermally expanded core technique. The MFD of SMF has been enlarged from 9.2 μm to 14.5 μm. We have conducted a detailed measurement of the MPI based on the S^2 system. The 10-m MMF with an MFA shows a lower MPI level and less insertion loss than that of the directly spliced device. We also measured the eye diagrams to evaluate the performance of FM transmission. A 10-Gbaud OOK signal has been transmitted over 1-km MMF at 1310 nm. The system with MFA performs better signal quality. The proposed mode field matching technique can provide a simple and robust way for FM transmission over MMFs. The size of MFA is small enough for integration, which is a potential solution to optimize the mode coupling efficiency of MMF links with SM transceivers.

6. Acknowledgements

The work was supported by National Key R&D Program of China under grant 2019YFB1803501 and National Natural Science Foundation of China (NSFC) under grant 61775165.

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