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Increased Transmission Bandwidth of Multimode Fiber by using Mode-Field Matched Center Launching Technique

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Abstract The mode-field matched center launching technique can drastically increase the transmission bandwidth of multimode fiber (MMF). In this paper, we evaluate the frequency response of the MMF link using this launching technique, and demonstrate the transmission of 10-Gb/s signal over 12.2 km of MMF.

I. Introduction

Recently, there have been growing interests in the high-speed multimode fiber (MMF) transmission for the use in the next-generation local area network (LAN). It has been reported that the maximum bit-rate and transmission distance of a MMF link depends highly on the launching conditions. Thus, extensive studies have been carried out to develop the proper launching techniques [1]-[3]. Recently, we have proposed the mode-field matched center launching technique for this purpose [4]. This technique requires matching the beam profile of the incident light to the fundamental mode of MMF. However, the mode field of single-mode fiber (SMF) matches well with the fundamental mode of MMF. Thus, this condition can be achieved simply by splicing the MMF to the SMF-pigtailed transmitter.

In this paper, we measure the frequency response of MMF after applying the input beam by using the mode-field matched center launching technique. The result shows that the frequency response of 12.2-km long MMF link did not roll off even at 10 GHz. Thus, by using the proposed launching technique, we could successfully demonstrate the 10-Gb/s transmission over 12.2 km of MMF.

II. Transmission bandwidth of the MMF link utilizing the mode-field matched center launching technique

It is well-known that a few lower-order modes of MMF can be selectively excited by launching the input beam at the center of MMF. However, to achieve the quasi single-mode transmission, it is necessary to match the input beam profile to the mode profile of LP_{01} mode (so that the incident power is dominantly coupled into LP_{01} mode). We designated this launching method as the "mode-field matched center launching technique" in our previous report [4]. To describe the fundamental mechanism of this launching method, we calculated the coupling efficiencies of several lower-order LP modes of a MMF as a function of the mode field diameter (MFD) of the input beam. Fig. 1 shows the result for a graded-index MMF with a core diameter of 50 µm. In this calculation, we used the index profile of MMF measured at 1304 nm, and assumed that the incident beam had a Gaussian profile. The result showed that, when the MFD was about 14 µm, most of optical power was coupled into LP_{01} mode. This was because the mode field of the launched beam matched well with LP_{01} mode of MMF. On the other hand, we noted that the MFD of the conventional SMF is in the range of 9 - 11 µm. Thus, it would be possible to achieve this mode-field matched launching condition simply by splicing the SMF to the MMF. For example, when we launched the light into the MMF through a conventional SMF, more than 80 % of the incident power could be coupled into LP_{01} mode.

The most important limiting factor on the transmission bandwidth of a MMF is the differential modal delay (DMD). However, by using the mode-field matched center launching technique, we can mitigate this limitation and improve the transmission bandwidth significantly. Although this technique can also excite some higher-order modes propagating in different group velocities, their total power is much smaller than that of LP_{01} mode. Because of their small power, these higher-order mode components broaden only the pedestal of the pulse, which can be resulted in the small incoherent crosstalk to the LP_{01} mode component.

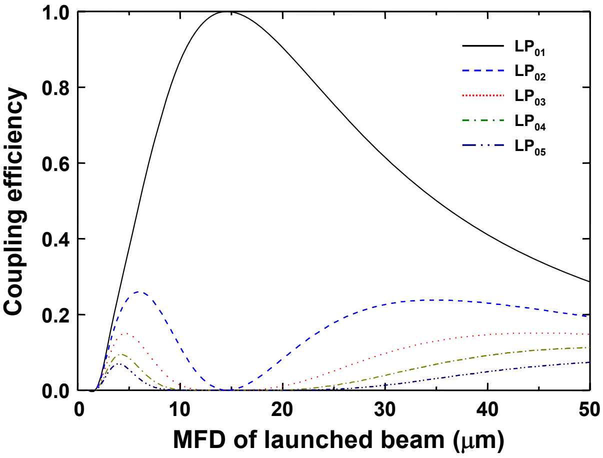
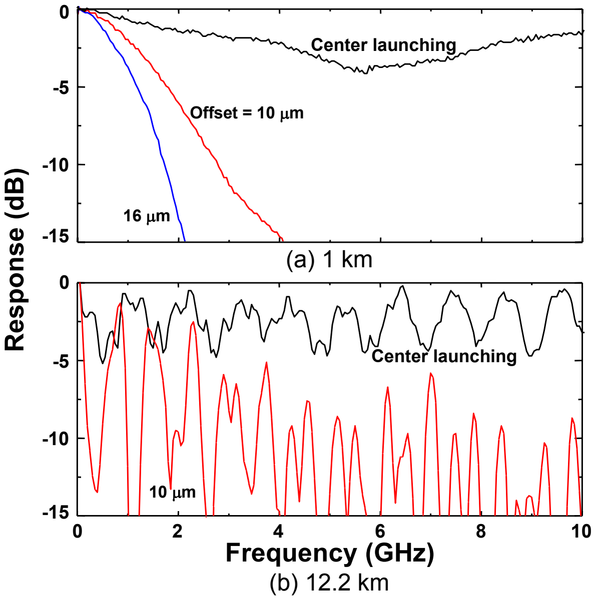


Fig. 1. Calculated coupling efficiency by varying the MFD of launched beam.

To evaluate the effectiveness of the mode-field matched center launching technique, we measured the frequency response of MMF using an intensity-modulated small signal. In this experiment, we sinusoidally modulated the laser output by using a SMF-pigtailed $LiNbO_3$ modulator, and launched the modulated light into OM-3 MMF. The MFD of SMF was 9.3 µm. The lateral offset between the MMF and SMF was adjusted by using a precision motion controller. We measured the amplitude of the modulation component as a function of frequency and lateral offset. Fig. 2(a) shows the frequency response measured after transmission of 1-km long MMF for different offset conditions. In the cases of using the offset launching techniques (10 and 16 µm in Fig. 2(a)), the measured frequency responses had low-pass characteristics, and the bandwidth decreased with the offset due to the DMD among the excited higher-order modes. On the other hand, when the mode-field matched center launching technique was used, the bandwidth limitation was moderate. For further understanding, we repeated the same measurement by using 12-km long MMF. Fig. 2(b) shows the result. Unlike in the case of using the offset launching technique (offset = 10 µm), the frequency response did not roll off even at 10 GHz when we used the mode-field matched center launching technique. This result indicates that a long-distance MMF transmission at the speed higher than 10 Gb/s would be possible by using the mode-field matched center launching technique. However, although the measured frequency response did not roll off, it had non-negligible fluctuations. These fluctuations were caused by the modal interference between LP_{01} mode and higher modes, and could result in the penalties in the receiver sensitivity. In this experiment, LP_{02} was dominant among the excited higher modes. Thus, the period and depth of the fluctuation were determined mainly by the DMD and power ratio between LP_{01} and LP_{02} modes.



(a) 1 km

(b) 12.2 km

Fig. 2. Measured frequency responses of MMF.

III. 10-Gb/s MMF transmission experiments

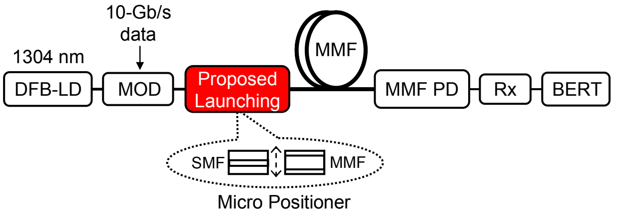


Fig. 3. Experimental setup.

Using the mode-field matched center launching technique, we demonstrated the transmission of 10-Gb/s signal over up to 12.2 km of commercial grade MMF. Fig. 3 shows the experimental setup. We modulated the output of the DFB laser operating at 1304 nm with 10-Gb/s non-return-to-zero (NRZ) signal by using a $LiNbO_3$ modulator. For the mode-field matched center launching, we simply spliced the output fiber of the modulator to the MMF. The lateral offset between these two fibers was less than ±1 μm after splicing. The core diameter and the overfilled launch (OFL) bandwidth of the MMF were 50 μm and 700 MHz·km, respectively. We measured the BER curves of the 10-Gb/s signal after the transmission over 5.6 km and 12.2 km of this MMF. It should be noted that, when the offset launching technique is used, the maximum transmission distance of this MMF is limited to only about 300 m at 10 Gb/s [4]. At the receiver, we detected the whole power from the MMF by using a free-space coupled photodetector. We did not use any mode-stripping devices to eliminate the effects of higher-order mode. The back-to-back receiver sensitivity was -18 dBm (@ BER = 10^{-9}). Fig. 4 shows the measured BER curves. The power penalty was only 1.6 dB when we transmitted the 10-Gb/s signal over 5.6 km of MMF. The power penalty remained to be almost same (1.7 dB), even when we increased the transmission distance to 12.2 km. To our knowledge, this result represents the longest transmission distance ever achieved in the MMF link using 10-Gb/s signals. We attributed the small power penalties in Fig. 4 to the ripples in the frequency response of MMF. As described in the previous section, the frequency response of the MMF did not roll off even when the fiber length was as long as 12.2 km. Thus, the power penalty should not increase with the transmission distance until the mode coupling to higher-order modes becomes significant. We also found that the performance of this MMF link was not sensitive to external perturbations such as bending.

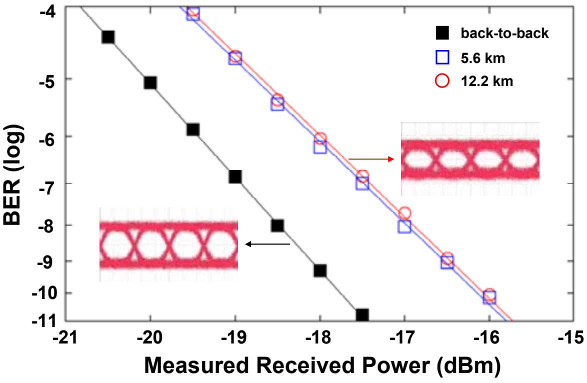


Fig. 4. Measured BER curves.

IV. Summary

We have demonstrated that the transmission bandwidth of MMF could be drastically increased by using the mode-field matched center launching technique. This was because we could selectively excite the fundamental mode of MMF by using this technique and avoid the limitation imposed by DMD. As a result, when we used this launching technique, the frequency response of the 12.2-km long MMF did not roll off even at 10 GHz. As a result, we could transmit 10-Gb/s NRZ signal over 12.2 km of MMF without using any dispersion compensation. To our knowledge, this result represents the longest transmission distance achieved in the MMF link using 10-Gb/s signals.

References

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