Effects of Multi-Level Format in MMF System Based on Mode-Field Matched Center-Launching Technique

M. S. Kim, B. G. Kim, S. H. Bae, and Y. C. Chung, *Fellow, IEEE*

***Abstract*— We evaluate the performances of 25.78-Gb/s signals modulated in on–off keying and four-level pulse amplitude modulation (PAM4) formats in the 12.2-km long multi-mode fiber (MMF) transmission system implemented by using the mode-field matched center-launching technique, which is realized simply by fusion-splicing the single-mode fiber (SMF)-pigtailed transceivers to the transmission MMF. The results show a serious bit-error rate (BER) fluctuation as well as a large power penalty for the PAM4 signal after the 12.2-km long MMF transmission. We identify that the power penalty and BER fluctuations are caused by the signal-to-interference beat noise generated in the SMF-pigtailed receiver, resulting from the small portion of the signal (~5%) unwantedly carried by the high-order modes of MMF. However, we can suppress this beat noise by replacing the SMF-pigtailed receiver with the MMF-pigtailed one since all modes are orthogonal in MMF. For example, when we utilize this proposed method, the power penalty of the 25.78-Gb/s PAM4 signal measured after the transmission over 12.2 km of MMF is reduced from 3.9 to 0.9 dB (@ BER = 5×10^{-5}). We also demonstrate the transmission of the 56-Gb/s PAM4 signal over 2.3 km of MMF by using this method.**

***Index Terms*— Multi-mode fiber, mode-field matched center-launching technique, pulse amplitude modulation, beat noise.**

I. Introduction

MULTI-MODE fiber (MMF) is continued to be widely used in various short-reach applications such as the data center interconnections and local area networks [1], [2]. However, the data rate used in such applications has now been increased to >25 Gb/s [3], [4]. For example, the 100GBASE-SR4 standard utilizes four lanes of MMF with a rate of 25.78 Gb/s per lane [3]. However, it is difficult to transmit such high-speed signals over MMF due to its inherently large modal dispersion. Previously, the mode-field matched center-launching technique has been proposed to overcome this problem [5], [6]. By using this technique, we can avoid the modal dispersion by utilizing only the fundamental mode of MMF. However, when we implement this technique by fusion-splicing the single-mode fiber (SMF) pigtailed transceivers to the transmission MMF, a small portion of the incident light (~5%) may not couple into the fundamental mode and excite high-order modes of MMF [6]. As a result, the performance of the MMF transmission system can be affected by these high-order modes, especially when we utilize the multi-level format such as four-level pulse amplitude modulation (PAM4) for the generation of the high-speed signal of >25 Gb/s. Thus, we evaluate the effects of using the PAM4 signal on the performance of the 25.78-Gb/s MMF transmission system implemented by using the mode-field matched center-launching technique. In this evaluation, we utilize an optical transmitter made of a 1.3-μm laser and an external modulator (to avoid the effects of chromatic dispersion as well as limited bandwidth of the transmitter) and compare the transmission performances achieved by using the on-off keying (OOK) and PAM4 signals. The results show that, unlike the OOK signal, the PAM4 signal is quite sensitive to the signal-to-interference beat noise caused by a small portion of the signal carried by the high-order modes in the transmission MMF. However, we can effectively suppress this beat noise by using the MMF-pigtailed receiver instead of the SMF-pigtailed one since all modes are orthogonal to each other in MMF. As a result, by using the mode-field matched center-launching technique together with a MMF-pigtailed receiver, we could successfully demonstrate the transmission of 25.78-Gb/s and 56-Gb/s PAM4 signals over 12.2 km and 2.3 km of OM3-type MMF, respectively. In these demonstrations, no electrical equalization technique is used for the compensation of the modal dispersion.

II. Experiment and Results

Fig. 1 shows the experimental setup to evaluate the effects of using the multi-level modulation format such as PAM4 on the performances of 25.78-Gb/s MMF transmission system based on the mode-field matched center-launching technique. In this experiment, we implemented the optical transmitter by using a 1.3-μm distributed feedback (DFB) laser and a $LiNbO_3$ Mach-Zehnder modulator (MZM). The SMF-pigtailed MZM had a sufficiently large modulation bandwidth of ~40 GHz. We fusion-spliced the output SMF of the MZM to the OM3-type transmission MMF to achieve the mode-field matched center-launching condition. For this purpose, the splicing condition was optimized to maximize the coupling into the fundamental mode of the MMF. We estimated the coupling efficiency (which was defined as the power

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The authors are with the School of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea (e-mail: mskim0628@kaist.ac.kr; qudrhs3414@kaist.ac.kr; bsh88@kaist.ac.kr; ychung@kaist.ac.kr).

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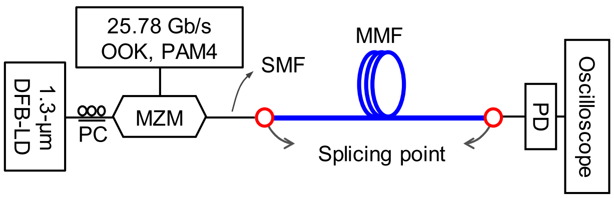

Fig. 1. Experimental setup to evaluate the performances of 25.78-Gb/s OOK and PAM4 signals in the MMF transmission system based on the mode-field matched center-launching technique.

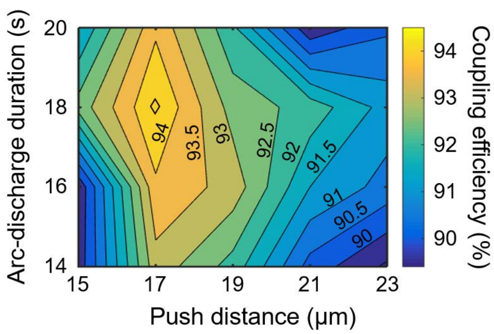

Fig. 2. Measured coupling efficiencies as functions of arc-discharge duration and fiber-push distance.

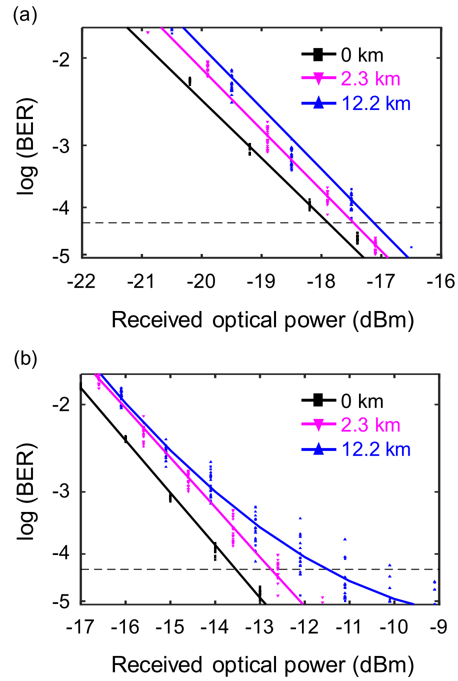

Fig. 3. Measured BER curves of 25.78-Gb/s (a) OOK and (b) PAM4 signals after the transmission over 0∼12.2 km of MMF. In this experiment, we repeated the BER measurement 20 times.

ratio between the fundamental mode and total modes in the MMF) by analyzing the impulse response of the 12.2-km long transmission MMF [7]. The results in Fig. 2 show that we could achieve the coupling efficiency of as high as 94.5% by setting the arc-discharge duration and fiber-push distance to be 18 seconds and 17 μm, respectively. However, the remaining optical power (∼5.5%) coupled into the high-order modes could deteriorate the performance of the MMF transmission system since a portion of it could eventually be coupled into the pigtail SMF of the receiver. In other words, it could generate the beat noise between the signal (i.e., the optical power coupled to the fundamental mode) and the interference (i.e., the optical power coupled to the high-order modes of MMF, of which a small fraction was coupled into the pigtail SMF of the receiver). The effects of this signal-to-interference beat noise would be more serious on the multi-level signal (such as PAM4) than the OOK signal [8], [9]. In fact, it has been reported that the PAM4 signal is ∼12 dB more sensitive to the signal-to-interference beat noise than the OOK signal [8]. We also evaluated the effects of this beat noise on the performances of 25.78-Gb/s OOK and PAM4 signals in the MMF transmission system implemented by using the mode-field matched center-launching technique with SMF-pigtailed transceivers. The extinction ratios of both signals were set to be 10 dB and the fiber length was in the range of 0∼12.2 km. After the transmission, we sampled these signals at 80 Gsample/s by using a real-time oscilloscope and used $8\text{x}10^6$ samples for the estimation of their bit-error rate (BER) performances. Fig. 3 shows the measured BER curves of 25.78-Gb/s OOK and PAM4 signals (pattern length: 2^{15}-1) after the transmission over 0∼12.2 km of MMF. Under the back-to-back condition, the receiver sensitivity of the OOK signal was measured to be -17.8 dBm, which was measured at the BER of 5×10^{-5} considering the Reed-Solomon (528,514) forward-error-correction code specified in the 100GBASE-SR4 standard [3]. Also, the power penalty of this signal was measured to be <1 dB even after the 12.2-km long MMF transmission. This small power penalty was resulted from the facts that the effects of chromatic dispersion was negligible (since the operating wavelength of the transmitter was 1312 nm), and the beat noise was small (since only ∼5% of the total power was carried by the high-order modes) while the OOK signal was relatively robust against it. In comparison, in the case of using the PAM4 signal, the back-to-back receiver sensitivity was measured to be -13.6 dBm. Thus, under the back-to-back condition, the difference in the measured sensitivities of the 25.78-Gb/s OOK and PAM4 signals was ∼4.2 dB, which showed a reasonable agreement with the theoretically calculated value of 3.3 dB [10]. However, a serious BER fluctuation was observed when we transmitted the PAM4 signal over MMF. This was because of the residual signal carried by the high-order modes in the transmission MMF. A small fraction of this power was then coupled into the pigtail SMF of the receiver and generated the beat noise with the signal transmitted by the fundamental mode of MMF. Thus, the BER could be fluctuated as the polarizations of the signals transmitted by the fundamental and high-order modes changed randomly over time. To estimate the effects of this signal-to-interference beat noise, we repeated the BER measurement 20 times. The results in Fig. 3(b) show that the average receiver sensitivity (depicted by the solid line) of the 25.78-Gb/s PAM4 signal after the transmission over 12.2 km of MMF was measured to be -11.4 dBm (@ BER=5×10^{-5}).

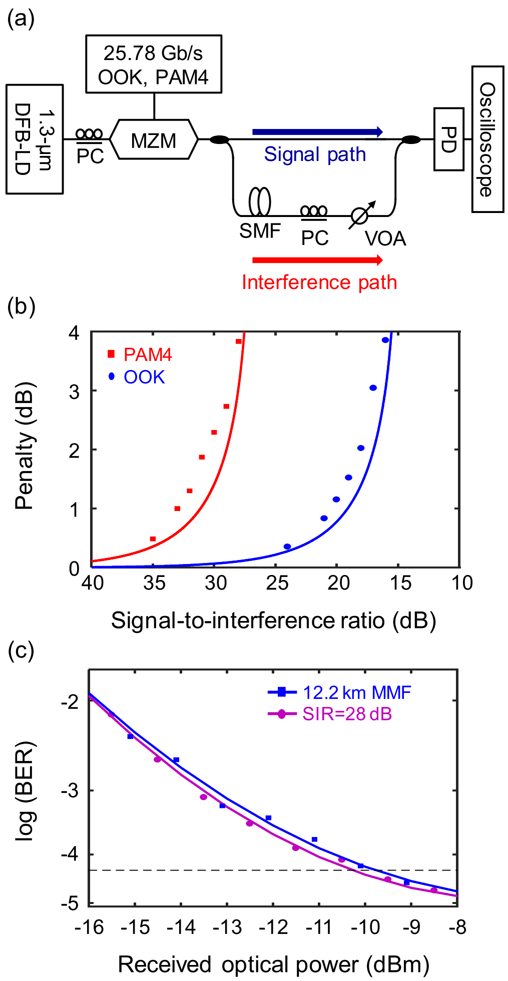

Fig. 4. (a) Experimental setup to verify the effects of the signal-to-interference beat noise on the performance of 25.78-Gb/s OOK and PAM4 signal. (b) Measured power penalties of 25.78-Gb/s OOK and PAM4 signals as a function of SIR in comparison with the theoretical curves (@ BER=5×10^{-5}). (c) The worst-case BER curve of 25.78-Gb/s PAM4 signal measured after the 12.2-km long MMF transmission (from Fig. 3(b)) in comparison with the BER curve measured by setting the SIR to be 28 dB (using the setup in Fig. 4(a)).

However, in the worst case among the 20 measurements, an error floor was observed at the BER of $\sim10^{-5}$.

Fig. 4(a) shows the experimental setup to verify the effects of the signal-to-interference beat noise on the BER performance of the PAM4 signals in the MMF transmission system based on the mode-field matched center-launching technique. After the generation of the 25.78-Gb/s OOK and PAM4 signals, we divided it into two paths; one for the signal and the other for the interference. The polarization states of these two paths were matched to maximize the beat noise. The signal-to-interference ratio (SIR) was adjusted by using a variable optical attenuator (VOA). We combined the signal and interference incoming from these two paths, detected it by using a PIN receiver, and then estimated the BER performances as a function of SIR. Fig. 4(b) shows the measured power penalties of 25.78-Gb/s OOK and PAM4 signals as a function of SIR in comparison with the theoretical curves [8]. As expected, the PAM4 signal was $\sim$12 dB more sensitive to the signal-to-interference beat noise than the OOK signal. For example, a power penalty of 3.8 dB was observed (@ BER= 5×10^{-5}) when we set the SIR to be 28 dB for the PAM4 signal, while a same power penalty was observed when we set the SIR to be 16 dB for the OOK signal. Fig. 4(c) shows the worst-case BER curve of 25.78-Gb/s PAM4 signal measured after the transmission through 12.2 km of MMF. We inferred that these worst-case BERs were obtained when the polarization states of the signal and interference were happened to be nearly matched. This was similar to the experimental condition used in Fig. 4(a). Thus, to estimate the SIR applied in the 12.2-km long MMF transmission system, we measured the BER curves while varying the SIR in 1-dB step and compared the result with the BER curve obtained after the MMF transmission. As shown in Fig. 4(c), the BER curve obtained by setting the SIR to be 28 dB had the closest fit to the measured data after the 12.2-km long MMF transmission. Thus, we assumed that the SIR used in the 12.2-km long MMF transmission experiment was also 28 dB. Accordingly, since the coupling efficiency to the fundamental mode of the transmission MMF was 94.5% (i.e., 12.3 dB), we attributed the remaining 15.7 dB as the coupling efficiency of the interference signal carried by the high-order modes in the transmission MMF to the pigtail SMF of the receiver. These results indicated that, despite the mode-field matched center-launching technique and mode filtering (occurred at the interface between the transmission MMF and pigtail SMF of the receiver) used in this experiment to suppress the high-order modes, it would be difficult to increase the SIR to be much higher than 28 dB and avoid the large penalty on the performance of the PAM4 signal.

As described above, if we realized the mode-field matched center-launching technique simply by fusion-splicing the SMF-pigtailed transceivers to the transmission MMF, a small portion of the signal ($\sim$5%) could be carried by the high-order modes of MMF. Thus, in the case of using the SMF-pigtailed receiver, a small fraction of this residual signal (carried by the high-order modes) could be coupled to the pigtail SMF, where it would be mixed with the main signal (carried by the fundamental mode of MMF and then coupled to the pigtail SMF of the receiver) to generate the signal-to-interference beat noise. We attempted to suppress this beat noise by using the MMF-pigtailed receiver, since different modes are orthogonal in MMF (i.e., different modes have different spatial distributions of the electric field) [11]. To verify this method, we measured the BER curves of the 25.78-Gb/s signals after replacing the SMF-pigtailed receiver with a MMF-pigtailed one in the experimental setup in Fig. 1. Fig. 5 shows the BER curves of the OOK and PAM4 signals measured after the transmission over 0$\sim$12.2 km of MMF. For the OOK signal, the power penalty was measured to be less than 1 dB even after 12.2-km long MMF transmission, which was comparable to the result obtained by using a SMF-pigtailed receiver shown in Fig. 3(a). On the other hand, for the PAM4 signal, the penalty was significantly reduced from 3.9 dB (worst case) to 0.9 dB when we replaced the SMF-pigtailed receiver with the MMF-pigtailed one. Also, the reduction of the BER fluctuation was evident after replacing the receivers (refer Fig. 3(b)), indicating the effectiveness of the proposed method for the suppression of the signal-to-interference beat noise. Thus, it would be helpful to utilize the MMF-pigtailed receiver for the transmission of

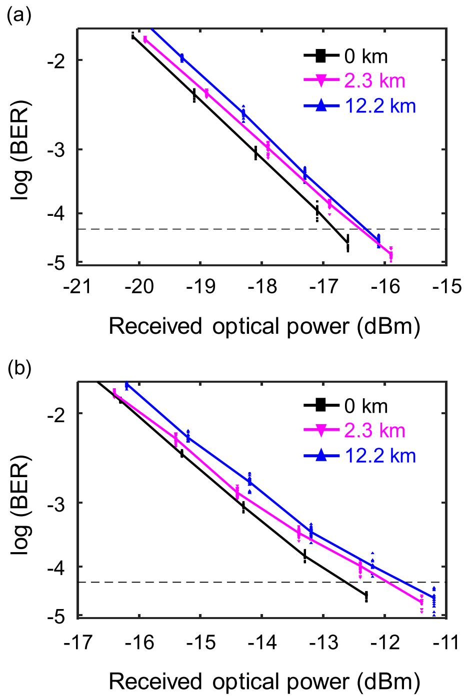

Fig. 5. Measured BER curves of 25.78-Gb/s (a) OOK and (b) PAM4 signals after the transmission over 0∼12.2 km of MMF by using a MMF-pigtailed receiver. The BER curves were measured 20 times.

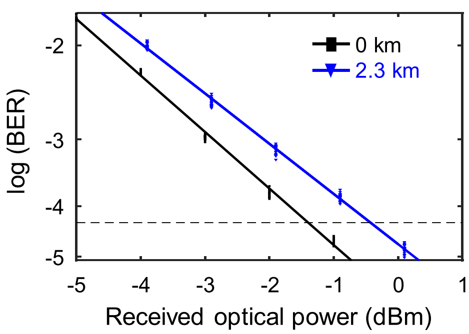

Fig. 6. Measured BER curves of 56-Gb/s PAM4 signals under the back-to-back condition and after the transmission over 2.3 km of MMF by using the mode-field matched center-launching technique with a MMF-pigtailed receiver. The BER curves were measured 20 times.

the high-speed signal modulated in multi-level formats such as PAM4. In fact, by utilizing the mode-field matched center-launching technique with a MMF-pigtailed receiver, we could demonstrate the transmission of 56-Gb/s PAM4 signal over 2.3 km of MMF. The results in Fig. 6 show that the transmission penalty was only ∼1 dB. However, in this case, we could not further increase the transmission distance since the MMF-pigtailed receiver used in this experiment had no transimpedance amplifier and, as a result, a poor sensitivity. It should also be noted that no electrical equalization technique was used in this experiment.

III. Summary

We evaluated the effects of using a multi-level modulation format such as PAM4 on the performance of the high-speed MMF transmission system based on the mode-field matched center-launching technique. For this purpose, we implemented the MMF transmission system by fusion-splicing the SMF-pigtailed transceivers to the OM3-type MMF and evaluated the transmission performances of the 25.78-Gb/s OOK and PAM4 signals. The results showed that, unlike the OOK signal, the PAM4 signal suffered from a large power penalty and a serious BER fluctuation after the transmission over 12.2 km of MMF. We found that this was because a small portion of the optical signal (∼5%) was unwantedly carried by the high-order modes in the MMF due to the imperfect realization of the mode-field matched center-launching technique. A fraction of this signal, carried by the high-order modes of MMF, was then coupled to the pigtail SMF of the receiver and generated the signal-to-interference beat noise with the main signal carried by the fundamental mode of MMF. However, we could suppress this beat noise by utilizing the MMF-pigtailed receiver instead of the SMF-pigtailed one in the MMF transmission system based on the mode-field matched center-launching technique. This was because, in the case of using the MMF-pigtailed receiver, the signal carried by the fundamental mode of MMF could not beat with the rest of the signal carried by the high-order modes since all modes are orthogonal to each other in MMF. By using this method, we could transmit both the 25.78-Gb/s OOK and PAM4 signals over 12.2 km of MMF with a power penalty of <1 dB and a negligible BER fluctuation. In addition, we could demonstrate the transmission of 56-Gb/s PAM4 signal over 2.3 km of MMF with only a small penalty. These results indicated that it would be possible to develop the high-speed (>50 Gb/s) MMF transmission system by using the mode-field matched center-launching technique with a MMF-pigtailed receiver and the spectrally efficient multi-level modulation format.

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