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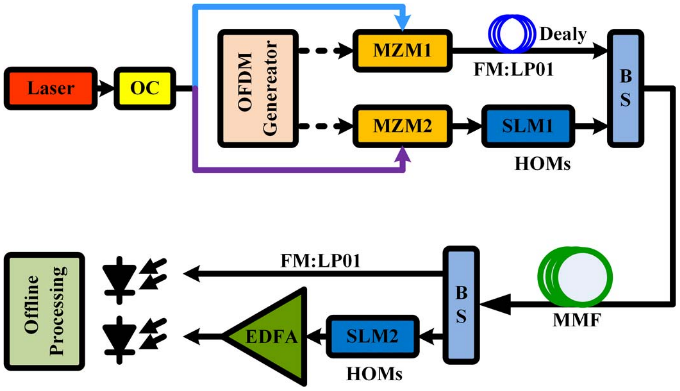

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40 Gb/s Mode-Division Multiplexed DD-OFDM Transmission Over Standard Multi-Mode Fiber

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Abstract: A 40 Gb/s mode-division multiplexed (MDM) direct detection optical frequency-division multiplexing signal transmission over standard multimode OM3 fiber (MMF) has been demonstrated in this paper. Error-free unidirectional and bidirectional transmissions over 200-m standard MMF under the forward error control (FEC)-limit can be realized. Advanced digital signal processing algorithms based on directed-detection techniques using single photodiodes have also been studied to eliminate the crosstalk and improve the performance of MDM systems.

Index Terms: Optical interconnects, fiber optic systems.

1. Introduction

Due to the fact that bandwidth and flexible switching demand in data center networks (DCNs) and high-performance computing (HPC) centers have been growing rapidly in recent years, there is a strong demand to increase the capacity of low-cost short-reach optical inter-connection systems. Many solutions have been proposed to increase the capacity effectively for long-haul transmission system, such as wavelength division multiplexing (WDM), polarization division multiplexing (PDM), and higher order modulation formats. However, because of the special requirement on cost, power budget and capacity density of the DCN and HPC, many technologies in long-haul transmission systems are not available for short reach optical inter-connection systems [1]. In addition, standard multimode fibers (MMFs) while not the standard single mode fibers, have been used in DCN and HPC extensively.

Therefore, it is necessary to adopt novel techniques to increase the transmission capacity of MMF-based short reach optical interconnection systems. In recent years, the space division multiplexing technologies, such as few mode or multi-core multiplexing based methods, have been proposed to increase the transmission capacity per fiber [2]–[8]. However, few mode fiber and multi-core fiber are specially designed fiber, which means that these fibers are not cost-effective, compared to the standard MMF.

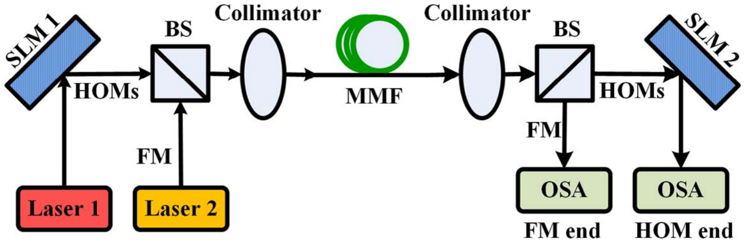


Fig. 1. Experimental setup of modal crosstalk measurement.

On the other hand, standard MMF has been widely used in short-reach optical interconnect systems including the DCN, HPC, passive optical network (PON), and so on. Recently, to increase the transmission capacity of MMF, the mode group division multiplexing (MGDM) based technology has been proposed and demonstrated [9]. Although the mode group channel can be excited relative simply, the useful channels are limited that resulted in the decrease of the available channel. Meanwhile, the mode dispersion due to the degenerated modes in a mode group will cause the degradation of the system performance.

In this paper, we propose a novel method based on the individual mode division multiplexing (MDM) in OM3 MMF to achieve large capacity per MMF used in short-reach optical interconnect system. This method shows the advantages of lower modal dispersion, simpler optical receiver, and lower cost compared with the multiplexing technologies used in short-reach optical interconnect in [10] and [11]. Meanwhile, the proposed method also has the ability to adopt the various advanced modulation formats used in short-reach optical interconnection [12], [13]. The experimental results indicate that the bidirectional 2×2 40-Gb/s OFDM transmission can also be achieved without the MIMO compensation. Advanced digital signal processing algorithms based on single photo-detector directed-detection techniques are also studied to improve the performance of MMF systems. In this way, the unidirectional 2×2 40-Gb/s OFDM signal transmission can be achieved with the simple MIMO compensation.

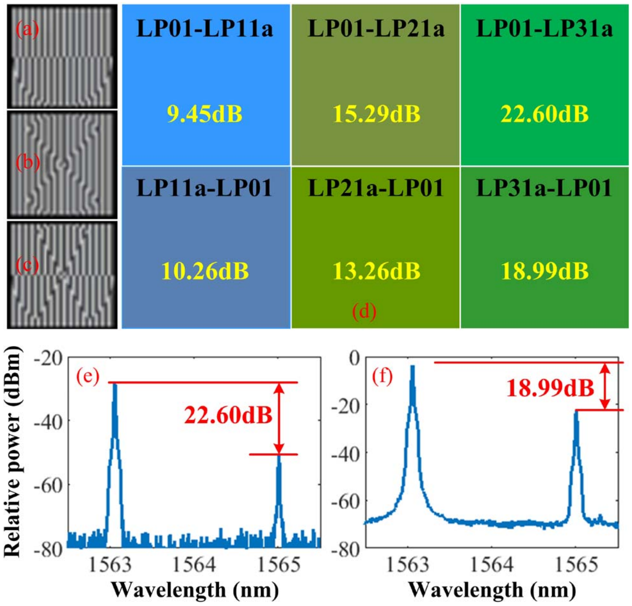
2. Modal Crosstalk Measurement

To realize the high performance transmission in standard MMF, good communication channel should be selected carefully, so modal crosstalk between different mode should be studied first.

Fig. 1 illustrates the experimental setup to measure the modal crosstalk of different LP modes in OM3 MMF. Two lasers with different wavelengths (one is 1563 nm, and the other is 1565 nm) are used in this experiment. The fundamental mode (LP01 mode) from Laser1 is converted to the LP11a mode or other higher order modes (HOMs) by spatial light modulator (SLM, Holoeye PLUTO-TELCO), then combined by the beam splitter (BS) and coupled into the MMF together with LP01 mode come from Laser2. MMF we use in this experiment is standard OM3 MMF with the length of 200 m. The other SLM at receiver is used to demodulate the high order modes and the optical spectrum analyzers (OSA) are used to show the received optical spectra of different LP modes. In this way, the modal crosstalk of different modes can be obtained from OSA directly.

In the experiment, we first design the patterns in Fig. 2(a)–(c) to generate the desired higher order modes (HOMs) through SLM, such as LP11a, LP21a, and LP31a, which are then transmitted over the standard MMF with LP01 mode, respectively.

We know that mode crosstalk between different mode channel will influence the transmission performance directly. Here we use the modal isolation (MI) to define the modal crosstalk. In order to study the mode isolation between the LP01 and high order modes effectively, we generate LP01 at 1563 nm DFB laser and generate the other high order modes at 1565 nm. Then, we can measure the power difference between the two wavelengths from the OSA, which indicates the modal crosstalk between the LP01 mode and other HOMs. The measured modal isolations between different modes are shown in Fig. 2(d). Taking the modal isolation between LP01 and



LP01-LP11a	LP01-LP21a	LP01-LP31a
9.45dB	15.29dB	22.60dB
LP11a-LP01	LP21a-LP01	LP31a-LP01
10.26dB	13.26dB	18.99dB

Fig. 2. Patterns used to convert LP01 mode to desired higher order mode by SLM of (a) LP11 mode, (b) LP21 mode, and (c) LP31 mode. (d) Modal isolation of different modes. Optical spectra of mode isolation measured from (e) LP01 to LP31a and (f) LP31a to LP01 mode.

LP31 modes as an example, we can find that the MI between LP01 and LP31 modes is 22.60 dB when the LP01 mode (1563 nm) is the transmitted mode channel as shown in Fig. 2(e). But, the modal isolation is reduced to 18.99 dB when the higher LP31 mode (also 1563 nm) is the transmitted mode channel. To show the similar feature with Fig. 2(e), we do this wavelength exchange that makes the power of LP31a mode shown in the spectrum is higher than the crosstalk power of LP01 in Fig. 2(f).

Obviously, the mode isolation between the LP01 and LP31 modes is better, which is due to the relative large difference of propagation constant between these two modes. This means that we can achieve MDM transmission over MMF with less crosstalk and good performance.

3. Experimental Results

3.1. Unidirectional Transmission of MDM-DD-OFDM

We first study the unidirectional transmission performance for MDM-DD-OFDM transmission over 200 m standard OM3 MMF, as shown in Fig. 3. The real-value OFDM signal is generated offline and its in-phase (I) and quadrature (Q) parts are used to drive the Mach–Zehnder modulators (MZMs) of different mode channels respectively. The input laser is split into two branches via optical coupler (OC) and then modulate through SLMs to form two mode channels of LP01 and LP31. Digital signal processing (DSP) required to generate DD-OFDM signal at transmitter consists of serial-to-parallel (S/P) conversion, QAM mapping, and inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion. After digital-to-analog conversion (DAC) by Tektronix AWG 7122B, the electric OFDM signal is amplified by electric drivers and then modulated onto the optical carrier with the wavelength of 1549.39 nm and power of 13 dBm through Covega 10 G optical intensity modulator (MZM1). Then two channels are collimated, multiplexed by the BS, and launched into the 200 m OM3 MMF link for the unidirectional transmission. After transmission, the signal is split into two branches by the BS and received by the Discovery R401HG photo-detector. Then the received OFDM signal is captured by a 16 GHz real-time Tektronix DSA 72004B with a sampling rate of 50 GSample/s and processed offline to calculate the bit-error-ratio (BER) performance.

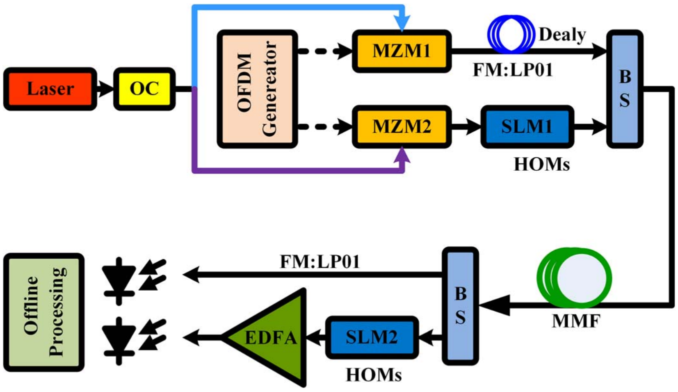


Fig. 3. Experimental setup of unidirectional MDM-DD-OFDM transmission. OC: optical coupler; MZM: Mach–Zehnder modulator; FM: fundamental mode; HOM: higher order mode; BS: beam splitter.

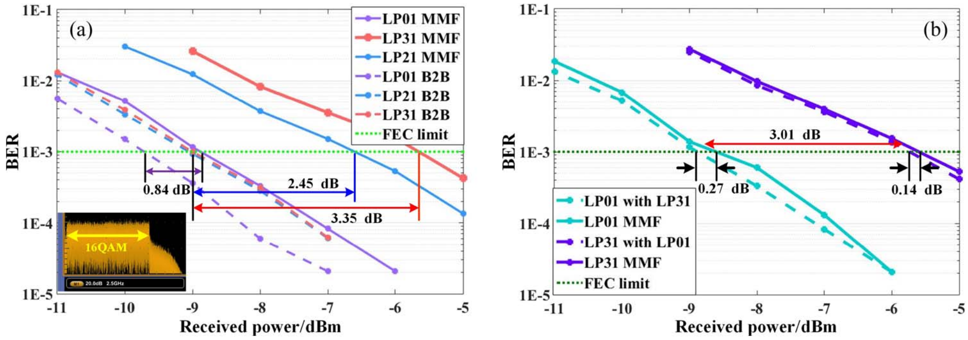


Fig. 4. (a) BER performance of the typical three mode channels (LP01, LP21, LP31) transmission over MMF separately and (b) LP01 mode and LP31 mode transmitted simultaneously without MIMO compensation.

To emulate the transmission capacity limit of MMF, the typical 16QAM-OFDM signal is used, and the corresponding electrical spectrum is shown as the insets in the Fig. 4(a). We can find from Fig. 4(a) that the error-free transmission over MMF for all fundamental and HOMs can be achieved with different power penalty. The power penalties are 0.84 dB, 2.45 dB, and 3.35 dB for LP01 mode, LP21 mode, and LP31 mode, respectively.

Then, we demonstrate the 2×2 MDM-DD-OFDM transmission over MMF based on LP01 and LP31 modes. The total symbol number per channel of the double-side modulation (DSB) OFDM signal is 350, and each symbol consists of 256 subcarriers with 108 effective carriers. Therefore, the effective bandwidth of the OFDM signal generated by the AWG is $12 \times 108/256 = 5.0625$ GHz. The modulation formats of these signals are both 16 QAM. After the MMF transmission, the transmitted signals are detected and then demodulated offline. Fig. 4(b) shows the BER performance when LP01 mode and LP31 mode are transmitted simultaneously.

We can find that there is only little penalty between the two BER curves since two modes only have little crosstalk, which are controlled by large mode isolation between them. The penalties induced by LP31 mode to LP01 mode, and LP01 mode to LP31 mode, are only 0.27 dB and 0.14 dB, respectively. Meanwhile, the power penalty between LP01 and LP31 modes is 3.01 dB at the forward error control (FEC). Thus, the total transmission rate of 40.5 Gb/s ($5.0625 \times (4+4) = 40.5$ Gb/s, a net rate of 37.665 Gb/s when the 7% FEC overhead is

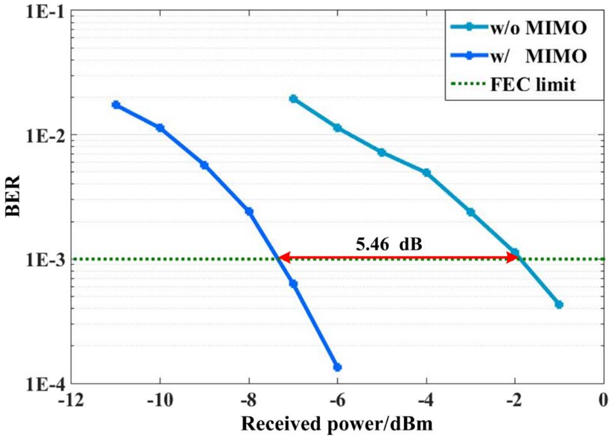


Fig. 5. BER performance of 2 × 2 MDM-DD-OFDM transmission with/without MIMO compensation.

removed) can be achieved by the 2 × 2 MDM-DD-OFDM transmission over MMF based on LP01 and LP31 modes. Meanwhile, this result demonstrates the MDM-DD-OFDM transmission over standard MMF without MIMO compensation.

However, to increase the transmission capacity of standard MMF, the potential mode channels that can be multiplexed and have large mode isolation should be as much as possible. According to Fig. 2, LP21 mode has a relative low modal isolation of 15.29 dB when transmitted together with LP01 mode. However, the transmission performance will become worse as the LP21 and LP01 modes are both transmitted in MMF. So, the simple MIMO compensation should be adopted to improve the BER performance. To implement the MIMO processing, the transfer function of the MMF should be measured. By considering that the short transmission distance, this transfer function should be simple and have the ability to compensate for the degradation induced by the reduced modal isolation. The experimental setup is the same as Fig. 3, except the pattern applied to SLM is changed from Fig. 2(c) to (b) to generate LP21 mode. We first transmit LP01 mode and receive the signal at the respective PDs to calculate the transfer matrixes H_{11} and H_{12} by offline processing. H_{12} means the crosstalk from LP01 mode to LP21 mode. Following the same way, we can also get another two transfer matrixes H_{21} and H_{22}. H_{21} shows the crosstalk from LP21 mode to LP01 mode. Then, the total transfer matrix H can be expressed as $\mathbf{H} = [H_{11}\ H_{12};\ H_{21}\ H_{22}]$.

Finally, the performance of the 40.5 Gb/s 2 × 2 MDM-DD-OFDM transmission over MMF based on LP01 and LP21 modes has been obtained with simple MIMO compensation as shown in Fig. 5. We can see that there is a 5.46 dB improvement of the power sensitivity after using the MIMO compensation when compared with that without compensation.

3.2. Bidirectional Transmission of MDM-DD-OFDM

For the short-reach optical interconnect, such as data center network, the data exchange within the data center is the dominant, which means that the data transmission over the MMF is not only a unidirectional behavior but is also usually a bidirectional transmission. Thus, we then demonstrate the bidirectional transmission of MDM-DD-OFDM signal. The experimental setup is shown as Fig. 6, which is similar with the unidirectional transmission except that the two signals are launched and detected in opposite direction, i.e., the direction of FM is from point “A” to “B,” while the HOM’s is from “B” to “A.” The total transmission rate is also 40.5 Gb/s

The BER performance of bidirectional MDM-DD-OFDM transmission has been shown in Fig. 7(a) and (b) where LP01 mode is transmitted together with LP21 and LP31 mode from another direction respectively. As shown in Fig. 7(a) that the transmission penalty of LP01 channel transmission influenced by LP21 mode from another direction is 0.08 dB. While the transmission penalty of LP21 is 0.06 dB influenced by LP01 mode. So, we can conclude the crosstalk between bi-directional

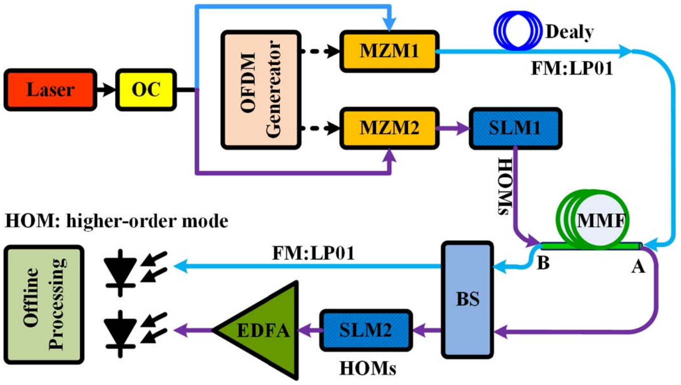


Fig. 6. Experimental setup of bidirectional MDM-DD-OFDM transmission.

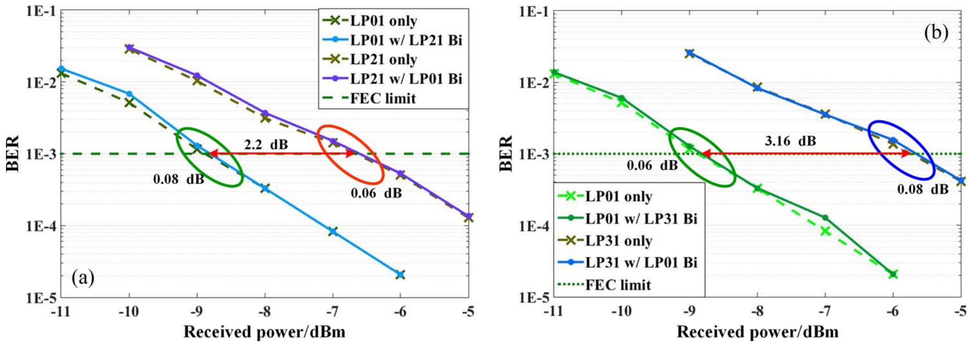


Fig. 7. BER performance of 2 × 2 MDM-DD-OFDM bidirectional transmission when LP01 mode together with (a) LP21 mode and (b) LP31 mode.

transmission mode can be nearly neglected. Meanwhile, the similar penalty can be observed shown in Fig. 7(b) when LP01 and LP31 modes are transmitted simultaneously. Although the HOM channels show some power penalties (2.2 and 3.16 dB, respectively) compared with the fundamental mode channel, there is almost no penalty when these two mode channels are transmitted bi-directionally. Due to the low crosstalk induced by the mode multiplexing, the bidirectional high-speed MDM-DD-OFDM transmission over MMF shows a better BER performance compared with the unidirectional transmission where the MIMO compensation should be considered.

4. Conclusion

We have demonstrated the mode-division-multiplexing based direct-detection OFDM transmission over standard OM3 MMF link. The inter-modal crosstalk has been measured to implement the MDM-DD-OFDM transmission over MMF with large mode isolation to avoid the MIMO processing. A 40 Gb/s 2 × 2MDM-DD-OFDM signal has been successfully transmitted over the 200 m MMF without MIMO DSP processing. Using a simple MIMO DSP we can have 5.46 dB improvement of the power sensitivity for LP01 and LP21 modes transmission with the reduced modal isolation. Besides, the bi-directional 40 Gb/s 2 × 2MDM-DD-OFDM signal over MMF transmissions without MIMO compensation have also been demonstrated for LP01 mode, together with other higher order modes (LP21 mode and LP31 mode) simultaneously. The experimental results have demonstrated that MDM-based DD-OFDM over MMF has a good potential in short-reach optical interconnect systems.

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