# Transmission of 25.5-Gb/s OFDM Signal over 200-m G62.5/125 MMF Using Mode Group Diversity Multiplexing

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**Abstract:** We experimentally demonstrate a 25.5-Gb/s OFDM transmission over 200-m OM1 MMF with a modulation bandwidth of 4.25 GHz, by using mode group diversity multiplexing. The power penalty induced by inter-channel crosstalk is only 0.5 dB.
**OCIS codes:** (060.2330) Fiber optics communications; (060.4080) Modulation.

## 1. Introduction

A multimode fiber (MMF) has a large core diameter that enables significant cost reduction in component manufacturing, installation, and maintenance [1]. For this reason, MMFs have been widely used in cost-sensitive broadband local area networks (LANs) to provide much higher bandwidth than the conventional copper-based transmission medium. However, fully exploring the great potential of optical communications over MMF is not straightforward, as an MMF is generally characterized by a much smaller bandwidth-distance product compared to a single mode fiber (SMF) due to its inherent modal dispersion. Various techniques have been investigated to break the capacity limitation imposed by modal dispersion, such as coarse wavelength division multiplexing (WDM) [2], subcarrier multiplexing [1], and electronic equalization [3]. In particular, the additional spatial modes in an MMF provide additional degrees of freedom and, thus can be used to provide additional capacity from the standpoint of information theory [4]. Although at present there is no simple way to independently harness each individual mode in an MMF, the propagating modes can be separated into a few subsets to create parallel communication channels, namely mode group diversity multiplexing (MGDM). In concept, the MGDM-based transmission is similar with the emerging few-mode transmission over specially designed few-mode fibers [5], but has the merit of being compatible with conventional MMFs. On-off keying (OOK) is the dominant modulation format in prior MGDM systems [6-8], in which the modal dispersion within a mode subset is the limiting factor of the transmission capacity. Due to its high spectral efficiency and strong resilience to dispersion, optical orthogonal frequency-division multiplexing (OFDM) can be a strong candidate for future high speed MGDM systems.

In this contribution, we experimentally investigate the feasibility of using OFDM in a 2×2 MGDM system, which is realized by mode multiplexing at the transmitter and demultiplexing at the receiver side. We demonstrate a 25.5-Gb/s (net data rate: 19.86 Gb/s) OFDM-MGDM transmission over a 200-m OM1 MMF, with a modulation bandwidth of 4.25 GHz for each channel. The power penalty (at BER=$10^{-3}$) induced by inter-channel crosstalk is as small as 0.5 dB when both channels have the same launching power. This result is achieved without using the multiple-input and multiple-output (MIMO) signal processing as in [9, 10].

## 2. Experimental setup

Fig. 1 illustrates the experimental setup of the 25.5-Gb/s 2×2 OFDM-MGDM transmission over a 200-m OM1 MMF. The real-valued 8-QAM OFDM signal was generated offline by using a complex conjugate extension for the IFFT input. The parameters of the OFDM signal were: input data stream of pseudo random bit sequence (PRBS) $2^{18}$-1, IFFT size of 1024, of which 363 subcarriers were used for data transmission, and a frequency gap of 10 subcarriers. A cyclic prefix (CP) of 32 samples was added to the OFDM signal, which was loaded into a Tektronix AWG7122B arbitrary waveform generator (AWG) with a bandwidth of 10 GHz. Each OFDM frame was composed of 182 OFDM symbols, 28 training symbols for equalization, and 2 training symbols for synchronization. Based on the aforementioned parameters, the gross data rate can be calculated as 12.76 Gb/s, whereas the net data rate is 9.93 Gb/s after removing the overheads of CP, FEC (7%), and preambles. The amplitude of the AWG output was clipped within 1 $V_{pp}$. After amplification, the baseband OFDM signal was used to drive a Mach-Zehnder modulator (MZM) that modulated the output of a continuous-wave (CW) laser at 1540 nm. The standard division of the driving OFDM signal was around one tenth of the MZM's switching voltage. The generated optical OFDM signal was split into two parts that were further decorrelated to emulate two independent signals. Two variable optical attenuators (VOA) were used in each arm for launching power adjustment and BER measurement. Following the VOAs two polarization controllers (PC) were used due to the slight polarization dependence of the MMF coupler that multiplexed two subsets of modes into a 200-m OM1 MMF. A PC was used after the MMF coupler to adjust the polarization of the launching signal, since the mode filtering at the receiver side was polarization dependent. The

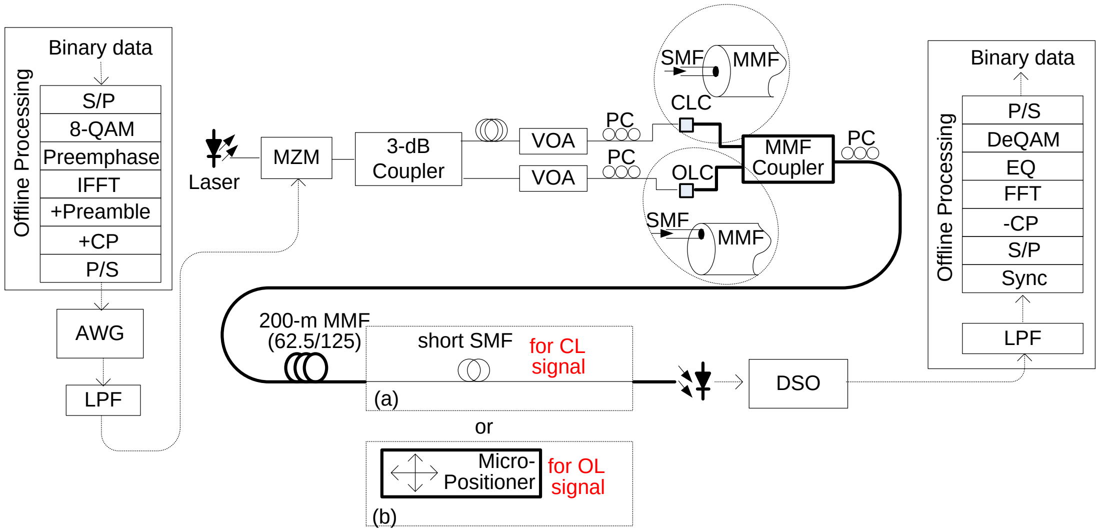


Fig. 1: Experimental setup of the 25.5-Gb/s 2×2 OFDM-MGDM transmission over a 200-m OM1 MMF. **CL:** center launching, **OL:** offset launching.

lower-order and higher-order mode groups were excited by centre launching (CL) and offset launching (OL), respectively. The centre launching was realized by the direct connection between an SMF (thin line) to an MMF (thick line) using a centre launching connector (CLC), whereas the offset launching was realized by an offset launching connector (OLC) with a 20-um offset. At the receiver side, the lower-order mode group, travelling mostly in the centre of the core [11], was filtered out using a short SMF, whereas the higher-order mode group, travelling close to the core cladding interface [11], was filtered out using a short MMF with proper offset. The offset between the transmission MMF and the reception short MMF was set to be around 50 μm by using a micropositioner, such that nearly all the CL signal can be filtered out from the OL signal. Note that since we used an offset MMF rather than an offset SMF as in [8] to select part of the higher-order modes, the modal noise can be significantly reduced. In practical implementation, a spatially resolved two-section detector as in [12] can be used to simultaneously detect both mode subsets. In this case, the modal noise can be further reduced due to the increased detection area for each mode subset. After amplification, the detected OFDM signal was captured by a 16-GHz real-time Tektronix DPO72004 digital storage oscilloscope (DSO) with a sampling rate of 50 GSamples/s, before being demodulated and evaluated offline.

## 3. Experimental results

For the OL signal, only a small portion of the higher-order modes are captured by the receiver, leading to the low-pass characteristic of the OL channel. The low-pass characteristic of the OL channel severely degraded the system's bit error ratio (BER) if no measure was taken. To solve this problem, power loading (or pre-emphasis) was employed: the amplitudes of the 8-QAM signals in each subcarrier of an OFDM symbol were linearly increased by 10 dB from the first to the last subcarrier, before the IFFT. Fig. 2(a)-(c) show the spectra with power loading for the optical back-to-back (B2B), CL, and OL signals, respectively. A relatively flat spectrum of the OL signal is obtained by using power loading. A modulation bandwidth of 4.25 GHz can be observed for each signal with a gross data

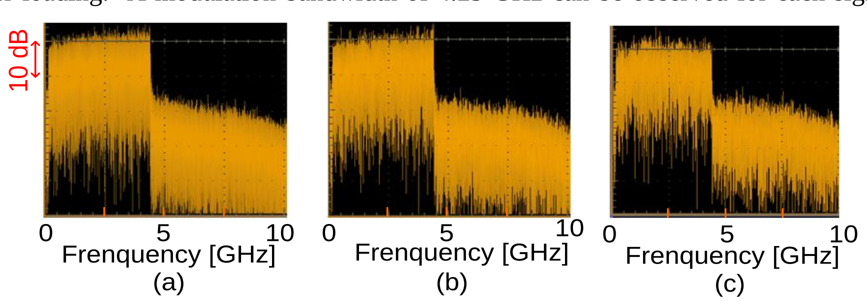


Fig. 2: Spectra (measured at the DSO) with power loading of (a) optical B2B signal, (b) center launching signal, (c) offset launching signal.

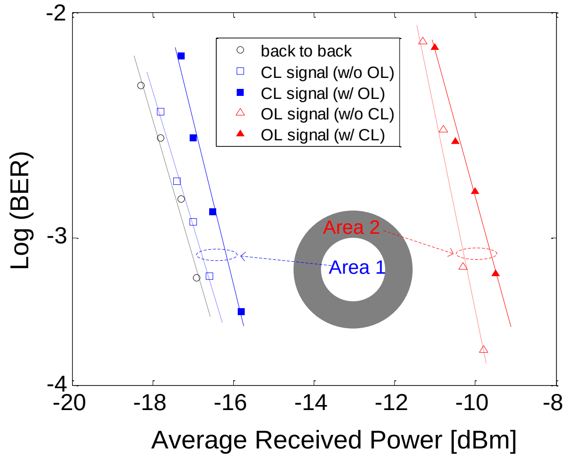


Fig. 3: BER measurement results. **CL:** center launching, **OL:** offset launching.

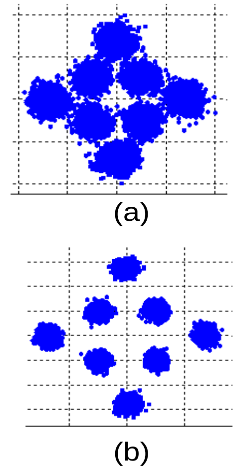


Fig. 4: Constellation of (a) offset launching signal, (b) center launching signal.

rate of 12.76 Gb/s. The BER measurement result is shown in Fig. 3, with 228690 bits (210 OFDM symbols) were measured for each BER point. The system performance was polarization dependent, especially for the OL signal, so the polarization controllers were carefully optimized when measuring the BER. Compared with the B2B BER curve, around 0.2-dB power penalty at BER of $10^{-3}$ is observed for the CL signal when the OL signal is switched off. After switching on the OL signal, an additional 0.5-dB power penalty can be observed due to the inter-channel crosstalk. Similarly, the CL signal induces only around 0.5-dB power penalty for the OL signal. Well converged constellations (measured with the same received power of -10 dBm) can be observed for both signals as shown in Fig.4(a) and (b). Note that the CL and OL signals had the same launching power in the measurement. The measured small inter-channel crosstalk demonstrates that the OFDM-MGDM scheme is a very promising solution to increase the capacity of an MMF link. A 7-dB power penalty is observed for the OL signal, compared to the B2B case, due to the low-pass characteristic of the OL channel (after power loading the signal to noise ratio was reduced) and modal noise. This power penalty can be significantly reduced by using a spatially resolved two-section detector as in [12] to simultaneously detect both CL and OL signals. This detector can also simplify the receiver structure.

## 4. Conclusions

We have experimentally confirmed the feasibility of a 2×2 OFDM-MGDM system. We demonstrate a 25.5-Gb/s (net data rate: 19.86 Gb/s) OFDM-MGDM transmission over a 200-m OM1 MMF, with a modulation bandwidth of 4.25 GHz for each channel. The power penalty induced by inter-channel crosstalk is as small as 0.5 dB.

## 5. References


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