Experimental demonstration of 60 Gb/s optical OFDM transmissions at 1550 nm over 100 m OM1 MMF IMDD system with central launching

Jian Chen (陈 健), Ling Fang (方 玲), Qianwu Zhang (张倩武)*, Junjie Zhang (张俊杰), Yingxiong Song (宋英雄), Yingchun Li (李迎春), and Min Wang (汪 敏)

Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Shanghai University, Shanghai 200072, China

**Corresponding author: zhangqianwu@shu.edu.cn*

Received September 6, 2016; accepted March 9, 2017; posted online April 10, 2017

Record-high 60 Gb/s optical orthogonal frequency division multiplexing (OFDM) transmissions over intensity modulation and direct-detection (IMDD)-based 100 m optical mode (OM1) multi-mode fiber (MMF) links are experimentally demonstrated, utilizing 10 GHz electro-absorption modulated laser intensity modulators at a single 1550 nm wavelength. Adaptive bit loading and a simple central launching scheme of the proposed scheme show an effective way for combating the channel fading and simplifying the system structure. It shows good potential in short reach data center interconnections.

OCIS codes: 060.2330, 060.3510, 060.0060, 060.4080.

doi: 10.3788/COL201715.060603.

Multi-mode fibers (MMFs) have been widely used in broadband local area networks (LANs) to provide cost-effective transmissions due to their large core diameters, which usually enable significant cost reduction in component manufacturing, installation, and maintenance[1–3]. In addition, the low cost, high capacity, and short reach MMF transmission systems attract more and more attention[4,5] due to the rapid growth of bandwidth intensive applications, like interconnections in datacenters and cloud computing. However, some disadvantages, such as narrow modulation bandwidth and variations in transmission system spectral characteristics[6–9], limit the practical implementation of MMF systems[10]. Intensity modulation and direct-detection (IMDD) optical orthogonal frequency division multiplexing (OFDM) is a promising candidate for the abovementioned high capacity MMF transmission systems because of its unique capability, such as excellent resistance to a large amount of differential mode delay (DMD), strong resilience to fiber dispersion, and great potential for cost-effective deployment[11–17]. Making use of adaptive subcarrier bit and subcarrier/sub-band power loading, 20.125 Gb/s real-time dual-band optical OFDM transmissions over 100 m optical mode (OM2)-only MMF systems and 20 Gb/s over 100 m OM1-only MMFs are experimentally demonstrated by Salas *et al.*[6]. The 25.25 Gb/s real-time end-to-end optical OFDM transmissions over an IMDD-based 300 m OM2 MMF link are experimentally demonstrated with tri-sub-band transceiver architecture[18]. Mode-division multiplexing of a 30 Gb/s 2×2 direct-detection OFDM transmission over a 200 m OM3 conventional MMF link is demonstrated by Luo *et al.*[19]. Xu *et al.* experimentally investigated a 25.5 Gb/s 2×2 mode group diversity multiplexing (MGDM) OFDM transmission over a 200 m OM1 MMF with a 4.25 GHz modulation bandwidth for each channel[20]. In addition, some outstanding works on >100 Gb/s optical OFDM [or discrete multi-tone (DMT)] in single-mode fiber (SMF) links have been reported[21,22]. However, such transmission capacity achievement in MMF systems is much lower than in the SMF system.

In this Letter, record-high 60 Gb/s optical OFDM transmissions over IMDD-based 100 m OM1 MMF links are experimentally demonstrated, utilizing a 10 GHz electro-absorption modulated laser (EML) intensity modulators at a single 1550 nm wavelength. Adaptive subcarrier bit loading[23] is also employed to combat the channel fading, which is mainly caused by intermodal dispersion, mode noise, and bandwidth limit of optoelectronic (O-E) devices. Both central launching[24] and offset launching[25] conditions are considered during measurements, and good potential in short reach data center interconnections is shown.

Our experimental setup is shown schematically in Fig. 1, the proposed 60 Gb/s OFDM transmission system in which all digital signal processing (DSP) procedures for both transmitter and receiver are realized by the offline approach. Detailed transceiver and system key parameters can be found in Table 1. At the transmitter side, the input pseudo random data (PRBS15) is first mapped into parallel complex data by using a four quaternatry amplitude modulation (4-QAM), 16-QAM, 32-QAM, or 64-QAM encoder. A 64 point inverse fast Fourier transform (IFFT) module is then used for the generation of OFDM time-domain symbols, where 31 of them can be used to allocate user data in order to satisfy the Hermitian symmetry for a real-valued IMDD OOFDM system. A cyclic prefix (CP) of 16 samples is inserted into each OFDM symbol to avoid inter-symbol interference (ISI) during transmission. Each frame is composed of 100 OFDM symbols, where the

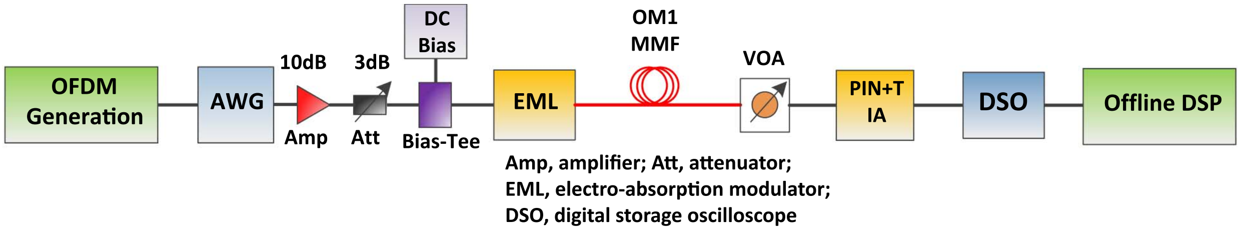

Fig. 1. Experimental setup for the 60 Gb/s OFDM MMF system.

Table 1. Transceiver and System Parameters

Parameter	Value
Modulation format	64/32/16/4-QAM
IFFT/FFT size	64 points
CP length	16 points
Signal line rate	60 Gb/s
OFDM symbols per frame	100 symbols
MMF length	100 m
MMF core size (fiber type)	62.5 μm (OM1)
EML modulation bandwidth	10 GHz
EML wavelength	1550 nm
EML reverse DC bias voltage	−0.38 V
EML driving voltage	1.23 Vpp
PIN detector bandwidth	12 GHz
AWG sampling rate	24 GS/s
DSO sampling rate	80 GS/s
DSO/AWG resolution	8 bit

first of them are occupied by the training symbol for channel equalization and synchronization. Then, 12 GHz electric OFDM signals are generated by a Keysight M8195A arbitrary waveform generator (AWG) with an 8 bit digital-to-analog converter (DAC) operating at a 24 GS/s sampling rate, and followed by an electrical amplifier and an electrical attenuator to properly adjust the driving voltage. Combined with a −0.38 V optimum reverse direct current (DC) bias, a 1.23 Vpp electric OFDM is used to drive an EML with an integrated 1550 nm distributed feedback (DFB) laser and an electro-absorption modulator with a 10 GHz modulation bandwidth. The 3.99 dBm optical OFDM signal is launched into a 100 m OM1 MMF. Two launching schemes, including central launching and 9 μm offset launching, are introduced during the measurements. A commercially available mode conditioning patch cord is employed to achieve offset launching.

At the receiver side, a 12 GHz PIN transimpedance amplifier (TIA) is utilized for O-E conversion by directly detecting the optical OFDM signal. And the received optical power (RoP) can be adjusted by a variable optical attenuator (VOA). The electric OFDM signal is then captured by a 25 GHz digital storage oscilloscope (DSO, Agilent DSO92504A) with an 8 bit analog-to-digital converter (ADC) operating at an 80 GS/s sampling rate. Signal demodulation can be realized by offline DSP procedures, which include symbol synchronization, CP removal, fast Fourier transforms (FFTs), channel estimation, QAM demodulation, and bit error counting. The transceiver parameters and operating conditions are fixed when the system performance measurements are made.

Adaptive subcarrier bits loading and online optimization of the EML operating conditions are applied for achieving maximum signal transmission capacity. At the first place of the bit loading procedure, the 64-QAM modulation format is assigned to all subcarriers, and then optimizations of transceiver parameters, including laser bias and modulation signal amplitude, are undertaken to push the total bit error rate (BER) lower than forward error correction (FEC) limit. If the total BER is still higher than the FEC limit after the mentioned optimizations, 1 bit is then decreased from the highest frequency subcarrier, according to the unequal bit error distribution caused by the system frequency roll-off. The abovementioned procedure can be repeated until the total BER meets the FEC requirement. The obtained optimum subcarrier bits allocation profile under a 100 m OM1 MMF with a central launching configuration is shown in Fig. 2, which offers a total raw signal bit rate of 60 Gb/s, of which 50 Gb/s can be employed to carry

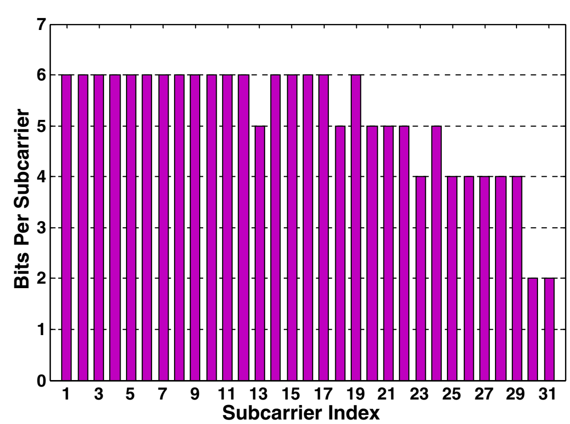

Fig. 2. Adaptively loaded optimum subcarrier bit allocation profile for 60 Gb/s over a 100 m OM1 MMF.

user data because of the use of the 20% CP. Figure 2 also shows that lower signal modulation formats tend to be applied in the higher frequency subcarriers, which is attributed by a high signal bandwidth induced intermodal dispersion, mode noise, and bandwidth limit of O-E devices.

Using the optimized adaptive loading parameters, the results in Fig. 3 show the BER performance of the 60 Gb/s IMDD OFDM system for both the optical back-to-back (OBTB) and the 100 m OM1 MMF configurations under two launching conditions, including central launching and 9 μm offset launching. All of the curves present similar BER developing trends. Compared to the OBTB curve, the performance of central launching has about a 1.4 dB power penalty at the adopted 7% FEC threshold (3.8×10^{-3}). The higher optical power requirement is mainly due to the fiber channel fading as mentioned above.

Compared to the central launching case, another 1 dB power penalty is introduced by using the 9 μm offset launching condition at the FEC threshold. Offset launching is usually adopted in MMF systems to avoid a central axial defect, which is mainly introduced during fiber manufacturing. In this case, the better performance of central launching can be contributed by (a) the employed adaptive loaded scheme, which is effective against fiber channel defects and (b) less intermodal dispersion impairment compared with the offset launching scheme. This indicates that the OM1 MMF can successfully support up to a 60 Gb/s signal line rate by using adaptive loaded optical OFDM signals with a simple central launching scheme without an additional mode conditioning patch cord, which gives a good potential solution to upgrading legacy MMF systems in data center interconnections. To our knowledge, this work is the highest capacity in MMF transmission systems with a directly modulated laser and direct detection.

To deeply understand the above behaviors of system performance, the frequency responses of systems from the input of EML in the transmitter to the output of the PIN detector in the receiver under the aforementioned three different configurations are experimentally measured via a vector network analyzer (VNA). It can be seen from Fig. 4 that the system frequency responses of the OBTB case and the central launching case have similar trend and have a 3 dB bandwidth of 9.8 and 8.7 GHz, respectively. For the offset launching case, the 3 dB bandwidth is around 6.3 GHz. For the frequency region higher than 9 GHz, the curves for all three cases drop sharply, which is mainly because of the effective modulation bandwidth limitation of practical commercial devices, such as the electro-optical modulator, photo detector, and MMF. Consider the employed signal spectral range from the DC to 12 GHz, an up to 8.2 dB frequency roll-off can be observed, which indicates that our adaptive load OOFDM scheme can effectively compensate the channel fading.

We can also find that the frequency roll-off of the offset launching case is more serious than the central launching case. Consider that the offset launching scheme inspires higher-order mode groups than the central launching scheme, which suffers a more serious intermodal dispersion impairment, so center launching scheme still can achieve a better performance even under the experience of slight deterioration due to the imperfect fiber structure. At this point, the MMF high-order mode dispersion becomes the dominant factor for influencing the performance on the current system configuration. This also explains the similar BER behaviors under the abovementioned three system configurations.

The received constellations of the representative subcarriers recorded after channel equalization are shown in Fig. 5 for the central launching case. The constellations are measured at their minimum BERs after transmissions over the 100 m OM1 MMF.

In conclusion, record-high 60 Gb/s optical OFDM transmissions over IMDD-based 100 m OM1 MMF systems are experimentally demonstrated by using 10 GHz EML intensity modulators at a single 1550 nm wavelength. Adaptive subcarrier bit loading is also employed

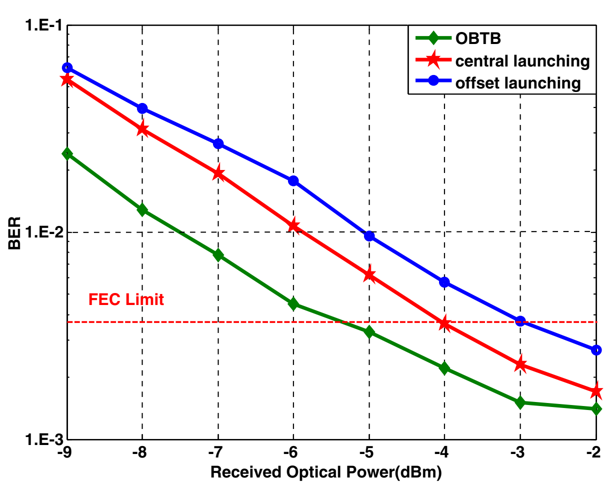

Fig. 3. BER performance of a 60 Gb/s OFDM signal at the OBTB, central launching, and offset launching condition over a 100 m OM1 MMF.

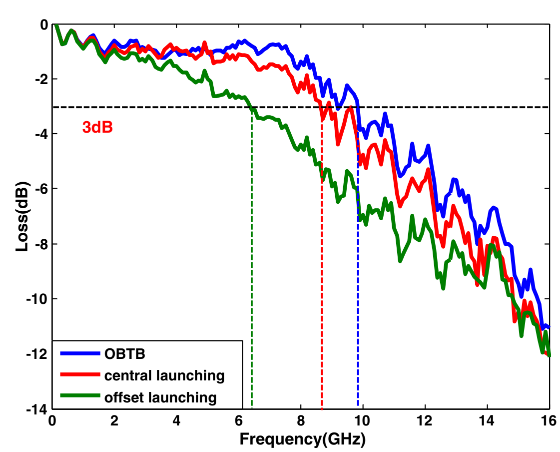

Fig. 4. Frequency responses of OBTB, central launching, and offset launching condition over a 100 m OM1 MMF.

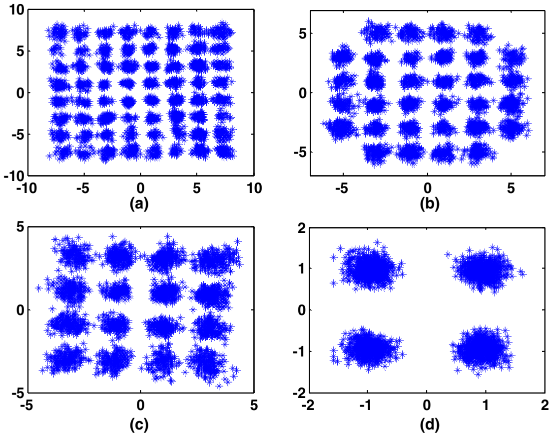

Fig. 5. Constellations of (a) 12th subcarrier (SC), (b) 21st SC, (c) 25th SC, (d) 31st SC for the central launching system over a 100 m OM1 MMF.

to combat the channel fading. Better system performance can be achieved by using simple central launching compared to the conventional offset launching.

This work was supported in part by the Natural Science Foundation of China (Nos. 61420106011, 61601279, and 61601277) and the Shanghai Science and Technology Development Funds (Nos. 15511105400, 15530500600, 16511104100, and 16YF1403900).

References

1. M. E. A. Diab, J. D. Ingham, R. V. Penty, and I. H. White, J. Lightwave Technol. **25**, 2976 (2007).
2. C. Kachris and I. Tomkos, in *Proceedings of OSA/OFC/NFOEC* (2012), paper JTh2A.
3. A. F. Benner, M. Ignatowski, J. A. Kash, D. M. Kuchta, and M. B. Ritter, IBM J. Res. Develop. **49**, 755 (2005).
4. R. E. Freund, C. A. Bunge, N. N. Ledentsov, D. Molin, and C. Caspar, J. Lightwave Technol. **28**, 569 (2010).
5. E. Giacoumidis, S. K. Ibrahim, J. Zhao, J. M. Tang, A. D. Ellis, and I. Tomkos, IEEE Photon. Technol. Lett. **24**, 52 (2012).
6. E. Hugues-Salas, Q. W. Zhang, R. P. Giddings, and M. Wang, in *Future Network and Mobile Summit* (2013), p. 1.
7. J. Xu, J. Von Hoyninhen-Huene, C. Ruprecht, R. Rath, and W. Rosenkranz, IEEE Photon. Technol. Lett. **25**, 206 (2013).
8. L. Cheng, H. Wen, X. Zheng, H. Zhang, and Y. Guo, Chin. Opt. Lett. **8**, 377 (2010).
9. J. Shang, J. Chen, R. Lin, Y. Song, and Y. Li, Chin. Opt. Lett. **11**, S20607 (2013).
10. Z. Yin, G. Liu, F. Chen, and B. Liu, Chin. Opt. Lett. **13**, 071404 (2015).
11. R. Zhang, J. Li, Z. Huang, and Y. Ji, Chin. Opt. Lett. **13**, 072302 (2015).
12. J. Su, X. Li, and J. Yu, Chin. Opt. Lett. **14**, 050608 (2016).
13. X. Q. Jin and J. M. Tang, J. Opt. Network **7**, 198 (2008).
14. Q. W. Zhang, E. Hugues-Salas, Y. Ling, H. B. Zhang, R. P. Giddings, J. J. Zhang, M. Wang, and J. M. Tang, Opt. Express **22**, 6339 (2014).
15. X. Gu, H. Chen, M. Chen, and S. Xie, Chin. Opt. Lett. **10**, 020601 (2012).
16. Y. G. Wang, Y. Q. Wang, and N. Chi, Photon. Res. **2**, 138 (2014).
17. C. C. Gui and J. Wang, Photon. Res. **4**, 168 (2016).
18. R. P. Giddings, E. Hugues-Salas, Q. W. Zhang, J. J. Zhang, M. Wang, and J. M. Tang, IEEE Photon. Technol. Lett. **25**, 2123 (2013).
19. J. W. Luo, J. P. Li, Q. Sui, and Z. H. Li, in *Proceedings of ACP* (2015), paper AS4D.
20. J. Xu, C. Ruprecht, J. Von Hoyningen-Huene, and W. Rosenkranz, in *Proceedings of OSA/OFC* (2013), paper OTh4A.2.
21. W. Z. Yan, T. Tanaka, B. Liu, M. Nishihara, L. Li, T. Takahara, Z. N. Tao, J. Rasmussen, and T. Drenski, in *Proceedings of OFC/NFOEC* (2013), p. 1.
22. T. Tanaka, M. Nishihara, T. Takahara, W. Z. Yan, L. Li, Z. N. Tao, M. Matsuda, K. Takabayashi, and J. Rasmussen, in *Proceedings of OSA/OFC* (2014), paper M2l.5.
23. Q. Yang, W. Shieh, and Y. Ma, IEEE Photon. Technol. Lett. **20**, 1305 (2008).
24. D. H. Sim, Y. Takushima, and Y. C. Chung, J. Lightwave Technol. **27**, 1018 (2009).
25. M. Webster, L. Raddatz, I. H. White, and D. G. Cunningham, J. Lightwave Technol. **17**, 1532 (1999).