600-Gbit/s/λ Mode-multiplexed Bit-loading DMT Signal Transmission for Short-reach Optical Interconnect

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Abstract: Single wavelength 600-Gbit/s bit-loading MDM-DMT signal transmission over 20m OM2 fiber with BER below SD-FEC threshold (2.7×10^{-2}) is demonstrated without MIMO-DSP for mode de-multiplexing. This report shows the potential for future large-capacity short-reach optical interconnects.
OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems

1. Introduction

With the broad applications of online services such as 5G, Internet of Things (IoT), and cloud computing, global data traffic is exploding. Optical transport systems and networks, as the key basis of the global communication infrastructure, are facing unprecedented challenges. Many advanced technologies, such as wavelength division multiplexing (WDM), polarization division multiplexing (PDM), higher-order modulation with coherent detection, are proposed to make the capacity of single-mode fiber (SMF) based systems rapidly approach the nonlinear Shannon's limit [1]. To break through the bottleneck, the space division multiplexing (SDM) has been regarded as the potential solution. Mode division multiplexing (MDM), as one type of SDM technologies, opens an opportunity to short-haul optical interconnects in terms of the widely deployed multimode fiber (MMF) in the existing networks [2, 3]. Recently, some demonstrations of MDM over MMF using coherent detection have been reported [4, 5]. To meet the demand for cost-effective and low power consumption of the short-haul interconnects, the intensity modulation with direct detection (IM/DD) combined with MDM and digital signal processing (DSP) technology has been widely demonstrated [6-10]. Among them, K. Benyahya et al have done a lot of research on high-speed IM/DD MDM transmission system based on multiplane light conversion technology [6, 7]. L. Grüner-Nielsen et al have also demonstrated 20 Gbit/s MDM on Standard 50/125 µm MMF using Photonic Lanterns [8]. In our previous works, 4λ × 405Gbit/s data transmission utilizing discrete Fourier transform spread discrete multi-tone (DFT-S DMT) modulation were implemented [10].

In this paper, we experimentally demonstrate 600-Gbit/s/λ data transmission over 20m OM2 fiber using mode-multiplexed bit-loading DMT modulation. With simple time domain Volterra equalization (TDVE) for nonlinear compensation, 1.11 dB received optical power (ROP) gain can be obtained under the 20% soft-decision forward error correction (SD-FEC) criterion (2.7E-2) [11]. To the best of our knowledge, it is the first report to carry out up to 600-Gbit/s/λ data transmission over standard MMF based on mode-multiplexed bit-loading DMT modulation without multiple in multiple out (MIMO) de-multiplexing. The results have also shown the potential in the large-capacity short-reach optical interconnects, such as the rack-to-rack optical interconnects within data centers.

2. Experimental Setup

Experimental setup and DSP diagram of MDM transmission system is shown in Fig. 1. At the transmitter, the Chow Cioffi Bingham (CCB) algorithm [12] is adopted to allocate the right bits to different subcarriers according to the system response obtained by training sequence (TS) with quadrature phase shift keying (QPSK) modulation format in the system calibration stage. Note that the TS with QPSK signal can obtain a more accurate channel response[13]. An efficient frame packed with 430 data symbols, 30 TS symbols and their complex conjugate is encoded onto 1024 subcarriers. Then 1024-point inverse discrete Fourier transform (IDFT), 32-point cyclic prefix (CP) padding, parallel-to-serial conversion (P/S) and hard clipping are sequentially executed. The DMT signal generated off-line is fed into an arbitrary waveform generator (AWG, Keysight M8194A) with a sampling rate of 115.2 GSa/s to perform digital analog conversion (DAC). The electric signal out of DAC is amplified to 16dBm by an electrical amplifier (EA) with 3-dB bandwidth of 30GHz. The optical carrier from an external cavity laser (ECL) operating at 1550nm with 15.5 dBm power is modulated by a 30GHz bandwidth Mach-Zehnder modulator (MZM) which is driven by 16dBm electric DMT signal. Then the generated optical signal is amplified by the high-power erbium doped optical

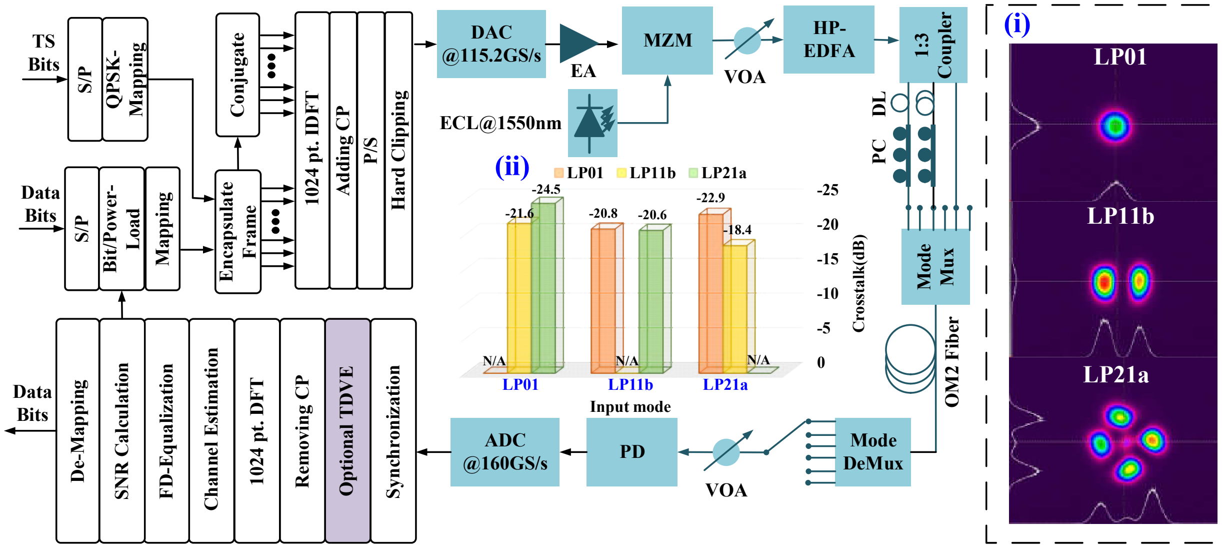

Fig. 1. Experimental setup and DSP diagram of MDM transmission over OM2 fiber. (i) The pattern of selected modes and (ii) inter-mode crosstalk among them.

fiber amplifier (HP-EDFA) and split into 3 uncorrelated optical signal paths to realize the MDM transmission. The entire MDM fiber link consists of a mode multiplexer, 20m OM2 fiber and a mode de-multiplexer. In the experiment, the LP01, LP11b and LP21a modes are selected as independent channels to implement the high speed and large capacity data transmission experiment. Insets (i) and (ii) shown in Fig. 1 display the pattern of selected modes, and the inter-mode crosstalk among them respectively. The mode isolation of used Mux/DeMUX (Cailabs) is less than -18dB that allows us to achieve MDM transmission without MIMO processing. At the receiver side, a PD with a 3dB bandwidth of 50GHz successively performs the photoelectric conversion of bit-loading DMT signals on different modes. Note that the PD used the experiments lacks the trans-impedence amplifier (TIA). And a variable optical attenuator (VOA) is used to adjust the received optical power. Then, the detected electric signal is sampled by Lecory real time oscilloscope with 160GSa/s and processed offline in Matlab. The offline DSP procedure includes synchronization, optional TDVE, removing CP, 1024-point DFT, channel estimation, 1-tap frequency domain equalization (FDE) with and de-mapping. Here, a simple optional TDVE are employed to mitigate nonlinear effects, which may be induced from the cosine modulation function of MZM, the electrical amplifier, clipping of the signal or the signal-signal beating interference (SSBI). The model of *m*-th order TDVE is given by

$$y(n)=\sum_{l_1=-L_1}^{L_1} h(l_1)x(n+l_1)+\sum_{l_1=-L_1}^{L_2}\sum_{l_2=l_1}^{L_2} h(l_1,l_2)x(n+l_1)x(n+l_2)+\ldots+\sum_{l_1=-L_1}^{L_m}\sum_{l_2=l_1}^{L_m}\ldots\sum_{l_m=l_{m-1}}^{L_m} h(l_1,l_2,\ldots l_m)x(n+l_1)x(n+l_2)\ldots x(n+l_m) \quad (1)$$

where $x(n)$ and $y(n)$ are the input and output signal, respectively. L_m is the memory length and $h(l_1, l_2,\ldots, l_m)$ is the *m*-th order Volterra kernel. In this paper, we use 3rd order TDVE, and L_1, L_2 and L_3 are set to 30, 5 and 2 respectively after sweep optimization.

3. Result and Discussion

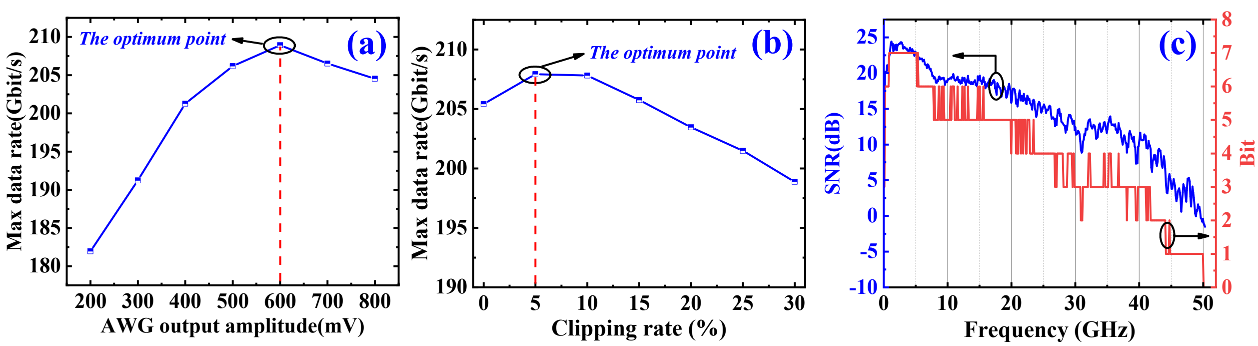

Fig. 2. (a) Max transmission data rate vs. AWG output amplitude, (b) Max transmission data rate vs. clipping rate and (c) Channel response and bit allocation for LP01 mode channel.

In the system calibration stage, we first take the LP01 mode as an example to optimize the system parameters based on the used devices to achieve the best performance. According to the results shown in Fig.2 (a), the optimum V_{pp} of AWG output amplitude of 600mV is chosen to realize the maximum data rate. Meanwhile, in view of the higher peak-to-average power ratio (PAPR) of bit-loading DMT signals, the impact of hard clipping on system performance is shown in Fig. 2(b) and then 5% hard clipping is executed in this paper. Fig.2 (c) shows the channel response of the band limited MDM transmission system and allocation of 1834 bits using the CCB algorithm. Then the total data rate can be reach to $1834/1024\times32/33\times115.2\times3$ = 600-Gbit/s/λ.

The BER performances vs. ROP with and without TDVE of the MDM transmission for LP01, LP11b and LP21a modes have been shown in Fig. 3. With the simple TDVE for nonlinear compensation, 0.58dB, 0.73dB and 1.11dB ROP gains can be obtained for the three mode channels under 20% SD-FEC criterion, respectively. Meanwhile, it is noted that, compared with B2B transmission scenario, LP01, LP11b and LP21a mode channel show a power penalty of 0.37dB, 1.23dB and 1.64dB respectively. This is attributed to the higher-order mode channel has relatively lower mode isolation. Fig. 4 displays the received bit-loading DMT signal constellations of LP21b mode with ROP of 7dBm, including 128QAM, 64QAM, 32QAM, 16QAM 8QAM, QPSK and BPSK. The experimental results indicate that the MDM based transmission system has the potential to upgrade to 800G/1.6T ultra-short reach data center interconnect (DCI) without replacing the deployed multimode fiber.

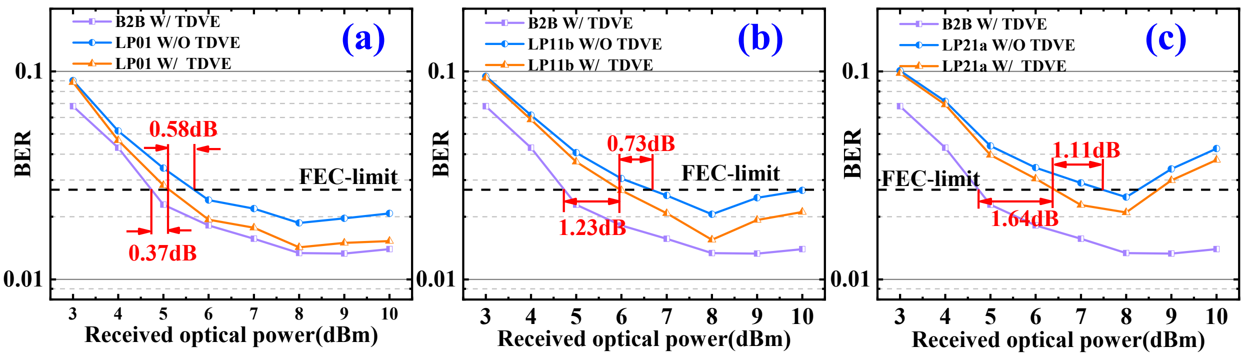

Fig. 3. BER vs. ROP with/ without TDVE for (a) LP01, (b) LP11b and (c) LP21a mode.

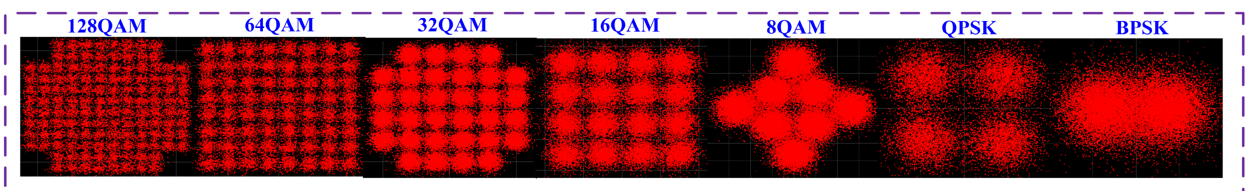

Fig. 4. Received bit-loading DMT signal constellations of LP21a mode with ROP of 7dBm

4. Conclusion

In this paper, we experimentally demonstrate a total data rate up to 600-Gbit/s/λ transmission over conventional OM2 fiber. Enabled by the simple nonlinear compensation with TDVE, a 1.11dB ROP gain can be obtained under the 20% SD-FEC (2.7E-2) criterion. To the best of our knowledge, it is the first report to achieve up to 600-Gbit/s/λ data throughput over standard MMF using bit-loading DMT modulation and IM/DD. The proposed scheme would be a promising candidate for future 800G/1.6T DCI.

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