

Transmission of 200 Tb/s ($375 \times 3 \times 178.125$ Gb/s) PDM-DFTS-OFDM-32QAM super channel over 1 km FMF

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Abstract A few-mode fiber (FMF) is designed to support three spatial modes (LP_{01} , LP_{11a} , and LP_{11b}) and fabricated through plasma chemical vapor deposition (PCVD) and rod-in-tube (RIT) method. Using PDM-DFTS-OFDM-32QAM modulation, wavelength division multiplexing, mode multiplexing, and coherent detection, we successfully demonstrated 200 Tb/s ($375 \times 3 \times 178.125$ Gb/s) signal over 1 km FMF using C and L bands with 25 GHz channel spacing. After 1 km FMF transmission, all the tested bit error rates (BERs) are below 20% forward error correction (FEC) threshold (2.0×10^{-2}). Within each sub-channel, we achieved a spectral efficiency of 21.375 bits/Hz in the C and L bands.

Keywords few-mode fiber (FMF), mode multiplexing, coherent detection

1 Introduction

Ever-increasing data traffic is recently driving an increasing demand for high-capacity optical transport system. The combination of high spectral efficiency (SE) modulation formats, coherent detection, digital signal processing (DSP), and wideband low-noise optical amplification techniques have been regarded as potential solutions to meet this demand [1]. Several optical transport systems from 10 to 100 Tb/s capacity have been demonstrated using single-mode fiber (SMF) in the past 15 years. In 2001, the SMF capacity reached 10 Tb/s for the first time [2]. This record was extended to 25 Tb/s in 2007 [3]. In 2010, Zhou et al. reported 64 Tb/s PDM-32QAM trans-

mission over 320 km SMF [4]. In 2011, Qian et al. reported the first 101.7 Tb/s PDM-128QAM-OFDM transmission over 165 km SMF [5], which is the first 100T demonstration in the world. Later in 2012, Sanol et al. recorded 102.3 Tb/s PDM-128QAM-SC-FDM transmission over 240 km SMF [6]. In 2014, we also demonstrated 100.3 Tb/s PDM-128QAM-DFTS-OFDM transmission over 80 km SMF with ITU-T standardized 25 GHz-channel spacing [7].

However, 100 Tb/s is considered the capacity limit of SMF, which is constrained by fiber nonlinearity and optical signal-to-noise ratio (OSNR). Few-mode fiber (FMF) and multi-core fiber (MCF) have been recently considered as the next step for further capacity increase [8]. From an energy perspective, the FMF is more efficient in (de-)multiplexing and amplification [9] and potentially offers higher information capacity flow per unit area, thereby making FMF a very interesting proposition. In 2011, Ip et al. reported the world's first 26.4 Tb/s DP-4QAM single-carrier wavelength division multiplexing (WDM) transmission over 50 km FMF with three spatial modes [10]. In 2012, Sleiffer et al. showed the 73.7 Tb/s-net rate mode division-multiplexed DP-16QAM single-carrier transmission over 117 km FMF [11]. In 2013, 24.6 Tb/s single-carrier transmission over 177 km FMF with six spatial modes and 26.63 Tb/s over 500 km FMF with three spatial modes and gain-equalized few mode Erbium-doped fiber amplifiers (EDFAs) were reported [12,13]. Table 1 lists the state-of-the-art high-capacity transmissions based on SMF and FMF in recent years.

In this study, we first designed FMF to support three spatial modes (LP_{01} , LP_{11a} , and LP_{11b}). The FMF is then fabricated through plasma chemical vapor deposition (PCVD) and rod-in-tube (RIT) method with ~ 2.9 ps/m. Finally, a $375 \times 3 \times 178.125$ Gb/s mode-multiplexed transmission system over 1 km FMF is experimentally

Table 1 Summary of high-capacity SMF and FMF transmission

transmission over SMF							
total capacity /(Tb·s ⁻¹)	modulation format per channel	bands	number of chan- nels	fiber type	spectral efficiency /(bit·s ⁻¹ ·Hz ⁻¹)	number of modes	year
101.7 [5]	PDM-128QAM-OFDM	C,L	370	SSMF	11	1	2011
102.3 [6]	PDM-64QAM-SC-FDM	C,L	224	PSCF	9.1	1	2012
100.3 [7]	PDM-128QAM-DFTS-OFDM	C,L	375	SSMF	10.7	1	2014
transmission over FMF							
26.4 [10]	PDM-QPSK-SC	C	88	FMF	6.19	3	2011
73.7 [11]	PDM-16QAM-SC	C	96	FMF	12	3	2012
24.6 [12]	PDM-16QAM-SC	C	32	FMF	32	6	2013
26.63 [13]	PDM- QPSK-SC	C	146	FMF	7.3	3	2013

demonstrated. Discrete Fourier transform spreading (DFTS)-OFDM-32QAM is used as the modulation format. Discrete Fourier transform (DFT) spreading is applied in this experiment to reduce the peak-to-average power ratio (PAPR) and mitigate fiber nonlinearity [14,15]. The channel estimation and equalization are based on 6×6 multi-input multi-output OFDM (MIMO-OFDM) DSP scheme. After 1 km of FMF transmission, all the tested bit error rates (BERs) are under the 2.0×10^{-2} FEC threshold, which corresponds to the 20% overhead. Within each sub-channel, we achieved an SE of 21.375 bits/Hz in the C and L bands.

2 Experimental setup

The experimental setup consists of three main building blocks to investigate the performance of 200 Tb/s mode division multiplexing (MDM) transmission systems: 1) generation of DFTS-OFDM signal and optical multi-carriers; 2) FMF design to support three spatial modes (LP₀₁, LP_{11a}, and LP_{11b}); and 3) simultaneous detection of OFDM signal with three spatial modes using commercially available integrated coherent receivers (ICRs). Figure 1 shows the experimental setup for the $375 \times 3 \times 178.125$ Gb/s transmission system modulated by PDM-DFTS-OFDM-32QAM.

2.1 Signal and optical carrier generation

Optical multi-carriers are required to support a 200 Tb/s transmission system. Eight ECLs in the C band and eight ECLs in the L band are first divided into four pairs based on the odd/even mode, respectively, to emulate the 25 GHz spacing of 375 optical channels in the two bands at the transmitter. Each pair is then fed into a phase modulator (PM), which is used as a multi-carrier generator. The PMs are driven by strong RF sine waves (~ 1.5 W) at a frequency of 25 GHz. Each laser is able to generate up to more than

23 optical carriers. In the experiment, 16 lasers provided a total of 375 optical carriers. Two programmable wavelength selective switches are used to combine the PM outputs, which also provides spectral shaping. The total shaped 375 optical carriers are shown in the inset (a) of Fig. 1 and combined after C/L MUX. For the measurement at each sub-wavelength of interest, the corresponding optical carrier is suppressed and replaced with an individual ECL. The transmitted signal is generated offline by MATLAB program with a data sequence of $2^{31} - 1$ pseudo-random binary sequence. The data sequence is then mapped to 32-QAM constellation. The 32-QAM signal is partitioned into two sub-bands, with each sub-band comprising 174 subcarriers. DFT spreading is achieved by taking fast Fourier transform (FFT) to each sub-band with a size of 174. Finally, another inverse FFT of size 512 is applied to the two sub-bands signal to achieve a baseband DFTS-OFDM signal with 348 payload subcarriers. The middle 2 subcarriers are unfilled. Other four subcarriers are also used to estimate the phase noise. About 1/8 of the symbol period (64 samples) is used for cyclic prefix (CP) to avoid channel dispersion and mode group delay. An arbitrary waveform generator (AWG) is used to generate the DFTS-OFDM baseband signal at 12 GSa/s. All optical carriers are then simultaneously modulated by an optical I/Q modulator. Another optical intensity modulator (IM) driven by 8.15625 GHz sine wave is used to further duplicate the signal to three copies. The bandwidth of the transmitted RF signal for each channel is 24.47 GHz, which is slightly less than the channel spacing (~ 25 GHz). The optical OFDM signal is then fed into a polarization beam splitter, with one branch delayed by one OFDM symbol period (48 ns) to emulate polarization-multiplexing. The modulated optical spectrum is shown in the inset (b) of Fig. 1. The data rate is $12 \times 5 \times 2 \times (348 - 2 - 4) / (512 + 64) \times 100 / 120 = 59.375$ Gb/s per sub-band. Thus, the data rate for each channel, considering the three spatial modes, is 3×59.375 Gb/s = 178.125 Gb/s. The optical signal that contains $375 \times$

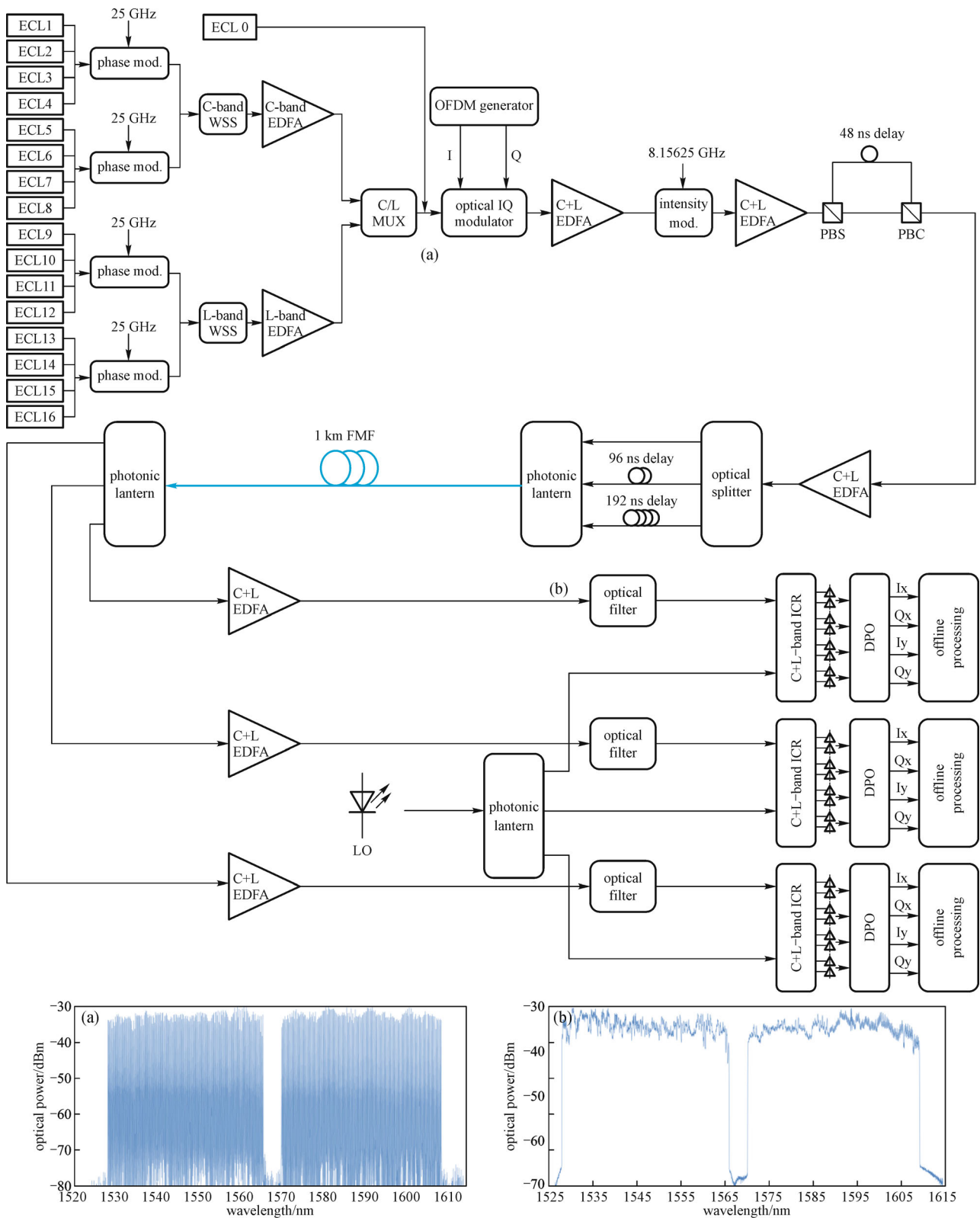


Fig. 1 Experimental setup for the 200 Tb/s PDM-DFTS-OFDM-32QAM over FMF transmission. ECL: external cavity laser. WSS: wavelength selective switch. mod.: modulator. EDFA: Erbium doped fiber amplifier. ICR: integrated coherent receiver. PBS: polarization beam splitter. PBC: polarization beam combiner. MUX: multiplexer. LO: local oscillator. DPO: digital-processing oscilloscope. Inset: (a) 375 generated optical carriers; (b) received spectrum of the OFDM signal

178.125 Gb/s PDM-DFTS-OFDM-32QAM is then split up into three equally powered signals, which are fed to the mode multiplexer. The signals going to the port2 and port3 of the mode multiplexer have delays of 2 (96 ns) and 4 (192 ns) symbols, with respect to the signal going to the port1.

2.2 FMF

We also designed and fabricated a 1 km FMF to support the propagation of LP_{01} mode and degenerate LP_{11} modes, which are referred to as LP_{11a} and LP_{11b} modes. The mode dispersion coefficient between LP_{01} and LP_{11} modes is designed to be ~ 2.91 ps/m. The FMF is based on step index structure with trench. The design is optimized to effectively stabilize LP_{11} mode and cutoff LP_{21} and LP_{02} modes. The FMF is fabricated using the PCVD method and drawn at a drawing speed of 250 m/min with a tension of 188 g using an online RIT process. The detailed specifications of the FMF are shown in Table 2.

Table 2 FMF specifications

optical properties	
numerical aperture	0.13±0.02
attenuation/(dB·km ⁻¹)	@ 1550 nm ≤ 0.23
profile type	step index (Ge doped)
support modes	LP_{01} , LP_{11}
dispersion/(ps·km ⁻¹ ·nm ⁻¹)	$LP_{01} < 22.0$ ps/(nm·km) $LP_{11} < 22.0$ ps/(nm·km)
geometry properties	
1550 nm mode field diameter/μm	8.2±3
cladding diameter/μm	125±2
coating diameter/μm	245±7
coating/buffer specification	
core material	Ge-doped
cladding material	silica
polymer coating	UV resin

The signals coupled randomly among the three spatial modes in FMF transmission. Inter-symbol interference (ISI) is introduced during FMF transmission as the LP_{01} and LP_{11} modes propagated with different group velocities. The ISI is removed through CP in OFDM transmission. We analyzed the mode coupling in 1 km FMF using single-carrier QPSK sequence, which is also transmitted before payload symbols for time synchronization in OFDM systems. The differential group delay (DGD) induced by mode dispersion can be identified by correlating the received QPSK sequence with the transmitted one. As shown in Fig. 2(a), 6 strong peaks are observed, which correspond to the delay of six modes (three spatial modes with two polarization states) at the transmitter side ($512 + 512/8 = 576$). As shown in Fig. 2 (a), each mode has three peaks with an interval of 30 and 5 symbols in Fig. 2(b), which are induced by DGD among the three spatial modes. The sampling rate of QPSK signal is 12 GSa/s in the system identification. Therefore, the DGD after 1 km FMF is about 2500 ($1/12\text{-GSa/s} \times 30 = 2500$ ps) to 2900 ($1/12\text{-GSa/s} \times 35 = 2916$ ps) ps between LP_{01} and LP_{11} modes and coincides with the parameters in FMF design (~ 2.91 ps/m). The CP length of 64 is sufficient to avoid ISI induced by mode dispersion in this experiment.

2.3 Receivers

The signal is sent into a mode de-multiplexer after FMF transmission. The three outputs of the mode de-multiplexer are all amplified by single-mode EDFAs (SM-EDFAs). The optical spectrum of the first output is shown in the inset of (b) in Fig. 1. After amplification, all the three outputs are all filtered out using a 10 GHz tunable optical filter. Therefore, the 8.15625 GHz OFDM sub-bands of interest in the three outputs are selected by the filters. Another ECL is used as local oscillator at the receiver side, which is also power-split into three streams. The three signals after the optical filters and LO are sent into three ICRs. All the receivers connected to the same 50 G-sample

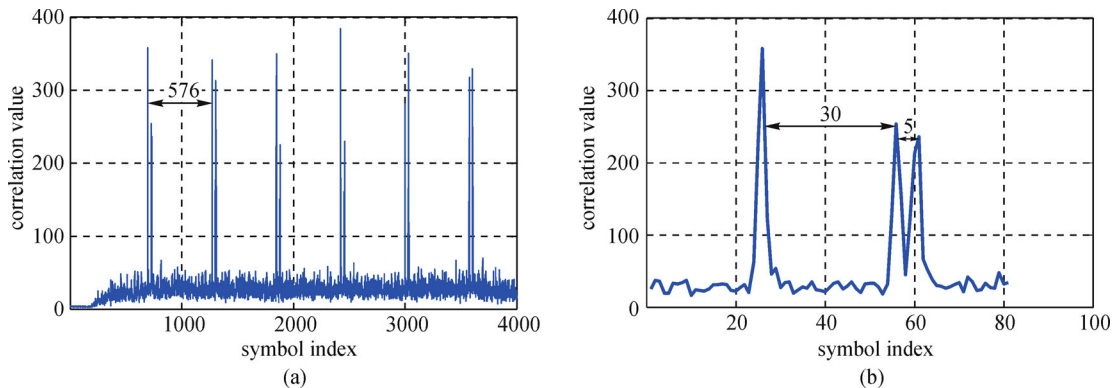


Fig. 2 DGD identification through QPSK sequence of (a) all the six modes; (b) one specific mode

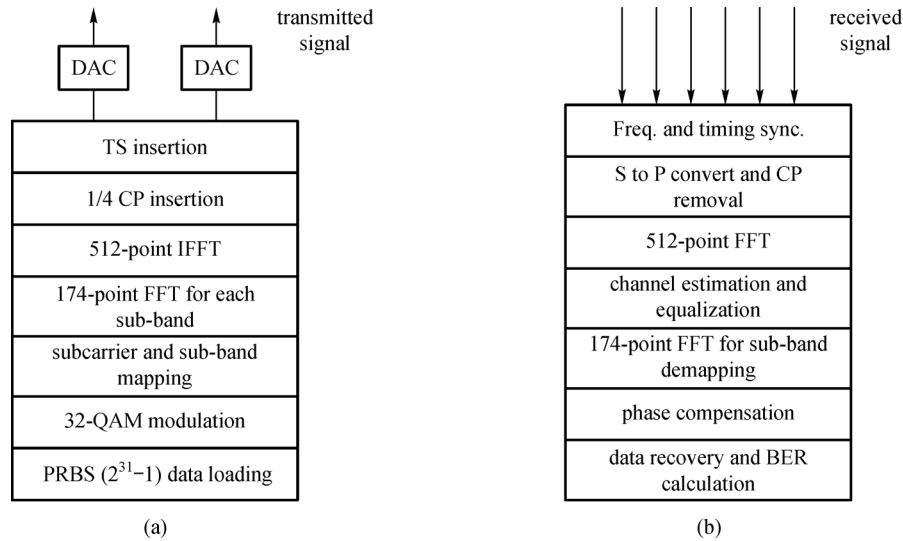


Fig. 3 Digital signal processing at the (a) transmitter side and (b) receiver side

digital sampling scope (DPO in Fig. 1). The delays between the scopes and signals were carefully synchronized before measurement. The samples obtained from the scopes were processed offline using 6 ± 6 MIMO-OFDM DSP algorithm. Consequently, the SE within each channel is $3 \times 178.125 \text{ Gb/s} \times 1/25 \text{ GHz} = 21.375 \text{ bits/Hz}$ after 20% forward error correction (FEC) threshold.

The offline DSP processing is required at the transmitter and receiver sides. The DSP processing at the OFDM transmitter are shown in Fig. 3(a), which is the same as the conventional DFTS OFDM signal generation. The offline DSP processing steps at the OFDM receiver shown in Fig. 3(b) are based on 6×6 MIMO OFDM signal processing [16]. In contrast to previous approaches of using long-memory finite impulse response (FIR) filters for single-carrier system, the use of MIMO-OFDM has the advantage of simplicity in both channel estimation and equalization using one-tap equalizer. The training symbols (TSs) are

designed based on conventional dual-polarization interleave TS scheme [17]. In the present experiment, six TSs are designed as one group, of which only the first time slot in the group is filled with 1 TS and the remaining five are empty.

3 Results and discussion

We first conducted BER versus OSNR performance measurement for PDM-DFTS-OFDM-32QAM signals at 1562.538 nm, which is shown in Fig. 4. The required OSNR for BER of 2×10^{-2} is 17.8 dB for 59.375 Gb/s (8.15625 GHz channel) PDM-DFTS-OFDM-32QAM signal in all three modes. We then performed the BER measurement for all 375 channels in three modes after 1 km FMF transmission; the result is shown in Fig. 5. All the tested BERs are under 20% FEC threshold (2.0×10^{-2}).

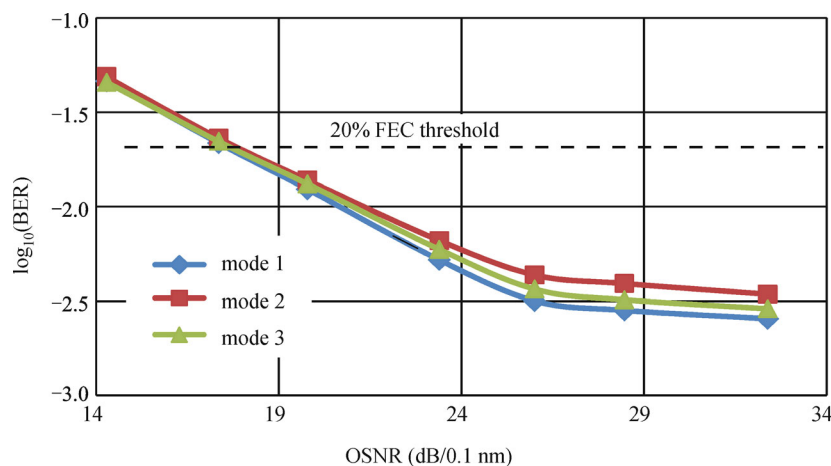


Fig. 4 BER performance of PDM-DFTS-OFDM-32QAM in three spatial modes after 1 km FMF transmission

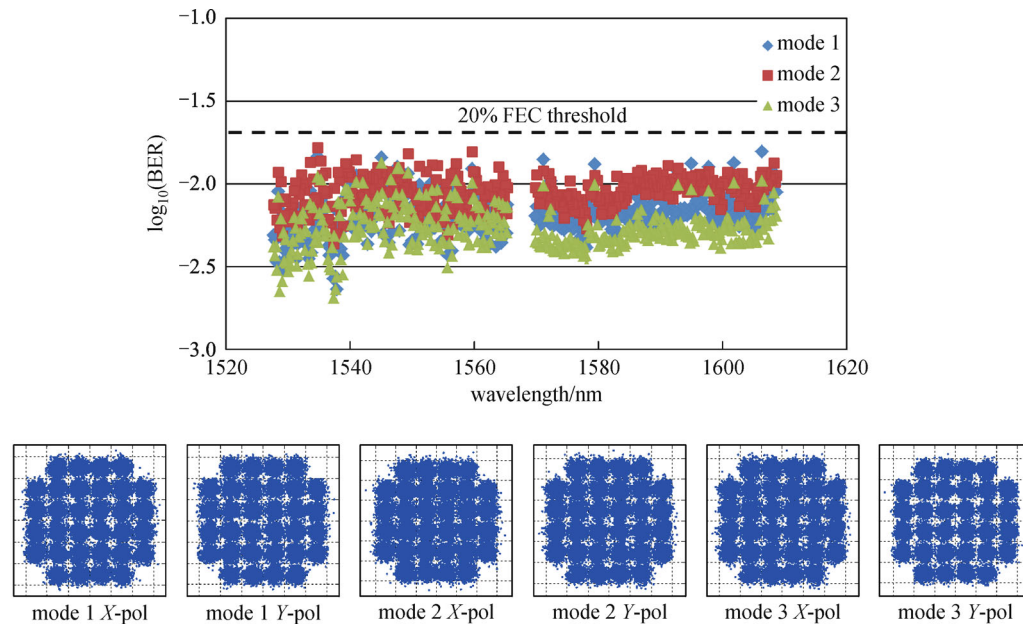


Fig. 5 BER performances of all 375 channels after 1 km FMF transmission. Inset: received optical spectrum and constellations of the recovered OFDM signal

The constellations of the recovered signal of the three modes with two polarizations are also shown in the insets of Fig. 5.

4 Conclusion

In this experiment, we successfully demonstrated a 200 Tb/s ($375 \times 3 \times 178.125$ Gb/s) PDM-DFTS-OFDM-32QAM transmission over 1 km FMF at 25 GHz channel spacing. All the measured BERs are below 20% FEC threshold when the 6×6 MIMO-OFDM DSP technique is applied. The SE within each 25 GHz channel is as high as 21.375 bits/Hz.

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Abbreviations

AWG: arbitrary waveform generator

BER: bit error rate

CP: cyclic prefix

DFT: discrete Fourier transform

DFTS: discrete Fourier transform spreading

DGD: differential group delay

DP: dual polarization

DPO: digital-processing oscilloscope

DSP: digital signal processing

ECL: external cavity laser

FDM: frequency division multiplexing

FEC: forward error correction

FFT: fast Fourier transform

FIR: finite impulse response

FMF: few-mode fiber

ICR: integrated coherent receiver

IM: intensity modulator

ISI: inter-symbol interference

ITU-T: International Telecommunication Union-Telecommunication

MCF: multi-core fiber

MDM: mode division multiplexing

MUX: multiplexer

OFDM: orthogonal frequency division multiplexing

OSNR: optical signal-to-noise ratio

PAPR: peak-to-average power ratio

PCVD: plasma chemical vapor deposition

PDM: polarization division multiplexing

PM: phase modulator

PRBS: pseudo-random binary sequence

QAM: quadrature amplitude modulation

QPSK: quadrature phase shift keying

RF: radio frequency

RIT: rod-in-tube

SC: single carrier

SE: spectral efficiency
 SMF: single-mode fiber
 TS: training symbol
 WDM: wavelength division multiplexing
 WSS: wavelength selective switch

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