32-λ×400 Gb/s Single-carrier 120-GBaud QPSK Coherent Transmission over 3075-km G.652.D Fiber Link Using OE-MCM Prototype under Field-deployed Configuration

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Abstract: Enabled by OE-MCM prototype, record 32-λ×400 Gb/s single-carrier 120-Gbaud DP-QPSK transmission is achieved over 49-span 3075-km G.652.D fiber with a link configuration emulating the legacy large-loss field deployment for the first time.

1. Introduction

Driven by the rapid developments of emerging services such as 5G, metaverse and cloud computing, the capacity demands of backbone optical transport network (OTN) have been experiencing explosively growth [1]. In response to the dramatical increase in data communication traffic, coherent optical transmission and digital signal processing (DSP) have promoted the single-carrier transmission rate from 10 Gb/s to 100 Gb/s and beyond over the past few decades [2-3]. To further scale up the transmission capacity for next-generation OTN, long-haul single-carrier 400G transmission techniques have gained extensive interests [4-6]. Benefitting from the employments of G.654.E fiber, field trial of 603-km single-carrier 400G dual-polarization 16-ary quadrature amplitude modulation (DP-16QAM) transmission is reported [5], and 60×400Gb/s DP probabilistic-constellation-shaped (PCS) 16QAM transmission is also demonstrated over 1910-km field-deployed fiber [6]. Nevertheless, the cost-effective G.652.D fiber is still the mainly deployed fiber in current OTN, and significant decrease of the transmission reach in the above 400G systems can be foreseen if the costly G.654.E fiber is replaced by G.652.D fiber having larger loss and stronger nonlinearity. To accelerate the practical applications of single-carrier 400G techniques, we should avoid the performance rollback of long-haul 400G transmission over legacy large-loss G.652.D fiber links. In this context, quadrature phase-shift keying (QPSK)-based 400G scheme may be a fascinated candidate since it is not only more tolerable to nonlinearity but also more resistant to the noise when comparing with the previously adopted 16QAM or PCS-16QAM. The former feature allows for higher launching power, while the later one can relax the requirements for received optical signal to noise ratio (OSNR).

In this paper, 120-GBaud DP-QPSK transceiver prototype is firstly built by optoelectronic multiple-chip module (OE-MCM) packaging technique. Then, a 49-span G.652.D fiber link is established with a configuration emulating the legacy large-loss field deployment, based on which 3075-km 32-λ×400 Gb/s DP-QPSK transmission experiment is demonstrated. To the best of knowledge, it is the longest reach of point-to-point single-carrier 400G transmission adopting engineering transceiver.

2. System Architecture

Fig. 1(a) shows the schematic diagram of the single-carrier 400G DP-QPSK point-to-point transmission system over 3075-km G.652.D fiber with a link configuration emulating the field deployment from Ningbo City to Guiyang City in China. The whole field-deployed G.652.D fiber link is divided into 49 spans, along which 8 wavelength-selective switches (WSSs) are used as optical gain equalizers for compensating the cascaded uneven gain of optical amplifiers. The fiber length of each span ranges from 37.22 km to 90 km, which is different from traditional laboratory trials with equal-length spans. Aside from the propagation loss of fibers, extra loss from 1 dB to 3 dB is introduced by movable connectors, and variable optical attenuators (VOAs) with power attenuation of larger than 2.5 dB are also placed in each span for engineering link budget reservation. Fig. 1(c) depicts the total loss of each span. We can see that the total loss for 53.1% of spans exceeds 22 dB, for 28.6% of spans exceeds 25 dB, and the maximum span loss has even reached about 33.2 dB. To verify the feasibility of single-carrier 400G DP-QPSK transmission applied for long-haul OTN, the G.652.D fiber link in this experiment is configured referring to the actual condition of field deployment presented above. The signal amplification is mainly achieved by Erbium-doped fiber amplifiers (EDFAs) and 25 backward distributed Raman amplifiers (BDRAs) are also adopted for the spans with loss of larger than 22 dB to improve the received OSNR.

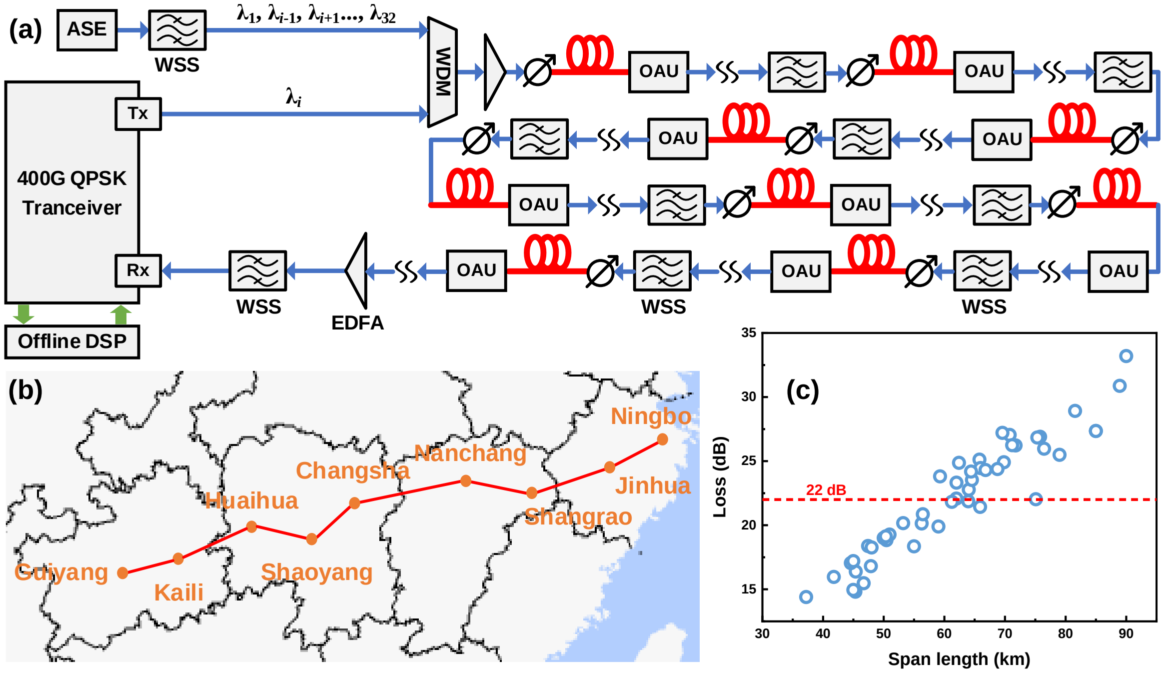

Fig. 1 (a) Schematic of the single-carrier 400G DP-QPSK transmission over 3075-km G.652.D fiber link with a configuration of emulating (b) the field deployment from Ningbo City to Guiyang City in China (OAU: optical amplifier unit which consists of BDRA and EDFA for spans with loss larger 22 dB, and is just EDFA for else spans); (c) scatter diagram of total loss for 49 spans versus the corresponding field-deployed length.

At the transmitter side, one tested channel is generated by a 120-GBaud DP-QPSK transceiver prototype, while 31 dummy channels are produced by an amplified spontaneous emission (ASE) noise source flattened by a WSS, which are shaped like the same as the spectrum of the tested channel. The central frequency of all 32 channels ranges from 191.4 to 195.9 THz with a channel spacing of 150 GHz. All the channels are multiplexed by a WSS and then fed into the transmission link. At the receiver side, the dense wavelength-division multiplexed (DWDM) signal is demultiplexed by another WSS and the tested channel is detected by the transceiver.

Fig. 2 (a) and (b) have illustrated the schematic and photo of the transceiver prototype, respectively. To ensure that the transceiver bandwidth is enough for the generation and reception of the 120-GBaud signal, advanced OE-MCM packaging is implemented, based on which high-speed and high-resolution DAC/ADC, high-baud silicon photonics integrated circuit (PIC) with IQ modulator and hybrid receiver have been integrated in the prototype, as well as dies of linear drivers and TIAs stacked on top of PIC. A dedicated controller is also included in the package. All these key components are packaged on an organic substrate with Ball Grid Array (BGA) attached on the bottom for standard Printed Circuit Board Assembly (PCBA) reflow process. In the future, the transceiver bandwidth can be further improved by stacking the DAC/ADC on top of linear drivers and TIAs to realize a fully-3D packaging. In the module, all optoelectronic devices, except DSP, are on-chip and commercially available. Because the DAC/ADC is

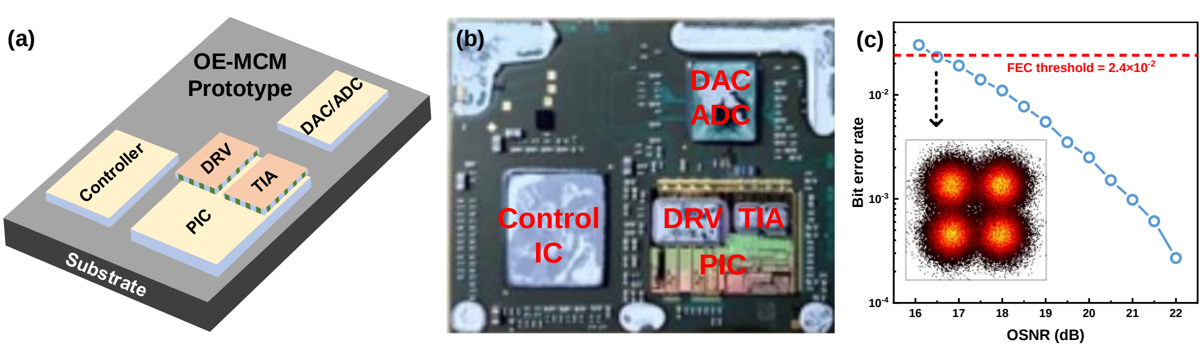

Fig. 2 (a) Schematic and (b) photo of the single-carrier 400G DP-QPSK transceiver prototype; (c) B2B BER curve versus OSNR.

still test-chip, the generation and demodulation of digital signal has to be performed by offline DSP which includes conventional symbol mapping, pulse shaping, pre-compensation at the Tx side and consists of chromatic dispersion compensation, adaptive equalizer, carrier phase recovery at the Rx side. The curve of back-to-back (B2B) bit error rate (BER) versus OSNR is shown in Fig. 2(c) where the inset is a recovered constellation diagram. Here, the B2B OSNR tolerance is about 16.5 dB at a forward error-correction (FEC) threshold of 2.4×10^{-2}, which is significantly better than that of 18.9 dB for PCS-16QAM [6] and implies a superior performance of QPSK for long-haul single-carrier 400G transmission.

3. Experimental results

The transmission performances of the built OE-MCM 400G DP-QPSK transceiver prototype are verified based on the experimental setup illustrated in Fig. 1(a). The measured B2B optical spectrum is depicted in Fig. 3(a) with a wavelength resolution of 0.05 nm. Due to the gain differences among different WDM channels, the overall spectrum is tilted at the transmitter side for balancing the performances after 3075-km G.652.D fiber transmission. Fig. 3(b) and (c) show the BER curve and the curves of OSNR and OSNR margin versus transmission distance, respectively. Because of the performance similarity among all WDM channels, only the channel at the central frequency of 193.2 THz is illustrated. It can be observed that the BER after 3075-km G.652.D fiber transmission is still well below the FEC threshold, and the corresponding OSNR is about 20.3 dB showing a 3.8-dB OSNR margin compared with the 16.5-dB B2B OSNR tolerance. In addition, the BER curve at the transmission reach versus OSNR is shown in Fig. 3(d), while Fig. 3(e) has depicted the curves of OSNR tolerance and OSNR penalty versus transmission distance. We can see that the OSNR tolerance at the transmission reach is about 19.1 dB, which indicates a 2.6-dB OSNR penalty and there is still about 1.2-dB OSNR allowance for accommodating dynamic channel impairment penalties. Fig.3(f) illustrates the scatter diagrams of BERs and OSNRs at the transmission reach for 5 tested WDM channels from short wavelengths to long wavelengths over the C4.8T band. Sufficient OSNR margins of larger than 3.4 dB can be found for all the WDM channels under test, and their BERs are also better than the FEC threshold.

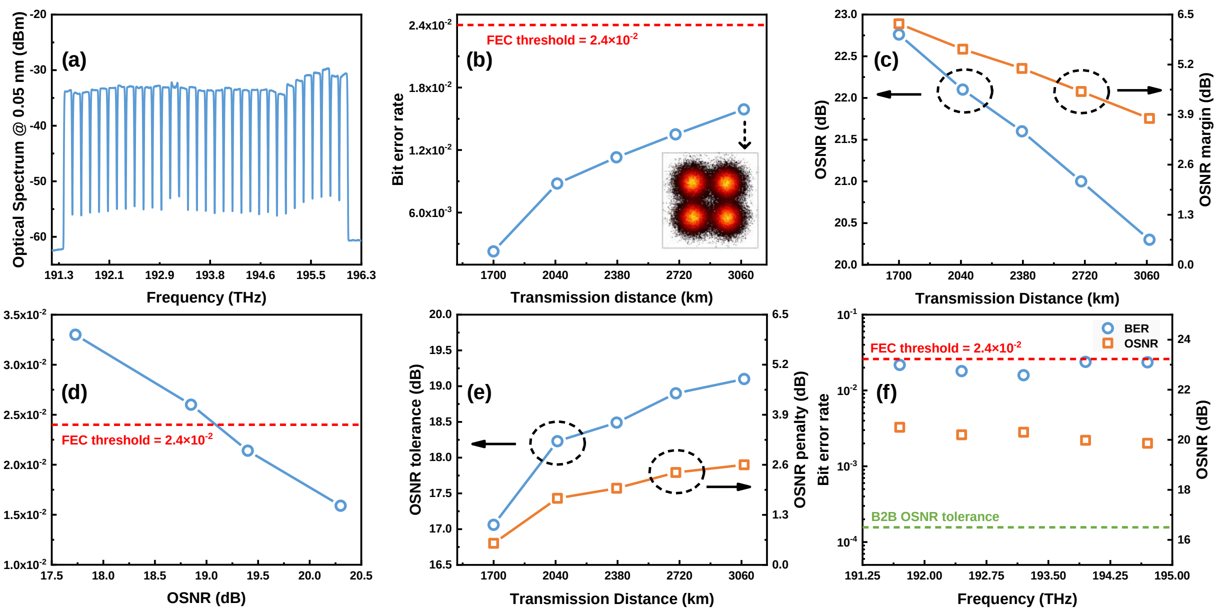

Fig. 3 (a) Measured B2B optical spectrum with a wavelength resolution of 0.05 nm; (b) BER curve versus transmission distance (the inset is the recovered QPSK constellation diagram); (c) curves of OSNR and OSNR margin versus transmission distance; (d) BER curve at the transmission reach versus OSNR; (e) curves of OSNR tolerance and OSNR penalty versus transmission distance; (f) the curves of BER and OSNR at the transmission reach versus five WDM channels under test.

4. Conclusion

Using OE-MCM prototype, record point-to-point 32-λ×400 Gb/s single-carrier 120-GBaud DP-QPSK transmission is achieved over unequal 49-span 3075-km G.652.D fiber with a link configuration emulating the legacy large-loss field deployment. *This work was supported by National Key Research & Development Program of China (No. 2019YFB1803605)*

5. References

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