Field Trial of Real-time 80-λ×400-Gb/s Single-carrier 128-GBd DP-QPSK Transmission Covering 12-THz C+L Band over 2502-km Terrestrial G.652.D Fibre

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Abstract *We demonstrate a record of real-time 80-λ×400-Gb/s DP-QPSK field transmission over 2502-km terrestrial G.652.D fibre based on 6-THz C-band and 6-THz L-band EDFAs jointly with backward distributed Raman pumping in partial large-loss spans.*

Introduction

Driven by rapid developments of various data-hungry applications, capacity demands of optical transport network (OTN) have been experiencing explosive growth [1]. With 100G and beyond dense wavelength-division multiplexed (DWDM) systems widely deployed, single-channel 400G techniques are promising to further increase the network capacity [2].

There have been some discussions on long-haul 400G terrestrial field transmission [3-5]. A field trial of 60-λ×400-Gb/s transmission over 1910-km G.654.E fibre is reported using 95-GBd dual-polarization 16-ary quadrature amplitude modulation with probability constellation shaping (DP-16QAM-PCS) [5]. However, given that cost-effective G.652.D fibre is still the mainly-installed one, its larger loss and greater nonlinearity would significantly degrade the transmission reach with 400G systems practically deployed. To address this challenge, the 400G scheme operating at a higher symbol rate could be a fascinating solution [6]. Utilizing single-carrier 120-GBd quadrature phase-shift keying (QPSK) signals, a 32-λ×400-Gb/s DWDM transmission experiment with a lab prototype has been demonstrated over 3075-km G.652.D fibre [7]. But it cannot be ignored that the increase of symbol rate would be accompanied with a broadening of DWDM grid, meaning that the available optical bandwidth must be extended correspondingly to ensure that the total capacity could be scaled up with single-channel rate. For example, 80-λ 100G DWDM systems in 50-GHz grid could be easily supported by conventional 4-THz C band, while a grid of 150-GHz is required to accommodate the high-symbol-rate DP-QPSK signals for 400G systems, causing that a total of 12-THz bandwidth over C+L band will be needed to enhance the single-fibre capacity by 4 times than the 100G counterparts. Nevertheless, the practical application of such a wideband system is always shackled by the difficulty of providing low-noise gain up to 1626 nm with mature L-band erbium-doped fibre amplifiers (EDFA) [8].

In this paper, we demonstrate, for the first time, a field trial of 80-λ×400-Gb/s single-carrier 128-GBd DP-QPSK transmission with 6-THz C (C6T, 1525~1572 nm) and 6-THz L (L6T, 1576~1626 nm) bands over 2502-km G.652.D fibre. Real-time modules with digital signal-processing (DSP) on Application Specific Integrated Chip (ASIC) are implemented for the signal generation and reception. The wideband amplification is realized here by adopting corresponding EDFAs for each band, and meanwhile backward distributed first-order Raman pumping is utilized as a supplement in partial large-loss spans to slow the reduction of optical signal-to-noise ratio (OSNR). This work shows that even with legacy G.652.D fibres, the requirements of long transmission reach and high throughput could still be met simultaneously for 400G systems, which would greatly promote single-channel 400G techniques toward practical applications in terrestrial backbone networks.

System Architecture

Figure 1(a) shows the schematic of the 80-λ×400-Gb/s field trial system with C6T- and L6T-band amplification over 2502-km G.652.D fibre, which is built on a Chinese terrestrial fibre link connecting two cities: Changsha and Guian. At the transmitter side, an amplified spontaneous emission (ASE) source is separately shaped for C6T or L6T band by corresponding wavelength-selective switches (WSS) to respectively emulate 40 WDM channels for each band with 150-GHz grid resulting in 6-THz bandwidth per band. The channel of interest (COI) is created for each band

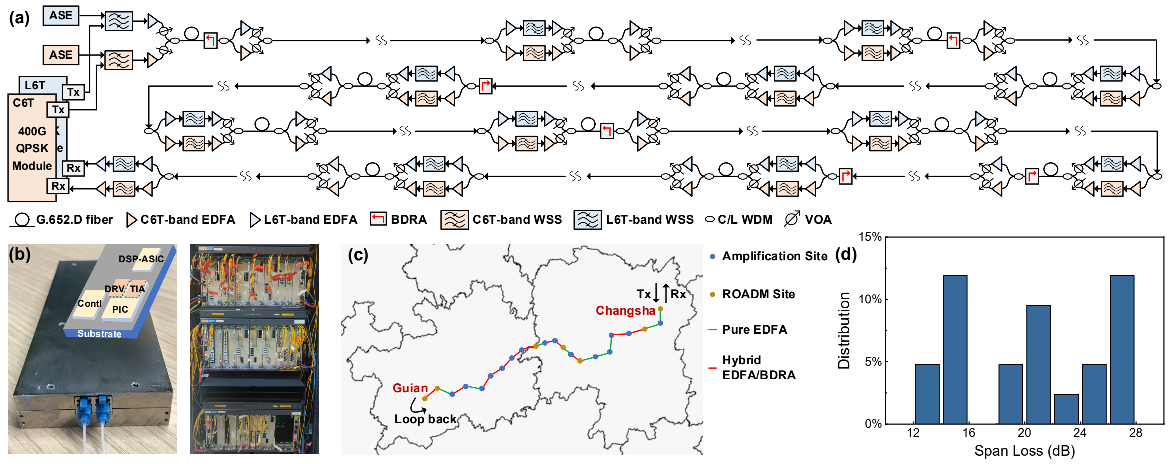

Fig. 1: (a) Schematic diagram of the 80-λ×400-Gb/s field trial system with 6-THz C-band and 6-THz L-band amplification over 2502-km terrestrial G.652.D fibre; (b) photos of the adopted real-time single-carrier 128-GBd DP-QPSK optical module (inset is the schematic of the 2.5D-stacked chip) and the optical sub-rack built at Changsha; (c) geographic location of the Chinese field-deployed fibre link between Changsha and Guian; (d) loss distribution of the 42 field-installed G.652.D fibre spans.

by a single-carrier 128-GBd DP-QPSK module, in which DSP-ASIC is co-packaged with photonics integrated circuit (PIC), Tx-driver (DRV) and Rx-transimpedance amplifier (TIA) in a 2.5D manner, as displayed in Fig. 1(b).

The transmission line is divided into 42 field-installed G.652.D fibre spans, along which 11 sets of WSSes deployed at reconfigurable optical add-drop multiplexer (ROADM) sites are adopted for equalizing cascaded gain ripples of optical amplifiers and power transfer introduced by inter-channel stimulated Raman scattering (ISRS) [8]. The signal is transmitted from Changsha to Guian and then looped back without regeneration. A pair of G.652.D fibres between the 2 cities are used for achieving a total transmission distance of 2502 km, and the span length ranges from 37.22 km to 85 km. Fig. 1(c) presents the loss distribution, in which the losses for 57% of spans are greater than 20 dB and the maximal one is up to 27.4 dB. The span loss includes propagation loss, fusion splicing loss, and engineering margin reservation of 0.06 dB/km provided by variable optical attenuators (VOA). The VOAs are placed before each span and plugged on EDFAs. At the end of each span, the signals are demultiplexed and then amplified by inline C6T- or L6T-band EDFAs. For partial spans with losses exceeding 22 dB, backward distributed Raman amplifiers (BDRA) are employed with 6 multiplexed first-order backward pumps at 1420 nm, 1435 nm, 1460 nm, 1473 nm, 1480 nm and 1513 nm. The Raman on-off gain is about 10 dB for the 2 bands. At the end of the transmission line, the COI is filtered by a WSS for each band and detected by corresponding coherent 400G modules.

Results and Discussion

Figure 2(a) shows the evaluated back-to-back (B2B) OSNR tolerance versus λ by sweeping the COI over 9 tested channels from the shortest to longest wavelengths in each band, while the inset depicts the curves of B2B bit error rate (BER) versus OSNR for 2 channels respectively centred at 193.6 THz and 187.4 THz. We can see that at the forward error-correction (FEC) threshold of $3{\times}10^{-2}$, the average OSNR tolerance of C6T band is about 15.87 dB, while that of L6T band slightly degrades to around 16.43 dB. The gain and noise figures (NFs) of C6T- and L6T-band EDFAs have also been experimentally measured across each band, as depicted in Fig. 2(b). For C6T- and L6T-

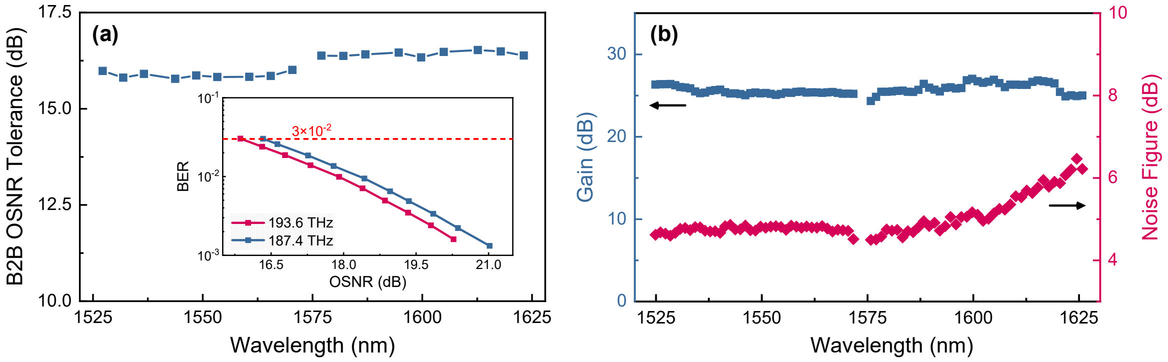

Fig. 2: (a) Measured B2B OSNR tolerance versus λ (inset is the B2B BER curve versus OSNR for 2 channels respectively centred at 193.6 THz and 187.4 THz); (b) Measured gain and NF versus λ for C6T and L6T EDFAs.

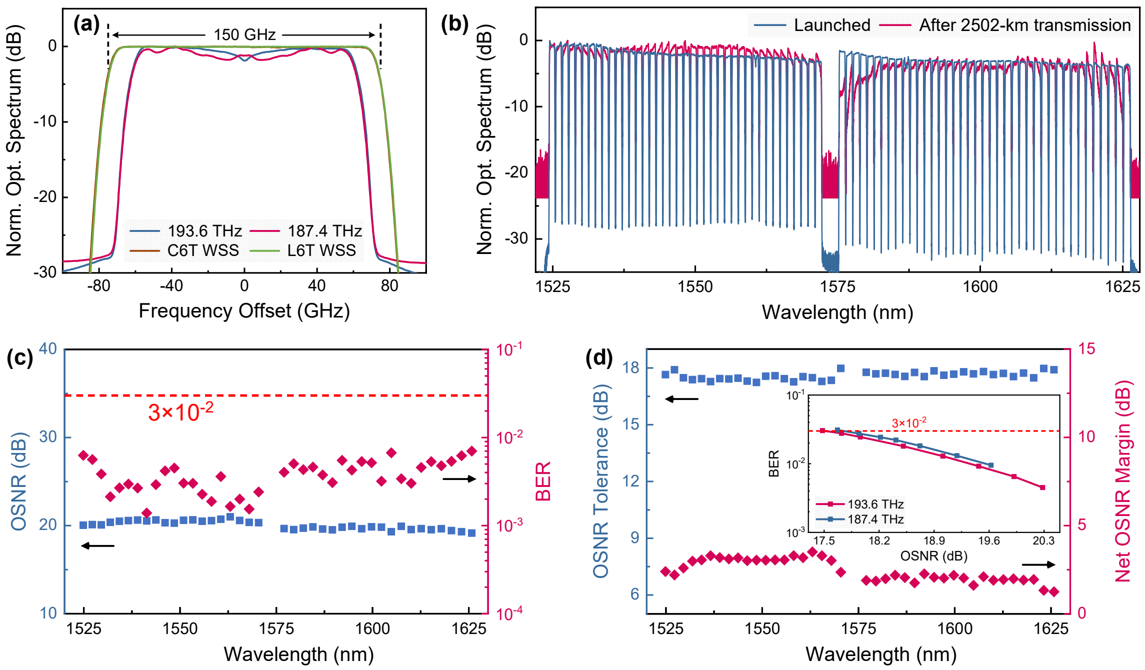

Fig. 3: (a) Measured spectra generated from DP-QPSK modules respectively centred at 193.6 THz and 187.4 THz, as well as the WSS response for C6T or L6T band; (b) measured overall spectra at the transmitter and receiver sides; (c) measured OSNR and BER versus λ; (d) measured OSNR tolerance after 2502-km transmission and the net OSNR margin versus λ (inset is the received BER curve versus OSNR for 2 channels respectively centred at 193.6 THz and 187.4 THz).

band EDFAs, their respective average gains are 25.5 dB and 25.9 dB with corresponding gain ripples of 1.4 dB and 2.7 dB, while the NFs are not larger than 4.9 dB and 6.5 dB, respectively.

Fig. 3(a) presents the signal spectra produced by the 400G modules of C6T and L6T bands, as well as the corresponding WSS responses. We can see that the 128-GBd DP-QPSK signals are well accommodated in the frequency grid of 150 GHz, which could be helpful for mitigating the cascaded filtering penalty introduced by inline WSSes. Fig. 3(b) shows the launched 80-λ×400-Gb/s DWDM optical spectrum across the whole C6T and L6T bands, as well as the received one after 2502-km G.652.D fibre transmission. The optimized launch power of C6T band is 23 dBm, and that of L6T band is 21.5 dBm. It should be noted that because the VOAs used for reserving engineering margins are placed in front of each span, ISRS has been greatly suppressed in the transmission line. The mean loss provided by VOAs is about 3.6 dB, which could produce ISRS reduction as equivalent as the increase of fibre effective area from 80 μm^2 to 182 μm^2 according to the coupled power equations describing ISRS [9]. Hence, the launched spectrum is only tilted slightly with a maximal per-channel difference of 3.1 dB to balance the transmission performances. The COI is swept over 20 tested channels from the shortest to longest wavelengths of each band for evaluating the DWDM system performances. As shown in Fig. 3(c), flat received OSNRs are achieved over C6T and L6T bands with average values of respectively 20.5 dB and 19.6 dB, while the BERs of tested channels are also well below the FEC threshold of 3×10^{-2}. It can be seen from Fig. 3(d) that the average OSNR tolerances after 2502-km transmission are respectively 17.5 dB and 17.7 dB for C6T and L6T bands, showing corresponding optical path penalties of about 1.6 dB and 1.27 dB. The similar OSNR tolerances for the 2 bands can also be observed in the inset of Fig. 3(d), which displays the BERs versus OSNR for 2 channels respectively centred at 193.6 THz and 187.4 THz. Moreover, the net OSNR margin defined by the difference between the OSNR and OSNR tolerance after 2502-km transmission are also shown in Fig. 3(d). For C6T and L6T bands, their respective average net OSNR margins are 3.0 dB and 1.9 dB, which ensures the service stability with dynamic system impairments.

Conclusions

In conclusion, we have demonstrated a total capacity of 32 Tb/s with 80×128-GBd DP-QPSK channels covering 12-THz optical bandwidth over 2502-km distance by implementing a 42-span C6T+L6T-band repeated system. This is the first field trial verifying the feasibility of long-haul high-capacity 400G DWDM systems built on legacy G.652.D fibre, which would pave the way for the upgrade of terrestrial long-haul networks.

Acknowledgements

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