Nonlinear-penalty-free Real-time 40×800Gb/s DP-64QAM-PCS Transmission with Launch Power of 28 dBm over a Conjoined-tube Hollow-core Fiber

Dawei Ge[1], Shoufei Gao[2], Mingqing Zuo[1], Yuyang Gao[3], Yinging Wang[2], Dechao Zhang[1], Wei Ding[2,*], Han Li[1,*], Xiaodong Duan[1] and Zhangyuan Chen[3]

[1]*Department of Fundamental Network Technology, China Mobile Research Institute, Beijing 100053, China*
[2]*Institute of Photonics Technology, Jinan University, Guangzhou 510632, China*
[3]*State Key Laboratory of Advanced Optical Communication Systems and Networks, Peking University, Beijing 100871, China*
*lihan@chinamobile.com, dingwei@jnu.edu.cn

Abstract: Real-time 40×800Gb/s DP-64QAM-PCS transmissions over three different optical fibers (i.e., CTF, G.652.D, G.654.E) are tested under 28-dBm launch power for the first time. No nonlinear penalty is observed in the CTF link. © 2023 The Author(s)

1. Introduction

Recent years have witnessed surprising progress in loss reduction of hollow-core fiber (HCF). After the emergence of the first low-loss anti-resonant conjoined-tube fiber (CTF) of 2 dB/km at 1512 nm [1], the latest attenuation record has come to <0.174 dB/km in a double nested anti-resonant nodeless fiber (DNANF) [2], already lower than the loss value of widely-used G.652.D fiber. These achievements open up a promising prospect that the revolutionary era of constructing a new optical communication network over HCF is coming. Apart from lower losses than conventional fibers, HCFs have extra advantages of ultra-low latency, ultra-low nonlinearity, ultra-wide transmission window, and low chromatic dispersion for optical communications. A number of data transmission experiments exploiting these HCF properties have been reported. A transmission of 61 C-band channels over a 618 km loop of NANF-6 with L-band interferers was demonstrated to validate the potential of long-haul transmission and negligible stimulated Raman scattering (SRS) influence [3]. Further, a 2070-km WDM loop transmission in a reduced intermodal interference (IMI) NANF-5 was recently reported that expanded the distance of HCF transmission system to 1000's km level [4]. A multi-band transmission with a record 700-nm bandwidth over 1-km NANF-6 was presented as well [5]. Variety of excellent characteristics of NANFs have been verified and pushed to the limit. However, Kerr nonlinearity as one of the most important characteristics has not been pushed to such limit yet in low-loss NANF, though a high launch power experiment has been reported on two sections of 220-m high-loss single-ring ARF with 41/58-dB/km attenuations, respectively [6].

In this paper, to verify the low impact brought by Kerr nonlinearity, i.e., self-phase modulation (SPM) and cross-phase modulation (XPM), we utilize a high-power erbium doped fiber amplifier (EDFA) with an output power up to 28 dBm, to enlarge the launch power into the hollow-core conjoined-tube fiber (CTF) fabricated by ourselves. A real-time 800Gb/s dual-polarized 64 quadrature amplitude modulation with probabilistic constellation shaping (DP-64QAM-PCS) optical module is used for signal transmission. After taking out the influences of connections and patch cords, no significant nonlinear penalty can be observed while G.652.D and G.654.E fibers with the similar length are all unable to transmit valid signals. This result proves that nonlinear-penalty-free ultra-high-power transmission for CTF is entirely feasible.

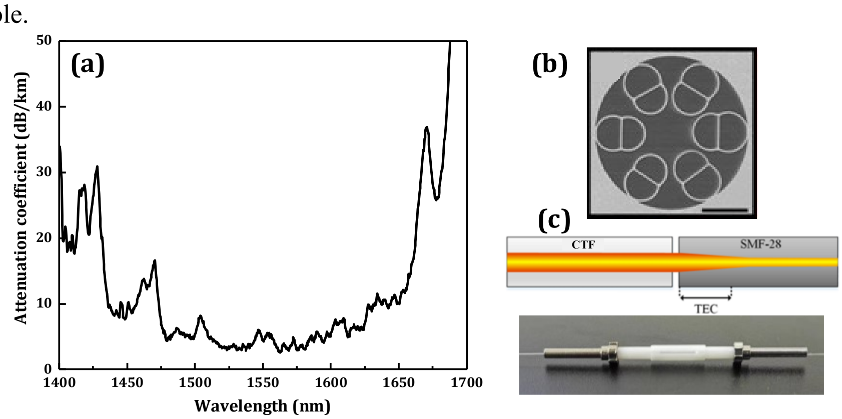

Fig. 1 (a) Measured loss spectrum and (b) cross-section of CTF. (c) Schematic mode evolution and (d) photograph of a CTF-SMF interconnection.

2. Fiber link preparation and data transmission setup

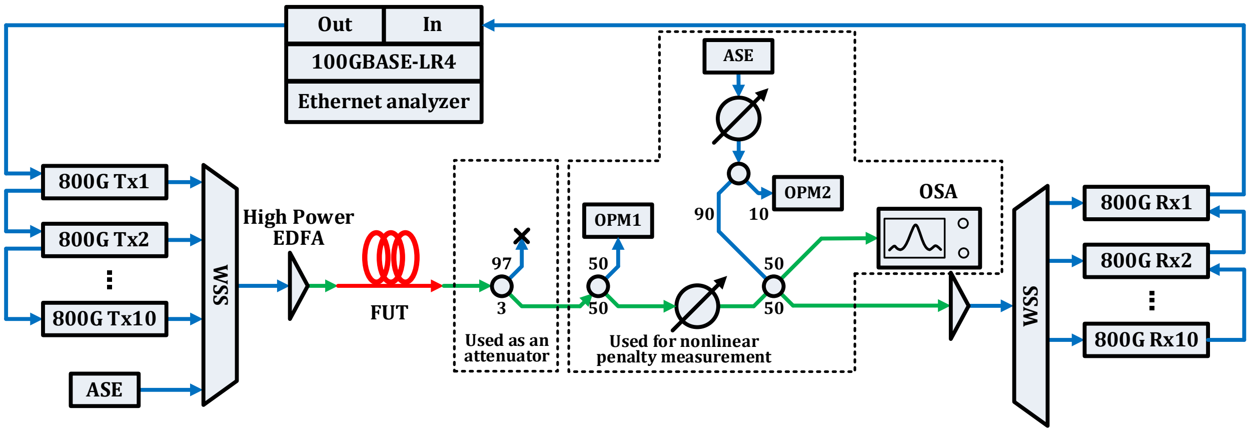

Fig. 2 Setup of real-time 40×800Gb/s DP-64QAM-PCS transmission over a fiber link.

Fig. 1(a) shows the loss spectrum of our CTF with the full length of 190 m warped around a bobbin with a diameter of 15 cm. The scanning electron microscope image of the cross-section of the CTF is shown in Fig. 1(b). To efficiently launch the power of an EDFA into the CTF, low-loss interconnections between the CTF and standard single-mode fiber single mode fibers (Corning SMF-28) are made with a thermally expanded core to play the role of mode-field adapter and an anti-reflection coating to mitigate the Fresnel reflection [7], as shown in Fig. 1(c). Around 0.3 dB insertion losses have been achieved in our CTF-G.652.D interconnections with this performance preserving for about 10 months.

The data transmission setup is shown in Fig. 2. Ten 800Gb/s DP-64QAM-PCS real-time optical modules are used as the transmitters and receivers, whose central frequencies are set to 191.6375, 191.75, 191.8625, 193.6625, 193.775, 193.8875, 195.6875, 195.8, 195.9125, 196.025 THz, respectively, with a channel spacing of 112.5 GHz. Their main parameters are listed in Table 1. It should be noted that no nonlinearity compensation process has been employed in all the 800G modules. A 100GBASE-LR4 module and an ethernet analyzer (VIAVI ONT 603) is used for error checking after transmission and forward error correction (FEC). An amplifier spontaneous-emission noise (ASE) source is used to emulate all the other vacant WDM channels in C-band. The 800G signal and emulated ASE noise are then combined by a wavelength select switch (WSS) and boosted by the high-power EDFA, whose output power can reach 28 dBm. VOA1 is inserted prior to the receivers. A second ASE and other components are used for penalty measurements.

Table 1 Parameters of 800 Gb/s DP-64QAM-PCS real-time module

Modulation		DP-64QAM-PCS	
Net rate	800 Gb/s	SD-FEC BER threshold	2×10^{-2}
Baud rate	95 GBd	B2B OSNR threshold	25.37
Line-side interface	OTU4	Client-side interface	100GBASE-LR4

3. Experimental Results

With the above setup, we can test the transmission performance of a CTF link. For the sake of comparison, we also prepare a 200-m G.652.D fiber link and a 200-m G.654.E fiber link with slightly different mode field areas of 80 μm^2 and 125 μm^2, respectively. Firstly, a single-channel high-power data transmission is conducted. The test wavelength is set to be 1550 nm. We measured the pre-FEC bit error ratio (BER) curves under different launch powers for all the three fibers under test (FUTs). Fig. 3(a) shows an exemplar output spectrum measured after the high-power EDFA. It is seen that although the total output power of the EDFA reaches 30 dBm, the in-band power (marked by the gray band) is ~2 dB lower than the total power. Hence, the launch powers mentioned afterwards will be the measure of in-band powers. As shown in Fig. 3(b), both the G.652.D and G.654.E fiber links (with the length of 200 m) quickly reach their transmission capacity limits as the launch power rises to 27.5 dBm. While for the CTF link, performance slightly deteriorates under a 28-dBm launch power. To clarify the origin of this performance degradation, we measure the pre-FEC BERs of a BTB link of ~10-m patch cord, which precisely overlaps with the curve of the 190-m CTF link. Almost no OSNR penalty caused by 190-m NANF-5 can be observed after taking out the influence of patch cords [Fig. 3(c)]. It is manifest that the loss spectrum of our CTF [Fig. 1(a)] is not ideally flat in C-band, implying that there may be strong overlap between mode field and glass nodes across the whole transmission window. For further

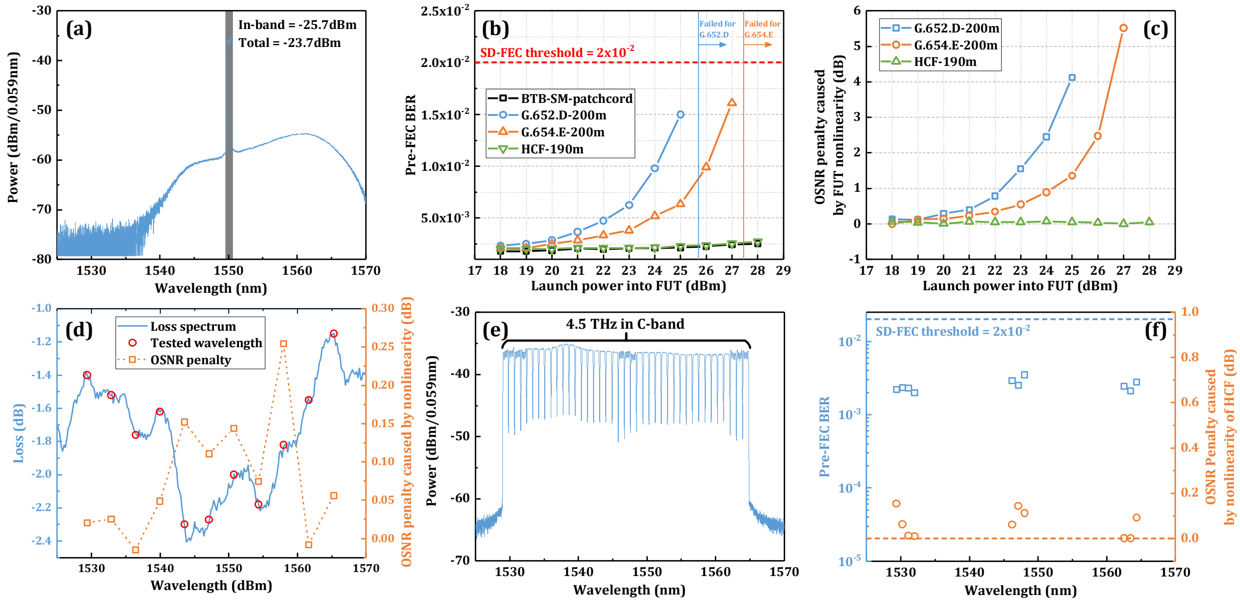

Fig. 3 (a) Measured output spectrum of EDFA. (b) Measured pre-FEC BERs and (c) derived OSNR penalties caused by nonlinearity of FUTs under different launch powers. (d) OSNR penalties measured at different wavelengths. (e) Output spectrum of 40×800-Gb/s DP-64QAM-PCS at receiver end. (f) Measured pre-FEC BERs and OSNR penalties of 10 different 800G channels.

testing, we choose 11 wavelengths in C-band, whose channel spacing is 450 GHz. As shown in Fig. 3(d), the OSNR penalties at these wavelengths tend to be higher when the loss rises, which coincides with our conjecture. Finally, we measure the performance of 40×800G transmission with 12-dBm launch power per channel. Fig. 3(f) shows the pre-FEC BERs and OSNR penalties of 10 selected channels. We can see that even for the CTF with an uneven loss spectrum, all the 10 channels experience negligible nonlinear impacts under high launch powers.

4. Conclusions

In conclusion, real-time C-band 40×800Gb/s transmission over a 190-m low-loss CTF with launch power as high as 28 dBm has been tested to confirm negligible nonlinear penalty. This result validates that nonlinear-penalty-free, high-throughput, high-power data transmission is feasible in CTF. *This work was supported by National Natural Science Foundation of China (61827820, 62075083, 62105122, U21A20506); Fundamental Research Funds for the Central Universities (21620316); Basic and Applied Basic Research Foundation of Guangdong Province (2021A1515011646, 2021B1515020030).*

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