Real-time 33.6 Tb/s (42 × 800 Gb/s) Unrepeatered Transmission over 302 km Using ROPA System

JianJun Wu*[1,2], Jiekui Yu[1,2], Jiasheng Liu[1,2], Qianggao Hu[1,2], Mingxiong Duan[1,2], Wenzhong Wang[1,2], Chao Huang[1,2], Han Long[1,2], Shujuan Sun[1,2], Man Tan[1,2], Liyan Huang[1,2], Jian Xu*[1,2]

1. Accelink Technologies Co. Ltd, Wuhan, 430205, China

2. State Key Laboratory of Optical Communication Technologies and Networks, Wuhan, 430074, China

e-mail: jianjun.wu@accelink.com; jian.xu2@accelink.com

Abstract: This paper demonstrates a record unrepeatered transmission with the capacity of 33.6 Tb/s (42 × 800 Gb/s) over 302.7 km (47.52 dB) with a single fiber configuration, using forward Raman pump, backward ROPA, and ultra-low loss & large effective area fiber.

OCIS codes: 060.2330 Fiber optical communications, 230.4480 Optical amplifiers, 060.1660 Coherent communications.

1. Introduction

The unrepeatered transmission systems aim at achieving ultra-long haul transmission without any in-line active elements, which are widely used in submarine networks, ultra high voltage (UHV) ac power grid construction, as well as in subsea links to connect sparsely populated islands. Such unrepeatered system which can achieve long-distance transmission, do not require in-line active elements, thereby simplify the transmission line and reduce the line complexity and the overall system cost. Over the past several years, people are focus on how to achieve an ultra-long unrepeatered transmission with only a few channels. However, with recent ever-increasing demand for traffic, the ultra high capacity unrepeatered transmission systems has attracted more an more attention. High-capacity transmission is usually realized by expanding the optical bandwidth or improving the spectral efficiency, which requires higher OSNR and lower non-linear threshold level of the system, this tend to reduce the transmission distance. So, it is quite challenging to increase the transmission distance in high-capacity unrepeatered link[1].

Due to the excellent performance of the electronic and optical subsystems, there are many researches on ultra high capacity unrepeatered systems with a throughput above 20 Tb/s so far. Ref. [2] applied a high-power booster and a third order Raman pump to realize a record capacity of 29.2 Tb/s over a 295 km-long unrepeatered link in 2018, and the capacity of 24.6 Tb/s unrepeatered transmission has been demonstrated over 200 km with a ROPA system in 2019[3]. Ref. [4] transmitted 80 Tb/s over 257 km with off-line processing using Semiconductor Optical Amplifiers and Raman Amplification in 2020, and the record real-time unrepeatered transmission of 30.5 Tb/s over 276.4 km without remote amplification was reported in 2021[5]. However, there are no reports to date on high-capacity unrepeatered transmission exceeds 30Tb/s over 300km with commercial transceiver.

Here in this paper, we demonstrated forty-two 800 Gb/s DWDM channels transmission over a 302.7 km unrepeatered link using commercial transceiver with only a single fiber, and the spectral efficiency is 7.11 b/s/Hz. This 33.2 Tb/s capacity unrepeatered transmission was achieved by using high performance high-order Raman pumps, ultra-low loss and large effective area G.654E fiber and enhanced optimal ROPA system. To the best of our knowledge, this is the first real-time 42 × 800 Gb/s unrepeatered transmission using commercial transceiver to reach a record distance.

2. Experiment setup

The experimental setup is shown in Fig.1. The signal generated by a integrated coherent card is PM-64QAM, which is modulated at 95GBaud. The SD-FEC, Probabilistic Constellation Shaping (PCS) and sub-carrier Frequency-Division Multiplexing (FDM) are used in the integrated coherent card at the transceiver. The SD-FEC can correct a BER of 2.0E-2 (Q=6.25 dB) to less than 1.0E-15, and the required OSNR for SD-FEC threshold is 26.8 dB. The spectrum and constellation map of the FDM signal are shown in Fig. 1(c). The spectrum consists of 4 digital sub-carriers which can improve the nonlinearity tolerance of the system[6], and the -20 dB bandwidth is 101.6 GHz. At the transmitter side, four independent real-time modulated signals are combined through Wavelength-Selective Switch (WSS) which can flexibly adjust the channel grid, and the filling dummy channels consist of ASE noise shaped with similar bandwidth as the modulated bandwidth to emulate WDM transmission. The modulated signals are combined with the filling dummy channels using a 1 × 2 coupler. We transmit 42 channels with a 112.5 GHz spacing, the single carrier rate of modulated signal is 800Gb/s. The total bandwidth is 4.7 THz with the frequency ranging from 191.3 THz to 196.1 THz, and the channels and pumps are directly multiplexed and launched into the transmission fiber by IWDM(ISO+WDM). At the receiver side, the signal is counter-directionally amplified by several Raman pumps, and the WSS is used to filter out the signals of different frequencies. The spectrum of the transmitter and receiver WDM signal is plotted in Fig. 1 (d) and (e) respectively.

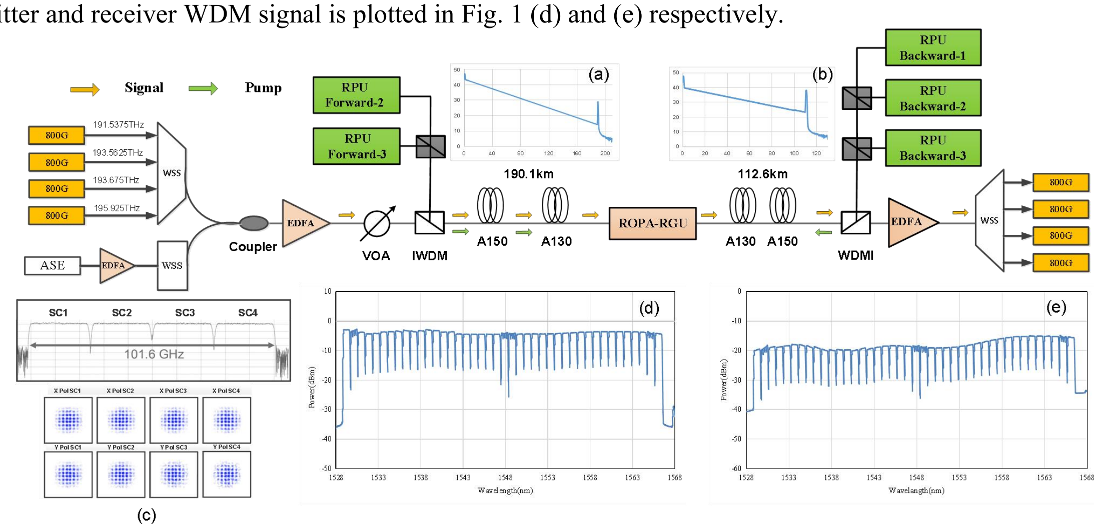

Fig. 1. Experiment setup

The backward ROPA is pumped by a high-order remote pump unit (RPU) located at the receiver side. The forward and backward RPU pumps consist of six and eight pump wavelengths distributed in the range between 1320 nm and 1500 nm respectively. The 1st order pump unit (RPU-1&RPU-2) which realizes Raman amplification for signal and provides residual pumping power for the remote gain units (RGUs) is amplified by the second-order pump unit (RPU-3). The two wavelengths of the RPU-1 operate in the range between 1470 nm and 1500 nm, the wavelength number of RPU-2 at transmitter and receiver side are two ranging from 1420 nm to 1450 nm, and the two wavelengths of RPU-3 operate in the range between 1320 nm and 1360 nm.

The span is assembled with two different G.654E ultra low loss Pure Silica Core Fibers, the effective area of the A150 and A130 are 150 μm^2 and 130 μm^2. The A150 fiber is used to increase the nonlinear threshold, which can support higher signal and pump power launched into the transmission fiber.The transmission link with two span sections divided by ROPA is optimized. The first span from the transmitter to ROAP is 190.1 km, and the second span from the receiver to ROPA is 112.6 km. The larger effective area fiber is placed at both ends, with 100 km at the transmitter side and the receiver side respectively. The total link loss including splices and connectors is 47.5 dB at 1550.12nm, corresponding to an average fiber loss of 0.157 dB/km including splices. As shown in Fig. 1 (a) and (b), the fiber length and the span loss are verified and measured carefully by OTDR and OSA.

3. Transmission results and discussion

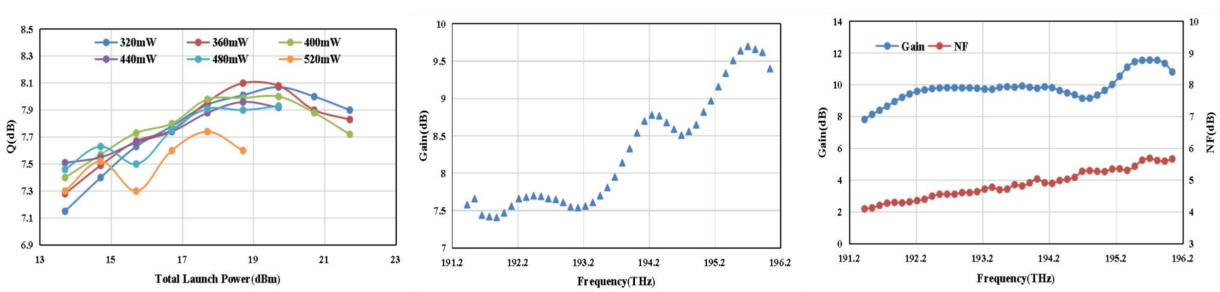

Fig. 2. The Q value under different signal total launched power and pump power(left).The gain spectrum of the forward Raman(middle). The gain and NF profiles of different channels of RGU(right)

The best performance required collective optimization of the signal launch power, RPUs power and the optical structure of RGU. Considering the influence of nonlinear cost in the transmission link, it is very important for ROPA system to select appropriate signal launch power and forward RPUs power. First, A rough optimum for forward RPU-3 power was found at around 1240 mW due to the maximum powers available in this experiment, then the forward RPU-2 powers was scanned at each launch power of signal. Figure 2 (left) shows the Q value of the system with different signal total launched power and different forward RPU-2 power, it should be noted that the best property total signal launched power and forward RPU-2 power in our transmission trial are 18.7 dBm and 360 mW respectively. The gain spectrum of forward Raman in different channels as shown in Fig. 2(middle). The optimized total power of backward associated RPUs delivered is 2360 mW, the residual pump powers reaching RGU is measured to be 20 mW, which can provide about 9.5 dB gain for each channel of RGU in our experiment. The erbium doped fiber (EDF) lengths optimized for RGU is 6 m, and the gain and noise figure profiles of the RGU for different channels are shown in Fig. 3(right).

The signal launched power and received power of each channel are shown in Fig. 3(left), the power of each channel have been adjusted by pre-emphasis processing at the transmitter side, and the gain tilt of received signal powers is accumulated about 5 dB after 303 km transmission. The OSNR of different channels which is measured at the output of the receiver amplifier is shown in Fig. 3(middle), the average OSNR is 29 dB/0.1 nm. We recorded the changes of Q factor and pre-FEC BER values in each different channels within 2 hours, and the maximum pre-FEC BER and Q factor over the duration of the test are shown in Fig.3(right). To check long-term stability of the system, we selected four channels with the worst performance to record the BER before FEC decoding in 24 hours, the absence of post-FEC errors on the client side was monitored using a BER-analyzer, and there are no uncorrected bits to be measured after FEC decoding, which demonstrates the stability of the system.

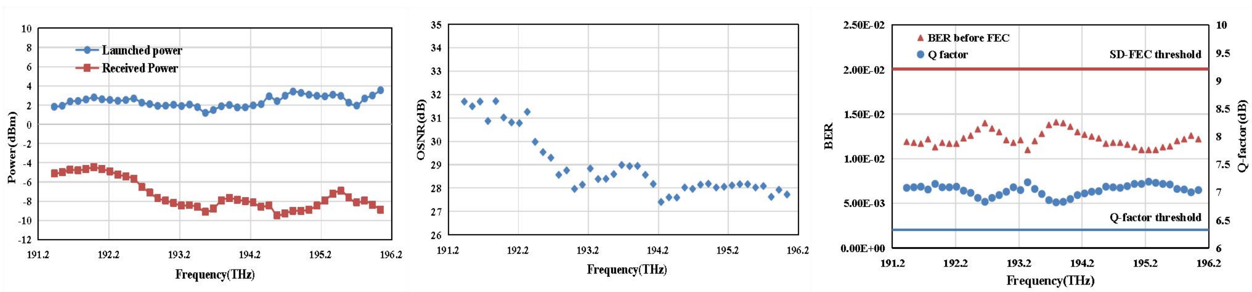

Fig. 4. Signal power of different channels at transmitter and receiver side(left). Receiver side OSNR of each channel(middle). The maximum Q factor and BER values in 2 hours for different channels(right).

4. Conclusion

We presented a new record unrepeatered transmission of 42 channels with the total capacity of 33.6 Tb/s at a spectral efficiency of 7.11 b/s/Hz over 302 km in a single fiber, using the commercial transceiver in 800Gb/s net data-rate per channel. Long-term error-free behavior is achieved by jointly optimization of the optical subsystems including ultra-low loss and large effective area G.654E fiber, optimal RGU design, backward remote optically pumped amplifier with high performance high-order cascaded pumping. This is the longest high-capacity (> 30 Tb/s) unrepeatered transmission over the C-band in a single core fiber today.

References

[1] JianJun Wu. Jian Xu et al. “Unrepeatered Transmission of Single-Carrier 800Gb/s over 404km with Commercial Transceiver and Enhanced ROPA System,” Proc. OFC, F4G.3(2021)

[2] H. Bissessur et al, “Unrepeatered transmission of 29.2Tb/s over 295km with Probabilistically Shaped 64 QAM” Proc. ECOC, Th.1.G (2018).

[3] H. Zhang et al, "Real-time Transmission of Single-Carrier 400 Gb/s and 600 Gb/s 64QAM over 200km-Span Link," Proc. ECOC, Tu.2.D (2019).

[4] M. Ionescu et al, "20.6 Pb/s • km Unrepeatered Transmission without ROPA: UWB SOA Booster and Backward Raman Amplification," Proc. ECOC (2020).

[5] H. Bissessur et al. “Real-Time Unrepeatered C-Band Transmission of 30.5 Tb/s over 276.4 km and 29.45 Tb/s over 292.5 km,” Proc. OFC, W1I.1(2021).

[6] Meng Qiu et al., “Digital subcarrier multiplexing for fiber nonlinearity mitigation in coherent optical communication systems ,” Opt. Express 22(15), 18770–18777 (2014)