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Unrepeatered Transmission over 670.64km of 50G BPSK, 653.35km of 100G PS-QPSK, 601.93km of 200G 8QAM and 502.13km of 400G 64QAM

Jian Xu, Shujuan Sun,Qianggao Hu, Jiekui Yu, Jiasheng Liu,Qing Luo, Wenzhong Wang, Liyan Huang, Min Xiang, Jianjun Wu, Fusheng Zheng, Weihua Li, Li Deng, Hongyan Zhou, Lei Zhang, Shugang Jia, Xiaohong Zhang, Haitao Chen

***Abstract*—We report the results of 50G, 100G, 200G, 400G unrepeatered transmission aimed at achieving the longest distance without any inline active elements, this system realizes record single-carrier 50 Gb/s (PM-BPSK), 100 Gb/s (PS-QPSK), 200 Gb/s (PM-8QAM) and 400 Gb/s (PM-64QAM) unrepeatered transmission over 670.64 km with 103.95 dB span loss, 653.35 km with 101.27 dB span loss, 601.93 km with 93.3 dB span loss, and 502.13 km with 77.83 dB span loss, respectively. This is achieved using optimized high-order Raman pumps, cascaded RGUs and coherent modulation format with concatenated FEC. G.654.E fiber with ultra-low loss & 130 μm² effective area is used as span fiber.**

***Index Terms*—Fiber optical communications, unrepeatered transmission, optical amplifiers, coherent communications, large effective area fiber, cascaded remote gain units (RGUs).**

I. Introduction

UNREPEATERED ultra-long haul systems are widely used in ultra high voltage (UHV) power grid constructions, which are beneficial to desert, depopulated, poor environment areas. In China, the existing ± 800 kV direct current (DC) UHV transmission line is about 2000 km long, ±1100 kV DC UHV transmission line has been exceeding 3000 km, and ±1000 kV alternating current (AC) UHV transmission line is more than 600 km. Due to the limitation of optical communication transmission distance, signal repeater stations can only be used between two converter stations. The goal of unrepeatered transmission systems is to reduce the number of repeater stations by extending communication distances between stations, thus offer a cost-effective solution.

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J. Xu, S. S. Sun, Q. G. Hu, J. K. Yu, Q. Luo, W.Z. Wang, L.Y. Huang and M. Xiang, J. J. Wu are with Accelink Technologies Co. Ltd, Wuhan, 430205, China (e-mail: jian.xu2@accelink.com; shujuan.sun@acclink.com, et al.).

F. S. Zheng, W. H. Li and L. Deng are with State Grid Information & Telecommunication Branch, NO.1 Lane 2, Baiguang Rd, Beijing, China (e-mail: zhengfusheng@sgcc.com.cn; weihuali@sgcc.com.cn, et al.).

H. Y. Zhou and L. Zhang are with State Key Laboratory of Optical Fiber and Cable Manufacture Technology, Yangtze Optical Fiber and Cable Joint Stock Limited Company, Wuhan, 430073, China (e-mail: zhouhongyan@yofc.com; zhanglei@yofc.com).

S. G. Jia, X. H. Zhang and H. T. Chen are with NOKIA Shanghai Bell Co., Ltd., Shanghai 201206, China (e-mail: shugang.jia@nokia-sbell.com; xiaohong.zhang@nokia-sbell.com).

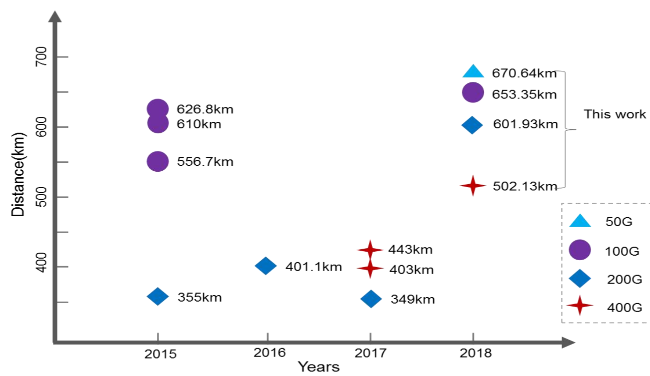


Fig.1. History of record distance of unrepeatered transmission with several generations of channel bit rate.

There has been an extensive research devoted to the unrepeatered transmission [1]-[15]. The current successful deployments of unrepeatered systems at 100 Gb/s, 200 Gb/s and 400 Gb/s per wavelength should owe to the polarization division multiplexing and the phase shift keying modulation format combined with a coherent receiver. So far, several articles have reported unrepeatered transmission distance at 100G [6]-[8], 200G [9]-[11] and 400G [12]-[14]. Fig. 1 shows record distances for unrepeatered transmission distances with several generations of channel bit rate. 100G unrepeatered transmission over 626.8 km was achieved by using commercial Raman pump modules, enhanced forward and backward ROPAs [6]. Recently, unrepeatered experiment at 200 Gb/s using PDM-16QAM modulation had been reported, and the transmission distance exceeded 401.1 km with 108 channels [10]. The longest unrepeatered transmission with single-carrier 400 Gb/s was achieved over 443.1 km, employing large effective area (A_{eff}) & low loss fiber and remote optically pumped amplifier (ROPA) [14].

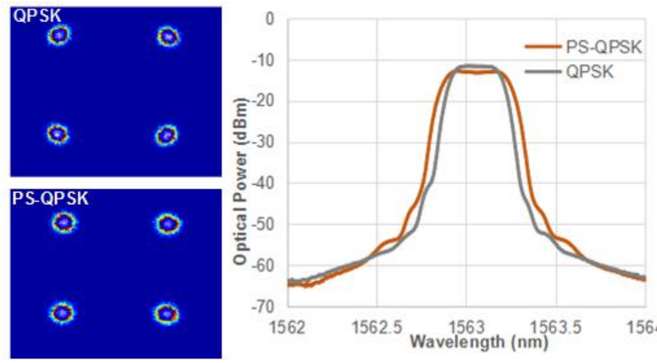
This paper reports new records unrepeatered transmission distances with a further optimized system configuration. We have achieved 50G unrepeatered transmission over 670.64 km (103.95 dB), 100G unrepeatered transmission over 653.35 km (101.27 dB), 200G unrepeatered transmission over 601.93 km (93.3 dB), and 400G unrepeatered transmission over 502.13 km (77.83 dB). These results are obtained through the application of optimal and tailor-made modulation format at the transmitter side, ultra-low loss and large effective area fiber, commercial forward and backward high-order Raman pump (HRP) modules, and cascaded RGUs [9].

II. Key technologies

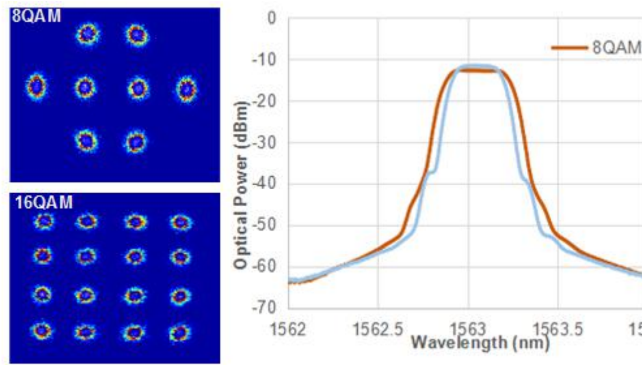
A. Different Modulation Formats with Concatenated FEC

The modulation formats of optical transmitter are different due to the limitation of the computing speed of electronic chips. Therefore, the 50G, 100G, 200G, and 400G signal are modulated using PM-BPSK, PS-QPSK (polarization- switched quadrature phase shift keying) [16-18], PM-8QAM and PM-64QAM format, respectively, which accounts for the 20% overhead of the concatenated forward error correction (FEC). The concatenated FEC is a soft-decision FEC followed by a hard-decision FEC, and it can correct a bit error rate (BER) of 3.3E-02 (Q=5.28 dB) to less than 1.0E-15. The measured OSNR sensitivity is 7 dB/0.1nm at 50G, 9.9 dB/0.1nm at 100G, 15.81 dB/0.1nm at 200G and 28.3 dB/0.1nm at 400G under Back-to-Back transmission.

Constellation diagrams and optical spectrum of QPSK and PS-QPSK (Constellation diagram of PS-QPSK just denotes a QPSK symbol which has been transmitted on the x-polarizationon) at 100G, 8QAM and 16QAM at 200G are shown in Fig. 2. Considering that PS-QPSK with wider spectrum supports higher sensitivity and launched signal power than QPSK with polarization-multiplexing [19], it is employed in 100G system instead of QPSK. And 8QAM with the wider spectrum which has more nonlinear tolerance is applied to 200G system instead of 16QAM.



(a)



(b)

Fig.2. (a) Constellation diagrams and optical spectrum of QPSK and PS-QPSK (Constellation diagram of PS-QPSK just denotes a QPSK symbol which has been transmitted on the x-polarizationon) at 100G. (b) Constellation diagrams and optical spectrum of 8QAM and 16QAM at 200G.

B. Ultra-Low Loss and Large Effective Area Fiber

In an optical fiber communication system, increasing transmission distance can be accomplished by lowering fiber loss, and allowing higher launched signal and pump powers through reduced fiber nonlinearity [20-21]. But the optimum launched optical power is usually limited by the type of optical fiber and transmission rate. In order to choose an appropriate fiber type, we simulated the optimum launched signal power and the backward Raman gain with total pump power of 1 W for different loss coefficients and effective areas of the fiber based on 400 Gb/s system, the results are shown in Fig. 3. One can see that the optimum launched signal power increases with both the effective area and the loss coefficient of the fiber, but the backward Raman gain increases with the decrease in the effective area and the loss coefficient. Fig. 3(a) shows that the optimum launched signal power of G.654.E fiber (A_{eff} is 130 μm^2, loss coefficient is 0.155 dB/km) is 8 dBm based on 400 Gb/s system, which has about 2 dB launched power advantages over the G.652 fiber (A_{eff} is 80 μm^2, loss coefficient is 0.18 dB/km), and Fig. 3(b) shows that the backward Raman gain of G.654.E fiber (A_{eff} is 130 μm^2, loss coefficient is 0.155 dB/km) is 16 dB, which is 7 dB smaller than that of G.652 fiber (A_{eff} is 80 μm^2, loss coefficient is 0.18 dB/km). In this work, the span is assembled with commercial YOFC Farband® Ultra A130 optical fiber which has a larger A_{eff} of 130 μm^2 and a typical loss coefficient of 0.155 dB/km (at 1563nm). It is a G.654.E (cutoff-shifted single mode fiber with cable cutoff wavelength below 1530 nm) fiber with an average chromatic dispersion of 20.9 ps/(nm·km) (at 1563 nm). Due to the larger A_{eff}, this fiber allows to increase the launch power of the signal and pump. Combined with ultra-low attenuation, this results into even longer distance. Therefore, it is an ideal transmission medium for ultra-large capacity, ultra-long transmission and ultra-high speed transmission systems.

C. High-order Raman Pump

Distributed Raman amplification is an effect of energy transfer from short-wavelength pump to long-wavelength signal in the optical media of transmission [22]. In this paper, high-order distributed Raman amplification technology which achieved by multistage Stokes transfer between pumps of different wavelengths is applied, as shown in Fig.4(a). And each HRP module contains six pump wavelengths distributed in the range between 1300 nm and 1500 nm, the structure is

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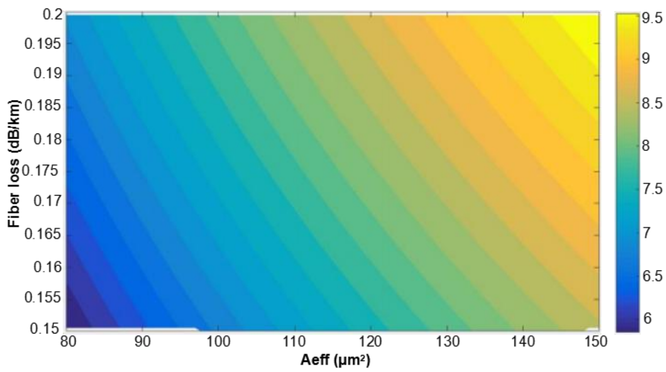

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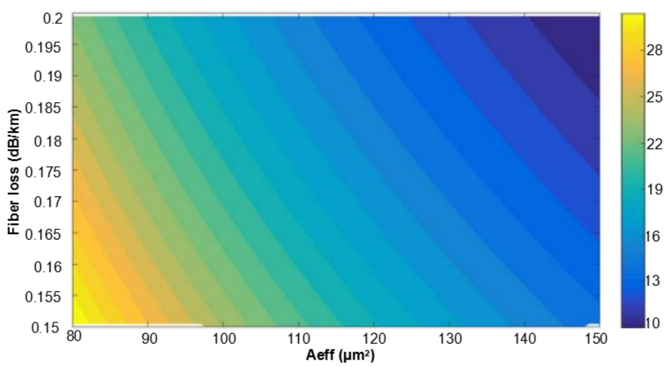
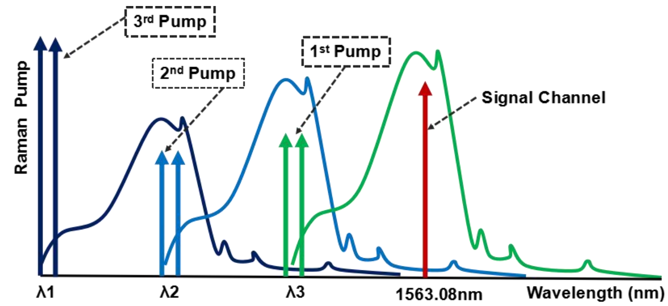


(b)

Fig. 3. (a) Optimum launched signal power into fiber, and (b) Raman gain with total pump power of 1 W as a function of fiber loss coefficient and effective area based on 400 Gbit/s system.



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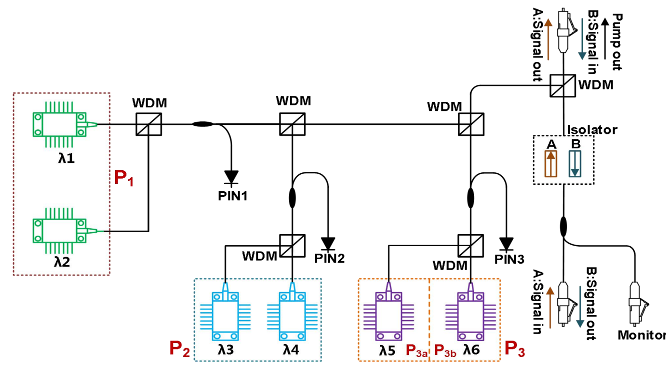


(b)

Fig.4. (a) High-order Raman gain spectrum with different pump laser wavelengths. (b) Structure of HRP.

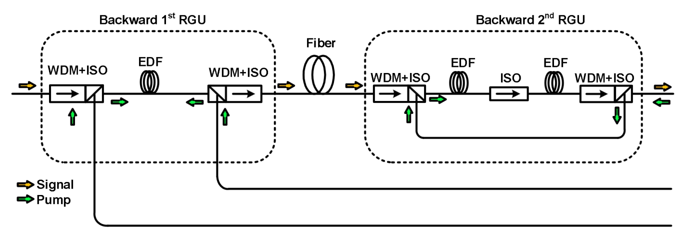


Fig.5. The structure of the backward cascaded RGUs

shown in Fig. 4(b). The two wavelengths of third-order pump source (P_1) operate in the range between 1300 and 1400 nm, the two wavelengths of second-order pump source (P_2) operate in the range between 1400 and 1450 nm, and the wavelengths of first-order pump source (P_3) include P_{3a} operating in the range between 1450 and 1475 nm just using in the forward signal path and P_{3b} working in the range between 1475 and 1500 nm. Detector (PIN2, PIN4, PIN6) have been inserted to monitor the pump power. This module can be used in both the forward and backward direction based on the direction of the isolators (isolator A is applied to the forward direction, isolator B is applied to the backward direction). These isolators can suppress reflections resulting from Fresnel reflections from connectors and Rayleigh scattering from lengths of fiber connected to either end [23]. Moreover, HRP modules have been used in all dedicated pump paths to provide pump for RGU. According to the need of this system, multiple pump wavelengths can be configured. In this experiment, the HRP module in the forward signal path do not use the pump at the longest wavelength such that the operating pumps are P_1, P_2 and P_{3a}, the wavelength of P_{3a} (with more "walk-off" between the signal and the pump) helps to mitigate the noise transfer in the forward direction [24]. The HRP modules in the backward signal path and pump paths turn on P_1, P_2 and P_{3b}.

D. Cascaded RGUs

ROPA consists of RGU and remote pump source which is provided by HRP in this system. Fig. 5 shows the configuration of the backward cascaded RGUs that is adopted in this experiment. The total length of EDF is optimized to 12 m (1st RGU) and 10 m (2nd RGU) in the cascaded RGUs, and 1st RGU of cascaded RGUs uses a bidirectional pump (pumps excite erbium fiber from both directions) to improves the Noise Figure (NF). According to the performance of RGU, the optimum distance between pump source and RGU has been selected. Here, we define $P_{pump,opt}$ as the optimum pump power at the input of the RGU, this $P_{pump,opt}$ balances between sufficient gain and a satisfactory noise performance. The pump power shows linear change with the average fiber loss at pump wavelength when fiber length is more than 100 km. And let P_{pump} be the pump power located at 100 km from the terminals and α_p be the average fiber loss at pump wavelength (including splices). In this system, the ideal RGU can be placed up to L_{opt} = 100 km + $(P_{pump,100km}-P_{pump,opt})/\alpha_p$ from the terminals.

III. Experiment Setup

The experimental setup is shown in Fig. 6. At the transmitter side, an integrated coherent card (NOKIA Bell) enables the generation of a multi-codes signal, which generate BPSK, PS-QPSK, 8QAM and 64QAM for 50G, 100G, 200G and 400G respectively. The setup is configured to transmit signal at 1563.05 nm. Chromatic dispersion compensation is achieved at the transmitter side (pre-compensation) introducing a tunable dispersion compensator (TDC). The variable TDC is adjusted to provide optimal pre-compensation, mitigating nonlinear transmission impairment when high-order distributed Raman amplification technology is used [25]. The configuration is optimized with approximately -2647 ps/nm of dispersion pre-compensation for 50G, 100G and 200G. The signal is amplified through a Erbium-doped Fiber Amplifier (EDFA) followed by 100 GHz pass-band filter and variable optical attenuator (VOA) to filter out the amplified spontaneous emission (ASE) noise from EDFA and configure the launched signal power respectively. At the receiver side, second 100 GHz pass-band filter and VOA are inserted into the transmission to reduce ASE noise and control received signal power of integrated coherent card.

The optical link with four signal paths (Line 1, 4, 7 and 8) also included four pump paths (Line 2, 3, 5 and 6 are just used to transport pump power to the RGUs). The forward signal path (Line 1) uses forward HRP, the backward signal path (Line 8) and all pump paths use backward HRP. These HRP modules require different pump wavelengths and different pump power settings to provide the best performance in signal paths and pump paths (The details of the pump configurations are described in Fig. 6). In the forward signal path, the launched signal power and forward HRP on-off gain depend on a balance between OSNR and nonlinear penalty, or relative intensity noise (RIN) transfer penalty [26]. In 400G 64QAM system, in order to obtain minimum OSNR penalty, forward pump power will reduce greatly, as a result, equivalent launched signal power (the sum of actual launched signal power and forward Raman gain) equals approximately to launched signal power by EDFA system, so there is no need to use forward HRP to amplify the signal at the transmitter side for 400G transmission. For the Line 8, the optimum pump power depends on the influence of multi-path interference (MPI) [26]. In this experiment, due to the Raman interaction between the pump wavelengths along the fiber, the longest pump wavelengths has the highest power at the RGU and are primarily used to excite the erbium fiber in the backward signal path and pump paths.

Considering that output optical power of forward RGU is limited by nonlinear effect and pump to signal energy conversion efficiency varies with the change of pump power of forward RGU, three forward RGUs are designed to be suitable for 50G/100G, 200G and 400G transmission systems, the relationship curve between output power and noise figure of them for experiment and pump power are measured (see curves F-RGU (50G/100G), F-RGU (200G), F-RGU (400G) in Fig.7). It's found that the optimum pump power of forward RGU is 15 dBm, 13.5 dBm, 13 dBm for 50G/100G, 200G and 400G

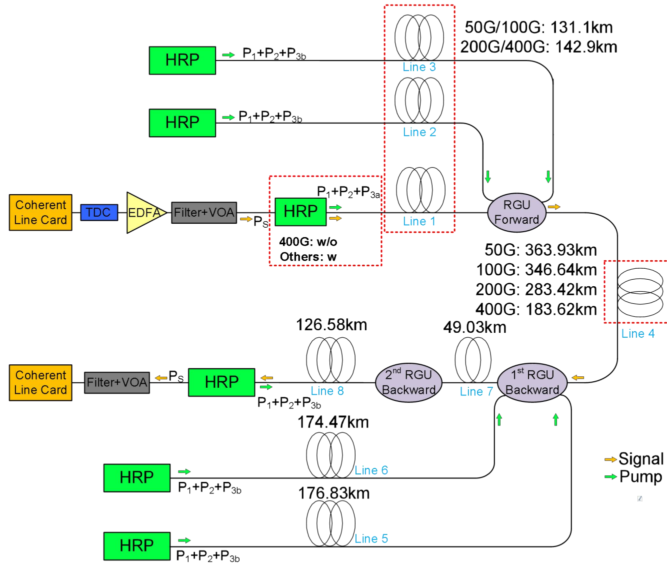
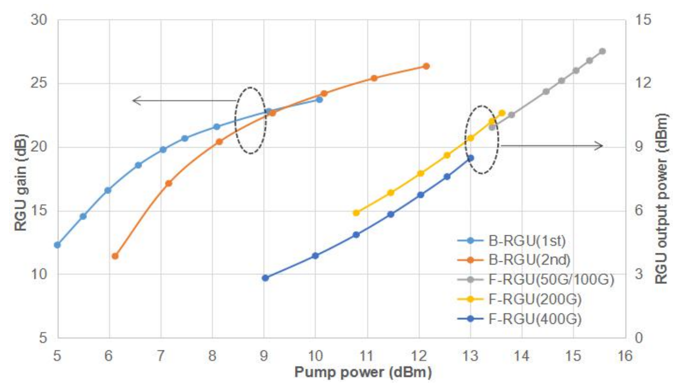
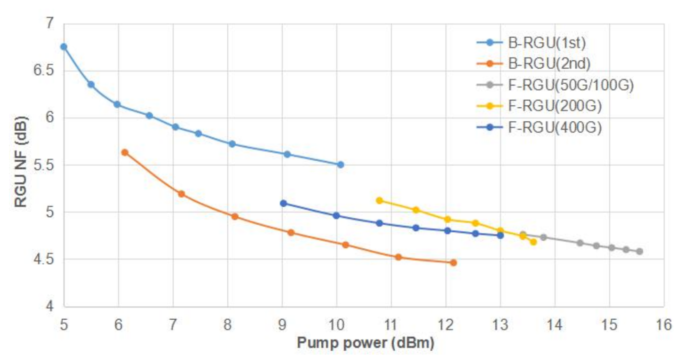


Fig.6. Experimental setup for single 50G/100G/200G/400G channel unrepeaterd transmission. Insert (dashed box) shows the different configuration used for 50G/100G/200G/400G transmission.



(a)



(b)

Fig.7. (a) Output optical power of forward RGU and gain of backward RGU versus pump power. (b) Noise figure of RGU versus pump power.

respectively. The gain of backward RGU is greatly affected by the pump power, when pump power of 1st RGU and 2nd RGU are less than 6 dBm and 8 dBm respectively, the gain and noise figure of RGUs will deteriorate (see curves B-RGU (1st) and B-RGU (2nd) in Fig. 7). Accordingly, if the RGU position is

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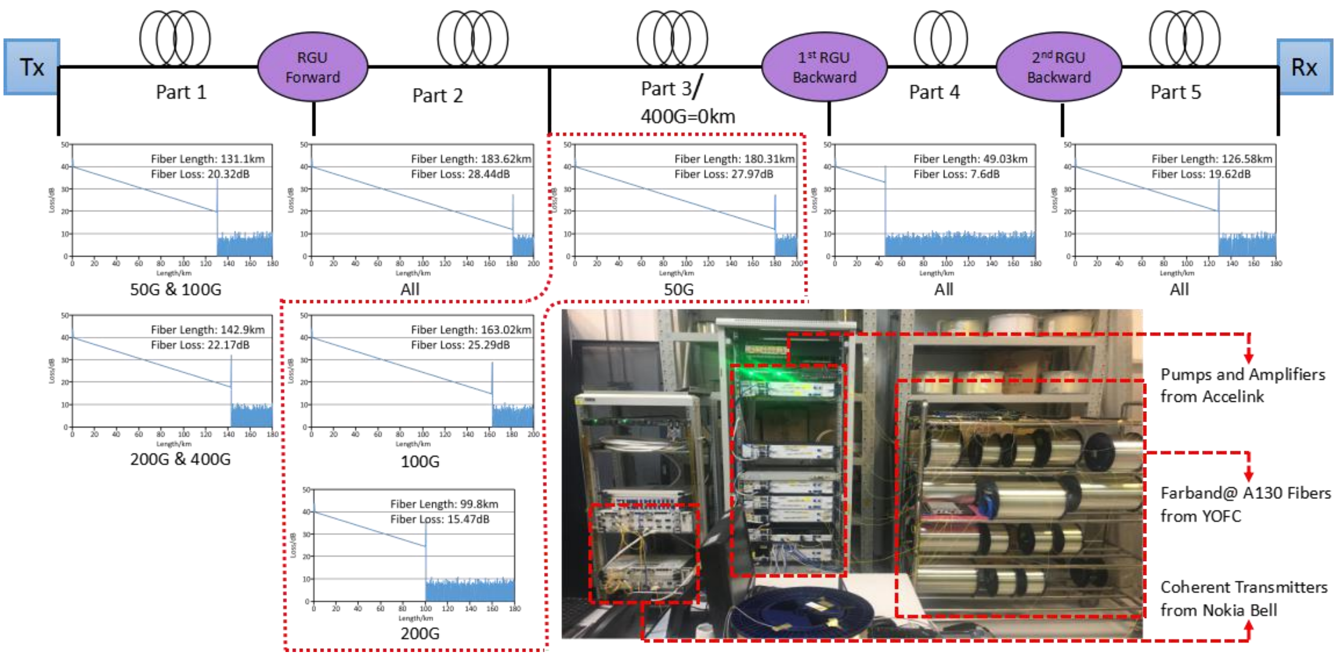

Fig.8. OTDR analysis for transmission fiber and photograph of optical fibers and equipment.

not properly placed, the system performance will be greatly affected. The results from Fig. 7 provide reference for RGU location selection.The forward RGU is located at 131.1 km for 50 G and 100 G, at 142.9 km for 200 G and 400 G from the transmitter side. The backward 1st RGU and 2nd RGU are located at 175.61 km and 126.58 km from the receiver side respectively. The second signal span (Line 4) is adjusted to 363.93 km for a total link length of 670.64 km at 50G system, 346.64 km for a total link length of 653.35 km at 100G system, 283.42 km for a total link length of 601.93 km at 200G system, and 183.62 km for a total link length of 502.13 km at 400G respectively. The transmission loss of line are 103.95 dB at 50G system, 101.27 dB at 100G system, 93.3 dB at 200G system, 77.83 dB at 400G system respectively (the loss of the RGUs are not included), the average fiber loss coefficient (including splices) is 0.155 dB/km at 1563.08 nm. The dedicated pump paths use the same fiber length as the signal paths. All the fiber lengths are verified by OTDR as shown in Fig. 8, and the transmission loss is carefully measured by optical spectrum analyzer (OSA). The measurement is done with 0.067 nm resolution using an EXFO Optical Spectrum Analyzer (OSA, FTB-5240S).

IV. Transmission Results and Discussion

Fig. 9 shows the constellation diagrams and spectrums of 50G (Fig. 9(a)), 100G (Fig. 9(b)), 200G (Fig. 9(c)), 400G (Fig. 9(d)) at the transmitter side. The signal first experiences HRP amplification. Then the signal is amplified by the forward RGU and attenuated by the fiber, and amplified again by the backward cascaded RGUs. Finally, the signal experiences the backward HRP amplification before reaching the receiver side. Fig. 10 shows the simulated optical power profiles of 50G (a), 100G (b), 200G (c), 400G (c). Measured input signal power, forward and backward pump powers, performance of RGU and fiber characteristics of G.654.E fiber are used in the simulation. The signal power launched in the fiber is -6.19 dBm, -3.32 dBm, -2.26 dBm and 7.27 dBm at 50G, 100G, 200G and 400G transmission respectively. The launched pump powers in the forward signal path (Line1) are 2692 mW for 50G, 2405 mW for 100G and 2025 mW for 200G transmission, and the launched pump powers in backward signal path (Line8) is 2764 mW for 50G, 100G and 200G, 2123 mW for 400G transmission. The forward pumps provide 26.2 dB, 22.23 dB, 18.29 dB distributed Raman gain (on/off) for 50G, 100G and 200G. A dual stage delivery link is configured to provide pump power for forward and backward 1st RGU with the same launched pump power of 2835mW per dedicated delivery fiber. The associated Raman pump power profiles along the pump path are shown in Fig. 11. The residual pump powers reaching the forward RGU is measured to be 7.31 mW, 6.01 mW, and 3.43 mW from the forward signal path (Line1) at 50G, 100G and 200G respectively, 12.53 mW for 50G and 100G, 8.13 mW for 200G and 400G from the first forward pump path (Line2), 12.61 mW for 50G and 100G, 8.29 mW for 200G and 400G from the second forward pump path (Line3). The forward RGU gain is 12 dB for 50G, 13.92dB for 100G, 15.64 dB for 200G, and 21.95 dB for 400G. The residual pump powers to the backward 1st RGU are measured to be 1.99 mW and 2.01 mW from the first backward pump path (Line5) and the second backward pump path (Line6). The backward 1st RGU provides 18.38 dB gain at 50G, 18.47 dB at 100G, 18.36 dB at 200G and 13.92 dB at 400G.

The five RGUs (three forward RGUs and two backward RGUs) are designed based on the optimization EDF classification and pump power for different transmission system. Meanwhile, compared with single backward RGU, the

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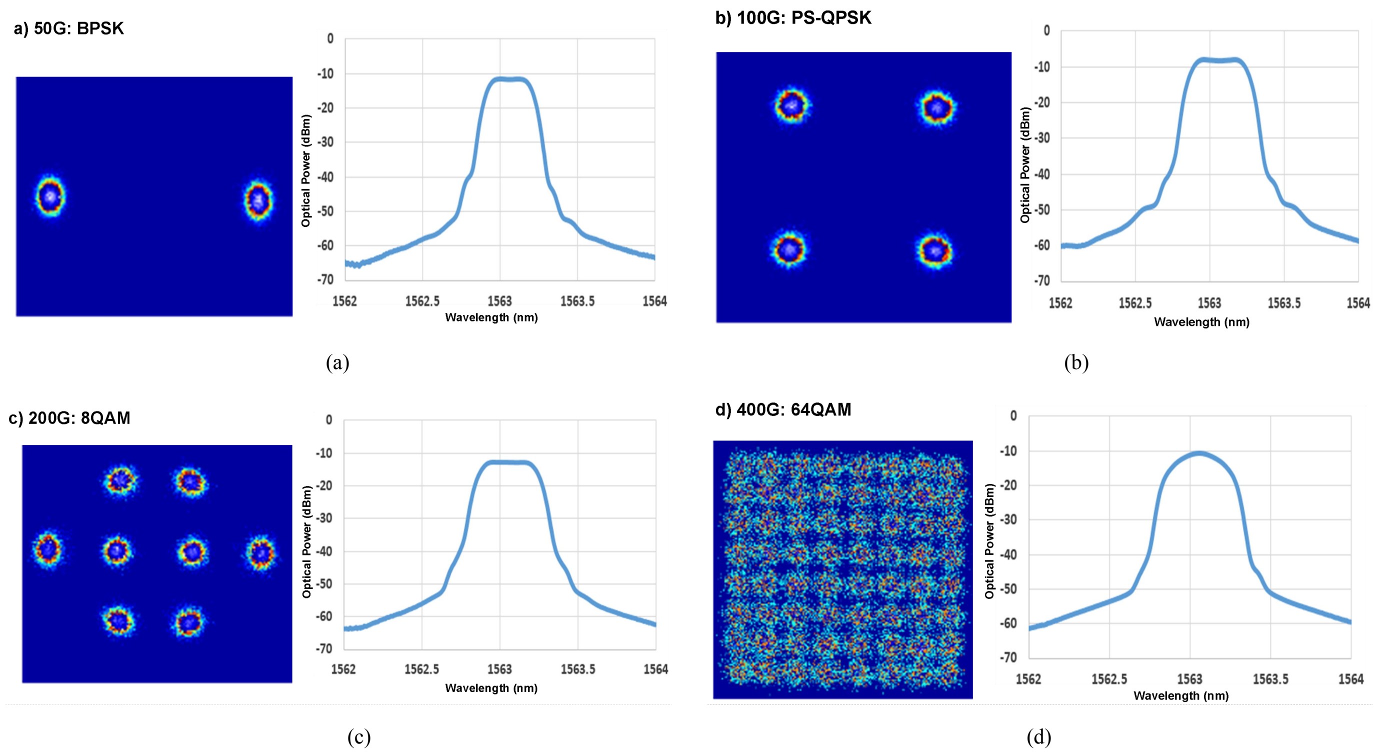

Fig.9. Constellation diagrams & spectrum of 50G(a), 100G(b), 200G(c), 400G(d) measured at the transmitter side.

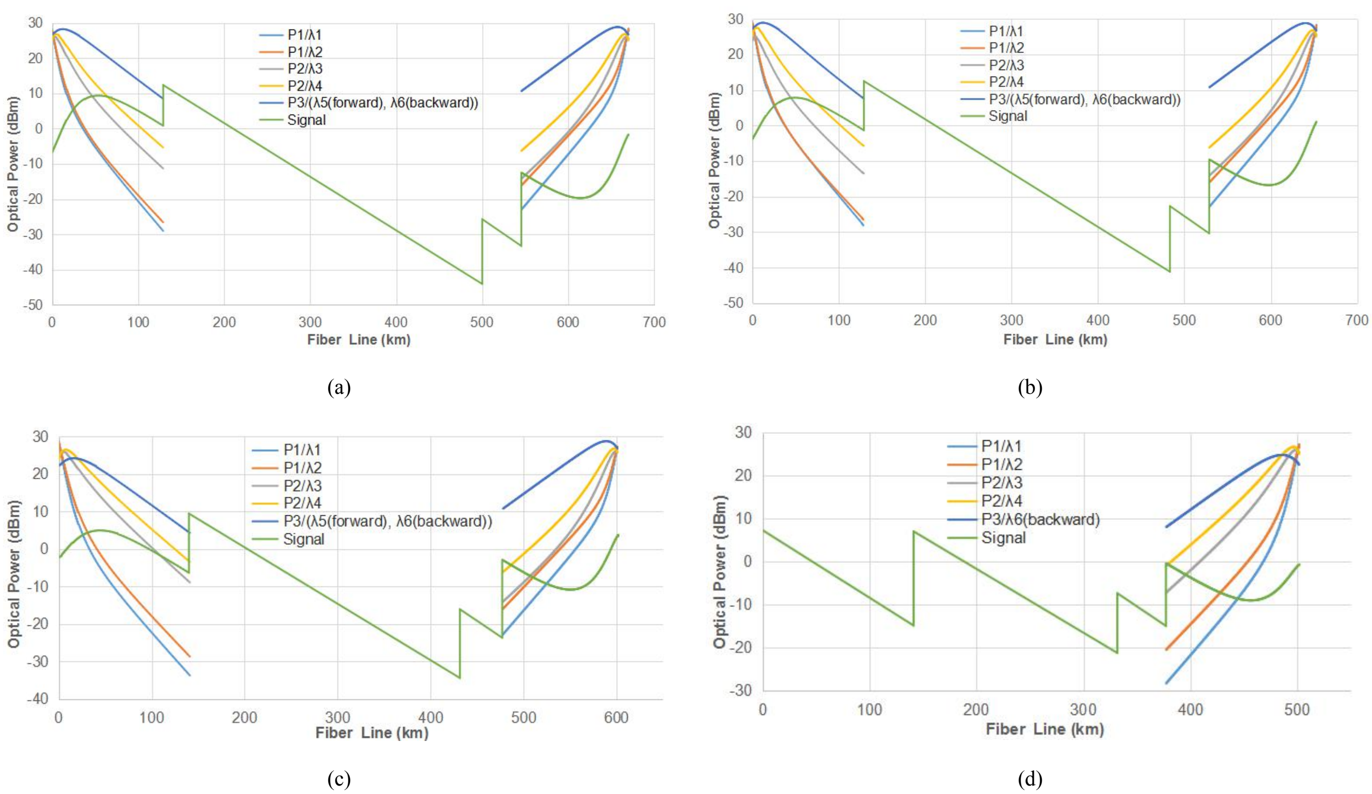

Fig.10. Simulated power distribution of signal and pumps in signal path for 50G(a), 100G(b), 200G(c) , and 400G(d).

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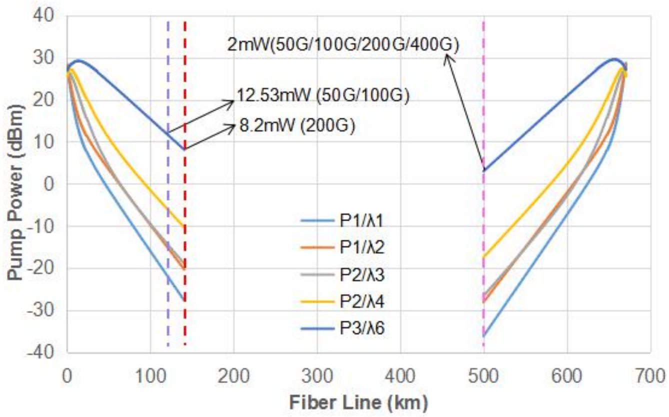

Fig.11. Simulated power distribution of pumps in pump path.

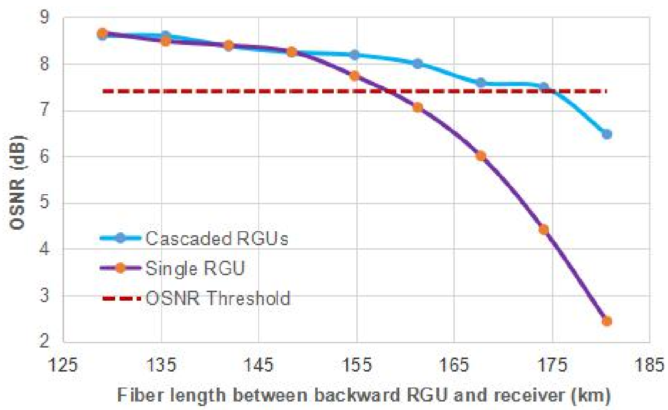

Fig.12. OSNR comparison between cascaded RGUs and single RGU.

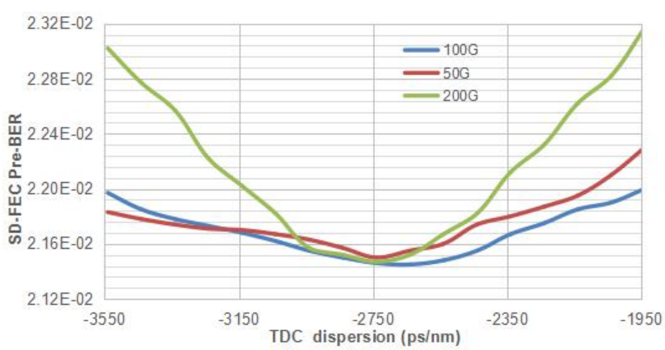

Fig.13. Measured BER versus pre-compensation dispersion at 50G, 100G, and 200G.

use of backward cascaded RGUs allow 2.9 dB increase in total link loss at the same pump power, as shown in Fig. 12.

Fig. 13 shows the relationship between BER and the pre-compensation dispersion when there is error-free at 50G, 100G, and 200G. The result shows that the BER decreased and then increased with the increase of dispersion. So the best performance of this unrepeatered transmission experiment is achieved at a total of -2647 ps/nm of pre-compensation dispersion.

The spectrums at the receiver side are shown in Fig. 14. The OSNR of the signal channel is are 7.49 dB/0.1nm at 50G, 10.91 dB/0.1nm at 100G, 17.39 dB/0.1nm at 200G, and 28.8 dB/0.1nm at 400G. The performance of all system is well

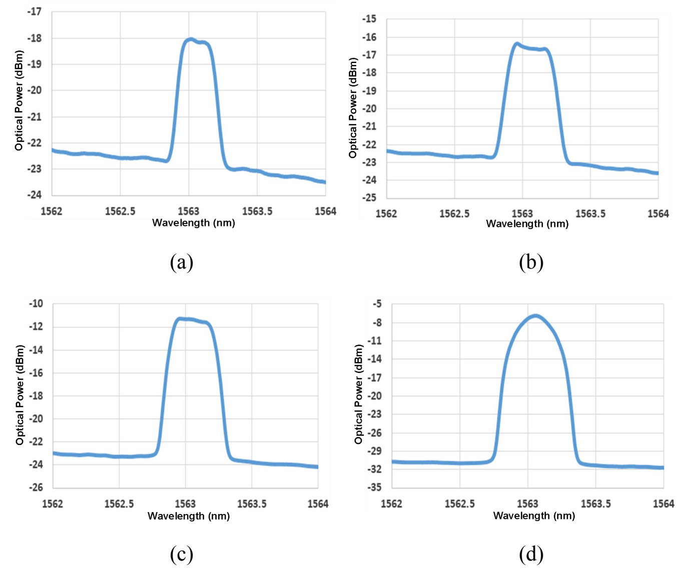

Fig.14. 670.64km, 653.35km, 601.93km and 502.13km transmission spectrum measured at the coherent receiver for 50G(a), 100G(b), 200G(c) and 400G(d).

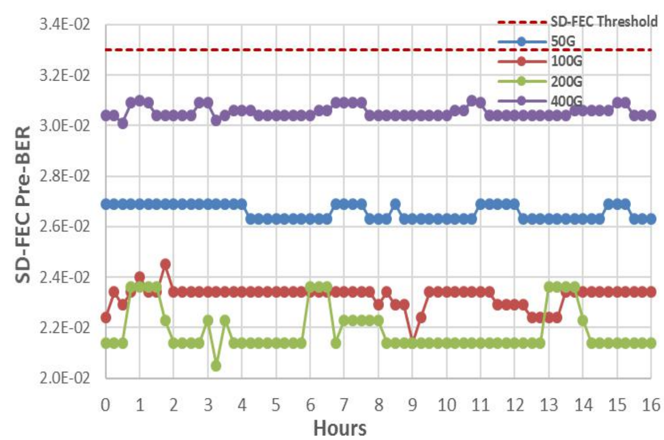

Fig.15. Stability measurement over 16-hour at 50G, 100G, 200G and 400G.

within the BER limit at FEC threshold of 3.3×10^{-2} for error-free operation. The average pre-FEC BER over the duration of the test are 2.69E-02 at 50G, 2.34E-02 at 100G, 2.19E-02 at 200G and 3.04E-02 at 400G. The results of a 16-hour BER stability test are recorded in Fig. 14.

V. Conclusion

We demonstrated unrepeatered transmission of single-carrier at 50 Gb/s over 670.64 km with 103.95 dB span loss, 100 Gb/s over 653.35 km with 101.27 dB span loss, 200 Gb/s over 601.93 km with 93.3 dB span loss, and 400 Gb/s over 502.13 km with 77.83 dB span loss. These are the longest span distance ever reported for an unrepeatered transmission in single-carrier at 50G, 100G, 200G and 400G, with the first application of single-carrier 50 Gb/s PM-BPSK format in single core unrepeatered transmission. Such recording results are achieved by using HRP configuration, innovative cascaded RGUs, optimization and tailor-made modulation format, ultra-low loss & large effective area fiber.

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