100G unrepeatered transmission over 626.8 km with a span loss in excess of 100 dB

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Abstract: This paper reports record unrepeatered transmission using a commercial Raman-line system, enhanced ROPAs, and large effective area, ultra-low loss fiber. 100G and 10G transmission is demonstrated over 626.8 km and 645.0 km, respectively.
OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications.

1. Introduction

Long distance optical communication links are being widely deployed over Optical Ground Wire (OPGW) cables as part of power distribution systems. As a communication medium, OPGW has the advantage of lower installation cost per kilometer and suffers less cable cuts compared to buried cable.

Since the Ultra-High Voltage (UHV) power grid can have a large power transmission radius, OPGW in UHV power grid can support ultra-long haul communications, with sub-stations where optical amplification and possibly regeneration can be provided along the way [1]. However, in many instances, UHV lines are deployed across hostile geographical areas (e.g., high mountain ridges, deserts…) where positioning repeater stations would prove to be impractical and cost prohibitive from an OpEx perspective.

Ultra-long unrepeatered transmission can help to reduce the number of repeater stations by extending communication distances between stations and thus offer a cost-effective solution. There have been a number of recent publications reporting increased unrepeatered distances [2-7]. In previous work [6], we introduced a novel enhanced ROPA configuration which utilizes multiple additional pumping fibers and demonstrated 100 Gb/s (100G) unrepeatered transmission over 607.3 km (97.2 dB) and 10G transmission over 632.3 km (101.0 dB).

This paper reports new record unrepeatered transmission distances by using stronger distributed Raman pumps with a further optimized system configuration. We have achieved 100G unrepeatered transmission over 626.8 km (100.8 dB) and 10G over 645.0 km (103.6 dB). The experiment was carried out at the laboratory of State Grid Information & Telecommunication in Beijing, China using commercially available DWDM Line Terminal Equipment (LTE) with distributed Raman pump modules and large effective area ultra-low loss fiber from Corning.

2. Experimental Setup

The experimental setup is shown in Fig. 1 and is configured to transmit 100G or 10G at 1563.86 nm. The 100G signal is RZ-PM-QPSK modulated at 120 Gb/s which accounts for the 15% overhead of the Soft-Decision Forward Error Correction (SD-FEC) code. The SD-FEC can correct a pre-BER of 1.9×10^{-2} to less than 10^{-15} (NCG of 11.1 dB). The 10G channel operates at 12.5 Gb/s which includes the 25% overhead of the Ultra-FEC (BER at FEC threshold is 9.5×10^{-3}). The 100G or 10G signal is amplified through a double-stage Erbium-doped Fiber Amplifier (EDFA) followed by a Wavelength Selective Switch (WSS) used to filter out the ASE from the transmit EDFA.

At the transmit side, a pre-dispersion compensation unit (DCU) is placed at the mid-stage of the EDFA to improve transmission performance for both 100G and 10G. The optimized DCU values of -2,760 ps/nm and -2,080 ps/nm are used for 100G and 10G operation, respectively. At the receive end, an EDFA amplifies the received signal and another WSS is used to de-multiplex the channels. For 10G operation, a post-DCU is used at the mid-stage of the receiving EDFA to provide optical post-dispersion compensation (shown in insert of Fig. 1). Approximately, -10,600 ps/nm dispersion compensation is used at the receiver side only for 10G transmission. The span is assembled with Corning® Vascade® EX2000 optical fiber which has an average chromatic dispersion of

20.2 ps/nm-km and a large A_{eff} of 112 μm^2. In the signal path, the forward and backward ROPAs are located at 116.1 km and 157.8 km from the terminals, respectively. For the 100G transmission, the distance between the ROPAs is adjusted to 352.9 km for a total span length of 626.8 km and a span loss of 100.8 dB (losses of the ROPAs are not included), resulting in an average fiber loss (including splices) of 0.161 dB/km. In the case of 10G transmission, the total distance is increased to 645.0 km (371.1 km between ROPAs) for a span loss of 103.6 dB.

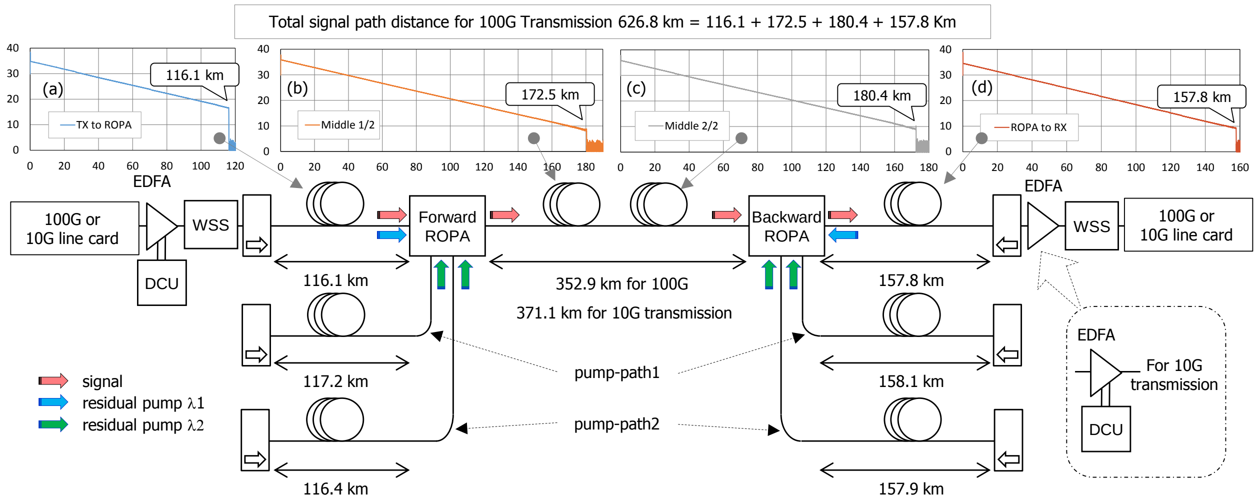

Figure 1 Experimental setup for single 100G/10G channel unrepeatered transmission.
Measured OTDR traces of signal path for 100G transmission: (a) section to forward ROPA,
(b) first section between ROPAs, (c) second section between ROPAs, (d) section from backward ROPA

The dedicated pump paths use fiber lengths of 117.2 km and 158.1 km in pump-path1 for forward and backward pumping, respectively. For pump-path2, 116.4 km and 157.9 km fibers are used. The span distance and the loss are carefully verified by OTDR measurement (EXPO, FTB-7600E, n = 1.4623, pulse width = 1.0 μsec) and direct loss measurement with an optical power meter (OPM). Measured OTDR traces with analyzed lengths are shown in Fig. 1 (a-d).

All distributed Raman pumps use the same commercial Raman pump modules (Nu-Wave Optima™ SE24 combined with high power add-on module, SE-HP) which include seven pump wavelengths distributed in the range between 1400 nm and 1500 nm. However, the Raman pump modules in the signal path do not use the pump at the longest wavelength such that the operating pump wavelengths are in the range between 1400 and 1480 nm. Turning off the longest pump wavelength (with less "walk-off" between pump and signal in a dispersive fiber) helps to reduce the RIN transfer penalty in the forward direction and also provides more efficient Raman gain to the signal wavelength around 1564 nm. The pump modules in pump paths 1 and 2 use the longest wavelength and therefore operate in the full range between 1400 and 1500 nm. Due to the Raman interaction between the pump wavelengths along the fiber, the longest wavelength in both the forward and backward pump modules has the highest power at the ROPA and is primarily used to excite the erbium fiber. The blue and green arrows in Fig. 1 represent residual pumps from the signal path and pump paths, respectively. The details of the enhanced ROPA configurations are described in reference [6].

3. Transmission Results

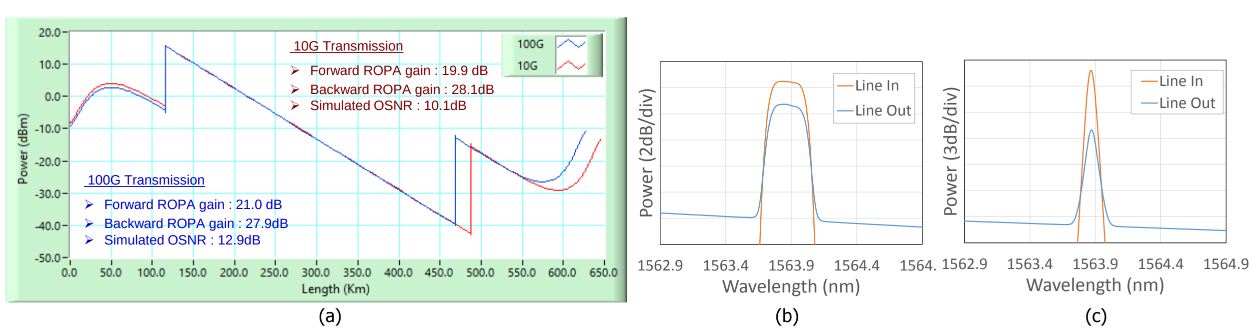

Figure 2 (a) Simulated signal power distribution, Output OSA spectra of (b) 100G, (c) 10G transmission.

Fig. 2 (a) shows the simulated power profiles of a single 100G channel over 626.8 km and of a single 10G channel over 645.0 km. Measured input signal powers, forward and backward pump powers and the characteristics of the Vascade EX2000 fiber [5] are used in the simulations. The signal first experiences the forward distributed Raman amplification, is then amplified by the forward ROPA, is attenuated by the fiber, amplified again by the backward ROPA, and then finally the signal experiences the backward distributed Raman amplification. The signal power launched in the span is -7.9 dBm at 100G and -6.7 dBm at 10G. The same distributed Raman pump powers are used for both 100G and 10G transmission. The launched pump powers in the signal path are 2,195 mW and 2,300 mW in the forward and backward directions, respectively. For the pump paths, the same pump power of 2,520 mW is used for both forward and backward pumping. The residual pump power reaching the EDF in the forward ROPA is measured to be 5.2 mW from the signal path and 8.7 mW, 8.2 mW from pump-path1 and pump-path2, respectively. The forward ROPA gain is 21.0 dB for 100G, and 19.9 dB for 10G. The maximum power of the signal right after the forward ROPA at 116.1 km is +15.6 dBm for 100G and +15.7 dBm for 10G. At the backward ROPA, the residual pump powers to the EDF sections are measured to be 1.7 mW, 2.4 mW and 3.3 mW from the signal path, pump-path1, and pump-path2, respectively.

The backward ROPA provides 27.9 dB gain at 100G and 28.1 dB at 10G. The measured spectra at the input and output of the span are shown in Fig. 2 (b) and (c). The measurement is done with 0.067 nm resolution using an EXFO Optical Spectrum Analyzer (OSA, FTB-5240S). The measured OSNR at the receiver is 13.1 dB/0.1nm for 100G and 10.3 dB/0.1nm for 10G, in very good agreement with simulations (12.9 dB, 10.0 dB).

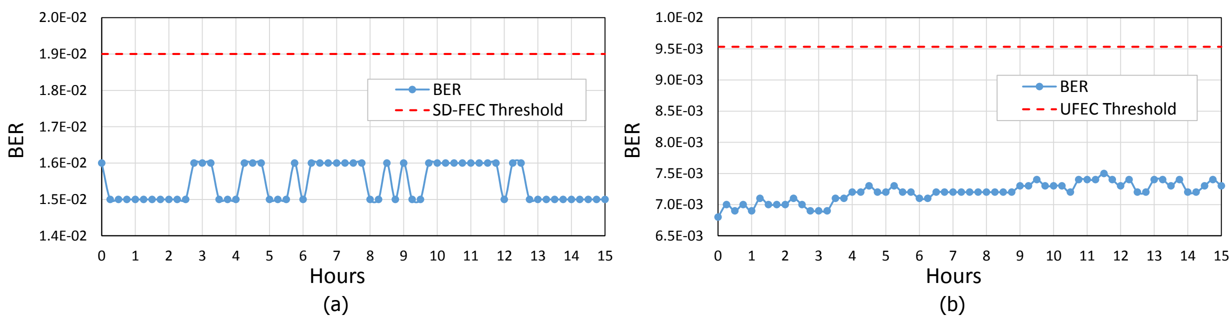

Figure 3 BER stability test over 15 hours for (a) 100G, and (b) 10G.

The result of a 15-hour BER stability test at 100G is plotted in Fig. 3 (a). The average pre-FEC BER over the duration of the test is 1.55 x 10^{-2} (corresponding to a Q of 6.7 dB) with less than 0.1 dB Q fluctuation and no uncorrected errors were observed after SD-FEC. The total signal propagation penalty which includes nonlinear, RIN, and MPI penalties is estimated to be 1.0 dB in Q compared to the back-to-back performance (Q = 7.7 dB at 13.3 dB OSNR). Fig. 3 (b) shows the result of a 15-hour stability test at 10G. The average pre-FEC BER is 7.20 x 10^{-3} (corresponding to a Q of 7.8 dB) with less than 0.2 dB Q fluctuation and no uncorrected errors were observed after UFEC.

4. Conclusion

We have achieved 100G unrepeatered transmission over 626.8 km (100.8 dB) which is (to our knowledge) the first demonstration of 100G unrepeatered transmission with a link attenuation exceeding 100 dB. We also successfully transmitted 10G over 645.0 km (103.6 dB) which also represents (to our knowledge) the longest unrepeatered transmission distance to date. Such record results are achieved by using a single fiber type, commercial Raman pump modules and 100G/10G channel cards, providing a practical solution for real field deployments.

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