15 Tb/s Unrepeatered Transmission over 409.6 km using Distributed Raman Amplification and ROPA

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Abstract: 15 Tb/s (150 x 120 Gb/s) unrepeatered transmission is achieved over 409.6 km (68.2 dB), corresponding to a record capacity-reach product of 6.14 Pb/s-km. We also demonstrate channel growth from 10 to 150 waves within 61 nm amplification bandwidth.
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1. Introduction

Larger network bandwidth to meet ever increasing traffic demand requires higher transport capacity. For unrepeatered applications, several reports have already been published on both high capacity and long reach unrepeatered transmission [1-8]. However, these results often require either a mix of fiber types in the span [2, 4-7], very strong (> 5W) high-order Raman pumping [1, 4, 7], or offline-channel processing [3, 6], which are less practical in real deployments. In this paper, we report 15 Tb/s (150 x 120 Gb/s) unrepeatered transmission over 409.6 km of large effective area (A_{eff}) G.654B fiber (Corning® Vascade® EX2000). The transmission is achieved using mature 100G technology over a single fiber type span with pump power of less than 2.5 W (per direction), resulting in a practical solution for deployments. To our knowledge, this result also represents the highest capacity-reach product (6.14 Pb/s-km) for unrepeatered transmission demonstrated to date.

2. Experimental Setup

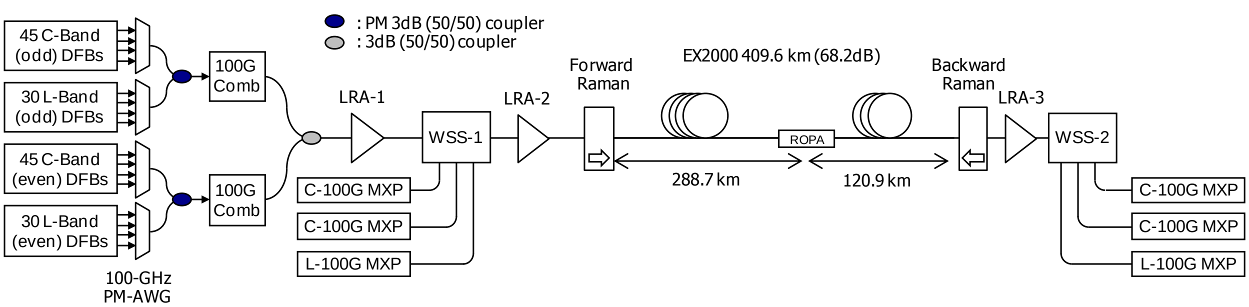

Fig. 1. Schematic of the experimental setup.

A diagram of the unrepeatered transmission experiment is shown in Fig. 1. Two modified 100G channel cards (hereafter referred to as comb modulators) are used to generate multiple modulated 100G loading channels. A comb modulator receives at its input a CW comb generated by a bank of external signal sources and outputs a 120 Gb/s NRZ PM-QPSK modulated comb with signals spaced 100 GHz apart. A total of 150 external distributed feedback (DFB) lasers in the C-band (1531.51 nm - 1567.13 nm) and L-band (1567.54 nm - 1592.10 nm) are separated into two groups (odd and even). The waves in each group (spaced 100 GHz apart) are multiplexed through a 100GHz polarization maintaining (PM) Arrayed Waveguide Grating (AWG) and PM 3-dB coupler. The channels in each group are then modulated by a comb modulator and combined with a 3dB coupler to generate a comb of 150 modulated channels spaced 50 GHz apart. The channels are amplified by a discrete (lumped) Raman amplifier (LRA), LRA-1. In addition, three tunable commercial 100G channel cards (with real-time processing; one in the L-band and two in the C-band) are combined with the modulated comb channels using a wide-band Wavelength Selective Switch (WSS), WSS-1. LRA-2 is used to boost the combined signals on the transmit side. The dispersion compensating fiber used as the Raman gain medium in LRA-2 also provides approximately -670 ps/nm of dispersion pre-compensation, improving the transmission performance. In this experiment, all the channels are modulated at 120 Gb/s, which accounts for the 15% overhead of the Soft-Decision Forward Error Correction (SD-FEC). This SD-FEC can correct a BER of 1.9 x 10^{-2} to less than 10^{-15}. At the receive end, LRA-3 is used to amplify the received signals and WSS-2 is used to select channels for Q measurement using the 100G channel cards.

Forward and backward Raman pumping is provided by commercial Raman pump modules which consist of seven pump wavelengths distributed in the range between 1400 nm and 1500 nm.

The unrepeatered span was assembled with only one fiber type: Corning® Vascade® EX2000, a G.654B-compliant (cutoff-shifted single mode fiber with cutoff wavelength ≤ 1530 nm) fiber with an average chromatic dispersion of ≤ 20.2 ps/nm-km and which has been deployed in submarine systems. It has a large A_{eff} of 112 μm^2, enabling higher launch powers into the fiber, therefore making it attractive for unrepeatered transmission systems. The span is 409.6 km long with a loss of 68.2 dB (mean fiber attenuation of 0.166 dB/km including splicing and connector losses) and includes a Remote Optically-Pumped Amplifier (ROPA). The ROPA consists of 16 m of erbium doped fiber and is placed at 120.9 km from the receive end.

3. Transmission Results

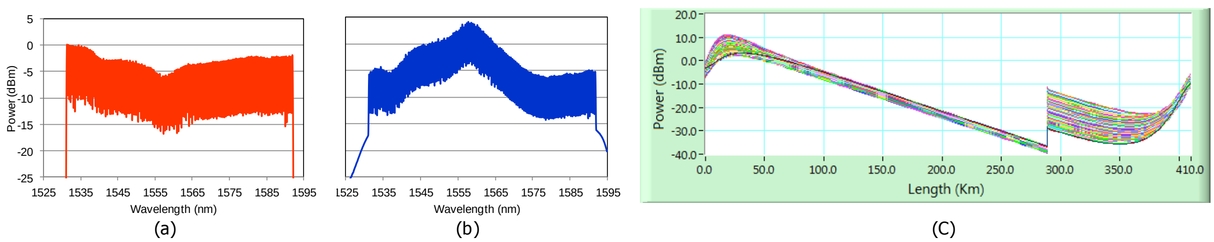

Fig. 2. OSA spectra at (a) transmit side, (b) receiver side, (c) simulated signal power profiles (0.1nm resolution BW)

Fig. 2 (a) and (b) show the measured spectra of the transmitted (at the output of LRA-2 in Fig. 1) and received (at the output of LRA-3 in Fig. 1) channels, respectively. The transmit channels are pre-emphasized to achieve an approximately uniform Q values across all channels at the receiving end. The average channel launch power is -2.8 dBm/ch. The large peak-to-peak signal power ripple (~ 10 dB) at the receive side comes from unequalized ROPA gain, but is flattened by WSS-2 before the receiver. Fig. 2 (c) shows the simulated power profiles (for all 150 channels) along the span. The longest pump wavelength of the forward pump module is turned off to reduce the RIN transfer penalty; therefore, 6 pump wavelengths in the range between 1400 and 1480 nm are used. The backward pump module uses all 7 pump wavelengths. The forward and backward distributed pump powers are 2,230 mW and 2,450 mW, respectively. The maximum signal power reaches +11.2 dBm at 18.7 km from the transmit side. Forward pumps provide 14.1 dB of distributed Raman gain (on/off). The ROPA provides 21.5 dB average total net gain for 150 channels with an estimated 14.2 mW residual pump power from the backward Raman pumps. The average backward Raman gain (on/off) is 7.7 dB.

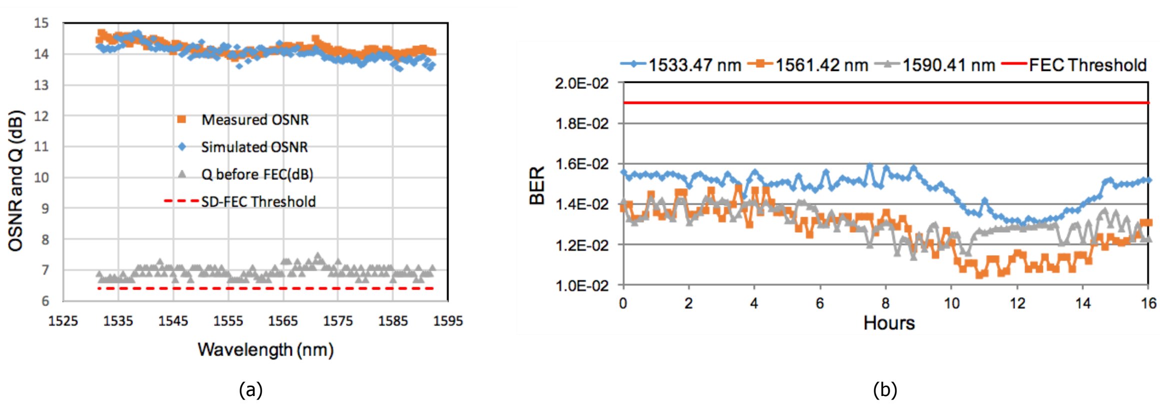

Fig. 3. (a) Measured and simulated OSNR and Q before FEC, (b) BER stability test over 16 hours for 3 selected channels

The measured and simulated OSNR as well as the calculated Q values from the measured pre-FEC BER are plotted in Fig. 3 (a). Since the noise level cannot be assessed due to the dense 50 GHz spacing, the OSNR is measured by switching off adjacent channels. The signals at shorter wavelengths experience more nonlinear transmission penalty due to the signal pre-emphasis (shown in Fig. 2(a)) and stronger forward Raman gain and, therefore, require higher OSNR. The average OSNR is 14.2 dB and the simulated OSNR show a good match with the measured values. The Q for all 150 channels is measured with a real-time processing 100G channel card. For the measurement, each individual comb channel is replaced by the channel of a 100G channel card tuned to the same wavelength and power level. The Q values of all 150 channels, with an average of 7.0 dB, are above the (pre-SD-

FEC) Q threshold of 6.4 dB (BER 1.9 x 10^{-2}). All the channels show error-free operation after FEC. The result of a 16-hour BER stability test is plotted in Fig. 3 (b). The performance of all 3 selected channels is well within the BER limit for error-free operation over the entire test duration.

4. Transmission as a function of channel growth

Generally, unrepeatered transmission systems operate with a lower capacity (lower channel count) at Beginning-of -Life. Capacity is increased by adding channels over time. The line system used in this experiment (Nu-Wave Optima^{TM}) can adaptively operate based on the channel count and therefore does not require loading channels for low capacity transmission. To support different channel counts, the LRA-2 in Fig. 1 is automatically controlled to meet signal output set points and the forward Raman pump power is controlled to provide optimal performance based on the number of channels. Since the backward distributed Raman gain is highly unsaturated due to the low signal power, the pump power in the backward pump module does not need to be changed. LRA-3 and WSS-2 operate together to provide optimal received power at the receiver.

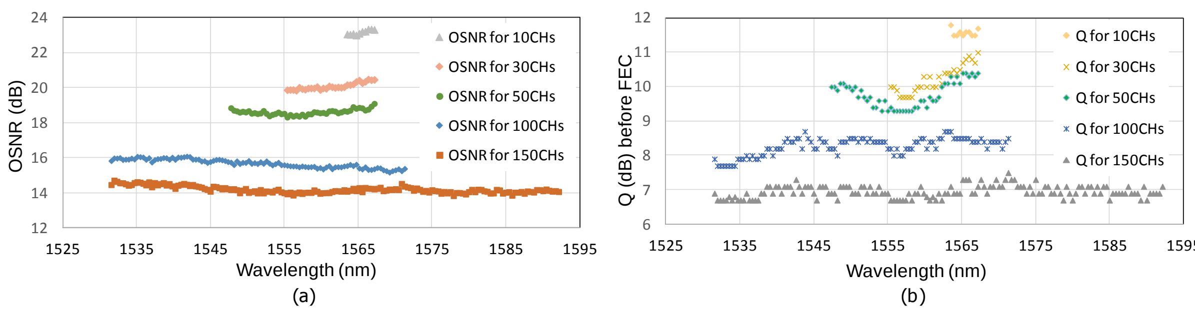

Fig. 4. Measurement of (a) OSNR, (b) Q before FEC for different channel counts

Fig. 4 (a) and (b) show the changes in OSNR and Q performance for different channel counts, respectively. To simulate a real deployment situation, the system is first equipped with 10 x 100G channels and is then upgraded to 30, 50, 100, and 150 channels. LRA-2 output signal set point uses a constant output signal profile of the full capacity (150 channels). The change in forward pump power (per wavelength) versus channel count is provided from the simulation. As the number of channels increases from 10 to 30, 50, 100, and 150, the average OSNR and Q change from 23.2 dB to 20.1 dB, 18.6 dB, 15.7 dB, 14.2 dB and from 11.6 dB to 10.2 dB, 9.8 dB, 8.3 dB, 7.0 dB, respectively. Even without loading channels, the system provides large margin for lower channel count.

5. Conclusions

A record capacity-reach product of 6.14 Pb/s-km (15 Tb/s over 409.6 km / 68.2 dB) unrepeatered transmission has been demonstrated. This result is achieved by using a single G.654-compliant fiber type, commercial Raman pump modules and real-time processed 100G channel cards, providing a practical solution for high-capacity and long-reach unrepeatered systems.

Acknowledgements

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