150 x 120 Gb/s Unrepeatered Transmission over 333.6 km and 389.6 km (with ROPA) G.652 Fiber

Do-il Chang[(1)], Hector de Pedro[(1)], Philippe Perrier[(1)], Herve Fevrier[(1)], Sergey Ten[(2)], Christopher Towery[(2)], Ian Davis[(2)], Sergejs Makovejs[(2)]

[(1)] Xtera Communications, 500 W. Bethany Drive, Suite 100, Allen, TX 75013, USA, dchang@xtera.com

[(2)] Corning Incorporated, 1 Riverfront Plaza, MP-HW-02-W12, Corning, NY 14831, USA, tens@corning.com

Abstract A record capacity of 15 Tb/s unrepeatered transmission has been demonstrated over 333.6 km (55.4 dB) and 389.6 km (64.3 dB) with ROPA. All transmission results have been achieved with G.652 fiber using forward and backward distributed Raman amplification.

Introduction

Unrepeatered transmission systems provide a cost-effective solution in submarine networks to communicate between coastal population centers or in terrestrial networks to connect remote areas where service access is difficult. One of the main goals of unrepeatered systems is to achieve the longest reach without any in-line active elements. Over the past 5 years, various demonstrations of 100G unrepeatered transmission over long distances have been reported [1-3]. On the other hand, increasing network bandwidth requirement to meet accelerating traffic demand now also requires higher transport capacity. As a result, there have been reports on high capacity unrepeatered transmission. For examples, 4.0 Tb/s over a 365 km system which consists of three different types of fiber [4]. Or, 6.0 Tb/s over 437 km with a Remote Optically-Pumped Amplifier (ROPA) and 6.3 W strong third-order backward Raman pumping over a span made up of mixed fiber types [5], and 6.3 Tb/s over a 402 km span with ROPA and three different types of fibers [6]. In this paper, we report 15 Tb/s (150 x 120 Gb/s) unrepeatered transmission over 333.6 km and 389.6 km of ultra-low loss G.652 fiber (Corning® SMF-28® ULL) without / with ROPA, respectively. The span consists of a single transmission fiber type, resulting in a practical solution for deployments. To our knowledge, these results represent the highest capacity for an unrepeatered transmission larger than 300 km.

Experiment Description

A schematic diagram of the unrepeatered transmission experiment is shown in Fig. 1. Two modified 100G line cards (hereafter referred to as comb modulators) are used to generate multiple modulated 100G loading channels. A comb modulator accepts an input CW comb generated from 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 100 GHz polarization multiplexed PM-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 lumped Raman amplifier (LRA) LRA-1. In addition, three tunable production 100G cards (with real-time processing; one in the L band

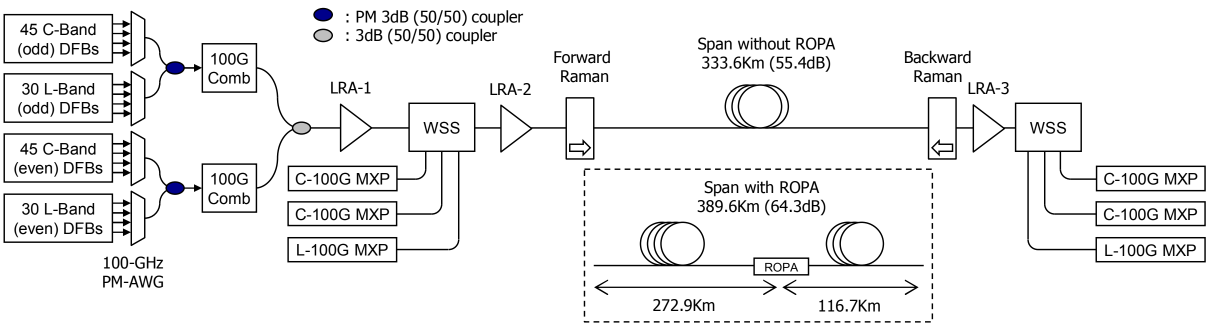


Fig. 1: System Configuration

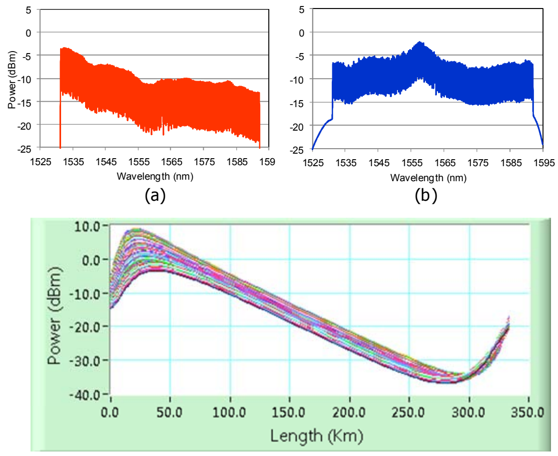
and two in the C-band) are combined with the comb channels using a wide-band Wavelength Selective Switch (WSS). LRA-2 is used to boost the combined signals on the transmit side. Dispersion compensating fiber which is used as the Raman gain medium in LRA-2 also provides approximately -600 ps/nm of dispersion pre-compensation and improves transmission performance. In this experiment, all of the channels are modulated at 120 Gb/s, which accounts for the 15% overhead of the Soft-Decision Forward Error Correction (SD-FEC). The SD-FEC can correct a BER of 1.9 x 10^{-2} to less than 10^{-15}. At the receiver end, another LRA-3 is used to amplify the receiving signals and a second WSS is used to select channels for Q measurement using a 100G channel card.

Forward and backward Raman pumping is provided by production Raman pump modules which consist of five pump wavelengths distributed in the range between 1420 nm and 1500 nm. Thanks to the multiple pump wavelengths, the Raman pump modules can provide flexible gain profiles depending on the applications. For example, the same Raman pump modules have been used for low capacity unrepeatered systems [2] as well as for terrestrial repeatered systems [7].

The ITU-T G.652 compliant Corning® SMF-28® ULL fiber is used as span fiber. It has an average A_{eff} of 83 μm^2. Two span configurations are tested in this experiment. A span without ROPA has a total length of 333.6 km fiber and a loss of 55.4 dB (mean fiber attenuation of 0.166 dB/km includes the high power connectors and fiber splice losses). The span with ROPA consists of 389.6 km of fiber with a span loss of 64.3 dB (mean fiber attenuation of 0.165 dB/km) and a standard C-band optimized ROPA. The ROPA consists of one isolator and 12 m of erbium doped fiber and is placed at 116.7 km from the receiver end.

Transmission over the span without ROPA

First, 150 x 120 Gb/s unrepeatered transmission is demonstrated over the 333.6 km span without ROPA. Fig. 2 (a) and (b) show the measured spectra with 0.1-nm resolution bandwidth of the transmitted (at the output of LRA-2 in Fig. 1) and receiving (at the output of LRA-3 in Fig. 1) channels, respectively. The transmit channels are pre-emphasized to achieve approximately flat Q over all channels at the receiving end. As shown in the figure, the transmit spectrum is negatively tilted to compensate higher fiber attenuation in the shorter wavelength region and Raman cross-talk between the channels. Fig. 2 (c) shows the simulated power profiles (for all 150 channels) along the span. The average channel launch power is -9.8 dBm/ch and the forward and backward distributed pump powers are 1590 mW and 1670 mW, respectively.



(C)

Fig. 2: OSA spectra at (a) transmit, (b) receiver side, (c) simulated signal power profile

The forward pumps provide 19.3 dB of distributed Raman gain (on/off) and the backward pumps provide 30.5 dB of distributed Raman gain (on/off). In the span, the signal peak power of the shortest wavelength reaches +8.9 dBm at 21.7 km from the transmit side.

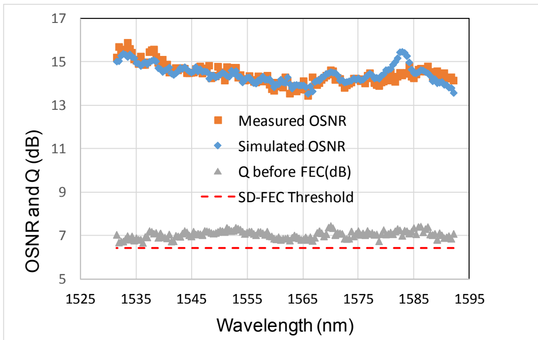


Fig. 3: measured and simulated OSNR and Q before FEC

The measured and simulated OSNR as well as the calculated Q values from the measured pre-FEC BER are plotted in Fig. 3. Since the noise level cannot be assessed due to the dense 50GHz 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 therefore, require higher OSNR. The average OSNR is 14.5 dB and the simulated OSNR show a good match with the measured values. The Q for all the 150 channels is measured with a real-time process ASIC 100G line card. For the measurement, each individual comb channel is replaced by the channel of a 100G line card tuned to the same wavelength and power level.

The Q values of all 150 channels, with an average of 7.1 dB, are greater than the (pre-SD-FEC) Q threshold of 6.4 dB. All the channels show error free operation after FEC.

Transmission over the span with ROPA

The second transmission experiment was carried out over the 389.6 km long span with ROPA.

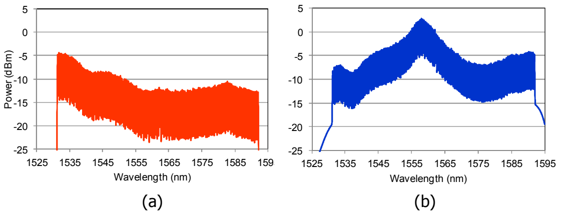


Fig. 4: OSA spectra at (a) transmit, (b) receiver side

Fig. 4 depicts the measured spectra of the pre-emphasized transmitted (a) and received channels (b). The large peak to peak signal power ripple (~ 10 dB) at the receiver side comes from uncompensated ROPA gain, but is flattened by the WSS before the receiver.

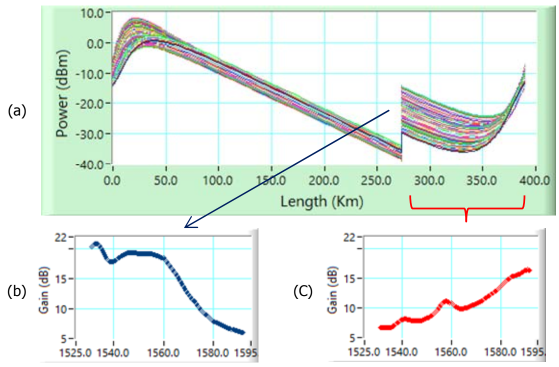


Fig. 5: Simulated (a) signal power profile, (b) ROPA gain and (c) Backward Raman gain,

Fig. 5 (a) shows the simulated signal power profile. In this case, the average launch signal power is -10.8 dBm/ch. The forward and backward distributed pump powers are 1590 mW and 1790 mW, respectively. The maximum signal power reaches +8.1 dBm at 21.3 km from the transmit side. Forward pumps provide 19.7 dB of distributed Raman gain (on/off). Fig. 5 (a) depicts the simulated ROPA gain using an estimated 11.5 mW of residual pump power from the backward Raman pumping. The ROPA provides 16.6 dB average total net gain for 150 channels but shows much lower gain in the L-band. The distributed backward Raman gain profile which is adjusted to compensate the gain tilt from the ROPA is shown in Fig. 5 (c). The average backward Raman gain (in/out) is 9.0 dB.

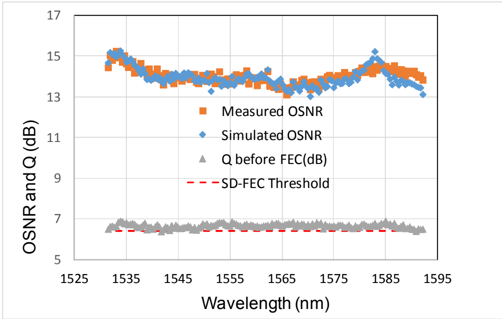


Fig. 6: measured and simulated OSNR and Q before FEC

Fig. 6 shows the measured and simulated OSNR and Q values. The average OSNR is 14.1 dB and the simulated OSNR matches very well with the measured values. The Q values of all 150 channels, with an average of 6.7 dB, are greater than the (pre-SD-FEC) Q threshold of 6.4 dB. All the channels are error free after FEC.

Conclusions

A record capacity of 15 Tb/s (150 x 120 Gb/s) unrepeatered transmission over 333.6 km (55.4 dB) and 389.6 km (with ROPA, 64.3dB) has been demonstrated. These results are achieved by using single G.652 compliant fiber type with standard C-band ROPA, production Raman pump modules and real-time processed 100G channel cards, therefore, providing a practical solution to increase the capacity of existing unrepeatered spans or the deployment of new systems with ultra-high capacity.

References

[1] H. Bissessur et al., “4 x 100Gb/s Unrepeatered Transmission over 462 km Using Coherent PDM-QPSK Format and Real-Time Processing,” Proc. ECOC, Tu.3.B.3, Geneva (2011).

[2] D. Chang et al., “8 x 120 Gb/s Transmission over 80.8 dB / 480.4 km Unrepeatered Span,” Proc. OFC, JThA2.42, Anaheim (2013).

[3] T.J. Xia et al., “557-km Unrepeatered 100G Transmission with Commercial Raman DWDM System, Enhanced ROPA, and Cables Large A_{eff} Ultra-Low Loss Fiber in OSP Environment.” Proc. OFC, Th5A.7, San Francisco (2014).

[4] J. Downie et al, “40 × 112 Gb/s Transmission over an Unrepeatered 365 km Effective Area-Managed Span Comprised of Ultra-Low Loss Optical Fibre,” Proc. ECOC, We.7.C.5, Torino (2010).

[5] H. Bissessur et al., “6 Tb/s Unrepeatered Transmission of 60 x 100 Gb/s PDM-RZ QPSK channels with 40 GHz Spacing over 437 km.” Proc. ECOC, Mo.1.C.3, Amsterdam (2012).

[6] B. Zhu et al., “6.3-Tb/s Unrepeatered Transmission over 402-km Fiber using High Power Yb-free Clad-pumped L-band EDFA” Proc. OFC, W1A.2, San Francisco (2014).

[7] D. Chang et al., “150 x 120 Gb/s Field Trial over 1,504 km using All-Distributed Raman Amplification,” Proc. OFC, Tu2B.2, San Francisco (2014).