ULTRA-LOW LOSS FIBER AND ADVANCED RAMAN AMPLIFICATION DELIVER RECORD UNREPEATERED 100G TRANSMISSION

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Abstract: We report the longest 100G unrepeatered transmission without any in-line active elements. The unrepeatered transmission is achieved by using a commercial distributed Raman system with coherent 100G transceivers (PM-QPSK) and ultra-low loss fiber with large effective area to support handling of high optical power levels. An enhanced ROPA configuration which utilizes additional pumping fibers is used to extend reach. A single 100G channel is transmitted over a record 626.8 km distance with a span loss in excess of 100 dB.

1. INTRODUCTION

Unrepeatered transmission systems remove the need for power feed equipment and active submerged repeaters and therefore provide a more cost-effective and operationally simpler solution for many applications. Such applications include subsea links connecting sparsely populated islands, communication links to offshore oil and gas platforms and terrestrial routes in remote and/or hostile areas. Ultra-long, unrepeatered reach can also enable the direct connection to inland points-of-presence or data centers with no need for additional equipment and a demarcation point at the cable landing station. This leads to a unified and seamless connection when the end-to-end distance remains within the unrepeatered reach.

Ultra-low attenuation and a larger effective area than found in conventional single-mode fiber are critical factors to extend the reach of unrepeatered transmission without sacrificing capacity performance. Ultra-low fiber attenuation extends the physical distance achievable for any particular span power budget whilst larger effective area enables a higher optimum launch power to be delivered into the fiber. Further reach can be achieved by employing distributed Raman amplification and Remote Optically Pumped Amplifiers (ROPAs).

There have been several reports of increased unrepeatered distances and capacity by using more elaborate technologies such as additional pumping fibers [1-4], high order Raman pumping [5-7], multi-wavelengths Raman pumping [4,8,9], and coherent detection with powerful FEC coding [3,4,7,9].

In a recent trial, several technologies were combined to extend the error-free reach for 100G transmission to a record 626.8 km with no active equipment between the end points of the links. The trial relied on the use of conventional erbium-doped fiber amplification, distributed Raman amplification (both counter and co-propagating) and ROPA. Further extension of the reach beyond a cable budget of 100 dB was made possible through the use of innovative ROPA design and an ITU-T G.654.B compliant fiber featuring ultra-low loss of average 0.157 dB/km and effective area of typically 112 μm^2.

This paper describes how these state-of-the-art technologies combine to maximize unrepeatered reach. A two month stability test of 100G unrepeatered transmission over 612.3 km distance will also be reported.

2. ULTRA-LOW LOSS AND LARGE EFFECTIVE AREA FIBER

To maximize the physical reach achievable from a 100 dB span loss, an ultra-low loss fiber with large effective area, Vascade® EX2000 was installed. In this study, the average attenuation of the fiber is 0.157 dB/km at 1550nm. This is an ITU-T G.654.B compliant fiber which has been extensively deployed in both repeatered and unrepeatered submarine networks to allow extended reach in high-speed operation.

Ultra-low attenuation in the fiber is achieved through a large silica-core. A fluorine-doped cladding is employed to achieve the required difference in core-cladding refractive indices. The large core extends the effective area to a nominal 112 μm^2. This is in contrast to a conventional G.652.D compliant fiber with a germania-doped silica core and silica cladding with nominal effective area of 85 μm^2. Other optical properties that are modified compared to a G.652.D fiber are the cable cut-off wavelength, which is raised from $\leq$ 1260 nm to $\leq$ 1520 nm, and chromatic dispersion which is elevated from $\leq$ 18 ps/nm·km to $\leq$ 22 ps/nm·km at 1550 nm.

Note that for a test-bed experiment, it is necessary to deploy the fiber wound under tension on a shipping spool. When this fiber is deployed in a low tension environment that reflects the actual deployment in an optical network, i.e. in a loose-tube cable, the attenuation typically falls by a further 0.002 to 0.003 dB/km.

3. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1 and is configured to transmit 100G at 1563.86 nm. The 100G signal is RZ-PM-QPSK modulated at 120 Gbit/s which includes the 15% overhead of the Soft-Decision Forward Error Correction (SD-FEC) code. The SD-FEC can correct a pre-BER of 1.9 x 10^{-2} to less than 10^{-15} (NCG of 11.1 dB). The 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, -2,740 ps/nm dispersion compensation unit (DCU) is placed at the mid-stage of the EDFA to improve transmission performance. At the

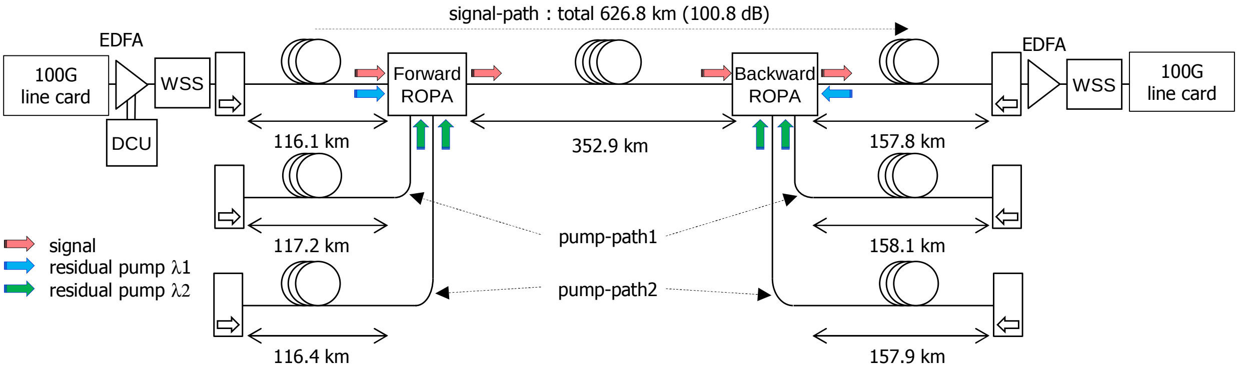


Figure 1 Experimental setup for single 100G channel unrepeatered transmission.

receive end, an EDFA amplifies the received signal and another WSS is used to de-multiplex the channels.

In the signal path, the forward and backward ROPAs are located at 116.1 km and 157.8 km from the terminals, respectively. 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). The span consists of 43 fiber lengths deployed on shipping spools and spliced together. Typical splice loss of 0.02 dB is achievable for this fiber type. The average loss of the total path (including splice losses throughout the span and connector losses at each terminal) is 0.161 dB/km at 1550 nm.

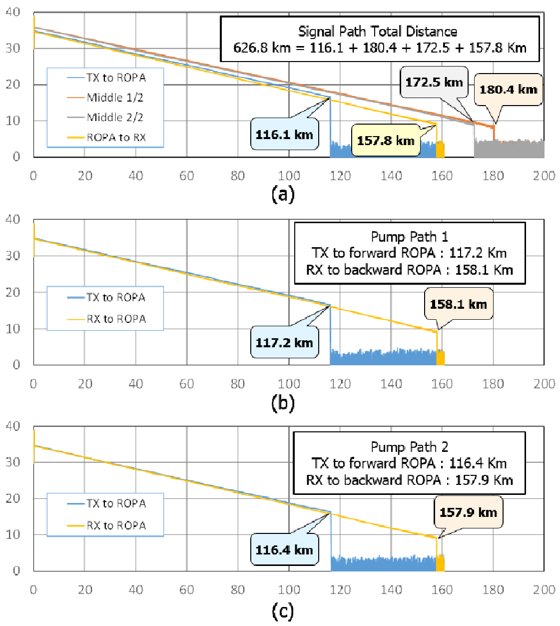


Figure 2 OTDR analysis over (a) signal path for 100G transmission, (b) dedicated pumping fiber1 and (c) pumping fiber2.

The dedicated pump paths use fiber lengths of 117.2 km and 158.1 km in pump-path 1 for forward and backward pumping, respectively. For pump-path 2, 116.4 km and 157.9 km fiber lengths are used. The span distance and the loss are carefully verified by OTDR measurement (EXFO, 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. 2.

All distributed Raman pumps use the same commercial Raman pump modules (Nu-Wave Optima™ SE24) that consists of five pump wavelengths distributed in the range between 1420 and 1500 nm and provide total power up to 2.1 W. The Raman pump module is designed to accept additional Raman pumps with wavelengths shorter than 1420 nm when the system requires more power. In this trial, an additional 0.9 W pump power is utilized by adding an additional module (SE-HP) which has two wavelengths between 1400 and 1420 nm.

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 Relative iItensity Noise (RIN) transfer penalty in the forward direction and also provides more efficient Raman gain to the signal wavelength at 1563.86 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-doped fiber. The blue and green arrows in Fig. 1 and Fig. 3 represent residual pumps from the signal path and pump paths, respectively.

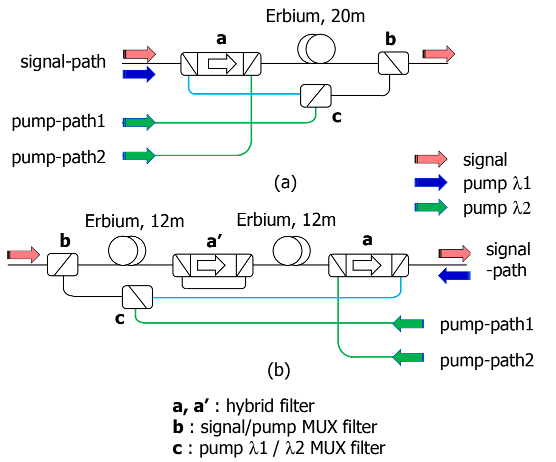


Figure 3 Configurations of (a) forward ROPA, (b) backward ROPA.

Fig. 3 shows the details of the enhanced ROPA configurations which utilize two additional fibers for pumping. In the forward ROPA (Fig. 3 (a)), the residual pump power which comes from the signal-path is separated from the signal at a hybrid filter (**a** in Fig. 3) and combined with residual pump power from pump-path 1 using pump λ1/λ2 Mux (**c** in Fig. 3). The combined powers then pump 20 m of erbium-doped fiber in the backward direction via signal/pump MUX filter (**b** in the figure). The residual pump from pump-path2 is combined with the signal by the hybrid filter (**a**) and then pumps the erbium-doped fiber in the forward direction.

The backward ROPA (Fig. 3 (b)) uses similar schemes to combine residual pump powers from each fiber path, with the difference that in the signal-path, the signal and residual pump travel in opposite directions. The backward ROPA uses an additional hybrid filter (**a'**), to split erbium gain into two sections while allowing the pumps to excite erbium-doped fiber sections from both directions, which improves the Noise Figure (NF) of the backward ROPA.

4. TRANSMISSION RESULTS

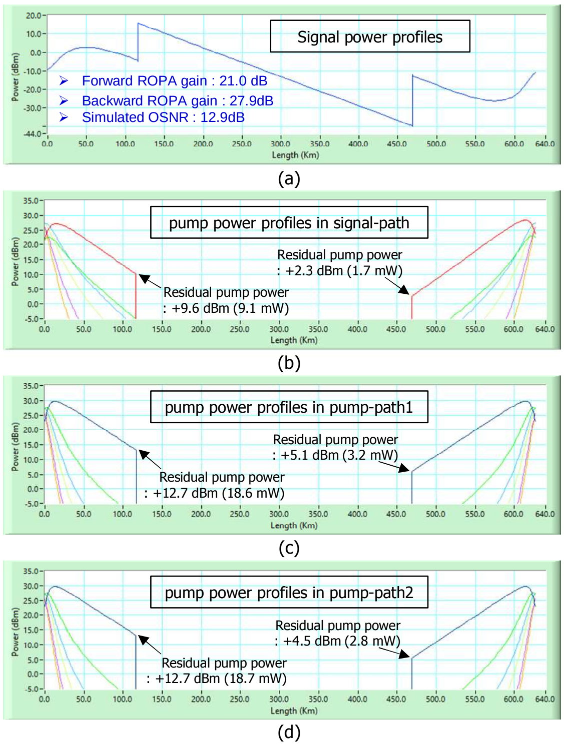


Figure 4 (a) Simulated signal power distribution and simulated Raman pump power distribution in (b) signal path, (c) pump-path 1 and (d) pump-path 2

Fig. 4 (a) shows the simulated power profile of a single 100G channel over 626.8 km. Measured input signal power, forward and backward pump powers and the characteristics of the Vascade EX2000 fiber [9] 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 and the maximum power of the signal right after the forward ROPA at 116.1 km is 11.9 dBm. The forward ROPA gain is 18.8 dB and the backward ROPA provides 27.9 dB gain.

The simulated pump power profiles used for single 100G channel transmission over 626.8 km are shown in Fig. 4 (b), (c), (d). 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 path 1 and 2, the same pump power of 2,520 mW is used for both forward and backward pumping. The residual pump power reaching the Erbium-Doped Fiber (EDF) in the forward ROPA is measured to be 9.1 mW from the signal path and 18.6 mW, 18.7 mW from pump-path1 and pump-path 2, respectively. At the backward ROPA location, the residual pump powers to the EDF sections are measured to be 1.7 mW, 3.2 mW and 2.8 mW from the signal path, pump-path1, and pump-path 2, respectively. As shown in the figures, most of the pump power is transferred to the longest wavelength (red in (b), blue in (c), (d)) at the ROPA location by Raman amplification between pumps. The simulation shows very good agreement with the measured residual pump powers.

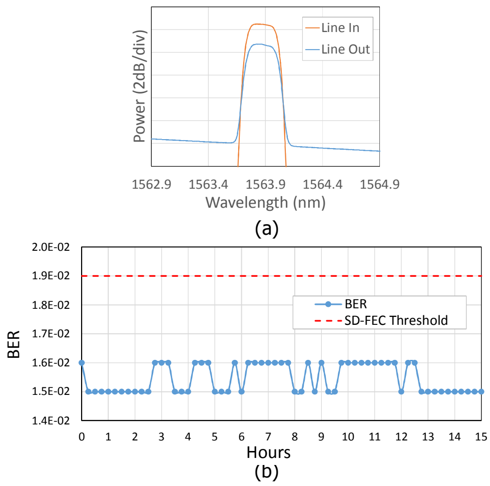


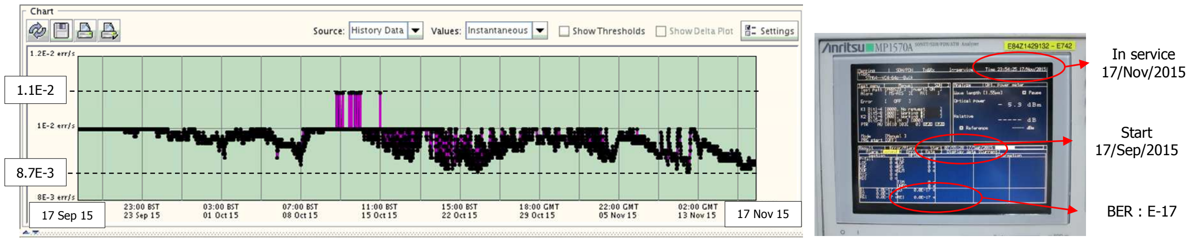
Figure 5 (a) Measured spectra, (b) BER stability test over 15 hours.

The measured spectra at the input and output of the span are shown in Fig. 5 (a). 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 in very good agreement with simulations (12.9 dB/0.1nm).

The result of a 15-hour BER stability test at 100G is plotted in Fig. 5 (b). 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; no uncorrected errors were observed after SD-FEC. The total signal propagation penalty which includes nonlinear, RIN, and multi-path interference (MPI) penalties is estimated to be 1.0 dB Q compared to the back-to-back performance (Q = 7.7 dB at 13.3 dB OSNR).

5. TWO MONTHS LONG TERM STABILITY TEST

Since the system uses a new configuration operating with additional pumping fibers, full safety features, such as automatic power shutdown in the case of fiber cuts or disconnection of the connectors, were not implemented at the time of test. These full safety features are available from a hardware perspective but require a new software release that was not downloaded onto the tested equipment. For the sake of safety, the high power add-on modules (SE-HP) were removed for the long-term stability test. As a result, the total launched pump power in the signal path was reduced to 1,860 mW for both forward and backward directions. For the pump-path 1 and 2, a total of 2,060 mW was used for both forward and backward pumping. The span length was also reduced to 612.3 km (98.5 dB) to compensate the performance degradation. Performance of 100 Gbit/s channel was recorded by the Network Management System (NMS). On the client side, 10 x 10 Gbit/s channels were daisy chained and the performance was monitored by network analyzer (Anritsu, MP1570A).



(a) (b)

Figure 6 Screenshot of (a) NMS which shows BER of 100G over two months, (b) network analyzer of 10 x 10G clients (daisy chained)

Figure 6 shows the results of the (a) line side 100G and (b) client side after 2 month test. Line-side BER of 100G shows very stable operation (Min BER of 8.7 x 10^{-3}, Max BER of 1.1 x 10^{-2}, before FEC) over two months. The network analyzer also ran clean over two months and shows estimated the BER of < 1 x 10^{-17}.

6. CONCLUSION

We have demonstrated the longest single 100G channel unrepeatered transmission distance over 626.8 km (100.8 dB) with a link attenuation exceeding 100 dB. Distributed Raman amplification combined with ultra-low loss / large effective-area fiber provides the foundation necessary to increase the distance in unrepeatered transmission systems. An enhanced ROPA architecture with additional pumping fiber, high FEC coding gain and pre-dispersion optimization are combined to extend the reach even farther.

Such record result is achieved by using a single fiber type, commercial Raman pump modules and 100G channel card, providing a practical solution for real field deployments.

7. REFERENCES

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