# 557-km Unrepeatered 100G Transmission with Commercial Raman DWDM System, Enhanced ROPA, and Cabled Large $A_{eff}$ Ultra-Low Loss Fiber in OSP Environment

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**Abstract:** This paper reports the longest 100G unrepeatered transmission distance to date. Enhanced ROPA, 100G coherent transceiver, commercial Raman system, and 557-km cabled large $A_{eff}$ ultra-low loss fiber in OSP environment are used in the trial.
**OCIS codes:** (060.2330) Fiber optics communications; (060.1660) Coherent communications.

## 1. Introduction

Many applications would benefit from very-long, “skinny” (low-capacity) unrepeatered systems. One such application is terrestrial routes in remote and hostile areas (tropical forest, desert…) for which the use of unrepeatered transmission alleviates the need for intermediate amplification sites (and associated operational expenses). Another application is subsea links to connect sparsely populated islands for which an unrepeatered system – without submerged repeaters and associated power feed equipment – yields a more cost effective and thus viable solution. Over the past 5 years, 100G transmission experiments have reported increasing unrepeatered distances [1-6], thanks to the introduction of more powerful FEC coding, ultra-low loss and large $A_{eff}$ optical fiber, and optimized Raman / Remote Optically Pumped Amplifier (ROPA) architecture. Figure 1 shows the trend of unrepeatered distances at 100G in recent years. In this paper, we report a new distance record for unrepeatered transmission at 100G. This result is obtained through the use of a commercially available DWDM Line Terminal Equipment (LTE) with distributed Raman, mature 100G coherent technology, large $A_{eff}$, ultra-low loss fiber, and a novel, patented ROPA design [7]. The cabled fiber is placed in an uncontrolled OSP environment to simulate real network situation.

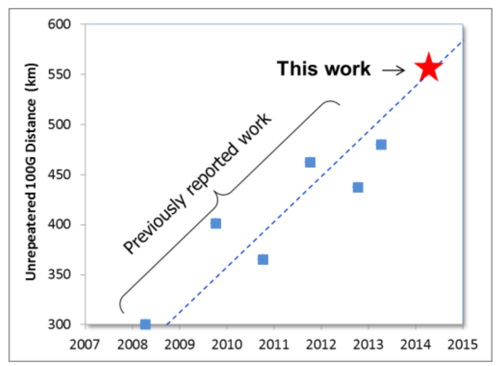


**Figure 1** Distances of unrepeatered single-carrier 100G transmission in recent years [1-6] and of this work.

## 2. Trial Setup

The trial setup is shown in Fig. 2a. The LTE is configured to transmit up to four channels. Four 100G line cards with wavelengths in the range 1561.42 to 1563.86 nm (100 GHz spacing) are multiplexed using 3-dB couplers. The signals are 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 BER of $1.9 \times 10^{-2}$ to less than $10^{-15}$. The WDM signals are then amplified through a double-stage Erbium-doped Optical Amplifier (EOA) with a mid-stage Dispersion Compensation Unit (DCU) followed by a Wavelength Selective Switch (100-GHz WSS) used to filter out the ASE from the transmit EOA. At the receive end, an EOA amplifies the received signals and another WSS is used to demultiplex the channels. The forward and backward distributed Raman pump modules consist of seven pump wavelengths distributed in the range between 1400 nm and 1500 nm. At the transmit side, approximately -900 ps/nm of dispersion pre-compensation is placed in the mid-stage of the EOA to improve transmission performance.

The span was assembled with Corning® Vascade® EX2000 optical fiber in Corning® Altos® gel filled loose tube cable that was deployed outside the laboratory on the cable shipping drum with a diameter of 0.91 m, in a walled enclosure open to the environment. The ~ 8.3 km Altos cable contained 204 Vascade® EX2000 fibers and its ends (approximately 100 m long) were pulled in the laboratory for splicing. The fiber attenuation at 1550 nm of each section was measured on the shipping spools (before cabling) and after the cable was made. The cumulative distributions of fiber attenuation are shown in Fig. 2b. All fibers have an attenuation <0.173 dB/km and the median attenuation shifts from 0.161 dB/km (on shipping spools) to 0.159 dB/km after cabling. The Vascade® EX2000 optical fiber has an average $A_{eff}$ of 112 $\mu m^2$ enabling higher optical launch powers for Raman pumping, ROPA, and data transmission.

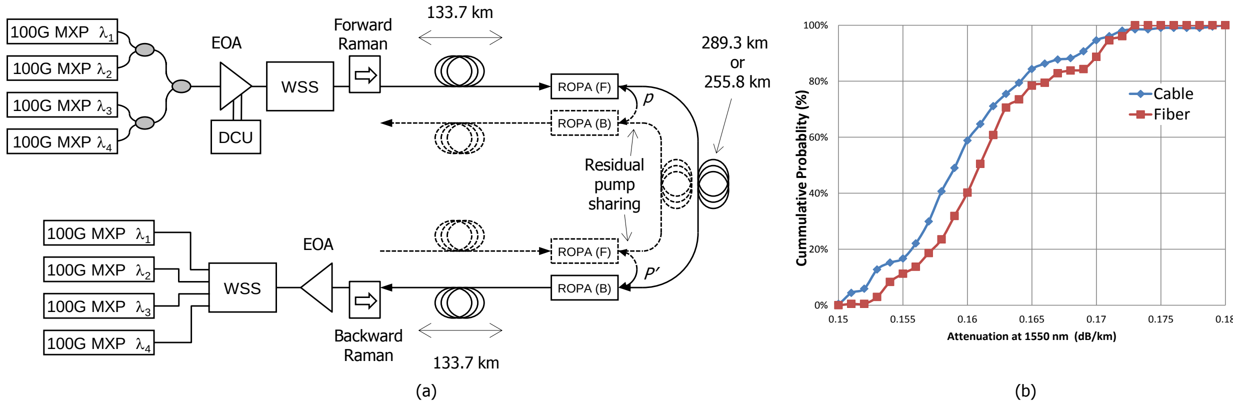


**Figure 2** (a) System Configuration, where Point p and p' are connected in the trial to mimic the transmission in another direction of real duplex system (in dashed line); (b) Histogram of the Vascade EX2000 fiber attenuation in the cable.

An enhanced ROPA configuration was introduced in this trial. The forward and backward ROPA are placed at the same distance (133.7 km) from the terminals. Placing the ROPAs at the same distance presents two major benefits in bi-directional transmission: firstly, the system requires the same number of ROPA enclosures as conventional systems which use a ROPA in the backward direction only; secondly, it allows to recirculate residual pump powers between the forward (in one direction) and backward (in the opposite direction) ROPAs, which has been shown to improve both gain and noise figure of the ROPAs. For this unidirectional transmission trial, sharing of the residual pump power between the forward and backward ROPAs is achieved in the same direction by connecting points *p* and *p'* shown in Figure 2a directly. The Erbium doped fiber is 7 m long in the forward ROPA and 12 m long in the backward ROPA.

For the single channel transmission case, the distance between the ROPAs is adjusted to 289.3 km for a total span length of 556.7 km and a deployed span loss 90.2 dB (loss of the ROPAs not included), resulting in an averaged cable attenuation (including splice losses between the ~8.3 km cable sections) of 0.162 dB/km. The accumulated chromatic dispersion is approximately +11,400 ps/nm at the signal wavelength. In the case of 4 x 100G transmission, the total distance is reduced to 523.2 km (255.8 km between ROPAs) for a span loss of 84.8 dB.

## 3. Transmission Results

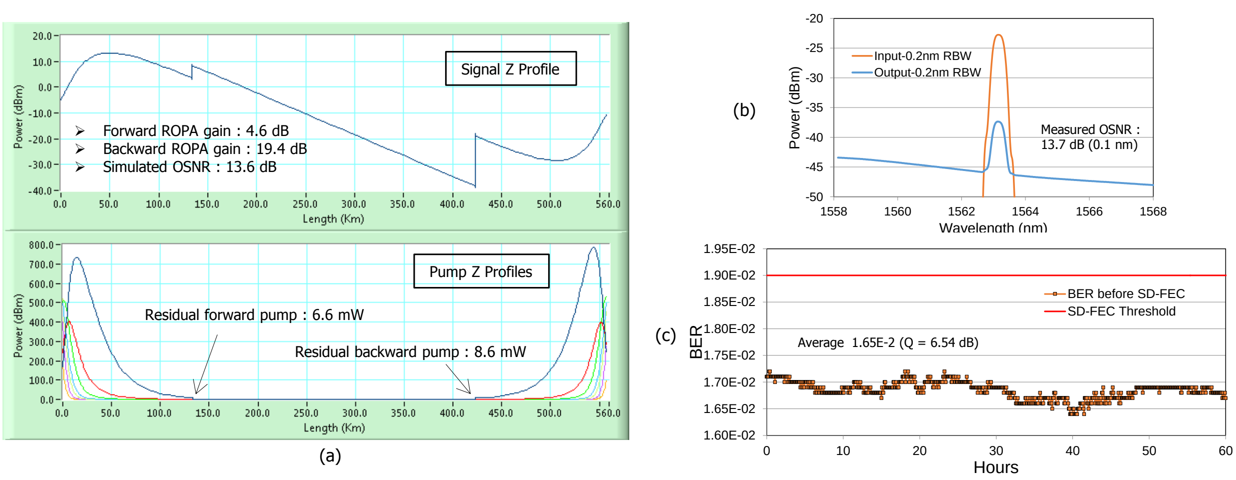


**Figure 3** (a) Power distribution of signals and pumps, (b) Input and output OSA spectra, (c) 60-hour stability test.

Figure 3a shows the simulated power profiles for a single channel signal power and associated Raman pump power distributions along the 556.7-km span. The signal first experiences the forward distributed Raman amplification. Then the signal is amplified by the forward ROPA, attenuated by the fiber, and amplified again by the backward ROPA. Finally, the signal experiences the backward distributed Raman amplification. For the single channel transmission trial, the launched pump power of the forward and backward Raman pump modules was of 2510 mW and 2520 mW, respectively. The longest wavelength in both the forward and backward pump modules is primarily used to excite the ROPAs. The residual pump powers reaching the ROPAs were measured to be 6.6 mW and 8.6 mW for the forward and backward ROPAs, respectively. The forward ROPA gain was 4.6 dB, while the backward ROPA provided 19.4 dB of gain to the signal. The peak power of the signal reached +13.3 dBm at 49.8 km from the transmit side. Figure 3b shows the measured spectra at both the input and output of the span. The measured OSNR at the receiver was 13.7 dB, in very good agreement with the simulation (13.6 dB). The result of a 60-hour stability test is plotted in Fig 3c. This long-term measurement shows excellent stability of the 100G channel, exhibiting less than 0.1-dBQ fluctuation. The average pre-FEC BER was $1.65 \times 10^{-2}$ (corresponding to a Q of 6.54 dB) and no uncorrected errors were observed after SD-FEC.

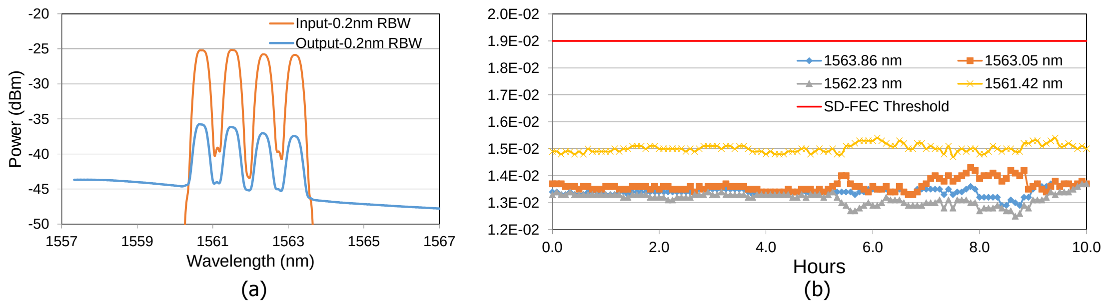


**Figure 4** (a) Input and output OSA spectra of four-channel transmission, (b) 10-hour stability test.

Figure 4 shows the measured input and output spectra of 4x100G channel transmission over 523.2 km (a) and the result of a 10-hour stability test (b). The settings of both the ROPAs and the backward Raman pump module remained the same as for the single channel transmission case, while the power of the forward pump module was increased by 180 mW to offset the decrease in forward Raman and ROPA gains caused by the additional 100G channels. The performance of all 4 channels is well within the BER limit at SD-FEC threshold of $1.9 \times 10^{-2}$ for error-free operation.

## 4. Summary

We have demonstrated the longest single 100G channel unrepeatered transmission distance to date as well as a new record for multi-channel100G unrepeatered transmission. In the trial, enhance ROPA architecture, 100G coherent transceiver, commercial Raman system, and 557 km of cabled large effective area ultra-low loss fiber in OSP environment are used for the single channel transmission (523 km for the four-channel transmission). This trial demonstrates the feasibility of extended unrepeatered distances for terrestrial and submarine applications.


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