Record Unrepeatered 400G 16QAM Signal Transmission over 526 km of Terrestrial Ultra-Low Loss Optical Fiber

Yaroslav Tezadov(1), Sergey Otradnov(1), Nikita Korotkov(2), Sergejs Makovejs(3), Cristiano Mornatta (4), Alessandro Festa (4)

(1) IPG IRE-Polus, Menzhinskogo 40, Moscow, Russia,yTezadov@ntoire-polus.ru
(2 Corning SNG, Staropimenovsky per.18, Moscow, Russia
(3) Corning, Lakeside Business Village, St. David's Park, Ewloe, CH5 3XD. UK
(4) IPG Photonics, Via Kennedy, 21 20023 Cerro Maggiore, Milan, Italy

Abstract We demonstrated a record transmission of 400G 16QAM signal over 526 km of terrestrial ultra-low loss and large effective area fibers. Third-order Raman amplifiers and Remote Optical Pump Amplifiers (ROPA) were used to achieve the best-in-class performance. The total span loss was 86.24 dB.

Introduction

Unrepeatered systems are widely used in the areas where any active signal amplification is hard to realize or is very expensive. In these systems ROPA and Raman amplification are often used to extend the maximum achievable distance. Previously, a number of record experiments were demonstrated for single-carrier transmission of 100G, 200G and 400G signals over long-haul distances up to 502 km for 400G 64QAM modulation format without using intermediate active amplifiers[1],[2].

In this paper we show a successful record 400G 16QAM unrepeated signal transmission over 526.14 km. The fiber span was a combination of ultra-low loss ITU-T G.652 fiber and ultra-low loss large effective area G.654.E terrestrial optical fibers[3], which allowed for an increase in signal and pump launch powers. We also used high-order Raman amplification as the most effective and low-noise way to achieve signal gain. For remote signal amplification forward and backward ROPAs with dedicated fiber for pump power delivery were used. The total span loss was measured to be 86.24 dB.

Components

- **Transponder**

The transmitter we used in this work generates 400Gbit/s signal using 16QAM modulation format and has 27% overhead for soft decision Forward Error Correction (FEC). The symbol rate is 69.4 Gbaud/s and SD-FEC threshold value is 3.7e-2. The measurements of receiver OSNR sensitivity at 0.1 nm resolution bandwidth are shown in Fig.1(a). We have tested OSNR penalty caused by nonlinear effects as a function of input optical power for 100 km of G.652 fiber, and the optimal input power was measured to be 12 dBm (Fig.1(b)).

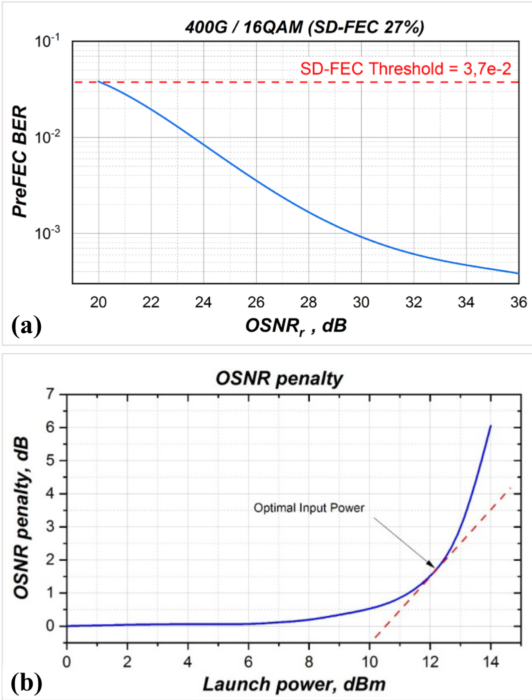

Fig. 1: (a) PreFEC BER at the receiver as a function of OSNR.(b) OSNR penalty as a function of launch power

- **High-order Raman Pump**

The most effective way to improve the ROPA efficiency is to increase the pump power within the 1470-1500 nm wavelength range. Although Raman fiber lasers with output power beyond 5W are commercially available, achievable power levels in telecom applications are limited by double-Rayleigh scattering effect and self-lasing, which are fiber dependent. For G.652 fiber the maximum achievable pump power is typically

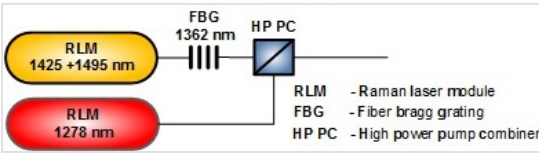

Fig. 2: High-order Raman Pump schematic diagram

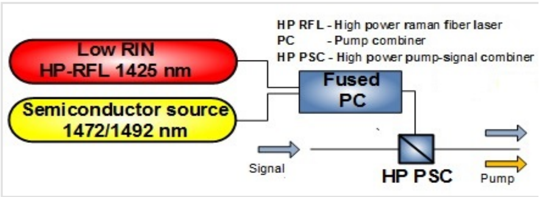

Fig. 4: Low-RIN Raman Pump schematic diagram

less than 1.4W. One of the most effective ways to increase this power level is to use the High Order Raman Pump (HO-RP). In our experiment we used IPG Raman Laser Modules (RLM) based on the Raman Fiber Laser (RFL) technology (Fig.2).

The RLM operating at 1278 nm with the output power of up to 5W was used as the first-order pump, and was subsequently converted to the second wavelength of 1362 nm using a Fiber Bragg Grating (FBG) and Stimulated Raman Scattering (SRS) effect[4]. For further conversion from 1362 nm to 1425 nm and, ultimately, to 1495 nm we used RLM that consisted of 1425 nm and 1495 nm RFLs.

The evolution of HO-RLM optical power in the first 150 km section, consisting of 50 km of Corning® TXF® fiber followed by the 100 km of Corning® SMF-28® ULL fiber is shown in Fig.3. The 1495 nm optical pump power at the end of the span was found to be more than 3.5 dB higher compared to a scenario in which first-order Raman pump and SMF-28 ULL fiber only were used.

- **Second-order Low-RIN Raman Pump**

A conventional Raman fiber laser is not suitable to achieve a co-pumped SRS (Stimulated Raman Scattering) amplification due to the comparatively high Relative Intensity Noise (RIN) of more than -110 dB/Hz[5]. Therefore, we used a low-RIN (less than -130 dB/Hz) high power 1425 nm Raman source with the optical power of up to 2W suitable

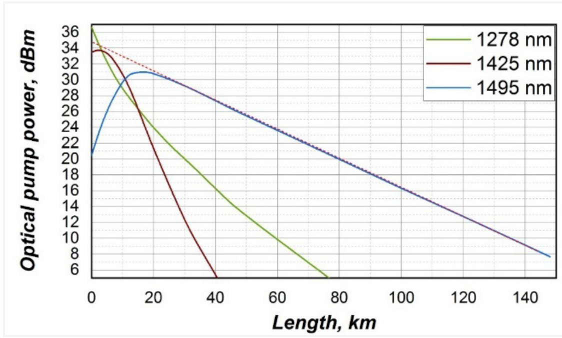

Fig. 3: Evolution of HO-Raman Pump optical power for the signal path with 50 km G.654.E and 100 km G.652 fibers

for large effective area fiber. The second source consisted of 4 semiconductor diodes (two operating at 1472 nm, and the other two – at 1492 nm).

The schematic diagram of second-order Low-RIN Raman Pump is shown on Fig. 4. Such a configuration allows for an increase in the optical budget by more than 1 dB compared to a conventional first-order Raman co-pumped configuration.

- **ROPA modules**

ROPA-TX is based on the single cascade optical scheme (Fig.5). The residual power from HO-RP and SO-RP at the transmitter side pumps ROPA-TX in the backward direction via Hybrid IWDM filters and PC. Faraday mirror is used to reflect unabsorbed pump power back to Er-doped fiber, which provides more than 5% pump-to-signal conversion efficiency increase. RJF optical filter is used to reject the noise caused by Raman scattering in 1565 – 1620 nm spectral region.

ROPA-RX is based on the double cascade optical scheme. The residual power from two HO-RP at the receiver side pumps each cascade in the forward direction via low loss Hybrid Thin Films filters IWDM (Fig.5). C-band filter is then used in the pump path to reject the noise caused by Raman scattering.

Transmission system experiment

The experimental set-up is shown in Fig.6, which consisted of a transmitter operating at 1560.61 nm. We used a large effective area terrestrial fiber for the first and the last sections of the

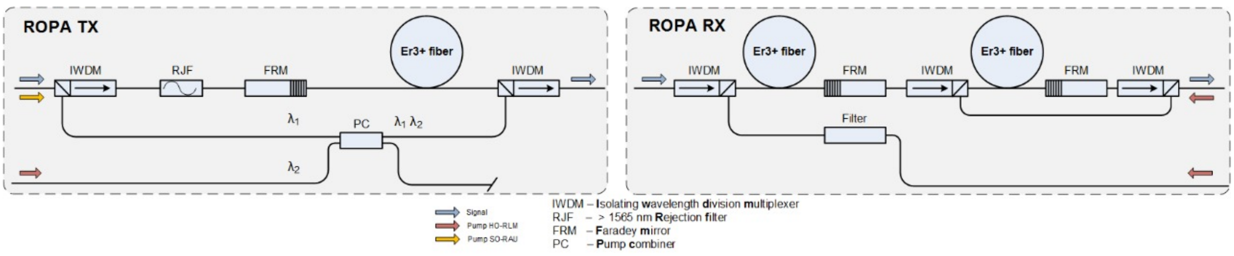

Fig. 5: ROPA TX and RX schematic diagram

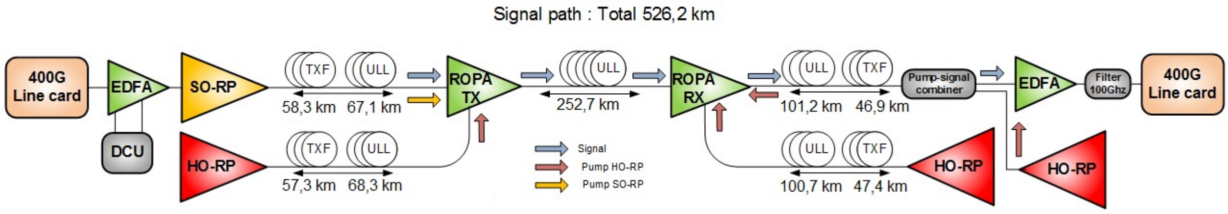

Fig. 6: Experimental set-up

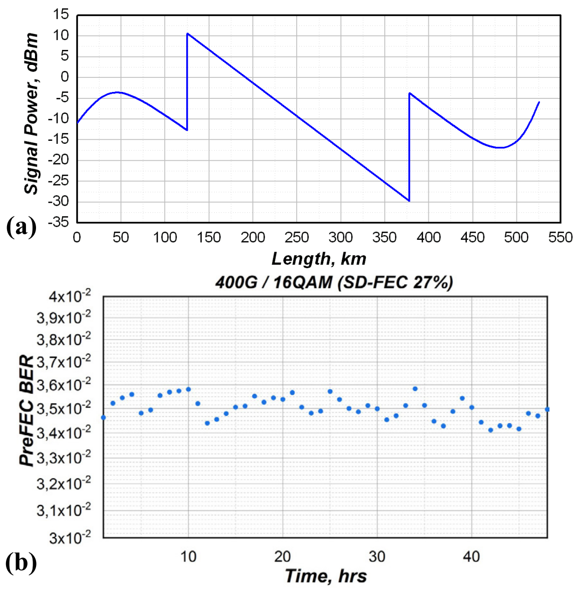

Fig. 7: (a) Power distribution of the signal along the line. **(b)** PreFEC BER at the end of the line during the 48 hours test

transmission line (TXF fiber with typical attenuation of 0.168 dB/km and typical Aeff of 125 μ^2), which is compliant with the ITU-T G.654.E standard. Due to its improved nonlinear tolerance, such a large effective area allows for an increase in signal and pump input power by up to 1.6 – 2 dB compared to a regular single-mode fiber[6]. For all other transmission link sections, in which optical power is less than a nonlinear limit for regular single mode fibers, we used SMF-28 ULL fiber. This is a silica-core, ITU-T G.652 compliant fiber with a typical attenuation of 0.162 dB/km at 1550 nm. This combination of large effective area and ultra-low loss fibers allowed for a 14 dB better link OSNR, compared to regular single-mode fibers.

Signal power evolution as a function of transmission length is shown in Fig.7a. The residual pump power received by ROPA-TX was +8.7 dBm and +11.8 dBm from signal and pump paths, respectively. ROPA-TX output power was measured to be +10.6 dBm and the gain was 23.3 dB. Optical signal power received by ROPA-RX was measured to be -29.78 dBm, while pump power received by ROPA-RX was +7.3 dBm and +7.7 dBm from signal and pump paths, respectively. ROPA-RX gain was measured to be 26.2dB. PreFEC BER value at the end of the line was (3.5±0.1)*10-2 and no uncorrelated errors were observed throughout the 48-hour test (Fig.7b).

Conclusions

In this work, we have demonstrated the feasibility of using 400G 16QAM transponder for ultra-long terrestrial unrepeatered applications and achieved the record 526 km (>86dB) single-span transmission. This was enabled using the latest generation of high-order Raman amplifiers, low-RIN laser sources, forward and backward ROPAs and fibers with ultra-low attenuation and large effective area.

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