

ULTRA-LONG REACH 400G (4x128Gb/s) UNREPEATERED TRANSMISSION USING LARGE-AREA ULTRA-LOW LOSS FIBERS

Benyuan Zhu, Peter I. Borel, Tommy Geisler, Rasmus Jensen, Matthias Stegmaier, Bera Palsdottir, David W. Peckham, Alan H. McCurdy, Robert L. Lingle Jr., Durgesh S. Vaidya, Man F. Yan, Patrick W. Wisk, and David J. DiGiovanni (OFS)
Email: bzhu@ofsoptics.com

OFS, 19 Schoolhouse Rd, Somerset, NJ 08873, USA

Abstract: We present the design and experimental demonstration of an ultra-long reach 400 Gb/s (4x128 Gb/s) unrepeatered link with real-time signal processing. This unrepeatered transmission is achieved by using commercially available transceiver modules and large-area, ultra-low loss (ULL) fibres. 400 Gb/s (4x128 Gb/s) unrepeatered transmission over 557km fibre is demonstrated, and TeraWave[®] SCUBA 150 fibre with effective area of 153 μm^2 and average attenuation of 0.153 dB/km at 1550 nm is employed in this demonstration. In addition, forward and backward remote optical pumped amplifiers (ROPAs) with 2nd-order Raman pumping schemes are used with the same single fiber for both signal and pumps. The system optimization of the forward and backward ROPA designs and the technical challenges to further increase the reach of the unrepeatered system are also briefly discussed in the paper.

1. INTRODUCTION

Unrepeatered transmission systems are cost-effective solutions for communication via optical fibres when the access to intermediate points are difficult. Typical applications are submarine links connecting islands with the mainland or island hopping, and the communication links to offshore oil and gas platforms. There are also use cases in terrestrial networks such as in desert, mountain, and forest areas. Usually, elaborate amplifiers and pumping lasers are installed at the transmitter and receiver terminals to allow data transmission without in-line active elements in the fibre cable links.

It is extremely challenging to increase the transmission reach in unrepeatered links, as the optical power is launched only from the terminals. Large effective area (A_{eff}) ultra-low attenuation fibre is a critical factor in this regard. High power booster and counter- or co-directional pumped distributed Raman amplification with high-order pumping are typically used in unrepeatered systems. High efficiency remote optical pumped amplifier

(ROPA) pumped from receiver terminals [1-4] are also employed in commercial submarine systems. Recently a forward-pumped ROPA, that is pumped from the transmitter terminal, is reported to increase the reach for low channel counts [5]. It has also been shown that dedicated fibres can be used to deliver high pump powers to ROPAs to improve the amplification process, thereby increasing the transmission distance [6]. However, these dedicated fibres serve only to convey pump power, and do not carry any data traffic. It will be more cost effective for operators if a simple single fibre configuration can be used to avoid the dedicated fibre. Using the single fibre configuration, Bissessur et al. recently reported a record capacity of 29.2 Tb/s unrepeatered transmission over 295 km fibre [4]. Xia et al reported four 100 Gb/s channels and a 100 Gb/s signal unrepeatered transmission over 523.2 km and 556.7 km fibre respectively [5].

This paper presents the design and experimental demonstration of real-time processed unrepeatered transmission of

400 Gb/s (4x128 Gb/s) over 557 km of fibre. This is achieved by using commercially available TeraWave[®] SCUBA 150 fibre and AC400-Flex transceiver modules with forward and backward ROPA. The ROPA is pumped by 2nd-order Raman pumping while using a single fibre for both signal and pumps. The real-time measurement results are reported and the system optimization of the forward and backward ROPA designs is also briefly be discussed.

2. LARGE-AREA ULTRA-LOW LOSS FIBER

Large A_{eff} and low attenuation are the two most important fibre parameters for ultra-long unrepeated transmission links. An increase in fibre A_{eff} improves system nonlinear tolerance, which allows higher optimum launch power into the fibre span and thus extends the reach of the link by improving OSNR and Q-factor. Ultra-low attenuation of fibres is vital to ultra-long unrepeated submarine cable system, as the value of fibre attenuation is directly related to the total maximum link loss of an unrepeated system.

The optical fibre used in this work is OFS TeraWave[®] SCUBA 150 fibre [7] that is G.654.D compliant (cutoff-shifted single mode fibre). The SCUBA 150 fibre has a large A_{eff} of 153 μm^2 that reduces nonlinearities. The macro- and micro-bending performance of the TeraWave SCUBA 150 fibre have been improved by optimizing the waveguide design for excellent bending performance for C+L band applications. This fibre meets all macro-bending requirements in G.654.D [8]. In addition, the fibre has average attenuation of 0.153 dB/km at 1550 nm. This ultra-low loss fibre is achieved by using a Ge-free silica core fibre design that reduces the Rayleigh scattering. This translates into benefits for transmission systems by reducing link loss and double Rayleigh scattering (DRB). An additional advantage of the silica core design

is a lower nonlinear refractive index, n_2 , that provides further nonlinearity mitigation compared to Ge-doped standard single mode fibres [9].

In order to reduce nonlinear effects, the TeraWave[®] SCUBA 150 fibre is also designed to have high chromatic dispersion (22 ps/nm/km) at 1550 nm. This fibre is manufactured using a manufacturing process proprietary to OFS, with the added benefit of ultra-low polarization mode dispersion (PMD). In addition, the SCUBA 150 fibre has exceptional resistance to mechanical stress.

Other benefits of this large-area ultra-low attenuation fibre accrue with the use of distributed Raman amplification (which is a very effective technique to extend the reach of unrepeated systems) as it provides gain over the fibre link and improves the noise figure (NF) of the system while the pumps are located in the terminals. Raman amplification can be applied at the transmitter station (co-propagation with the signals) or at the receiver station (counter-propagation). The reach can be further increased with high-order Raman pump schemes as previously mentioned [1-4]. The system penalty from multi-path interference (MPI) noise is reduced due to the lower DRB in large-area fibres [10], because the capture efficiency of the Rayleigh backscattered light is inversely proportional to the fibre A_{eff} , [11]. Additionally, the Ge-free silica-core fibre design further reduces the Rayleigh scattering. These two factors enable the OFS TeraWave[®] SCUBA 150 fibre to exhibit much smaller DRB in Raman amplification unrepeated systems.

3. EXPERIMENT SET-UP

Figure 1 shows a schematic diagram for the 4x100 Gb/s ultra-long reach unrepeated transmission experiment. Four adjacent channels of 100 Gb/s polarization-multiplexed (PM) QPSK signals from two

Acacia AC400-Flex modules with 100 GHz channel spacing and wavelengths ranging from 1558.98 nm to 1561.42 nm are

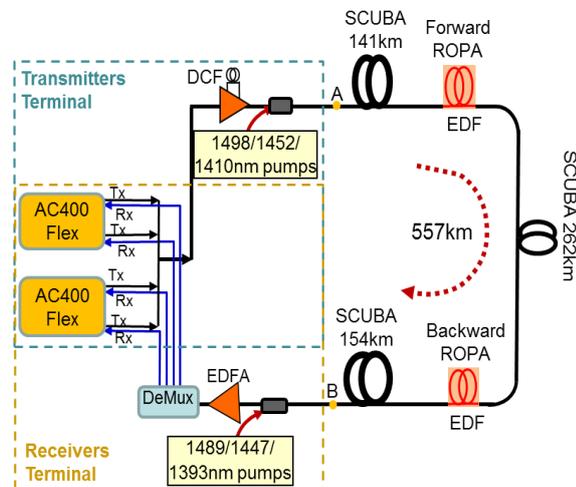


Figure 1: Schematic diagram of experimental set-up for ultra-long reach unrepeated transmission system

combined using couplers. The AC400-Flex is a flex-rate coherent transceiver module [12] that has two channels, and each channel in the module can operate at 100 Gb/s PM-QPSK, or 150 Gb/s PM-8QAM, or 200 Gb/s PM-16QAM. The 100 G channels operate with a soft-decision forward-error-correction (SD-FEC) overhead of 25%, which can correct the bit-error-ratio (BER) of 3.28×10^{-2} (Q^2 -factor = 5.3dB) to better than 10^{-15} . To improve transmission performance, a dispersion compensating fibre (DCF), with dispersion equal to -940 ps/nm at 1550 nm, is placed in the middle of the two-stage erbium-doped fibre amplifier (EDFA). The EDFA is used to boost signal power before launching into the link.

The link consisted of three sections of OFS TeraWave® SCUBA 150 fibre [7]. The 1st section of the fibre span, from transmitter terminal to forward ROPA, is 141 km; the 2nd section, from forward ROPA to backward ROPA, is 262 km. The 3rd section, from backward ROPA to receiver terminal, is 154 km. The total link loss from A to B, as shown in Figure 1, including splice and connectors at 1550-nm (but not including the absorption losses in ROPAs) is 86.3 dB. In order to enhance the performance of both the

co-propagating distributed Raman gain and the forward ROPA in the 1st section, two low RIN (< -130 dB/Hz over 1-100 MHz) semiconductor lasers at 1452 and 1498 nm, (amplified by 2nd order Raman pump at 1410nm), are used. The backward ROPA is remotely pumped by 1489 nm semiconductor lasers which are also Raman-amplified by a 2nd-order pump at 1393-nm. In addition, a 1447 nm semiconductor pump laser is used to provide Raman gain for the 3rd section of the span. The four 100 G signals are amplified by the EDFA at the receiver terminal, then de-multiplexed and sent back to the AC400 Flex receiver.

The ROPA designs, using a high efficiency EDF (peak absorption of 5.9 dB/m, NA of 0.33, mode-field diameter of 4.2 μ m at 1550 nm), are first simulated, and then a set of measurement data (such as signal input power and available residual pump power from the optimization of transmission performance) are used to further optimize the ROPA. Figure 2 (a) shows the gain of the forward ROPA from simulation using pump powers of 8.5 or 10 mW and signal power input to the ROPA of -1.1 dBm/channel for EDF lengths of 10, 12, and 14 m. The 12 m EDF provides relatively high gain for pump power from 8.5 to 10 mW. Therefore, a 12 m EDF is used

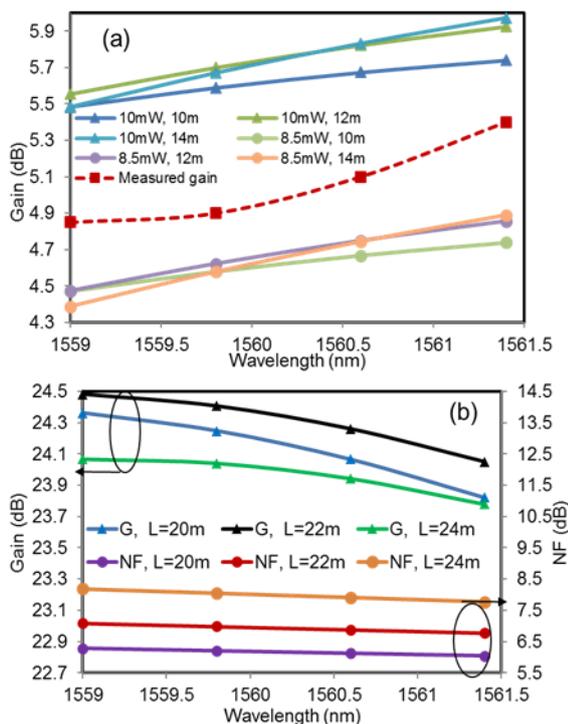


Figure 2: (a) Gain of forward ROPA from simulation and measurement, (b) backward ROPA gain and NF

for the forward ROPA in the experiment. The measured total signal input power to the ROPA is ~ 5 dBm (about -1 dBm average power per channel), and the residual power of the 1498 nm pumps reaching the forward ROPA is measured to be 8.7 mW (9.4 dBm). The measured forward ROPA gain is in the range 4.9 \sim 5.4 dB (in Figure 2(a)). Figure 2(b) shows the simulated gain and NF of the backward ROPA using an input signal power of -35.6 dBm/channel and a 1489 nm pump of 5.7 mW. It can be seen that the 22 m EDF has high overall gain so a 22 m EDF is used for the backward ROPA in the experiment. After transmission performance optimization, the total signal power and the residual power of the 1489 nm pump reaching the backward ROPA are measured to be about -29.5 dBm (-35.5dBm/channel) and 5.9 mW, respectively.

4. TRANSMISSION RESULTS AND DISCUSSION

The BER performance of the 100 Gb/s channels from the AC400-Flex coherent transceiver modules are now characterized. The real-time BER is measured as a function

of received OSNR and subsequently converted into Q^2 -factor. Figure 3 plots the Q^2 -factor as a function of required OSNR in back-to-back operation. The measured BER at the FEC threshold (without uncorrected error) is 3.28×10^{-2} (Q^2 -factor = 5.3dB) and the required OSNR at the FEC threshold in back-to-back operation is 10.3 dB/0.1nm. The transmission performance is collectively optimized by changing the signal launch power and the co- and counter-pump powers. The powers of the 1452/1498 nm and 1447/1489 nm semiconductor lasers are fixed to be 250/ 300 mW and 200/ 300 mW, respectively, and the powers of both 2nd-order 1410 nm and 1393 nm pump fibre lasers are varied. First, a rough optimum for each power is found; then one of the powers is scanned while other two are fixed. The

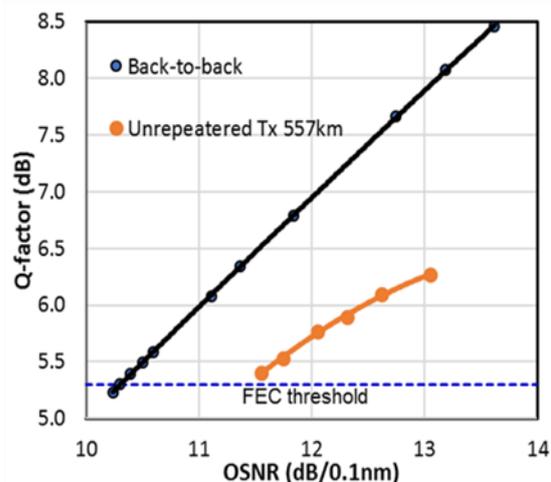


Figure 3: Q^2 -factor vs required OSNR for back-to-back and for 557km unrepeated transmission

optimum pump powers of the 2nd order co- and counter-pumps are found to be about 2.4 W and 2.2 W, respectively, and the total optimal signal launch power is about 2 dBm (-4 dBm per channel). The Q^2 -factor as a function of received OSNR after 557 km unrepeated transmission is also shown in Figure 3. Compared to the back-to-back case the OSNR transmission penalty is only about 1.2 dB at the FEC threshold.

Figure 4 shows the simulated results of optical power evolution for the four signal channels and Raman pumps along the

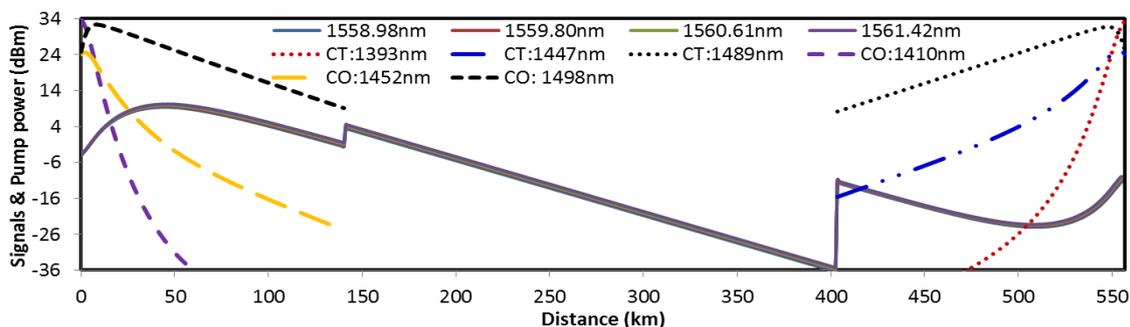


Figure 4: Optical power evolution for the four signal channels and all pumps along 557km fiber line.

557 km fibre link at the optimized operating conditions. This illustrates the benefits of 2nd-order Raman amplification and enhanced ROPA for extending the reach of the unrepeated system. The input signal power, and co- and counter-pump powers, which are measured at the aforementioned optimized transmission conditions, are used in the simulation. It can be seen from Figure 4 that the signals first experience the co-pumping distributed Raman gain, then they are amplified by the forward ROPA and attenuated by fibre loss. The signals are amplified again by the backward ROPA, and distributed Raman amplification before reaching the receiver station. The peak signal power per channel reaches ~ +10 dBm at ~ 50 km from the transmitter station. The 2nd -order Raman pumps at 1410 nm and 1393 nm finally they experience the backward allow the co-pumping 1498 nm and counter-pumping 1489 nm pump light to penetrate much deeper into the large- A_{eff} ultra-low loss fibre spans, so that sufficient 1498/1489nm pump power can be delivered to the forward and backward ROPAs. The 1452 nm and 1447 nm semiconductor lasers, which are relatively far away from the Raman gain peaks of the 1410 nm and 1393 nm pumps, experience less Raman gain from the 2nd-order Raman pumps and also help to keep enough residual 1498/1489 nm pump power for the ROPA.

It should be pointed out that the performance of the forward ROPAs is mainly limited by the available pump power from the 2nd -order

1410 nm pump laser in this experiment. However, the backward ROPA is fundamentally limited by the nature of the system. We observe that the transmission system becomes unstable when

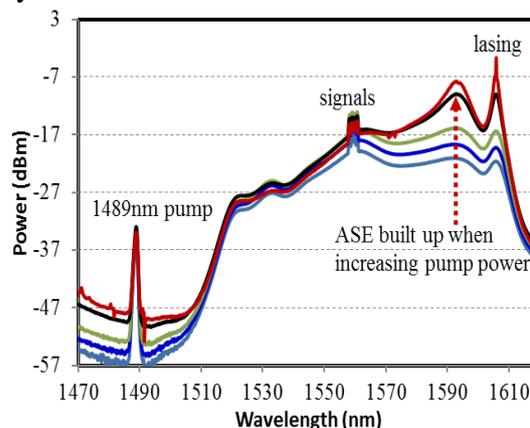


Figure 5: Optical spectra at output of receiver, showing the growth of ASE when increasing the pump power and eventually lasing.

the 2nd -order counter-pumping 1393 nm pump power is increased beyond a certain value (e.g. > ~2.3 W) even using the large A_{eff} fibre. This is because of the growth of strong amplified spontaneous emission (ASE) noise in the transmission fibre due to DRB when the pump light is strong, eventually causing lasing. Figure 5 plots an example of the optical spectra at the output of the receivers as the 1489 nm pump power, (amplified by the 2nd-order 1393nm laser), is increased. It is seen that the signal channels (near 1560 nm) go through a maximum, the ASE (around 1590 nm) increases and the pump power at 1489 nm saturates. Here small reflections can easily form a laser cavity and lead to lasing, thus destabilizing

the transmission system. (red spectral curve in Figure 5).

The gain of the forward and backward ROPAs have opposite wavelength tilt (see Figure 2), however the received powers are still positive tilted after 557-km transmission, mainly due to the relatively high Raman gain from the 1489 nm pump. This is corrected by using channel pre-emphasis at the transmitters. Figure 6(a) shows the optical spectra at transmitter, the output from the forward ROPA and the receiver. It can be seen from Figure 6 (a) that the short wavelength channel launch power at is adjusted slightly high, but the received signal power of the four channels is relatively equal after 557 km unrepeated transmission. Figure 6(b) shows that the average measured OSNR over the four receive channels in 0.1nm resolution

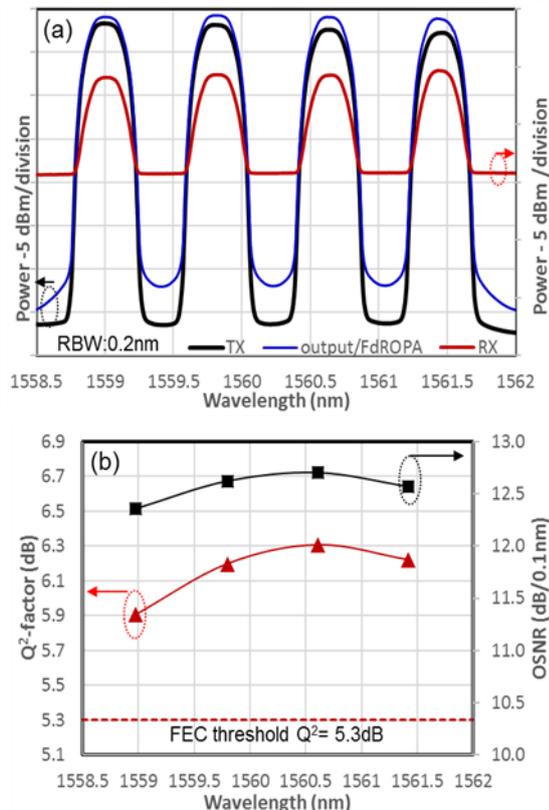


Figure 6: (a) Optical spectrum from transmitter, output forward ROPA and receiver, (b) received OSNR and measured Q²-factors after unrepeated transmission over 557km fiber.

bandwidth (RBW) is 12.6 dB with a minimum OSNR of 12.4 dB/0.1nm. To test

the transmission performance as a function of wavelength, the real-time BER of the four 100Gb/s PM-QPSK channels after 557 km unrepeated transmission is measured and subsequently converted into Q²-factor (see Figure 6(b)). These channels have an average Q²-factor of 6.2 dB with an 0.9 dB Q²-factor margin above the FEC threshold (5.3 dB). The worst Q²-factor is 5.92 dB, so all channels are above the FEC limit and would yield a BER below 10⁻¹⁵ after correction by SD-FEC.

5. SUMMARY

The key enabling techniques for ultra-long reach, unrepeated submarine cable systems have been described with particular focus on the role of large-area, ultra-low loss fibre, which is critical for extending the distance of such transmission systems. The design and experimental demonstration of real-time signal processed, unrepeated transmission of 4x128 Gb/s over 557 km of fibre is reported. This is achieved by using commercially available large-area, ultra-low loss TeraWave® SCUBA 150 fibre and transceiver modules (AC400-Flex) in a single fibre configuration. Elaborately designed forward and backward ROPA, which utilize 2nd-order Raman pumping, are employed in this demonstration. The real-time measurement results show 400 Gb/s error-free unrepeated transmission over 557 km with 0.9 dB Q²-factor margin.

Acknowledgments: We acknowledge Hongbin Zhang of Acacia for help on the AC400 Flex coherent transceiver module.

6. REFERENCES

- [1] H. Bissessur, et al., "4x100Gb/s Unrepeated transmission over 462 km using coherent PDM-QPSK and real-time process", at ECOC 2011, Tu.3. B.3 (2011)
- [2] B. Zhu et al., "6.3-Tb/s Unrepeated transmission over 402 km fiber using high power Yb-free clad-pumped L-band EDFA", Proc. OFC 2014, paper W1A.2 (2014)

- [3] B. Zhu, et al., “800 Gb/s (8x128 Gb/s) unrepeated transmission over 515-km large-area ultra-low-loss fibre using 2nd-order Raman pumping,” *Optics Express* 24, no. 22, p. 25291 (2016).
- [4] H. Bissessur et al., “Unrepeated transmission of 29.2 Tb/s over 295 km with probabilistically shaped 64 QAM” in *ECOC 2018, Th1G3.4* (2018)
- [5] T. Xia, et al., “557 km Unrepeated 100 G transmission with commercial Raman DWDM system, enhanced ROPA, cabled large A_{eff} ultra-low loss fibre in OSP environment” in *OFC 2014, Th5.A7*, (2014).
- [6] J. Januario et al., “Single-carrier 400 G unrepeated WDM transmission over 443.1 km”, *Proc. ECOC 2017, M1F4*, (2017)
- [7] <https://fiber-optic-catalog.ofsoptics.com/Asset/TeraWave-Scuba-150-Ocean-Fibers-fiber-168-web.pdf>
- [8] ITUT, “Characteristics of a cut-off shifted single-mode optical fibre and cable”, <https://www.itu.int/rec/T-REC-G.654-201611-I/en>
- [9] K. Nakajima, et al., “Dopant dependence of effective nonlinear refractive index in GeO₂- and F-doped core single-mode fibres,” *IEEE Photon. Technol. Lett.*, vol. 14, no. 4, p. 492–494, Apr. 2002.
- [10] J. Bromage, et al., “Multiple path interference and its impact on system design,” in *Raman Amplifiers for Telecommunications 2*, M. Islam, Ed. New York: Springer-Verlag, 2004, pp. 491–568.
- [11] E. Brinkmeyer, “Analysis of the backscattering method for single-mode optical fibres,” *J. Opt. Soc. Am.*, vol. 70, pp. 1010–1012, 1980.
- [12] <https://acacia-inc.com/product/ac400-flex/>