LARGE CAPACITY LONG REACH UNREPEATERED TRANSMISSION USING FIBER A_{EFF}-MANAGED SPAN WITH OPTIMIZED AMPLIFICATION SCHEME

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Abstract: This paper describes the recent development of enabling fibre technologies for high capacity, long span, unrepeatered transmission systems, including ultra-large-area low loss fibre and high efficiency Er-doped fibre (EDF) for remote optically-pumped amplification (ROPA). We present the system design and experimental demonstration of 3.2 Tb/s (32 x 120-Gb/s) transmission over a 445-km long unrepeatered link by using an A_{eff}-managed fibre span. This paper also discusses design trade-offs for performance enhancement of unrepeatered transmissions.

1. INTRODUCTION

Unrepeatered transmission is mainly used in submarine optical fibre cable systems for applications in coastal festoons, island hopping, lake crossings and even long bridge spans in terrestrial systems [1-7]. Since the submarine fibre cable systems do not use optical repeaters, and therefore do not need power feed equipment or a power supply, their construction costs can be much lower than for repeatered cable systems. Over the years, technology development has targeted achieving span distances as long as possible without any in-line active elements [1-3]. However, with ever-increasing demand for traffic, system advances have recently been reported to achieve both a longer reach and also a higher transport capacity [4-7].

In this paper, we will first briefly describe enabling fibre and amplifier technologies for high capacity, long span unrepeatered transmission systems, including ultra-large-area (ULA) low loss fibre, high efficiency Er-doped fibre (EDF) for remote optically-pumped amplifier (ROPA), and associated amplification schemes. We then present the system design and experimental demonstration of 32 x 120-Gb/s polarization division multiplexed quadrature phase shift keying (PDM-QPSK) DWDM channels transmitted over a 445-km unrepeatered link. This 3.2-Tb/s capacity unrepeatered transmission is achieved by using an effective area (A_{eff}) managed fibre span optimized for co- and counter-propagating 2^{nd}-order pumped Raman amplification and ROPA. The paper further discusses the system performance and design trade-off of the nonlinear tolerance, optical signal-to-noise ratio (OSNR), and Raman gain efficiency.

2. FIBRES ENABLING FOR UNREPEATERED SUBMARINE SYSTEMS

The unrepeatered submarine optical cable system comprises terminal equipment usually installed at the landing station and a submarine optical fibre cable which does not include optical repeaters or any in-line active elements. Typically a high power booster at the transmitter station or co-pumped distributed Raman amplifier is used to provide high system gain. The receiver characteristics can be improved by means of ROPA which is remotely pumped by a 1480nm pumping light from the receiver station. The technical challenges to extending span length of unrepeatered submarine optical fibre cable systems includes: (i) reduction/avoidance of nonlinear optical effects in the optical fibre transmission line, (ii) improvement of ROPA performance and receiving sensitivity, (iii) increase the launched signal power or improvement of Raman amplification schemes, (iv) reduction of loss in transmission line. In this section, key optical fibre technologies to improve the transmission performance of unrepeatered system are briefly described.

One effective method for extending the span length of an unrepeatered system is to increase the signal power launched into the fibre. However, nonlinear effects in transmission fibre limit the maximum signal power that can be injected into fibre. ULA low-attenuation fibres have thus been employed for reduction of nonlinear effects in the transmission line. A new trench-assisted ULA fibre with A_{eff} of 150µm² and attenuation of 0.175dB/km at 1550nm has been developed [7]. In addition, this new ULA fibre features low macro-/micro-bend losses and zero-water-peak attenuation, which allows the pump light and 2nd-order Raman pump in the 1363nm range to penetrate very deep into the transmission fibre, thus improving overall performance of the distributed Raman amplifiers and ROPA.

Applying ROPA to submarine optical fibre cable makes it possible to significantly extend its span length. In ROPA, an EDF is installed at a distance in the range of a hundred kilometres from the receiving station and it is remotely pumped by laser source near 1480nm, because the loss of the transmission fibre is unacceptably high near 980 nm. Both the pump and signal begin at high power levels at the transmitter and both experience loss traveling through the long span, resulting in very low pump and signal powers into the EDF at the ROPA. Therefore, the EDF used for the ROPA must provide high small-signal gain with high gain efficiency and a low noise figure (NF) using as little pump power as possible. EDF with high numerical aperture (NA) and small core diameter has lower saturation power and higher mode intensity, so it produces high gain and lower NF at low pump power levels. High signal intensity in the doped region with novel dopant confinement design also enhances the gain and noise performance of the ROPA. In addition, optimized design of the EDF index profile reduces the splice losses between the ROPA's EDF (which has very small MFD) and SSMF [8]. In order to maximize the system gain and improve noise performance of the ROPA, it is important to choose the EDF location by considering the balance between the 1480nm pump power arriving at the EDF from the receiver station and the power of the WDM signals arriving from the transmitter station. Maintaining gain flatness is also important for larger capacity unrepeatered system.

Another effective way of improving the transmission performance of unrepeatered systems without increasing the transmission power are distributed Raman amplification technologies. In order to improve the system performance, high-order Raman amplification can be used [2]. For co-pumping, the maximum signal power occurs further out in the span than for simple 1st-order pumping, resulting in an effective increase of launch power even further above the direct-launch nonlinear limit (see Figure 2). To prevent pump-signal cross-talk from causing signal degradation in the co-pumping scheme, it is desirable to use low relative intensity noise (RIN) (e.g. < 130 dB/Hz within the range of around 1 - 100 MHz) semiconductor lasers as the 1st-order co-pumping source, followed by high power fibre lasers as 2nd- or 3rd-order pumps. Compared with a high power booster, co-propagating, distributed Raman amplification also improves overall noise performance. For counter-(CT) pumping, 2nd-order pumping also allows the 1480nm pump light to penetrate much deeper into the transmission fibre, thus improving overall performance of both the ROPA and the CT-pumped Raman amplifier.

3. EXPERIMENT

This section presents the unrepeatered transmission system experimental demonstration. The schematic diagram for the unrepeatered transmission experiment is shown in Figure 1. The transmitters consisted of 32 DFB lasers at wavelengths ranging from 1549.31nm to 1561.83nm in the C-band on the 50-GHz-spaced ITU frequency grid. Two sets of 100-GHz spaced channels, corresponding to odd and even channels, were multiplexed separately by two arrayed waveguide grating routers (AWR). The odd and even channels were modulated independently by two transmitters with two separate QPSK modulators, fed with 30-Gb/s pseudo-random bit sequences (PRBS) with a length of 2^{15}-1. The output from each modulator was split into two paths with a relative delay of 84 symbols (or 3.14 ns) before being polarization-multiplexed by a polarization beam combiner (PBC) to form a PDM-QPSK channel at 120 Gb/s. This bit-rate accounts for the 20% overhead of soft-decision forward-error-correction (SD-FEC), which corrects a bit-error ratio (BER) of 1.9×10^{-2} (i.e. 6.4-dB Q-factor) to better than 10^{-13} [9]. The odd and even channels were then spectrally interleaved through a 50-GHz interleaver (IL). A tunable external cavity laser (ECL) with a linewidth of ~100 kHz was used for bit-error ratio (BER) measurement. Each channel under measurement was switched from the DFB source to the tunable ECL source. The 32 DWDM channels were sent to a booster amplifier followed by a variable optical attenuator (VOA) for adjusting launch power, and then launched into the 445-km fibre link.

The link consisted of two sections using three types of fibres with different A_{eff}: OFS ULA, UltraWave SLA+, and AllWave™ *ZWP* fibre with effective areas of 150-µm², 125-µm², and 80-µm², respectively, and average losses of 0.175 dB/km, 0.18 dB/km, and 0.18 dB/km, respectively. The first section of the fibre from transmitters to ROPA, was 304-km long with 30-km UltraWave SLA+, 114-km ULA, 60-km UltraWave SLA+, and 100km AllWave™ *ZWP* fibre, and the second section from receiver to ROPA was 141-km long with 101-km ULA and 40-km AllWave™ *ZWP* fibre. The total fibre loss of link at 1550-nm was 79-dB. Two low RIN semiconductor diodes at 1440/1455nm combined with a Raman fibre laser at 1363nm (as 2nd-order pump) using CWDM coupler were employed to provide co-propagating distributed Raman amplification in the first section. A high gain efficiency EDF was used in the ROPA

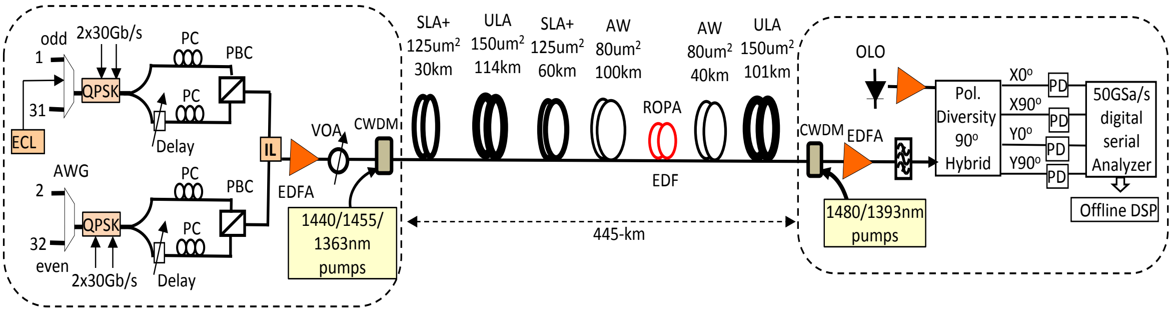

Figure 1: Schematic diagram of experimental setup for unrepeatered transmission system.

which was remotely pumped by 1480nm semiconductor lasers. A second order pump at 1393-nm was also employed in the counter-propagating direction to provide Raman gain to the 1480nm pump light.

At the receiver side, each channel was selected by a tunable filter and sent to a coherent receiver with off-line processing. The receiver was a typical digital coherent receiver consisting of a polarization-diversity optical hybrid, an optical local oscillator (OLO) using a tunable ECL, and four balanced photo-detectors. The electrical waveforms were digitized by four 50-Gsamples/s analog-to-digital converters (ADCs) in a real-time sampling scope. The digitized waveforms of 1-million samples each were processed offline in a computer to perform electronic chromatic dispersion (CD) compensation, polarization de-multiplexing, and frequency /phase recovery using typical PDM-QPSK algorithms [10]. Finally the BERs were calculated using direct error-counting and averaged over 1-million samples from which Q factors were calculated.

4. RESULTS AND DISCUSSION

Figure 2 shows the simulated results of evolution of optical powers for the WDM channels and pumps along the fibre line under optimized conditions, illustrating the advantages of 2nd-order Raman amplification and ROPA for extending the span length of unrepeaterd system. The input signal power per channel, and co- and counter-pump powers, which were measured under optimization of transmission performance (see below), were used in the simulation. The span configuration in the first section (see Fig.1) was designed with a combination of different A_{eff} to balance nonlinear tolerance, OSNR and Raman gain efficiency to optimize overall transmission system performance. It should be noted that 101-km of ULA fibre with A_{eff} of 150-μm^2 (as shown in Fig.1) was used at the end of the second section of the span to reduce Raman power transfer from 1480nm pump to 1555nm signal band (at the expense of a lower Raman efficiency for conversion of the second order 1393nm pump to the 1480nm light). This ULA fibre plus the second-order Raman pump in the ZWP fibre allow the 1480nm light to penetrate deeper into the fibre spans so that sufficient 1480nm pump power can be delivered to ROPA. This design also helps to reduce the gain tilt for 32 DWDM channels transmission.

The ROPA, which employed a new OFS EDF with NA of 0.33 and MFD of 4.4-µm at 1550nm, was optimized via numerical simulation. Figure 3 (a) shows the gain and NF of thirty-two WDM signals when the 1480nm laser is counter-pumped at fixed pump power of 7.5mW

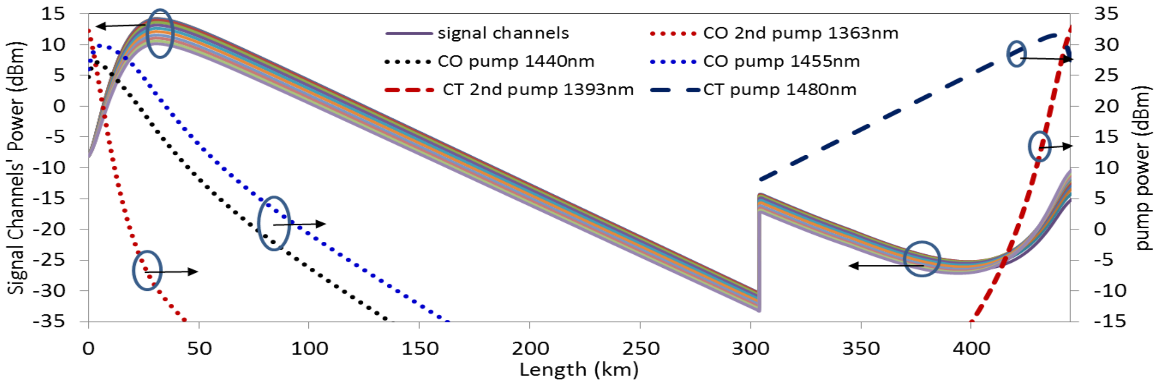

Figure 2: Simulation result of optical powers for the WDM channels and pumps evolution along the fiber line under optimized conditions

(optimized EDF length is 15m) at signal input power of -30, -32.5, -35, and 37.5-dBm per channel; Figure 3 (b) plots the gain and NF when the signal input power is fixed at -30dBm per channel with 1480nm pump power of 2.5, 5, 7.5 and 10mW. It can be seen that a gain of more than 16dB with NF less than 6dB can be obtained in the ROPA when the signal power is larger than -37.5dBm per channel and 1480nm pump power as low as 5mW, exhibiting excellent performance.

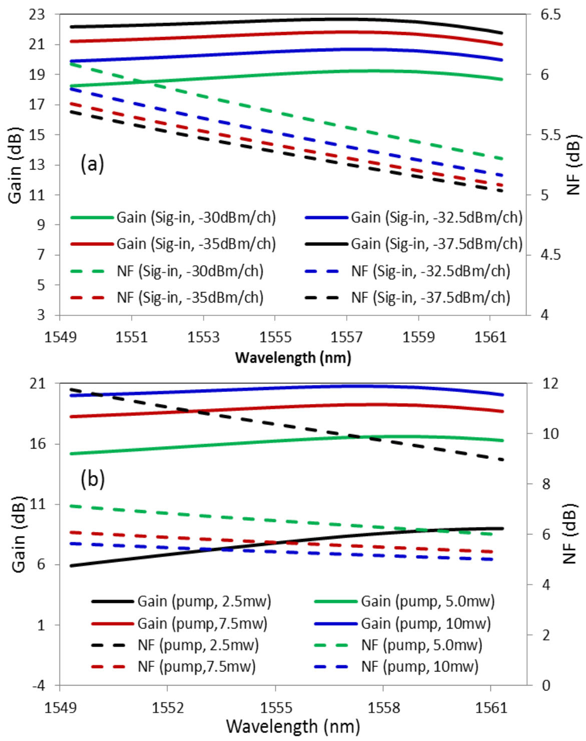

Figure 3: Simulation result of the gain and NF of ROPA

For 120-Gb/s PDM-QPSK transmitters and coherent receivers, the back-to-back performance was characterized, and the required OSNR for SD-FEC threshold (BER of 1.9×10^{-2}) is 11.6dB (with 0.1nm resolution bandwidth (RBW)). The best performance required collective optimization of the signal launch power and co- and counter-pump powers. The powers of the 1440/1455/1480nm semiconductor lasers were fixed to be 300, 400, 410 mW respectively due to the maximum powers available in this experiment, and the powers of 2nd-order pump fibre lasers (1363nm and 1393nm) were varied. To simplify the optimization process, a rough optimum for each power was found first; then one of the powers was scanned while other two were fixed. Figure 4 (a) shows the Q-factor, derived from the measured BER, and OSNR (with 0.1nm RBW) of the centre channel as a function of total launched power when 2nd-order co- (1363nm) and counter (1393nm) pump powers were set to be 32-dBm and 33-dBm respectively. The total optimal signal launch power was found to be about 7.9-dBm (-8.15dBm per channel). Figure 4(b) shows the Q-factor performance vs. 2nd-order co- and counter-pump (1363/1393nm), and optimum powers of 2nd-order 1363nm and 1393nm pumps were about 32-dBm and 33dBm respectively. The performance optimization of short wavelength channel (ch#1) was also investigated to make sure that error free transmission can be achieved after SD-FEC.

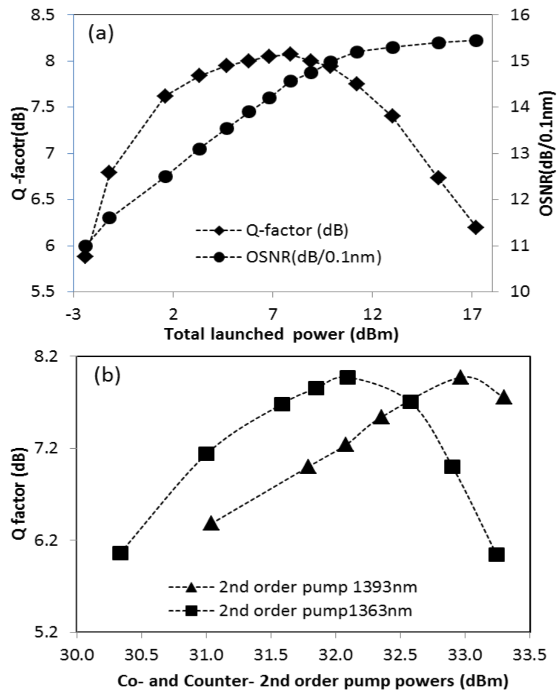

Figure 4: (a) Q-factor and received OSNR of center channel vs. total launch power when the co and counter 2nd pump power were fixed at optimum levels; (b) Q-factor

performance vs. 2nd-order co- and counter pump powers.

Fig. 5 shows the transmitted and received optical spectrum of 32 120-Gb/s PDM-QPSK DWDM channels after 445-km with the signals power and 2nd-order pumps set to the optimum powers. The channel pre-emphases were not adjusted, and received signal powers were tilted about 5dB (see Fig. 5-b) after 445-km transmission due to the Raman gain of DWDM channels (1549-1562nm) from the 1480nm pump (which was not set at the optimum Raman wavelength for these DWDM channels in order to pump the ROPA). Nevertheless the tilt of the received OSNR was much smaller.

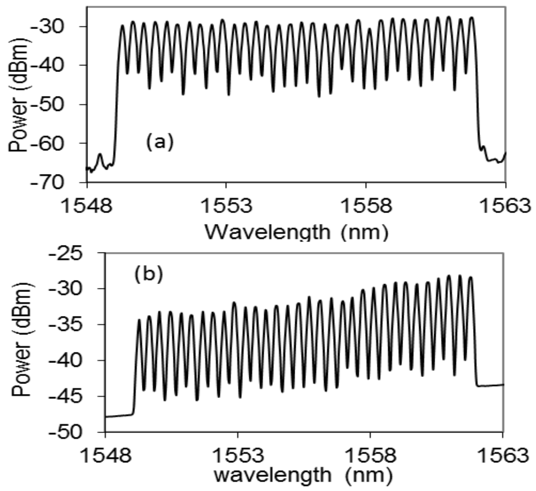

Figure 5: Transmitted (a) and received (b) optical spectra of DWDM 120-Gb/s channels after 445-km transmissions

Figure 6 shows the measured on-off co-pumped Raman gain from first section and net gain of ROPA plus counter-pumped Raman amplification from second section when the launched signal powers and 2nd order pumps were set to the optimum level. The averaged on-off co-pumped Raman gain was about 26.5dB with a negative gain tilt of about 1dB from the first section of span. The averaged net gain from the ROPA plus 1480nm Raman counter gain in second section of the span was about 19dB with a gain tilt of about 6 dB (arising mainly from the 1480nm Raman gain). The measured OSNR is shown in Figure 7, and the average received OSNR in 0.1nm RBW was 15dB, and OSNR was tilted only about 1.5dB. The BERs of all the channels were measured and the resulting Q-factors are plotted in Figure 7, the average Q-factor was 7.6dB and the worst Q-factor was 6.8dB; all channels are therefore above the FEC limit of 6.4 dB and would yield a BER below 10^{-13} after correction by SD-FEC.

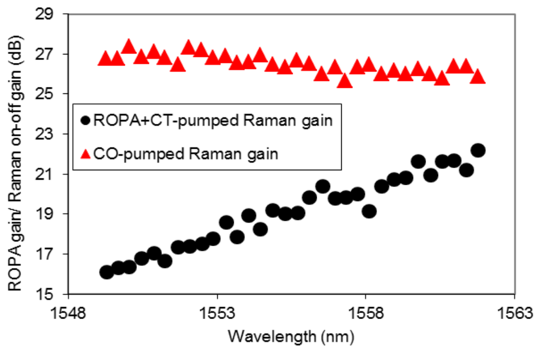

Figure 6: The measured on-off co-pumped Raman gain in the first section and net gain from ROPA/1480nm Raman gain in the second section.

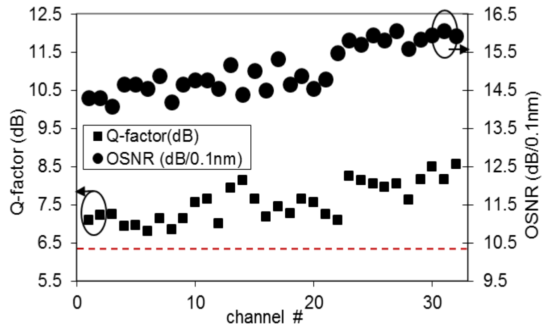

Figure 7: Received OSNR (in 0.1nm RBW) and Q-factor for all 120-Gb/s PDM-QPSK channels after 445-km

5. SUMMARY

We have discussed recent developments of enabling fibre technologies for high capacity, ultra-long span, unrepeated transmission systems, including ULA low loss fibre, high efficiency EDF for ROPA, and high-order pumped distributed Raman amplifier schemes. We have further presented an experimental demonstration of 445-km unrepeated transmission with total capacity of 3.2-Tb/s. All 32 x 120-Gb/s PDM-QPSK DWDM channels were transmitted above the SD-FEC limit of 6.4 dB with minimum Q margin of 0.4 dB. This result has been achieved with A_{eff} managed span using OFS ULA low loss fibres, newly developed EDF for ROPA, and 2nd-order pumped co- and counter propagating distributed Raman amplification and ROPA energized by the 2nd order Raman pump.

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6. REFERENCES

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