ENABLING FIBRE AND AMPLIFIER TECHNOLOGIES FOR SUBMARINE TRANSMISSION SYSTEMS

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Abstract: This paper describes the key fibre and amplifier technologies that enable high capacity and long reach for submarine transmission systems. We discuss the optical fibre properties of new ultra-large-area ultra-low-loss fibres and their impacts on the transmission performance for undersea coherent systems. We will then describe a few key amplification techniques for repeatered and repeaterless submarine systems including high performance C+L band Er-doped fibre amplifier (EDFA), remote-optical-pumped amplifier (ROPA), wideband high power Yb-free clad-pumped booster EDFA, and distributed Raman amplifiers using 2nd order Raman pumping.

1. INTRODUCTION

In order to support exponential growth of global data traffic, 100Gb/s submarine systems with capacity as much as ~10Tb/s on a single core fibre using C-band Er-doped fibre amplifier (EDFA) are currently being installed in transoceanic links. A total transmission capacity ~ 50Tb/s on a single core fibre has recently been reported in research laboratory demonstrations based on digital coherent technology using coded modulation schemes and advanced forward-error-correction techniques [1-3]. In addition to increasing capacity by improving spectral efficiency (SE) using high-level modulation formats (e.g. 16-quadrature amplitude modulation (QAM)), and Nyquist pulse-shaping, further gain can be achieved by adding L-band. One of the major challenges for realizing high capacity transoceanic distance transmission systems is to improve optical signal-to-noise ratio (OSNR) within entire C- and L-bands. Another main limitation of the current submarine transmission systems is the delivered electrical power of the offshore power feeding equipment to supply EDFA pumps. Compared to a terrestrial network, the long haul submarine systems possess unique requirements for optical fibre cables and repeaters, which must be designed to support operation and recovery in the harsh undersea environment. Typically undersea systems are much longer than terrestrial ones. The undersea repeaters use optical amplifiers exclusively, and no intermediate regeneration is applied due to the challenges in delivering electrical power from offshore. In addition, the undersea systems must have high reliability and typically require a 25 year design life. Therefore the performance and quality of optical fibre cables and amplifiers are extremely important to submarine systems.

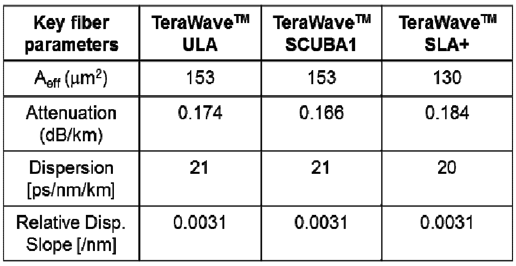
In this paper, we will discuss key fibre and amplifiers technologies that enable to achieve high capacity and long reach for submarine transmission systems. The optical fibre properties of new ultra-large-effective area low-loss fibres will be described and their impacts on the transmission performance for polarization-multiplexed multiple-level modulated (e.g. 16QAM) coherent submarine systems will be discussed. The key amplification techniques for the repeatered and repeaterless submarine systems including high performance C+L-band EDFA, remote-optical-pumped amplifier (ROPA), wide-band high power Yb-free clad-pumped booster EDFA, and distributed Raman amplifiers using 2nd order Raman pumping will be described.

2. NEW FIBRES

Ultra large effective area (A_{eff}) and low attenuation are the two most important fibre properties for submarine systems. An increase in fibre A_{eff} improves system nonlinear tolerance, which allow higher optimum launch power into fibre and thus improves OSNR and Q-factor. Reducing the nonlinearity of fibres is particular vital to transoceanic submarine systems, because the repeater span length for such submarine systems is much shorter (typically ~50km) compared to terrestrial systems (typically ~100km), which means accumulating more nonlinear impairments; it is especially important for high capacity submarine systems with high SE because they employ polarization-multiplexed multiple-level modulation formats (e.g. 16-QAM) which are more susceptible to fibre nonlinear impairments [4]. Higher OSNR and Q-factors enable system benefits such as longer reach, higher capacity, longer span length (hence, fewer repeaters and lower cost) or better system margin and higher overall link reliability. A reduction in fibre attenuation can lower repeater span loss, however, the reduction of fibre attenuation can increase fibre effective nonlinear length, hence increase the accumulated nonlinear effects. Overall the low loss fibre allows an improvement in power efficiency for repeaters and benefits system OSNR because lower span loss. It is also important to have high local chromatic dispersion in fibres in order to reduce nonlinear effects in the polarization-multiplexed coherent systems where chromatic dispersion can be digitally compensated in the electrical domain. The polarization-mode-dispersion (PMD) in the fibres are not necessary to be very low, as a certain amount of PMD helps mitigate the nonlinear impairments in polarization-multiplexed coherent systems and the PMD can be digitally compensated in the coherent receivers.

In order to fully realize the technical advantages of ultra large effective area low loss fibres, it is necessary to increase the A_{eff} of the fibre while not jeopardizing the bend performance. Step-index profiles with small index differences and large core diameters can be used to design large A_{eff} fibres. However, the light confinement in the core becomes weaker, increasing the cutoff wavelength and degrading both macro- and micro-bending performance. Placing a depressed-index region in the cladding, or placing a trench, slightly apart from the core can improve the bending performance and reduce the cut-off wavelength. A low Young's modulus primary coating [5] can also be used to improve the micro- and macro-bending performance of the large A_{eff} fibre. It is also crucial to ensure that splicing loss in the submarine spans is low when deploying ultra-large A_{eff} fibre cables. An acceptable splice loss needs to be achieved between large A_{eff} fibre to itself as well as to smaller A_{eff} fibres (e.g. standard single-mode fibre (SSMF)). The former is important since a fibre span between two repeaters typically consists of several

Table 1. Key fibre properties of TeraWave™ Ocean fibres at 1550nm



Key fiber parameters	TeraWave™ ULA	TeraWave™ SCUBA1	TeraWave™ SLA+
A_{eff} (μm^2)	153	153	130
Attenuation (dB/km)	0.174	0.166	0.184
Dispersion [ps/nm/km]	21	21	20
Relative Disp. Slope [/nm]	0.0031	0.0031	0.0031

shorter length fibre sections, which are spliced together. Hence, low splice loss between two large A_{eff} fibre segments will result in lower span loss. The last part is also important as the large A_{eff} fibres need to be spliced to smaller A_{eff} fibre pigtails in the submarine repeater. Therefore, low splice loss between the two fibres with dissimilar A_{eff} results in a lower overall span loss.

We have recently developed a number of ultra large A_{eff} fibres for submarine systems. The key fibre properties of TeraWave^{TM} Ocean fibres are shown in table 1. Some of them with super performance are designed for transoceanic distance transmission in C+L-bands (1530 nm - 1625 nm) at 100 Gb/s and beyond; while others provide cost effective solutions for regional undersea applications. The TeraWave Ocean fibres are ITUT G.654.D compliant. The macro- and micro-bending performances of the large A_{eff} fibres are improved by optimized waveguide design. They use the DLUX Ultra coating for excellent bending performance, and meet all macro-bending requirements in G.654.D [6]. Volume splicing studies using commercial available splicers show that the average splice loss between one ULA fibre (large A_{eff} 153μm^2) to another ULA fibre (large A_{eff} 153μm^2) are 0.03dB/splice. For the splices between one ULA fibre (large A_{eff} 153μm^2) and a SSMF (small A_{eff} 83μm^2), we optimized the splicing recipes using a tapering technique within a commercially-available splicer to achieve a better mode field diameter (MFD) match with an adiabatic transition from the large MFD to the smaller MFD, and the splicing loss is 0.15dB/splice.

Ultra-low loss (ULL) of fibre is an important attribute for repeaterless submarine systems, we have also developed TeraWave™ ULL large A_{eff} fibre with a loss of 0.155dB/km at 1550nm. The detailed characteristics of the fibre and system transmission results will be presented in the conference.

3. HIGH PERFORMANCE EDFA

The EDFA is the most efficient optical amplifier for repeaters in submarine systems, and Er-doped fibre (EDF) is the key element to build EDFA repeaters. High power conversion efficiency (PCE), low noises figure (NF) and wide bandwidth is essential for undersea application. For C-band EDFA, up to about 38nm can be readily developed by using highly Al co-doped EDFs. The increasing depth and steep edges of gain equalization are required for the bandwidth greater than 38nm (see Figure 1 (a)). A practical limitation on useful bandwidth for a C-band EDFA is around 40nm; in this case precision build and athermal packaging are required to keep gain shape error within acceptable limits for the submarine systems. Typically one-stage EDFA with co-pumping 976nm diodes can be designed for the repeaters with output ~19 dBm (for

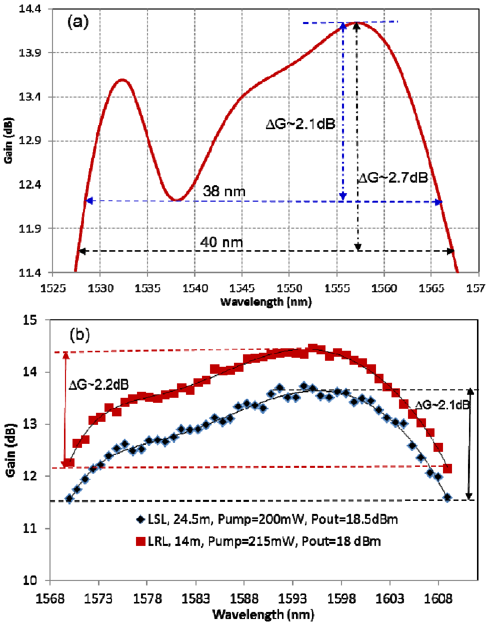


Figure 1 (a): achievable gain shape for C-band using MP980 EDF, (b) measured gain spectra from L-band EDFAs

11~12 dB span loss). In this example, a PCE of more than 47% can be achieved by using high efficiency EDF and average NF less than 4dB can be obtained.

An L-band EDFA requires a low population inversion for a flat gain operation. The gain coefficient of EDF in L-band is also ~ 3-4 times smaller than in C-band. So the L-band EDFA usually require longer erbium coils than C-band. The drawbacks on this are lower PCE, poor NF, susceptible to fibre FWM nonlinearity, and long erbium length etc. In addition, the backward amplifier spontaneous emission (ASE) power (peaked in the C-band) affects the PCE. A high concentration EDF helps reduce erbium length; however increasing Er content degrades PCE due to the pair-induced quenching. Therefore, a comprehensive optimization design on the doping types, concentration and waveguide structure is even more important for L-band EDF. We have developed a number of high performance EDFs for L-band applications. Figure 1(b) illustrates an example of the measured gain spectrum of L-band EDFA with a bandwidth of ~ 39nm; the PEC~ 35% and output~19dBm can be obtained in one-stage EDFA using co-pumping with 976nm diode.

4. REMOTE OPTICAL PUMPED AMPLIFIERS (ROPA)

In a repeaterless submarine optical cable system, the terminal equipment is installed at the landing stations and the submarine optical fibre cable between two terminal stations does not include optical repeaters or any in-line active elements. The total reach can be significantly improved by means of ROPA. In ROPA design, 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 landing stations and both experience loss traveling through the long span undersea, resulting in very low pump and signal powers into the EDF at the ROPA. Therefore, the ROPA must provide high small-signal gain with high gain efficiency and a lower NF using as little pump power as possible.

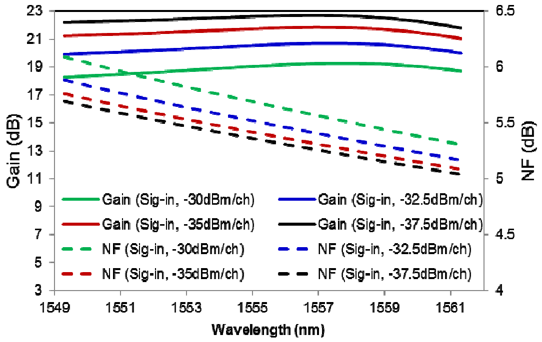


Figure 2: Gain and NF of ROPA used in 445km repeaterless transmission experiment

The EDF for ROPA is usually designed with high numerical aperture (NA) and small core diameter, and it has lower saturation power and higher mode intensity, so it produces high gain and lower NF at low pump power level. High signal intensity in the doped region with novel dopant confinement design also can enhance the gain and noise performance of the ROPA. In order to maximize the system gain and improve noise performance of the ROPA, it is important to choose the EDF location in the fibre cables 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.

We have demonstrated 3.2 Tb/s (32x120Gb/s) repeaterless transmission over 445km fibre employing the ROPA with optimized design [7]. The EDF used for the ROPA had NA of 0.33 and MFD of 4.4-µm at 1550nm, and the length of EDF was further optimized to be about 15m. Figure 2 shows an example of gain and NF of 32 WDM signals from the ROPA when the 1480nm laser is counter-pumped at fixed pump power of 7.5mW at signal input power of -30, -32.5, -35, and 37.5-dBm per channel. It can be seen that a gain of more than 18dB with NF less than 6dB can be obtained in the ROPA when the signal power is as low as -37.5dBm per channel and 1480nm power is as low as 7.5mW, exhibiting excellent performance.

5. RAMAN AMPLIFIERS WITH HIGH ORDER PUMPING

One of effective techniques for extending the reach of a repeaterless 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. Distributed Raman amplifiers plus ultra large A_{eff} low attenuation fibre can be employed to allow higher signal power launching into fibre links. The high order Raman pumping can be used to further provide high system gain. For co-pumping, the maximum signal power occurs further out in the span than that using high power booster amplifier, resulting in an effective increase of launch power even further above the direct-launch nonlinear limit. For counter-pumping, high order Raman 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 counter-pumped Raman amplifier. We have designed the distributed Raman amplifiers using low RIN semiconductor diose at ~1450nm as 1st order Raman pump and a 1363nm high power laser as 2nd order pump, and we further experimentally demonstrated a high capacity (3.2Tb/s) repeaterless transmission over 445km fibre links using this pumping scheme [7]. It was found that ultra large A_{eff} fibre with low zero-water-peak (ZWP) loss plus 2nd order Raman pumping can enhance the repeaterless transmission system performance with less total required Raman pump power when compared the system using high power booster and 3rd-order Raman pumped schemes [8].

6. HIGH POWER BROADBAND L-BAND BOOSTER EDFA

In order to reduce the overall system cost and complexity, it is preferred to use a high power booster at transmitter station rather than using co-propagation distributed Raman amplifiers from transmitter station. In this case, low cost high power wide bandwidth booster amplifiers are required. We have recently designed and demonstrated high power broadband Yb-free clad-pumped EDFA booster using commercially available low cost 980nm MM diodes for L-band applications. The Yb-free clad-pumped L-band EDFA comprised of a 49 m Yb-free double-clad large core diameter low numerical aperture (NA) EDF, and it was configured in co-/counter-propagation pumping scheme using low cost multimode (MM) 976nm diodes and WDM combiners. The double-clad EDF has a circular core diameter of ~17µm and a NA of 0.11, relative to inner-clad, and the inner-clad has a diameter approximately 105µm and with a NA of

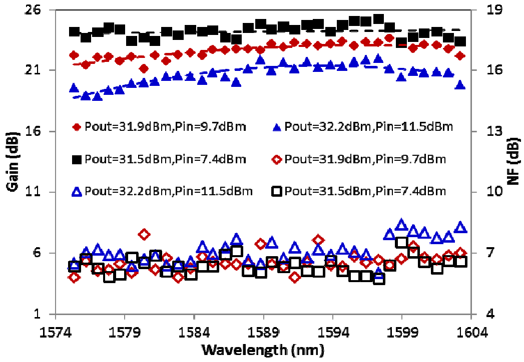


Figure 3: Net gain and NF from the clad-pumped L-band EDFA

0.45, relative to the outer-clad. The outer fibre coating was made of low-index fluoroacrylate (250μm). The core has a peak absorption ~14.5 dB/m at round 1530nm. Figure 3 shows the net gain and NF measured from the clad-pumped L-band EDFA for different input power at the total MM pump power of 9.5 W. It can be seen that a total output power of +32 dBm can be achieved and NF in range of 5.1-8.3 dB can be obtained at total input power of 9.7dBm. We further demonstrated repeaterless transmission of 6.3-Tb/s signals over 402-km fibre using this high power clad-pumped L-band EDFA as the booster [9]. This clad-pumped scheme permits the use of low cost 976 MM pump didoes which reduce electrical serial resistance compared with single-mode pump diodes; this can result in significant energy saving.

7. CONCLUSION

We have described the key fibre and amplifier technologies for submarine systems. The optical fibre properties of new ultra-large-area ultra-low-loss fibres are discussed. Examples of design and characteristics of C+L-band EDFAs for repeaters are presented. For unrepeatered submarine systems, the key amplification techniques including distributed Raman amplifiers using 2nd order Raman pumps, ROPA, and high power booster EDFA are described. Transmission experimental results using the new fibres and amplifiers will be presented in the conference.

8. REFERENCES

[1] J.-X. Cai, et al., “transmission over 9100km with a capacity 49.3 Tb/s using variable spectral efficiency 16QAM based coded modulation”, Proc. OFC2014, Los Angeles, CA, paper Th5B.4 (2014)

[2] A. Ghazisaeidi et al., “52.9 Tb/s transmission over transoceanic distance using adaptive multi-rate FEC”, Proc. ECOC 2014, Cannes, France, paper PD3.4 (2014)

[3] A. Ghazisaeidi et al., “54.2 Tb/s transoceanic transmission using ultra low loss fibre, multi-rate FEC and digital nonlinear mitigation’, Proc. ECOC2015, Valencia, Spain, paper Th2.2.6 (2015)

[4] G. Charlet, “Impact and mitigation of non-linear effects in coherent transmission”, Proc. OFC2009, NthB.4 (2009)

[5] Y. Yamamoto, et al., “OSNR-enhancing pure-silica-core fibre with large effective area and low attenuation”, Proc. OFC2010, OTuI2 (2010)

[6] ITUT, “Characteristics of a cut-off shifted single-mode optical fiber and cable”, www.itu.int/rec/T-REC-G.654-201210-I/

[7] B. Zhu et al., “Unrepeatered transmission of 3.2-Tb/s (32x120-Gb/s) over 445-km fibre link with A_{eff} managed span”, Proc. OFC/NFOEC 2013, paper OTu2B.2 (2013)

[8] H. Bissessur et al., “6-Tb/s Unrepeatered transmission of 60x100Gb/s PDM-RZ-QPSK channels with 40 GHz spacing over 437-km”, Proc ECOC2012, paper Mo.1.C.3 (2012)

[9] B. Zhu et al., “6.3-Tb/s Unrepeatered Transmission over 402-km Fibre using High Power Yb-free Clad-pumped L-band EDFA”, Proc. OFC2014, paper W1A.2 (2014)