A Study of the Power Conversion Efficiency of EDFAs for Future Multicore Submarine Transmission Systems

Sijing Liang(1), John D. Downie(2), Sergejs Makovejs(3), Merrion Edwards(3), Yongmin Jung(1)

(1) Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK, s.liang@soton.ac.uk
(2) Corning Research and Development Corp., 1 Riverfront Plaza, Corning, NY 14831, USA
(3) Corning Incorporated, Corning Optical Communications, Lakeside Business Village, CH5 3XD, UK

Abstract *We performed simulations and experiments to evaluate the performances of three representative erbium-doped fibre designs for subsea SDM-based systems. Small-core high-NA fibre design which can maintain high power conversion efficiency and deep saturation at low-power operation is favourable for large-scale power-constrained SDM systems.*

Introduction

Space division multiplexing (SDM) technology based on multicore fibres (MCFs) is now generally acknowledged as a potential system approach for future submarine cables that can deliver ≥1 Pb/s capacity over transoceanic distances to accommodate the ever-increasing data traffic [1-5]. Power efficiency is one of the most critical factors in designing long-haul subsea networks due to the limited electrical power supply to repeaters from land stations [6]. This power constraint is more pronounced in subsea SDM systems aiming for ultra-high capacity.

Methodologies for maximizing the power efficiency of subsea SDM systems have been studied both theoretically and experimentally [6-11]. It was found that the most power-efficient SDM system has a relatively low optimal signal-to-noise ratio (SNR) and spectral efficiency (SE), e.g., SNR≈1.72 and SE≈2.89 b/s/Hz for a system operating at the Shannon limit [6]. This implies that a lower data rate modulation format such as QPSK becomes more favourable and the required channel power is reduced. Fig.1 shows a calculation example to illustrate this method for optimizing the power efficiency. Note that amplified spontaneous emission (ASE) from the erbium doped fibre amplifier (EDFA) is the only source of noise considered in this calculation. For the same transmission distance, the resultant OSNR at the link output is worse when the system operates at a lower signal input power. However, the required pump power to achieve the same amplifier gain decreases with the input signal power, which means that a fixed power supply can support more spatial channels if each spatial channel operates at low input power. Consequently, the linear scaling of capacity by increasing the spatial dimension is more efficient than the logarithmic scaling by increasing the signal OSNR [6-8]. New analytical models have been developed to include the impact of the generalized droop effect in long-haul submarine systems which rely on constant output power amplifiers [12-14]. These models, which account for ASE noise, nonlinear noise and crosstalk-induced noise, show good agreement with the experiments measured at a low channel power level deep into the linear regime of transmission.

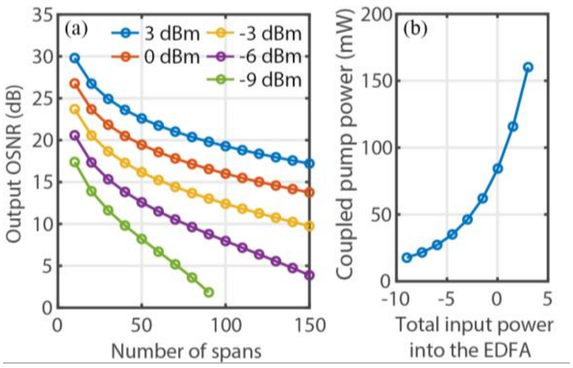

Fig. 1: (a) OSNR degradation as a result of signal droop; legends denote the total signal power of 45 WDM channels launched into the EDFA; (b) required coupled pump power to achieve 14-dB net gain for different input signal powers.

To date, most studies have focused on system-level optimization of submarine SDM networks, but a power-efficient design of multicore EDFAs (MC-EDFAs) is indispensable for the future implementation of SDM systems. Core-pumped MC-EDFAs are more advantageous than the cladding-pumped MC-EDFAs in terms of capacity and relative system cost/bit, provided that the electrical-to-optical conversion efficiency is not compromised by the MCF components and integration [15]. The in-line EDFA for the existing single-mode fibre-based systems employs a conventional fibre design with a moderate fibre NA (~0.2) and core diameter (~3-4 μm) allowing the EDFA to operate in the deep saturation regime with high power conversion efficiency (PCE) when the channel power is high and approaches the nonlinear optimum. However, the compatibility of this conventional design needs to be examined in the context of submarine applications where the power supply limit will drive the large-scale SDM systems to operate at lower channel power. An incompatible fibre design will reduce the PCE and impair the level of gain saturation.

In this paper, we compare the performances of three different EDF designs over a range of operating powers by simulation and experiment. These three designs are typical fibre geometries representing preamplifiers, in-line amplifiers and power amplifiers. Our simulation and experimental results suggest that the small-core high-NA (e.g., NA≥0.3) fibre design is beneficial in terms of maintaining a high PCE and deep gain saturation in the EDFA if undersea SDM systems operate at a low signal power (e.g., <-5 dBm of total power into the amplifier). But this advantage diminishes with higher input signal power. If the electrical power supply in the future does not limit the submarine SDM networks to low-power operation, the conventional EDF design (~0.2 NA) for present in-line amplifiers can continue to be used and deliver high performance.

Simulation

Through simulation, we first evaluated the impact of the EDF geometry (i.e., fibre NA and core size) on the PCE and the level of gain saturation for different input powers. As shown by the black line in Fig. 2(a), the core diameter can be calculated as a function of the fibre NA with a fixed single mode cut-off wavelength of 940 nm. Here, we consider three fibre geometries which are commonly used in preamplifiers (NA=0.3), in-line amplifiers (NA=0.22) and power amplifiers (NA=0.12). The corresponding core diameters from the calculation were 2.4, 3.2 and 6 μm. The simulation considers WDM amplification (1528.8-1563.9 nm) in the forward-pumping structure with isolators (ISOs) at both the input and output. Losses of the passive components (0.5 dB each) and the splices between the passive and the doped fibres (0.2 dB each) were considered. The EDF transition cross-sections and the dopant concentration were kept the same so that the fibre geometry was the only variable in the simulation. The EDF length and the coupled pump power were optimized to achieve the same gain profile at different input powers. Note that the coupled pump power was used to calculate the PCE in this study. Fig. 2(b) plots the net gain and NF calculated at a total input power of 3 dBm. As shown, the same gain profile can be obtained by using three different EDF designs with negligible difference in NF between these fibres when the input power is high. As the input power decreases, the NF for all three geometries degrades slightly (e.g., average NF increases from 4.7 to 4.9 dB for 0.12-NA EDF), but the NF difference between fibres remains small (~0.1 dB) for the input power range investigated.

However, different coupled pump powers are required for the three geometries to achieve the same gain, resulting in a noticeable difference in the PCE shown in Fig. 2(c). Irrespective of the fibre designs, the PCE increases with the input power because a higher signal input power depletes the inversion more quickly and extracts energy from the pump more efficiently. At low input power levels like -9 to -6 dBm, the PCE of 0.3-NA EDF is >5% and >20% higher than the PCEs of the 0.22-NA and 0.12-NA EDFs, respectively. The high-NA, small-core structure can enable higher population inversion in the fibres at the same pump power level, which subsequently leads to more efficient amplification. However, this PCE improvement starts to diminish as the input power increases, since the pump power becomes strong enough to invert most ions even in fibres with larger mode areas. This is consistent with the calculated saturation power which depends on the mode area and thus on the fibre design [16]. The saturation powers of the 0.3, 0.22, and 0.12-NA EDFs are -5.1, -2.3 and 2.9 dBm. The 0.3-NA design has the lowest saturation power and can therefore enable deeper gain saturation at relatively low input powers compared to the other two structures. It can also be inferred from the simulation results

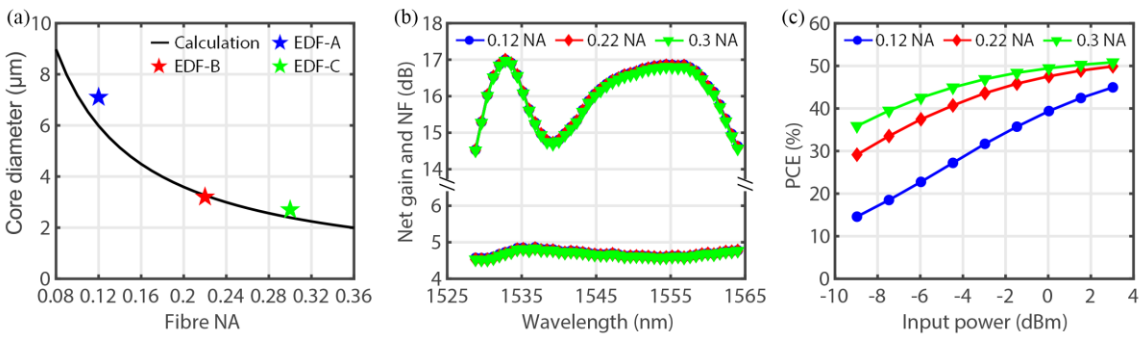

Fig. 2: (a) Calculated core diameter as a function of NA (black line) and dimensions of the three EDFs used in the experiment; (b) calculated net gain and NF when the NA is 0.12, 0.22 and 0.3; (c) corresponding PCE at varied input signal powers.

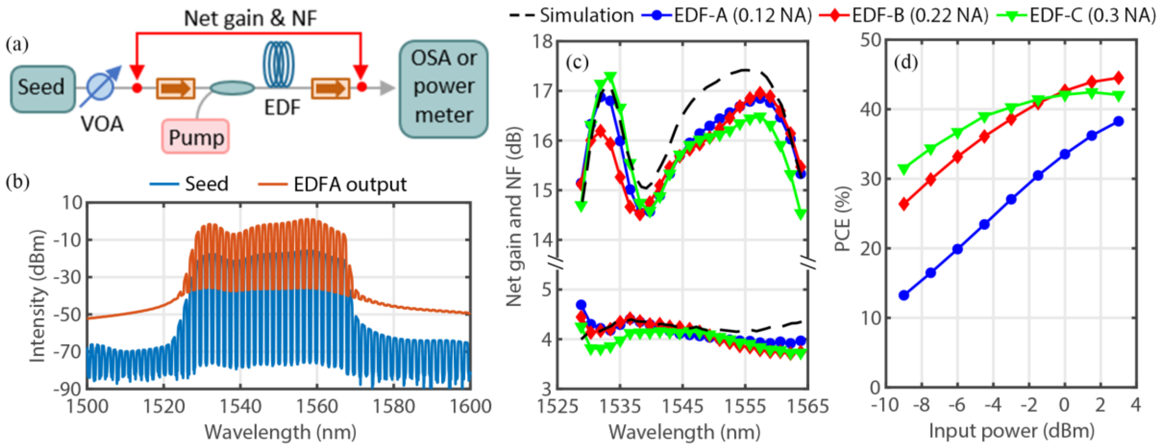

Fig. 3: (a) Schematic of the experimental setup; (b) spectra of the seed source and the EDFA output (0.2 nm resolution); (c) measured net gain and NF compared to calculation; (d) measured PCE of the three EDFs under test.

that a fibre design with an even higher NA and smaller core size can further improve the PCE and the saturation level at very low input signal powers.

Experiment

We then performed experiments to verify our observations in the simulation. Note that single-core EDFs were used in the experiments but the conclusions remain applicable to core-pumped MC-EDFAs. Three commercial EDFs were chosen and denoted as EDF-A (nLIGHT, NA=0.12), EDF-B (FiberCore, NA=0.22) and EDF-C (FiberCore, NA=0.3). EDF-A, B, and C had single mode cut-off wavelengths of 1172, 940 and 1048 nm with corresponding core diameters of 7.1, 3.2, and 2.7 µm, respectively. The absorption levels of EDF-A, B, and C at 1530 nm were 16, 18.7, and 28.2 dB/m.

Fig. 3 (a) shows a schematic of the experimental setup. The insertion losses of the input ISO, output ISO and WDM were measured to be 0.2 dB, 0.6 dB and 0.5 dB. The optimized splice loss between the passive and the active fibres was 0.15 dB for all the three types of EDF. An in-house built 200-GHz-spaced incoherent seed source (1528.8–1563.9 nm) was used to test the amplifier. A variable optical attenuator (VOA) was placed after the seed source to control the input power launched into the amplifier. The amplifier output was characterized using a power meter and an optical spectrum analyser. Fig. 3(b) shows the example spectra of the seed source (3-dBm input power) and the amplifier output when EDF-B was used. For each type of EDF, the optimum fibre length was determined when the measured net gain reached >14 dB for all the signal channels. The fibre lengths of EDF-A, B, and C were 4.6, 4, and 2.4 m, respectively. Once the optimum fibre length was determined, the amplifier was tested over a total input power range from -9 to 3 dBm, and the pump power was always optimized to achieve the same net gain profile when the input power was changed. Fig.3 (c) shows that these three different EDFs can all demonstrate >14-dB net gain and <5-dB NF. The small difference in the gain shape and NF is due to the slightly different fibre compositions and thus different transition cross-sections. The measured net gain and NF are in good agreement with the simulation results. Fig. 3 (d) compares the PCE of the three fibres at different input powers. The measured PCE aligns with the observation in simulation (see Fig. 2(c)), despite a slight roll-off in the PCE of EDF-C when the input power increases beyond 0 dBm. This can be attributed to the much higher doping concentration of EDF-C leading to a stronger interaction between ions and subsequently a decrease in the PCE. The saturation powers were also measured [16], with -6.7, -4.3 and 0.5 dBm for the EDF-A, B, and C. This measurement confirmed that higher-NA fibres can provide better gain saturation when the operating signal power is low.

Conclusion

We have evaluated the impact of the EDF geometry on the PCE and the level of gain saturation for future submarine systems based on SDM. The conventional fibre design for current in-line amplifiers is compatible with future submarine SDM networks only when the system operates at a high channel power with no power supply limit imposed. In large-scale SDM systems where maximizing the power efficiency is of prime importance, small-core high-NA fibre design shows advantages in retaining high PCE and deep saturation. The findings presented in this work can form the foundation for determining the optimum MC-EDFA design for transoceanic transmission.

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