

Experimental Demonstration of Semiconductor Optical Amplifiers for 2064 km Link Loss Compensation

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Abstract—We present the first experimental investigation of SOAs for long-haul high-speed communications. The impact on performance when using both SOA and EDFA amplification for multi-span WDM transmission systems was compared. For three-channel transmission over distances of up to 2064 km using a recirculating optical fibre loop, we observed a >5 dB and >2.5 dB penalty in optimal SNR when using the SOAs for 15 GBd and 49.5 GBd channels, respectively. This is attributed to the SOA's higher noise figure and nonlinearities. At 516 km this equates to a throughput reduction of 28% at optimal launch power, demonstrating the impact of device nonlinearities that needs to be overcome for the development of low power consumption optical transmission systems. This experimental first sets a baseline for long-haul high-speed optical communication using SOAs for inline amplifiers.

Index Terms—Optical communications, semiconductor optical amplifiers, recirculating loop, wavelength-division multiplexing

I. INTRODUCTION

The use of semiconductor optical amplifiers (SOAs) in optical communication systems offers significant advantages over conventional doped optical fibre amplifiers, such as erbium-doped fibre amplifiers (EDFAs). In addition to lower power consumption, wider gain bandwidth and a smaller footprint, SOAs are also integrable with other photonic components, key for the development of compact and efficient network solutions. As the demand for higher bandwidth continues to grow, SOAs are a potentially attractive option to meet the needs of future wideband optical networks. The amplification of light directly within the semiconductor, without the requirement for conversion of a pump laser (in contrast to doped-fibre amplifiers), increases energy efficiency, critical for meeting the demand of future networks sustainably.

Whilst the energy efficiency is an attractive property of the SOAs, it comes with some drawbacks [1]. Compared to EDFAs, SOAs exhibit strong nonlinear gain dynamics,

together with a higher effective noise figure (NF) due to losses associated with coupling from fibre to waveguide and losses within the amplifier. The coupling losses also affect their gain and output power, and polarisation-dependent gain (PDG) may result from the gain medium being based on anisotropic waveguides. However, with the global goal of reducing power consumption in communication networks, SOAs should be investigated for their use as inline amplifiers in optical networks.

The use of SOAs in coherent transmission systems has been demonstrated several times over the last decade [2]–[8], specifically in transmission over short distances in straight line experiments. The performance of SOAs in these systems was investigated, showing the broad bandwidth of the gain of the SOAs, with over 100 nm in a single amplifier [9], [10]. These results were supported by several theoretical models published over the years [11]–[13], leading to several nonlinearity compensation techniques [14]–[19]. Although the feasibility of SOAs for long-haul transmission has been investigated in simulation [20], [21], there has been, to date, no rigorous experimental investigation into the performance of SOAs for long-haul transmission applications.

In this work, we present a long-haul experimental demonstration of WDM transmission using SOAs. An optical fibre recirculating loop was used to explore transmission performance of a 3-channel WDM system over a range of distances up to 2064 km. The transmission was carried out for both 15 GBd and 49.5 GBd signals spaced by 50 GHz. The results are compared to those obtained using the same setup, when using an EDFA for amplification. To the best of our knowledge, this is the first demonstration of high-speed long-haul transmission using SOAs as well as the first direct comparison between SOAs and EDFAs for high-speed long-distance transmission, using a recirculating loop.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. It consists of three independent transmitters, an optical fibre recirculating loop and a 100-GHz coherent receiver. Three dual-polarisation 64 quadrature-amplitude modulated (DP-64QAM) channels were generated offline, with transmitter-based compensation applied [22]. Signals from three external cavity lasers (ECLs), spaced by 50-GHz, were modulated with three 4-channel 92-GS/s 32-GHz digital-to-analogue converters (DACs) and three

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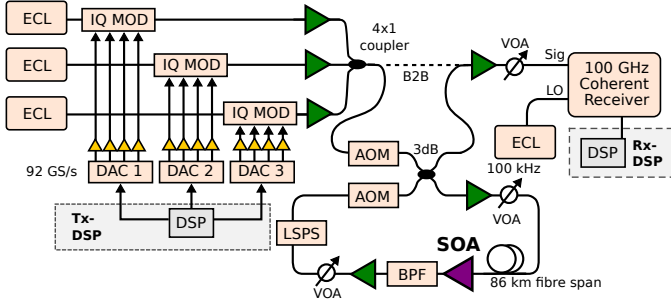


Fig. 1. Recirculating loop transmission setup.

dual-polarisation in phase-quadrature modulators (IQ-MOD). The signal from each of the modulators was then amplified using separate EDFAs, following which they were combined with a 4×1 coupler. In the back-to-back (B2B) configuration, the signal was connected directly to the receiver amplifier after the power was attenuated. A fourth ECL was used as the local oscillator (LO) and tuned to the wavelength of the centre channel. The 100-GHz coherent receiver digitises all three channels for offline receiver DSP (Rx-DSP). Pilot-based DSP [23] was used with 1024-symbol quadrature phase shift keyed (QPSK) header and $1/32$ QPSK symbols inserted for carrier phase estimation (CPE). The best result out of 5 captures are reported within the manuscript. The B2B SNR was 26.2 dB and 21.1 dB for 15 GBd and 49.5 GBd respectively.

The data was transmitted using a recirculating optical fibre loop. The loop used two acousto-optic modulators (AOMs) with a 3 dB coupler for switching between loading and transmission. Two EDFAs with variable optical attenuators (VOAs) were used to compensate for the additional loop losses (due to the AOM and 3 dB coupler) and balance the loop powers. A bandpass filter (BPF) was used to filter out-of-band noise and a loop-synchronous polarisation scrambler (LSPS) was used to spread the impact of PDG across both polarisations. The transmission fibre in the loop was 86.2 km Corning® Vascade® EX2500, with $125 \mu\text{m}^2$ effective area, chromatic dispersion of 21 ps/(nm·km) at 1550 nm, and a total attenuation of 13.3 dB, including splicing losses. The fibre output was connected to a commercial Optilab SOA [24], with gain over the wavelength range 1450 nm and 1600 nm, 7-dB NF, 16 dBm saturated output power and 350 mA drive current. The linewidth enhancement factor and carrier lifetime are unknown, but could be estimated with further analysis [25]. For the comparison of the SOA performance with that of an EDFA, the SOA was replaced with a 15-dB gain 5-dB NF EDFA pumped by a single 1000 mA pump diode.

III. SOA CHARACTERISATION

Prior to using the SOAs for multi-span transmission, the SOA was characterised in transmission over a single span. The SOA output power and gain versus fibre launch power were measured, and the results are shown in Fig. 2. Three 15 GBd channels on a 50-GHz grid at 1550 nm were launched into the fibre span, amplified by the SOA. The SOA was driven with a maximum current of 350 mA. The output power was

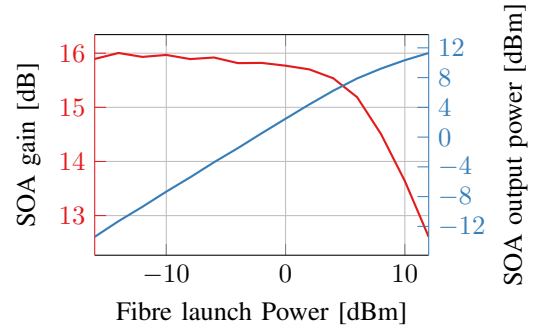


Fig. 2. Experimentally measured SOA gain and output power vs launch power into the fibre. The SOA gain compensates for the 13.3 dB fibre loss up to 10 dBm launch power.

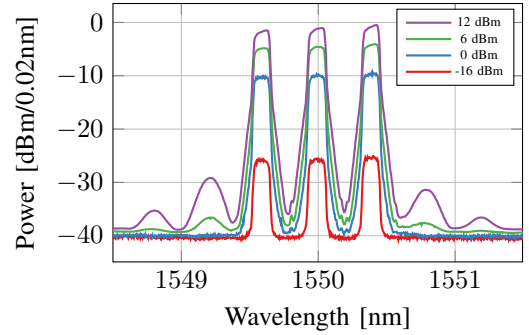


Fig. 3. Output power spectral density of the SOA at different launch powers into the fibre.

measured with an optical spectrum analyser (OSA) and the noise floor was subtracted from the signal. It can be seen that the SOA has a 16 dB gain, which begins to compress for power in fibre of 0 dBm or higher. The 3-dB compression is at an output power of approximately 11 dBm.

In the 3-channel transmission experiment, the output spectrum of the SOA was measured and is shown in Fig. 3 for different launch powers. For launch powers over 0 dBm, at which point the gain starts to compress, new spectral products can be observed due to either four-wave mixing (FWM) or cross-gain modulation. Although the OSA traces can only show spectral products outside the transmitted channels, the products are also generated within the channel wavelengths. In the 49.5 GBd transmission, the power spectral density is decreased due to the same power per channel spread over 49.5 GHz instead of 15 GHz.

IV. SNR RESULTS

In Fig. 4, the received signal-to-noise ratio (SNR) after Rx-DSP is plotted versus the launch power into the fibre. This was measured for 1, 3, 6, 12 and 24 recirculations, corresponding to transmission distances of 86, 258, 516, 1032 and 2064 km respectively. The transmission for both 15 GBd and 49.5 GBd are compared in the same graph for both SOA and EDFA amplification. The SNR is calculated as $\text{SNR} \triangleq \frac{\mathbb{E}[|X|^2]}{\mathbb{E}[|Y-X|^2]}$ where X and Y are transmitted and received symbols, respectively.

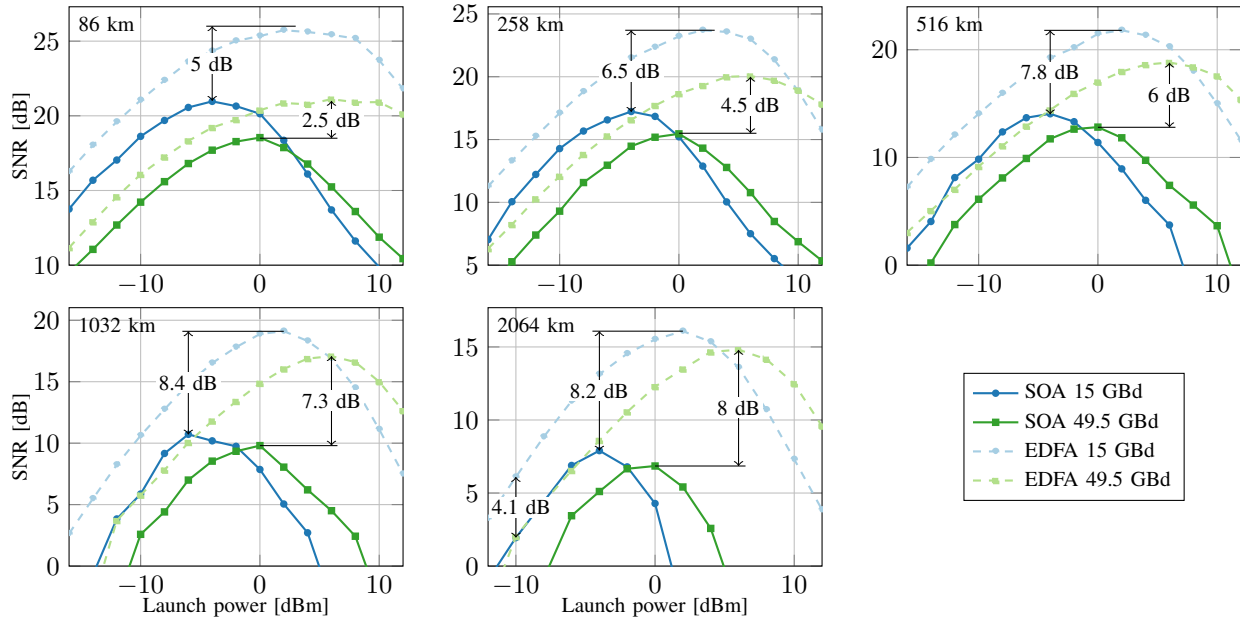


Fig. 4. Measured SNR versus fibre launch power for 1, 3, 6, 12 and 24 recirculations, 86, 256, 516, 1032 and 2064 km respectively, for both 15 GBd and 49.5 GBd in SOA/EDFA-amplified transmission.

The impact of the higher NF of the SOA can be seen in the graph, and results in a lower SNR compared to the EDFA for launch powers below 0 dBm. In this regime, the transmission performance is limited by the amplified spontaneous emission (ASE) noise of the amplifier. SOAs have higher insertion loss and thus have a higher NF (7 dB NF versus 5 dB NF for the EDFA). The PDG of the SOA combined with the LSPS also impacts the amount of noise [26], together explaining the lower SNR.

The optimal launch power for the SOAs is much lower, by approximately 7 dB, than the optimal launch power for EDFAs in all cases. From this observation, we can conclude that the SOA performance is not limited by fibre nonlinearity. Therefore, the nonlinear performance degradation at launch powers above 0 dBm is predominantly caused by amplifier nonlinearities.

For shorter distances, 86 and 258 km, the EDFA performance and, to some extent, the SOA performance are limited by the transceiver noise. This is visible in the flatness of the SNR around optimal launch power. This results in the SOA transmission exhibiting a relatively low SNR penalty, in comparison to EDFA transmission, i.e., 2.5 dB and 5 dB for 15 GBd and 49.5 GBd, respectively, at 86 km. For 258 km, the gap in performance increases to 4.5 dB and 6.5 dB, respectively.

For the longer distances, above 516 km, the relative impact of transceiver noise on overall SNR is greatly reduced, and the performance is dominated by the amplifier noise. This results in the increasing performance gap between SOA and EDFA. At 2064 km, the gap stabilises to approximately 8 dB for both symbol rates. This 8-dB difference is caused, in part, by the increased NF, approximately 2 dB, and another 2 dB penalty for PDG, with the remainder of the penalty being due to semiconductor amplifier nonlinearity.

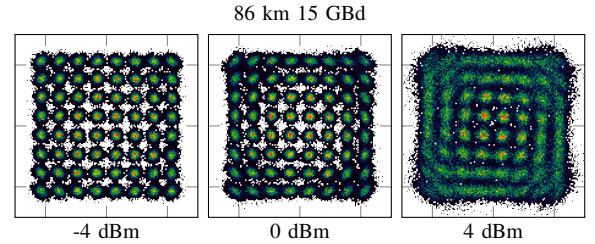


Fig. 5. Received symbol constellations for single-span 15-GBd transmission are shown.

The received symbol constellations are shown in Fig. 5 and indicate the increased nonlinear distortion for higher launch powers. This distortion is caused by the SOA, and not the Kerr nonlinearity from the fibre, as can be seen from the launch powers being below optimum launch power for the EDFA amplified measurements. Compared to the constellation at the optimum launch power for the SOA of -4 dBm, the centre 4 points of the constellation at higher launch power look relatively unaffected, whilst the outer constellation points display an appreciable level of nonlinear phase noise. This suggests that nonlinear mitigation techniques could have great impact.

V. THROUGHPUT COMPARISON

Data throughput results with the use of EDFA and SOA amplification are presented in Fig. 6, shown for the centre channel. This was calculated from the generalised mutual information (GMI), with the overhead from the pilot header and the CPE pilots subtracted, and multiplied by the symbol rate. The transmission distance of 516 km was selected for this comparison because this is the shortest distance at which the transmission is no longer transceiver noise limited. The

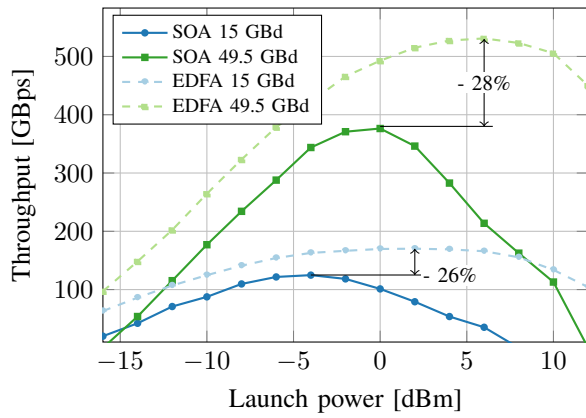


Fig. 6. Throughput of the centre channel for 516 km transmission.

criterion for this was SNR at optimum launch power being 2 dB lower than B2B SNR.

The throughput penalty for SOA transmission was 26% and 28% for 15 GBd and 49.5 GBd, respectively. The power consumption of the total transmission system can depend on many aspects and therefore it is difficult to draw general conclusions. However, if the energy savings by replacing EDFAs with SOAs and using lower spectral efficiency transceivers exceed this percentage, the use of inline SOAs might be an interesting proposition. Increasing the occupied bandwidth from only 3 channels to fully loaded will lessen the impact of nonlinearities [9]. Together with recent advances in nonlinearity mitigation for SOA gain dynamics [17], this gap in performance could be further reduced, ultimately making the SOA a more attractive option in energy-efficient optical communications.

VI. CONCLUSION

In this paper, we presented, for the first time, an experimental investigation into long-haul high-speed WDM transmission using an SOA to compensate for link losses. The experiment was carried out using a recirculating fibre loop, and the results were compared against those obtained for transmission with inline EDFAs. For 2064 km transmission, we found an 8-dB SNR penalty for both 15 GBd and 49.5 GBd. However, we found the performance penalty (percentage reduction in throughput) with SOAs compared to EDFAs at 516 km to be 26% and 28% for 15 GBd and 49.5 GBd, respectively. This reduction in performance may be tolerable, given the potential for reducing energy consumption in optical transmission systems. Note that these results are specific to the commercial SOA used in this work. Several improvements can still be made, the most obvious is tailoring the SOA for in-line amplification with higher saturation power and longer carrier lifetimes. Another is to increase the transmitted bandwidth launched into the SOA. Finally, with the development of DSP tailored for SOA nonlinearity mitigation, we predict this gap in performance to further close.

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