C+L Ultra-Wideband Semiconductor Optical Amplifier for WDM Systems

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Abstract *We report the performance of a UWB SOA designed for the C+L band and evaluate its nonlinearity in single-wavelength and WDM systems through SNR measurements with real-time transceivers. ©2023 The Author(s)*

Introduction

One approach in boosting the capacity of future optical communication networks is the extension of the optical transmission bandwidth. The most significant challenge in Ultra-Wideband (UWB) systems lies in the amplification operation, which ultimately determines the transmission window and the achievable data rate. Extending this window to the S- or the L-band has already been investigated through a multitude of techniques [1-7].

The potential of Semiconductor Optical Amplifiers (SOAs) in UWB systems has already been demonstrated through implementations of Dense Wavelength Division Multiplexing (DWDM) transmission links, where the C- and L-bands are amplified seamlessly [2,4] or separately using discrete components [1]. Similar demonstrations for SOAs include Booster amplification within a transponder to compensate for the modulator loss [8,9] or post-amplification in Reconfigurable Optical Add-Drop Multiplexer (ROADM) applications [10-12], where they can compensate for the insertion losses of the Wavelength Selective Switches (WSS). In addition, ROADM applications require flexibility in the channel loading as they involve add/drop operations, therefore SOAs have proven to be a popular candidate for amplification, owing to their relatively fast response to input power variations [10,12]. However, this characteristic is also the cause of their nonlinear behaviour in signal amplification, which is the main limitation in the practical use of SOAs.

In this paper, we report a dual-polarization UWB-SOA unit designed to operate seamlessly in the C+L band and evaluate its performance on a coherent communication testbed, using real-time transceivers. The Gain and Noise Figure (NF) are reported for an optical window of 1525 to 1625 nm, while the nonlinearity is quantified using an Optical Signal-to-Noise Ratio (OSNR) penalty metric. Finally, measurements under multiple-channel loading conditions are presented to demonstrate how the maximum achievable power in the linear regime increases by increasing the channel count and confirm the potential of the SOA for WDM amplification applications.

Amplifier Static Characterisation

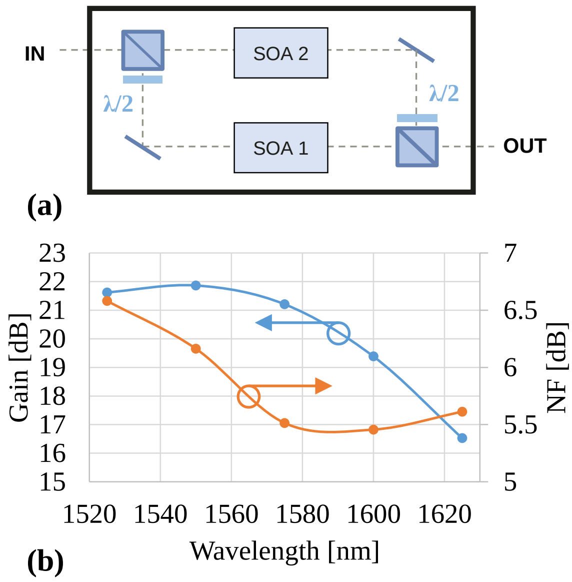

Fig. 1: (a) Schematic of the amplifier unit, (b) SOA Small-Signal Gain and Noise Figure across the C+L band.

The dual-polarization amplifier unit consists of two SOAs configured in a free-space Polarization-Division Multiplexing (PDM) scheme, as shown in Fig. 1a. Each of them is driven by a diode controller at 1.2 A, while the device temperature is stabilised at 20°C by means of a Thermoelectric Cooling (TEC) controller. The SOA gain was designed to cover the extended C+L band (1525-1625 nm) and the fibre-to-fibre Gain and Noise Figure (NF) values are illustrated in Fig. 1b. The curves represent the small-signal values measured using a single-wavelength input at -25 dBm which was swept across a 100-nm window in the C+L band. A Gain higher than 16 dB was observed for all wavelengths, while the NF was lower than 6.6 dB in the entire band.

Figure 2 shows the amplifier saturation. The curves in 2a represent the gain measured at each wavelength for up to 24 dBm of output power. Figure 2b shows the gain curves normalised with respect to their small-signal values in order to portray the compression effect. Shorter wavelengths are more susceptible to compression, while 3-dB-saturation output powers higher than 20 dBm were observed for all examined wavelengths.

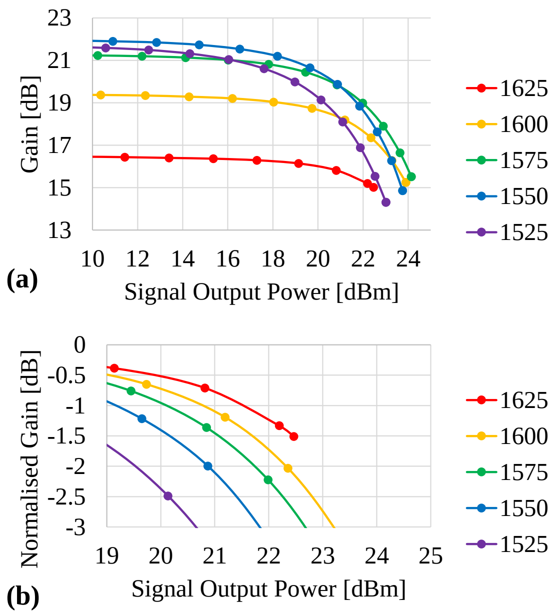

Fig. 2: (a) SOA Gain and **(b)** Compression vs. output power for five wavelengths in the C+L bands.

Experimental Setup & Results

To evaluate its performance in a real communication system, the SOA was used to amplify coherent dual-polarization signals in the entire C+L band. The setup illustrated in Fig. 3 was constructed to characterise the SOA in terms of nonlinearity in the context of a realistic C+L system.

Real-time transmitters were used to generate 68-GBaud signals in a PDM-16QAM format, amounting to a total data rate of 400 Gbit/s. To study the effects of nonlinearity for a large range of input (and output) powers to the SOA, the modulated signal was also pre-amplified with an EDFA before being sent to the SOA, while any out-of-band Amplified Spontaneous Emission (ASE) noise was filtered out using a bandpass tunable optical filter beforehand. To test the SOA at different wavelengths, this transmitter configuration was duplicated for both the C- and L-band respectively and a multiplexing scheme was used, as shown in Fig. 3.

A variable optical attenuator (VOA) was used to sweep the input power launched to the SOA, while the output spectrum was monitored with an Optical Spectrum Analyser (OSA). After the SOA amplification, the signal was sent to a post-amplifier and a filter before entering the real-time receiver for each band, and the same multiplexing scheme was used to render the measurement setup wavelength-transparent.

The transceivers were operated at five different wavelengths in order to first characterise the back-to-back transmission and then evaluate the SOA performance based on the received Bit Error Ratio (BER) and the estimated Signal-to-Noise Ratio (SNR). Figure 4a illustrates the SNR trend with respect to the signal output power. It is noted that in the cases of 1525 and 1550 nm the measurements were taken using the C-band transceiver, while the rest of the curves correspond to the L-band transceiver.

Comparing the SNR and OSNR values measured at the Receiver with the back-to-back performance of the system (without a SOA), the OSNR penalty was extracted. This metric denotes the penalty in OSNR required to reach the Forward Error Correction (FEC) limit and it was used to quantify the nonlinearity of the SOA. This technique is more thoroughly described in [13].

The trend of the OSNR penalty with respect to SOA output power is shown in Figure 4b for wavelengths up to 1610 nm. Longer wavelengths

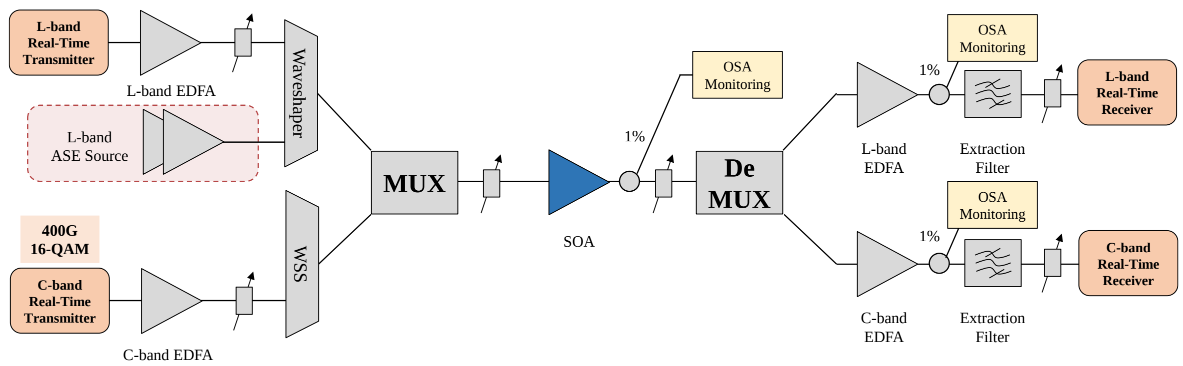

Fig. 3: Experimental Setup used to measure the OSNR Penalty of the UWB-SOA in both C and L bands.

were not measured due to limitations in the available equipment (EDFA pre- and post-amplifiers). The curves suggest that the nonlinearity is more prominent for shorter wavelengths, as the 1525-nm signal shows the highest levels of penalty. Assuming an acceptable margin of 0.1 dB for this penalty value, it is shown that the SOA is practically linear for up to 11 dBm of signal output power in the C+L band.

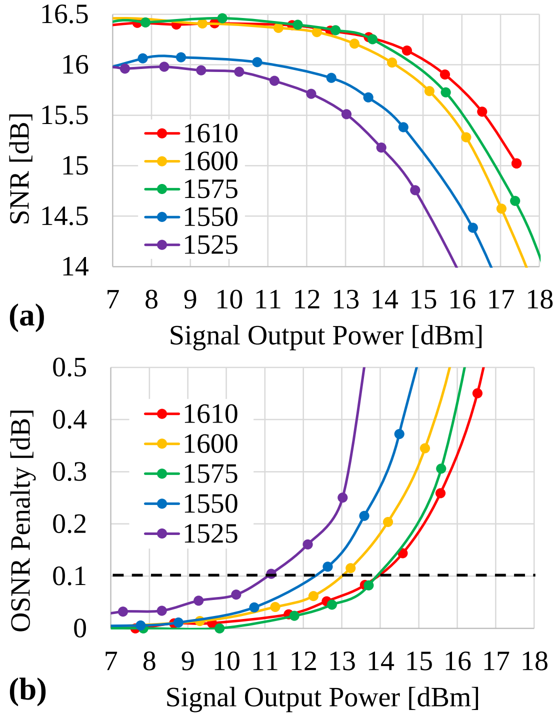

Fig. 4: (a) SNR at the SOA output and (b) OSNR Penalty vs output power for five different C+L wavelengths.

To investigate the suitability of this amplifier for WDM use cases such as contentionless, colourless, directionless (CDC-) ROADM applications, multiple-channel loading tests were performed. The target was to emulate the amplification stage used to compensate for the loss of multicast switches (MCS) in these applications, where the typical number of channels varies from 1 to 8. It has previously been shown that operating the SOA under WDM conditions shows greater tolerance to nonlinearity, provided that the signals are uncorrelated [14]. For the current test conditions, this was ensured by the use of additional dummy channels with identical bandwidth, which were emulated using an ASE source combined with an optical programmable filter (Fig. 3 in dashed outline frame) to provide the appropriate spectral shaping. The SOA was tested under 1-, 2-, 4- and 8-channel loading conditions, which are illustrated in Fig. 5a. It is noted that the dummy channels were spectrally offset with respect to the Channel under Test (CUT) in order to avoid any performance penalty due to filtering crosstalk. The results are shown in Fig. 5b, where the OSNR penalty of the CUT at 1577.4 nm is plotted against the total output power of the SOA. Considering the same margin of 0.1 dB of acceptable penalty, the maximum achievable output power is observed to be higher for a larger number of channels, as it can reach ~17 dBm for the 8-channel case, while this limit corresponded to only 14 dBm when a single channel was used. This confirms the potential of the SOA in WDM amplification, as the maximum achievable power appears to increase for larger channel count.

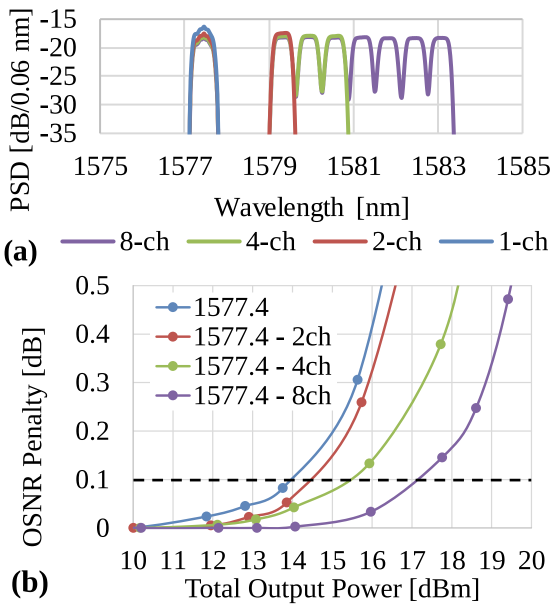

Fig. 5: (a) Channel loading at the SOA input, (b) SOA OSNR Penalty vs output power for different channel loading configurations.

Conclusions

A dual-polarization Ultra-Wideband SOA was reported for operation in the C+L band. A fibre-to-fibre small-signal gain higher than 16 dB was reported with a NF lower than 6.6 dB in a wavelength range of 1525-1625 nm. The 3-dB-saturation output power was measured to be higher than 20 dBm in the entire band, while nonlinearity measurements were performed through SNR measurements using real-time transceivers. An OSNR penalty lower than 0.1 dB was measured for up to 11 dBm of output power in the C+L band, while WDM tests showed that increasing the channel count can increase the maximum achievable power for linear operation. The results demonstrate the potential of SOAs as amplifiers in ROADM applications that require seamless operation in the C+L band, and show that their main limitation, their nonlinear behaviour, can be mitigated for cases of WDM input.

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