320 Gb/s WDM Transmission in Monolithically Integrated $Al_2O_3:Er^{3+}$ Spiral Amplifier on Si_3N_4

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Abstract: We report an 8×40Gb/s WDM data transmission through an $Al_2O_3:Er^{3+}$ spiral waveguide amplifier on Si_3N_4 featuring 1.8dB/cm net gain. All data channels present clear eye diagrams and bit-error rate values above the KR4-FEC limit.

1. Introduction

On-chip optical amplifiers have emerged as a widely adopted solution in Wavelength Division Multiplexing (WDM) optical networks to offer optical power boost for high-speed data transmission [1]. To serve this purpose, on-chip integrated optical amplifiers need to provide excellent gain characteristics, ease of fabrication with low manufacturability cost i.e. CMOS compatibility, WDM and high data rate transmission capabilities to enable practical applications. In this frame, Semiconductor Optical Amplifiers (SOAs) have been for long the preeminent on-chip amplifier solution in the network designer toolkit however their employment requires hybrid integration and their fast dynamics combined with gain saturation can affect signal quality in WDM-based systems [2]. To overcome non-linear SOA-induced phenomena, Er^{3+} integrated amplifiers [1], have emerged as an alternative amplification solution for high speed WDM on-chip amplification. Among all hosting materials for the Er^{3+} ion [1], Al_2O_3 presents a promising case for waveguide amplifiers. Impressive results have been demonstrated for Erbium Doped Waveguide Amplifier (EDWA), such as 20 dB net gain in spiral shaped waveguides, developed on silicon wafer [3]. Also, a large gain bandwidth of 80 nm at an $Al_2O_3:Er^{3+}$ waveguide has been reported in [4], supporting broadband operation in the C-band. At the same time Si_3N_4 platform is gaining traction due to low loss [5], and low cost for realizing $Al_2O_3:Er^{3+}$-Si_3N_4 based optical amplifiers [6-7]. Still none of the reported demonstrations [1-7], combines all the necessary critical features together, while the only high-speed transmission demonstration with Er^{3+} amplifiers has achieved up to 170 Gb/s [6], missing any WDM capability credentials.

In this paper, we demonstrate for the first time, to the best of our knowledge, a record high-speed WDM data transmission operation of an aggregated 320 Gb/s data stream through a 5.9 cm long $Al_2O_3:Er^{3+}$ spiral amplifier featuring monolithic integration on a low-loss CMOS compatible Si_3N_4 platform, offering of 1.8dB/cm net gain [7]. Figure 1(a) shows a SEM image of the coupling section between $Al_2O_3:Er3^{+}$ and Si_3N_4 layers. WDM operation capability successfully verified by introducing simultaneously 8×40 Gb/s data channels. The obtained results for all data channels revealed clear eye patterns with an Extinction Ratio (ER) above 3.8 dB and an Amplitude Modulation (AM) of 1 dB while all the Bit-Error Rate (BER) values were below the KR4-Forward Error Correction (FEC) limit.

2. Experimental Evaluation and Results

Figure 1(b) depicts the experimental setup employed for the evaluation of the 8×40 Gb/s WDM transmission through the EDWA chip with the inset showing the $Al_2O_3:Er^{3+}$ spiral when pumped at 980 nm. Eight laser sources were used to produce continuous waveform (CW) signals with the corresponding wavelengths presented in the legend of fig.1(b). Then the CW signals were multiplexed in an 8×1 Planar Lightwave Circuit (PLC) coupler and injected into the $LiNbO_3$ Mach-Zehnder Modulator (MOD) for the generation of an 8-channel WDM data stream. An 1Km-length Single Mode Fiber (SMF) spool was inserted after the MOD for data channel decorrelation. The 8-channel WDM data stream was then combined with the pump laser signal at 980 nm through a WDM coupler and its output was injected into the chip

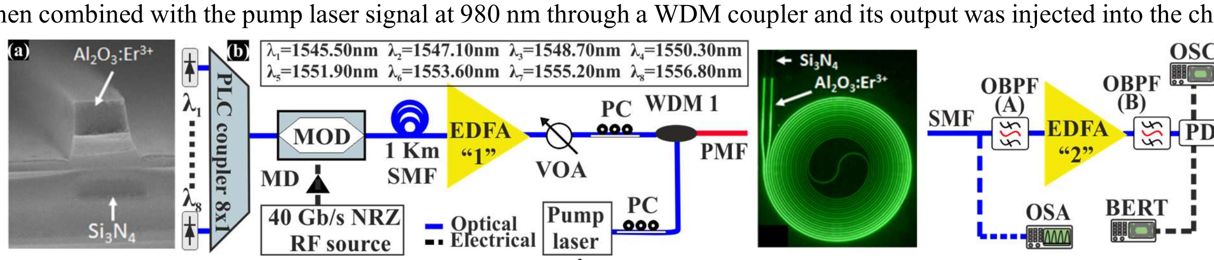

Fig. 1. (a) SEM image of the coupling section between $Al_2O_3:Er^{3+}$ and Si_3N_4 layers. **(b)** Experimental setup used for the 8×40 Gb/s WDM transmission evaluation in Er^{+3} integrated amplifier, inset exhibits the characteristic green light emission when pumped at 980 nm.

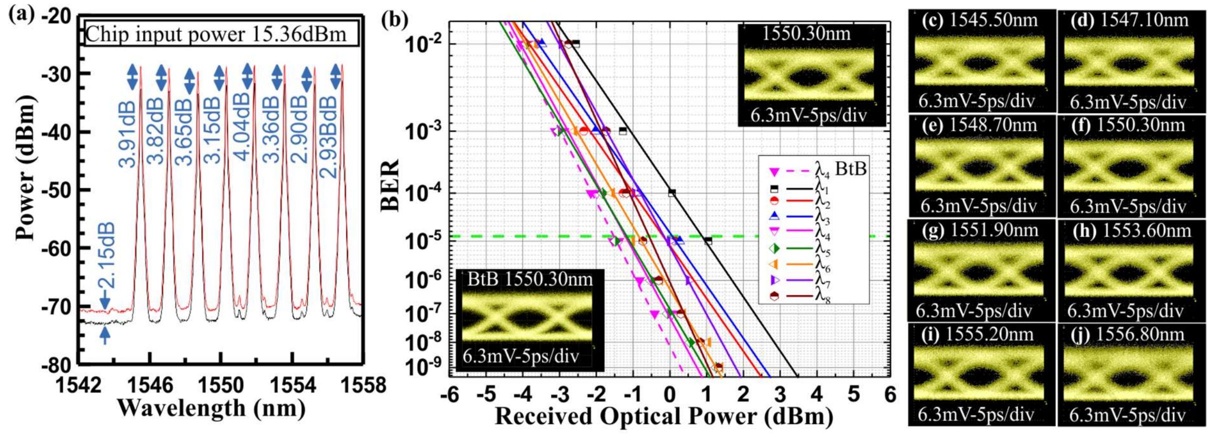

Fig. 2. (a) Optical spectra of the 8 channel WDM signals at chip output for 15.36 dBm total input power. Black and red lines correspond to the pump laser being OFF and ON, respectively. **(b)** BER measurements at 8×40 Gbps transmission. The horizontal dashed line denotes the error rate threshold for KR4-FEC at 2.1×10^{-5}, BtB vs transmission eye diagram at 1550 nm. **(c)-(j)** Transmission eye diagrams for 8×40 Gb/s.

by means of a Polarization Maintaining Fiber (PMF). The chip output was filtered by an Optical Bandpass Filter (OBPF) (A) so as a) to remove the transmitted pump light and b) to reject the Amplified Spontaneous Emission (ASE) noise. Erbium Doped Fiber Amplifiers (EDFAs) were employed in the setup to boost the power before and after the chip to compensate the coupling losses. Variable Optical Attenuators (VOAs) and Polarization Controllers (PCs) were used to adjust the power levels and polarization of the transmitted signals. A 40 Gb/s photodiode (PD) was used for the optoelectronic conversion of the amplified signal. To achieve the minimum input power which is needed to be inserted in the PD for BER floor of 10^{-9}, the second EDFA (2) was placed to amplify the low power signal exiting of the EDWA chip. The ASE noise of the EDFA (2) was filtered out by a second tunable OBPF (B) with 1 nm 3 dB bandwidth. The output transmitted data stream was monitored by an Optical Spectrum Analyzer (OSA), a digital sampling Oscilloscope (OSC) and a Bit Error Rate Tester (BERT).

Figure 2(a) shows the spectrum at the saturated gain region of the amplifier for the WDM transmitted signals with (red line) and without (black line) pump. The EDWA was operated in the saturated gain region to achieve the required input power of the PD for error-free transmission by injecting 15.36 dBm total input power in the chip, achieving a signal enhancement of 2.9 dB – 4.04 dB for the data channels. Net gain values of > 8dB around 1550 nm were also measured in the small signal gain regime of the amplifier [7]. Figure 2(b) depicts the obtained BER values versus the received power at the photoreceiver for each channel. The dashed line represents the Back-to-Back (BtB) measurement at 1550.30 nm, where the chip was replaced by a VOA to emulate the chip losses. As can be observed in fig. 2(b) there is no indication for significant degradation of the signals quality by comparing the BtB and output eye diagram shown in the insets. Solid lines are used for the respective transmitted signals through the EDWA and the horizontal dashed line denote the threshold for the KR4-FEC. The results demonstrate minimum error-rate values of 10^{-5} (1545.5 nm, 1547.1 nm and 1548.7 nm), 10^{-7} (1550.3 nm), 10^{-9} (1551.9 nm, 1553.6 nm and 1556.8 nm) and 10^{-6} (1555.2 nm), that is above the KR4-FEC threshold value of 2.1 x 10^{-5}. The power penalty is below 1 dB for all channels. The slope difference observed among the curves occurs from the slightly different bias conditions of the modulator during the measurements. Figure 2(c)-(j) present the clearly open eye diagrams for all transmitted signals at 40 Gb/s as obtained at the EDWA output. The ER of all channels ranges between 3.8dB-4.2dB while the AM values is approximately 1 dB. The above measurements were obtained, for 15.36 dBm total signal power with co-propagating pump light of 300 mW at 980 nm injected into the EDWA chip. The EDFA 2 input power range was from -26.2 dBm to - 20.7 dBm and the received power for the KR4-FEC threshold was varying from -1.02 dBm to 1.05 dBm. All BER curves were received without any Digital Signal Post Processing (DSP).

3. Acknowledgements

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4. References

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