Lossless Silicon Photonic ROADM based on a Si_3N_4 platform and a Monolithically Integrated Erbium Doped Amplifier

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Abstract: The first demonstration of a lossless four-port silicon photonic ROADM-node based on a monolithic-integrated spiral $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ Erbium Doped Waveguide Amplifier and MZI-interleaver layout on a Si_3N_4 platform is presented, routing a $4 \times 50\text{Gb/s}$ WDM data-traffic capacity.

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1. Introduction

The ever-increasing demand for high-bandwidth inter-connectivity at Data Centers, Metro-Access and 5G networks has been scaling linerates beyond $100\text{Gb/s}/\lambda$ [1], pushing for enhanced optical routing/switching functionalities and Erbium Doped Fiber Amplifiers (EDFAs) forming the dominant amplifier technology with well-proved gain, noise and linearity credentials [2]. To this end, Wavelength Division Multiplexing (WDM) allows transmitting multiple channels at a single fiber, while Reconfigurable Optical Add Drop Multiplexers (ROADMs) provide wavelength-selective cross-connect (WXC) functionality with dynamic lightpath reconfiguration, traditionally relying on MEMS or piezoelectric actuators and forming key-components of high-speed, energy-efficient core and metro networks [3]. Lately, integrated photonic spatial and wavelength switches have been gaining strong momentum in Data Centers and 5G networks, to facilitate dynamic network provisioning and optical flow control at reduced size or cost [4]–[6].

To this end, Silicon Photonics (SiPho) switches and ROADMs stand out as a promising cost-effective solution with large integrability, energy-efficiency and broad bandwidth [4]. Yet, their main drawback is the accumulation of large insertion losses [6], typically in the order of $>10\text{ dB}$, rendering in-line optical amplification as a pre-requisite of optical switched networks and promoting rapid advances towards on-chip amplification for lossless operation and scalable network topologies [7]–[10]. Owing to the inherent amplification-gain properties of III-V materials, arrays of SOAs are being monolithically integrated as On-Off gating elements of up to 1×8 ROADMs on InP platform and 40 Gb/s channel-rates for Metro-Access and 5G networks [7] or hybridly-integrated as gain-elements of 4×4 [8] and 8×8 SiPho switches [9],[10] with 33 Gbd/s channel-rates for Data Centers. Yet, this type of hybrid schemes require careful and challenging optical assembly processes, while most importantly SOAs generally induce non-linear phenomena or inter-channel cross-talk, that severely degrade the signal quality and dynamic range [9][10]. In parallel, rare earth integrated amplifiers have made significant progress the last decade [2], with Erbium Doped Waveguide Amplifiers (EDWA) using aluminum oxide offering enhanced integration potential [11], broadband gain of 70 nm at values up to 18 dB , large ($>20\text{ dB}$) dynamic range of launch power and single-waveguide transmission-rate up to 170 Gb/s [12].

In this work, we experimentally demonstrate for the first time a lossless ROADM node architecture that exploits a photonic integrated chip (PIC) of a spiral $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ EDWA monolithically integrated on a Si_3N_4 waveguide platform, followed by a low-loss 1×4 ROADM of a lattice MZI waveguide-routing layout also on a Si_3N_4 platform. The fiber-to-fiber (ftf) loss exclusively for the Si_3N_4 ROADM is measured to be 5 dB in the 1550 nm region, which can be

Fig. 1. (a) Conceptual schematic of a WDM Ring with three lossless ROADMs that monolithically co-integrate an EDWA on a Si_3N_4 waveguide and a ROADM layout on MZI interleavers b) Microscope images of the two PICs .

compensated by the average signal enhancement of 5.6 dB per channel provided by an 5.9 cm-long spiral EDWA acting as a pre-amplifier. Proof-of-principle lossless wavelength-routing is experimentally demonstrated at up to 200 Gb/s (4×50 Gb/s) WDM OOK data-traffic with error-free operation, forming to the authors' knowledge, the first lossless SiPho ROADM node demonstration and a record 200 Gb/s WDM transmission capacity at integrated EDWAs.

2. Photonic Integrated Circuits and Experimental Setup

Introducing SiPho switches and ROADMs in optical networks inevitably poses a strict challenge to compensate the ftf loss. A representation of the envisioned lossless ring network is shown in Fig. 1(a), including 1×4 ROADMs that simultaneously provide pre-amplification and wavelength-space routing. Specifically, our proposed ROADM architecture deploys a 5.9 cm-long $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral amplifier monolithically integrated above a Si_3N_4 waveguide core, followed by a low-loss MZI-based layout patterned on a similar Si_3N_4 platform. The current demonstration relies on two discrete PICs, which are shown in Fig. 1(b), fabricated separately and coupled together through fiber-patchcords. The Si_3N_4 waveguide of the EDWA PIC was fabricated using standard LPCVD, UV contact lithography and reactive ion etching processes, to form strip waveguides core of $1.4 \times 0.2 \mu\text{m}$ cross-sectional dimensions, also with propagation losses of 0.14 dB/cm [11]. The Al_2O_3 waveguide above the Si_3N_4 platform features cross-sectional dimensions of $1.4 \times 0.8 \mu\text{m}$ deposited by RF magnetron sputtering, followed by UV contact lithography and RIE, co-doped with erbium concentration of $1.7 \times 10^{20} \text{ cm}^{-3}$. Vertical tapering sections of the Si_3N_4 waveguide from 200 nm to 30 nm and horizontal tapering of the Al_2O_3 waveguide from 1.4 μm to 0.8 μm provide coupling both for the 980 nm-pump and the C-band data signals. A conceptual schematic and an SEM image of the coupling tapering sections between the Si_3N_4 and Al_2O_3 waveguide layers are depicted in Fig. 2(b). The EDWA internal gain was measured to be in the order of ~ 18 dB at 1532 nm region and ~ 10 dB at 1550 nm [11] for Al_2O_3 spirals of 10 cm, when operated in the small signal region. The EDWA was mounted on a probe station with fiber-alignment stages.

The ROADM relies on a $\text{Si}_3\text{N}_4/\text{SiO}_2$ TriPleX platform with ultra-low losses below 0.1 dB/cm [5], relying on a lattice of asymmetric MZI interleavers with tunable couplers, as shown in Fig. 2(a). It is capable of add/dropping four C-band wavelengths with 100 GHz spacing. Specifically, the incoming 4λ -WDM lightstream is subdivided into two pairs of (λ_1, λ_3) and (λ_2, λ_4) by the first grey-colored MZI cascade with 872.1 μm differential path and 200 GHz Free Spectral Range (FSR), which then flow towards the upper and lower branches respectively. There, the wavelength pairs are further subdivided by the next orange-colored cascade of MZIs with an FSR of 400 GHz, allowing finally to drop each of the four 100 GHz spaced WDM channels to a separate drop channel or propagate to the Through port. Each MZI drop filter was designed with a 32.5 GHz flat-top pass-band, as described in detail in [5]. The ROADM was electrically and optically packaged in a bench-top solution, as shown in in Fig. 2(c).

The rest of the experimental setup is shown in Fig. 2(a). Four Continuous Wavelengths (CW) at λ_1 - λ_4 of 1549.6, 1550.4, 1551.2 and 1552 nm were generated by DFB lasers and optically multiplexed by an AWG. The 4λ CWs were modulated by a LiNbO_3 MZI modulator at 25 Gb/s and 50 Gb/s, generating typical 100 Gb/s or 200 Gb/s WDM data-traffic, that was propagated through a 200m fiber to partially de-correlate the data, followed by polarization controller (PC) and variable optical attenuator (VOA) to handle polarization and power. An EDFA pre-amplifier compensated the losses of the modulator and external fiber-pigtails. The WDM data with 12 dBm average power were coupled with the 24.7 dBm CW of a 980 nm laser pump and optically injected to the EDWA, whose output is inter-connected to the ROADM PIC, before being monitored at an Optical Sampling Scope (OSC).

3. Experimental Results

Initially, the output spectral transfer function of the ROADM was evaluated by feeding the Amplified Spontaneous Emission (ASE) noise of an EDFA at its input port and recording the output of each of the Drop ports at an OSA. The

Fig. 2. (a) Experimental setup for the evaluation of the lossless ROADM, (b) conceptual schematic of the EDWA to Si_3N_4 coupling and SEM cross-sectional image and (c) Photo of the packaged ROADM.

Fig. 3. Experimental results: (a) ROADM spectrum output with ASE input, (b) EDWA gain estimation with Pump On-Off, (c) Eye diagrams of 4×50 Gb/s WDM data transmission with ROADM reconfiguration, (d) BER and eye diagrams for 4×25 Gb/s data at the four Drop ports.

recorded spectrum for each of the four Drop channel are reported in Fig. 3(a) with different color, verifying a 3-dB bandwidth of 0.66 nm per channel with 0.25 nm flat-top response, while the cross-talk between each central peak pass-band and the stop band of the neighboring channel was -18 dB. The ROADM ftf losses were measured 5 dB, with 0.6 dB estimated for the longest on-chip path and the rest attributed to non-optimal fiber-coupling.

Subsequently, the EDWA on-chip gain was evaluated in a WDM transmission scenario, where four CW signals were propagated through the EDWA along with or without the 980nm-pump. The output spectra for the two cases with/without pump recorded at an OSA are presented with black and red color in Fig. 3(b) for comparison purposes. The four signals were enhanced by a factor of 4.8-6.6 dB for the given optical power inputs, being equal or slightly higher than the ROADM ftf losses (coupling interface and on-chip propagation), allowing to achieve lossless operation in case of co-integration on the same PIC. Owing to the use of two PICs, the coupling and absorption losses of the EDWA PIC are not accounted for in this proof-of-concept work, yet have to be also compensated.

Finally, the lossless ROADM operation was evaluated in two WDM routing scenarios. In the first case, 4×50 Gb/s wavelength channels were either passed at the Through port or reconfigurably dropped at the four Drop outputs. The eye diagrams of the input signal, the four Drop output signals and an indicative signal (λ_4) at the Through port, after being amplified by the EDWA and routed by the ROADM are shown in Fig. 3(c). The measurements reveal open eye diagrams for all output signals with an Extinction Ratio (ER) of around 4.5 dB and an Amplitude Modulation (AM) less than 1 dB. Finally, similar lossless routing operation was performed also for 4×25 Gb/s data signals for benchmarking with a 25Gb/s-capable Bit Error Rate (BER) equipment. The eye diagrams of all output wavelengths along with the plotted BER curves at Back-to-Back (BtB) and Drop-output configuration are shown in Fig. 3(d). The eye diagrams reveal equal performance of 4.5 dB ER and 1 dB AM as in the 4×50 Gb/s scenario, while error-free operation at the 10^{-9} condition was achieved for all signals with an average BER penalty of around 1.7 dB.

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