Low loss SiN optical modulator for kHz-rate switching applications

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In this paper we present the design and characterization of a low loss, kHz rate, silicon nitride modulator. By minimizing the linewidth of channel transmission thanks to low loss waveguide propagation (0.2 dB/cm), the presented thermally tuned microring resonator in add/drop configuration shows 10dB ER at 1kHz modulation and has a static insertion loss of 2dB.
Keywords: *Microring resonators, silicon nitride, optical modulators*

INTRODUCTION

In the last 10 years, silicon photonic circuits have played a fundamental role in the development of many applications fields, ranging from telecommunications and sensing, touching also frontier research themes such as those related to optical computing and advanced non-von Neumann machines [1]–[3]. The main target of these research efforts has always been related to the operational speed, targeting to improve the pJ/bit figure of merit, leading to the development of 100G+ optical modulators, with compact footprints and high integration capabilities. Differently, frontier and emerging applications related to quantum processing and machine learning require modulators (either phase or amplitude) with different requirements: here extremely low optical loss, low optical power consumption and thermal stability are the main requested ingredients, operating at modest speed values (kHz range). For such applications, modulation utilizing the thermo-optic effects is an effective option [4]. In this context SiN has emerged as a very attractive option for large-volume and low-cost fabrication, thanks to its CMOS compatibility and availability in all major foundries. Despite the low refractive index contrast that implies a larger footprint with respect to Si, SiN offers a larger transparency bandwidth (bandgap ~5eV) and very low linear propagation losses that can be two orders of magnitude less with respect to Si providing new opportunities for the design and development of complex integrated circuits.

Here we present the design and experimental characterization of a thermally tunable ring resonator modulator based on SiN offering extremely low optical loss and low power consumption operating at telecom wavelengths.

DESIGN AND EXPERIMENTAL RESULTS

We present the design of a SiN intensity modulator based on low loss, high Q-factor microring resonator. Modulation is achieved via a local change of the refractive index through thermo-optics effect that, in turns, allows shifting the resonance frequencies of the device. Intensity modulation can be achieved if a continuous wave laser is placed at the initial resonance frequency and a driving voltage is applied to the integrated heater. Here, the required power to achieve a deep (>10 dB) on-off keying (OOK) modulation is related to the capability to design MRR exhibiting a sharp and narrow (in frequency) resonances: in this way a small amount of applied voltage will result in an enhanced modulation performance of the MRR. The main requirement to achieve such behaviour is related to the waveguide optical loss. We initially compared the attainable performance of the two main silicon photonic-based platforms: silicon on insulator (SOI) and SiN. The outcomes of the comparison of figures of merit of MRRs in these two platforms are reported in Table 1. For such comparison we have assumed the ideal case: coupling and bend sections are lossless and MRRs fulfill the theoretical critical coupling condition. Typical propagation loss values for SOI and SIN platforms were considered as 3dB/cm and 0.1dB/cm and modest minimum radii were chosen as 20μm and 70μm, respectively. The main output of our modelling is the required temperature change to achieve 10 dB ER modulations with MRR size as a free parameter. Our results show that, despite the lower thermo-optics effect of SiN compared to the one of SOI, thanks to the low losses of SiN waveguides, the required temperature change to achieve the desired modulation can be lower than in the case of SOI.

Technology and Design parameters	Si	SiN
Loss [dB/cm]	3	0.1
T/O coefficient [1/K] @ 1550 nm	2.08×10^{-4}	2.45×10^{-5}
Bending radius [µm]	20	70
Results of the analytical model	**Si**	**SiN**
FWHM [pm] (minimum)	31.8	1.87
Q-factor (maximum)	48×10^3	820×10^3
Temperature Increase needed for modulation	2 °C	1.4 °C

Table 1: Comparison of figures of merit according to typical technology parameters of Si and SiN MRRs with given propagation loss and bend radius. In the analytical model, couplers and bends are assumed to be lossless and the MRR is in the critical coupling regime.

The designed MRR was fabricated by Ligentec using standard MPW fabrication platform. The layer stack of the deep etched Si_3N_4 waveguide with SiO_2 cladding is depicted in Fig. 1a. The propagation loss of the single mode waveguide was 0.2 dB/cm with a fibre to chip coupling coefficient of 1.7 dB. An image of the fabricated SiN microring resonator in add/drop configuration is shown in Fig. 1b. The MRR was designed with a 60 µm of radius and 500 nm gap between the ring and the bus waveguide. Numerical simulations were performed in to feed the analytical model. The power coupling coefficient for 500 nm of gap through the 3D FDTD simulation was calculated to be 0.025 which corresponds to 3.5 dB of the bandwidth of drop port channel at λ=1.55µm. By using the obtained effective refractive indices and group index of the TE mode within the C-band in the analytical model, we set the Free-Spectral-Range (FSR) to be 375 GHz.

Subsequently, we performed preliminary static and dynamic characterizations of the device. The transmission of the Through and Drop ports of the MRR and the used characterization set-up are shown in Fig.1c-d. For the static transmission characterization, only the output of the EDFA was used without the tunable laser source (TLS) since the EDFA output was broadband enough to cover the C-band. The drop port transmission of the EDFA was fed to the fibre-based Polarization Beam Splitter (PBS). The slow-axis port of the PBS was then adjusted to the TE polarization which was used as the input for the Device Under Test (DUT). The signals between the PBS and DUT were transferred by a PM fibre. The measured FSR and 3dB bandwidth of the drop channel are 376 GHz and 5GHz, respectively. Resonance wavelengths with Q- factor of 3.9 10^4 at 1.55 µm has the Extinction Ratio (ER) larger than 30 dB. Since the incoming lights from EDFA were unpolarized, the secondary peaks that appear with lower transmissions confirmed high polarization extinction (~20 dB) provided by input PM fibre alignment in the set-up. The obtained experimental results show extremely good agreement with the expected parameters in terms of FSR and BW.

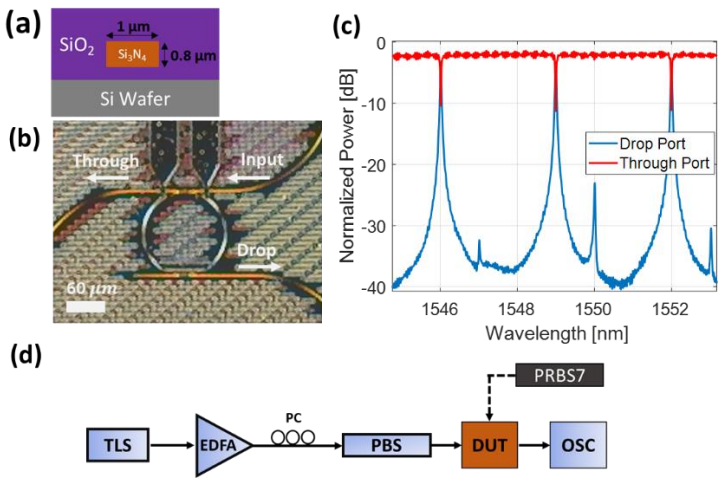
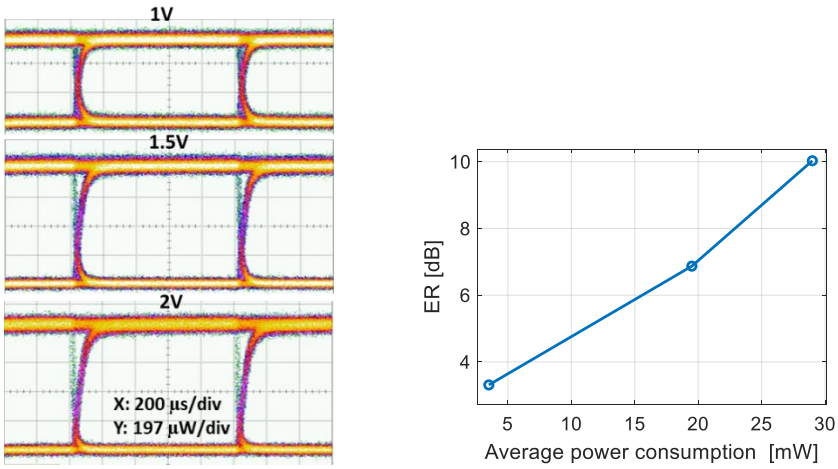


Figure 1. (a) Layer stack of the deep etched SiN waveguide. (b) a photograph of the fabricated MRR. (c) Static transmission of the drop port (blue) and through port (red) of the MRR modulator. d) The experimental setup.

Dynamic behaviour was evaluated using the modulator to synthesize OOK signals (PRBS7) at a rate of 1 kHz. To carry out modulation operations, the output wavelength of a CW laser output was first tuned to reach the resonance wavelength and then modulated by thermal tuning. Preliminary results of the obtained eye diagrams at 1 kbps OOK modulation with different applied voltages and measured ER values with respect to applied powers are shown in Fig. 2. Average power consumption of ones and zeros of the bit patterns, when 1, 1.5 and 2 applied volts have been measured as 3.5 mW, 19.5 mW and 29 mW, respectively. As shown in Fig. 2b, the ER obtained from the eye diagrams exceeds 10 dB with 29 mW of the applied power.



(a) (b)

Figure 2. Eye diagrams at 1kbps OOK modulation with different voltage levels (a) and corresponding extinction ratios as a function of average power consumption (b).

Overall, it has been shown that the modulation performance of the thermally-tuned MRR fabricated in SiN has been evaluated in terms of required modulation power and ER at kHz rate.

CONCLUSIONS

In this work we reported the design and the preliminary characterization of a silicon nitride kHz- rate thermo-optical modulator. By using a proper design approach based on both numerical simulations and the analytical model, an excellent agreement between the expected and obtained parameters has been achieved. The device was operated with a maximum of 29 mW of electrical power for an OOK modulation signal that showed a maximum of 10 dB of ER. The insertion loss of the device was 2dB. This modulator can be employed as a basic switching component for more complex architectures where low speed and power efficient modulators are needed.

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