Air Trenches-assisted Highly Selective, Fully Flexible SOI Filtering Element

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Abstract: We demonstrate a SOI fully flexible filtering element based on serial coupled ring resonators exhibiting 12-116 GHz bandwidth tunability, ER values up to 37.5 dB, high bandwidth tuning efficiency of 3.95 GHz/mW and compact footprint.
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1. Introduction

Elastic Optical Networks are considered the next evolution step of currently deployed optical networks since, among others, they properly address the challenge of traffic volatility and bandwidth demand [1]. To support this network transformation, a new generation of optical systems, sub-systems and components is being developed over the last few years, with the focus being primarily on flexible transceivers, elastic optical switches and flexible filtering modules, as they enable the flexible use of spectral resources in a cost- and energy-efficient way. Concerning the latter, Micro-Ring-Resonator (MRR) based implementations are gaining momentum in literature since they meet the demands for spectrum flexibility and sliceability [2],[3]. Significant work has been reported proposing a 2nd order MRR structure enhanced with variable coupling elements that control the light power within the resonant cavities [4]. A more sophisticated architecture of reconfigurable filtering elements is demonstrated in [5]. The proposed approach exhibits enhanced bandwidth and wavelength tunability as well as better-quality filter response. Although the above structures pose several benefits, further improvement is required in order to achieve broader bandwidth and wavelength tunability, augmented Extinction Ratio (ER) values and increased reliability.

In this article, we extend our previous work [5] and present a novel, fully flexible SOI filtering element exhibiting 104 GHz bandwidth tunability, full FSR tuning capability at enhanced FSR values. Moreover, a remarkable ER value of 37.5 dB, proliferates the structure's sliceability. Furthermore, the introduction of air trenches formed between adjacent electrodes, results to a considerable improvement in terms of thermal crosstalk between the respective waveguides and provide higher thermo-optic tuning efficiency (>5× and 1.5× enhancement on thermo-optic bandwidth and wavelength efficiency respectively), leading to augmented filter elasticity and lower power consumption. The compactness (3× area reduction factor), low power consumption and the reduced control complexity of the proposed scheme, pose an elegant solution for high density system-on-chip implementations.

2. Principle of Operation

The proposed filtering element is based on a thermo-optically controlled serial double ring resonator. The bandwidth tuning mechanism relies on the use of three variable optical couplers (3-dB MZI structures - MZIs A, B & C at Fig. 1(a)), while conventional in-cavity phase shifters allow wavelength tuning of the resonances (blue shifters at Fig. 1 (a)). A low complexity DC electrodes' geometry enables the filter's bandwidth and wavelength tuning control, via two single electrodes, as described in [5]. To improve the FSR and ER values compared to [5], targeting a > 50% increase on FSR value, a set of modifications were carried out. More specifically, each MZI arm length was reduced from 52.5 μm to 30 μm, whereas the in-cavity phase shifters length was reduced from 20 μm to 10 μm.

The flexible filtering element's performance is further improved by introducing air trenches between adjacent electrodes (Fig. 1 (a)), so as to reduce thermal crosstalk to the respective waveguides. Air trenches were fabricated between each MZI arm, as well as between each MZI structure, with lateral dimensions of 30 μm × 2 μm. The air trenches between the MZIs and the phase shifters are 15 μm × 10 μm in lateral dimensions. In order to quantify the performance enhancement due to the air trenches introduction, thermo-optic simulations were carried out in Lumerical DEVICE/FDE Solver Environment. In more detail, the thermal crosstalk on a reference waveguide with lateral separation of 10 μm to an electrode (Fig. 1 (a)) is plotted against applied power in Fig. 1 (b). The graph shows that the use of air trenches significantly reduces the thermal crosstalk between adjacent waveguides, resulting into 4× less phase induction to the reference waveguide when 80 mW of power is applied to its adjacent electrode. In Fig. 1 (c), the phase difference between the two arms of the same MZI, is plotted against power applied to one of their electrodes. The results indicate that the use of air trenches in the structure reduces the required control power to achieve the desired MZI waveguide phase differences. More specifically, to achieve a required phase difference of 0.9 rad in the

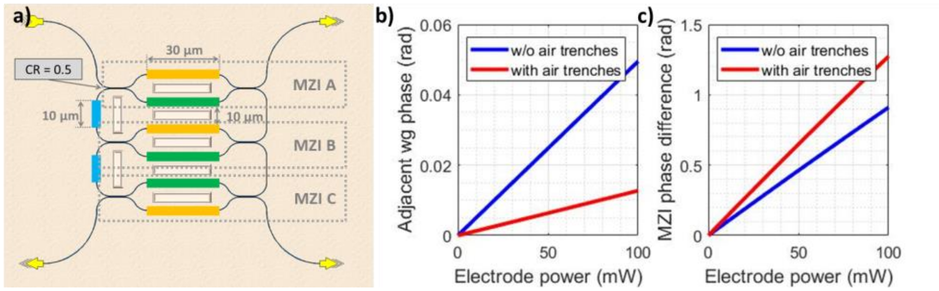

Fig. 1. (a) Fully tunable filtering element, (b) thermal crosstalk simulation results and improvement after air trenches introduction, and (c) MZI arms phase difference and improvement after air trenches introduction

MZI configuration, the presence of air trenches allows for a power consumption reduction of 32% compared to a device developed without air trenches. This power consumption reduction is a direct result of the improved thermal isolation of the MZI branches and increased thermal power confinement underneath the electrode, leading to higher waveguide temperatures.

3. Fabrication and Experimental results

The flexible photonic filtering elements were fabricated on a full 6-inch Silicon-On-Insulator (SOI) wafer. A 220 nm thick top-Si layer was employed to well support the propagation of Transverse Electric (TE) polarization mode, while the thickness of the Buried Oxide (BOX) layer was 3 µm. After the definition of the silicon waveguide layer, a 300 nm thick SiO_2 (LTO), an 80 nm thick Si_3N_4, and a 500 nm thick SiO_2 layer were deposited on the entire wafer. On top of this stack, 100 nm thick titanium joule heaters-electrodes were fabricated to enable the thermo-optic control of the guided modes [6]. Subsequently, the patterned wafers were etched using a reactive ion etching process through the multilayer material stack, to form the air trenches. The air trenches were etched down to the silicon handle wafer. The fabricated structure, with silicon element footprint of 0.077×0.056 mm^2 (3× area reduction compared to [5]), as well as the electrode and Fiber-Array (FA) I/Os deployments required for its experimental evaluation, are depicted in Fig. 2(a).

The experimental performance evaluation of the flexible filtering element was carried out through the use of a vertical-alignment probe station, employing a fiber array (FA) assembly of 16x Single Mode Fiber (SMF) channels, facet-polished to match the 10° acceptance angle of the TE Grating Couplers (GCs) of the SOI chip. An Erbium Doped Fiber Amplifier (EDFA) was employed serving as a broadband Amplified Spontaneous Emission (ASE) noise source. The filter's spectral response was captured by an Optical Spectrum Analyzer (OSA) whereas an Optical Power Meter was used to monitor the output power levels of the SOI chip and ensure optimum FA-to-chip alignment. The heating wires were controlled through a Direct Current (DC) probe tip. The experimental setup for this type of measurements is depicted in Fig. 2 (b). To perform ER measurements and to overcome limitations imposed by the OSA's noise floor, an alternative experimental approach was introduced (Fig. 2 (c)). A tunable Continuous Wave (CW) laser source was amplified by means of an EDFA and used as a reference input signal at the SOI chip. A Polarization Controller (PC) was set prior to the EDFA to ensure the desired TE-polarization mode of the incident light.

The bandwidth tunability of the filtering element was investigated by utilizing the minimum number of control signals. The filter was set to 12 GHz Full Width Half Maximum (FWHM) by adjusting the green electrodes that control the initial biasing state of MZI (A), MZI (B) and MZI (C). More specifically, for the 12 GHz FWHM filter response achieved, only MZI (A) needed to be biased, with a power consumption of 9.5 mW. By keeping constant the initial biasing state of the three MZIs, a set of different FWHM filter responses was achieved by adjusting the voltage applied to the yellow electrode group (Fig. 1(a)). The filter shapes acquired, varying from 12 GHz to 116 GHz at FWHM, are depicted in Fig. 3(a), whereas the filtering element insertion loss stands below 3.6 dB for all filter shapes.

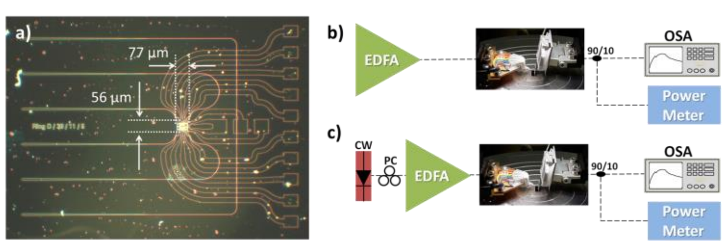

Fig. 2 (a) Fabricated filtering element, and Experimental set-up to evaluate: (b) filter response, and (c) Extinction Ratio values

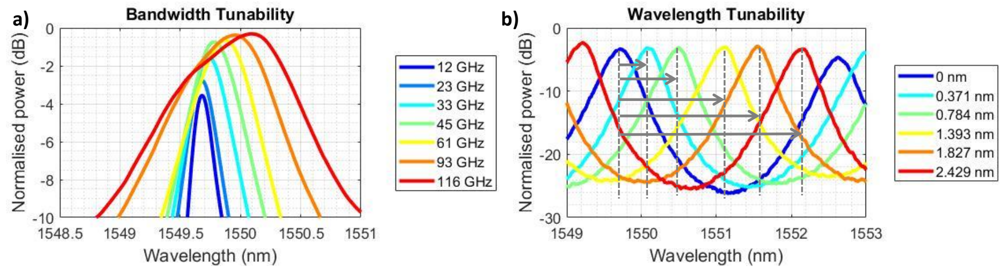

Fig. 3 (a) Bandwidth tunability and (b) Wavelength tunability operation

The next evaluation step focused on the resonance shift of the filtering element, being measured for the filter shape of 50 GHz filter shape. Evaluation results are shown in Fig. 3(b). The initial biasing conditions for the 50 GHz FWHM filter shape required a power consumption of 31.86 mW. Resonance wavelength tunability was achieved by adjusting the applied voltage on the blue electrode group, heating the ring cavities' waveguides. A maximum of 2.429 nm wavelength tunability was achieved, covering all the FSR area, while the filter shape remained practically unchanged.

The quality of the fabricated filtering element as well as its tuning capability was further investigated by measuring the ER values and the Shape Factor (SF) values for various 3-dB bandwidths. The ER values (Fig. 4(a)) were measured with the use of the evaluation set-up depicted in Fig. 2(c). A high value of 37.5 dB ER was measured for the narrowest filter shape, whereas the minimum ER value was found to be 10 dB. The Shape Factor (*SF = 1 dB BW/10 dB BW*) of the transmission band was measured for various FWHM values as depicted in Fig. 4(b). The experimental results are in good agreement with the simulation outcomes, confirming the exceptional fabrication quality of the presented filtering element. The bandwidth and wavelength tunability of the filtering element with respect to total consumed power is depicted in Fig. 4(c), revealing the low power requirements of the structure. Finally, the bandwidth tuning efficiency was found to be 3.95 GHz/mW while the wavelength tuning efficiency was found to be 0.0365 nm/mW.

4. Conclusions

We presented a novel SOI-based filtering element exhibiting 12-116 GHz bandwidth tunability and high ER values of more than 37 dB for the narrow filtering shapes. The use of air trenches between different on-chip control sections allows for ultra-dense integration, high bandwidth tuning efficiency of 3.95 GHz/mW and offers thermally stable operation by alleviating the thermal crosstalk. The reported results denote the strong potential of the SOI ring-based elements as flexible filtering elements in support of elastic optical networking concepts.

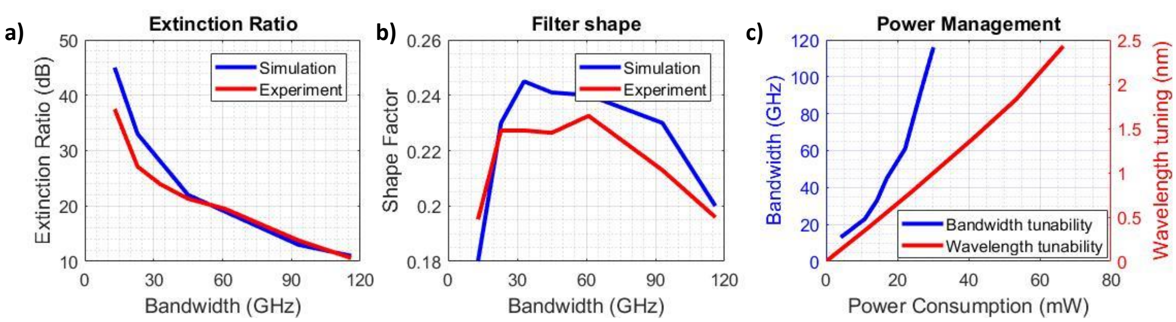

Fig. 4 Simulation and experimental evaluation results varying filter bandwidth, regarding: (a) Extinction Ratio, and (b) Filter shape. (c) Bandwidth and wavelength tunability varying corresponding electrode power consumption

Acknowledgments

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5. References

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