Ultra-compact optical filters in Silicon-on-Insulator and their Applications

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***Abstract*— We present ultra-compact wavelength filters in SOI photonic wires: Mach-Zehnder lattice filters and ring resonators, as well as demultiplexers such as AWGs, and planar concave gratings. We also discuss devices for WDM communication and sensing. The circuits were fabricated with CMOS Technology.**

I. Introduction

Silicon-on-insulator (SOI) photonic wires offer a dramatic reduction in circuit size [1]. While in today's devices building blocks have a length scale of $100\mu m$-$1cm$, using nanophotonic waveguides results in a footprint that is orders of magnitudes smaller. This is possible by using a high refractive index contrast to confine the light. SOI, with a thin Silicon core ($n = 3.45$) on top of a silica cladding ($n = 1.45$) allows for single-mode, submicron photonic wires. The small dimensions require nanometer-precision fabrication, and therefore we used advanced CMOS technology, including deep UV lithography.

We used SOI photonic wires to implement various known types of wavelength filters. These include drop filters based on ring resonators [2] or Mach-Zehnder lattice filters [3], as well as demultiplexers based on arrayed waveguide gratings (AWG) [3] or planar concave gratings (PCG) [4]. The high contrast of SOI resulted in a dramatic reduction in size. The small size and possibilities for mass-fabrication enable a host of new applications for these components.

II. Waveguides, Fabrication and Characterization

Photonic wires function just like conventional index-guiding optical waveguides, but the high index contrast and submicron core has a very strong confinement. Because these waveguides are highly birefringent, all the components discussed here are designed for a quasi-TE polarization only. We have already demonstrated propagation losses as low a $2.4dB/cm$ in straight photonic wires [1], [2]. Bend losses remain manageable for bends with a radius larger than $2\mu m$ [3]. Photonic wires are more dispersive than low-contrast waveguides, with a group index between 4 and 4.7. This is beneficial in wavelength-selective functions, as it results in even shorter delay lines in interferometric structures. However, narrow wires are prone to phase noise due to fabrication imperfections.

For all devices discussed here, we used SOI wafers with a $220nm$ top silicon layer. Fabrication was done with standard CMOS tools: 248nm Deep UV lithography for pattern definition and an ICP-RIE etch for the Silicon core [1]. The devices were characterized using direct transmission measurements. Incoupling and outcoupling into the photonic wires is easily accomplished using grating fiber couplers that couple from a broad ridge waveguide (TE-mode) to a standard single-mode fibre [5]. Coupling efficiency is 33% ($-5dB$).

III. Wavelength-Selective Elements

Depending on the application, one can implement wavelength filters for single-channel drop filters (if necessary implementing one for each channel), or for (de)multiplexing all wavelength channels in a single operation. In this paper, we discuss drop filters based on ring resonators and Mach-Zehnder interferometers, and demultiplexers based on AWGs and PCGs.

A. Arrayed Waveguide Gratings

An AWG is the most widely used integrated device for multiplexing and demultiplexing wavelength channels. As already mentioned, the high group index of photonic wires make it possible to have short delay lines. In addition, delay lines can be organized more efficiently thanks to the short bend radius. Fig. 1 shows an AWG from [3] with $16 \times 200GHz$ channels. To reduce the crosstalk due to phase noise in the narrow photonic wires we have broadened the waveguides in the long straight sections [3]. At the interface of the photonic wires and the slab region, reflections are suppressed by broadening the wires and reducing the lateral index contrast with a local shallow etch [3]. The Free Spectral Range (FSR) is $25.6nm$ and the footprint $500 \times 200\mu m^2 = 0.1mm^2$. Crosstalk is $-20dB$ and the insertion loss is $2.2dB$ for the center ports.

B. Planar Concave Gratings

The PCG is the other widely used technique to implement a demultiplexer. A PCG combines the function of a flat diffraction grating with that of a focal lens. The wavelength channels from the input waveguide are separated by the grating and focused onto the aperture of different output waveguides. Figure 2 shows a PCG from [4]. The output waveguides are spaced only $5\mu m$ apart. The grating period is $4.35\mu m$, with 31 facets (inset in Fig. 2) [4]. The entire device has a footprint of only $280 \times 150\mu m^2$. As with the AWG, the interface between the waveguides and the slab region is implemented with a shallow etched waveguide to reduce reflections. The device has 4 channels with a $20nm$ spacing, and a very low crosstalk

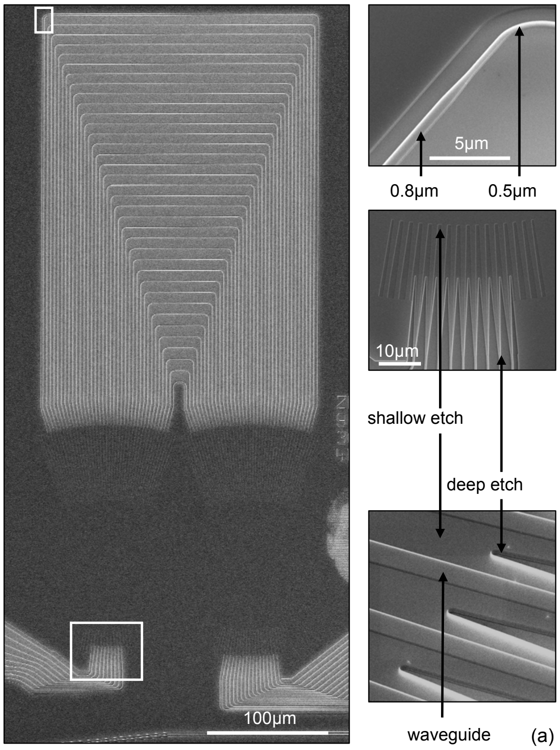

Fig. 1. Arrayed waveguide grating with $16 \times 200GHz$ channels from [3]

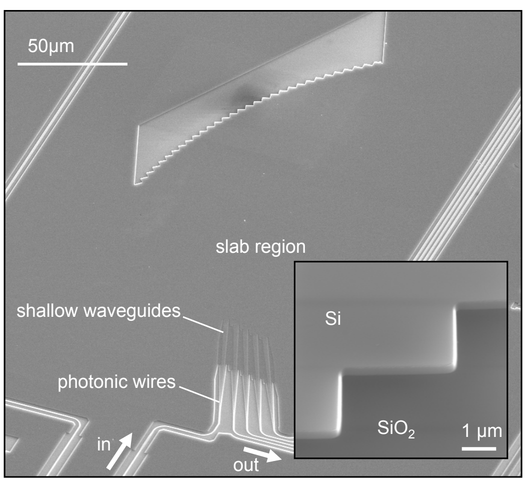

Fig. 2. Planar concave grating from [4].

better than $-30dB$. Insertion losses are high at $7.5dB$, mainly due to the limited reflectivity of the grating facets, at only 35%.

C. Mach-Zehnder Lattice Filters

A Mach-Zehnder lattice filter (MZLF) is constructed as a series of Mach-Zehnder interferometers with a constant path-length difference but with varying coupling ratio. The coupling ratios can be optimized for the desired filter spectrum (e.g. Chebychev-like with low sidelobe levels). Figure 3 shows an example of a 5-stage MZLF with 6 directional couplers and 5 delay sections [3]. The filter has a bandwidth of $2.6nm$, an

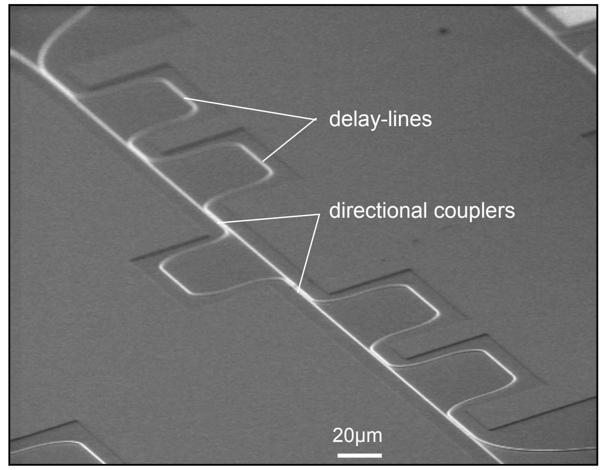

Fig. 3. A 5-stage Mach-Zehnder lattice filter from [3].

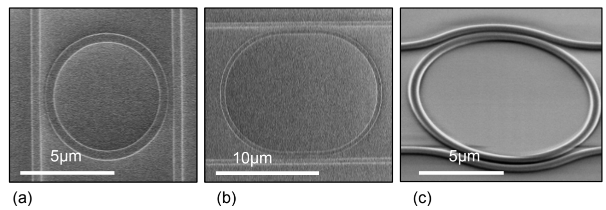

Fig. 4. Ring resonators from [2], [3], [6]. (a) Circular ring resonator, $3\mu m$ bend radius; (c) racetrack resonator with a $6\mu m$ bend and a $3\mu m$ coupling section and (c) bend-coupled ring resonator with a $5\mu m$ bend radius.

FSR of $17nm$ and nearly 100% coupling efficiency. Crosstalk in this example is $10dB$ and is caused by a non-optimal coupling ratios and phase errors in the delay sections. As in the AWG, improvements are possible using broadened wires.

D. Ring Resonators

Ring resonators with two access waveguides can be used as a channel drop filter. In photonic wires, the sharp bends allow for very compact rings, resulting in a large FSR. Reliable fabrication of such devices is challenging however. We have demonstrated ring resonators with a radius between $1\mu m$ and $8\mu m$ [2], [3], [6], and various coupling geometries (Fig. 4).

In the circular resonator (Fig. 4a), the waveguide couples to the ring over a very short distance. With $200nm$ waveguide spacing the coupling is very weak. Using a straight coupling section (Fig. 4b.) dramatically improves the coupling efficiency. Examples in [2], [3], [5], [6] demonstrated various resonators with Q-values between 3000 and 12000 and drop efficiencies near 100%, but at the price of a larger resonator, and thus a smaller FSR. To improve the coupling efficiency of a ring without adding length to the resonator, one can use a bent waveguide (Fig. 4c.) By carefully designing the width of the resonator and the access waveguide, good phase matching is possible and high coupling efficiencies can be achieved.

IV. Applications

Wavelength-selective elements can be used for a number of different applications. The most obvious is in WDM systems, where (de)multiplexers are required wherever signal processing on the individual channels is needed. One can also implement wavelength-based routing with such element. The PCG from [4] shown above could be used as a 4-channel demultiplexer in a coarse WDM network, where $20nm$ channel spacing is common.

SOI photonic wires allow for extremely compact (and therefore cheap and lightweight) components. The last aspect is important for instance in space applications. In [7] a 4-channel wavelength routing backplane based on SOI Photonic wires is presented. The routing device itself measures only $0.1mm^2$, which allows for the entire component to be glued directly to a fiber connector. The low cost of the technology (which basically can rely on an installed base of CMOS foundries) is the use for mass-market applications, like fiber-to-the-home (FTTH) networks. In [8] a compact wavelength duplexer is used for an FTTH access point. By using a polarization-diversity approach, the entire component is transparent with respect to the fiber polarization, even though the photonic wires on the chip only function for a single polarization.

Single-channel drop filters can be used for splitting of an entire wavelength channel, other applications could include wavelength monitoring. Here low coupling efficiency can be an advantage. However, there are many other applications. Optical sensors based on wavelength response are becoming an increasingly important field. Typically, such sensors rely on the fact that the effective or group index of the waveguide is modified by an environmental factor, such as mechanical stress, temperature or the composition of the waveguide or cladding material. Especially the latter property is interesting. While SOI photonic wires have a strong confinement, there is still about 20% of the light present in the top cladding of the waveguide (either air or an overlay material). With a ring resonator, it becomes possible to measure index changes smaller than10^{-4}, which can be used to measure e.g. changes in salt concentrations as small as 0.05% in a water top cladding [9]. This principle can also be used for the sensing of biomolecules; a field that is gaining interest due to its applications in many areas such as bacterial and virus detection, medical diagnostics, drug development, food and environmental control. In such miniaturized label-free biosensors the light can feel the change in the top cladding when biomolecules attach to a chemically functionalized layer above the resonator [10]. Combined with these wavelength selective sensors, demultiplexers could be used to implement extremely compact spectrometers.

V. Conclusion

We have discussed a variety of ultra-compact wavelength-selective elements in silicon-on-insulator photonic wire. Photonic wires allow for sharp bends and a high group index, but they make wavelength-selective devices prone to phase noise. To alleviate this problem in AWGs, we broadened the waveguides in straight sections with dramatic improvement in the crosstalk. This technique could also be applied to the MZLF. All devices show a considerable reduction in size with respect to their counterparts in low-contrast material systems. In addition, the use of SOI brings in the advantage of manufacturability in existing CMOS foundries.

While these components are not yet showing the same performance as todays's commercial WDM components, their small size and potentially low cost can be exploited for other applications. We have discussed some examples like coarse WDM networks and FTTH access networks, as well as sensing for environmental and biomedical applications.

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