SOI Photonic Wire Based Components with Compact and Efficient Fiber Couplers

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Abstract: We present compact wavelength selective functions based on SOI photonic wires, like AWGs, Mach-Zehnder filters and ring resonators, fabricated with CMOS processes. We couple to single-mode fiber with grating couplers, which also allow polarization-independent behaviour.

OCIS codes: (130.0130) Integrated Optics, (130.1750) Components , (230.3120) Integrated Optics Devices

1. Introduction

Silicon-on-Insulator (SOI) nanophotonic circuits will play a strong role in large-scale photonic integration [1]. Today's commercial integrated optic devices are typically based on low refractive index contrast and as a consequence the relatively large dimensions allow to integrate only a few functions on a chip. The high index contrast of SOI (3.45 to 1.45) increases confinement, but requires a submicron waveguide core for single-mode operation. With these so-called *photonic wires*, very compact wavelength-selective elements become possible. However, the photonic wires need to be made with an accuracy of 1 to 10nm. The high index contrast makes the waveguides very sensitive to perturbations, so we need high-quality fabrication tools. For this work we used deep UV lithography, as used for advanced CMOS fabrication [1].

Photonic wire waveguides can be used to implement a number of functions in a very compact way. In this paper we will demonstrate a number of wavelength-selective functions, similar to those used in today's WDM optical fiber links. Where wavelength channels need to be combined or separated one needs wavelength selective elements, either single-wavelength filters or all-out (de)multiplexers, like Arrayed Waveguide Gratings (AWG). In today's low-index-contrast materials an AWG easily uses many cm^2, making it difficult to add more functionality. Photonic wires dramatically reduce the required real-estate.

One of the main obstacles for nanophotonic waveguides is the difficulty to couple to standard optical fibre. The large mode mismatch makes an efficient mode converter necessary. We use a coupler based on a diffraction grating, enabling alignment-tolerant access, wafer-scale testing and polarization insensitive operation of the photonic IC [3].

2. Photonic Wires

Photonic wires are optical waveguides with a submicron core and a high index contrast. We use a core thickness of 220nm with a width smaller than 580nm for single-mode operation at 1.55µm wavelength. Currently, all our components are exclusively designed for TE-polarized light. Dispersion is higher than low-contrast waveguides [6], but lower than that of many photonic crystal waveguides. Depending on the waveguide width, the group index lies between n_g=4 and n_g=4.7. This high group index is attractive in interferometric structures, but the narrow wires are more susceptible to width fluctuations, resulting in phase noise in delay lines.

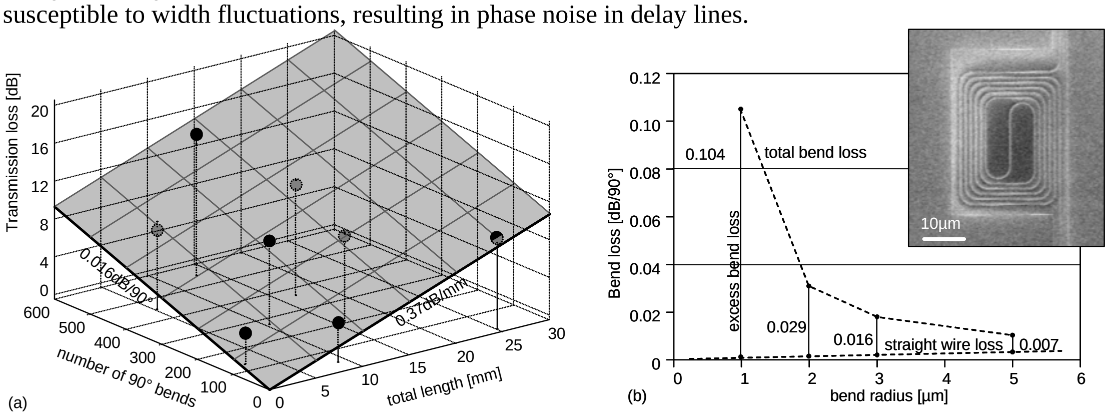

Fig. 1. Bend losses in photonic wire waveguides. (a) transmission of various spiral waveguides with a 3µm bend radius (SEM picture in inset). (b) extrapolated bend losses of spirals with different bend radius.

In straight photonic wires, we have demonstrated propagation losses as low as 2.4dB/cm [1][7]. We have also studied bend losses using large spiral waveguides (inset in Fig. 1b) with sufficient length (up to 50mm) and number of bends (up to 550 bends). From Fig. 1a, which shows the transmission for spirals with a 3µm bend radius we can extract the propagation loss and the excess loss per bend. As can be seen in Fig. 1b the excess bend losses increases dramatically for sharper bends. For a 5µm 90° bend, the losses are lower than 0.01dB/bend.

3. Wavelength-Selective Elements

Due to the high group index of photonic wires and the tight bends, a dramatic reduction of passive wavelength-selective elements can be obtained. One can implement small resonant cavities for channel drop filters with a large free spectral range (FSR), or use interferometric filters with compact delay lines. This is also the case for arrayed waveguide gratings (AWG) [8]. In Fig. 2a we demonstrate an AWG with 16 channels spaced at 200GHz, resulting in a 25.6nm FSR [8]. The device itself fits in a 200µm × 500µm area [10]. To ease the coupling between the photonic wires and the slab region, the star coupler is implemented in a lower-contrast shallow etch [9]. The transition between photonic wire and lower-contrast waveguide is made in a 15µm long taper. Alignment accuracy between the deep and shallow etch is about 50nm and guaranteed by the optical lithography. This double-etch scheme keeps the insertion loss of the device below 3dB for the center wavelength channels. The transmission of the 16 output channels is plotted in Fig. 2b. Because the photonic wires in the delay lines are susceptible to phase noise due to non-uniformities and variations in the delay line geometry, we have broadened the waveguides to 800nm in the straight sections. While this makes the waveguides multimode, we narrow them down to single-mode width for the bends. This lowers the crosstalk floor to -20dB for the center channels.

Apart from AWGs, we have also implemented compact wavelength drop filters, based either on ring resonators [7][10] or Mach-Zehnder lattice filters [10].

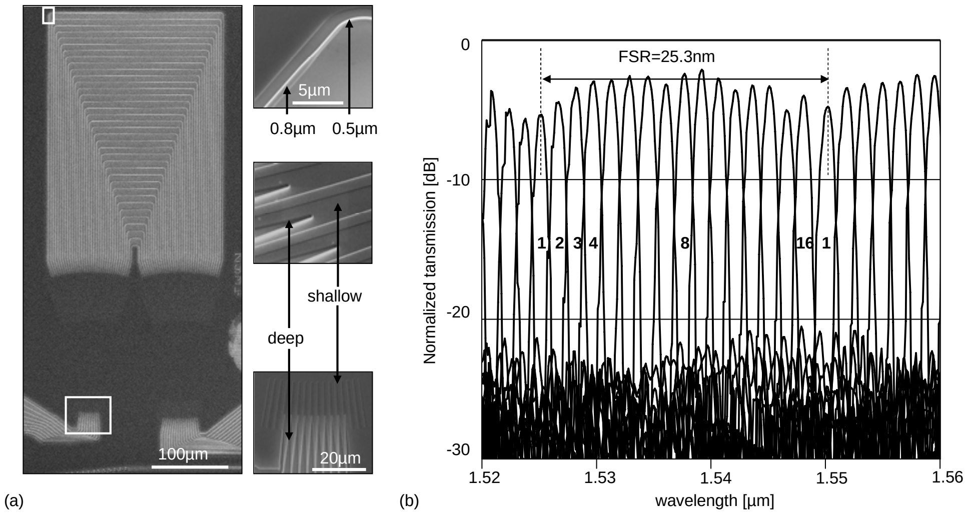

Fig. 2. Arrayed Waveguide Grating with 16 × 200GHz channels. (a) SEM view. The device has a footprint of 200µm × 500µm. (b) Overlaid transmission spectrum of the 16 output channels.

4. Coupling to Fiber

Due to the large mode mismatch between a single-mode fiber and a SOI photonic wire, a spot-size converter is required to achieve efficient coupling. We use a diffraction grating to couple light from an out-of-plane fiber to a planar SOI waveguide. The grating pitch is 630nm. The depth of the grating is approximately 70nm for the SOI layer structure we used. The grating couples light from a fiber into a wide (10-12µm) waveguide. To couple light from this wide waveguide to a photonic wire, an adiabatic taper is used. Alternatively it is possible to used curved focusing gratings that focus the incoming light into a photonic wire. The advantage of the curved grating is the smaller footprint compared to a straight grating combined with an adiabatic taper.

Simple SOI couplers have a coupling efficiency of >30% and a 1-dB bandwidth of approximately 40nm but we have demonstrated that this efficiency can be increased to almost 70% by extra processing steps and more sophisticated designs. We expect that further improvements are possible while remaining CMOS-compatible. [12]. The grating couplers allow wafer-scale testing, because light is coupled in and out from the top surface of the wafer. They are also suitable for coupling large arrays of fibers to one chip. In [5], a 1x8 fiber array consisting of fibers in V-grooves was used to demonstrate a 4-by-4 wavelength router. The ferrule is glued or bonded directly to the SOI chip, no polishing steps and no lenses are needed.

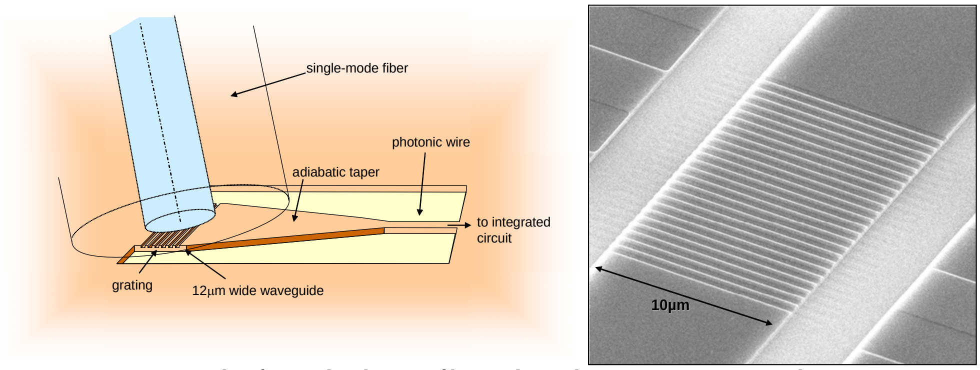

Fig. 3. Grating couplers for coupling between fibers and SOI photonic wires : concept and SEM picture.

The grating couplers and also the SOI components and circuits are polarization dependent. The presented structures require TE-polarized light. To solve this polarization problem, a polarization diversity configuration can be used. Using a 2-D grating as a polarization splitter **Error! Reference source not found.**, it is possible to integrate the required components for a polarization diversity circuit on the same SOI chip. In this way, we have recently demonstrated wavelength-selective elements (AWG) in SOI that are polarization insensitive, using 2-D grating couplers with 21% efficiency [11].

5. Conclusion

We have demonstrated wavelength-selective elements based on low-loss photonic wire waveguides. As an example, we showed an 16-channel AWG with 3dB insertion loss and better than -15dB crosstalk. For easy characterisation, we make use of high-efficiency grating fiber couplers. Not only do these allow for wafer-scale testability, but using a polarisation-diversity approach a polarization-insensitive device becomes possible.

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