Silicon Nanophotonic Waveguide Circuits and Devices

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***Abstract*—Silicon on Insulator is an ideal platform for large-scale nanophotonic integration. We show that tight process control is needed for well-functioning filters, and discuss a number of devices based on these filters.**

I. Introduction

Silicon on Insulator (SOI) has already proven itself as a very suitable material for integrated photonics [1]. Not only because of the high refractive index contrast, which allows for submicron waveguides and sharp bends with radii of $3\,\mu m$ or less [2], but also because the material can be processed with the same tool set as used for electronics manufacturing. This combination, a small footprint and an a potential industrial manufacturing base, gives silicon photonics the scalability needed for low-cost, large-volume applications.

We use these photonic wires to implement a variety of wavelength-selective components. These include ring resonators, but also arrayed waveguide gratings scaled to very small footprints. However, the submicron dimensions of the photonic wires make these filters exceptionally sensitive to process variations. While in the end there will always be the need for a tuning mechanism, good process control can already bring the device very close to its desired specification. This, in turn, reduces the power consumption required for tuning. We show that this is possible with classical CMOS technology. Finally, we also discuss a number of device concepts which can only become viable through SOI nanophotonics, because of cost and volume considerations.

II. Passive wavelength-selective components

The high contrast photonic wires in SOI allow for very sharp bends, which in turn reduces the footprint of many common waveguide components. Because of that, wavelength selective elements such as ring resonators can be made very compact, thus they can have a very large free spectral range [2]. Also, the relatively strong dispersion of photonic wires (n_g 4.0) allows for shorter delay lines. This, in combination with acceptable propagation losses of a few dB/cm [3], [1], makes photonic wires ideal to construct wavelength selective components.

A result of this is shown in Fig. 1. This $8 \times$ 400GHz arrayed waveguide grating (AWG) has a footprint of only $200 \times 350\,\mu m^2$. Because of the tight process control (discussed in the next section) the path length difference in the arms is well controlled, resulting in a low crosstalk level of $-25\,dB$; the lowest reported in a demultiplexer device of this size with a similar channel spacing. Also, by using a combination of deep and shallow etch layers [2], the insertion loss of the entire AWG is only $1.1\,dB$.

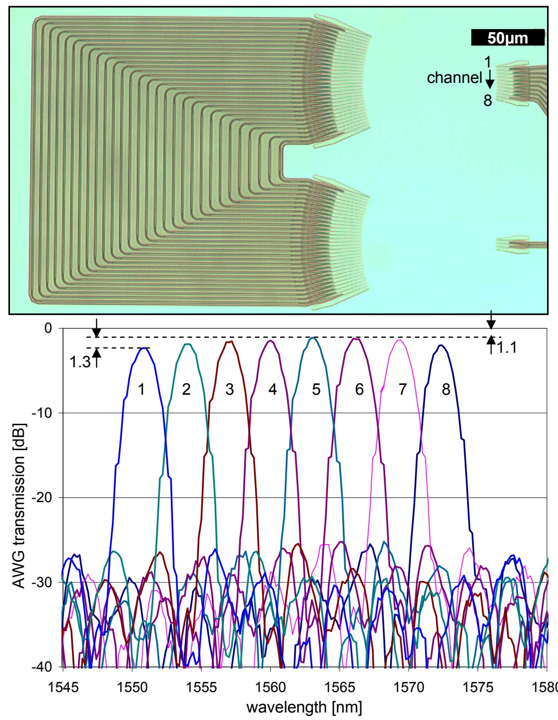

Fig. 1. Compact 8-channel arrayed waveguide grating

III. Process Control

With waveguide dimensions of $500\,nm$, photonic wires fall well within the fabrication capabilities of high-end CMOS manufacturing tools. However, the fabrication tolerances of photonic components are much more strict that for electronics, where margins of 5% or 10% are acceptable. For wavelength-selective filters, a deviation of waveguide width of $1\,nm$ will correspond to approximately $1\,nm$ wavelength shift. While such a shift can be compensated for by thermal or other tuning mechanisms, the acceptable tolerances are still of the order of 1%. However, we have demonstrated that with reasonable process control, these tolerances can be met with standard CMOS fabrication tools [4].

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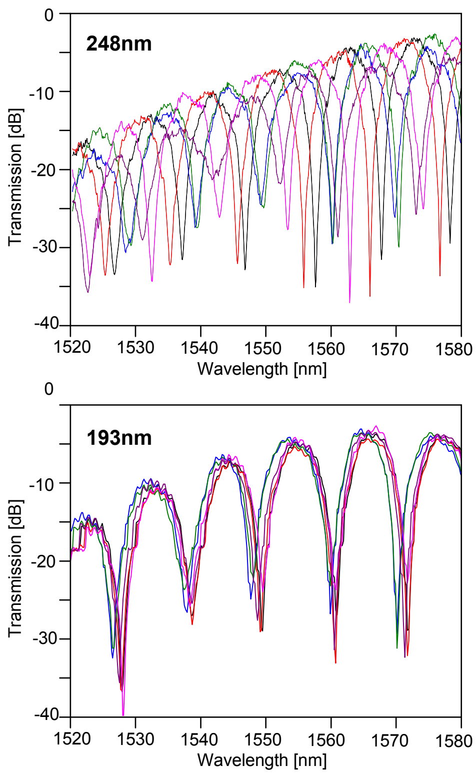

Fig. 2. Transmission of 6 nominally identical Mach-Zehnder interferometers. Top: made with $248\,nm$ deep UV lithography. Bottom: with $193\,nm$.

One of the critical steps in the fabrication process is the lithography. While for research purposs e-beam lithography is attractive for its flexibility and high resolution, we make use of standard CMOS tools, based on optical projection lithography at deep UV wavelengths ($248\,nm$ and $193\,nm$). The resolution of these tools is typically less than that of high-end e-beam lithography, and this is not only reflected in final device geometry, but also in the uniformity and reproducibility of the fabrication process. This is illustrated in Fig. 2, where we plotted the transmission of 6 nominally identical Mach-Zehnder interferometers on a single chip. The design was fabricated from the same mask plate both with $248\,nm$ and $193\,nm$ lithography. It is clear that the highest resolution process gives the best uniformity, with deviations of the transmission dip wavelength of approximately $1\,nm$.

IV. Photonic wire devices

Wavelength-selective components can be used for various applications. In communications, wavelength division multiplexing is the obvious candidate, and in its simplest form, a very low-cost duplexing system based on SOI photonic waveguides could drive wide deployment of fiber access networks [5]. The WDM principle could also be applied for wavelength routing of high-speed signals between chips or boards in high-performance computing systems [6]. When used together with fiber arrays, the actual chip of the routing backplane, has a smaller footprint than the connector, allowing for an elegant packaging approach [7].

The sharp wavelength response of a ring resonator can also be applied for optical sensors. The group index of the waveguide can be changed modified by an outside influence, such as mechanical stress, temperature or the presence of specific molecules in the cladding material. Especially the latter property is interesting. In SOI photonic wires, about 20% of the optical power is located in the top cladding of the waveguide (either air or an overlay material). With a ring resonator one can measure index changes smaller than 10^{-4}. In addition, by chemically activating the surface of the ring the sensor can be made extremely sensitive to specific biomolecules, which enables bacterial and virus detection. 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 [8].

V. Conclusion

SOI Photonic wires allow for very compact wavelength selective functions, which can be used in a variety of devices, from telecommunications to biosensing. Modern CMOS fabrication technologies now allow sufficient process control to meet the strict tolerances required for such applications.

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