Low-loss photonic wires and compact ring resonators in silicon-on-insulator

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We demonstrate low-loss, single-mode photonic wires in silicon-on-insulator as an enabling technology for future dense photonic integrated circuits. These waveguides are defined with 248nm deep UV lithography and have losses as low as 2.4dB/cm for a width of 500nm at 1550nm wavelength. Bends and directional couplers are fabricated and used to build ring resonators with 5μm radius, Q-factors higher than 3000 and insertion loss of around 2dB. The experimental results show clear agreement with a theoretical model of the resonators. We analyze the fabrication tolerances allowed for these resonators to be suitable as a building block for WDM filtering components.

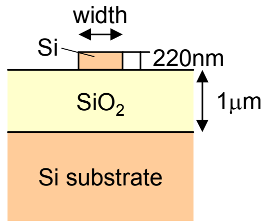
Introduction

In order to increase the integration scale of photonic IC's several orders of magnitude above today's level, waveguiding technologies using a high in-plane index contrast can be used. These allow for very compact bends and structures, both for interconnecting and building functional elements on an IC. So-called photonic wires are wavelength-scale index confined waveguides with a high in-plane index contrast achieved by etching through the guiding layer. We have fabricated photonic wires in silicon-on-insulator using deep UV lithography (DUV) [1]. Silicon-on-insulator (SOI) is an attractive material system for waveguiding, and it allows for exploring the possibilities of volume fabrication technologies already widely used in the CMOS world, such as deep UV lithography. The major loss mechanism in this type of waveguides is scattering at sidewall roughness [2]. As it is well-known that scattering losses in traditional index-confined waveguides increase with index contrast, sidewall roughness was one of our major concerns.

Photonic wires

The waveguide cross-section is illustrated in figure 1. The silicon core is separated from the substrate by a silica cladding. By etching only through the silicon layer, we were able to keep the sidewall roughness within bounds. No additional roughness reduction method like thermal oxidation [3] was applied. Such a method could be applied, but care should be taken of the final waveguide width and the mode confinement.

We measured the transmission spectrum of a cavity formed by 2 cleaved facets in a 3μm wide waveguide. In the middle of the cavity, the waveguide was tapered down to a photonic wire using an adiabatic taper. Cavities with different lengths of photonic wires were measured. From the Fabry-Pérot transmission spectrum we could then extract the total cavity loss. When plotted on a logarithmic scale as a function of length, the propagation loss of the photonic wires can be extracted from the slope of the fitted straight line. This is illustrated for a photonic wire of 450nm width in figure 2.



width	propagation losses	loss/taper*
400nm	33.8 ± 1.7 dB/cm	0.27 dB
450nm	7.4 ± 0.9 dB/cm	0.22 dB
500nm	2.4 ± 1.6 dB/cm	0.19 dB

Figure 1: SOI photonic wire structure with losses as calculated from the Fabry-Perot transmission spectrum

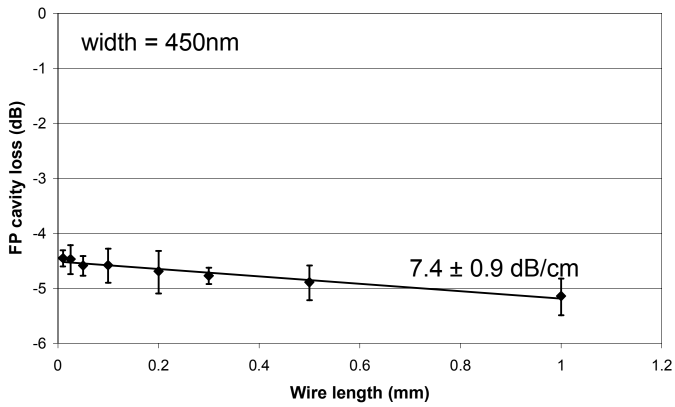


Figure 2: Total Fabry-Pérot cavity loss (dB) for cavities with photonic wire 450nm wide with different length at 1550nm wavelength. The wire loss can be extracted from the slope of the fitted line. The sum of facet reflection and loss of the tapters can be calculated from the intercept. Fron this, we estimate an upper boundary for the loss per taper, given in figure 1.

We find that the propagation losses decrease exponentially for broader wires. This is in agreement with sidewall roughness as the primary loss mechanism. For a 500nm wide wire, which is still a single-mode waveguide, we have measured a propagation loss of 2.4dB/cm at 1550nm wavelength. For this waveguide, 76% of the light is confined within the core, making it suitable for compact bends. We can also make an estimate of the taper losses, by replacing the facet reflection by its theoretical value as an upper boundary. This gives an upper boundary of 0.19dB for the loss of a 200µm long taper from 3µm width down to a 500nm wide wire.

Bends and corner mirrors

We fabricated double bends width several radii and angles and measured the excess loss of a bend. Because of the low losses, an anti-reflective coating was evaporated onto the facets to avoid Fabry-Pérot oscillations in the output spectrum. For a bend with a radius of a few µm, the loss is in the 1 dB range. For a 90º bend with 15µm radius, the excess loss is around 0.5 dB.

An alternative to a smooth bend is a more abrupt corner facet serving as a mirror [4], illustrated by figure 3. Due to the high out-of-plane index contrast, mirror orientation is rather uncritical. The measured excess loss of a 60º mirror is around 1dB, as shown by the transmission spectrum in figure 4. The mirror region was designed 100nm wider than the waveguides. Further widening resulted in higher excess loss, which is in agreement with [4], [5].

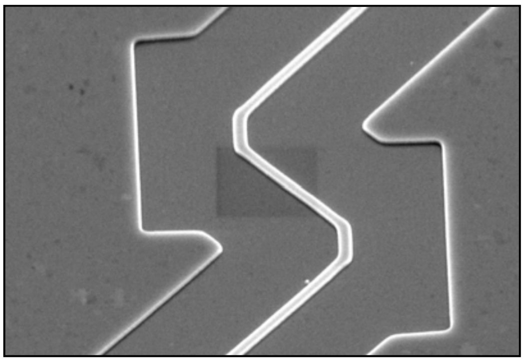


Figure 3. SEM picture of a double bend with mirror –like bends

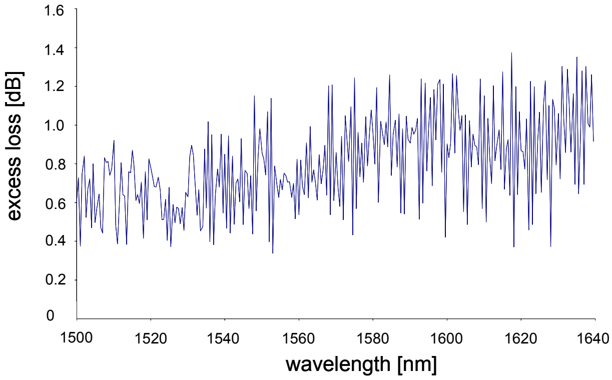


Figure 4. Excess loss of a mirror bend from figure 3. The oscillations are due to the non-optimal AR coating

Ring resonators

Resonators can provide building blocks for a large number of functional components on a photonic IC. We fabricated ring and so-called racetrack resonators using low-loss photonic wires. The coupling from the ring to the in- and output waveguides is identical.

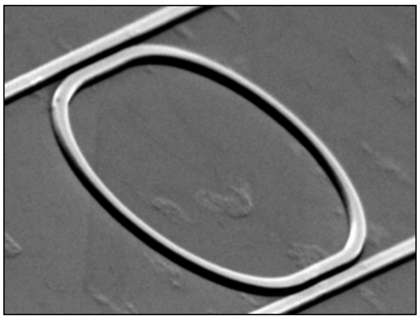


Figure 5. SEM-picture of a racetrack resonator with 5μm radius and 3μm straight section.

We measured the transmission spectra of both output ports and fitted the experimental data to the theoretical model of the ring resonator to extract the physical properties of the structures such as waveguide group index and coupling coefficients. The obtained group index of the waveguides is around 4.7, showing the large waveguide dispersion.

The cavity loss is not only caused by the loss of the bent waveguide: in the coupling regions, the waveguides are smaller due to optical proximity effects of the deep UV lithography [2]. This causes the wires to taper non-adiabatically near the coupling regions. A second effect is the lower confinement in the coupling region, leading to higher scattering at sidewall roughness (as well as better coupling). These effects make the Q factor of the resonator loss-limited.

By exploiting the possibilities of the deep UV fabrication method, we were able to experimentally verify the influence of coupler spacing, waveguide widths and waveguide loss. The Q factor increases with coupling strength between the ring and the waveguides. The coupling should not be chosen too low however, to limit add-drop crosstalk. Figure 6 shows the normalized transmission spectrum of a racetrack resonator with 5μm radius (figure 5), and a coupling factor of about 0.3, which is fairly optimal, leading to a finesse of over 30 (Q>3100). This resonator has a free spectral range of 13.7nm, a FHWM of 0.5nm and an add-drop crosstalk of around 20dB. By including optical proximity corrections in the DUV mask design, the extra losses in the ring can be lowered and the finesse will rise.

When used as part of a WDM filter, the FWHM is sufficient to tolerate some channel wavelength variation. Measurements and calculations show that a 5% deviation on the gap and waveguide widths in the coupling region can be tolerated without too much influence on the cross-talk figures. However, small resonators are well-known to have very tight fabrication tolerances when it comes to controlling the resonance wavelength. Our measurements confirm that the group index and therefore the resonance wavelength change drastically (0.2% - 0.8%) with a small change (1%) of waveguide width.

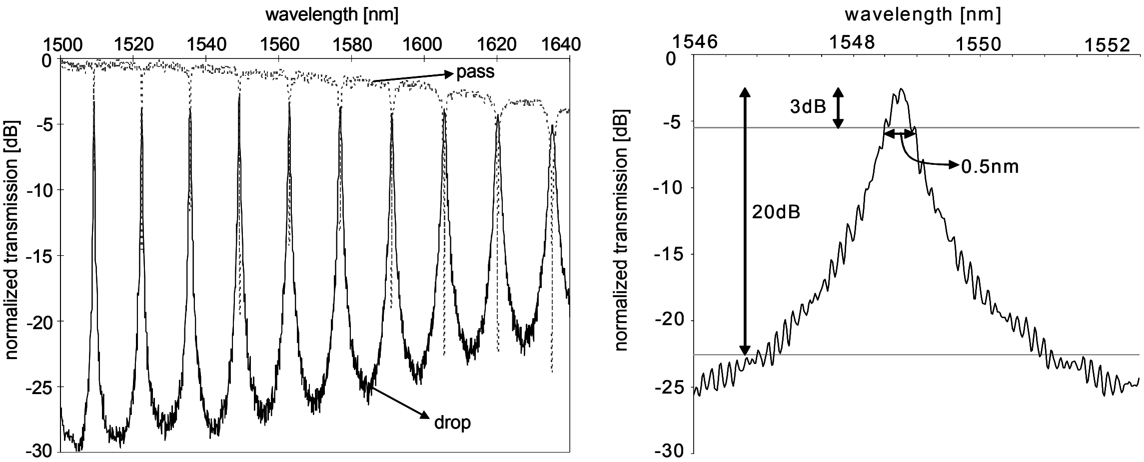


Figure 6. (left) transmission spectrum of pass port (dotted line) and drop port (solid line) of the racetrack resonator in figure 5 (right) detail

Conclusion

We fabricated low-loss (2.4dB/cm) single-mode photonic wires in silicon-on-insulator suitable for realizing highly integrated structures and on-chip interconnects. Ultra-sharp bend structures have an excess loss of about 1dB. We fabricated ring and racetrack resonators with high quality factors. Tight control over the optical length of the cavity is needed however for these resonators to be suitable for real-life applications.

References

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