Record Low-Loss Hybrid Rib/Wire Waveguides for Silicon Photonic Circuits

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Abstract: We report a very low-loss hybrid silicon waveguide circuit consisting of straight rib sections with a propagation loss of 0.272±0.012 dB/cm and compact photonic wire bends of 5µm radius with a loss of 0.0273±0.0004 dB/90°bend.

I. Introduction

Propagation loss of photonic wire strip waveguides is considered as one of the key figures of merit in silicon photonic circuits. Deeply etched photonic wire waveguides are preferred for their high modal confinement, which allows micrometer-scale bends for compact waveguide circuits. Low loss and compactness is vital for many applications, including optical delays lines and non-linear applications. However, a major disadvantage of photonic wire strips is their large propagation loss, mainly due to scattering from sidewall roughness. The best stepper-fabricated wires demonstrated have losses larger than 2 dB/cm and with e-beam fabrication it is 1 dB/cm [1].

Low-loss waveguides have been demonstrated using aggressive oxidation of silicon, but this either results in very small guiding cores (and thus weak confinement) or large oxidized claddings which limit the waveguide layout on the chip (e.g. difficult to make directional couplers or ring resonators) [2].

A solution would be to use wires where they are useful (e.g. sharp bend sections) and use a waveguide with lower propagation loss elsewhere (e.g. long straight waveguides). The propagation loss of silicon waveguide could be reduced by going to cores with larger mode sizes, but this typically requires quite long mode converters. It has been shown that low-loss (0.35 dB/cm) waveguide circuits can be achieved by multimode straight and single mode bends [3] .

Alternatively, one can switch from a wire strip waveguide to a shallow-etched rib waveguide: The propagation loss can be significantly mitigated by reducing the modal overlap between the mode and the sidewall, while still keeping the mode size quite small. However, the small lateral index contrast makes small microbends difficult [4].

In this paper, we demonstrate a low-loss single-mode hybrid waveguide using shallow-etched rib straight sections and a narrow photonic wire strip bend sections connected by a short tapered mode converter.

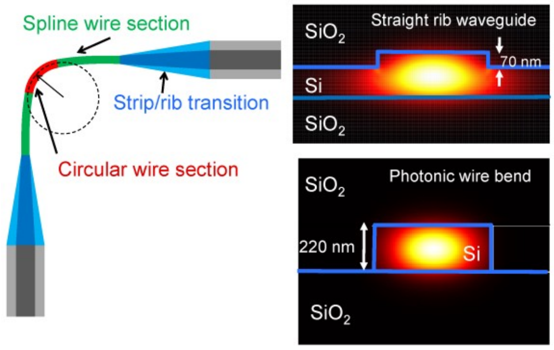

Fig. 1. Schematic of the implemented waveguide circuit with shallow-ridge straight section and deep etched photonic wire bends with the fundamental mode profiles.

This configuration takes advantage of low propagation loss in the straight section and compactness of photonic wire bends. Furthermore, the entire fabrication process was done in the 200 mm complementary metal-oxide-semiconductor (CMOS) fabrication line of *imec*, Belgium. This shows that the present technology can deliver good performance for silicon photonic circuits without any post-processing.

II. Design of low-loss compact waveguide

In high contrast waveguides, sidewall effects are the most important contributors to loss. In single-mode strip waveguides the field intensity on the sidewall is especially high due to the discontinuities of the electric field. In rib waveguides it is possible to laterally confine the light using only a shallow etch, which leaves much less sidewall exposed to the light. The transition of rib to strip consists of a 15 µm long linear tapering of the deep-etched waveguide, with a slower tapering of the shallow-etch waveguide core. This is shown in Figure 1.

The wire bend itself is also optimized to reduce the loss. Even in high contrast waveguides there is a small mismatch of the mode profile between the bend mode and the straight mode, resulting in losses and reflections. While this problem can be solved using an offset in low-contrast systems, this is difficult in wires, as the required offset is of the order of nm. Instead, we replaced the abrupt straight-bend transition with a cubic spline section covering 20° on each side of the bend. The curvature of both ends of the spline is matched to that of the straight waveguide (zero curvature or 'natural') and the bend radius of 5µm, respectively. The middle 50° consists of a circular arc segment with the same radius. The addition of a spline adds somewhat to the footprint of the bend, depending on the angular coverage of the spline. For a 5° this is only 20%, but when we cover the entire bend using a complete natural spline (with the same minimum bend radius) the footprint of the bend becomes almost 4 times larger than a circular bend with the same radius.

III. Fabrication

The designed circuit was fabricated in a 200 mm SOI wafer consisting of 220 nm of silicon on top of 2000 nm of buried oxide layer. Fabrication of the hybrid waveguide was done in two patterning steps. The patterns were lithographically defined in a 330 nm thick photoresist using a PAS5500/1100 Deep-UV scanner operating at 193 nm optical. First the shallow-etch structures were defined, including the grating fiber couplers which are used for characterization. For this, 70 nm of silicon is etched by using a dry etch process. Next, the photonic wire structures are lithographically aligned to the previously defined shallow etched structure. High alignment accuracy (≤12 nm) of the 193 nm optical scanner allows good alignment between the two layers, which is crucial to avoid the mode mismatch between the shallow rib waveguide and photonic wire bends. During optical lithography the exposure dose was swept from east to west over the wafer, resulting in varying waveguide widths for the deep-etched wires. The shallow-etched structures were not varied. After lithography, the pattern in the photoresist is transferred by using chlorine and bromine based etch chemistry [5]. After patterning, the wafer was then covered with silicon dioxide as a top cladding by using plasma deposition. No additional post-processing (e.g sidewall oxidation, chemical passivation) was done on the fabricated structures. After cladding deposition, individual chips were cleaved from the wafer for optical characterization.

IV. Measurement results and discussion

We characterized the propagation and bend loss of the hybrid waveguide by measuring the transmitted power through 4-16 cm long spiral waveguides with 34-456 number of wire bends. Light from a broadband light source is coupled into the waveguides from a single-mode fiber using grating couplers. This allows reproducible and alignment-tolerant coupling. The transmitted light is coupled back to a second fiber and fed into an optical spectrum analyzer. All the measurements were for TE polarized light between 1500 and 1580nm.

Figure 1 shows the transmission plotted against the shallow-rib waveguide length and number of bends. The waveguide and bend loss is extracted by fitting a 2D-plane to the 9 measured data points. From the fitting, we extracted a propagation loss of 0.2718±0.012 dB/cm propagation loss for the straight shallow rib waveguide and a bend loss 0.0273±0004 dB per 90°bend. This bend loss includes all contributions from the bent waveguide itself as well as the transition sections. To our knowledge, this is the lowest loss reported for an etched single-mode waveguide in a 'thin' SOI substrate.

As mentioned in section III, we varied the exposure dose over the wafer for the patterning of the strip waveguides, so we end up with a variation in wire widths. Table I summarizes the propagation and bend loss for different wire waveguide widths. It can be clearly seen that the bend loss increases with decrease in photonic wire width, which can be attributed to a decrease of modal confinement in the wire. This in turn increases in radiation loss in the bends, but most likely also the transition loss in the taper. As the shallow-ridge waveguide width was kept constant, the propagation loss did not change significantly.

In order to discriminate the bend loss from the taper loss from the total bend loss, and to study the effect of the natural spline section, we characterized the bend loss by measuring the transmission through a set of photonic wire spirals with a fixed length of 2.3 cm – but a variation in the number of bends from 18 to 387, and with bend radii of 2, 3 and 4.5 µm. The spline angle was varied between 0 (no spline) and 45° (complete spline). Figure 3 shows the expected decrease in the bend loss with increasing bend radius. In addition, we observe an improvement of the transmission with increasing spline angle. A lowest bend loss of 0.004, 0.005 and 0.018 dB/90° was observed for 4.5, 3 and 2 µm bends with a spline angle of 25°. For a bend radius of 2 µm, the bend loss decreases by over 80% when the spline angle is increase from 0° to 45°. Also, even though the spline has a footprint penalty, it is possible to use a smaller bend radius, resulting in an overall smaller bend for the same loss (e.g. the 10° spline on a 3µm bend has less loss than a 5µm bend without a spline section). For the bends in the hybrid waveguides, deducting the photonic wire bend loss (0.004 dB) from the total bend loss of 0.0273 dB, we estimate an insertion loss of 0.012 dB per rib-strip transition.

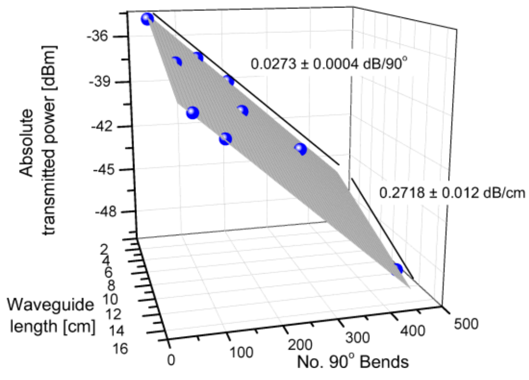

Fig. 2. Propagation loss and bend loss extraction from the fitting a 2D plane to the measured

transmitted power.

TABLE I
PROPAGATION LOSS AND BEND LOSS OF 700 NM WIDE RIB WAVEGUIDE WITH WIRE BENDS.

Wire width [nm]	Ridge waveguide loss [dB/cm]	Total bend loss [dB/90°]
470	0.2718 ± 0.012	0.0273 ± 0.004
460	0.286 ± 0.019	0.032 ± 0.001
420	0.33 ± 0.05	0.068 ± 0.002

In addition to hybrid waveguides, we also characterized the propagation losses of simple photonic wire strip waveguides, again using a dedicated spiral set. Figure 4 depicts the propagation loss spectrum of a 460 nm wide photonic wire waveguide. We measured an average wire loss of 1.49±0.38 dB/cm over a wavelength range of 80 nm and a loss of 1.36±0.06 dB/cm at 1550 nm. These values are the lowest reported for single-mode photonic wires fabricated using CMOS fabrication technology.

The propagation loss of both hybrid and photonic wire waveguides demonstrate the capability of standard CMOS fabrication process to achieve low-loss silicon waveguides, without compromising on device layout flexibility. Depending on the application, either long-range rib waveguides or short-range wire can be used.

V. SUMMARY

We demonstrated record low-loss strip/rib hybrid waveguide consisting of a shallow etched waveguide and deep etched photonic wire. We have achieved a propagation loss of 0.272±0.012 dB/cm for a 700 nm wide shallow-ridge waveguide and a total bend loss of 0.0273±0004 dB per 90°Bend. In addition, we have achieved a propagation loss of 1.36±0.06 dB/cm for a 460 nm wide photonic wire, respectively. Shallow-ridge waveguide and a total bend loss of 0.0273±0004 dB per 90°Bend. In addition we have achieved a propagation loss of 1.36±0.06 dB/cm for a 460 nm wide photonic wire, respectively.

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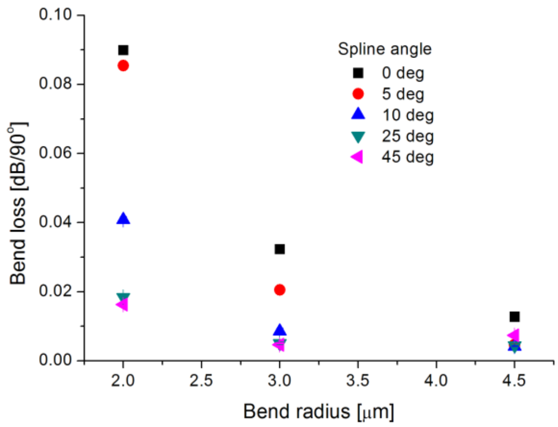

Fig. 3. Bend loss of photonic wires (460x220nm) with 5μm bend radius for different spline angles.

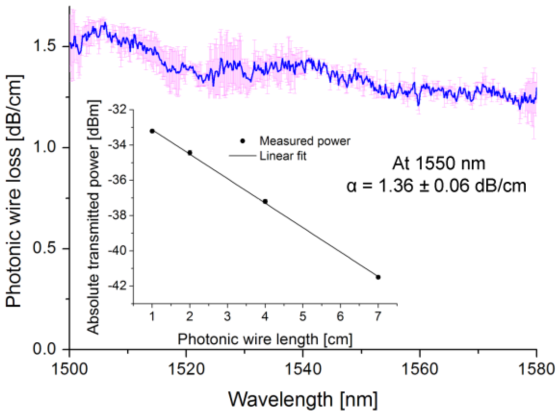

Fig. 4. Propagation loss of a photonic wire of 460 nm wide and 220 nm high.

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