Low-loss simple waveguide intersection in silicon photonics

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Proposed is a simple silicon wire intersection with low diffraction loss and crosstalk. Finite-difference time-domain analysis shows the lowest loss to be as small as 0.14 dB. A nearly optimum structure was fabricated on SOI substrate, the measured loss being 0.24 dB, which is only 0.01 dB larger than the theoretical loss.

Introduction: For high-density photonic integrated circuits, low-loss and low-crosstalk intersection of waveguides is a basic but important component. However, in high-index-contrast waveguides such as photonic wires in Si photonics, a 1.2 dB loss and –11.5 dB crosstalk occur even in a simple intersection shown in Fig. 1a due to strong diffraction of the guided mode. The diffraction can be suppressed by expanding the guided mode in a taper, as shown Fig. 1b. We have shown, using three-dimensional finite-difference time-domain (FDTD) analysis, that the loss can be reduced to 0.4 dB by employing an elliptical taper structure [1]. However, this value is not sufficiently low for high-density interconnects containing many intersections. Several similar structures have been discussed and demonstrated [2–4]. In particular, tapers fabricated by a two-step etching process smoothens the mode expansion and reduces the loss to 0.14 dB [4]. In this Letter, we propose a novel intersection, which can be fabricated by a single-step process, and completely suppresses diffraction by slightly modulating the standard taper structure (Fig. 1b).

**Fig. 1** Structure of intersection and calculated modal profile

(a) Simple cross-structure
(b) Standard taper structure
(c) Proposed structure

Normalised $H_z$ is the magnetic field normal to the substrate plane. Right Figure shows parameters.

Structure: In the standard structure, sidewalls of two waveguides cross at $\geq 90^\circ$, in which case diffraction loss is reduced but cannot be suppressed completely at the centre of the intersection. The proposed structure (Fig. 1c) consists of four offset ellipses. Since the taper is slightly narrowed just before the centre of the intersection, light is focused towards the centre and diffraction is suppressed.

Simulation: We performed a FDTD analysis of the mode propagation through a structure corresponding to the fabricated device described below: Si (index $n = 3.5$) wire of 400 nm width and 220 nm thickness clad by SiO$_2$ ($n = 1.45$). The major-axis $2a$, minor-axis $2b$, and offset-length $x$ were varied as parameters. The wavelength was set at $\lambda = 1.55 \mu m$, and the polarisation fixed to transverse electric (TE). Fig. 1 shows calculated profiles of light propagation (magnetic field normal to the plane). In the simple intersection (Fig. 1a), diffraction is clearly observed. In the standard taper (Fig. 1b), the profile asymmetry between the left and right hand side suggests a small amount of diffraction. In the proposed structure (Fig. 1c), the mode is first expanded in the ellipse, then focused slowly so that the focal point is located at the centre of the intersection, and finally transmitted to the opposite side. The profile is almost symmetric with the minimum loss evaluated to be 0.14 dB for $a = 3.60 \mu m$, $b = 1.00 \mu m$ and $x = 2.76 \mu m$.

**Fig. 2** Transmission spectra of fabricated intersections ($a = 5.67 \mu m$)

Intensity normalised by that without sample

Inset: Near-field pattern of scattered light at $\lambda = 1.55 \mu m$ overlapped with optical microscope image of device

**Fig. 3** Loss per intersection at $\lambda = 1.55 \mu m$

Solid line shows FDTD simulation; circular plots, average values of measured results

Inset: Change in output intensity with $N$ at $a = 5.67 \mu m$

Experiment: We fabricated the device on an SOI substrate using the foundry service NTT-ATN, where the pattern is formed by electron beam direct writing. Many intersections were inserted with a 50 $\mu m$ period into the photonic wire waveguide with the same design parameters as in the FDTD analysis. The number of intersections $N$ was set at 5, 10, 20 and 30. Both ends of the waveguide were terminated by spot-size converters consisting of inverse tapers and SiON/SiO$_2$ low-index-contrast large core waveguides. For the intersection, we fixed $a + x = 7.58 \mu m$ and $b = 1.19 \mu m$, and changed $a$ in each sample. The value of $a + x$ is slightly different from the above optimum value, because we fabricated the device before completing the optimisation. In the measurement, light from a tunable laser source was coupled to the spot-size converter using objective lenses in TE polarisation. The output light was collected by another objective lens and measured by an optical power meter. Fig. 2 shows transmission spectra of samples with different $N$. It exhibits the broadband transmission characteristics at $\lambda = 1.50–1.63 \mu m$. Fine oscillation of...
<1 dB amplitude in the spectra is caused by the reflection of waveguide end facets. On the other hand, slow oscillation is observed clearly for $N \geq 20$. We believe this is due to Fabry-Pérot resonance arising from the starting and ending points of the intersection. From the period of oscillation, we infer the cavity length to be 13 µm for a group index $n_g = 4.5$ [5], which is equivalent to the length of the intersection. Furthermore, the inset in Fig. 2 shows the combined near-field pattern/optical micrograph of the device, showing scattering at the device end points and further supporting our hypothesis. Fig. 3 summarises the transmission intensity with varying $N$ and the loss per intersection at $\lambda = 1.55$ µm. The intensity decreases monotonically with $N$, suggesting each intersection gives a uniform loss. The experimental and numerical results are in good agreement, indicating the minimum loss to occur at $a = 5.67$ µm. The average loss is determined to be 0.24 dB, which is almost the same as the theoretical value of 0.23 dB.

**Conclusion:** We propose a simple Si wire intersection which sufficiently suppresses diffraction loss and can be fabricated by a single-step etching process. We have experimentally demonstrated a 0.24 dB loss at $\lambda = 1.55$ µm. If the optimum design is used, the loss will be reduced to 0.14 dB. Also, if the two-step etching process [4] is acceptable, the remaining loss, mainly caused by light scattering, can be further reduced.

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**References**