Design of silicon Mach-Zehnder interferometer and ring resonator with a free spectral range tolerant against waveguide-width variations

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We propose a design method for Mach-Zehnder interferometers and ring resonators with a free spectral range tolerant against waveguide-width variations as occurring in a silicon-on-insulator platform. The systematic deviation of fabricated waveguide widths from related design widths is established, to calibrate the dependence of the group index on the design width. The width dependence of the group index suggests two waveguide widths in a single device to create tolerance of the free spectrum range against width variations.

Introduction

Silicon-on-insulator (SOI) is a popular photonic integration platform owing to its high index contrast and CMOS compatible fabrication technology. The strong light confinement in a Si waveguide enables small device footprints, but also leads to sensitivity of device properties due to size variations. For Mach-Zehnder interferometers (MZIs) and ring resonators (RRs), commonly used SOI devices, accurate control of the free spectral range (FSR) is often needed, *e.g.* in wavelength-filters [1, 2]. However, with the FSR depending inversely on the group index n_g, it often shows deviations from the design value due to variations of the fabricated waveguide width. To overcome this, we first obtain the average width deviation by combining simulations with measurements of test MZIs. Using the corrected widths, we then design MZIs and RRs with two widths to obtain tolerance of the FSR against small width variations.

Design approach

The FSR of an MZI or a RR of constant waveguide width is given by:

$$\mathrm{FSR} = \frac{\lambda^2}{n_g L} \tag{1}$$

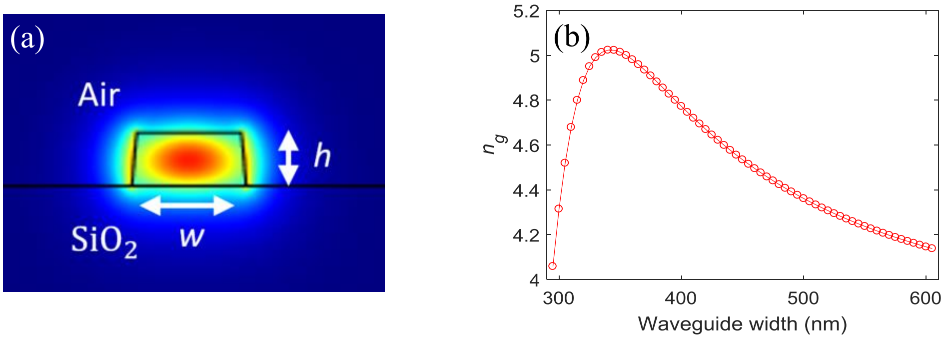

Fig. 1. (a) Profile of the TE$_0$ mode of a silicon waveguide of w = 450 nm and h = 220 nm. (b) Simulated group index n_g of air cladded waveguides (h = 220 nm) as a function of waveguide width.

Here, λ is the operation wavelength, n_g the waveguide group index and L the path-length difference of the MZI arms or the RR circumference. In Fig. 1(a) the TE_0 mode profile of a Si waveguide with w = 450 nm and h = 220 nm is shown for $\lambda = 1550$ nm, as simulated with COMSOL. In Fig. 1(b) we plot the group index n_g, also simulated with COMSOL, for air cladded Si waveguides similar to the one in Fig. 1(a) as a function of their width w, for h fixed at 220 nm. n_g reaches a maximum for $w =$ 340 nm. Thus, the derivative $\partial n_g / \partial w$ reverses sign with increasing width. Design of MZIs and RRs with an FSR tolerant against waveguide-width variations is based on this sign reversal. Using two widths for either device type, as shown in Fig. 2, we can write the following equations for the FSR:

$$\mathrm{FSR}_{\mathrm{MZI}} = \frac{\lambda^2}{n_{g,w1}L_{w1} - n_{g,w2}L_{w2} + 2\overline{n_{g,t1}}L_{t1} - 2\overline{n_{g,t2}}L_{t2}} \tag{2}$$

$$\mathrm{FSR}_{\mathrm{RR}} = \frac{\lambda^2}{n_{g,w1}L_{w1} + n_{g,w2}L_{w2} + 2\overline{n_{g,t}}L_{t}} \tag{3}$$

Here, L_{w1} and L_{w2} are the two waveguide lengths, and L_{t1}, L_{t2} and L_t are the lengths of the applied tapers (see Fig. 2). $n_{g,w1}$, $n_{g,w2}$, $\overline{n_{g,t1}}$, $\overline{n_{g,t2}}$ and $\overline{n_{g,t}}$ are the group indices of the waveguides and tapers. Neglecting the taper contributions in Eqs. (1) and (2), the following design rules for a tolerant FSR of the MZI and RR, respectively, are obtained:

$$\left.\frac{\partial n_g}{\partial w}\right|_{w1} L_{w1} - \left.\frac{\partial n_g}{\partial w}\right|_{w2} L_{w2} = 0 \tag{4}$$

$$\left.\frac{\partial n_g}{\partial w}\right|_{w1} L_{w1} + \left.\frac{\partial n_g}{\partial w}\right|_{w2} L_{w2} = 0 \tag{5}$$

Eqs. (4) and (5) can be satisfied for the MZI for widths on the same side of the n_g maximum and for the RR for widths on each side of the maximum. Thus, n_g variations due to width variations are compensated. Here we assume that variations of the two widths have very similar magnitude and are small enough, which is usually the case when these originate from the process steps lithography and etching.

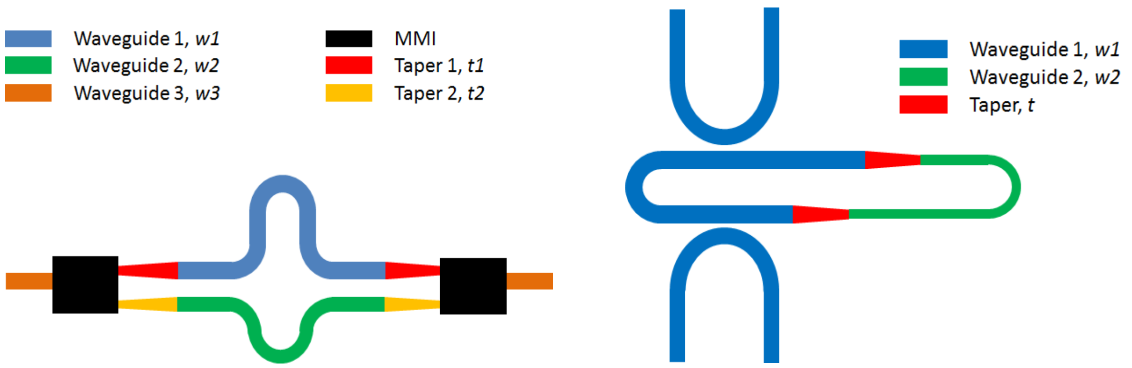

Fig. 2. Schematics of the MZI (left) and the RR (right) with an FSR tolerant against waveguide-width variations due to fabrication.

Establishing the systematic width increment in fabrication

$\partial n_g / \partial w$ depends on the waveguide width, as can be seen from Fig. 1(b), making it hard to satisfy Eqs. (4) and (5) for large differences between fabricated widths and design widths. Thus, we first established the systematic deviation of fabricated widths from design widths. This was done by comparing simulated n_g values (Fig. 1b) with n_g values extracted from transmission measurements of MZIs with a constant waveguide width fabricated at IMEC through the Europractice MPW service. In the simulations, the design waveguide width varies from 295 nm to 600 nm, with a 5 nm step, the waveguide height is assumed to be 220 nm and the waveguide side angle 5°. Ten MZIs were measured over the wavelength range 1549−1551 nm, the waveguide width ranging from 310 to 490 nm. Fig. 3(a) shows an example of a measured MZI transmission spectrum, for a design waveguide width of 450 nm. The usual cosine function was fitted to the transmission data to extract the FSR, giving n_g via Eq. (1). Multiple realizations of the same MZI design being present on the wafer, each design was measured several times from different wafer locations to obtain several representative results. The final experimental n_g values were obtained by averaging over several extracted values from different MZIs of the same design.

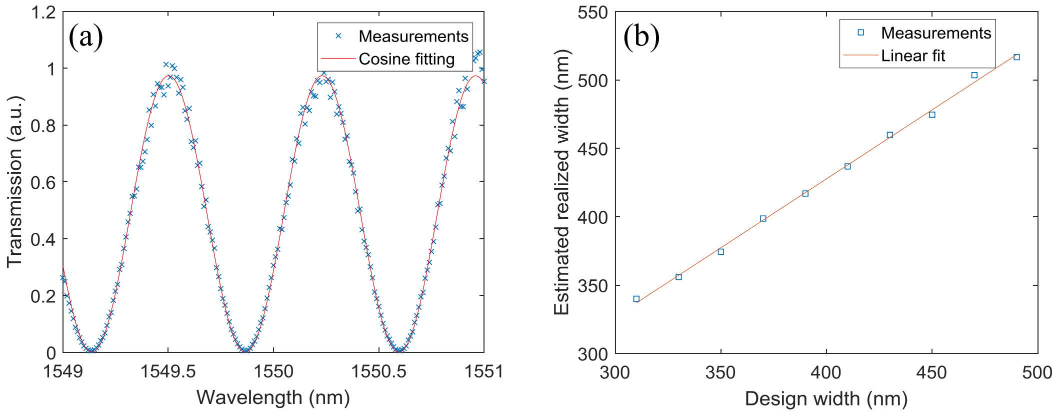

Fig. 3. (a) Transmission of an MZI with design waveguide width of 450 nm. (b) Estimated realized waveguide width as a function of design width.

Then, by picking the various measured n_g values from the simulation results, we found the real waveguide widths of the fabricated MZIs. This is a simple method to estimate the increase of the waveguide width after fabrication. As can be derived from the fitted straight line in Fig. 3(b), the fabricated waveguides are about 27 nm wider than designed, in agreement with the information in the foundry technology handbook. The data points in Fig. 3(b) closely follow the fitted line. Thus, the line nicely describes the systematic width increment, to which small variations due to fabrication are still superimposed.

Design implementation

For a highly developed fabrication process, waveguide width variations are reproducible. So, using the fitted line (Fig. 3(b)), we may calibrate the simulated n_g function of Fig. 1(b) for the design process or our tolerant RR and MZI. Since after fabrication the waveguide is wider than designed, the corrected n_g function has shifted to the left, as shown in Fig. 4(a). The corrected n_g function enables designing a more predictable FSR. The $\partial n_g / \partial w$ function can also be re-calculated from the corrected n_g function.

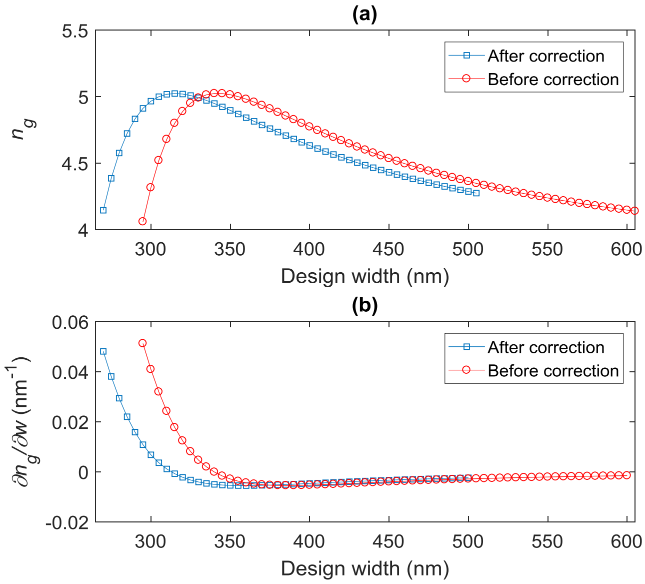

Fig. 4. Correction according to the established linewidth increment for (a) the simulated n_g function and for (b) the corresponding $\partial n_g / \partial w$ function.

As an example of a RR designed according to our method for tolerance, we mention the choice $w1 = 296$ nm and $w2 = 450$ nm. $w2 = 450$ nm is a regular width and $w1$ is in the range where $\partial n_g / \partial w$ changes slowly enough and remains positive. The two waveguide lengths are found by combining Eq. (3) with Eq. (5). For the MZI design, the example is $w1 = 360$ nm and $w2 = 450$ nm. In this case, combining Eq. (2) with Eq. (4) leads to the waveguide lengths. For reference, one may include in a fabrication run MZIs and RRs with a constant waveguide width, $e.g.$ $w = 450$ nm, for which the waveguide lengths are calculated from Eq. (1) using the un-corrected n_g. Small and realizable offsets of design widths can be included in the optical mask, both for the tolerant devices and the reference devices. This enables an experimental test of our design method to obtain tolerance against width variations.

Conclusion

We propose a design method for MZIs and RRs with an FSR tolerant against waveguide-width variations, comprising two steps: i) the average waveguide-width increment due to fabrication is established from simulations and measurements of fabricated MZIs, and ii) using this increment, we correct the simulated n_g and $\partial n_g / \partial w$ functions and use two design widths to counteract FSR variations resulting from small width variations.

References

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