Measurements of Effective Refractive Index of SOI Waveguides using Interferometers

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Abstract: We demonstrate an accurate method of measuring the effective refractive index of SOI waveguides in the C-band using three Mach-Zehnder Interferometers. Over wafer the average extraction error of effective index and group index is 0.003 and 0.004.

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1. Introduction

Silicon is a high index contrast material and due to this it is possible to make micron size devices on chip. However, the exact value of the effective refractive index (n_{eff}) is critical for the performance of wavelength filters [1]. Given the extreme sensitivity of a silicon wire waveguide to the exact geometry, it is important to measure the effective index *in situ*, without perturbing the actual waveguide geometry. Existing methods to extract the dispersion such as prism coupling are either not suited for high refractive index waveguides, or actively perturb the waveguide [2]. Non-invasive methods such as ellipsometry cannot be easily applied to narrow waveguides. Techniques using scattering with weak higher-order periodic perturbations [3] actively modify the waveguide, but also change the local pattern density, and thus could even influence the fabrication process. Methods which rely on features in the tranmission spectrum of interferometric devices will measure the group index n_g rather than the effective index n_{eff} [4]. Because silicon wire waveguides are very dispersive, n_g and n_{eff} are very different, and highly wavelength dependent. Therefore, a method to extract both values unambiguously, and with their wavelength dispersion, is needed. We present a simple approach to measure accurately the n_{eff} of a silicon photonics wire. This method uses three Mach-Zehnder interferometers (MZIs) designed with the same photonic wire and located adjacent to each other. MZIs are the best candidates due to being simple in design, linear in phase response and flexible in choosing the filter order. Other methods of parameter extraction using ring resonators [5] suffer from nonlinearity in terms of phase and higher input optical power due to their resonant nature. It also averages the n_{eff} over bends and straight sections.In our method two MZIs have a low order *m*, i.e. a large *free spectral range* (FSR) which allows us to estimate the order of the filter correctly within the C-band.The third one, of much higher order, has a small FSR to extract the wavelength dependence of the group index (n_g). Wafer-scale measurements are also performed and presented.

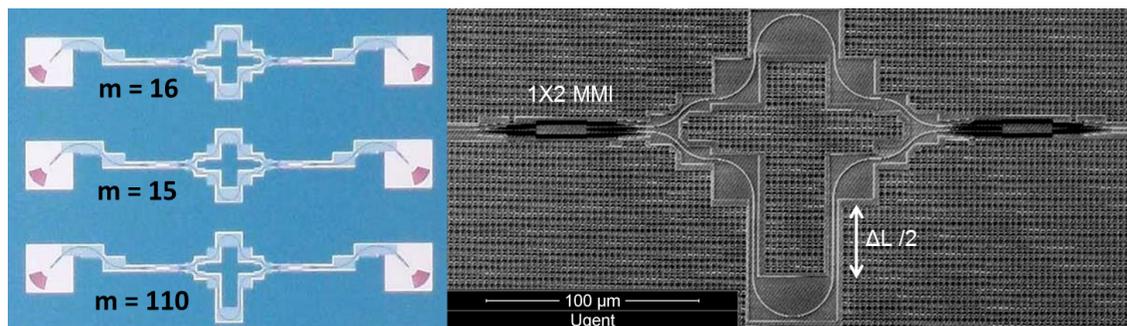

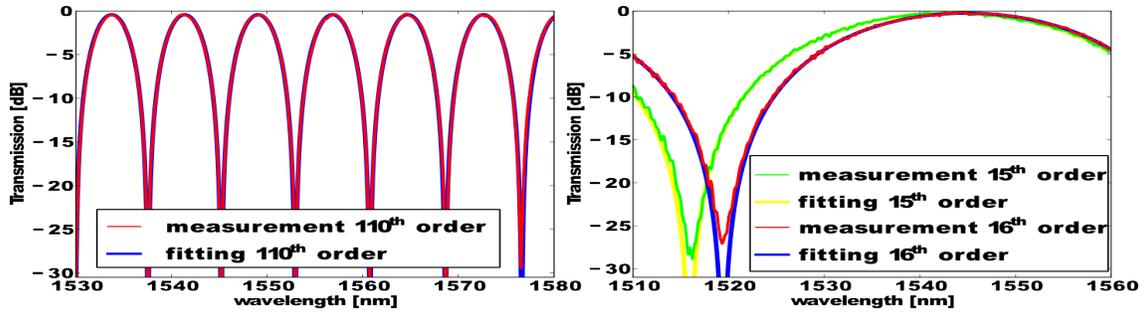Fig. 1: (a). Camera image of fabricated devices and (b) SEM image of fabricated MZI with m =110.

Fig. 2: Measured and fitted normalized spectrum of MZI (a) higher filter order and (b) lower filter order.

2. Method and Design

The presented method is generic in nature and should work for all integrated waveguide platforms. In a Mach-Zehnder interferometer, we get constructive interference at the output when

$$m.\lambda = n_{eff}.\Delta L \tag{1}$$

where λ is resonant wavelength, m is the filter order, n_{eff} is effective index of the waveguide at that wavelength and ΔL is the physical path length difference. The FSR of the filter is the difference between two consecutive peaks of the filter:

$$FSR = \lambda^2 / n_g.\Delta L \tag{2}$$

From Eq.1, we designed two MZIs with consecutive order m and $m+1$ in such a way that only one resonant wavelength falls in the entire C-band. For this, we used a simulated model of n_{eff}, making sure that even with a significant deviation from the model we could still identify the peaks of the right order. The third MZI has a much higher order such that we can get number of peaks and valleys in the wavelength band. From this device, measuring n_g of the waveguide is relatively straightforward by extracting the wavelength dependent FSR. With this n_g, we can now extract n_{eff} based on the exact references of the two low-order MZIs, by modifying the Taylor's expansion

$$n_g(\lambda) = n_{eff}(\lambda_0) - \lambda_0.(dn_{eff}/d\lambda) - \lambda_0.\Delta\lambda.(d^2 n_{eff}/d\lambda^2) \tag{3}$$

where λ_0 is the center wavelength, in our case its 1550 nm. The further terms of the Taylor's expansion are neglected since they are comparable to the fitting error for the designed TE-polarized waveguide. The eigen mode simulations for the initial estimate of the SOI waveguide mode are performed by the finite element method (FEM) taking a wavelength and temperature dependent material model based on the Sellmeier equation. The MZIs are designed and simulated for 450 nm wide and 215 nm thick silicon wires and for values m = 15, 16 and 110 respectively. Devices are designed using the IPKISS parametric design framework. The device uses compact grating couplers [6] with reduced back reflections for light coupling in and out from the SOI chip. MZI delay lines are designed with a relatively large bend radius of 20 μm to minimize the reflections from bends and loss. The actual ΔL comes only from the straight section of the lower arm of the MZI and not from the bends. this cancels out possible effects of bend-radius dependent n_{eff}. Here we focus on measuring and extracting the n_{eff} of straight photonic wire. For splitter and combiner we use a 1×2 multimode interference (MMI). The device was fabricated in the imec 200 mm CMOS pilot line, using silicon-on-insulator wafers with an initial 220 nm of silicon and 2 μm of buried oxide. Camera images of all three MZIs and SEM image of fabricated MZI with m = 110 are shown in Fig. 1.

3. Measurements and Analysis

The transmission measurement is performed in a thermally controlled environment to eliminate the effect of the high thermo- optic (TO) coefficient of silicon, which can induce a wavelength peak shift about 80 pm/ K. The device is first normalized to a simple straight waveguide to eliminate the grating coupler spectrum. The 10 dB bandwidth of the grating coupler is around 80 nm from 1505 nm to 1585 nm. The insertion loss of the devices are less than 0.3 dB. The normalized transmission spectrum is fitted using the non-linear least square method and cosine square interferometric model as a base function. The measured and fitted transmission spectrum of higher and lower are MZIs are shown
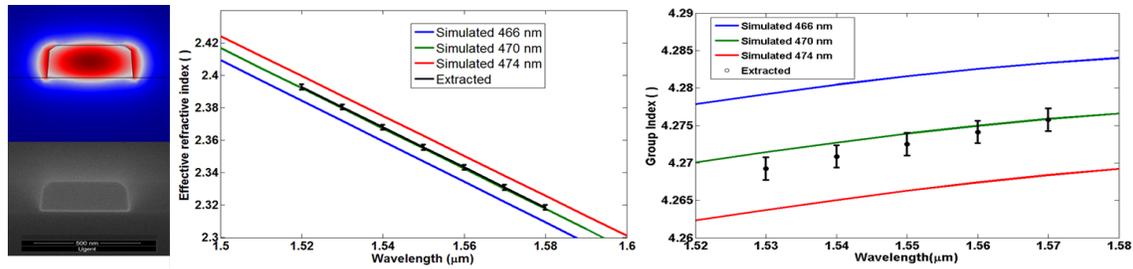
Fig. 3: (a) Simulated mode profile and XSEM image of 470 nm wide and 211 thick waveguide (b) Simulated and extracted n_{eff} and (c) Simulated and extracted n_g over C-band
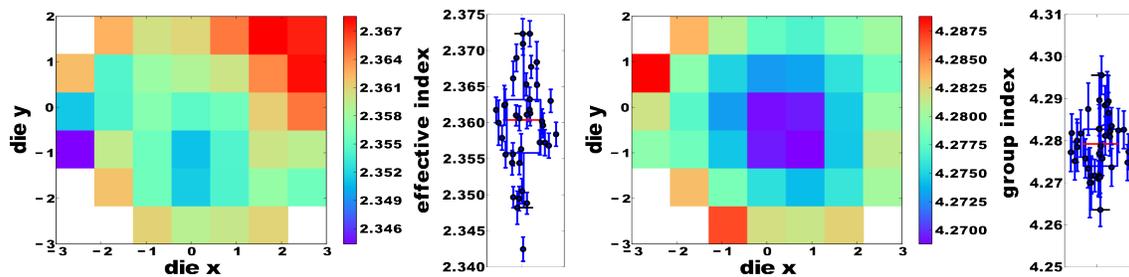

Fig. 4: Wafer statistics and map at 1550 nm (a) n_{eff} and (b) n_g

in Fig. 2.The designed waveguide is 450 nm wide and 215 nm thick (5nm silicon is removed during processing). However, the measured width and thickness of the waveguide is closer to 470±4 nm and 211±1 nm respectively, as extracted from SEM inspection. The cross-section SEM (XSEM) of the waveguide, the simulated mode profile, the extracted n_{eff} and n_g over the entire C-band is shown in Fig. 3 (a), (b) and (c) respectively. The extracted n_g from the higher order filter and then the n_{eff} from low order filter of the 470 nm wide and 211 nm thick waveguide at 1550 nm is 4.272±0.0015 and 2.356±0.0045 respectively. The uncertainty is mainly due to fitting and measurements errors. The mismatch between the extracted value and the simulations of the waveguide according to XSEM (with best fitted width, taking into account the uncertainty of the SEM measurement itself) is less than 0.0007 for n_{eff} and 0.005 for n_g and it mainly comes from local environmental variations, and fabricated waveguide geometrical non-idealities. The wafer statistics and map plot of extracted n_{eff} and n_g are shown in Fig.4 (a), (b). Across the wafer the mean value and standard deviation of n_{eff} is 2.360±0.0030 and 0.007 at 1550 nm and for n_g its 4.279±0.0040 and 0.006 respectively.

4. Conclusion

We proposed and demonstrated a generic method for measuring the refractive index of TE polarized SOI waveguides. This method should work for TM polarization and can be extended to other waveguide platforms as well.

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