

Extracting Fabricated Geometry on Die-Level

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We built an accurate model to link silicon waveguide geometry to its effective index and group index. We developed a technique to extract waveguide parameters with a greatly improved accuracy. We extracted linewidth and thickness of SOI waveguides on a die fabricated by IMEC MPW service. Strong local location-dependent correlation is presented in the thickness variation while no such correlation is observed for the linewidth.

Introduction

Extracting the fabricated linewidth and layer thickness is essential to get a good idea of the fabrication variation. However, metrology measurement of a fabricated photonic chip using an SEM is expensive and destructive. So, an alternative is to use optical transmission measurements of a waveguide on-chip to extract its parameters. A recent paper has shown that from effective index and group index, it is possible to extract line width and thickness of a waveguide^[1]. However, the authors measured ring resonators which use both straight and bent waveguides. Since straight and bend waveguides have different effective and group indices, we cannot accurately extract linewidth of a straight waveguide.

In this research, we used the curve fitting method to extract n_{eff} and n_g from a *Mach-Zehnder interferometer* (MZI). The method is more accurate and easy to implement. We also built a very accurate model to derive waveguide linewidth and thickness from effective index and group index. We applied the method and extracted effective and group indices over a die at 44 different positions. The thickness and linewidth map is obtained over the die from these extractions.

Geometry Model

To get width and thickness of a waveguide, we need to relate them with n_{eff} and n_g of the corresponding geometry. The relation should be very accurate, otherwise large errors will be introduced in the extracted geometry. Recent research^[1] extracted width and thickness variation of the waveguide in a ring resonator. They represented the waveguide geometry as the first order polynomial in the deviation of resonance wavelength, as well as the average group index n_g from the design. They have assumed maximum deviation of fabricated width to be 20 nm and thickness to be 10 nm. The error of the geometry alone is 0.85 nm and 0.55 nm in extracted width and thickness, which does not yet take into account the error in extracting resonance wavelength and n_g . The model error is quite large compared to the fabrication variation reported. For example, the within-wafer fabrication variation for a 200-nm wafer fabricated by the 193-nm dry lithography is 0.78 nm in linewidth^[1].

To offer a good estimation of the fabricated geometry variation, a much lower extraction error is needed. We simulated an oxide-clad Si waveguide cross section in Fimmwave with the *Film Mode Matching* solver, sweeping the width w from 425 nm to 475 nm and the thickness t from 200 nm to 240 nm, and calculated n_{eff} and n_g for wavelengths from 1500 nm to 1600 nm. Then, we wrote w and t as a third order polynomial of n_{eff} and n_g and first order of wavelength λ as:

$$w = p_0 + \sum_i^3 p_i n_{eff}^i + \sum_j^3 p_{j+3} n_g^j + p_{j+6} \lambda$$

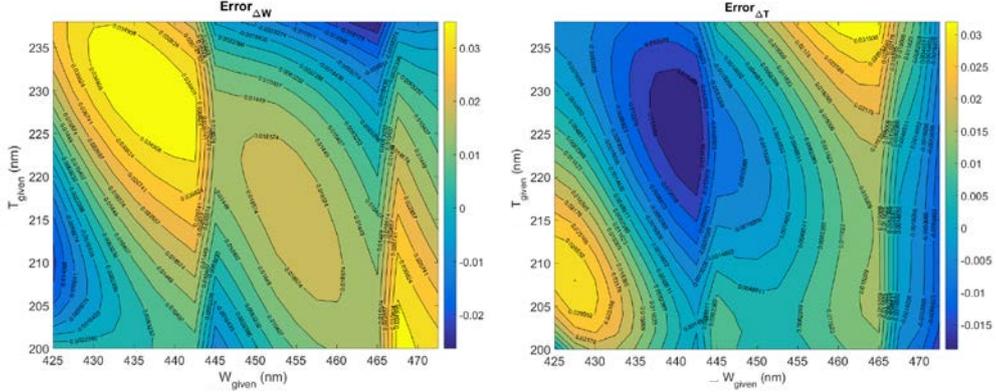


Figure 1 Error contour of the geometry with wavelength at 1550 nm. Left: width error. Right: thickness error. The visual discontinuity is due to the sampling grid to build up the geometry model, which is very small.

$$t = q_0 + \sum_i^3 q_i n_{eff}^i + \sum_j^3 q_{j+3} n_g^j + q_{j+6} \lambda$$

The polynomial model is very accurate over the wide span of the spectral measurement range. The maximum error for width and thickness extraction is 0.034 nm and 0.031 nm respectively (Fig. 1), which is small compared to the geometry variation. This would make geometry extraction from n_{eff} and n_g very accurate so that variability analysis on the geometry variation is credible.

Extraction Technique

We can derive n_{eff} and n_g from interfering structures such as a ring resonator or an MZI. As mentioned, a ring is not advisable to extract the straight waveguide linewidth. We use a low order (order $m = 15$) and a high order ($m = 150$) MZI (Fig. 2). The resonance of the MZI will drift when the fabrication deviates from the design. Therefore, we chose the low order MZI with a large FSR that ensures the drift is within half a reference order under an estimated fabrication tolerance (± 20 nm in linewidth and ± 10 nm in thickness)^[2]. For the low order MZI, we are sure of its interference order m to get an accurate n_{eff} . The high order MZI has a small FSR and we can extract n_g accurately. However, the n_{eff} of the high order MZI is hard to decide because the fabrication error can shift the designed resonance by several orders and it becomes difficult to determine the exact order of an interference at a transmission peak.

Two arms in our MZI have the same shape, except the length of the straight waveguide is longer in one arm. Thus, it makes the interference spectrum only affected by the n_{eff} and n_g of the straight waveguide and the length difference ΔL between two arms. n_{eff} and n_g of the MZI arm is linked to the resonance wavelength λ_{res} and the *free spectral range* (FSR) as:

$$m \cdot \lambda_{res} = n_{eff} \cdot \Delta L, \quad n_g = \frac{\lambda_{res}^2}{FSR \cdot \Delta L}$$

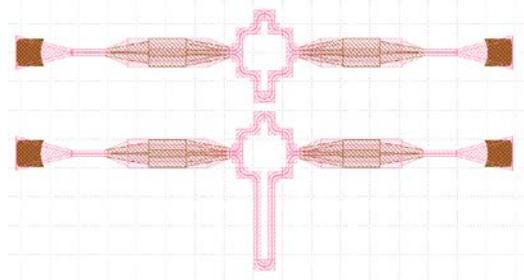


Figure 2 The MZI used for geometry extraction. Each MZI use two MMIs with 50-50 splittig ratio.

We can derive λ_{res} and the FSR from the transmission spectrum by finding all the peaks in the spectrum. Then, for a designed interference order m and arm length difference ΔL , we calculate n_{eff} and n_g . Using peak detection is simple but not accurate. A waveguide is dispersive, so n_g and the FSR are wavelength dependent. The FSR on both sides of a resonance peak can be slightly different leading to the extraction of a different group index value. Also, detecting peaks from the spectrum is prone to noise especially for a less sharp peak such as in the MZI transmission.

To improve the extraction accuracy, we used the curve fitting technique. Peak extraction only uses information at the peaks and ignores information on the rest part of the spectrum. On the contrary, curve fitting method utilizes the information from the entire measured spectrum, which should give more reliable extraction. It extracts parameters through the minimization of the difference between a circuit simulation and the measurement data. We built a *Caphe* circuit model of the MZI with *grating couplers* (GCs) at the in port and the out port. We used a fourth-order polynomial to represent the logarithmic transmission spectrum of the GC. In our test, using a fourth order polynomial model reduces the fitting error by one order of magnitude compared to using a measured reference GC, because also the grating coupler transmission is subject to variability effects. From fitting, we can get circuit parameters such as n_{eff} , n_g and coefficients of the polynomial describing the GC.

As shown in Fig. 3, the curve simulated from *Caphe* circuit model fits the measurement very well. We have repeated the fitting for all 44 pairs of MZIs in a die. Now we get the accurate n_{eff} and inaccurate n_g from the low order MZI and the accurate n_g from the high order MZI. Without constraint, the extracted n_{eff} of the high order MZI has multiple solutions. We limit the possible extracted solutions by using all the accurate extracted information. From those accurate extracted parameters, we derived that the average and standard deviation of the n_{eff} for the low order MZI is 2.317 and 0.00576 respectively. Then, 99.7% of the n_{eff} value lie within the three-sigma range from 2.300 to 2.334. Similarly, n_g has a three-sigma range between 4.205 and 4.220. For the n_{eff} and n_g range, the waveguide width ranges from 465.0 nm to 476.8 nm, and the thickness ranges from 196.9 nm to 204.7 nm. With the constraint on the geometry we can get a constrained n_{eff} and n_g parameter space calculated by the geometry model. Then, we get the extracted n_{eff} and n_g of the high order MZI as shown in Fig. 4. The average fitting error for n_{eff} is $\Delta n_{\text{eff}} = 8.5 \cdot 10^{-6}$ and the average fitting error for n_g is $\Delta n_g = 8.1 \cdot 10^{-4}$. These fitting errors correspond to extraction errors of 0.28 nm in w and 0.12 nm in t . Considering the modelling error in mapping geometry on n_{eff} and n_g , the total extraction error for width err_w and thickness err_t is:

$$err_w = 0.28nm + 0.034nm = 0.314nm, \quad err_t = 0.12nm + 0.031nm = 0.151nm$$

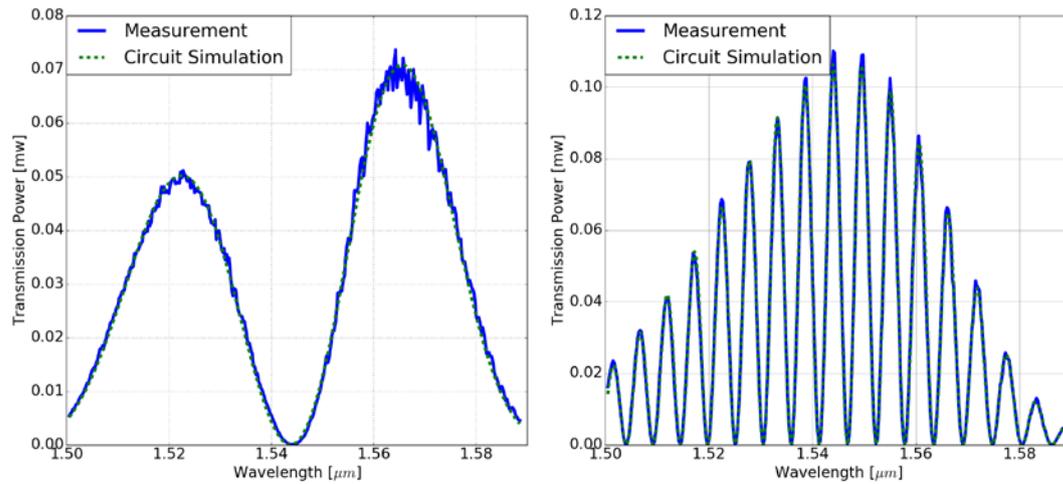


Figure 3 Fit the measured spectrum using Caphe circuit model. Left: low order MZI. Right: high order MZI.

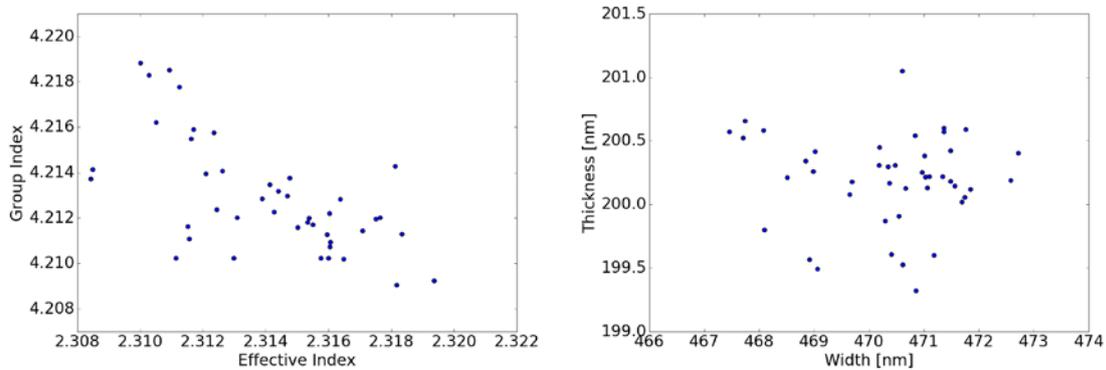


Figure 4 Left: Extracted n_{eff} and n_g of the high order MZI. Right: Extracted geometry of 44 MZI waveguide in the die.

Die-Level Variability

We distributed 44 copies of the MZI pair on the die (Fig. 5). Extracted linewidth ranges from 467.7 nm to 472.7 nm and thickness from 199.3 nm to 201.0 nm with standard deviations of 1.30 nm and 0.37 nm respectively. No correlation (correlation coefficient = -0.0541) is observed between the linewidth and the thickness. Strong local correlation is presented in the thickness variation while no such correlation is observed for the linewidth.

Conclusions

Using a rigorous model fitting approach for n_{eff} and n_g , we could obtain a very accurate mapping of waveguide linewidth and thickness variations at 44 sites on a silicon photonics die.

Table 1 Statistical results for the manufacturing variations on a die fabricated with 193-nm DUV lithography.

| | w (nm) | t (nm) |
|------------------------------|----------|----------|
| Mean, μ | 470.33 | 200.20 |
| Standard deviation, σ | 1.30 | 0.37 |