# 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 measurements of a waveguide on-chip to extract the parameters. A recent paper has shown that from effective index and group index, we can extract line width and thickness of a waveguide [1]. However, they measured ring resonators which use both straight and bend waveguides. Since straight and bend waveguides have differed effective and group indices, we cannot get linewidth of a straight waveguide from the extraction accurately.

In this research, we used the curve fitting method to extract $n_{eff}$ and $n_g$ from Mach-Zehnder Interferometer (MZI). The method is more accurate and easy to implement. We also build 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 would be introduced in the extracted geometry. A recent research [1] extracted width and thickness variation of the waveguide in a ring. They represented the waveguide geometry as the first order polynomial of the deviation of resonance wavelength and 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 not yet count in 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-mm 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, it is required to obtain much lower extraction error. We simulated Oxide-clad Si waveguide cross section in Fimmwave with the Film Mode Matching solver. We swept width from 425 nm to 475 nm and thickness from 200 nm to 240 nm, and calculated $n_{eff}$ and $n_g$ for wavelength range of 1500 nm to 1600 nm. Then, we write the width w and thickness t as a third order polynomial of $n_{eff}$ and $n_g$ and first order of wavelength $\lambda$ as:

$$\mathrm{w} = \mathrm{p}_0 + \sum_i^3 p_i n_{eff}^i + \sum_j^3 p_{j+3} n_g^j + p_{j+6}\lambda$$

$$\mathrm{t} = \mathrm{q}_0 + \sum_{i}^{3} q_i n_{eff}^{i} + \sum_{j}^{3} q_{j+3} n_g^{j} + q_{j+6}\lambda$$

The polynomial model is very accurate over the wide span of the spectral 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 $\mathrm{n_{eff}}$ and $\mathrm{n_g}$ very accurate so that variability analysis on the geometry variation is credible.

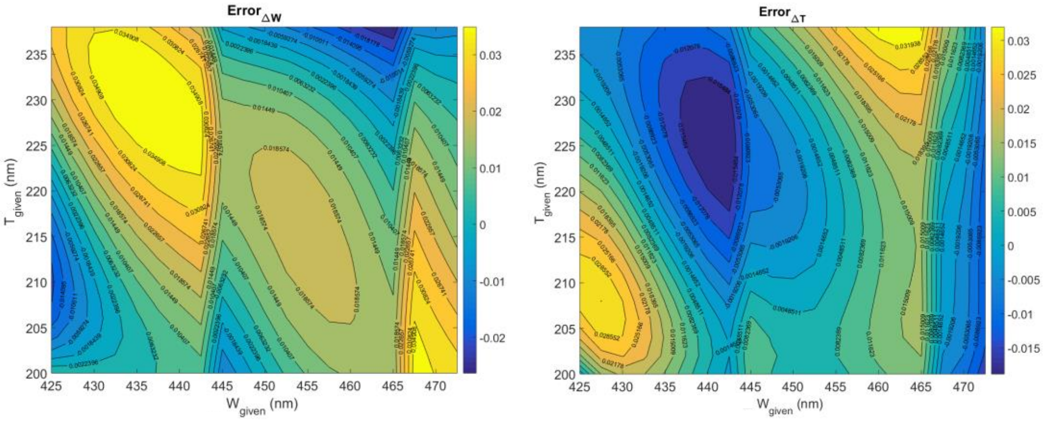

*Figure 1 Error contour of the geometry with wavelength at 1550 nm. Left: width error. Right: thickness error.*

# Extraction Technique

We can derive $\mathrm{n_{eff}}$ and $\mathrm{n_g}$ from interfering structures such as a ring or a Mach-Zehnder Interferometer (MZI). As we mentioned, ring is not advisable to extract the linewidth of a straight waveguide. So, we have used a low order (order m = 15) MZI and a high order (m = 150) as shown in Fig. 2. The fabricated resonance of the MZI will drift if 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 $\mathrm{n_{eff}}$. High order MZI has small FSR and we can extract $\mathrm{n_g}$ accurately. However, the $\mathrm{n_{eff}}$ of the high order MZI is hard to decide because the fabrication error would probably shift the designed resonance by several orders and it becomes difficult to determine the 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 $\mathrm{n_{eff}}$ and $\mathrm{n_g}$ of the straight waveguide and the length difference ΔL between two arms.

$\mathrm{n_{eff}}$ and $\mathrm{n_g}$ of the MZI arm is linked to the resonance wavelength $\lambda_{\mathrm{res}}$ and the Free Spectral Range (FSR) as:

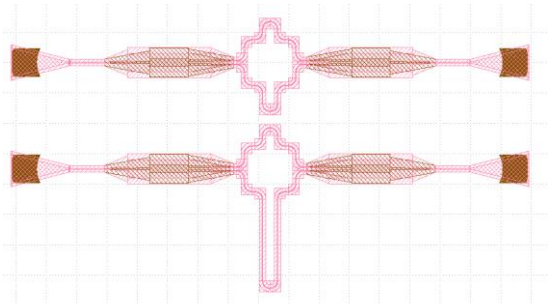

*Figure 2 The MZI used for geometry extraction. Each MZI use two MMIs with 50-50 splittig ratio.*

$$\mathrm{m} \cdot \lambda_{\mathrm{res}} = \mathrm{n_{eff}} \cdot \Delta \mathrm{L}$$

$$n_g = \frac{\lambda_{res}^2}{FSR \cdot \Delta L}$$

We can derive $\lambda_{res}$ and FSR from the transmission spectrum by finding all the peaks in the spectrum. Then, for a designed interference order m and arm length difference $\Delta L$, we can calculate $n_{eff}$ and $n_g$. Using peak detection is straightforward but not accurate. A waveguide is dispersive. $n_g$ and the FSR are wavelength dependent. The FSR on the left and right 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 up 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. From fitting, we can get circuit parameters such as $n_{eff}$, $n_g$ and coefficients of the polynomial describing the GC.

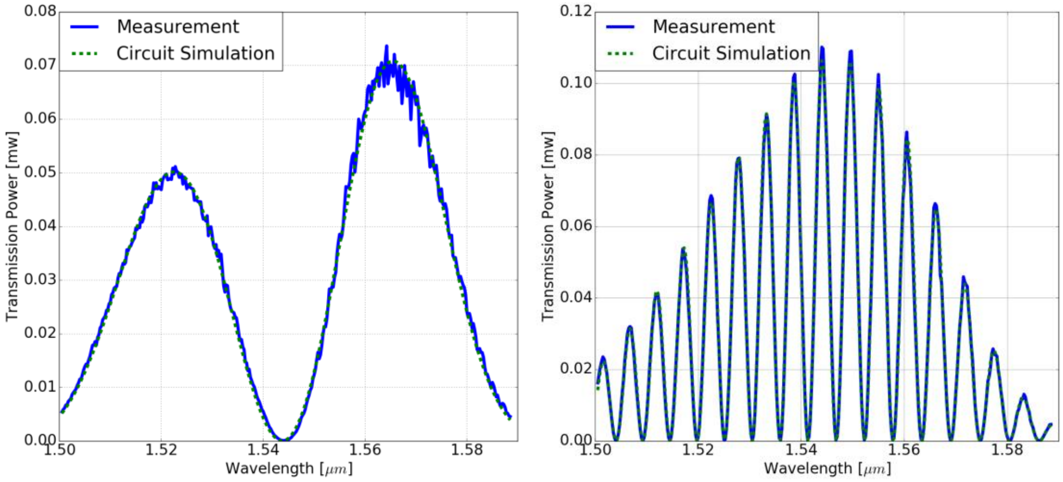

*Figure 3 Fit the measured spectrum using Caphe circuit model. Left: low order MZI. Right: high order MZI.*

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 $n_g$ of the low order MZI and the accurate $n_g$ of the high order MZI. Without constraint, the extracted $n_{eff}$ of high order MZI has multiple values. 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 $n_{eff}$ lies within the three-sigma range from 2.300 to 2.334. Similarly, $n_g$ has three-sigma ranging from 4.205 to 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 $\Delta n_{eff} = 8.5 \cdot 10^{-6}$ 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 width and 0.12 nm in thickness. Considering the modelling error in getting geometry from $n_{\mathrm{eff}}$ and $n_g$, the total extraction error for width $err_w$ and thickness $err_t$ are:

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

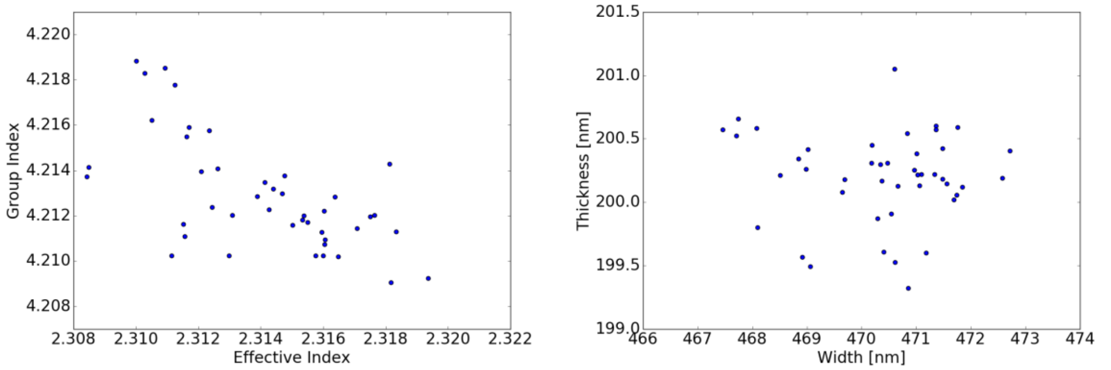

*Figure 4 Left: Extracted $n_{eff}$ and $n_g$ of the high order MZI. Right: Extracted geometry of 44 MZI waveguide in the die.*

## 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.

*Table 1 Statistical results for the manufacturing variations of a 200-mm wafer fabricated through a 193-nm DUV lithography process*

| | $w$ (nm) | $t$ (nm) |
|---|---|---|
| Mean, $\mu$ | 470.33 | 200.20 |
| Standard deviation, $\sigma$ | 1.30 | 0.37 |

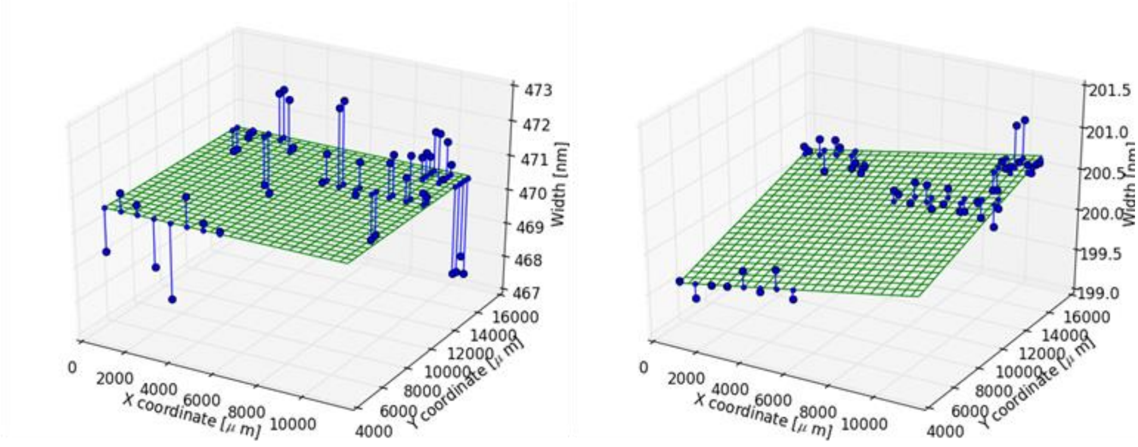

*Figure 5 Extracted width and thickness map of the die. Blue balls are extracted values.*

## References

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