Extracting Multiple Parameters from a Compact Circuit for Performance Evaluation

Student Paper

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ABSTRACT

We designed a two-stage Mach-Zehnder Interferometer for process monitoring control. Using Restart-CMA-ES global optimization algorithm, we can extract multiple on-chip waveguide and directional coupler parameters simultaneously. The compact design greatly reduces the footprint and number of measurements and improves accuracy for parameter extraction, making it useful for detailed wafer-level variability analysis.

1 DESIGN OF THE MONITORING CIRCUIT

Silicon Photonics offers a high material contrast and strong light confinement, enabling large scale integration and complex circuits. However, it is also susceptible to process variation. Process variation in linewidth and thickness would affect component behavior such as effective index and group index of waveguides and coupling coefficients of directional couplers (DC). Performance variation in each component propagates and accumulates in a circuit and leads to circuit performance degradation.

To monitor the process parameters and evaluate the performance of the fabricated circuit, we designed the two-stage Mach-Zehnder Interferometer (MZI) shown in Fig. 1a. We discussed the design principle of waveguide index extraction in [1], where the low-order stage offers a reference of the effective index under the overall process variation while the high-order stage allows accurate effective index and group index extraction. The arm length differences of the two stages are 15 μm and 150 μm, and they are joined by three DCs designed at 25%, 50% and 75% cross power coupling, respectively. The gap between the waveguides in the DC is 250 nm,

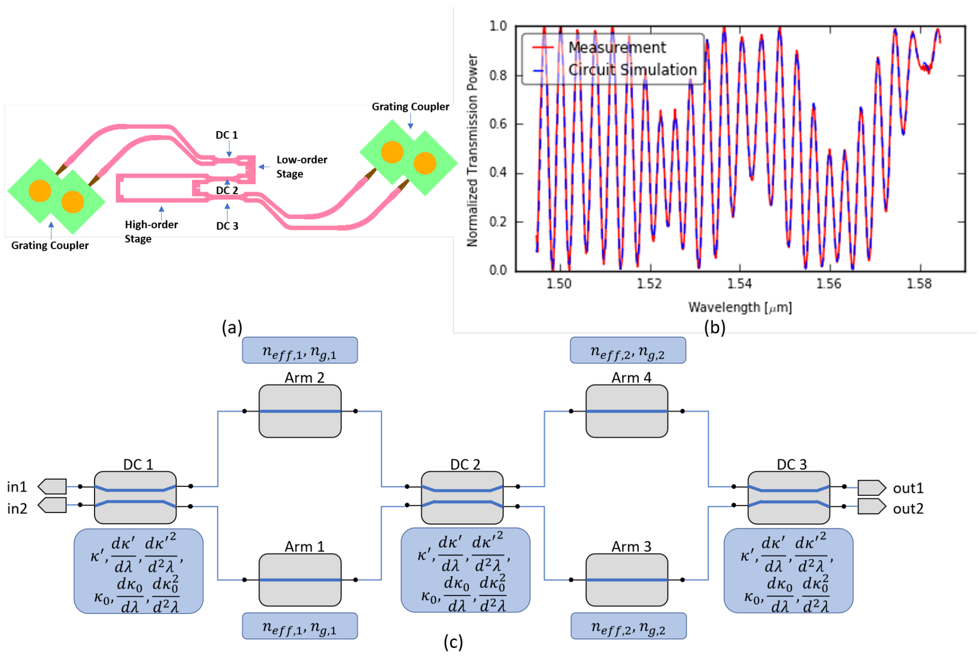

Figure 1. (a) The layout of the two-stage MZI. (b) The measured spectrum of a two-stage MZI. (c) The circuit model of the device. Two MZI stage have different n_{eff} and n_g led by the local process variation.

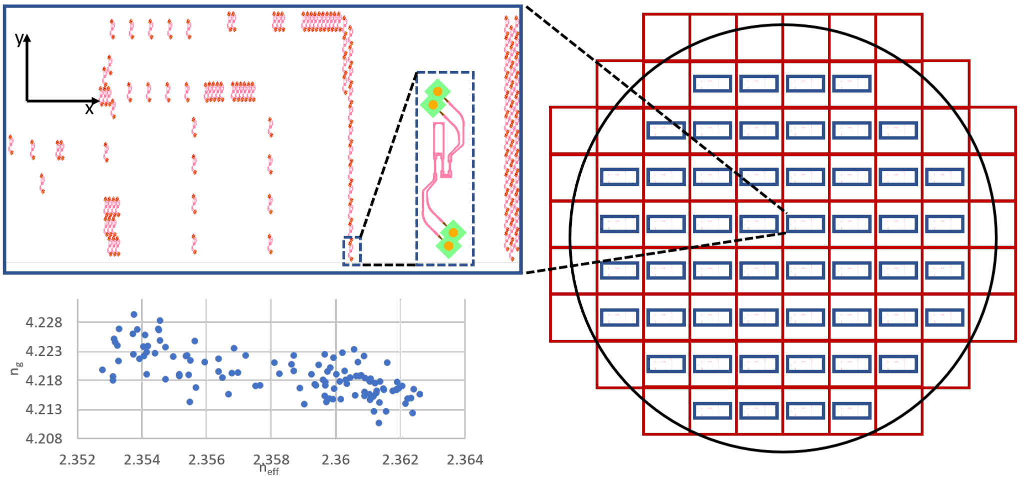

Figure 2. (a) Locations of the two-stage MZI on a die. (b) Extracted n_{eff} and corresponding n_g of die (X=0, Y=0) (in the center of the wafer). (c) Locations of dies on the wafer. Red grid indicates dies on the wafer. The black circle is the boundary of the wafer.

and the corresponding coupler lengths in three DCs are 6.65 μm, 12.91 μm, 19.17 μm. To extract the coupler parameters, we designed the three DCs with the same properties except for their coupler lengths [2]. The single circuit design greatly reduces the number of measurements required to extract the set of waveguide and DC parameters. Its compactness also reduces the local variation within the circuit which improves the extraction accuracy. To further reduce the footprint of the device, we also folded the MZI. The circuit is so compact that we can easily squeeze it in various locations on a chip to construct a granular map of the process variation on the fabricated chips as input for location-dependent variability analysis [3].

2 MULTIPLE PARAMETERS EXTRACTION BY THE RESTART-CMA-ES OPTIMIZATION

We extracted the circuit parameters by matching the optical measurement with simulated spectrum. Using the IPKISS circuit simulator we implemented the compact model of the two-stage MZI. Figure 1c shows the compact circuit model of the monitoring circuits. We assume that the effective index $n_{eff,1}$ and group index $n_{g,1}$ at $\lambda_0 = 1550\ nm$ for lower-order stage and $n_{eff,1}$ and group index $n_{g,1}$ of the high-order stage have a slight difference because of local variation. The DC model consists of length-specific coupling coefficients of the straight coupling part κ' and its first and second-order derivative $\frac{\partial \kappa'}{\partial \lambda}$ and $\frac{\partial^2 \kappa'}{\partial \lambda^2}$ of the straight coupling section parameters, and lumped power coupling of two bends κ_0 and its first and second-order derivative $\frac{\partial \kappa_0}{\partial \lambda}$ and $\frac{\partial^2 \kappa_0}{\partial \lambda^2}$. We removed the effect of grating couplers in the spectrum by measuring both the spectra from port *in1* to *out1* and *in1* to *out2* and normalized the transmission spectra to the sum of the two spectra. The solid red curve in Fig. 1b shows a normalized measured spectrum from port *in1* to port *out1*.

As in Fig. 1b, the spectrum of the circuit has a complicated shape. Standard curve fitting methods (e.g., from the scientific python package 'scipy') often only find a local minimum in the difference between the simulated and measured spectrum. The classical curve-fitting methods fail to handle the non-convex parameter landscape and will obtain a local optimum instead of the global optimum. Instead, we used the Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES), which is a smart global optimization algorithm that adaptively chooses the samples to significantly reduce the number of simulations for the non-convex parameter landscape optimization [4]. The CMA-ES is especially powerful to extract multiple parameters simultaneously. However, it also does not guarantee to always find the global optimum. A variation, the Restart-CMA-ES method is a global optimization method that restarts the CMA-ES search if it only obtains a local optimum. After each restart, the population of each generation is increased to make the search more global[5] until it finds out the global optimum. While slower, it works robustly for the waveguide variation we used, i.e. (w∈[465,485] nm, t∈[205,215] nm) and DC gap ∈[100,400] nm in our experiment. As shown in Fig.1b, simulation matches measured spectrum perfectly using the algorithm. A high accuracy is usually obtained within 20,000 iterations. The behavior parameters have been extracted with good accuracy (Table 1).

3 EXTRACTION OF A DIE MAP AND A SIMPLE WAFER MAP

We measured 117 copies of the folded MZI on the die (X=0,Y=0) in the center of the wafer (Fig. 3a). Using the restart-CMA-ES method, we extracted the high-order n_{eff} and n_g as in Fig. 2b. We mapped the width and thickness of the high-order stage arm from n_{eff} and n_g using an geometry model with sub-nanometer

TABLE 1. MAPPED GEOMETRY PARAMETERS WAVEGUIDE WIDTH AND THICKNESS OF THE HIGH-ORDER STAGE ARM.

Parameter	$n_{eff,l}$	$n_{g,l}$	$n_{eff,2}$	$n_{g,2}$	κ'	$\frac{d\kappa'}{d\lambda}$	$\frac{d\kappa'^2}{d^2\lambda}$	κ_0	$\frac{d\kappa_0}{d\lambda}$	$\frac{d\kappa_0}{d\lambda}$
Extracted Value	2.356	4.228	2.356	4.220	4.173e-2	2.149e-1	1.990	2.315e-1	1.438	8.110e-1
Extracted Error	1.456e-6	1.322e-4	2.284e-7	2.105e-5	5.863e-6	9.147e-5	4.060	7.852e-5	1.266e-2	6.325e-2

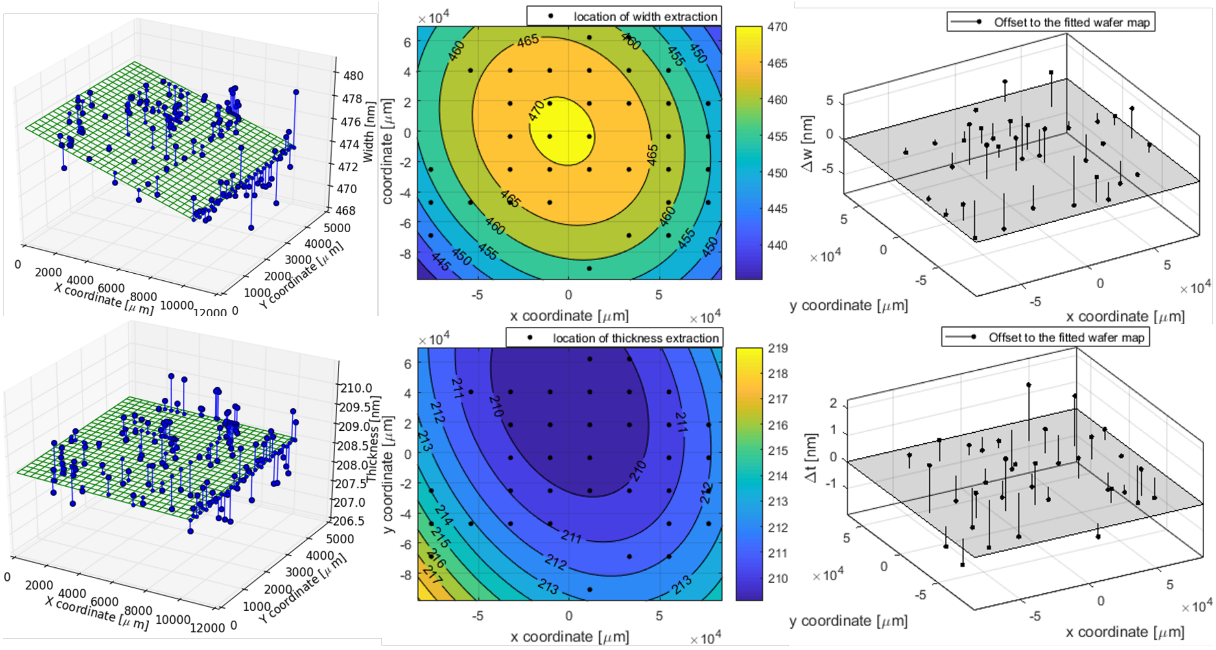

Figure 3. Top: linewidth. Bottom: thickness. (a) Extracted width map of the die. Blue solid dot: extracted value. Green grid: fitted map of extracted values using a linear function. (b) Systematic variation. (c) Random remnant. x and y coordinates give the locations of the MZIs on the die (a) or on the wafer (b,c).

accuracy[1]. The extracted linewidth on the die ranges from 468.9 nm to 479.5 nm (Fig. 3c) and thickness ranges from 207.6 nm to 209.6 nm (Fig. 3d). The standard deviations are 1.9 nm and 0.5 nm respectively.

We also measured the circuit in Fig.2a, framed by the dotted rectangle, over 35 dies over the wafer. These circuits shared the same position on every die. The extracted simple wafer map (Fig.3b) shows a clear location dependence of fabricated geometry. We fit a wafer map using a second-order bivariate polynomial. The linewidth exhibits dome-like trend which is the wafer-level systematic variation ranging from 445 to 475 nm. The residue (Fig. 3c) has a maximum of 5 nm. The wafer-level systematic variation of thickness exhibits slow-varying trend ranging from 209 to 216 nm. The residue (Fig. 3c) has a maximum of 2 nm.

4 CONCLUSION

In conclusion, we designed a folded two-stage-MZI that is very compact to extract process parameters. We applied the Restart-CMA-ES global optimization algorithm to extract multiple waveguide and DC parameters from the circuit using only two optical measurements. We mapped the fabricated linewidth and thickness of a waveguide from the extracted effective index and group index. We extracted die maps and simple wafer maps of the fabricated geometry. The compact circuit is promising for process monitoring and extracting granular wafer maps for performance evaluation and variability analysis.

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