Effects of a random process variation on the transfer characteristics of a fundamental photonic integrated circuit component

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ABSTRACT

Silicon photonics is rapidly emerging as a promising technology to enable higher bandwidth, lower energy, and lower latency communication and information processing, and other applications. In silicon photonics, existing CMOS manufacturing infrastructure and techniques are leveraged. However, a key challenge for silicon photonics is the lack of mature models that take into account known CMOS process variations and their effect on photonic component behavior. A key factor for the adoption of silicon photonics into high-yield manufacturing is to extend process design kits (PDKs) to include photonic process variability models that are aware of variations that may occur during the fabrication process.

We study the effect of a well-known random process variation, line edge roughness (LER), present in the lithography and etch process, on the performance of a fundamental component, the Y-branch, through virtual fabrication simulations. Ideally, the Y-branch transmits the input power equally to its two output ports. However, imbalanced transmission between the two output ports is observed when LER is imposed on the Y-branch, depending on the statistical nature (amplitude and correlation length) of the LER. The imbalance can be as low as 1% for small LER amplitudes, and reach up to 15% for large LER amplitudes. In addition, LER increases the excess loss compared to the nominal (smooth) case. Ensemble statistical virtual fabrication and FDTD photonic simulations across a range of LER amplitude and correlation lengths are reported. These results can be captured as worst-case corner models and included in variation-aware photonic compact models.

Keywords: Silicon photonics, line edge roughness, process variation, Y-branch.

1. INTRODUCTION

Silicon photonics is the subject of a substantial active research effort in both academic and industrial settings. In addition to providing a means to enable novel applications, silicon photonics also has exciting potential to revolutionize existing technologies. Among the most useful and immediate applications is the ability to enable higher data transfer rates. Faster connections and higher bandwidth can be achieved by using optical links and photonic integrated circuit (PIC) based transceivers to replace conventional circuitry for both data center and on-chip communications. Among the many other interesting applications of silicon photonics technology are biomedical sensing, Lab-On-A-Chip (where the whole system, including the optical sensors and the CMOS processing unit, can be integrated in the same chip, providing a compact, fast sensing system with real time measurements), and wave front engineering and beam steering of light from the Nanophotonic Phased Array (NPA).

One of the most compelling features of silicon photonics is its relatively seamless integration with existing CMOS fabrication technologies. That means, however, that it is subject to the same random and systematic process variations inherent in these incumbent manufacturing processes. One common source of process variation is Line Edge Roughness (LER), which occurs due to random fluctuations in the lithography tools, materials, and processes, as well as variations in the plasma etching process. Since LER affects the fabricated component geometry by introducing random perturbations to its sidewalls, it has a significant impact on the light-guiding abilities of waveguides and is the dominant contribution to propagation loss. These spatial perturbations can be characterized by two statistical parameters, the root mean square amplitude (referred to here as RMSA) and the correlation length (denoted CL). RMSA is the standard deviation of the displacements from and normal to the smooth (no roughness) surface at each point along the surface. The CL specifies the longitudinal spatial frequency content for the roughness along the surface: large correlation lengths will cut off high frequency components of the roughness, resulting in a “smoother” profile with fewer oscillations per unit length, and low correlation lengths will retain the higher-frequency parts of the roughness.

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To understand the impact of LER on PIC components, it is crucial to be able to model these effects. Previous work has considered LER impact on loss in simple silicon waveguides\(^8\). In this paper, we report the first study to consider the performance impact of LER on a more complicated fundamental photonic structure, a Y-branch, through virtual fabrication and optical simulation. The Y-branch serves as either a means to split one stream of light into two or combine two streams of light into one, which makes it a common element of a PIC (for example, two Y-branches can be used in a Mach-Zehnder interferometer)\(^2\). Three critical performance factors of the Y-branch will be considered: transmission imbalance at the two output ports, excess loss, and fractional reflection back into the input port (back reflection).

2. SIMULATION DETAILS

In this paper, we focus on a Y-branch silicon-on-insulator (SOI) waveguide splitter that was previously optimized to minimize backscatter at 1550 nm\(^9\). The silicon waveguiding regions have widths of 500 nm, thicknesses of 220 nm, and the overall component length is 15 \(\mu\)m as shown in Figure 1. The Y-branch is encased in SiO\(_2\) cladding extending 1 \(\mu\)m below the bottom silicon surface, and 1 \(\mu\)m above the bottom silicon surface (2 \(\mu\)m in total). The fundamental TE mode is launched into the input port and the output power is measured at the input port (to measure back reflection) and at the two output ports, which will be referred to as the “upper” and “lower” ports. The frequency range is chosen to span a wavelength window around the common operating wavelength of \(\lambda = 1550\) nm. All process modelling (including line edge roughness) is performed in Coventor’s SEMulator3D\(^10\) software. Figure 2 shows the Y-branch splitter output from SEMulator3D\(^8\) with the roughness applied to its sidewalls. The structures with the LER imposed on the sidewalls are then exported from SEMulator3D via a surface mesh and imported into Lumerical FDTD\(^11\) for optical simulation.

LER can be modelled by generating noise using a Fourier synthesis technique\(^12,13\), and applying that noise as geometric width perturbations to the sides of the structure. This technique generates roughness \(N\) that corresponds to the power spectrum of the Gaussian autocorrelation function defined by the LER amplitude \(RMSA\) and correlation length \(CL\). The autocorrelation function used is

\[
N = RMSA^2 e^{-\left(\frac{x}{\text{CL}}\right)^2}
\]

where \(x\) is the distance along the length of the structure. In this study, various \(RMSA\) and \(CL\) values are simulated. Amplitudes between 1 nm and 15 nm and correlation lengths between 10 nm and 50 nm are chosen to span realistic observed values reported in previous works\(^12-15\). For each \(RMSA\) and \(CL\) combination that is simulated, many structures (referred to here as instantiations) are generated with different random seeds for the edge noise in order to capture the statistical variation of the optical response.

Figure 1: Overview of the Y-branch geometry and its dimensions.
3. RESULTS

3.1 Transmission

With no LER applied, the ideal Y-branch transmits power equally between its two output ports, as seen in the simulation (dashed lines) in Figure 3. In this ideal case, we also see the expected wavelength dependence of transmission from $\lambda = 1.5 \, \mu m$ to $\lambda = 1.6 \, \mu m$, with maximum transmission of 0.4865 near 1550 nm, corresponding to excess loss (discussed further in Section 3.2) of about 3%. However, when LER is present, imbalanced transmission between the upper and lower ports is observed (solid lines in Figure 3). The amount of the imbalance changes for different instantiations of the same LER parameters, but the power generally favors one port over the other.

![Figure 2: (a) Overview of the Y-branch geometry generated from SEMulator3D® (top cladding not shown), (b) Close-up view showing line edge roughness applied to the Y-branch.](image)

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![Figure 3: Power splitting between the two output ports of the Y-branch. The dashed lines represent the ideal (no LER) case and the solid lines represent one LER case.](image)

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To explore the range of deviations from the ideal case in both the upper and lower ports, 200 instantiations for the same $RMSA$ and $CL$ (3 nm and 10 nm, respectively) are simulated, as shown in Figure 4. The imbalance in normalized power (magnitude of the difference in power between upper and lower ports) is as high as 2.7%. At $\lambda = 1550$ nm, the variations for each port are Gaussian as seen in Figure 5, with a mean that is almost equal to the ideal transmission value of 0.4862 and with a standard deviation of 0.004. Therefore, for the relatively small $RMSA$ and $CL$ values of 3 nm and 10 nm, the effect of LER is a modest degree of statistical variation of the transmission response that fluctuates about the ideal (smooth) result. In contrast, higher values of $RMSA$ and $CL$ can lead to more pronounced device degradation where the mean for both upper and lower ports is shifted from the ideal device mean. For $RMSA$ of 10 nm and $CL$ of 40 nm, the results in Figure 6 show a much larger spread in the upper and lower branch transmissions at $\lambda = 1550$ nm.
Figure 4: Normalized transmitted power for 200 different instantiations for roughness of $RMSA$ 3 nm and $CL$ 10 nm: (a) for the upper port and (b) for the lower port.

Figure 5: At $\lambda = 1550$ nm, $RMSA = 3$ nm, and $CL = 10$ nm: (a) distribution of the transmitted power for the upper port; (b) distribution of the transmitted power for lower port; (c) joint distribution plot of the transmitted power for the upper and lower ports. Mean of upper port is 0.4863 and that for the lower is 0.4845. Red point is nominal (no LER) case.
Figure 6: For RMSA = 10 nm and CL = 40 nm, joint distribution plot of the transmitted power for the upper and lower ports. Mean of upper port is 0.4727 and that for the lower is 0.4783. In this case the correlated transmissions are below the nominal, indicating substantial excess loss. Red point is nominal (no LER) case.

To further study the effect of RMSA and CL on imbalanced transmission at the two output ports, 50 instantiations for different RMSA and CL combinations are generated and analyzed. The resulting transmission for the upper ports at 1550 nm, shown in Figure 7, indicates that as RMSA or CL increases, the deviation of the transmission value from the ideal (smooth) case increases, which in turn means that the imbalance between the two output ports increases. The effect of RMSA on this imbalance is larger than the effect of CL, as shown in Table 1.

Figure 7: Distribution of the transmitted power for the upper port for: (a) RMSA = 3 nm and CL = 10 nm; (b) RMSA = 3 nm and CL = 40 nm; (c) RMSA = 10 nm and CL = 10 nm; (d) RMSA = 10 nm and CL = 40 nm.
Table 1. Maximum imbalance in transmission between Y-branch upper and lower ports for 50 instantiations carried for different amplitude and correlation length combinations at 1550nm wavelength.

<table>
<thead>
<tr>
<th>RMSA</th>
<th>CL 10 nm</th>
<th>CL 40 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 nm</td>
<td>2%</td>
<td>2.4%</td>
</tr>
<tr>
<td>10 nm</td>
<td>8%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Figure 8 shows the relative imbalance between the transmitted power between the Y-branch two output ports as a function of the LER amplitude and correlation length, for ten different combinations of $RMSA$ and $CL$; the radius of the bubble indicates the magnitude of imbalance. The highest imbalance increases more along the amplitude axis than along the correlation length axis, ranging from 1% for the smallest case ($RMSA = 1$ nm and $CL = 25$ nm) to 15% for the largest case ($RMSA = 15$ nm and $CL = 60$ nm).

While Figure 8 and Table 1 report the maximum imbalance percentage between the two output ports across the 50 instantiations for a single wavelength ($\lambda = 1550$ nm), Figure 9 shows the average imbalance (averaged for all the 50 instantiations) across the whole wavelength range. Figure 9 clearly shows that increasing the $RMSA$ (moving from the top row to the bottom row) has a greater impact on the imbalance than increasing the $CL$ (moving from the left column to the right column). The imbalance increases over all wavelengths sampled in both the increasing-$RMSA$ and increasing-$CL$ directions. At $\lambda = 1550$ nm specifically, the imbalance increases by $\sim 4x$ [3.864] when the $RMSA$ increases from 3 nm to 10 nm for $CL = 10$ nm and by $\sim 4x$ [4.2868] in the $CL = 40$ nm case. For increasing the $CL$ from 10 nm to 40 nm, the imbalance increases by $\sim 1.5x$ [1.5689] for the $RMSA = 3$ nm and by $\sim 1.5x$ [1.5186] in the $RMSA = 10$ nm cases. Thus we see that increasing the LER amplitude and correlation lengths both lead to increased imbalance in the output ports.

These effects can be attributed to the distortion of the junction region where the two output branches split. The ideal device and mode source are fully symmetric, hence the equal transmission in the two output ports for the ideal case shown in Figure 3 and Figure 10(a). However, LER introduces defects to the center region that break the symmetry of the device, causing more light to enter one branch than the other, as can be seen in Figure 10(b). As was mentioned in [9], for short values of $CL$ (as compared to the effective wavelength in the waveguide core, which is $\sim 440$ nm here), the propagating mode does not interact with the rapidly-oscillating sidewall roughness significantly. However, as $CL$ increases, there are fewer spatial oscillations per unit length, and the mode will begin to interact with the sidewall perturbations more, until $CL$ becomes much larger than the wavelength and the mode effectively sees no oscillations at all. Increasing the $RMSA$ has a more obvious effect on the junction-region distortion. Higher values of $RMSA$ will introduce larger peaks and valleys on the device sidewall surfaces, which cause larger deviations from the ideal symmetric junction shape and more power will inevitably end up in one output branch than the other.
Figure 9: Average imbalance between two output ports: (a) $RMSA = 3$ nm and $CL = 10$ nm; (b) $RMSA = 3$ nm and $CL = 40$ nm; (c) $RMSA = 10$ nm and $CL = 10$ nm; (d) $RMSA = 10$ nm and $CL = 40$ nm.

Figure 10: Electric field profiles at the Y-branch junction for the (a) smooth case and (b) LER case with $RMSA = 15$ nm and $CL = 60$ nm, where the roughness breaks the device symmetry and causes more power to go into the upper port for this instantiation.

### 3.2 Excess losses

Figure 6 indicates that a significant amount of incident power is being lost for the large $RMSA$ and $CL$ case, as the mean power for both ports have deviated significantly from the nominal value, and the highly anticorrelated upper and lower port transmissions are shifted downward from the nominal balanced transmission case. Several studies have been reported to characterize and minimize loss due to LER on straight SOI waveguides\(^7\),\(^1\),\(^4\),\(^6\). The perturbations introduced by LER to the Y-branch sidewalls not only affect the power imbalance between the two outputs, but also contribute to
increased propagation loss the light experiences as it travels down the Y-branch. Excess loss is defined here as ratio of the sum of the power in the two output ports relative to the power in the input port:

\[
EL = \frac{P_{\text{upper}} + P_{\text{lower}}}{P_{\text{input}}} \tag{2}
\]

This serves as a metric to determine how much energy is lost as the light travels the length of the structure (excess loss does not include the coupling loss from the source). Ideally, in the case of no losses, this ratio is 1 (0 dB). However, in real devices there are inevitable back reflections and scattering losses that make this ratio less than 1 (some negative value on a dB scale).

To analyze the effect of LER on excess loss for the Y-branch, 50 instantiations of the Y-branch with different RMSA and CL are simulated in the same manner as before, but this time the excess loss is recorded. The results for all 50 instantiations for \(\lambda = 1550\) nm are shown in Figure 11, along with the results for the nominal (smooth) case. We see that the LER causes an increase in the excess loss values in the majority of the instantiations, and the fraction of instantiations with loss values greater than the ideal case increases with increasing values of RMSA and CL. At large enough values (for example, \(RMSA = 15\) nm and \(CL = 60\) nm), all of the instantiations have higher excess loss than the ideal case. The maximum loss observed over all instantiations increases as well with increasing RMSA and CL. Figure 11 shows that excess losses can reach -0.8dB (16.8%) when \(RMSA = 15\) nm and \(CL = 60\) nm, while the excess loss is only about -0.12dB (3%) for the smooth case. The smooth case still suffers loss due to the junction region where the mode splits into the two paths\(^a\), which also occurs in the LER cases. This means that losses greater than this nominal case can be attributed to the LER. Thus, in addition to causing imbalanced transmission between the two output ports of the Y-branch, LER also increases the excess loss that the light experiences as it propagates.

![Figure 11](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Figure 11: The Y-branch excess loss variation from the nominal case (red line) with LER for 50 instantiations at the center wavelength of 1550 nm with LER. (a) \(RMSA = 3\) nm and \(CL = 10\) nm, (b) \(RMSA = 7\) nm and \(CL = 30\) nm, (c) \(RMSA = 12\) nm and \(CL = 50\) nm, (d) \(RMSA = 15\) nm and \(CL = 60\) nm. Note differences in vertical scales.
3.3 Back reflection

In sourced waveguiding structures, it is also instructive to analyze the back reflection, which is the fractional power returned to the input port. Since the excess loss defined in Section 3.2 is the ratio of the total output power (upper port plus lower port) to the input port, the power lost to back reflection is included in the excess loss. However, back reflection can be measured separately in FDTD simulation, which will decouple its effect on excess loss from that of propagation loss.

Figure 12 shows the back reflection, as a percentage of total incident power, for four combinations of $RMSA$ and $CL$. The LER has a lesser effect on the back reflection than on the total excess loss reported in Section 3.2. Although the back reflection can reach higher values as the $RMSA$ and $CL$ increase, as shown in Figure 12, and the fraction of instantiations in which the back reflection goes above the nominal case also increases with $RMSA$ and $CL$, the loss values even in the worst-case scenario never exceed 1%. Despite the fact that the back reflection losses decrease in almost half of the instantiations, the overall losses still increase with $RMSA$ and $CL$ because the back reflection is very small compared to the excess loss.

![Figure 12](image-url)

Figure 12: The Y-branch back reflection variation from the nominal case (red line) with LER for 50 instantiations at the center wavelength of 1550 nm with LER. (a) $RMSA = 3$ nm and $CL = 10$ nm, (b) $RMSA = 7$ nm and $CL = 30$ nm, (c) $RMSA = 12$ nm and $CL = 50$ nm, (d) $RMSA = 15$ nm and $CL = 60$ nm. Note differences in vertical scales.

4. CONCLUSION

Line edge roughness with different combinations of experimentally-observed RMS amplitude and correlation length values is applied to many instantiations of a Y-branch through virtual fabrication, and the optical transmission characteristics of the resulting structures are studied. The results show that LER causes the optical power to split to some ratio that is not 50% – 50% between the upper and lower port, which differs substantially from the ideal (smooth) case where the power is split evenly between the two output ports. The amount of the imbalance is dependent on the statistical parameters of the LER (namely amplitude and correlation length). The largest imbalance between the two output ports
for a single run over all the wavelengths is 15% for LER amplitude of 15 nm and correlation length of 60 nm at an operating wavelength of 1550 nm, which represents a substantial device performance offset from the nominal case. However, this imbalance is relatively small (1%) for LER amplitude of 1 nm and correlation length of 25 nm. The effects from both the LER amplitude and correlation length are considered jointly, and it is seen that the amplitude has a greater impact on the imbalance than correlation length. In addition, LER increases the excess losses the Y-branch experiences, as compared to the nominal case. These results indicate that component performance can be adversely impacted by random variations in the lithography and etch processes, depending on the statistical nature of the LER perturbations. These results motivate the desirability of advanced lithography nodes where LER is reduced, as well as the need to compensate and/or account for such variations in the design and/or manufacturing process.

The analysis of this process variation, and others, will help in developing variation-aware models that will enable photonic designers to predict and optimize behavior, performance, and yield of complex silicon photonic devices and circuits in the face of unavoidable manufacturing variation.

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