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# Fabrication aware design of sensitive photonic devices

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## ABSTRACT

Since the turn of the century, Silicon Photonics (SiPh) has advanced data communication and computing via diverse integrated optical functions and multiplexing strategies. However, conventional design methodologies limit scalability, and inverse designs lead to features sensitive to fabrication process variations. This talk explores the harnessing of machine learning (ML) to predict and rectify these deviations in the design phase. This technique enhances design fidelity and device performance, while facilitating smaller design features, bypassing constraints of traditional methods. Highlighting PreFab, an innovative ML technology, applicable to both conventional and inverse designs, it predicts and corrects fabrication deviations, enabling refined design processes.

**Keywords:** Silicon Photonics, Nanophotonics, Advanced Nanomanufacturing, Topological Optimization, AI/ML Applications in Predictive Analytics

## 1. INTRODUCTION

Over the past decade, advances in topological optimization have significantly enhanced the compactness of silicon-based photonic integrated circuits. This optimization process has led to designs with increasingly smaller features, which present considerable challenges in terms of design fidelity. These challenges stem primarily from the limitations of current fabrication processes, which struggle to accurately reproduce intricate shapes. Additionally, there is uncertainty regarding the precision with which silicon materials can be etched, further complicating the realization of these sophisticated designs. This practical limitation tempers the potential benefits and impact that inverse design methods could have in real-world applications. The discrepancy between the theoretical design capabilities and the practical constraints of fabrication processes thus remains a critical hurdle in fully harnessing the advancements in topological optimization for deployed silicon photonics systems.

## 2. PREFAB – PREDICTION

Leveraging the power of deep learning, we have now entered an era where it is possible to accurately predict deviations that may occur during the fabrication process. This technological advancement equips designers with a comprehensive understanding of how structural variations can impact their designs [1]. The introduction of a virtual fabrication process, termed PreFab, marks an interesting milestone in this context. PreFab has exhibited capabilities in forecasting the actual performance of various photonic devices that are sensitive to fabrication nuances. Examples include a three-channel mode demultiplexer [2] and a mode selective phase shifter [3], as illustrated in figure 1. While there is a 66% difference between the insertion loss obtained through simulation between the nominal design and the resulting structure (SEM image), the simulation of the predicted structure is only 8% off (i.e., 0.39 dB versus 0.36 dB). In terms of modal crosstalk prediction, PreFab allows to more accurately predict the performance with 7% difference relative to 31% difference between the resulting fabricated structure and the nominal design layout. In our work reported in [3], the selectiveness of the fabricated mode-selective phaser shifter is predicted using the PreFab prediction of the fabricated structures.

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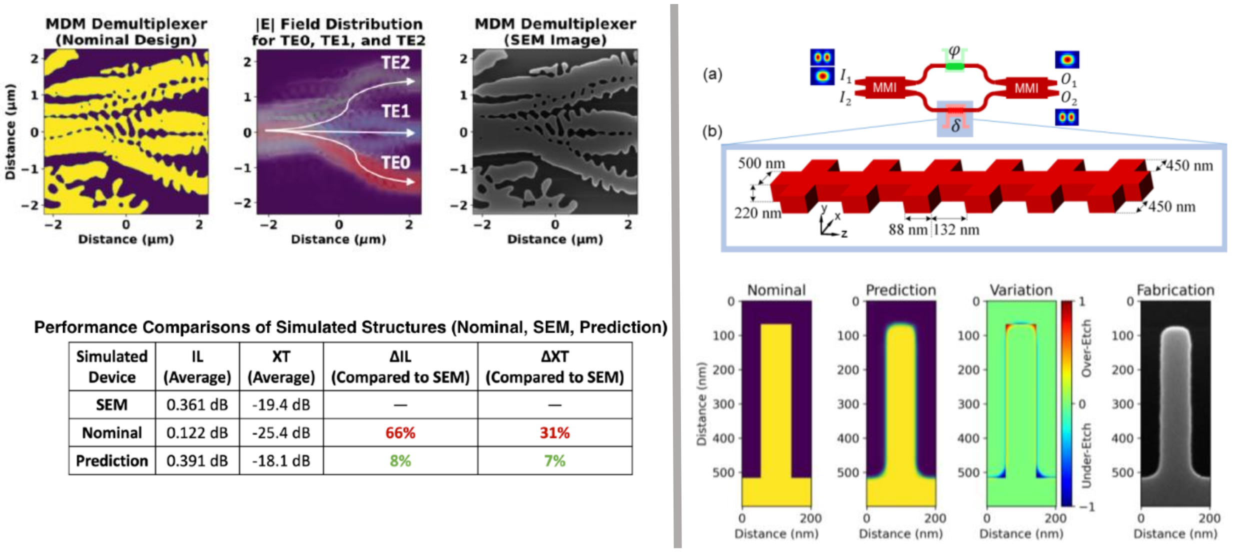
The benefits of providing accurate predictions have significant implications. By providing a realistic preview of how designs are likely to behave post-fabrication, PreFab enables designers to make more informed, fabrication-aware decisions. This foresight facilitates the optimization of design layouts, allowing for strategic adjustments that enhance design performance. Additionally, it contributes to an overall improvement in system performance, addressing critical issues that have long plagued the field of photonics.

Moreover, this approach opens doors to iterative design enhancements, where designers can refine their creations in a virtual environment before actual fabrication. This iterative cycle, supported by deep learning predictions, reduces the time and resources spent on physical prototyping, leading to more efficient development cycles and quicker deployment of advanced photonic devices. The integration of deep learning with virtual fabrication thus represents a transformative step in the field of photonics, potentially revolutionizing the way photonic integrated circuits are designed, tested, and deployed.



**Performance Comparisons of Simulated Structures (Nominal, SEM, Prediction)**

| Simulated Device | IL (Average) | XT (Average) | ΔIL (Compared to SEM) | ΔXT (Compared to SEM) |
|---|---|---|---|---|
| **SEM** | 0.361 dB | -19.4 dB | — | — |
| **Nominal** | 0.122 dB | -25.4 dB | 66% | 31% |
| **Prediction** | 0.391 dB | -18.1 dB | 8% | 7% |

Figure 1: The left panel showcases the layout, field distribution, and a scanning electron microscope (SEM) image of a fabricated, topologically optimized three-channel mode division multiplexing (MDM) demultiplexer. The accompanying table provides a detailed comparison, illustrating the efficacy of the PreFab virtual fabrication process in accurately predicting the actual insertion loss (IL) and modal crosstalk (XT) performance metrics of the device [2]. The right panel displays the intricate subwavelength grating structures incorporated within a Mach-Zehnder interferometer, designed for a mode-selective thermo-optic phase shifter. It also includes the PreFab predictions, highlighting the anticipated structural modifications due to over-etching in the fabrication process [3]. This figure collectively demonstrates the advanced capabilities of PreFab in bridging the gap between theoretical design and practical fabrication outcomes in complex photonic devices.

## 3. PREFAB – CORRECTION

The implementation of deep learning in virtual fabrication tools like PreFab has markedly enhanced the design fidelity between fabricated photonic devices and their nominal designs. This advancement is particularly significant in the realm of photonics, where even minute deviations from the intended design can lead to substantial performance degradation. PreFab, trained with scanning electron microscope (SEM) images of devices fabricated through specific processes, offers an invaluable capability to adjust and correct device layouts before the final GDS files are sent for fabrication [4]. This preemptive correction ensures that the fabricated devices align more closely with their intended designs, thereby improving performance and reducing the need for costly and time-consuming iterative fabrication cycles.

In figure 2, we illustrate the profound impact of PreFab in correcting two types of sensitive photonic devices: 1) a Bragg structure, and 2) a resonating nanobeam. The Bragg structure, typically used for filtering specific wavelengths, and the resonating nanobeam, which can be used in sensing and switching applications, are both highly sensitive to fabrication errors. The figure showcases how PreFab's predictive capabilities successfully identify and rectify potential deviations in these structures.

The corrected designs, as visualized in figure 2, demonstrate restored optical performances, closely mirroring the intended theoretical outcomes. Indeed, the corners of the Bragg grating are sharpened enabling a re-narrowing of the optical bandwidth from 18 to 13 nm, with a repositiong of the central wavelength to 1529 nm. The resonating nanobeam exhibits restored holes in the structure corrected using PreFab with an increased Q-factor, from 2,700 to 5,000, accompanied with an increased transmission, from 72% to 80%. The before-and-after comparison vividly illustrates the effectiveness of PreFab in enhancing the fidelity of the photonic devices. This represents a significant leap forward in photonics manufacturing, ensuring higher consistency, reliability, and efficiency in the production of complex photonic components. Ultimately, PreFab's integration into the fabrication workflow stands as a testament to the transformative power of deep learning in advancing the precision and practicality of photonic device manufacturing.

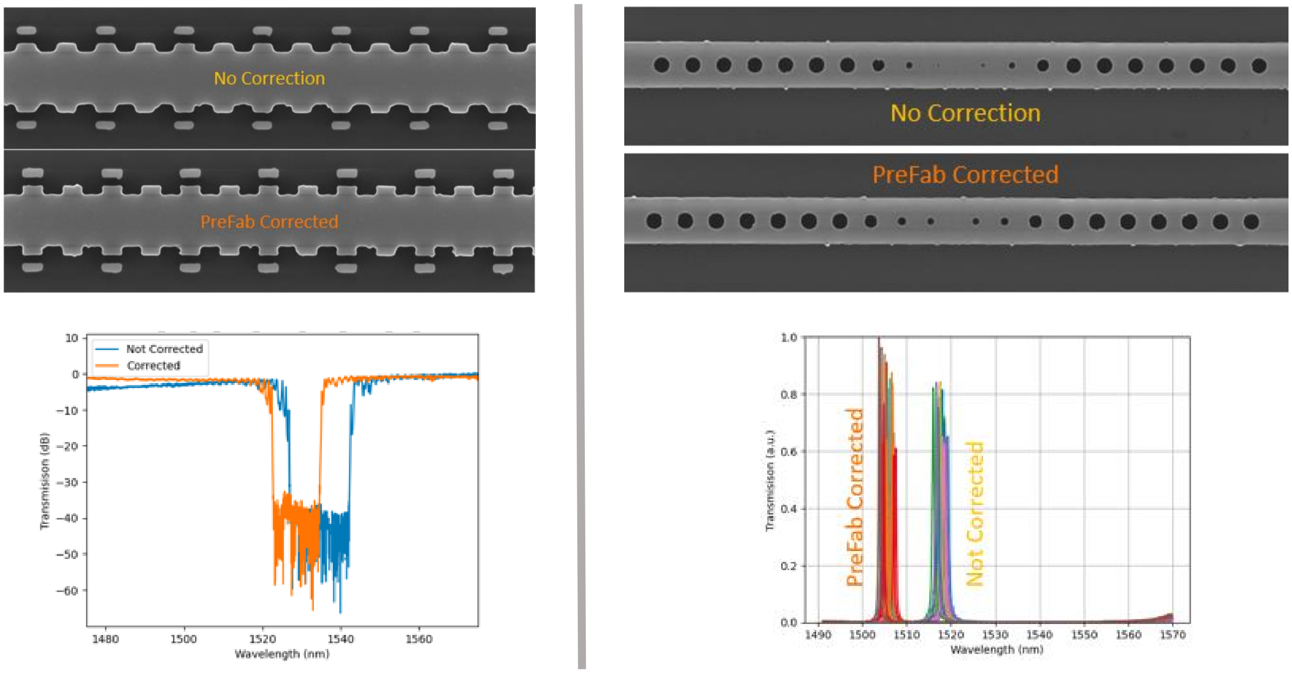


Figure 2: Illustration of Enhanced Design Fidelity via PreFab Virtual Fabrication Corrections. (Left) Top – Comparison between the original and PreFab-corrected layouts of a Bragg grating structure featuring loading elements; Bottom – Restoration of the optical bandwidth and central wavelength achieved through layout correction. (Right) Top – Juxtaposition of the original and PreFab-corrected layouts of a nanobeam, focusing on the restoration of eroded holes; Bottom – Enhancement of the Q-factor and transmission efficiency as a result of the layout corrections for several fabricated structures. This figure vividly demonstrates the capability of PreFab in refining photonic device designs for optimized performance.

## 4. PREFAB AI PHOTONICS – THE ACCESSIBLE TOOL

PreFab AI Photonics has emerged as a pioneering solution in the realm of silicon photonics, offering specialized models tailored for the NanoSOI fabrication service provided by Applied Nanotools Inc. This service is particularly instrumental for designers seeking rapid prototyping of silicon photonic integrated circuits. The unique proposition of PreFab lies in its ability to offer predictive insights and corrective measures for design layouts through its open-access models [5,6]. This integration not only streamlines the design-to-fabrication process but also ensures higher fidelity between the designers' intended layouts and the final fabricated structures.

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