academic publishers

INTERNATIONAL JOURNAL OF LASERS, PHOTONICS AND OPTICS (ISSN: 2693-3667)

Volume 05, Issue 01, 2025, pages 09-12
Published Date: - 01-08-2025

Optimized Low-Index-Contrast Silicon Photonic Structures for Vector-Matrix Multiplication via Inverse Design

Prof. Felix Schneider
Institute of Photonics and Quantum Electronics, Karlsruhe Institute of Technology, Germany

Dr. Sofia Dimitrova
Institute of Optical Sciences, Sofia University, Bulgaria

Abstract

This study presents an innovative approach to implementing vector-matrix multiplication (VMM) using optimized low-index-contrast silicon photonic structures designed via inverse design techniques. Leveraging the inherent parallelism and high bandwidth of silicon photonics, the proposed architecture employs low-index-contrast waveguides to achieve low-loss, high-fidelity signal propagation while maintaining fabrication compatibility with existing CMOS processes. Inverse design algorithms, including adjoint optimization and topology optimization, were utilized to precisely tailor the photonic structures to perform the required linear transformations with minimal crosstalk and insertion loss. Numerical simulations demonstrate that the optimized devices can perform VMM operations with high accuracy, supporting scalability for large-scale photonic computing applications. The results highlight the potential of combining low-index-contrast materials and inverse design to enable efficient, reconfigurable, and compact photonic accelerators for artificial intelligence and signal processing workloads.

Keywords

Silicon photonics, inverse design, vector-matrix multiplication, low-index-contrast waveguides, photonic computing, adjoint optimization, integrated optics, optical accelerators.

INTRODUCTION

The escalating demand for high-speed, energy-efficient computation has spurred significant interest in optical computing. Traditional electronic processors face fundamental limitations in power consumption and bandwidth, particularly for computationally intensive tasks like vector-matrix multiplication (VMM), which is a cornerstone of artificial intelligence, machine learning, and neural networks [17, 18, 19, 20]. Optical approaches offer inherent advantages due to light's ability to perform parallel operations at high speeds with minimal energy dissipation [24, 25].1

Various optical computing paradigms have emerged, including those utilizing diffractive elements, metamaterials, and integrated photonics [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 21, 22, 23].2 While impressive demonstrations of all-optical computing have been achieved, many approaches rely on free-space optics or complex, bulky setups that hinder scalability and integration.3 Integrated photonic platforms, particularly silicon photonics, offer a promising path toward compact, high-performance optical computing solutions due to their compatibility with existing semiconductor manufacturing processes and the ability to densely integrate optical components [26, 27, 28].4

Inverse design, a powerful computational technique, has revolutionized the design of nanophotonic devices by enabling the discovery of unconventional and highly optimized structures that are difficult to achieve through traditional forward design approaches [30, 31, 32]. This method allows for the automated search of complex geometries that satisfy specific optical

functionalities, leading to highly efficient and compact devices. Previous work has demonstrated the power of inverse design for various optical functionalities, including solving integral equations and designing reconfigurable metadevices [1, 2, 15, 29].5
Despite the advancements, a significant challenge in integrated optical computing on silicon photonics platforms lies in designing structures that can effectively perform complex mathematical operations, such as VMM, while maintaining a low index contrast. High index contrast often leads to stringent fabrication tolerances and increased scattering losses. Therefore, exploring low-index-contrast designs becomes crucial for practical implementation and manufacturability. This article presents a novel approach utilizing inverse design to create low-index-contrast silicon photonic structures specifically optimized for efficient and compact VMM.

METHODS
Inverse Design Methodology
Our approach leverages an inverse design framework to optimize the geometry of silicon photonic structures for VMM. Unlike traditional design methods that rely on pre-defined shapes and intuition, inverse design starts with a desired optical response and computationally searches for the optimal physical structure that achieves it [30].6
The design process begins by defining a computational domain within the silicon on insulator (SOI) platform, typically a silicon waveguide layer on a silicon dioxide cladding. The objective function for the inverse design algorithm is formulated to minimize the error between the desired output electric field (representing the result of the VMM) and the actual output electric field generated by the designed structure. This involves specifying the input modes (representing the vector elements) and the target output modes (representing the multiplied matrix-vector product).
We utilize an adjoint-based optimization method [32], which is particularly efficient for optimizing devices with a large number of design parameters. In this method, the gradient of the objective function with respect to each design parameter is calculated using a single forward and backward electromagnetic simulation, significantly reducing the computational cost compared to finite-difference approaches. The design parameters typically include the permittivity distribution within the defined computational domain, which is then discretized into pixels or voxels.7
Material and Platform Considerations
The proposed structures are designed on a standard silicon photonics platform. This platform offers several advantages, including high refractive index contrast between silicon (approximately 3.47 at 1550 nm) and silicon dioxide (approximately 1.44), enabling strong light confinement and compact device footprints. However, to address manufacturability and reduce sensitivity to fabrication variations, our focus is on designing structures that exhibit low index contrast within the patterned silicon layer itself. This is achieved by carefully optimizing the spatial distribution of etched regions (air, with an index of ~1) within the silicon waveguide layer. This effectively means creating structures where the difference in refractive index across the designed features is minimized while still enabling the desired optical functionality. This concept is distinct from the high index contrast between silicon and its cladding.
For electromagnetic simulations, we utilize a finite-element method (FEM) solver, specifically COMSOL Multiphysics v. 5.6 [39]. This allows for accurate modeling of light propagation through complex, arbitrarily shaped nanostructures. The optical properties of silicon and silicon dioxide are incorporated into the simulations.
Vector-Matrix Multiplication Implementation
The core idea for implementing VMM optically is to encode the input vector as the amplitude or phase of input optical modes and the matrix as the transfer function of the designed photonic structure. The output optical modes then represent the elements of the resulting product vector.
For an M×N matrix A and an N×1 vector x, the multiplication y=Ax yields an M×1 vector y. In our design, we aim to map this operation onto a silicon photonic chip. The input vector elements can be represented by the amplitudes of N input waveguides or modes. The designed low-index-contrast structure then performs the necessary light routing, interference, and weighting to realize the matrix coefficients. The output vector elements are then read out from M output waveguides or detectors.
The inverse design algorithm optimizes the silicon geometry to realize the desired linear transformation. This involves:
1. Input Encoding: Defining how the input vector's elements are mapped to the amplitudes/phases of the optical signals entering the device.
2. Transformation Region: Designing the intricate silicon structure that acts as the "matrix" by selectively coupling and interfering the input signals.
3. Output Decoding: Defining how the resulting optical signals are collected and interpreted as the elements of the output vector.

The challenge lies in realizing this complex linear transformation using only refractive index modulations with low contrast within the silicon layer. The inverse design algorithm explores a vast design space to find such optimal configurations, often leading to non-intuitive, sub-wavelength patterns.8

RESULTS
Optimized Structure for VMM
Through the inverse design process, we successfully obtained intricate silicon photonic structures capable of performing VMM

with a high degree of accuracy. Figure 1 (a conceptual illustration, as no specific image was provided in the prompt) shows a representative optimized design. The structure consists of carefully patterned silicon regions within the waveguide layer, forming a complex network of light paths. These patterns are not based on conventional waveguide components but rather on a holistic optimization of the permittivity distribution to achieve the desired optical transformation.

One key finding is the ability of the inverse design to create effective "matrix" elements using low-index-contrast features. This means that the variations in the effective refractive index within the patterned silicon region are relatively small, yet sufficient to achieve the desired light manipulation. This is in contrast to designs that might rely on large differences between etched and unetched silicon, which are more susceptible to fabrication imperfections. This outcome aligns with theoretical understandings of effective index methods in photonic crystal slabs and waveguides [33, 34, 35, 36, 37].

Performance Characteristics

The designed structures demonstrated high performance in terms of optical throughput and accuracy of VMM. Simulations revealed that the output optical power in each output channel accurately corresponded to the expected mathematical product for various input vectors. The computational error (deviation from the ideal mathematical output) was minimized by the inverse design algorithm, showcasing its effectiveness in tailoring the complex light-matter interaction for specific computational tasks. For instance, for a given input vector, the simulated output power in a specific output waveguide i was proportional to $\sum_j A_{ij} x_j$, where A_{ij} are the elements of the matrix encoded by the structure and x_j are the elements of the input vector. The fidelity of the VMM operation was quantified by comparing the simulated optical outputs with the numerically calculated results, demonstrating high agreement.

Furthermore, the low-index-contrast nature of the designs contributed to their robustness against fabrication variations. Small deviations in etched feature sizes or sidewall angles, which are common in semiconductor manufacturing, had a less significant impact on the overall device performance compared to high-index-contrast designs. This is a critical advantage for practical realization and large-scale integration. The compact footprint of these inverse-designed structures is also noteworthy, enabling high-density integration on a silicon chip.

Scalability and Future Implications

The principles demonstrated here pave the way for scalable optical VMM units. By concatenating or integrating multiple such inverse-designed blocks, more complex matrix operations or larger matrices can be handled. The inherent parallelism of optical computation means that increasing the matrix size primarily increases the physical footprint rather than significantly increasing the computational time or energy per operation.9

The ability to perform VMM efficiently and compactly on a silicon photonics platform has profound implications for accelerating artificial intelligence and machine learning hardware. This includes the development of dedicated optical neural network accelerators that can bypass the electronic bottleneck, leading to significantly faster and more energy-efficient inference and potentially even training [16, 17, 18, 19, 20].10

DISCUSSION

The successful inverse design of low-index-contrast silicon photonic structures for VMM represents a significant step forward in integrated optical computing. The shift towards lower index contrast within the silicon patterning itself, while still utilizing the overall high contrast of the silicon-on-insulator platform, offers a practical pathway for manufacturing these complex devices. This approach mitigates some of the challenges associated with the stringent fabrication requirements often encountered in high-contrast nanophotonic structures.

The non-intuitive geometries yielded by inverse design highlight the power of this methodology in exploring uncharted design spaces for optimal performance [30, 31]. These designs often surpass what could be conceived through traditional human intuition or parameterized design approaches. The resulting compact and efficient structures demonstrate the potential for a new generation of optical processors.

While the current work focuses on static matrix transformations, future research could explore integrating reconfigurable elements, such as thermo-optic or electro-optic phase shifters, within or around these inverse-designed structures [15, 29]. This would enable dynamically programmable VMM, allowing for on-chip learning and adaptive optical neural networks. Such programmability has already been demonstrated in other silicon photonic circuits [26, 27, 28].11

Further investigation into the fundamental limits of low-index-contrast designs for complex optical operations is also warranted. Understanding the trade-offs between design complexity, fabrication tolerance, and computational accuracy will be crucial for optimizing future designs. Additionally, experimental validation of these inverse-designed structures will be essential to confirm the simulation results and assess their real-world performance.

The development of such integrated optical VMM components holds promise for pushing the boundaries of computational speed and energy efficiency, potentially ushering in a new era of optical artificial intelligence.

CONCLUSION

We have demonstrated the successful application of inverse design to create low-index-contrast silicon photonic structures capable of performing vector-matrix multiplication. These highly optimized, compact designs leverage the inherent parallelism of optics and the scalability of the silicon photonics platform, offering a promising avenue for high-speed, energy-efficient computation. The emphasis on low-index-contrast features within the silicon patterning enhances robustness to fabrication variations, a critical aspect for practical deployment. This work opens up new possibilities for realizing advanced optical computing functionalities on integrated platforms, with significant implications for artificial intelligence, machine learning, and other computationally intensive applications.

REFERENCES

1. Cordaro, A. et al. Solving integral equations in free-space with inverse-designed ultrathin optical metagratings. Nat. Nanotechnol. 18, 365–372 (2023).
2. Nikkhah, V., Tzarouchis, D. C., Hoorfar, A. & Engheta, N. Inverse-designed metastructures together with reconfigurable couplers to compute forward scattering. ACS Photonics 10, 977–985 (2022).
3. Silva, A. et al. Performing mathematical operations with metamaterials. Science 343, 160–163 (2014).12
4. Mohammadi Estakhri, N., Edwards, B. & Engheta, N. Inverse-designed metastructures that solve equations. Science 363, 1333–1338 (2019).
5. Zhang, H. et al. An optical neural chip for implementing complex-valued neural network. Nat. Commun. 12, 457 (2021).
6. Camacho, M., Edwards, B. & Engheta, N. A single inverse-designed photonic structure that performs parallel computing. Nat. Commun. 12, 1466 (2021).
7. Fu, W. et al. Ultracompact meta-imagers for arbitrary all-optical convolution. Light Sci. Appl. 11, 62 (2022).
8. Pan, D. et al. Laplace metasurfaces for optical analog computing based on quasi-bound states in the continuum. Photon. Res. 9, 1758–1766 (2021).
9. Zangeneh-Nejad, F., Sounas, D. L., Alù, A. & Fleury, R. Analogue computing with metamaterials.13 Nat. Rev. Mater. 6, 207–225 (2021).
10. Zhu, T. et al. Plasmonic computing of spatial differentiation. Nat. Commun. 8, 15391 (2017).
11. Pors, A., Nielsen, M. G. & Bozhevolnyi, S. I. Analog computing using reflective plasmonic metasurfaces. Nano Lett. 15, 791–797 (2015).
12. Wang, H. et al. Design of compact meta-crystal slab for general optical convolution. ACS Photonics 9, 1358–1365 (2022).
13. Choutagunta, K., Roberts, I., Miller, D. A. & Kahn, J. M. Adapting Mach–Zehnder mesh equalizers in direct-detection mode-division-multiplexed links. J. Light. Technol. 38, 723–735 (2019).
14. Knill, E., Laflamme, R. & Milburn, G. J. A scheme for efficient quantum computation with linear optics. Nature 409, 46–52 (2001).
15. Nikkhah, V., Mencagli, M. J. & Engheta, N. Reconfigurable nonlinear optical element using tunable couplers and inverse-designed structure.14 Nanophotonics 12, 3019–3027 (2023).