

Programmable Inverse-designed Devices

CNF Project Number: 2971-21

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Primary Source(s) of Research Funding: National Science Foundation (award CCF-1918549)

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Primary CNF Tools Used: Oxford PECVD, PVD75 Sputter, Disco Dicing Saw

Abstract:

Inverse design has emerged as a powerful approach in nanophotonics, enabling compact devices with complex functionalities that are difficult to realize using conventional hand-designed layouts. Yet its practical scale remains limited by discrepancies between simulated and real-world devices, long and costly fabrication iterations, and the inflexibility of static lithographic devices. Here we demonstrate an in situ inverse-design platform based on a two-dimensionally programmable thin-film lithium niobate slab waveguide. Patterned illumination of a photoconductive layer redistributes the electric field across the chip, producing optically controlled electro-optic modulation that sculpts the refractive-index distribution over $\sim 10,000$ programmable regions. This architecture removes the need to fabricate a new nanostructure for each function and enables reconfiguration in 1.5 s with no known rewriting limit. Using the same physical device, we realized diverse photonic functions without the need to modify existing device or optical setup, including 4×4 mode permutations with -28 dB crosstalk, 4×4 Hermite–Gaussian mode demultiplexing with -15 dB crosstalk, 8×8 mode permutations, and matrix–vector multiplication. We also demonstrated in situ trained broadband operation from 1500 nm to 1600 nm and wavelength demultiplexing of 1310 nm and 1550 nm signals. Such a programmable platform could also enable applications for reconfigurable and on-chip spatial modulation in optical telecommunications. Our in situ way of inverse design can also extend to conventional inverse design to improve performance.

Summary of Research:

Integrated photonics enables compact, scalable, and energy-efficient systems for communications, sensing, signal processing, and computing. However, conventional photonic devices are typically assembled

from hand-designed components whose footprints, fabrication sensitivity, and performance constraints limit their scalability. Inverse design addresses these limitations by using computational optimization to explore large design spaces and discover compact, non-intuitive structures[1]. Nevertheless, conventional inverse design still depends on accurate numerical simulation followed by sophisticated cleanroom fabrication and experimental characterization. As device complexity increases, computational costs grow rapidly, simulation–experiment gaps become more significant, and repeated fabrication cycles become increasingly expensive[2]. Moreover, lithographically defined devices are fixed after fabrication, preventing post-fabrication correction and limiting their ability to perform multiple or changing functions.

Programmable photonics offers a route to overcome these constraints by allowing device behavior to be modified and optimized after fabrication. Here, this capability is realized using a two-dimensionally programmable thin-film lithium-niobate slab waveguide whose refractive-index distribution is controlled by patterned illumination of a photoconductive layer[3], as shown in Figure 1. Experimental measurements are incorporated directly into the optimization loop through physics-aware training, enabling the programmed index pattern to adapt to the actual device rather than relying solely on simulation. The platform can be reconfigured in approximately 1.5 seconds and supports repeated programming without a known rewriting limit. Using a single chip, it implements 4×4 and 8×8 mode permutations, Hermite–Gaussian mode demultiplexing, matrix–vector multiplication, wavelength-independent operation from 1500 to 1600 nm, and wavelength demultiplexing between 1310 and 1550 nm. These demonstrations establish in situ inverse design as a promising approach for rapidly creating diverse photonic functions while reducing fabrication iterations and the simulation–reality gap.

Inverse-designed Single-wavelength Devices

At an operating wavelength of 1550 nm, the programmable waveguide was in situ inverse-designed to implement several representative spatial transformations, including 4×4 and 8×8 Gaussian-mode permutations, 4×4 Hermite–Gaussian mode demultiplexing, and 4×4 matrix–vector multiplication. The results are shown in Figure 2. During training, each input mode was generated sequentially, the corresponding output intensity was measured, and the illumination pattern was optimized using a loss function that promoted coupling to the desired output while suppressing the largest crosstalk channel. The optimization converged within approximately 7–20 minutes, achieving maximum crosstalk values of -27 dB for the 4×4 permutation, -15 dB for Hermite–Gaussian demultiplexing, and -13 dB for the 8×8 permutation. The platform also reproduced ten independently trained random matrices, demonstrating that the same physical device can be reprogrammed to perform general linear transformations.

Inverse-designed Broadband Devices

The same in situ inverse-design approach was extended to produce wavelength-independent operation across the 1500–1600 nm telecommunications band. Rather than optimizing the device at only one wavelength, the training loss combined experimental performance measured at 1500 and 1600 nm, encouraging a single illumination pattern to satisfy the target transformation at both spectral endpoints. This method was applied to random matrix generation, 4×4 and 8×8 mode permutations, and Hermite–Gaussian mode demultiplexing, with performance characterized across the full 100 nm range at 1 nm resolution. The results are shown in Figure 3. The 4×4 permutation maintained crosstalk below -20 dB, while the Hermite–Gaussian demultiplexer and 8×8 permutation remained below approximately -10 dB, demonstrating that in situ optimization can suppress wavelength-dependent dispersion and preserve device functionality over a broad optical bandwidth.

Inverse-designed Wavelength Demultiplexer

In contrast to the broadband devices, which were optimized to behave similarly across wavelength, the wavelength demultiplexer was designed to deliberately exploit dispersion and route 1310 nm and 1550 nm signals to different output channels. A task-specific digital model was trained using illumination patterns and experimental measurements collected at 1550 nm, with augmented patterns introduced to capture device distortions and improve model robustness. During physics-aware training, the two laser wavelengths were

injected sequentially through a shared optical path, and the measured losses at both wavelengths were combined so that the programmed pattern simultaneously directed each wavelength toward its designated output. The results are shown in Figure 4. The resulting two-channel wavelength demultiplexer achieved a maximum crosstalk of approximately -9 dB.

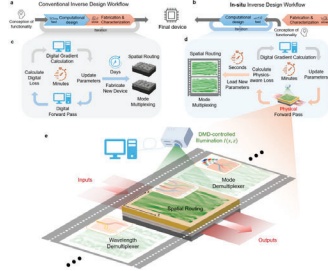


Figure 1.

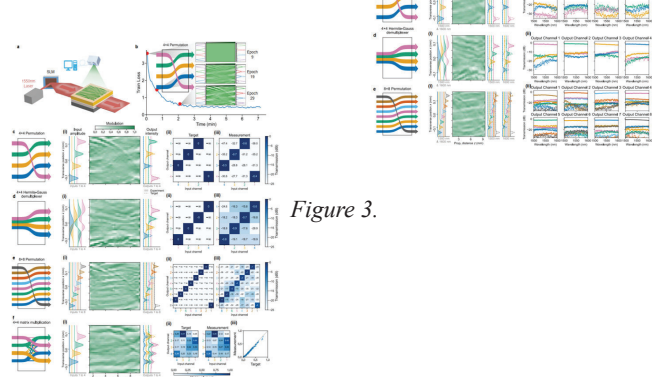


Figure 2.

Figure 3.

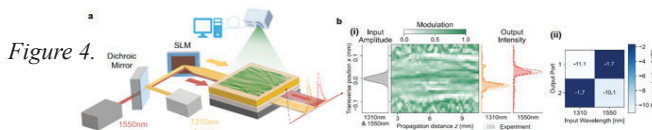


Figure 4.

Acknowledgements:

PLM gratefully acknowledges financial support from a David and Lucile Packard Foundation Fellowship.

The authors wish to thank NTT Research for their financial and technical support.

We gratefully acknowledge the Air Force Office of Scientific Research for funding under Award Number FA9550-22-1-0378.

This work was performed in part at the Cornell NanoScale Facility, a member of the National Nanotechnology Coordinated Infrastructure (NNCI), which is supported by the National Science Foundation (Grant NNCI-2025233).

References:

- [1] P. L. McMahon, *Nature Reviews Physics* 5, 717 (2023).
- [2] T. Onodera, M.M. Stein, B.A. Ash, M.M. Sohoni, M. Bosch, R. Yanagimoto, M. Jankowski, T. P. McKenna, T. Wang, G. Shvets, M. R. Shcherbakov, L.G. Wright, and P.L. McMahon, Arbitrary control over multimode wave propagation for machine learning. *Nat. Phys.* 22, 164–171 (2026).
- [3] R. Yanagimoto, B.A. Ash, M.M. Sohoni, M.M. Stein, Y. Zhao, F. Presutti, M. Jankowski, L.G. Wright, T. Onodera, P.L. McMahon, Programmable on-chip nonlinear photonics. *Nature* 649, 330–337 (2026).