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Integrated Wavefront Shaping for High-Dimensional Photonic Processing

Wavefront shaping has emerged as a powerful framework for controlling light propagation in complex optical systems [1], enabling programmable beam steering, adaptive microscopy, and reconfigurable quantum networks. To date, however, most wavefront-shaping setups rely on bulky free-space optics, which fundamentally limits scalability and footprint. Here, we propose a fundamentally different approach: programmable wavefront shaping entirely inside a single integrated multimode waveguide.

Our concept harnesses thermo-optic perturbations distributed along a silicon nitride multimode waveguide to dynamically control the propagation and interference of guided spatial modes. By sequentially applying localized refractive-index perturbations, inspired by large-scale multimode fiber “pianos” with stress-induced refractive-index control [2], the multimode field undergoes mode mixing and phase modulation during propagation. We develop a perturbative theoretical model [3], revealing that control of the output response requires multi-variable optimization strategies, such as gradient descent [4]. This establishes a powerful framework enabling the optimization of hundreds of thermo-optic control elements within only a few tens of iterations.

In this abstract, we demonstrate two core results using our numerical simulations. First, we show programmable wavefront shaping by directly optimizing the output intensity distribution of the multimode waveguide toward a desired target intensity using the squared field difference as a cost function. This demonstrates the implementation of the basic wavefront shaping concept, where a target intensity distribution is generated through a complex scattering medium. Second, we demonstrate optimization toward arbitrary target transmission operators by sampling the forward model with ensembles of random input fields. Prospectively, this enables universal high-dimensional unitary transformations within a single multimode waveguide. This approach could replace large interferometric photonic meshes [5] by control of modal propagation inside one compact integrated multimode waveguide. Beyond programmable linear optics, the presented architecture can be extended toward active multimode waveguide amplifiers, building upon recent advances in high-power multimode fiber amplifiers and wavefront shaping [6]. Such programmable active waveguides may further enable scalable integrated platforms for on-chip high-capacity optical communications [7], quantum information processing [8], and nonlinear optical computing [9].

References

[1] Cao, H., Mosk, A. P., & Rotter, S. (2022). Shaping the propagation of light in complex media. *Nature Physics*, 18(9), 994-1007.

[2] Finkelstein, Z., Sulimany, K., Resisi, S., & Bromberg, Y. (2023). Spectral shaping in a multimode fiber by all-fiber modulation. *APL Photonics*, *8*(3).

[3] Osnabrugge, G., Leedumrongwatthanakun, S., & Vellekoop, I. M. (2016). A convergent Born series for solving the inhomogeneous Helmholtz equation in arbitrarily large media. *Journal of computational physics*, *322*, 113-124.

[4] Rothe, S., et al. (2025). Output beam shaping of a multimode fiber amplifier. *Optics Communications*, *577*, 131405.

[5] Taballione, C., et al. (2019). 8× 8 reconfigurable quantum photonic processor based on silicon nitride waveguides. *Optics express*, *27*(19), 26842-26857.

[6] Rothe, S., et al. (2025). Wavefront shaping enables high-power multimode fiber amplifier with output focus. *Science*, *390*(6769), 173-177.

[7] Yang, K. Y., et al.. (2022). Multi-dimensional data transmission using inverse-designed silicon photonics and microcombs. *Nature communications*, *13*(1), 7862.

[8] Leedumrongwatthanakun, S., Innocenti, L., Defienne, H., Juffmann, T., Ferraro, A., Paternostro, M., & Gigan, S. (2020). Programmable linear quantum networks with a multimode fibre. *Nature Photonics*, *14*(3), 139-142.

[9] Onodera, T., et al. (2024). Scaling on-chip photonic neural processors using arbitrarily programmable wave propagation. *arXiv preprint arXiv:2402.17750*.