Inverse-designed energy-efficient nonlinear photonic multi-channel neural network

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As transistor counts plateau, current computing architectures with memory-access bottlenecks face limitations resulting in high power consumption on data-intensive tasks. An energy-efficient, high-speed, and scalable alternative computing paradigm is necessary to advance our civilization. As an alternative approach, optical computing, an analog computing paradigm, has been around for decades and is closely following developments in data science and AI (G. Wetzstein et al. **Nature** 588.7836, 2020). However, photonic neural networks suffered from fundamental challenges like redundant electro-optic connections and a lack of versatile nonlinearities with low power consumption in a scalable and small form factor. Utilizing spatiotemporal nonlinear dynamics in multimode fibers, scalable optical nonlinear computing has been demonstrated for machine learning applications (U. Teğin et al., **Nature Computational Science**,1.8, 2021). Although, this study presents a promising platform with all-optical complex nonlinearity, a pulsed laser with kW peak powers, and bulky optical components needed to create nonlinear dynamics.

To revolutionize photonic neural networks and optical computing technologies, developing all-optical nonlinear computing that is low-energy, fast, compact, and reliably manufacturable is crucial. We propose an energy-efficient nonlinear photonic neural network designed through inverse methods to achieve this goal, enabling multi-channel computing. Our approach features an integrated nonlinear optical computing architecture using multimode silicon nitride waveguides and includes inverse-designed units to manipulate light propagation, facilitating the training of photonic neural networks. The spatiotemporal nonlinear Schrödinger equation governs the nonlinear spatiotemporal propagation in these silicon nitride waveguides, with the inverse-designed control units inducing mode mixing between the waveguides.

Our innovative solution leverages **spatiotemporal nonlinear dynamics, integrated optics, and inverse design**, offering three key features:

1. Strong Nonlinear Optical Computing with Low Power Consumption: Silicon nitride's high material nonlinearity (n2) and the effective nonlinearity of waveguides (γ) result in 5000 to 7000 times greater nonlinearity than optical fibers depending on the waveguide geometry. This makes multimode silicon nitride waveguides highly effective for spatiotemporal nonlinear optical computing with continuous wave lasers, enabling strong all-optical nonlinear computing with just a few watts.

2. Small-Footprint Scalable Nonlinear Photonic Neural Network: Our technology uses waveguide modes to nonlinearly process optical information. These modes, acting as channels, couple linearly and nonlinearly. The high refractive index of silicon nitride allows for small-area multimode optical waveguides, facilitating high-resolution data processing and scalable optical computing. Our solution offers a small footprint and scalability by increasing the number of modes with increasing propagation area or decreasing the operation wavelength, significantly enhancing the effectiveness of integrated photonic computing.

3. High-Performance Multi-Channel Optical Computing with Inverse Design: Utilizing an inverse design approach, our solution incorporates mode mixing units for training photonic neural networks. By further implementing an inverse-designed wavelength division multiplexing unit, we propose an advance wavelength-selective optical computing with different paths to achieve multi-channel photonic neural network design. It creates a versatile platform that integrates various optical computing architectures into a single design.

The framework introduced by our inverse-designed energy-efficient nonlinear photonic multi-channel neural network has the potential to provide extreme utility in diverse areas of application. This approach provides compelling evidence that inverse-designed integrated platforms can be utilized for various geometries for task-oriented applications.