Ultra-compact Four-Channel Short-Wavelength Division Multiplexing Metastructures in Silicon Nitride for High-Performance Optical Backplanes

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Abstract: We present an inverse-designed four-channel SWDM device on a SiN–SiO_2 platform operating from 850–940 nm within a 6×6 μm² footprint. Sub-wavelength metastructures enable broadband, low-loss routing, supporting multi-wavelength optical backplanes for high-speed applications.

Optical backplanes provide higher bandwidth and lower signal interference than copper wiring in avionics and data-center systems [1][2][3][4]. The 850–950 nm band is particularly attractive because it supports VCSEL sources and is compatible with low-loss Si_3N_4 waveguides. In contrast to narrowband directional-coupler or MMI-based approaches, the proposed device utilizes inverse-designed sub-wavelength metastructures for broadband aggregation and separation of four channels. Such inverse design techniques optimize the permittivity distribution to achieve desired field responses under Maxwell's constraints [5][6], enabling structures that surpass the bandwidth-footprint limits of conventional templates. This work extends multi-dimensional multiplexing concepts from silicon platforms into a short-wavelength Si_3N_4 backplane environment.

The proposed device functions as a four-channel wavelength-division-multiplexing (WDM) interface that supports single-mode operation throughout the Si_3N_4 bus waveguide. It is designed to aggregate optical data from multiple boards by assigning each board a distinct wavelength channel—850, 880, 910, or 940 nm—within the same optical path. All waveguides operate in the fundamental TE mode to ensure minimal dispersion and low modal crosstalk. The device architecture consists of four wavelength-selective branches connected to a central Si_3N_4 bus. Each branch is optimized for a specific wavelength, allowing light at that wavelength to be coupled efficiently into or out of the bus while remaining transparent to other channels. The wavelength selectivity are realized through sub-wavelength metastructures, which modify the effective refractive index distribution.

These nanoscale features are spatially engineered to provide broadband, smooth coupling behavior and are readily fabricable using standard lithography. Figure 1 shows the inverse-designed layout of the proposed WDM device. The entire structure occupies an ultra-compact area of approximately 6 μm × 6 μm, enabling high integration density for photonic backplanes. The same physical structure operates bidirectionally. During multiplexing, four single-mode inputs at distinct wavelengths are combined into the Si_3N_4 bus for transmission. During demultiplexing, the multiplexed bus signal is separated into four wavelength outputs. Because single-mode propagation is preserved throughout, the device achieves consistent performance with low insertion loss.

Three-dimensional finite-difference time-domain (FDTD) simulations were performed to evaluate spectral performance and wavelength routing. Figures 2(a–d) show the simulated electric-field distributions for the four wavelength channels, demonstrating wavelength-dependent coupling and minimal crosstalk between ports. The transmission spectrum in Fig. 2(e) reveals four well-separated passbands centered at 850, 880, 910, and 940 nm. The simulated insertion losses range from 1 to 2.2 dB per channel (approximately 80–50% transmission), with the highest loss observed at 940 nm due to weaker modal overlap near the design boundary. These results confirm that the sub-wavelength-metastructure approach enables broadband and fabrication-robust multiplexing without relying on periodic gratings or resonant filters. The compact footprint and performance metrics are consistent with the scalability demonstrated in recent inverse-designed multiplexed photonic circuits

All results presented in this work are obtained from numerical simulations; fabrication and experimental validation are planned for future stages. The device is designed for a standard Si_3N_4-on-SiO_2 platform with a 230-nm-thick Si_3N_4 core on a 2-μm buried oxide and a 1-μm SiO_2 top cladding. The minimum feature size of 200 nm ensures compatibility with conventional ultraviolet or electron-beam lithography processes while maintaining high fabrication tolerance. This relaxed resolution requirement allows straightforward integration into existing silicon-nitride foundry workflows.

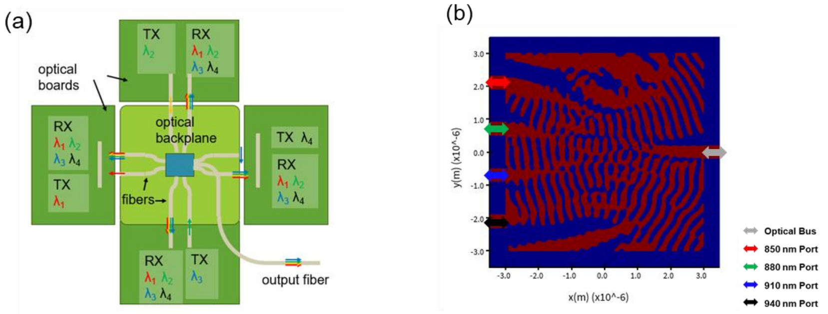

Fig. 1. Optical backplane architecture (a) Architecture of optical backplane system with four optical boards (b) Inverse-designed layout of the four-channel wavelength-division-multiplexing (WDM).

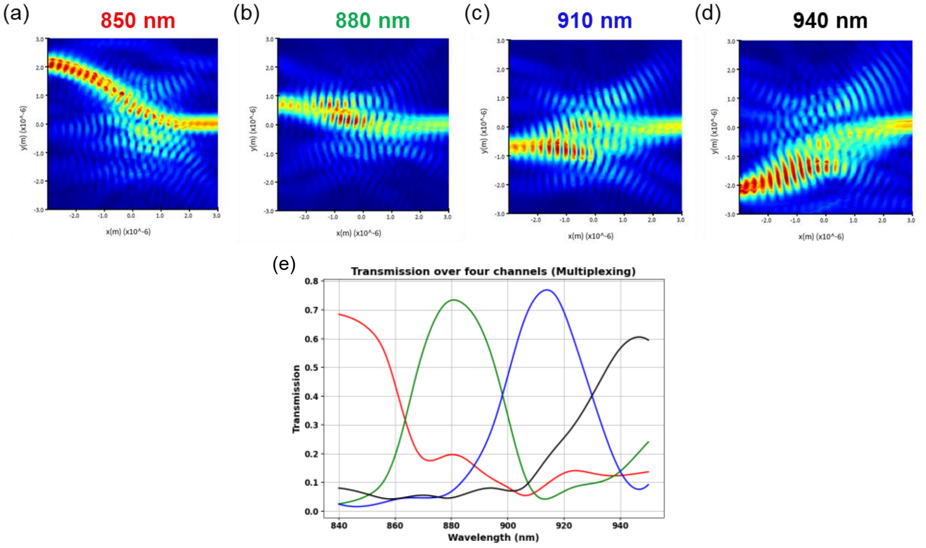

Fig. 2. Simulated optical performance of the inverse-designed four-channel WDM device. (a–d) Electric-field intensity for individual wavelength channels at 850, 880, 910, and 940 nm. (e) Transmission spectra of the four channels.

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