FY24 R&TD Innovative Spontaneous Concepts (ISC)

Piezo-optic Phase Shifters for Astrophotonics

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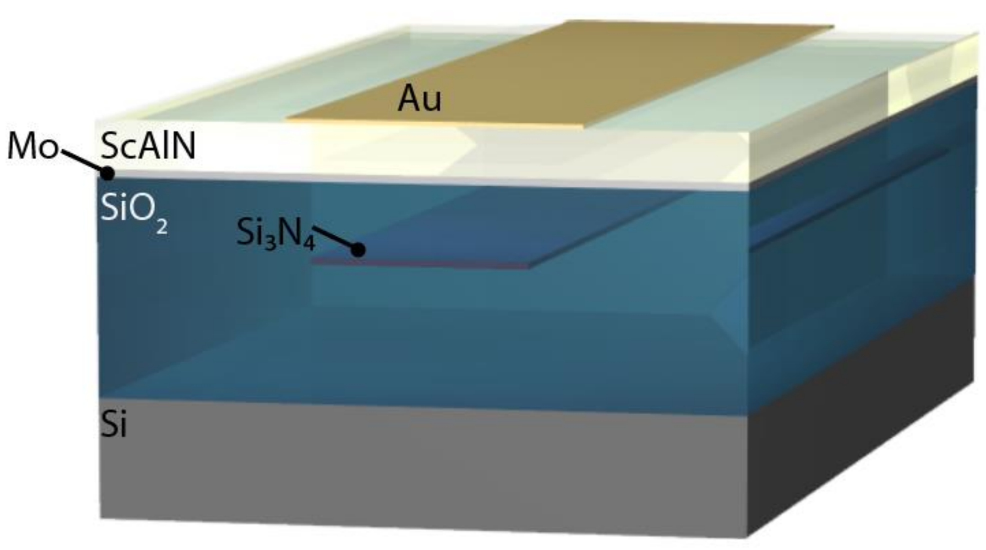
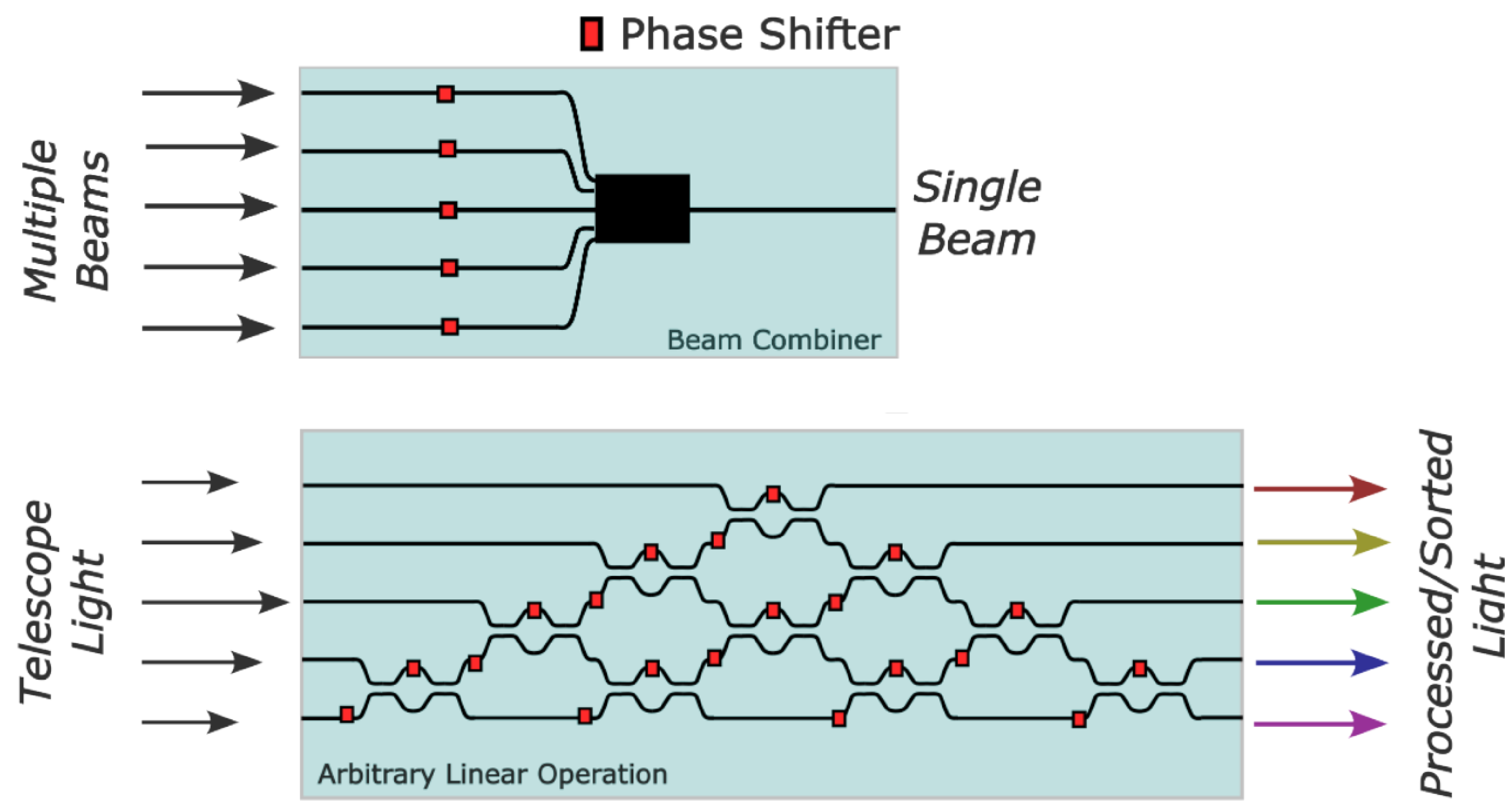
Strategic Focus Area: Innovative Spontaneous Concepts



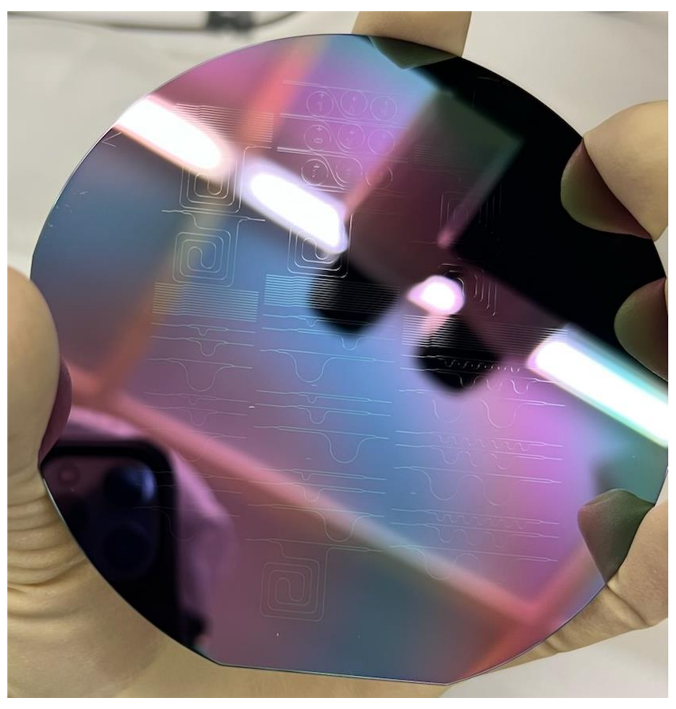


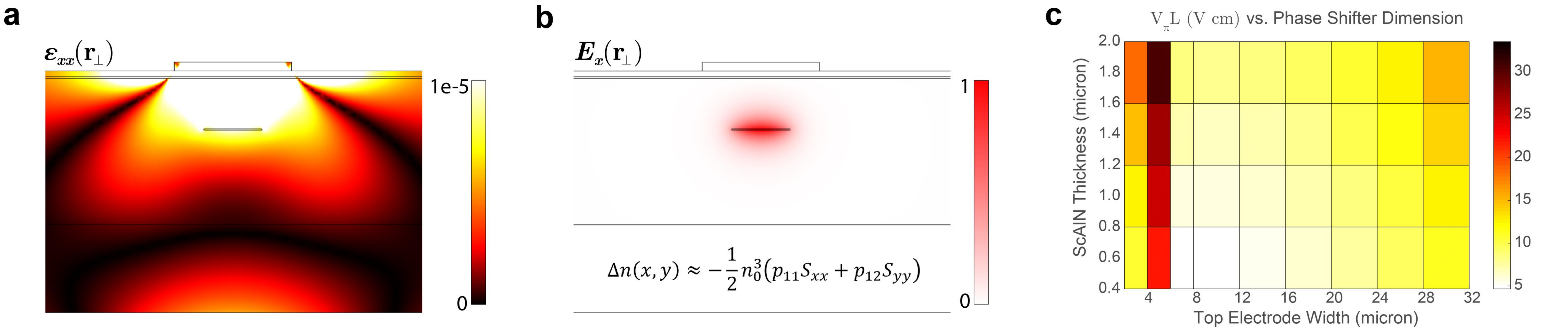
(left) Cross-section depicting phase-shifter geometry. (top) An integrated-photonic beam-combiner controls the phase of each input beam before they are combined in a multi-mode-interference coupler. (bottom) Architecture of a complex MZI mesh photonic circuit, which allows linear operations on input light for applications such as high-contrast starlight rejection by mode sorting.

Objectives: We seek to establish the feasibility of integrated photonic phase shifters based on piezo-optic modulation of low-loss silicon nitride waveguides. This technology, which will allow precise phase control and interferometry of light on-chip, represents a significant advance over thermo-optic phase shifters currently under study for astrophysics applications at JPL, which require high power dissipation and suffer from thermal lag, cross-talk, and low speed. The enhanced performance and flexibility of the piezo-optic approach will improve stability, permit cryostat operation, enhance scalability, and reduce power consumption for next-generation astrophotonics instruments such as nulling interferometers, beam combiners, laser metrology, and chip-based coronograph architectures.

Background: New astrophotonic device technologies that apply principles of photonics to astronomy provide a potential means to simplify the design and implementation of phase-sensitive optical instruments. However, so far these have been limited primarily to laboratory proofs-of-concept due to high optical losses and lack of active functionalities. Silicon nitride (Si_3N_4) is a promising material platform for astrophotonics applications since it offers low losses and wide transparency from ~400-6000 nm. However, while Si_3N_4 can be used to produce extremely high-performance passive optical components, it lacks the key capability of active electro-optic control. As a result, basic operations such as switching, phase shifting, and frequency and amplitude modulation are not readily available. Existing proofs-of-concept for active silicon nitride-based circuits, such as photonic nullers studied for exoplanet detection, rely instead on the thermo-optic effect. Unfortunately, even state-of-the-art thermo-optic phase shifters are slow (10 kHz), power hungry, experience hysteresis, and offer limited functionality compared to conventional discrete electro-optic components.

Approach and Results: The proposed devices leverage a silicon nitride photonic platform commonly used for existing integrated photonics research. Phase control is achieved using additive piezoelectric transducers that control light via the stress-optic effect. To achieve high efficiency, we utilize piezoelectric ScAlN, a novel material with piezoelectric coupling coefficients 3-5× larger than conventional AlN. Our design approach is directly compatible with existing architectures for astrophotonic integrated circuits, and may be extended to wider wavelength ranges with future engineering. We have developed detailed multi-physics simulations to validate the design approach and optimize device geometry for initial test structures. Initial multi-physics simulations in COMSOL (Fig. 1) with non-optimized device geometries suggest that sufficiently strong material strains can be generated to achieve phase shift figure of merit V_π L~ 5 V·cm, where V_π is the voltage required for π (180°) phase shift, and L is the device length. Using serpentine waveguide and transducer structures, this should permit the creation of compact (mm-scale) phase shifters with operating voltages Vπ<5V to eliminate the need for high-voltage drive electronics. Building on these simulations, we fabricated two test wafers, which were sent to an external foundry (AMSystems, Inc.) for ScAlN deposition. Final electrode fabrication and experimental test is ongoing as of 9/13/24.





Multi-physics finite element simulations of phase shifter performance. (a) shows the simulated xx-directed strain profile for one device geometry under an applied potential of 1 Volt. (b) shows the TE-like optical mode that experiences a phase shift. (c) shows the calculated figure of merit $V_\pi L$ in units of $\mathrm{V \cdot cm}$ as a function of two key dimensions—the top electrode width and the piezoelectric ScAlN film thickness.

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