Design and Characterization Techniques to Advance Integrated Photonics for Space Missions

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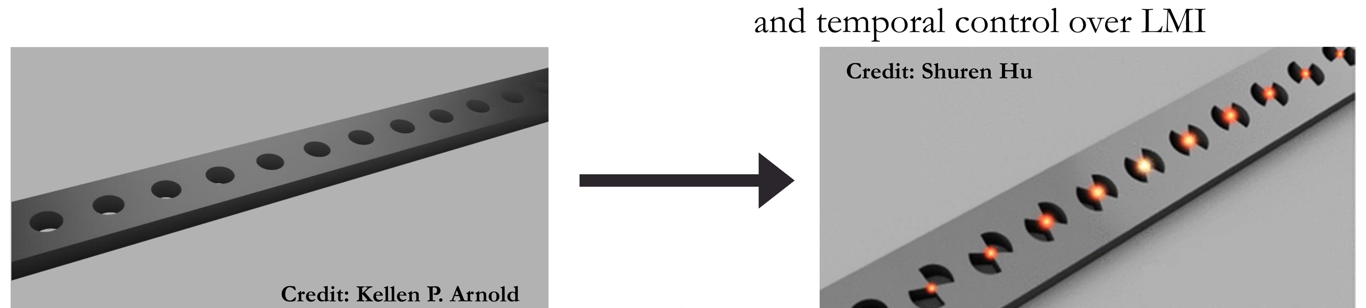
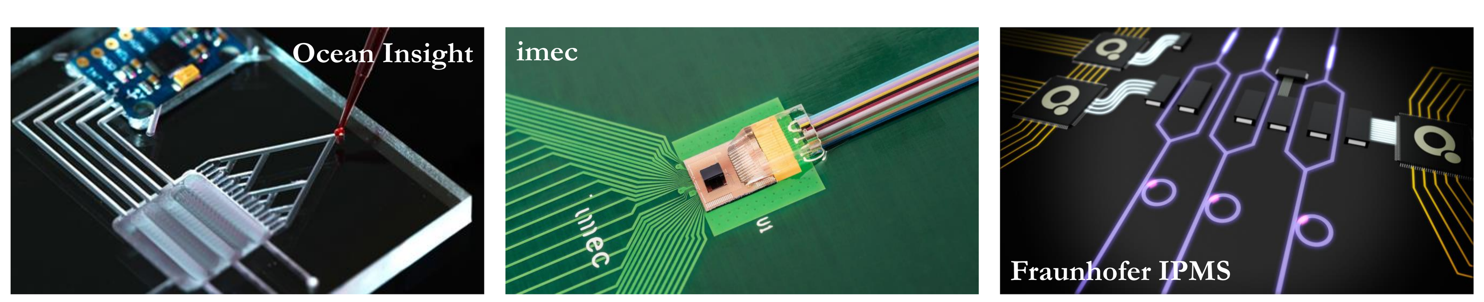
ABSTRACT

Photonic integrated circuits (PICs) are hybrid circuit designs that marry the data transmission efficiency of optical signaling with the compact, powerful data processing of electrical integrated circuits (ICs) on a single chip. Integrated photonics are useful for a wide range of applications where size, weight, power, and performance advantages are critical to advancing the capabilities of satellites and scientific instruments used in the space industry. In the Weiss group, we innovate photonic design methods for controlling light-matter interactions and advancing the performance of on-chip photonic components. Here we report our progress made in nanoscale photonic crystal geometric design and integrated photonic waveguide polishing to analyze commercially fabricated PhCs.

BACKGROUND

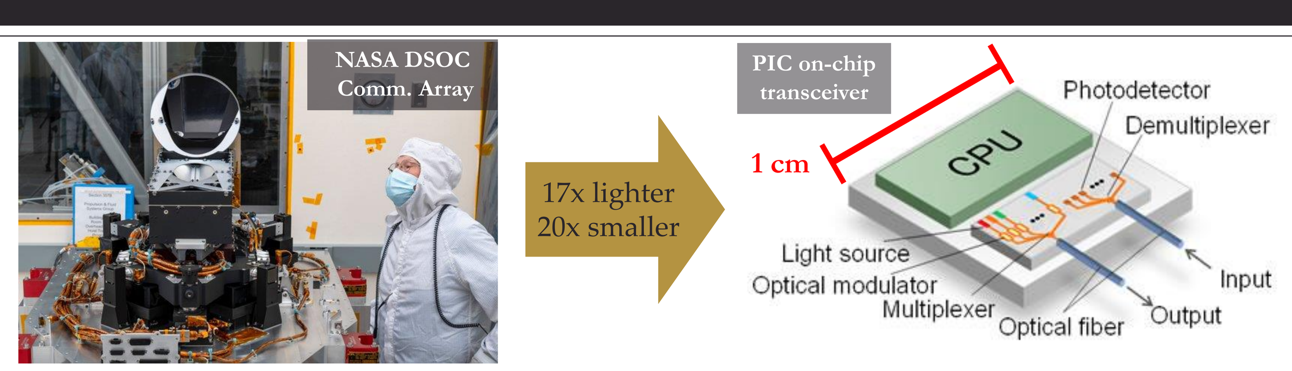
- **Photonics** is a rapidly-growing field where **light-matter interaction (LMI)** is leveraged to improve information processing
- Current photonics research includes: materials research, **nanoscale feature design**, optical mode engineering
- **Photonic crystals (PhCs)** are periodic, wavelength-scale structures set in dielectric (insulating) waveguides offering strong temporal confinement and LMI
- The addition of **deep subwavelength features** in PhC unit cells enables both spatial and temporal control over LMI



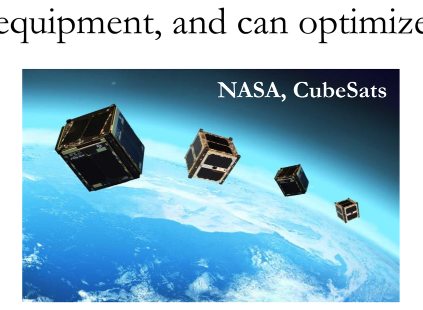


Biosensing: Sensitivity ↑ | **Data communications:** Speed ↑ | **Quantum computing:** Fidelity ↑

MOTIVATION



- PICs have revolutionary implications for **size, weight, and power (SWaP)** of space-mission equipment, and can optimize current technology by:



- Providing fast speeds and energy efficiency to information transfer for data communications

- Developing compact equipment (e.g. laser spectrometers) for improved footprint consumption

- Minimizing power demands for probe communications for prolonged mission life cycles

OBJECTIVES

1. Analyze nanoscale optical energy concentration in subwavelength-engineered PhCs using finite-difference time domain (FDTD) simulations
2. Establish polishing & etching post-processing and scanning electron microscope (SEM) techniques for foundry-fabricated PhC devices to (a) compare fabricated structures to simulated designs and (b) increase sample size of prototype imaging for improved design feedback and machine learning algorithms
3. Future Project Goals: (1) analyze and characterize properties and performance degradation of PhC-based devices when exposed to radiation analogous to space environments (2) develop design strategies for high-performance radiation-tolerant integrated photonic components

PHC UNIT CELL DESIGN

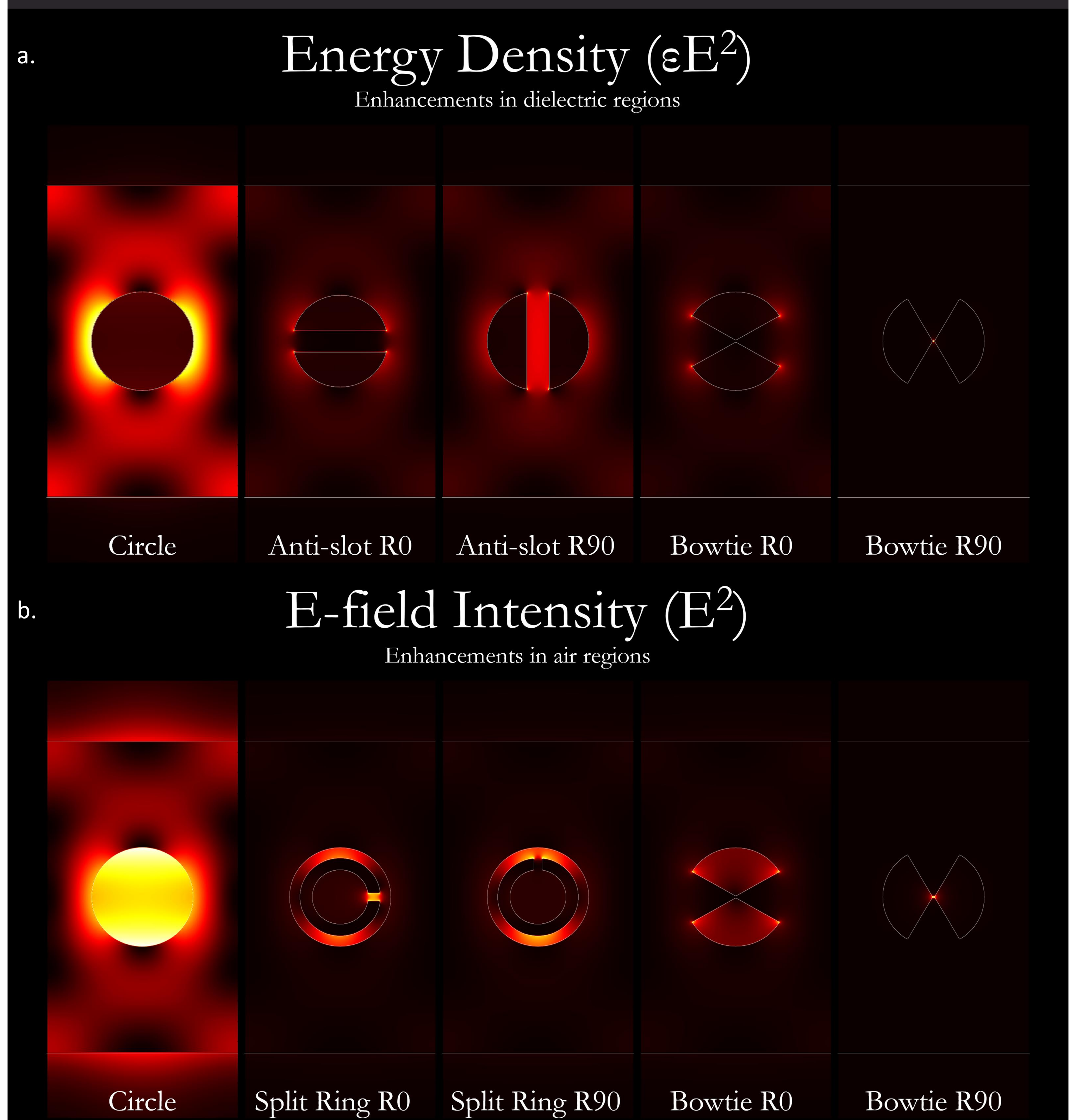
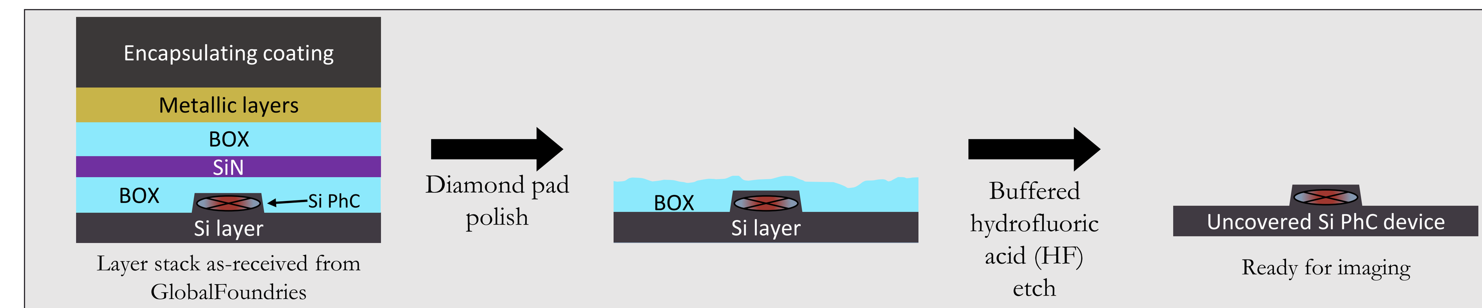


Fig. 1. (a) Self-normalized plots of optical energy density (εE^2). (b) Self-normalized plots of electric field intensity (E^2). Plots generated from FDTD simulations with periodic boundaries using transverse electric (TE) dipole excitation.

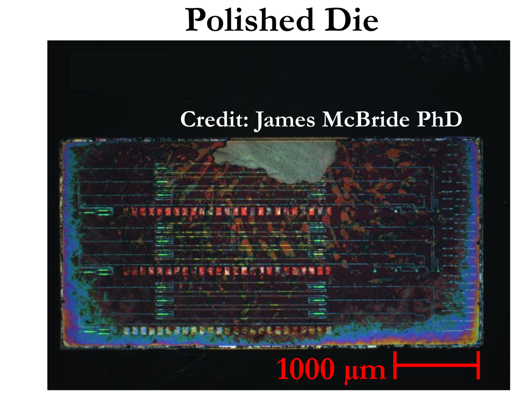
- **Types of unit cells** (*airhole, bowtie, anti-slot, split ring, etc*) and their parameters can be customized to **match fabrication capabilities and specific PIC applications**
- **Anti-slot and bowtie** designs exhibit intense field energy enhancement in **silicon or high refractive index media**
  - Favorable in **data communications** (modulate waveguide / PhC material)
- **Circular airhole and split ring** designs exhibit intense field energy enhancement in **air or low refractive index media**
  - Favorable in **biosensing** and **quantum** applications (probe external material)
- Strong light-matter interactions reduce SWaP and improve performance in PICs

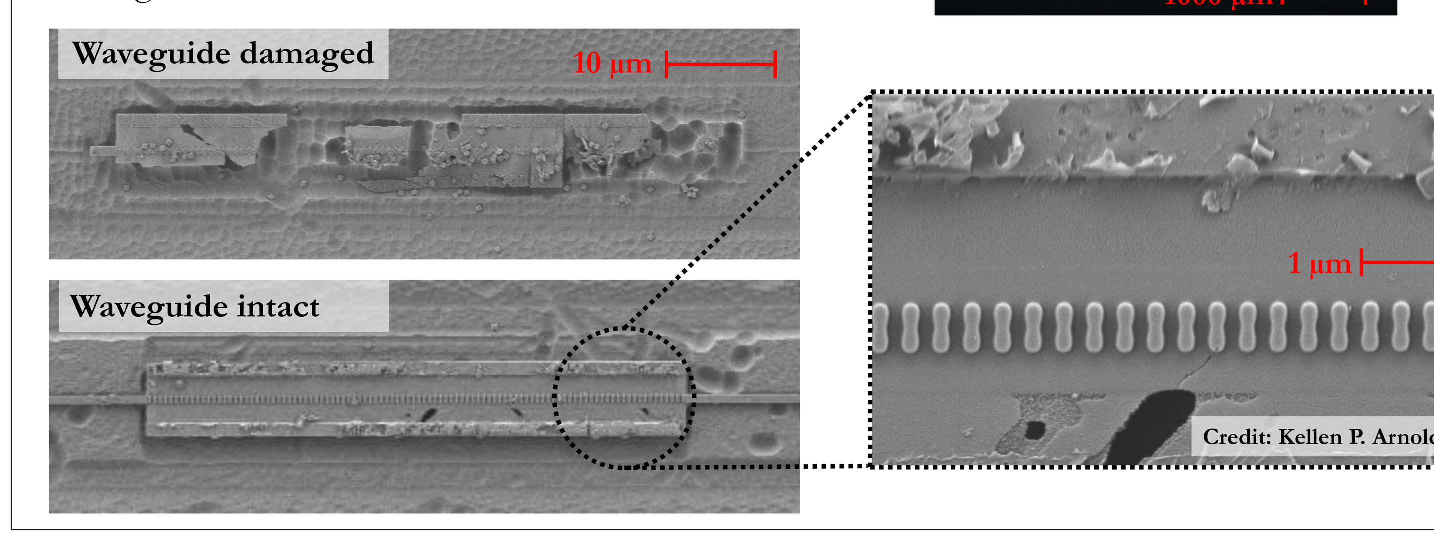
WAVEGUIDE PROCESSING



- GlobalFoundries (GF) material stack covers photonic layers with oxides, metallization, and encapsulating coatings, so any images need to be taken on "short-loop" wafers (removed early expressly for imaging)
- Performed mechanical polishing and buffered HF etching to reveal designs
- Uses: imaging for publications, machine learning & design feedback

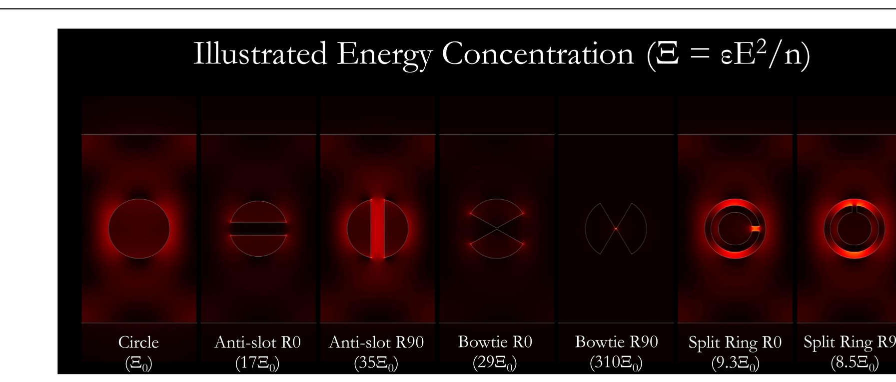
Optical Microscope Image: Polished Die





SUMMARY AND OUTCOMES

- Developed strategic comparisons of nanoscale energy redistribution in simulation among subwavelength engineered PhC unit cell designs that have been achieved in the Weiss group



- Supported post-processing of commercially fabricated silicon photonic die to uncover waveguides and nanostructures, supporting collaboration with GlobalFoundries to improve design feedback and setting foundations for future work
- Future work: this work will be used for future research into design of high-performing integrated photonic components, the effects of radiation on PhC-based PIC devices, and other commercially viable PhC design and analysis

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Citations:

[1] Hu, S. & Weiss, S. M. ACS Photonics 3, 1647-1653 (2016).

[2] Bozovich, A. (2022). *Photonic Integrated Circuits for Next Generation Space Applications.* NASA JPL, 2020 NEPP Electronics Technology Workshop.

[3] Arnold, K. P., Halimi S. I., Allen J. A., Hu, S., Weiss, S. M., Opt. Lett. 47, 661-664 (2022)

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