Investigation of adjoint method inverse design applied to fiber-to-chip edge coupling

Student:	Bernard M. Melus
Student Email:	melus.1@osu.edu
Faculty:	Prof. Ronald M. Reano
Faculty Email:	reano.1@osu.edu
AFRL Sponsor:	Dr. Joseph S. Suelzer
AFRL Directorate:	AFRL/RY

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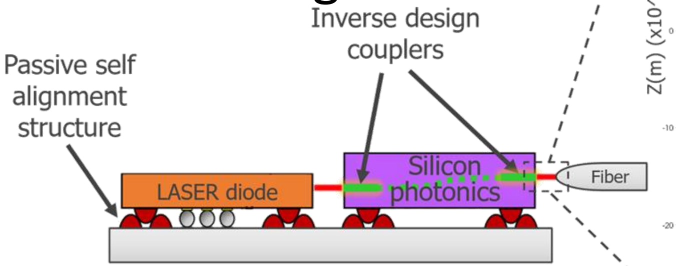
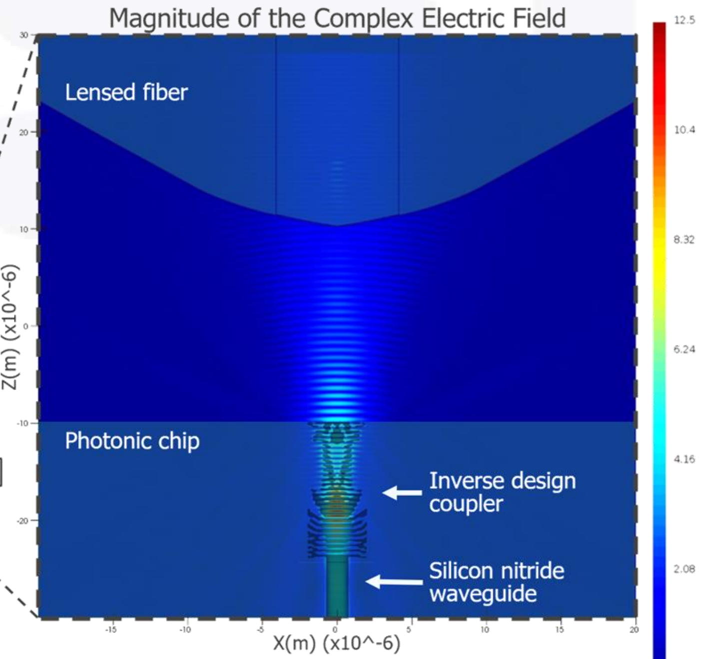
Background and Motivation

- Full-vectorial electromagnetic modeling of nanophotonic components on large simulation domains (> 1000 λ^3) is computationally complex
  - Solvers incorporating GPU accelerated hardware have mitigated computation time challenges in finite-difference EM modeling
- Leveraging this capability, inverse design edge couplers are optimized, fabricated, and characterized in a study to:
  1. Reduce the footprint of typical photonic edge couplers for the silicon nitride on insulator material platform
  2. Understand the performance tradeoffs of inverse design
  3. Determine if inverse design is a viable design methodology for future projects and research in photonic heterogeneous integration [1]

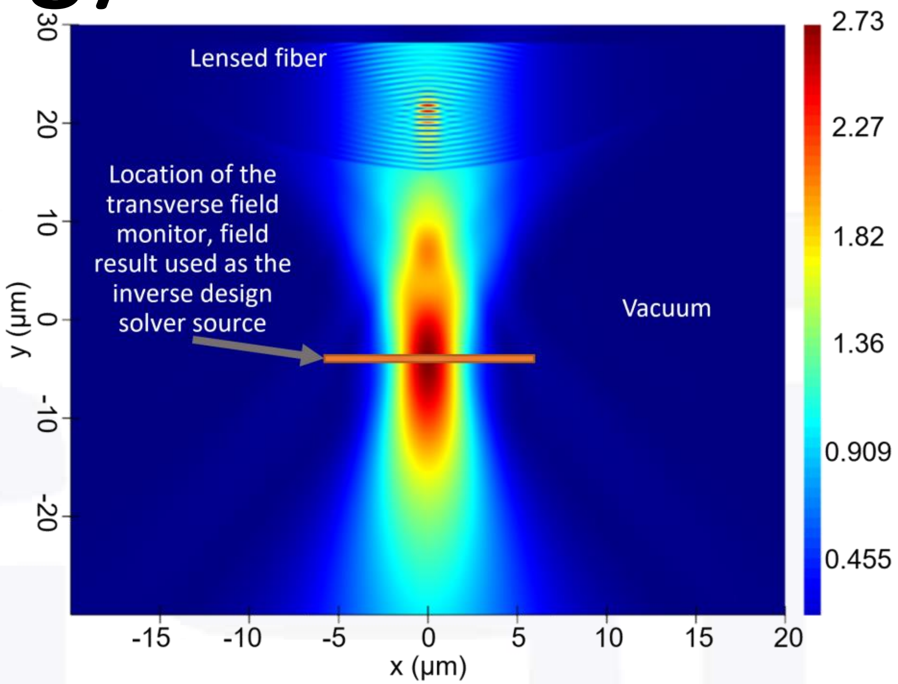


J. L. Gonzalez, et al., Submicrometer PSAS-to-PSAS Self-Alignment Technology for Heterogeneous Integration" [2]

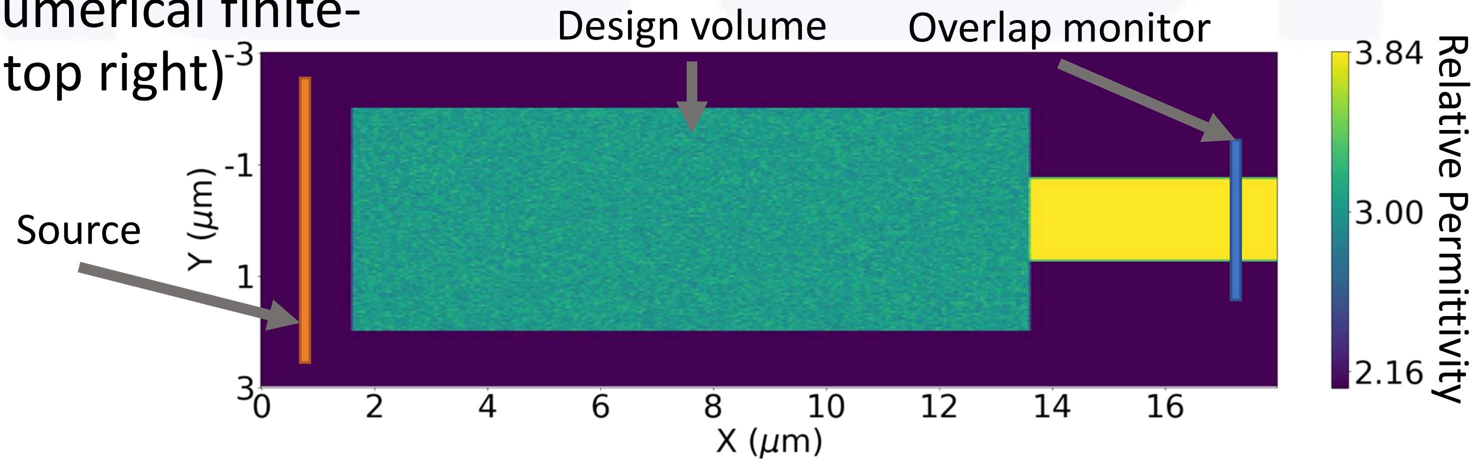


Edge Coupler Design Methodology

- In-plane lensed fiber-to-chip coupling adjoint method inverse design in SPINS-b [3]
  - Finite-difference frequency-domain (FDFD) solver
  - Randomly pixelated 12.0x4.0x0.04 μm design region (bottom right plot)
  - 17x6x6 μm computational domain with 40 nm grid spacing and PML absorbing boundary condition (9.69M grid cells)
  - 6.4 μm S-polarized spot size source placed at the component facet; source mode field determined by modeling a lensed fiber in the Lumerical finite-difference time-domain solver (top right)



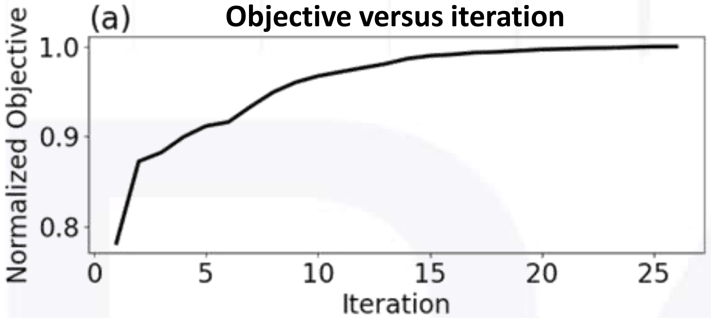
Electric field DFT monitor of the lensed fiber source model simulated in Lumerical FDTD

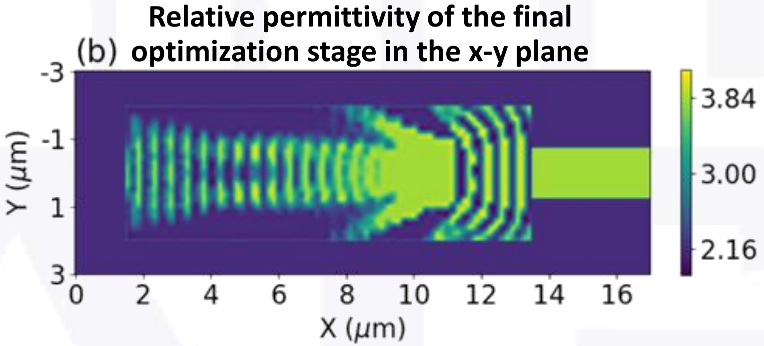


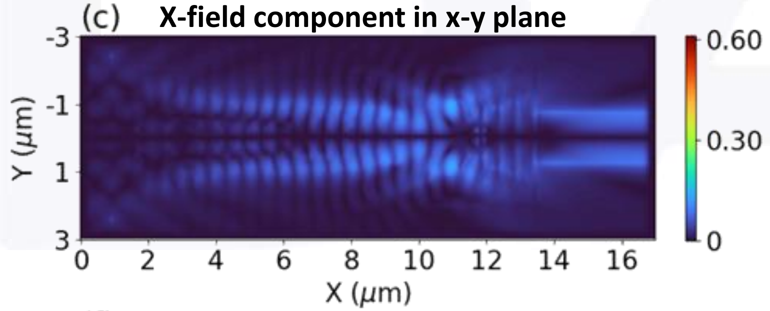
Optimization Results

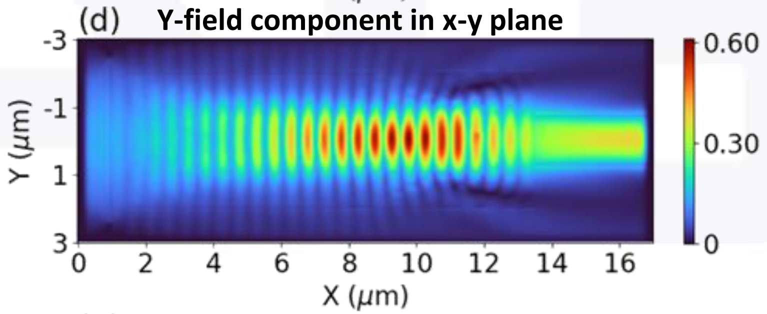
- Permittivity and FDFD field solution after 26 optimization iterations
- Elapsed computation time: 3 hours

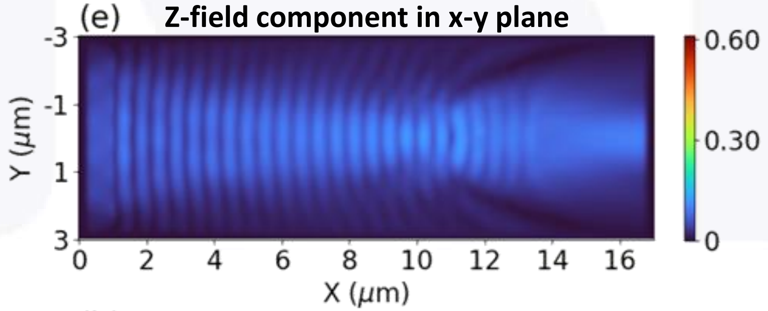
Comparison of the
inverse design coupler
beside a 220 μm long
adiabatic coupler design

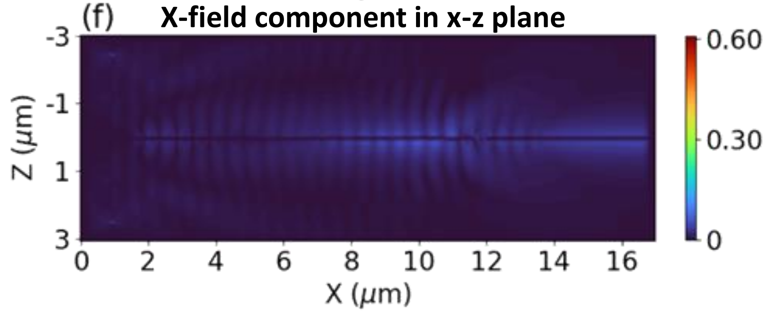


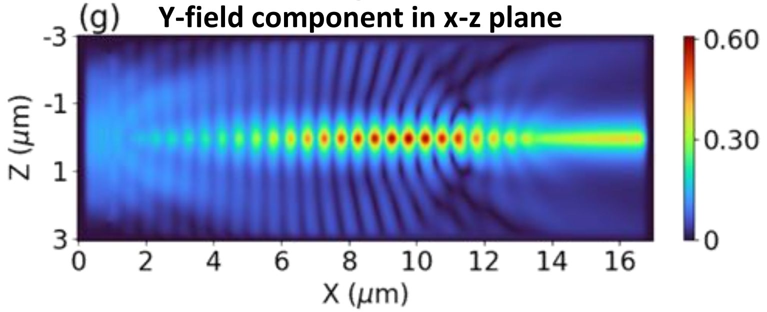


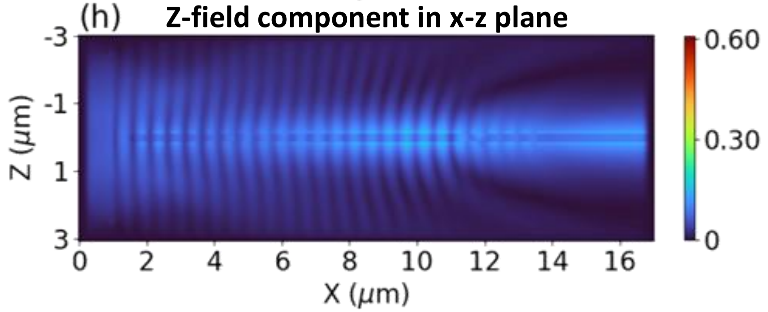






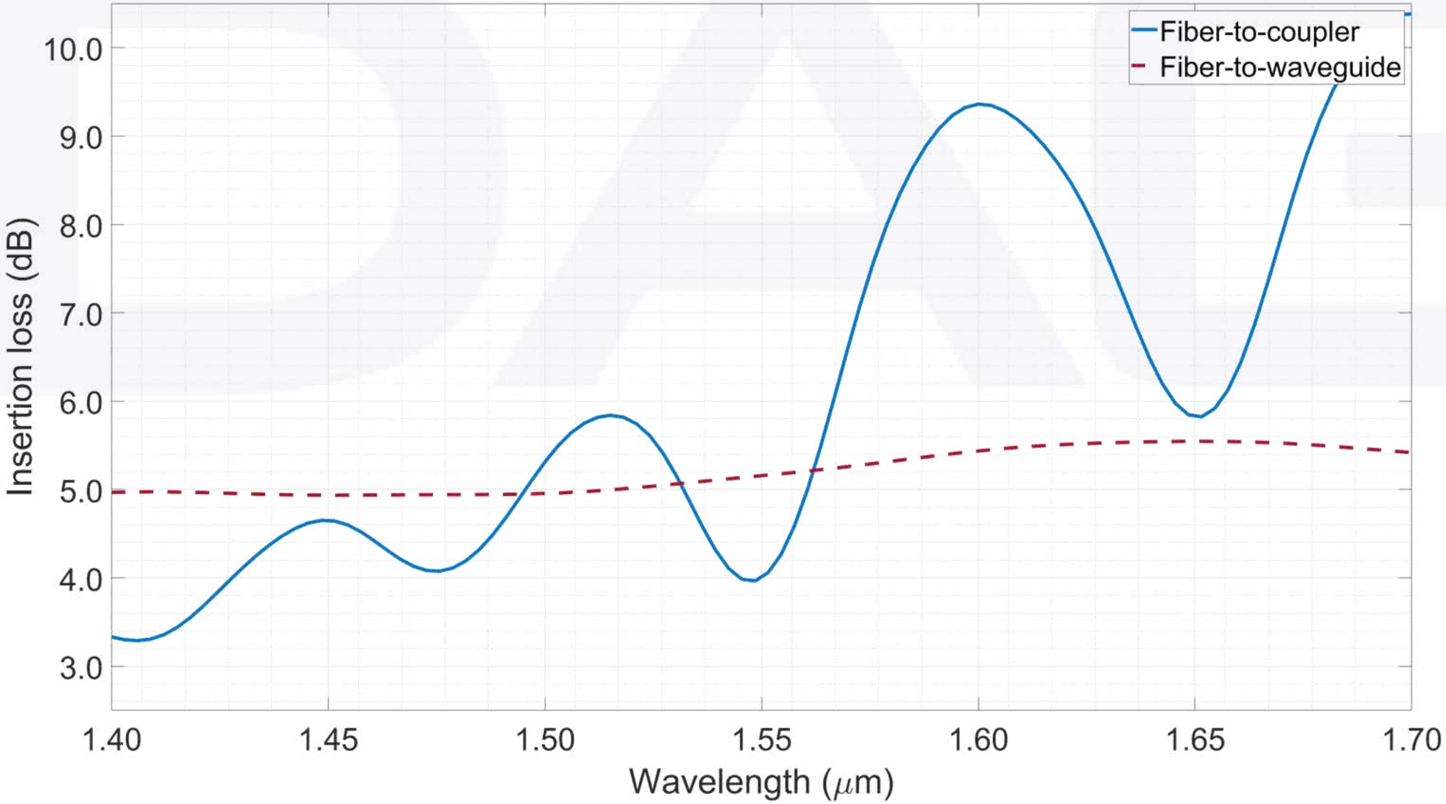


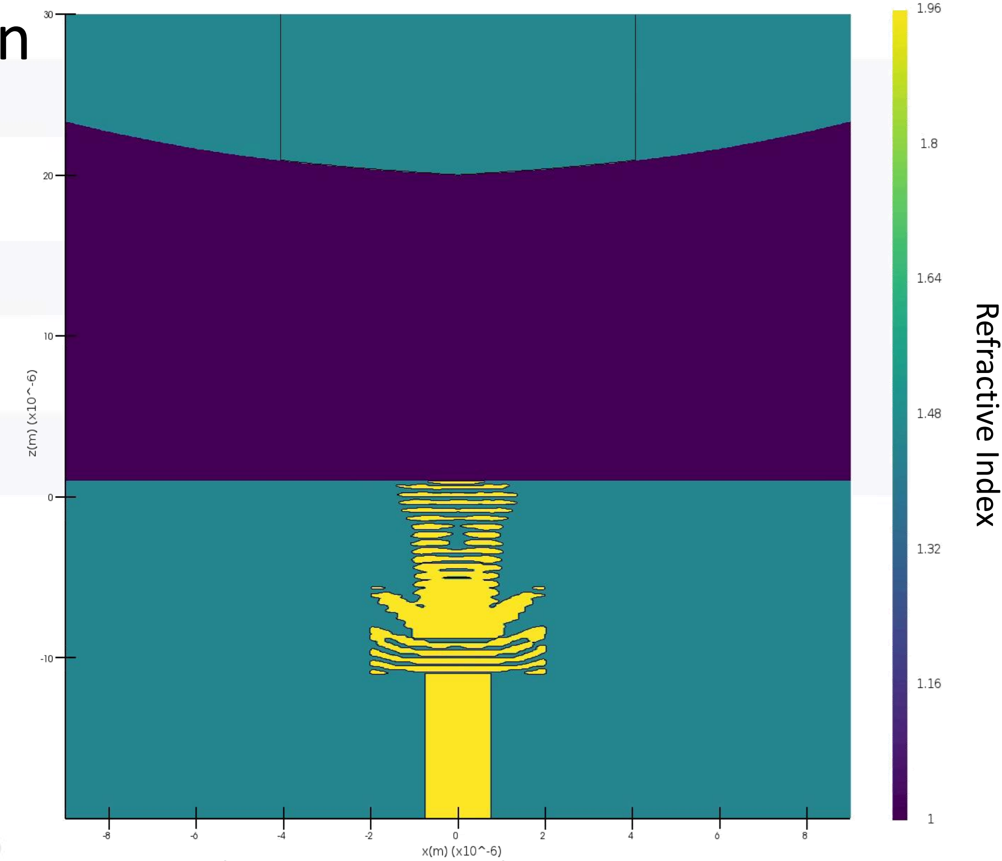




Broadband fiber-to-chip FDTD Validation

- To simulate the coupling loss, the lensed fiber-to-chip coupling experiment was modeled in Lumerical FDTD
- Pulsed source used to extract broadband performance
- 4 dB loss at 1.55 µm in the quasi-TE polarization

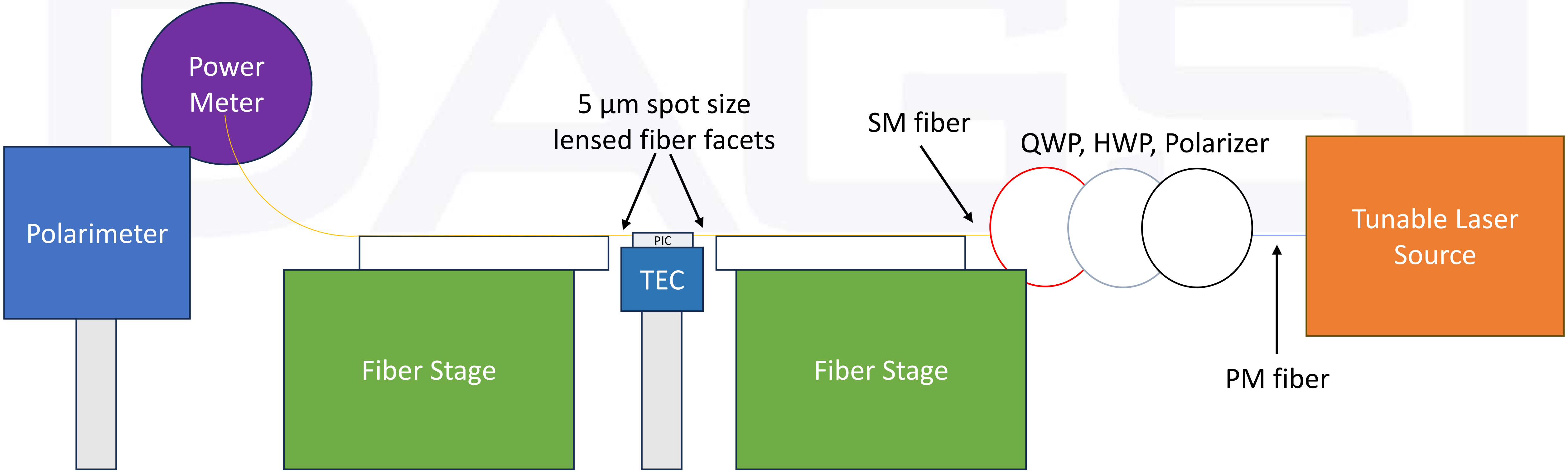




Lensed fiber to coupler facet index monitor

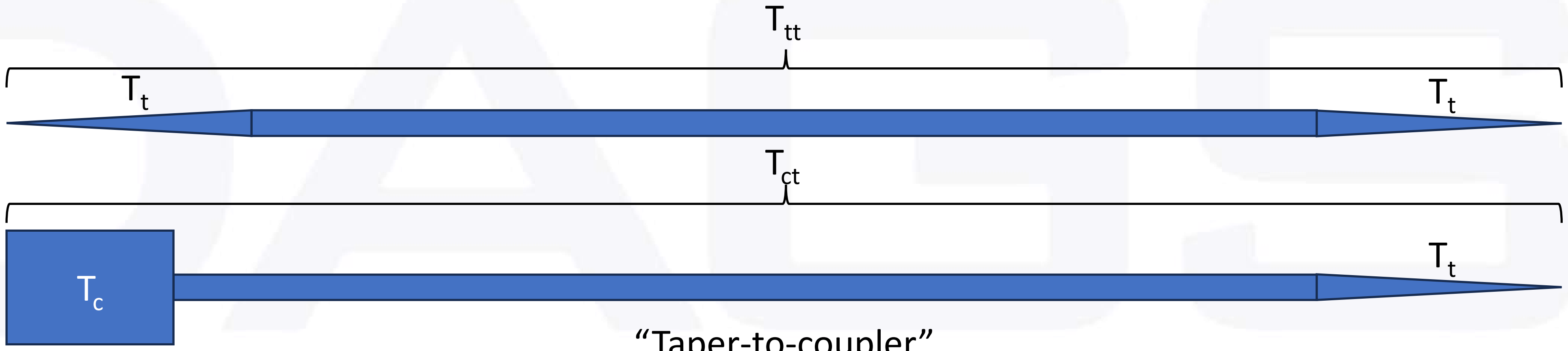
Experimental Setup

- Prior to taking data, the input fiber stage is raised to couple light into the polarimeter for feedback to tune the desired polarization state using the two waveplates
- The couplers are actively aligned to maximize power at 1.55 µm, laser wavelength swept between 1.51 µm and 1.63 µm wavelength



Determining Coupling Loss

- Using three measurements: baseline power (measurement excluding PIC), taper-to-taper layout, and taper-to-coupler layout, the transmission of the inverse design coupler can be determined as shown below
- Waveguide loss is negligible for the lengths used in the experiment



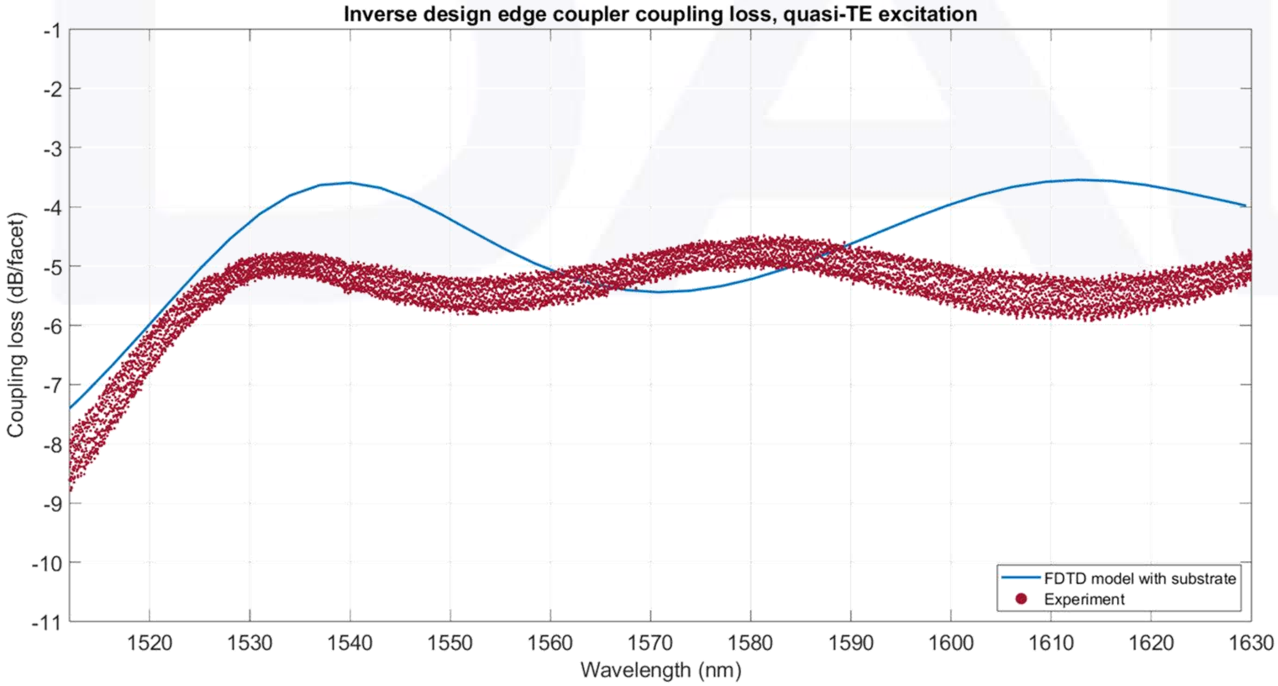
"Taper-to-coupler"

$$T_c(\lambda) = \frac{T_{ct}(\lambda)}{T_t(\lambda)}$$

$$T_c(\lambda)^2 = \left(\frac{\frac{P_{ct}(\lambda)}{P_{baseline}(\lambda)}}{\sqrt{\frac{P_{tt}(\lambda)}{P_{baseline}(\lambda)}}}\right)^2 = \frac{P_{ct}(\lambda)^2}{P_{tt}(\lambda) * P_{baseline}(\lambda)}$$

Experimental Results

- Experiments were executed coupling to the quasi-TE and quasi-TM waveguide modes and compared to the FDTD model
- Experimental results show close resemblance to FDTD simulations with losses between 4.8 to 6 dB coupling loss in the quasi-TE polarization and 2.2 to 3.5 dB coupling loss in the quasi-TM polarization throughout the optical C-band



Conclusion

- Design, validation, fabrication, and characterization of inverse design edge couplers was performed to create a compact coupling solution
- Discrepancy between simulation and experiment may be attributed to:
  - Dielectric averaging and grid size in the FDTD model causing a misrepresentation of small features
  - Lithographic patterning feature size limitation
  - Lens shape in model vs. experiment
  - Laboratory environment and model assumptions w.r.t. material parameters
  - Assumptions in the coupling loss calculation
- Quasi-TM polarization showed lower coupling loss compared to quasi-TE in simulation and experiment, suitable for quasi-TM applications where die area is a constraint
- For low-loss applications, coupling can be improved by increasing the fractional area between the coupling mode and design region
  - This may be facilitated by adding more layers vertically or coupling out of plane

References

[1] Bernard M. Melus, Joseph S. Suelzer, Matt Hagedon, Ronald M. Reano, "Investigation of adjoint method inverse design applied to photonic integrated circuit fiber-to-chip edge couplers," Proc. SPIE 12892, Optical Interconnects XXIV, 1289208 (11 March 2024); https://doi.org/10.1117/12.3001211

[2] J. L. Gonzalez, S. K. Rajan, J. R. Brescia and M. S. Bakir, "A Substrate-Agnostic, Submicrometer PSAS-to-PSAS Self-Alignment Technology for Heterogeneous Integration," in IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 11, no. 12, pp. 2061-2068, Dec. 2021, doi: 10.1109/TCPMT.2021.3109913.

[3] Su, L., Vercruysse, D., Skarda, J., Sapra, N. V., Petykiewicz, J. A., and Vuckovic, J., “Nanophotonic inverse design with spins: Software architecture and practical considerations,” (2019).