Inverse Design of Photonic Interconnects for Heterogeneous Integration

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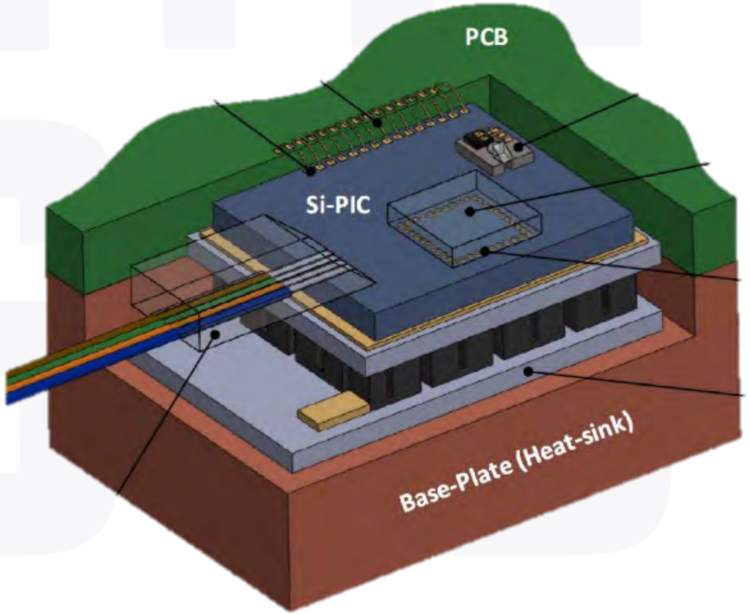
Motivation

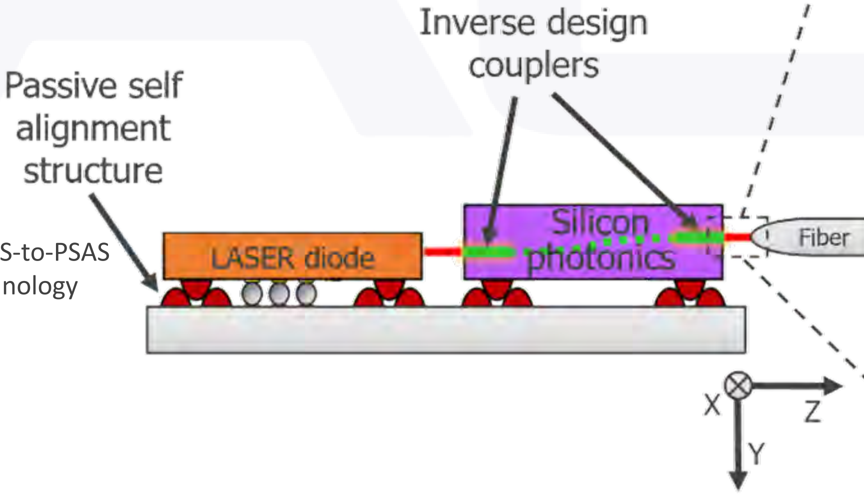
- Applications in signal processing, navigation, and quantum information are turning from electronics to photonics for solutions
- Several challenges exist with photonic integrated circuit (PIC) design
  - Packaging
  - Component fabrication variations
  - Large component footprint: increases cost/size of PICs, low component density
- Photonic inverse design is a promising solution to these issues



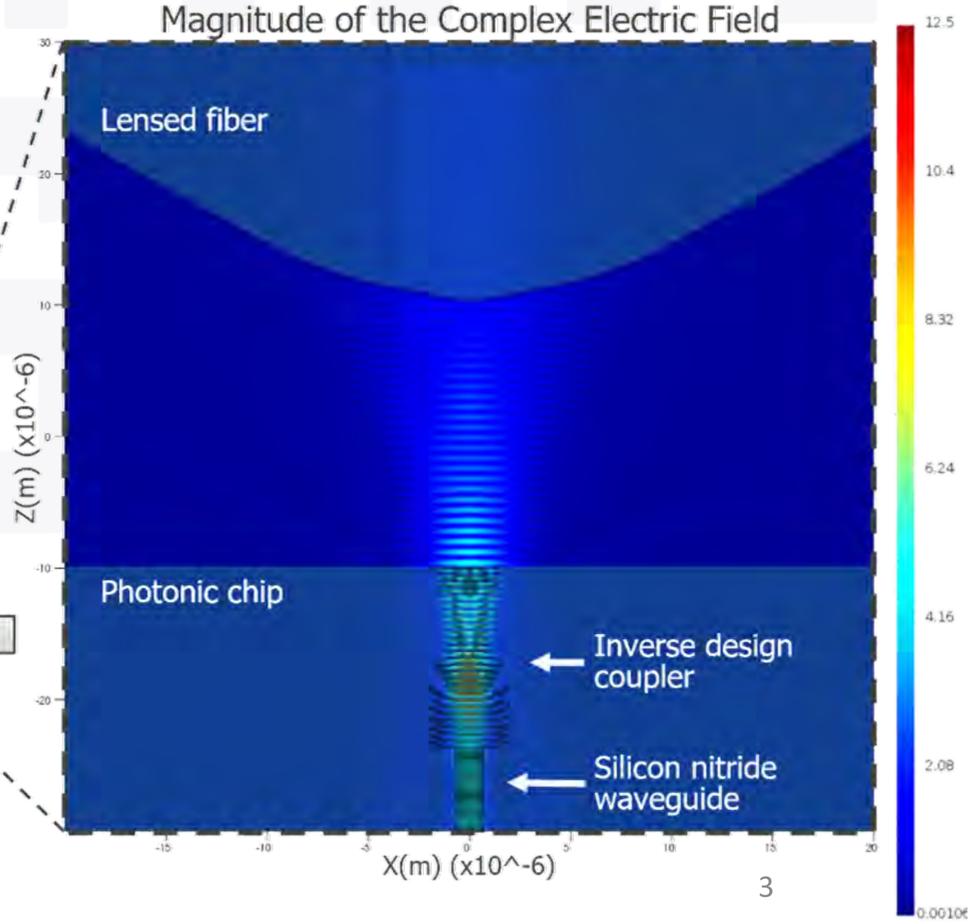
Packaged Si-PIC [1] L. Carroll et al.,

Introduction and Proposed Solution

- Efficiently coupling light into photonic waveguides requires precision alignment and transverse optical mode matching
  - Classical approach: active alignment, lensed fibers, inverted taper structures
- Goal: Use inverse design to create an efficient spot size converter for fiber-to-chip or chip-to-chip coupling

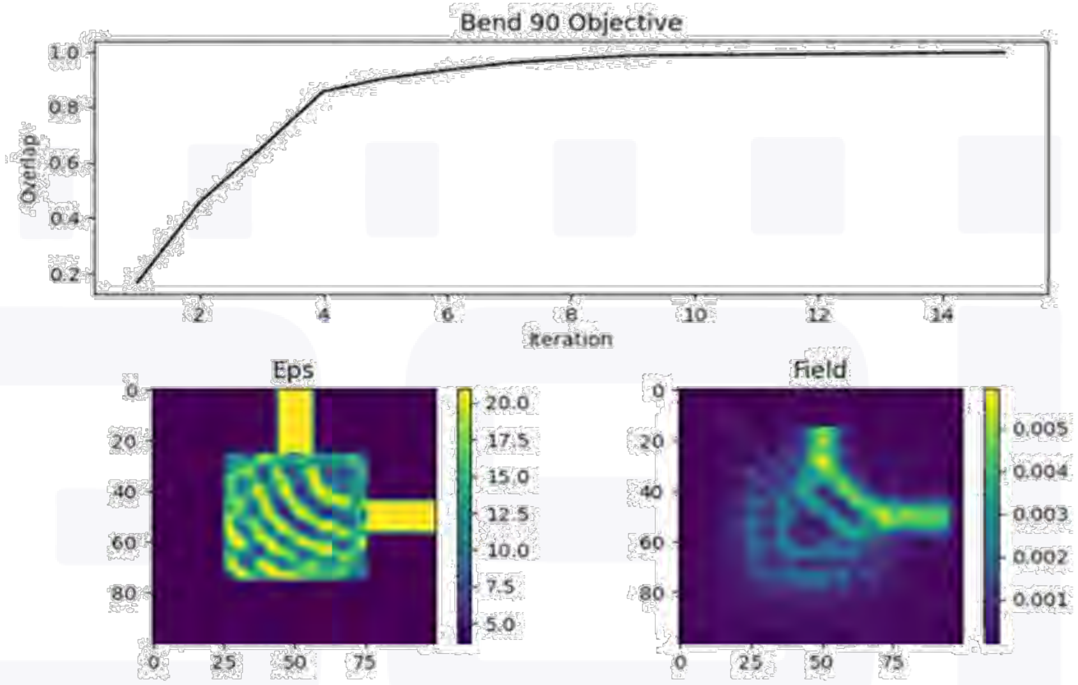


J. L. Gonzalez, et al., Submicrometer PSAS-to-PSAS Self-Alignment Technology for Heterogeneous Integration" [2]



Inverse Design

- Classical photonic components are designed using intuitive geometries
- Inverse design uses adjoint method optimization
- Can be formulated for any passive, linear photonic component
- Finite-difference frequency-domain solver (FDFD)
- Open-source Stanford Photonic Inverse Design framework (SPINS-b) [3]



Example 90 degree bend optimization using SPINS-b

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{E} - \boldsymbol{\omega}^2 \boldsymbol{\epsilon}(\boldsymbol{p})\mathbf{E} = -\mathbf{i}\boldsymbol{\omega}\mathbf{J} \quad (1)$$

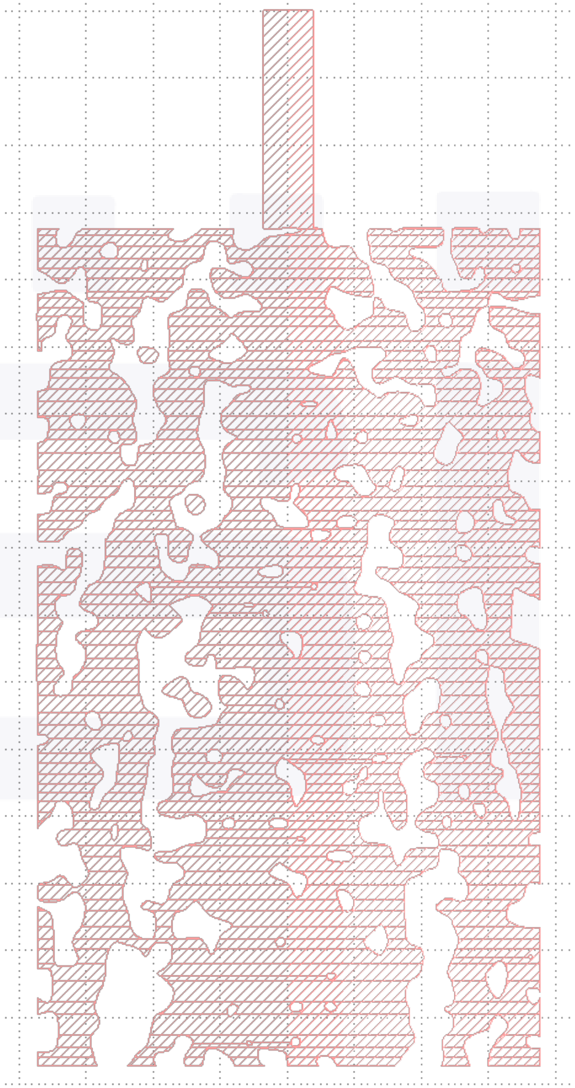
$$\mathbf{E} = \left(\nabla \times \frac{1}{\boldsymbol{\mu}} \nabla \times \; -\left(\boldsymbol{\omega}^2 \boldsymbol{\epsilon}(\boldsymbol{p})\right)\right)^{-1} (-\mathbf{i}\boldsymbol{\omega}\mathbf{J}) \quad (\mathbf{2})$$

$$\max_{\mathbf{p}} \; \mathbf{f_{obj}}(\mathbf{E}(\boldsymbol{\epsilon}(\mathbf{p})))$$

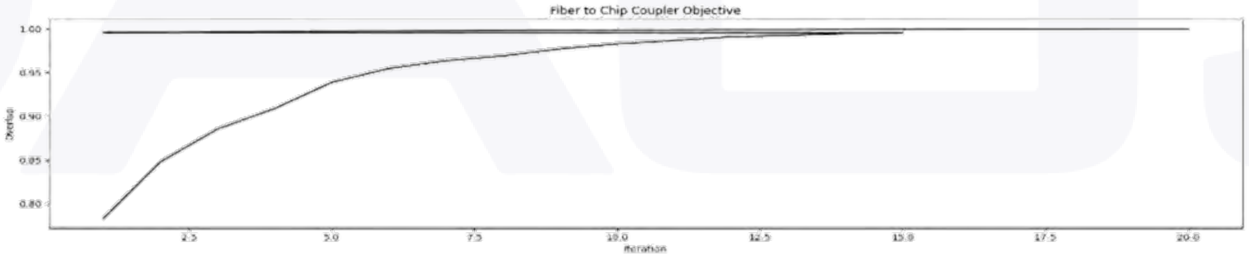
$$\textbf{subject to } \mathbf{p} \in \boldsymbol{S}$$

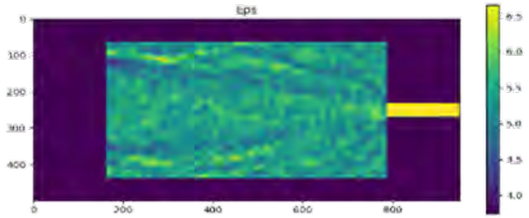
Frequency domain inverse design optimization objective formulation

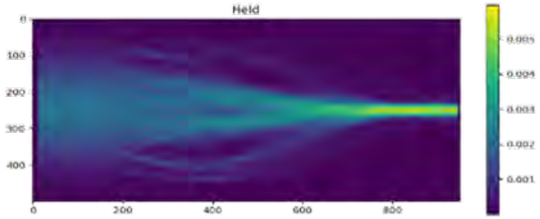
2D Inverse Design Cleaved SMF-28 Fiber-to-Chip Edge Coupler



- Optimization parameters:
    - 10.4 µm Gaussian source, λ = 1.55 µm wavelength, 11 x 25 µm footprint
    - Objective function = overlap of field solution with the fundamental TE silicon nitride waveguide mode
    - Optimized on a CPU matrix solver with a 2D field solution
- Fabricated on the silicon nitride (SiN) American Institute for Manufacturing Integrated Photonics (AIM) passive multi-project wafer (MPW) process

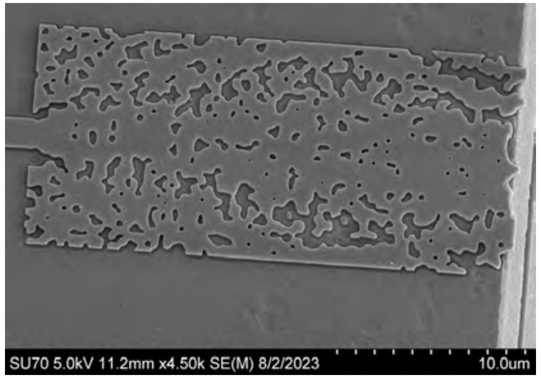


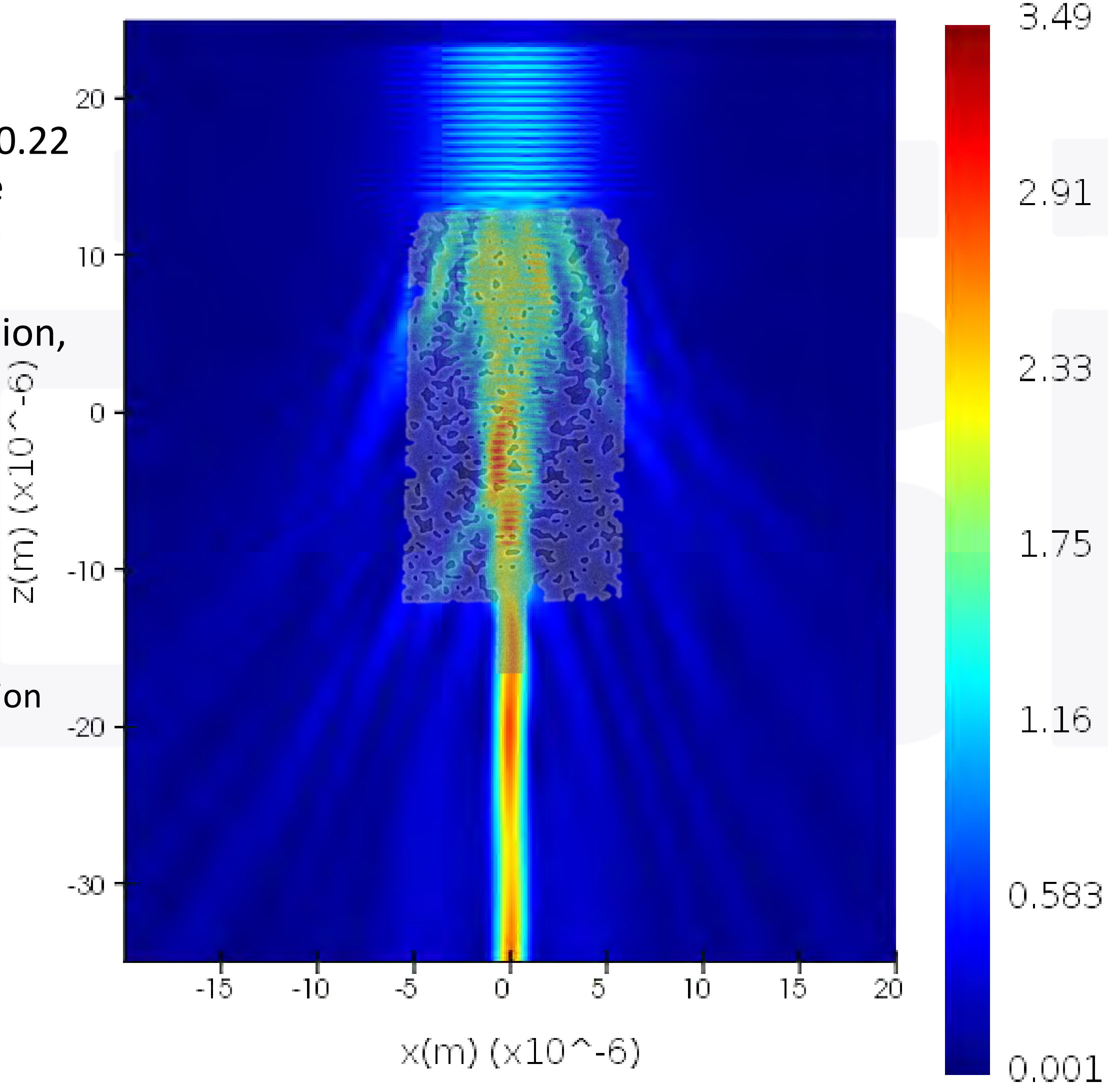




2D Inverse Design Cleaved Fiber-to-Chip Edge Coupler Results

- Lumerical finite-difference time-domain (FDTD) verification: 10.22 dB loss transmittance to the fundamental waveguide TE mode
- Experimental: 8.47 dB insertion loss
- High insertion loss as a result of using a 2D FDFD implementation, and failure to converge to a binary permittivity distribution
- Takeaways:
    - Proved that inverse design is a promising solution for designing efficient spot size converters
    - Optimization solver needs to be in three spatial dimensions to accurately model the problem
    - SEM imaging of the fabricated device helped determine fabrication and feature size constraints for future devices

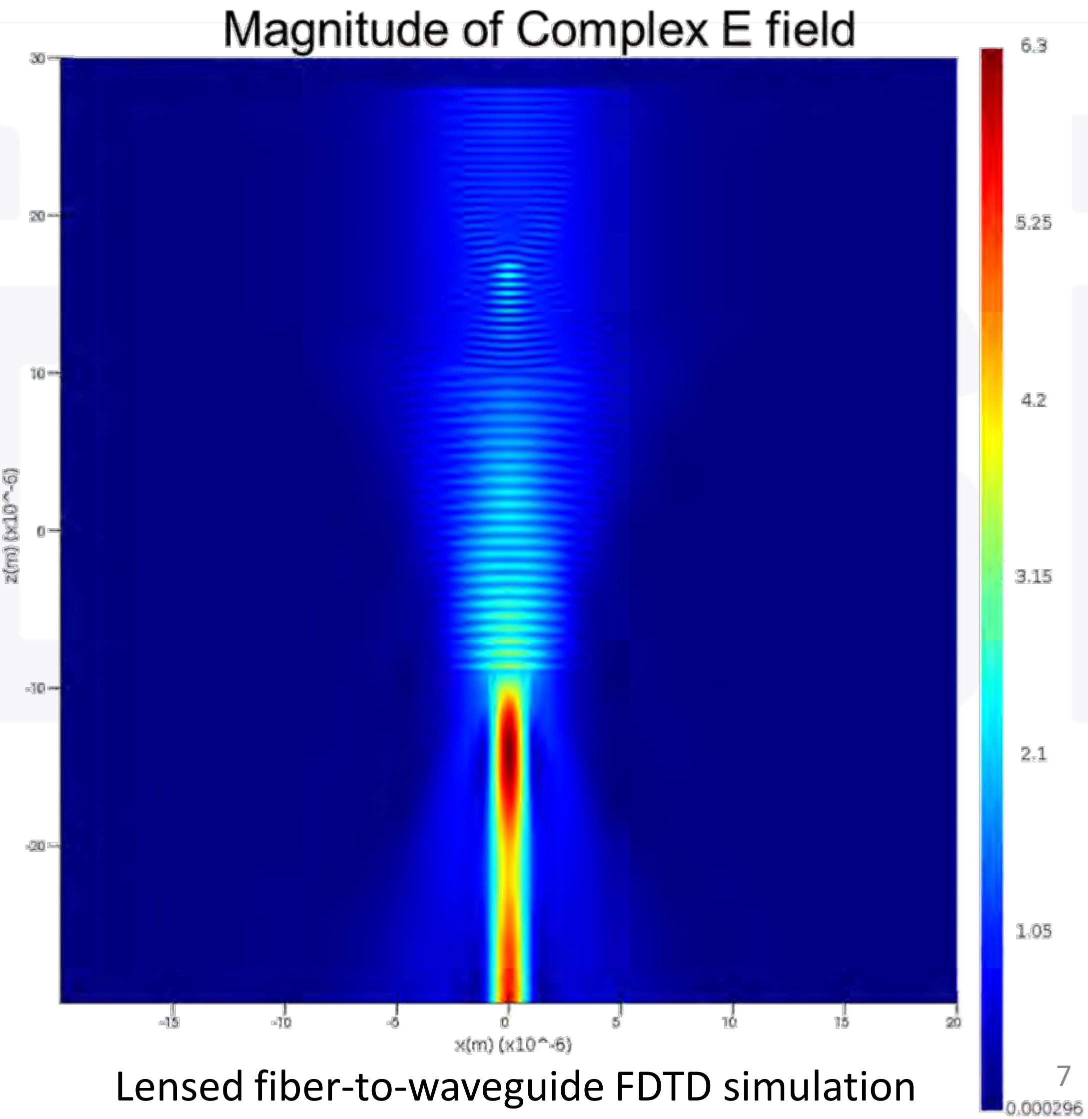



Magnitude of Complex E field

FDTD verification of the 2D coupler

3D Inverse Design of a Lensed Fiber-to-Chip Edge Coupler

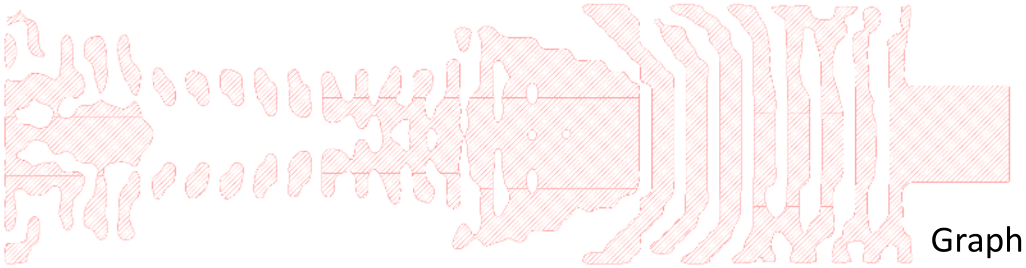
- Biconjugate gradient GPU solver based on the NVIDIA CUDA architecture substantially reduced computation time allowing for 3D optimization
- Modeling the cleaved fiber problem in three dimensions requires a large simulation domain which is computationally demanding and accumulates numerical error due to ill-conditioned matrix
    - Optimization of a lensed fiber coupler reduced simulation domain size, 3.5 µm beam diameter vs. 10.4 µm cleaved fiber diameter
- As a baseline, coupling from a lensed fiber directly to the fundamental SiN TE waveguide resulted in a 4.41 dB loss in Lumerical FDTD



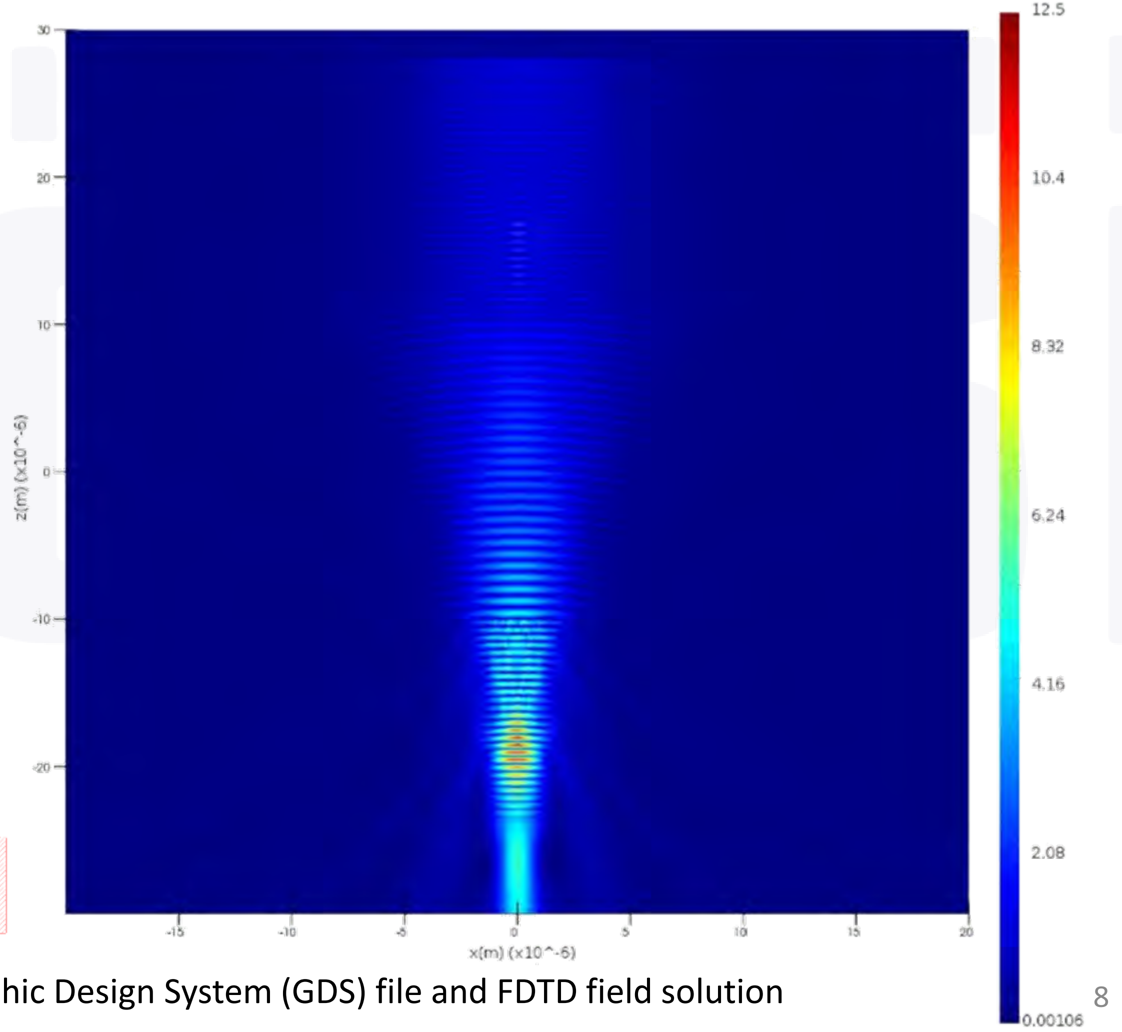
Lensed fiber-to-waveguide FDTD simulation

3D Inverse Design Fiber-to-Chip Edge Coupler Preliminary Simulation Results

- The FDTD field solution at the focal point of a lensed SMF-28 fiber was used as the source initial condition in the FDFD solver
- The computational graph was formulated in a similar manner to the 2D problem, several alterations were made to optimize for different objectives:
    - No fabrication constraints, 4 x 10 µm footprint, 2.77 dB loss
    - Minimum feature size constraint, 4 x 12 µm footprint, 5.37 dB loss
    - Minimum feature size constraint, wideband optimization between 1.5 and 1.6 µm, 4 x 14 µm footprint, 4.53 dB loss at λ = 1.55 µm



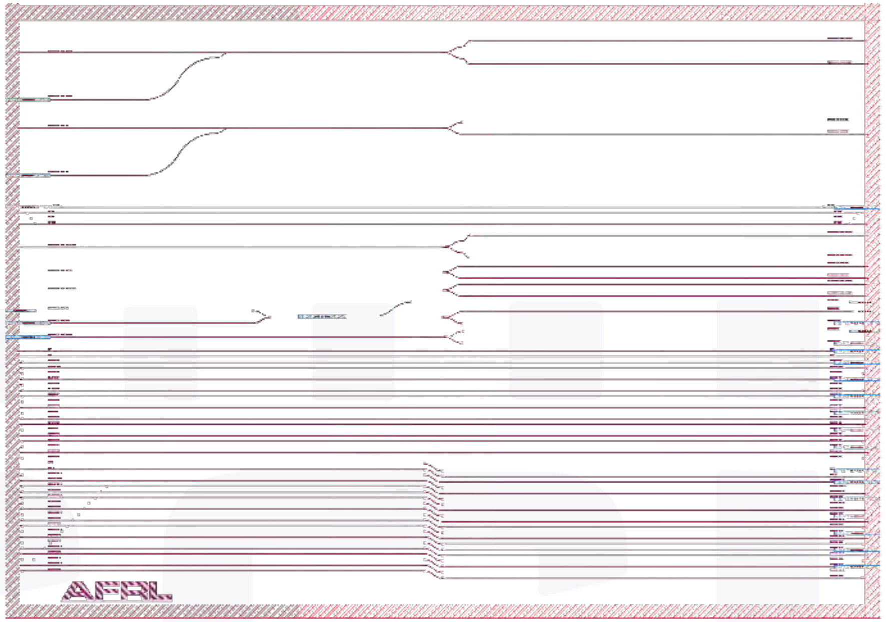
Magnitude of Complex E field



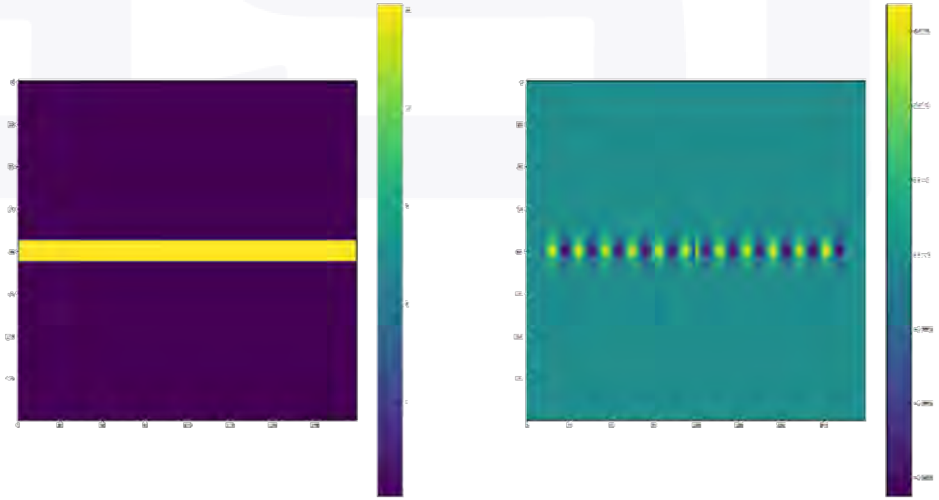
Graphic Design System (GDS) file and FDTD field solution

Summary and Direction

- The coupler designs were laid out for fabrication on an AIM SiN MPW run along with several other inverse design components and coupling experiments
- A GPU-based FDTD solver is being implemented that would expand the possibilities for rapid inverse design [4]
  - Exploit the inherent bandwidth property of time-domain solutions
  - Larger computational domain without the error in FDFD
- In addition to couplers, inverse design of coupled mode resonator components [5] and optical pulse shaping using nonlinear materials [6] is being explored



August AIM tapeout layout



Permittivity and instantaneous time-domain electric field solution of a waveguide simulated with fdtd-z

References

[1] L. Carroll et al., “Photonic Packaging: Transforming Silicon Photonic Integrated Circuits into Photonic Devices,” Applied Sciences, vol. 6, no. 12, p. 426, Dec. 2016, doi: 10.3390/app6120426.

[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 et al. Nanophotonic Inverse Design with SPINS: Software Architecture and Practical Considerations. arXiv:1910.04829 (2019).

[4] J. Lu and J. Vuckovic, “*fdtd-z*: A systolic scheme for GPU-accelerated nanophotonic simulation,” https://github.com/spinsphotonics/fdtdz (2023).

[5] Ginis, V., Benea-Chelmus, IC., Lu, J. et al. Resonators with tailored optical path by cascaded-mode conversions. Nat Commun 14, 495 (2023). https://doi.org/10.1038/s41467-023-35956-9

[6] Joshua Baxter and Lora Ramunno, "Inverse design of optical pulse shapes for time-varying photonics," Opt. Express 31, 22671-22684 (2023)