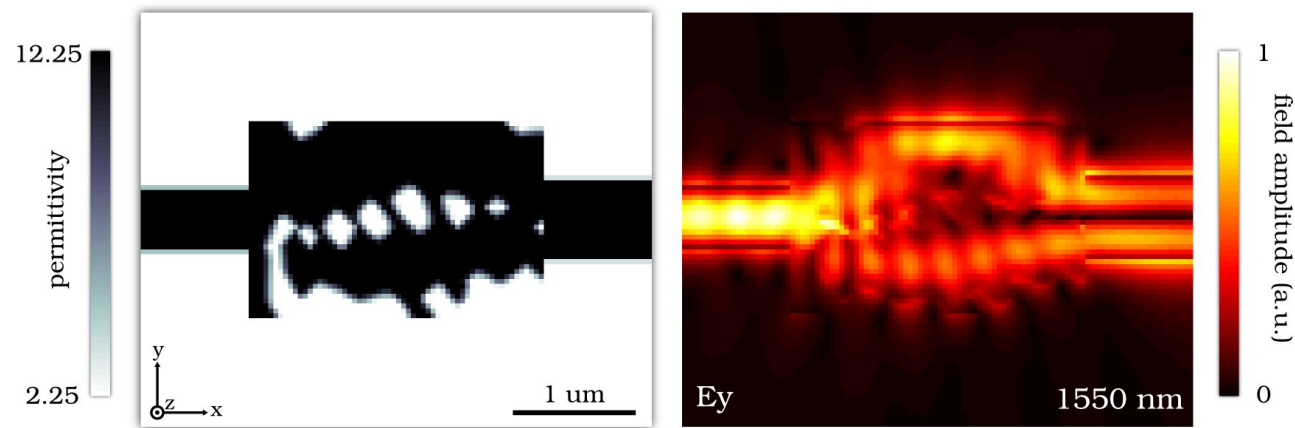


# Nanophotonic Computational Design

Jesse Lu

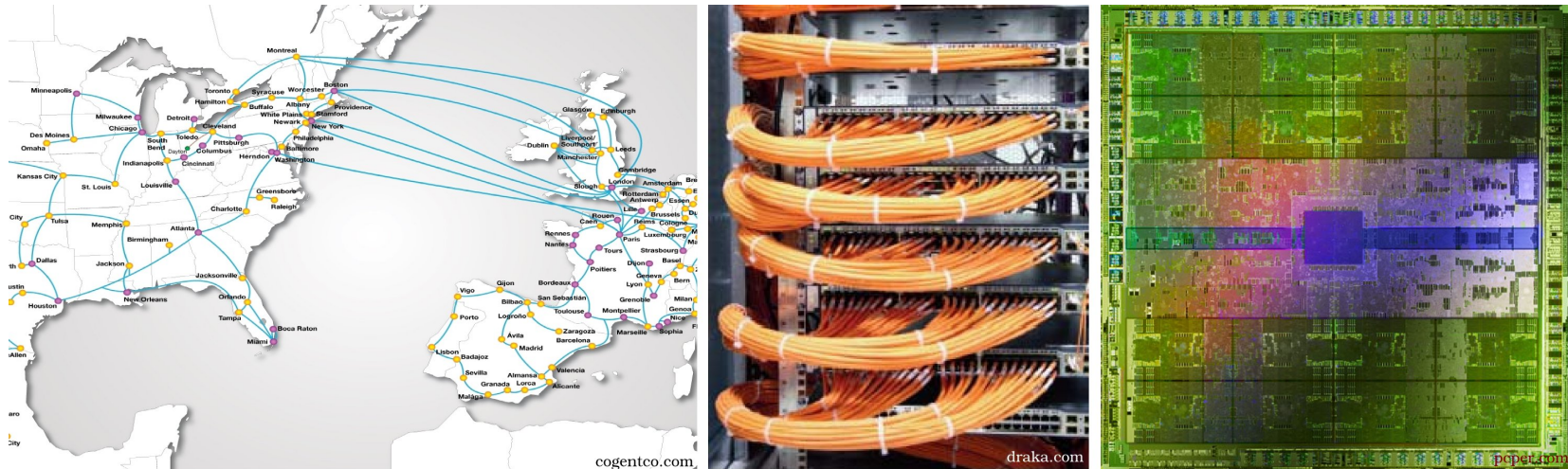
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Takeaway: Taught a computer to design nanophotonic devices



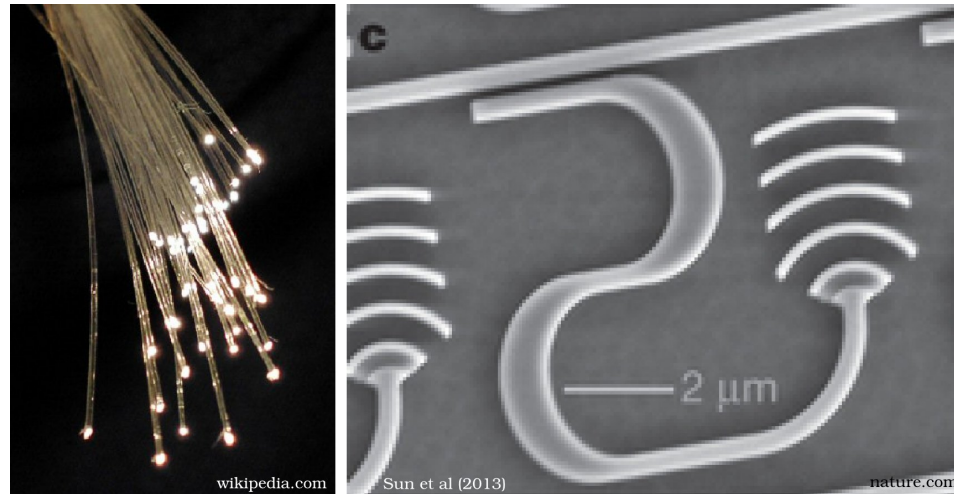
- full 3D
- multi-mode
- manufacturable (mostly)

# Part 1: Motivation



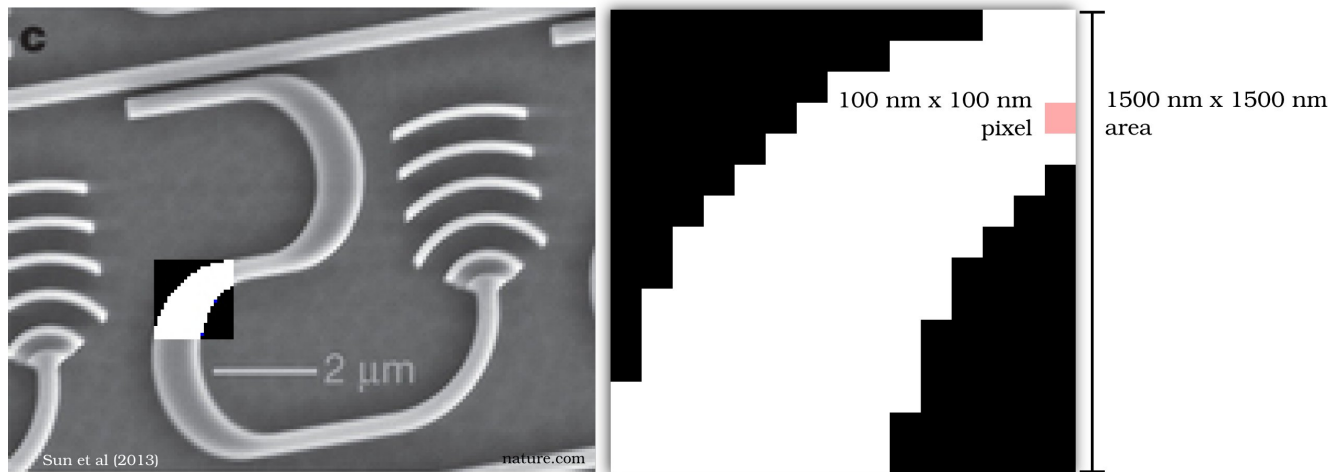
- As information grows, optical networks needed
  - across continents
  - within a datacenter
  - between chips and on-chip

- An on-chip optical network is a fundamentally new optical communications technology: *the integrated optical circuit*



- Miniaturization drives
  - component price down
  - functionality up
  - design complexity (way) up

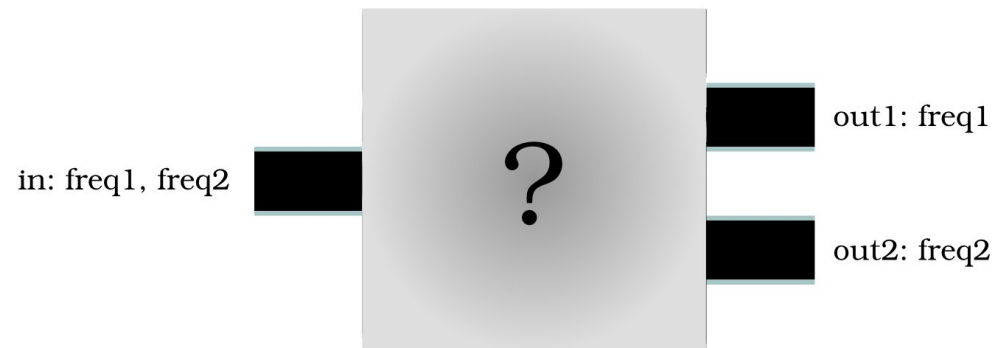
- Increasing design complexity requires additional degrees of freedom
- Fortunately, we have a virtually unlimited amount



- Include/exclude per pixel gives us  $2^{(15^2)} = 2^{225}$  possibilities, uncountable

- Only feasible solution: Humans describe, Computers design

```
device mux2
  in: {freq1, freq2}
  out1 <= freq1
  out2 <= freq2
```



## Part 2: Theory

- First, cast electromagnetic wave equation into linear algebra terms

$$(\nabla \times \mu_0^{-1} \nabla \times -\omega^2 \epsilon) E + i\omega J = 0 \longrightarrow A(z)x - b = 0$$

where

$$E \rightarrow x$$

$$\epsilon \rightarrow z$$

$$\nabla \times \mu_0^{-1} \nabla \times -\omega^2 \epsilon \rightarrow A(z)$$

$$-i\omega J \rightarrow b$$

- $A(z)x - b$  is called the *physics residual*

- Secondly, formulate our optimization objective

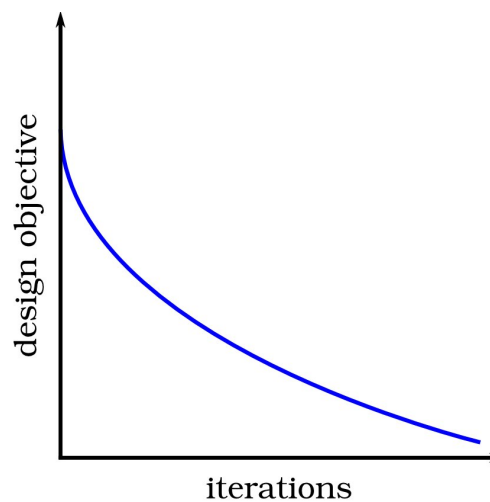
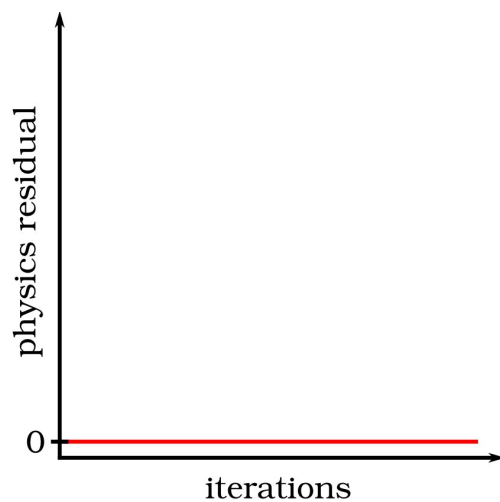
$$f(x) = (\alpha - |c^\dagger x|)^2$$

- $c^\dagger x$  is equivalent to overlap integral  $\int E_t^* E$
- To design linear devices, objective chosen to be overlap integral with target field at output port
- $f(x)$  is called the *field design objective*



- Typically,

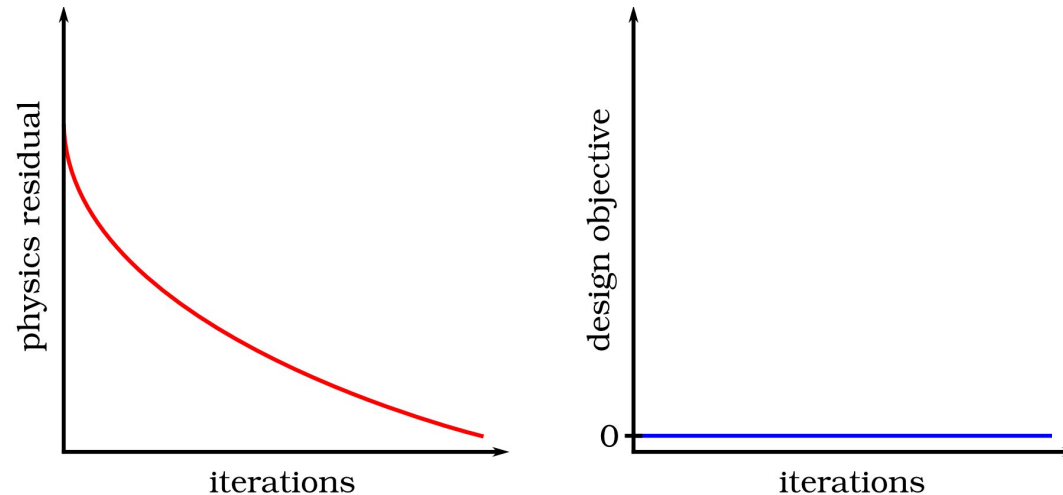
$$\begin{aligned} &\text{minimize} && (\alpha - |c^\dagger x|)^2 \\ &\text{subject to} && A(z)x - b = 0 \end{aligned}$$



- Efficient algorithm known as the *adjoint method*

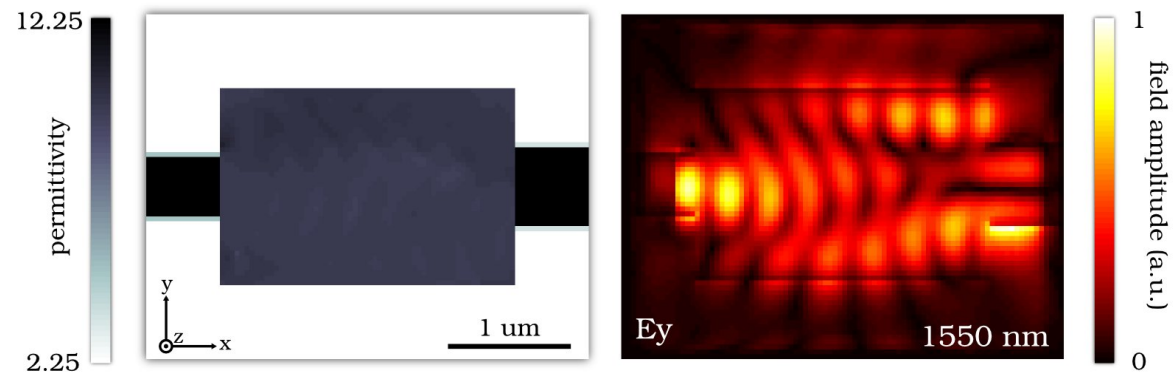
- Our alternative formulation, known as *objective-first*

$$\begin{aligned} & \text{minimize} && \|A(z)x - b\|^2 \\ & \text{subject to} && |c^\dagger x| = \alpha \end{aligned}$$



- Perfect performance always enforced, even at the expense of breaking physical laws

- Results in *soft-physics* solves



- Key insight: soft-physics solution suggests optimal structure

$$\begin{aligned} & \text{minimize} \quad \|A(z)x - b\|^2 \\ & \text{subject to} \quad |c^\dagger x| = \alpha \end{aligned}$$

- Could be solved by iteratively solving for  $x$  and  $z$ 
  - Known as *alternating directions*
  - Takes advantage of bi-linearity of the physics residual,

$$A(z)x - b = B(x)z - d(x)$$

- *Alternating directions method of multipliers (ADMM)*<sup>1</sup> gives much faster convergence
  - Due to introduction of dual variable

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<sup>1</sup>S. Boyd et al, Foundations and Trends in Machine Learning (2011)

- Full problem is multi-mode and multi-output
- Objective-first formulation:

$$\begin{aligned} & \text{minimize} && \sum_i^M \|A_i(z)x_i - b_i\|^2 \\ & \text{subject to} && \alpha_{ij} \leq |c_{ij}^\dagger x_i| \leq \beta_{ij}, \quad \text{for } i = 1, \dots, M \text{ and } j = 1, \dots, N_i \end{aligned}$$

- Adjoint method formulation:

$$\begin{aligned} & \text{minimize} && \sum_{ij}^{M, N_i} \max\{\alpha_{ij} - |c_{ij}^\dagger x_i|, |c_{ij}^\dagger x_i| - \beta_{ij}, 0\} \\ & \text{subject to} && A_i(z)x_i - b_i = 0, \quad \text{for } i = 1, \dots, M \end{aligned}$$

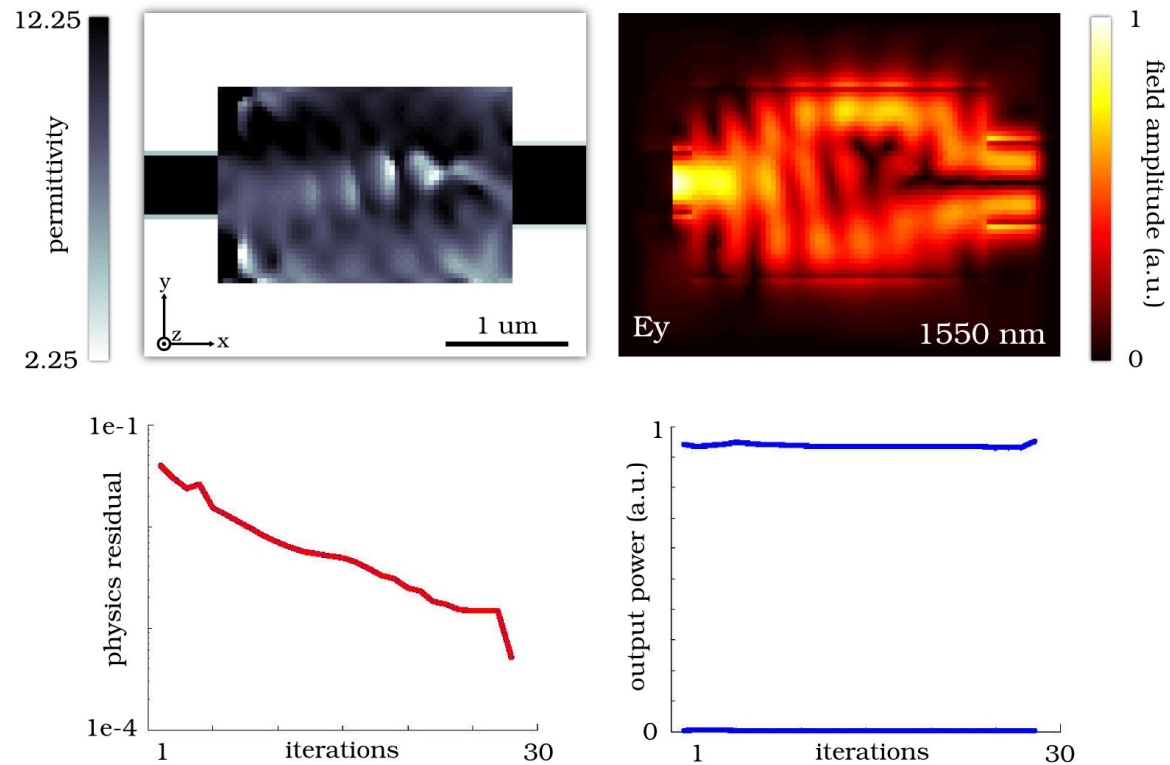
## Part 3: Implementation

- Both objective-first and adjoint methods implemented in Matlab:  
`github.com/JesseLu/lumos`
- In both cases, solving for  $A_i(z) \in \mathbf{C}^{\text{millions} \times \text{millions}}$  dominates computation
  - $A_i(z)^{-1}$  solved iteratively<sup>2</sup>
  - Accelerated on GPUs and brought to scale in the cloud (EC2)
  - Allows for arbitrarily large number of modes without sacrificing runtime (in theory)

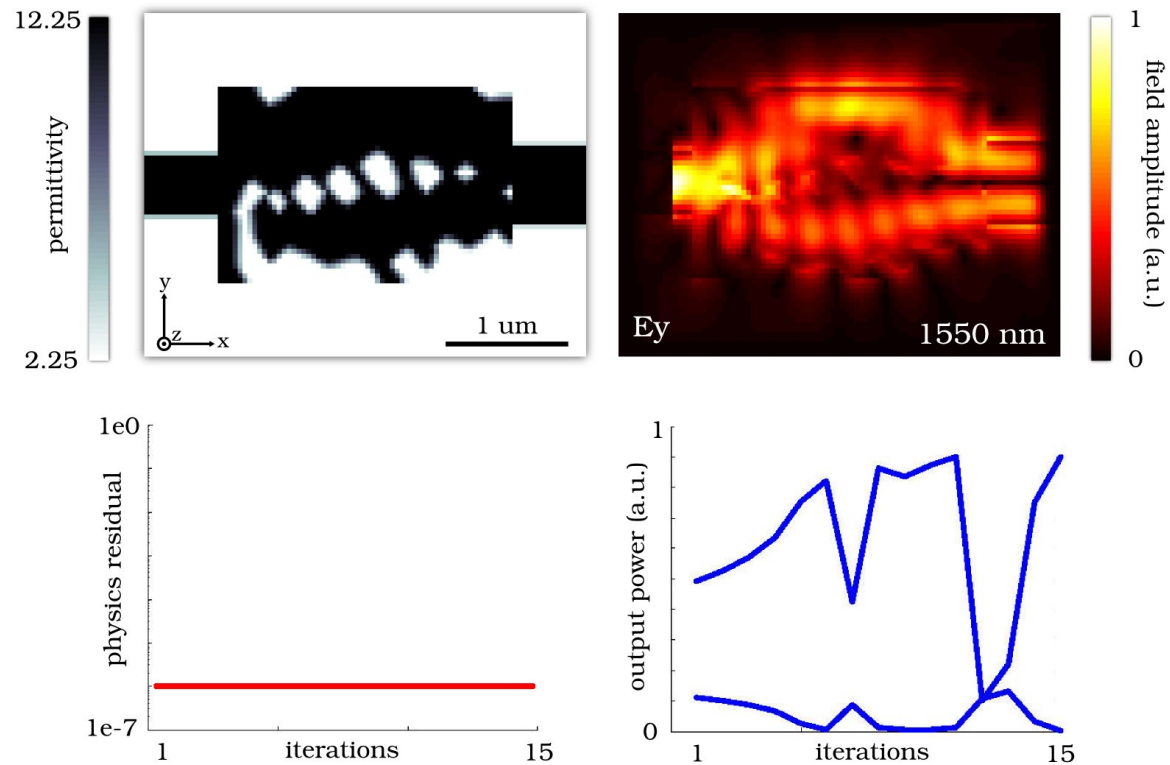
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<sup>2</sup>W. Shin, J. of Computational Physics, (2012)

- Design phase I: Objective-first method with density parameterization

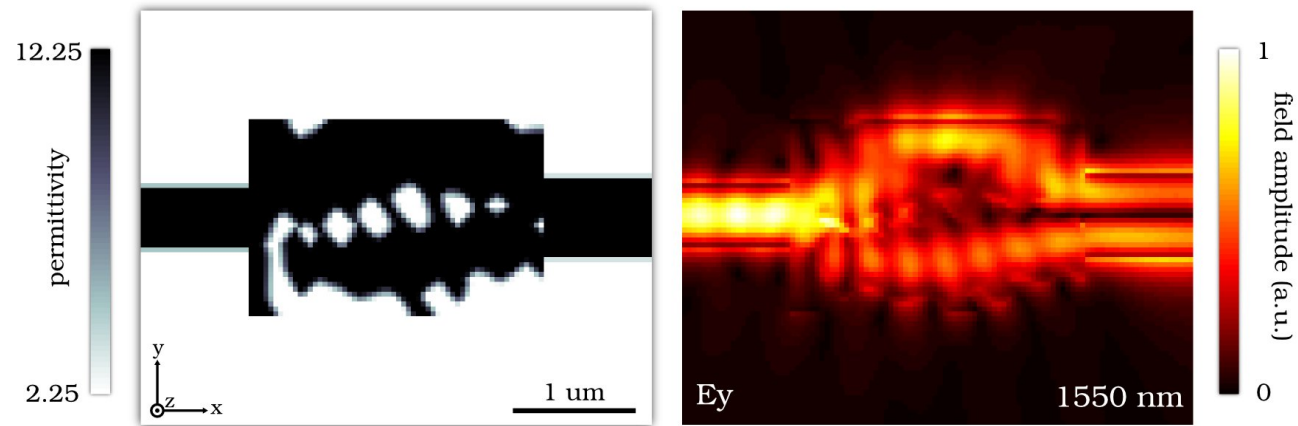


- Design phase II: Adjoint method with boundary parameterization



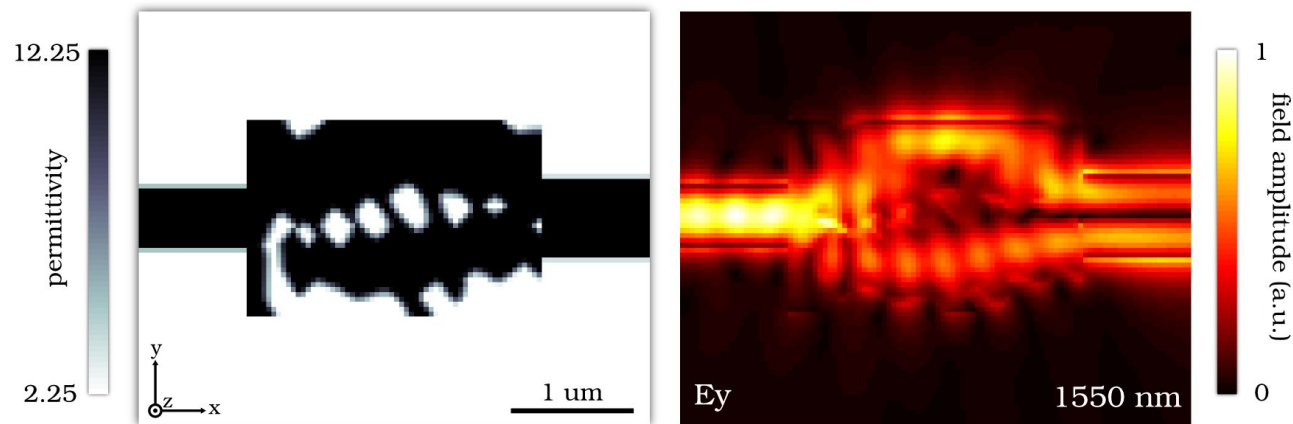


- Verification with larger simulation



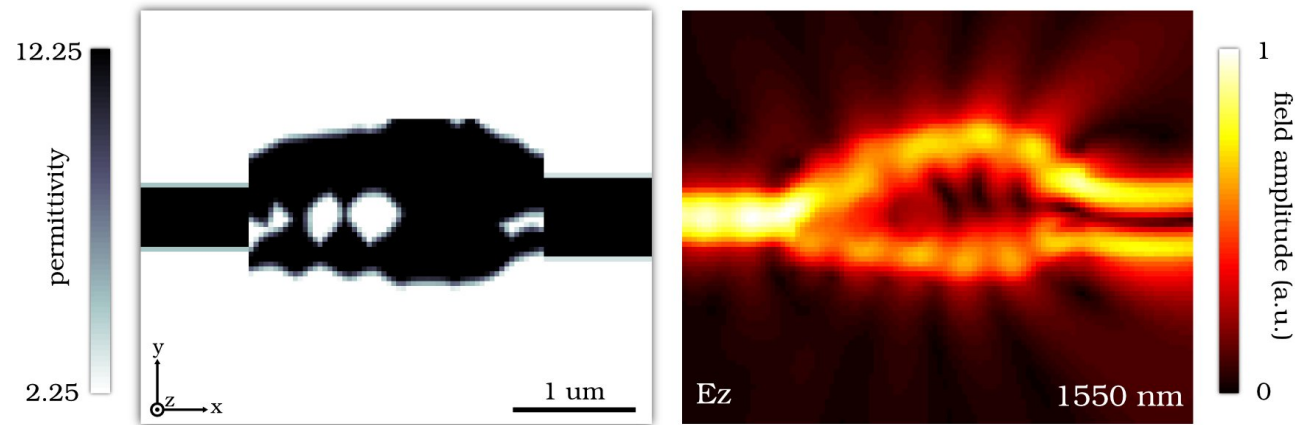
## Part 4: Results

- TE mode converter



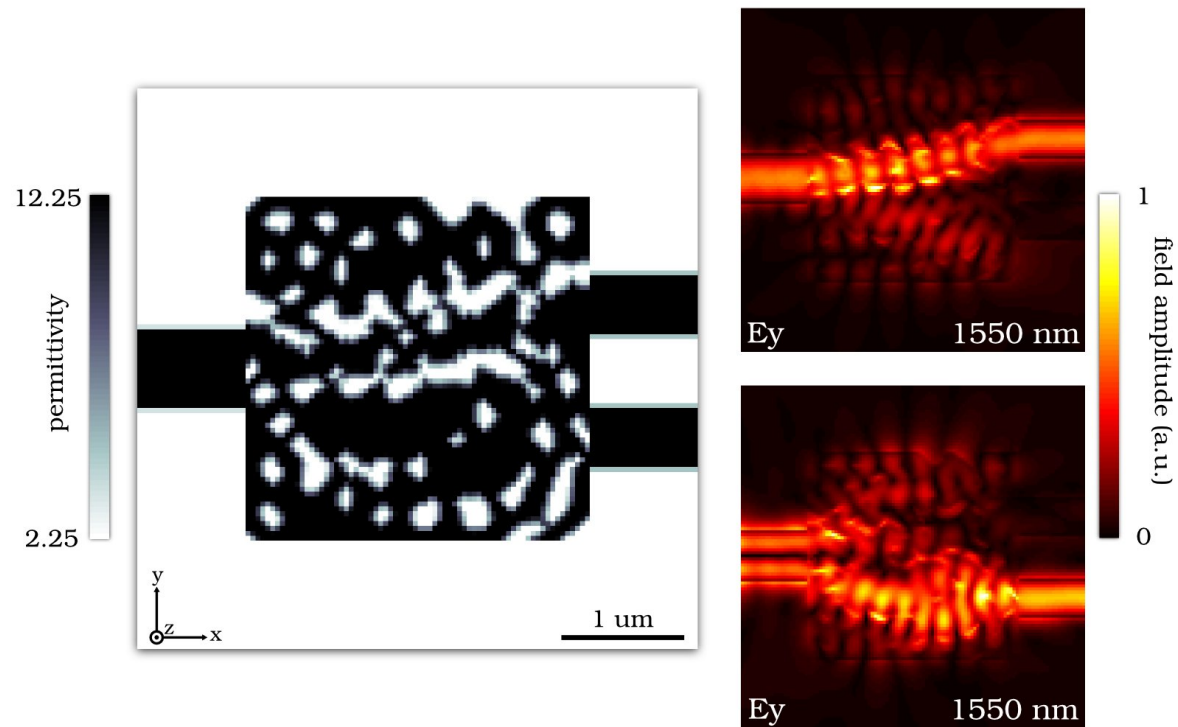
- Efficiency: 86.4%
- Power in rejection mode (transmitted fundamental): 0.7%
- 250 nm silicon slab surrounded by silica

- TM mode converter

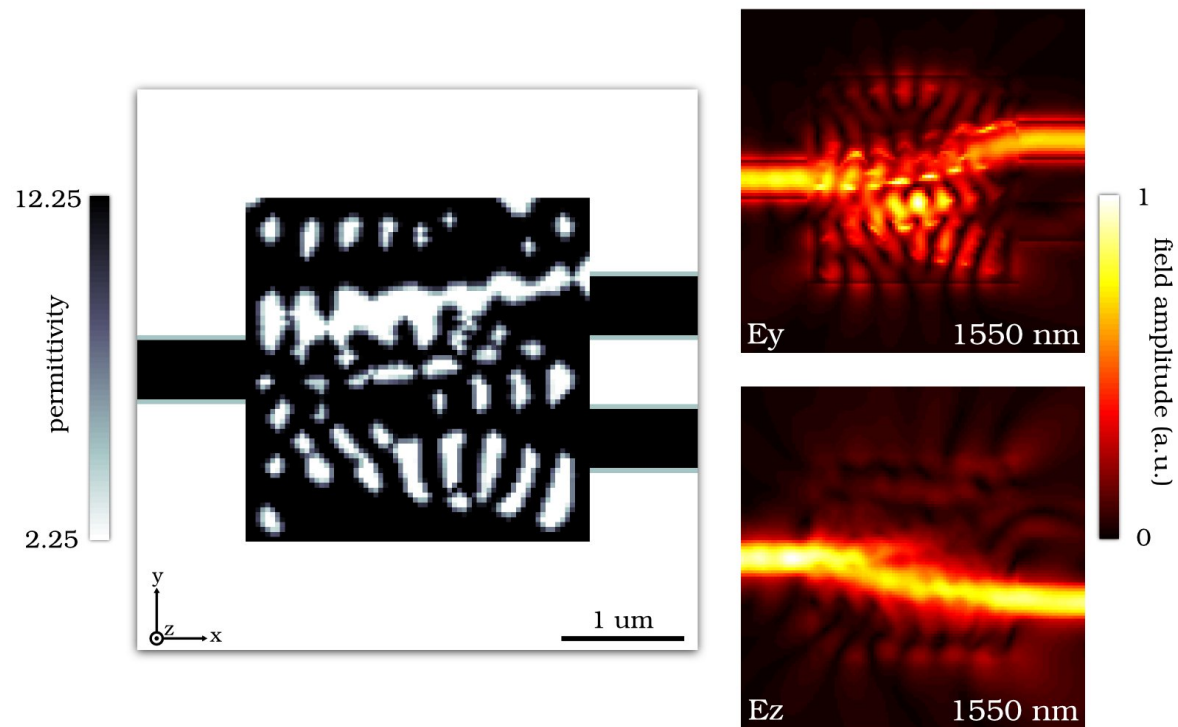


- Efficiency: 76.9%
- Power in rejection mode (transmitted fundamental): 1.0%

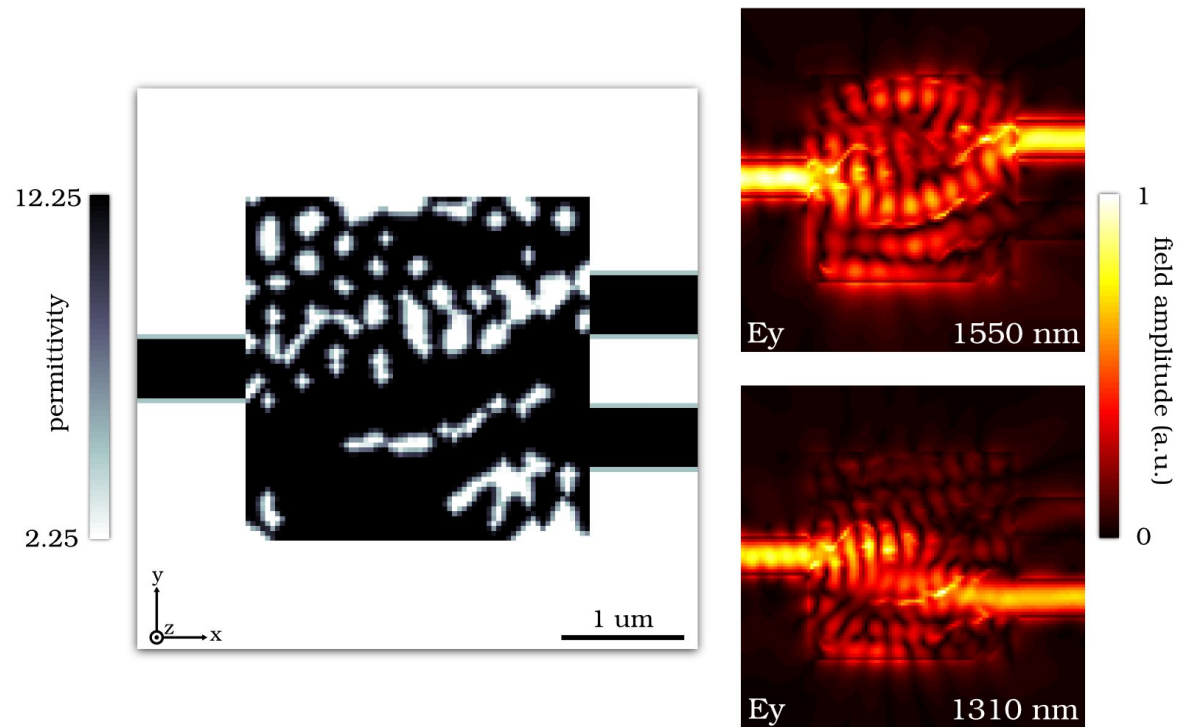
- Spatial mode splitter
  - Efficiency: 88.7%, 77.4% (0.27%, 0.20%)



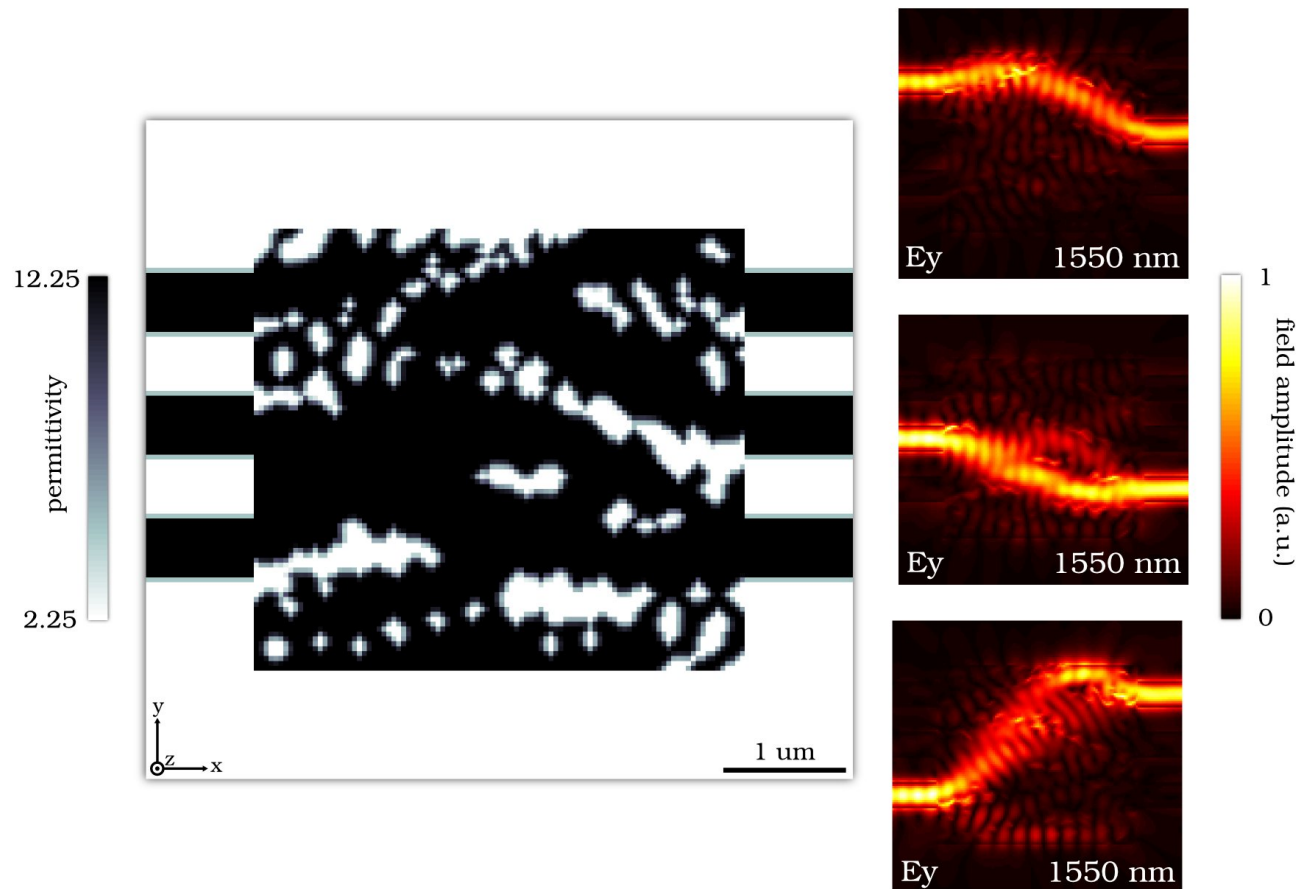
- TE/TM splitter
  - Efficiency: 87.6%, 88.8% (1.06%, 0.58%)



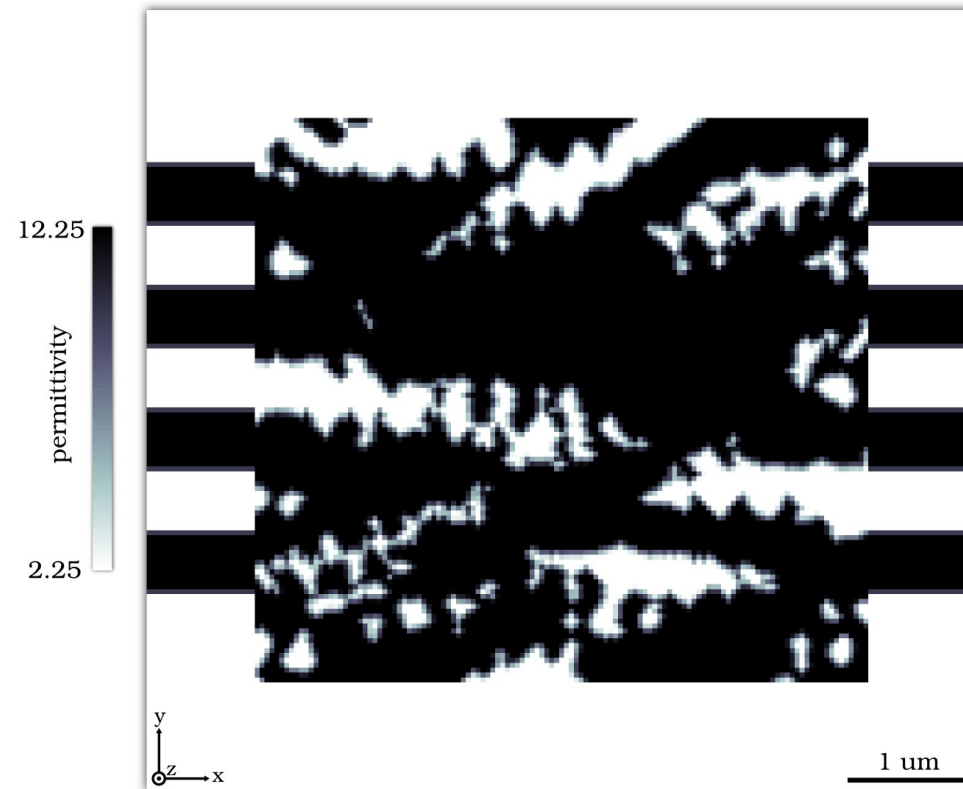
- Wavelength splitter
  - Efficiency: 83.2%, 78.7% (0.49%, 1.66%)



- 3x3 hub (88.6%, 90.6%, 87.3% efficiency)

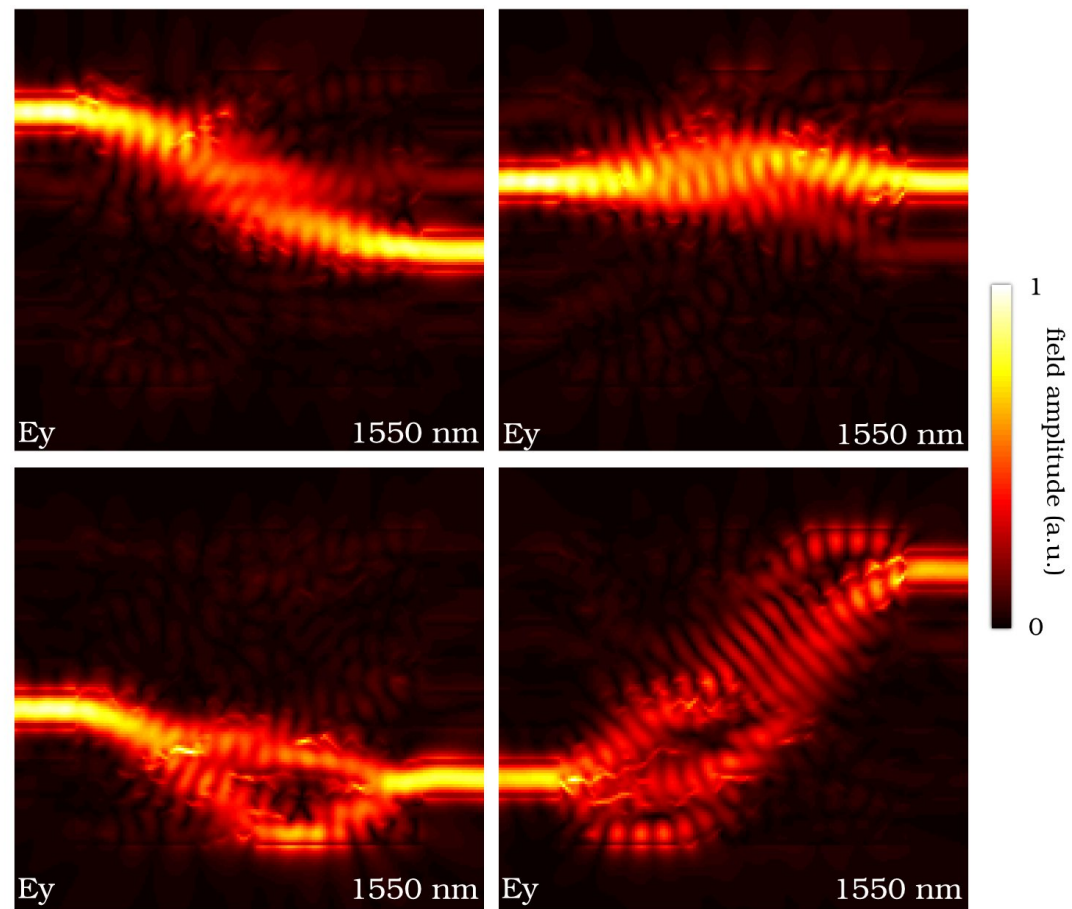


- 4x4 hub

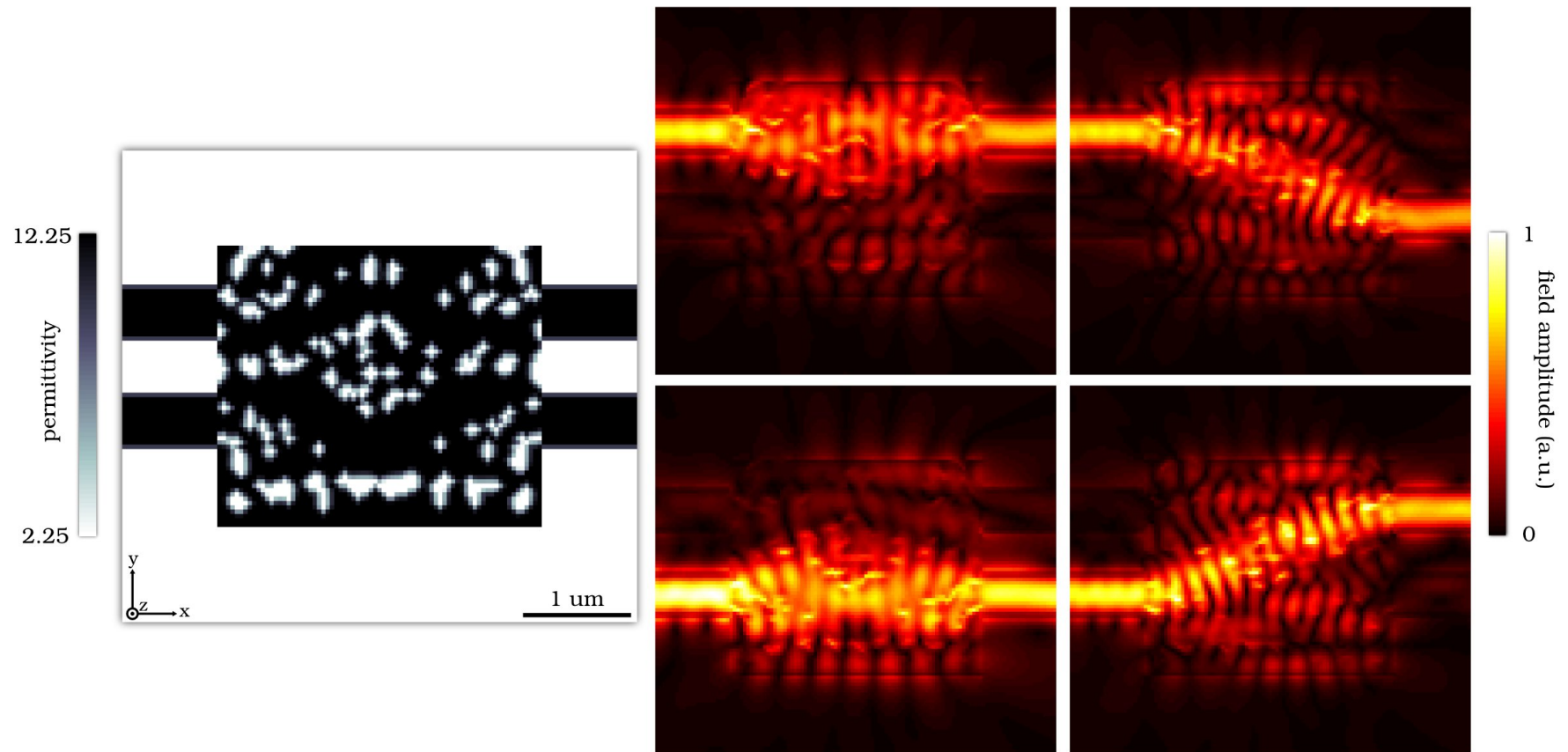




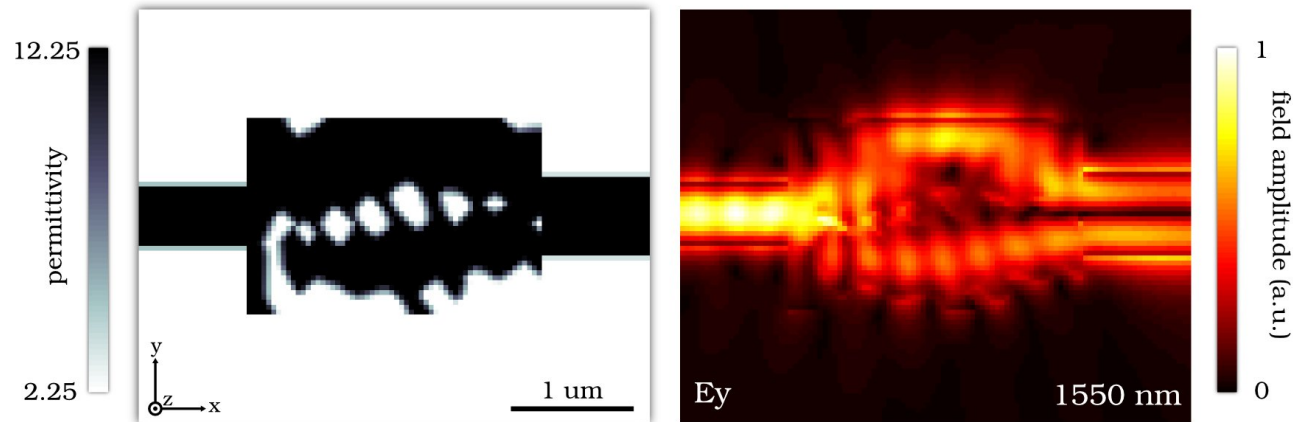
- Efficiency: 85.9%, 88.1%, 85.4%, 84.3%



- 4x4 compacted hub (77.6%, 73.7%, 75.7%, 75.2% efficiency)



# Summary



- Developed a system to design three-dimensional, multi-mode, linear nanophotonic devices
  - Compact nanophotonic designs which open up the full parameter space
  - Key enabler for future dense integrated optical systems