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From Modeling to Implementation of High Index Contrast Microphotonics

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Overview

Goals: To communicate the following . . .

- The importance of analytical intuition
- The importance of rigorous numerical design
- The ease of implementing numerical codes
- The need for both multiphysics and VLSI codes

Outline

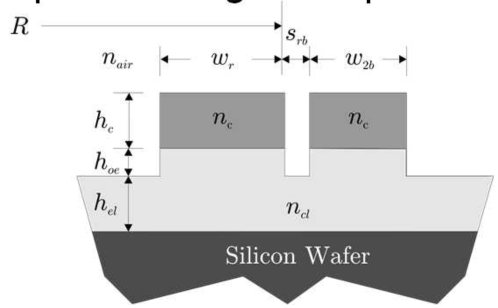
- The Finite Difference Time Domain (FD-TD) Technique
- Mode Evolution Devices
- Filter Design and a Polarization Independent Microphotonic Circuit
- Some Special Cases: Periodic Boundary Conditions and Conductors
- A Multi-Physics Problem: Thermal Microphotonic Focal Plane Array (TM-FPA)

Analytic Intuition: Coupled Mode Theory

Coupled Mode Theory (CMT) Application

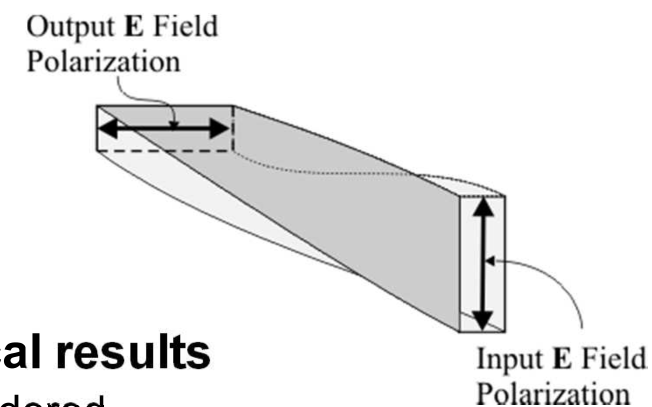
- ❑ Between a pair of waveguides: The coupling between otherwise orthogonal modes is determined by the degree of the overlap in the region of perturbation

$$\kappa_{mn} = -j\frac{\omega}{4}\int_A \Delta\varepsilon e_m^* \cdot e_n dA$$



- ❑ Adiabatic Transition:

$$\kappa_{mn} = -j\frac{\omega}{4\delta\beta(z)}\int_A e_m^* \cdot e_n \frac{d}{dz}\varepsilon(z)dA$$



Use CMT for intuition but not numerical results

- ❑ CMT is limited by number of modes considered
- ❑ Scattering, loss, and even coupling strength are generally off
- ❑ CMT will not provide generate non-intuitive results
- ❑ Computers have become sufficient fast to do rigorous numerical simulations

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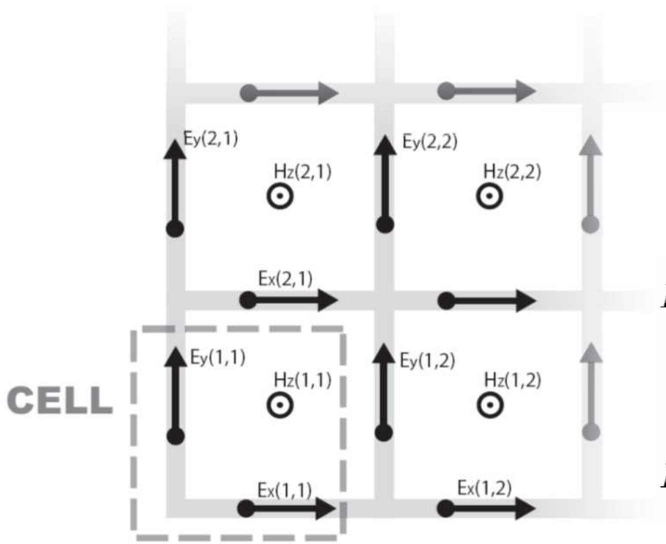
Finite-Difference Time-Domain Technique

Why choose FD-TD?

- Simple discretization of Maxwell's equations with no other approximations
- Why not Beam Propagation Method and/or Eigenmode Expansion?
  - Beam Propagation Method based on Paraxial Wave Equation (limited angles)
  - Eigenmode Expansion great for tapers, but not for abrupt transitions

How FD-TD is implemented



$$\frac{\partial E_x(z,t)}{\partial t} = -\frac{1}{\varepsilon_0}\frac{\partial H_y(z,t)}{\partial z}$$

$$\frac{\partial H_y(z,t)}{\partial t} = -\frac{1}{\mu_0}\frac{\partial H_y(z,t)}{\partial z}.$$

$$E_x(z',t'+\frac{\Delta t}{2}) = E_x(z',t'-\frac{\Delta t}{2}) - \frac{\Delta t}{\epsilon_0 \cdot \Delta x}\left(H_y(z'+\frac{1}{2}\Delta z,t') - H_y(z'-\frac{1}{2}\Delta z,t')\right)$$

$$H_y(z',t'+\frac{\Delta t}{2}) = H_y(z',t'-\frac{\Delta t}{2}) - \frac{\Delta t}{\mu_0 \cdot \Delta x}\left(E_x(z'+\frac{1}{2}\Delta z,t') - E_x(z'-\frac{1}{2}\Delta z,t')\right)$$

Finite Difference Time Domain Considerations

Commercial Code, Own Code, Open Source Codes

- Commercial codes tend not to be well parallelized or portable → limited utility
- FD-TD is easy to program with some guidance (book by A. Taflove)
- If you write your own code, you will always know what you is in the code
- Also, open source codes by (e.g. Steven Johnson's MEEP)

Computer Selection

- Why is FD-TD so slow? Memory bandwidth code, cores alone will not help
- Specfp benchmark *swim_m.f* www.spec.org a good metric of performance
  - 32-core SGI Altix 4700 Bandwidth System, swim_m.f (62.8 seconds)
  - 16-core IBM, swim_m.f (58.8 seconds)
  - 8-core Intel (i.e. Xeon Quad Cores), swim_m.f (834 seconds)
- What is the difference between these machines → Memory Bandwidth

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Microring-Resonator Based Filters and the first Polarization Microphotonic Circuit

Michael R. Watts, Milos Popovic, Tymon Barwicz, Peter Rakich, Luciano Socci, Hermann A. Haus, Henry I. Smith and E. P. Ippen

Research Performed at the

Massachusetts Intitute of Technology

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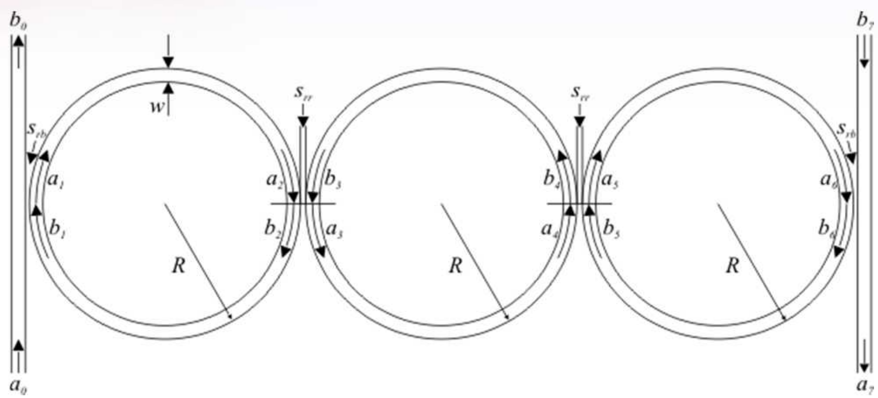
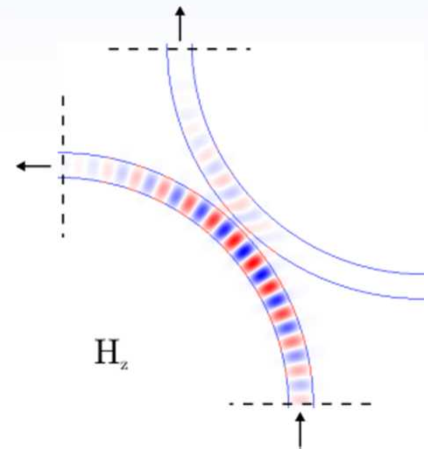
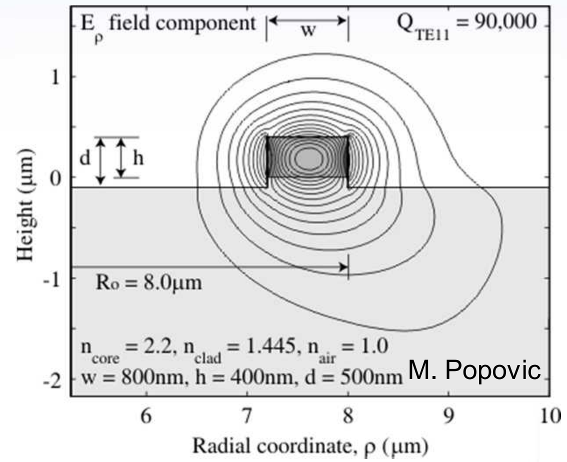
Implementation of FD-TD

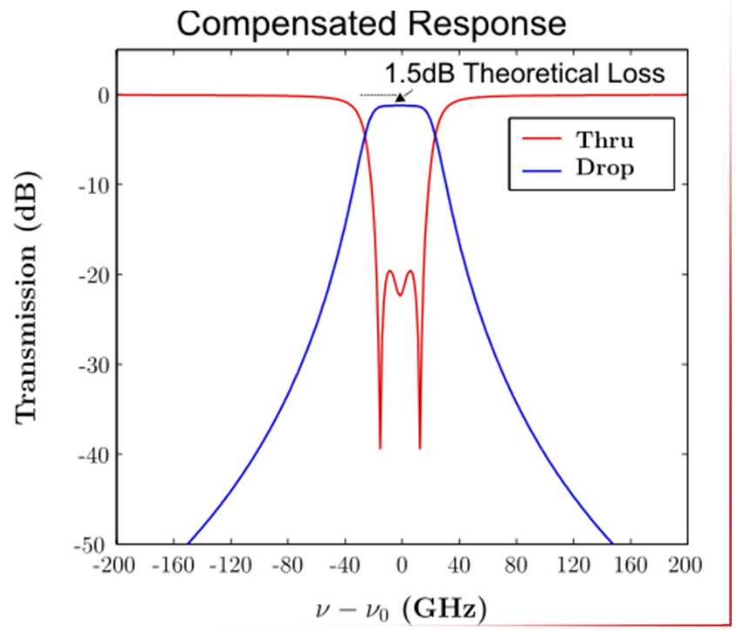






Procedure

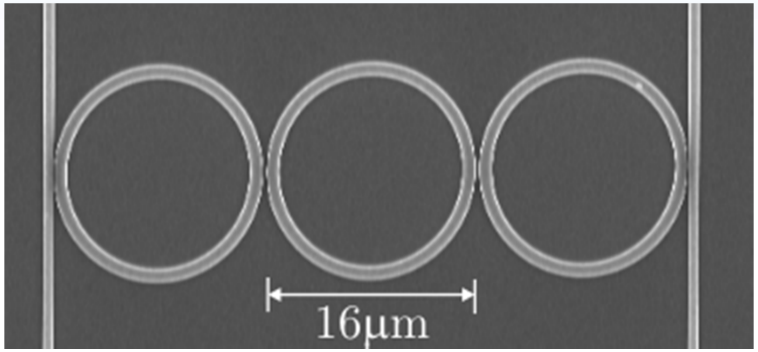
- ❑ Complex vector mode-solver to determine Q and find bus and ring waveguide modes
- ❑ Launch appropriate modes as Gaussian pulse
- ❑ Take Discrete Fourier Transforms (DFTs) & overlaps to determine complex scattering coefficients
- ❑ Use scattering coefficients in Transfer Matrix Method to generate filter response

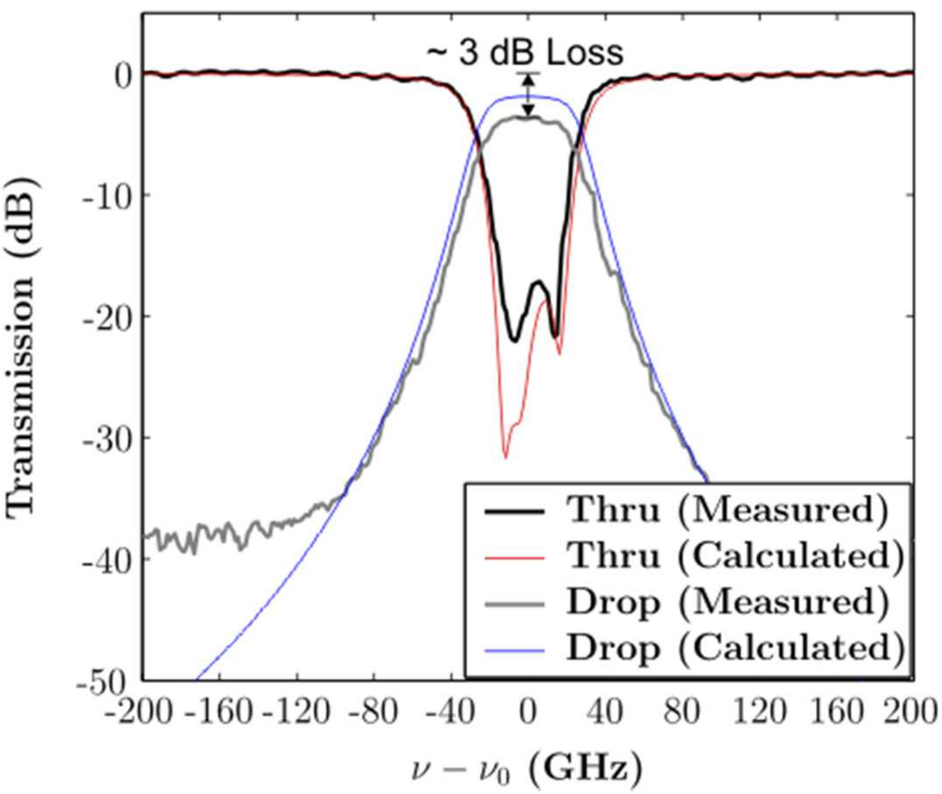


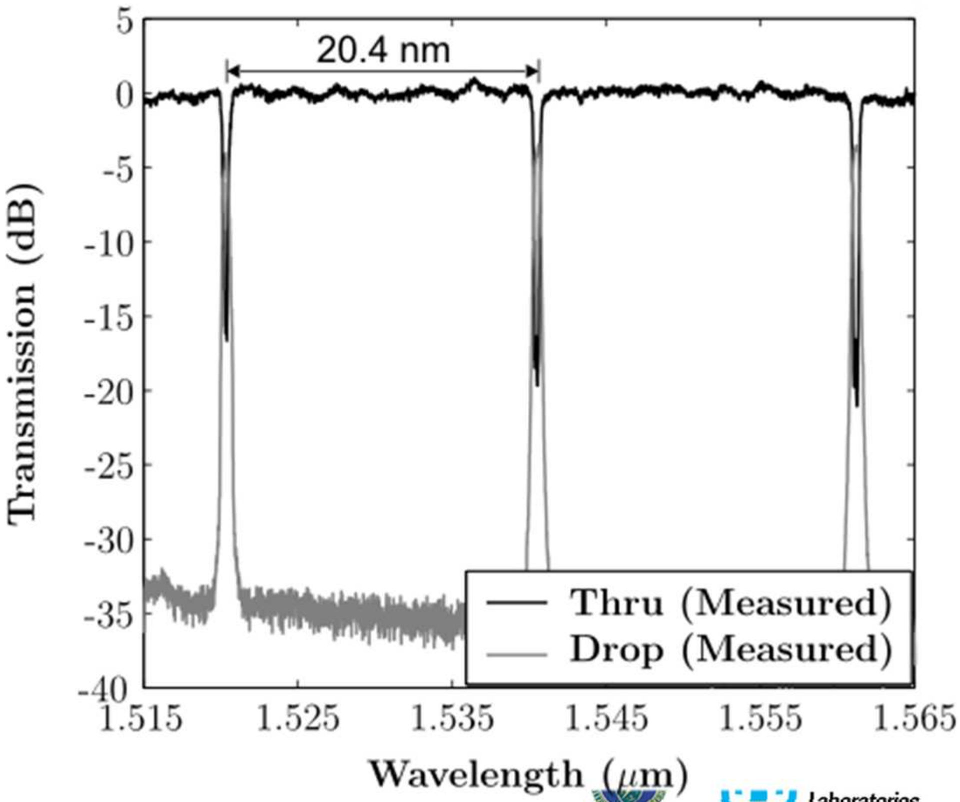
Redesigned Filters

Improvements

- ❑Advanced coupler design incorporated
- ❑Higher-Q ring waveguide utilized
- ❑Slightly wider bandwidth
- ❑Achieved 3dB drop-port losses
- ❑> 15 dB thru-port extinction







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Mode Evolution Based Devices

Michael R. Watts, Minghao Qi, Tymon Barwicz,
Luciano Socci, Hermann A. Haus, Henry I. Smith
and E. P. Ippen

Research Performed at the
Massachusetts Intitute of Technology

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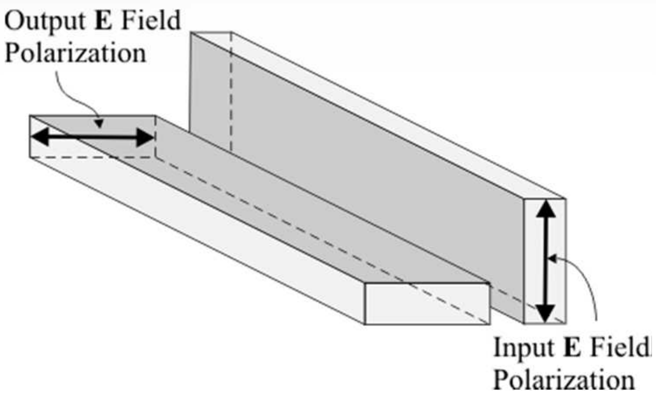
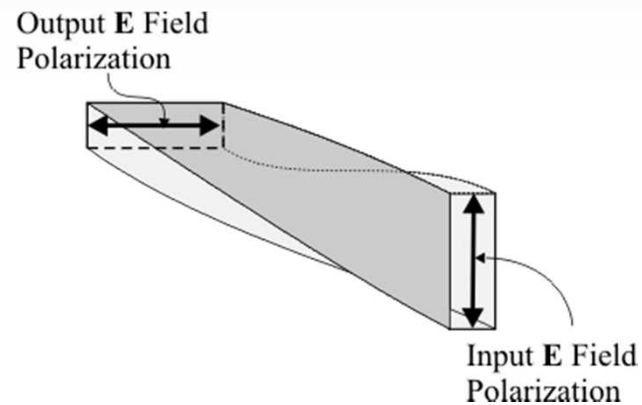
Example: Microphotonic Polarization Rotator

Mode Coupling



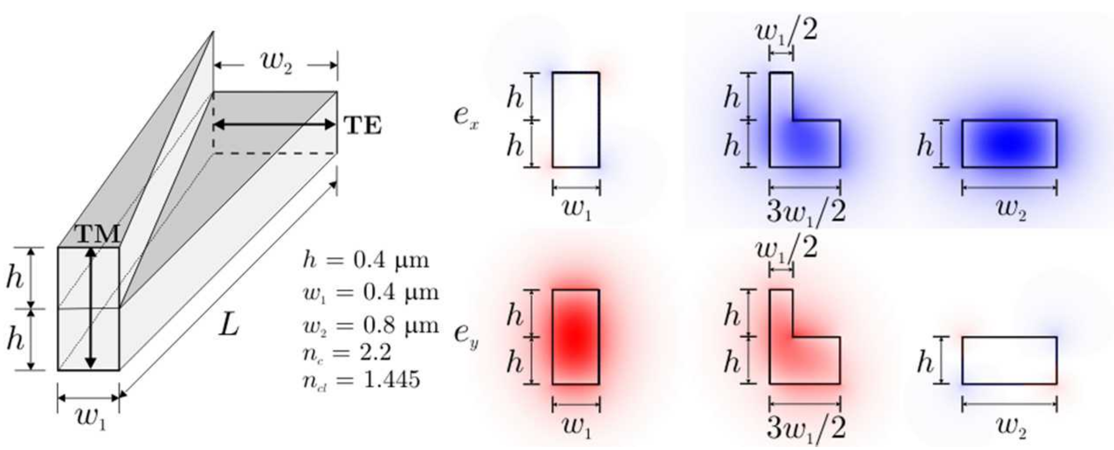
- ❑ **Requires:** Precise coupling & phase matching
- ❑ **Result:** Wavelength & fabrication sensitive

Mode Evolution



- ❑ **Requires:** Prevent mode coupling (max $\Delta\beta/\kappa$)
- ❑ **Result:** Inherently wavelength & fabrication insensitive
- ❑ **Challenge:** Implementing a twist on a chip

Mode Evolution Based Polarization Rotator



- ❑ Most confined mode aligned to geometric axis of guide (result of Gauss' Law)
- ❑ Large aspect ratio enhances $\Delta\beta/\kappa \rightarrow$ minimizes coupling
- ❑ Intuition indicates is should work, but rigorous simulations are required to confirm the design

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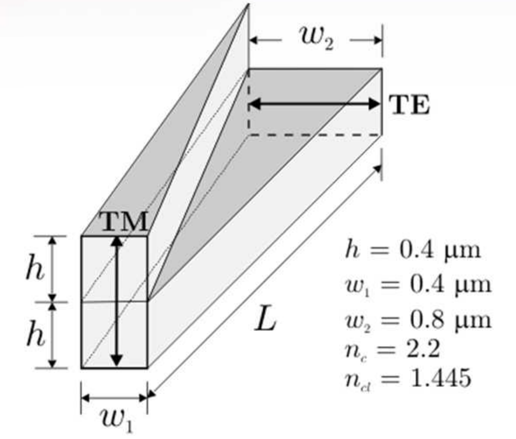
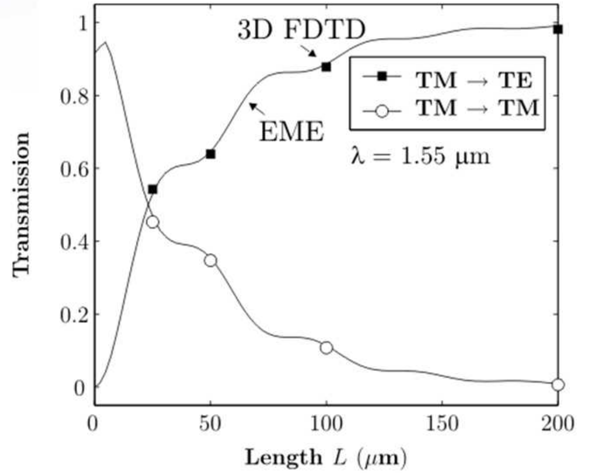
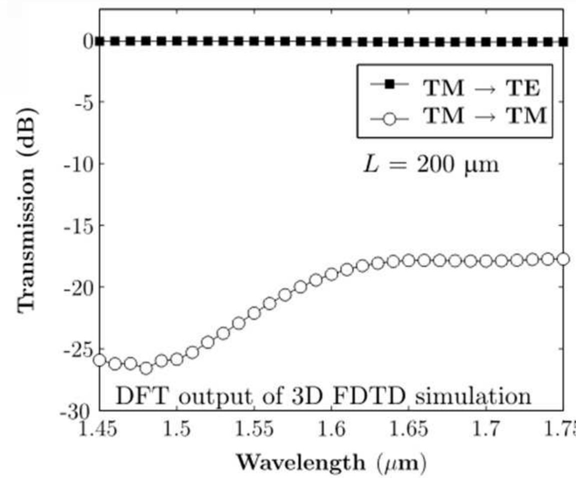
Design and Experimental Results

Polarization Rotator - Numerical Results

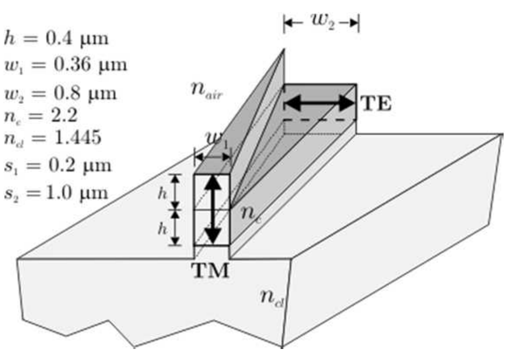


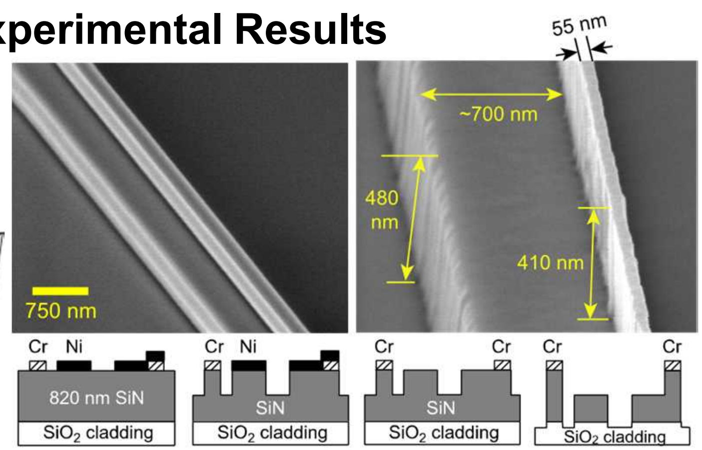




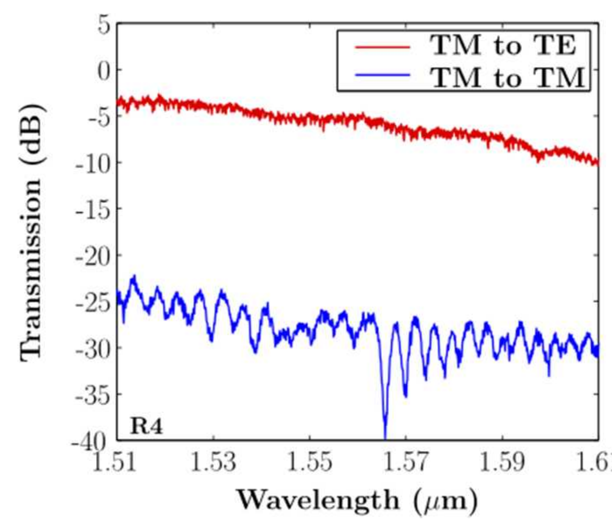
M. R. Watts and H. A. Haus, "Integrated mode-evolution-based polarization rotators," *Optics Letters* **30,** 138-140 (2005).

Polarization Rotator - Experimental Results

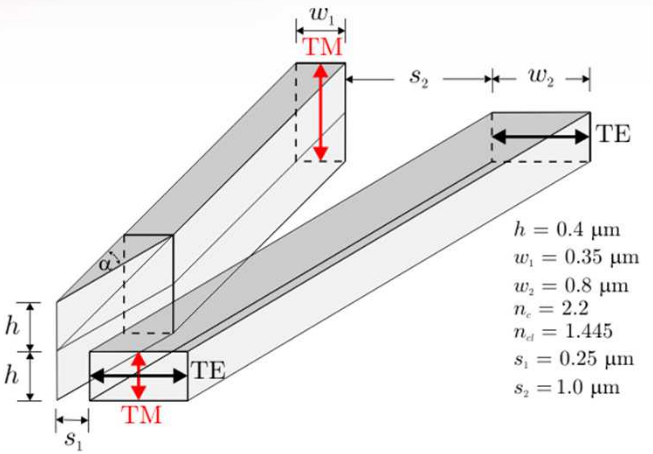


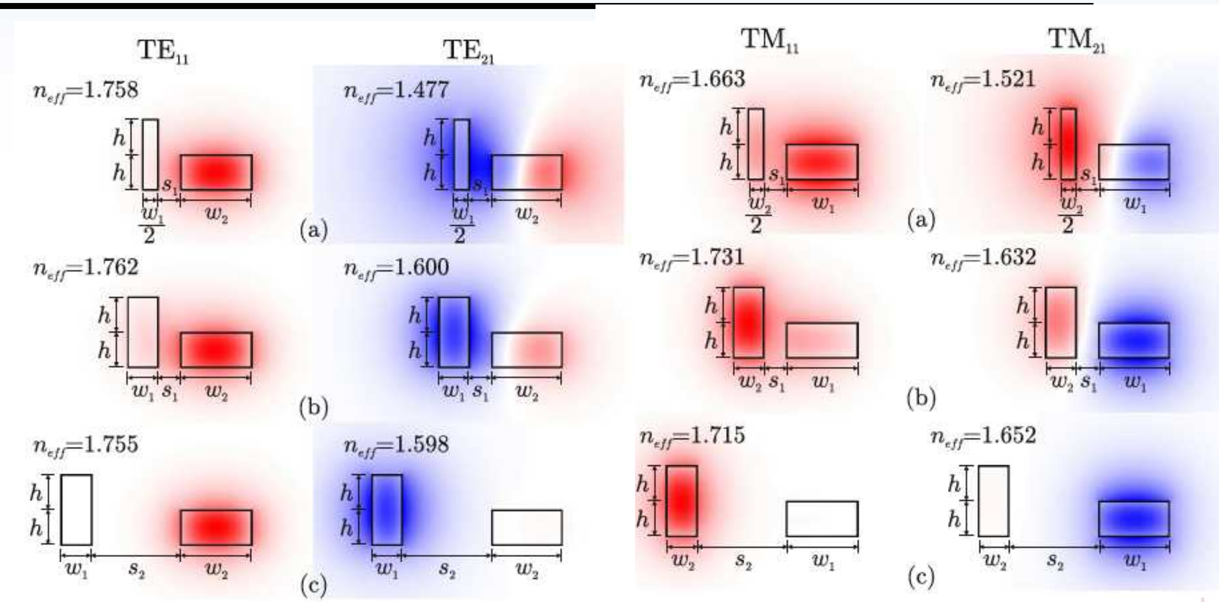


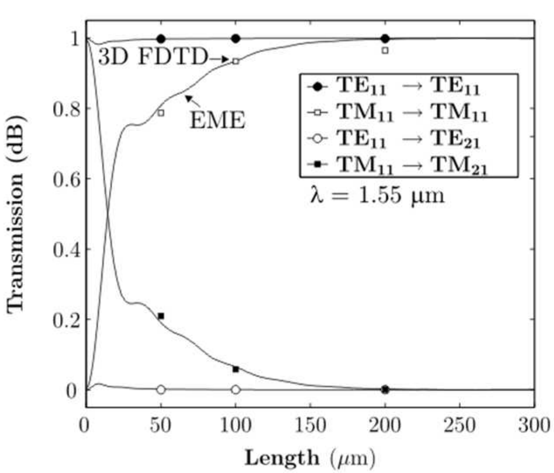
Fabrication performed by Minghao Qi

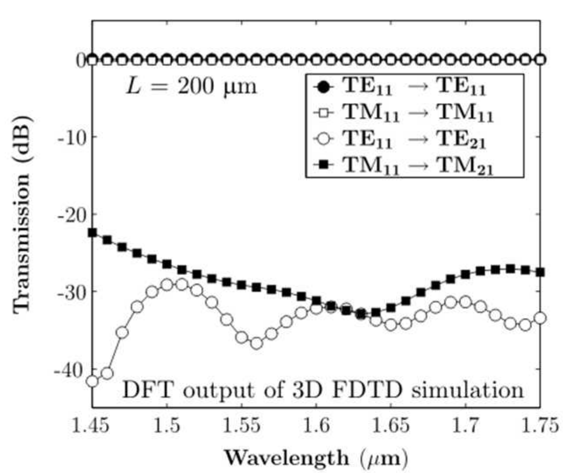


Mode Evolution Based Polarization Splitter









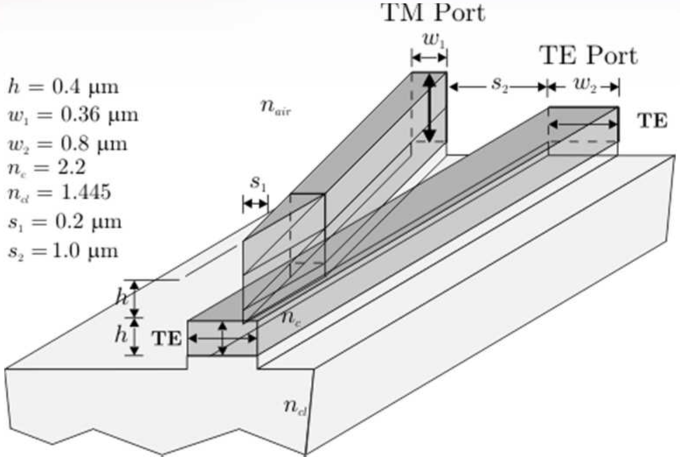
M. R. Watts, H. A. Haus, and E. P. Ippen "An integrated mode-evolution-based polarization splitter," to be published *Optics Letters*

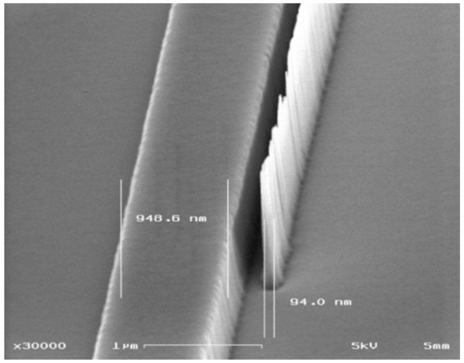
Polarization Splitter Design

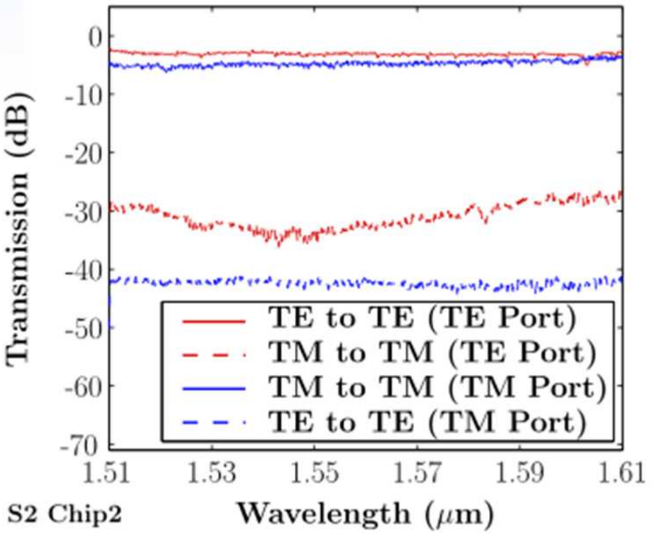
- TE_{11} and TM_{11} modes separate
- Large ratio of $\Delta\beta/\kappa$ by geometry
- Coupling between TM_{11} and TM_{21} modes limits device performance
- Splitter / Rotator can be combined

Polarization Splitter-Rotators

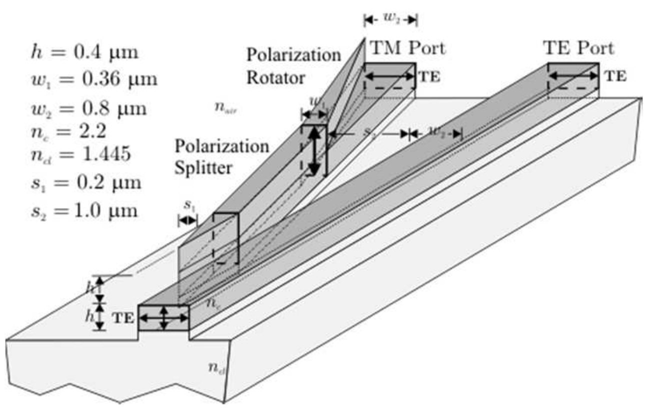
Integrated Polarization Splitter - Experimental Results

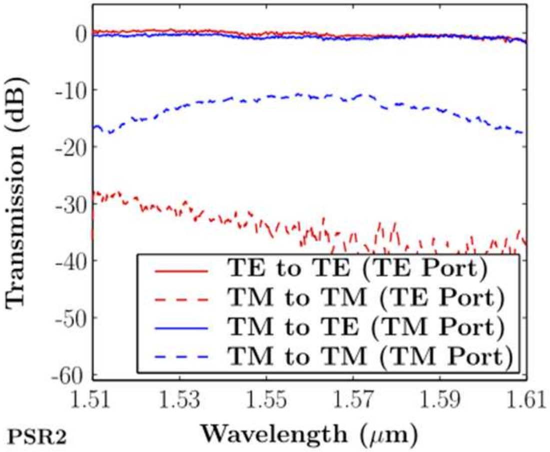


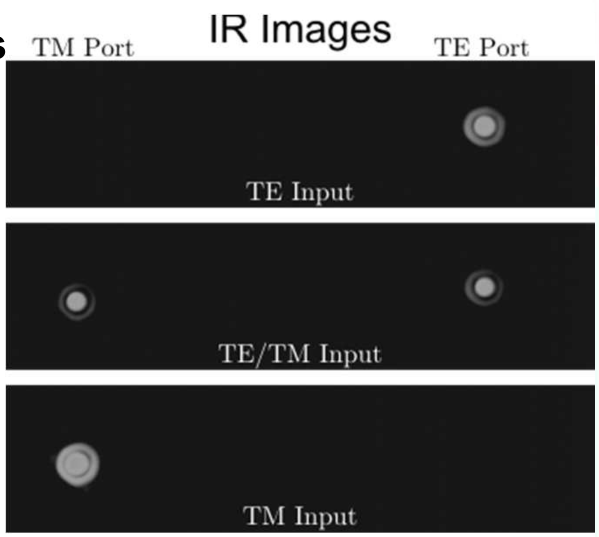




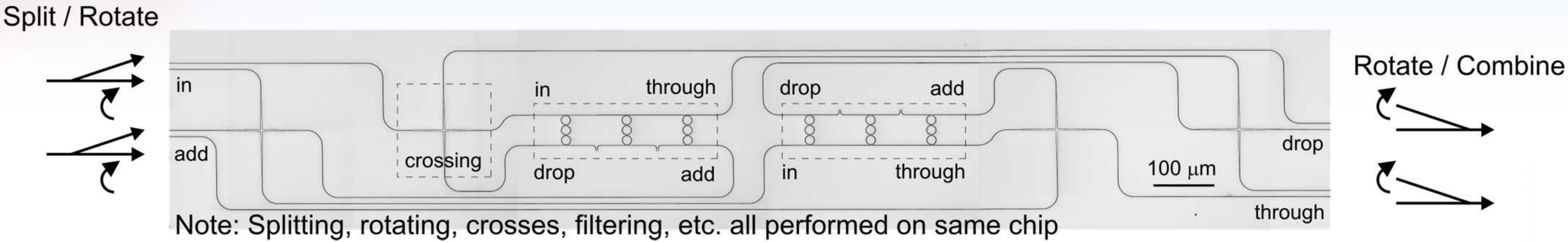
Integrated Polarization Splitter-Rotator - Experimental Results







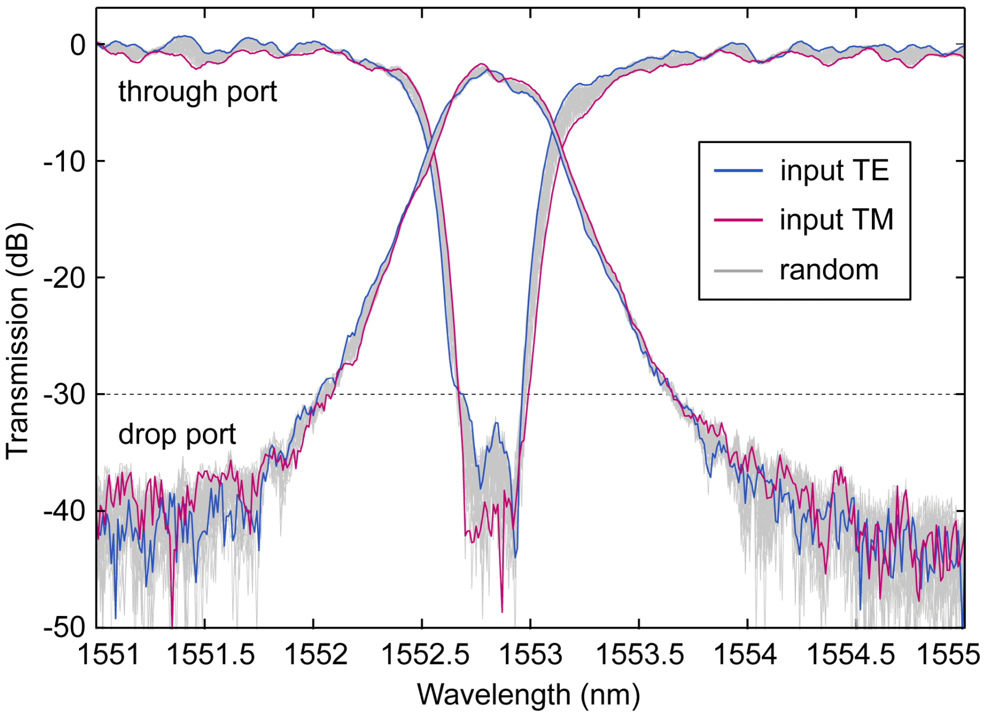
Integrated, P-Independent Optical Add-Drop



Note: Splitting, rotating, crosses, filtering, etc. all performed on same chip

Results

- ❑Demonstrated polarization independence in terms of frequency matching and loss
- ❑Matching of resonant frequencies to ~1GHz
- ❑Worked on the 1st try with all devices on the chip



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Some Special Cases of FD-TD: Conductors and Periodic Boundary Conditions

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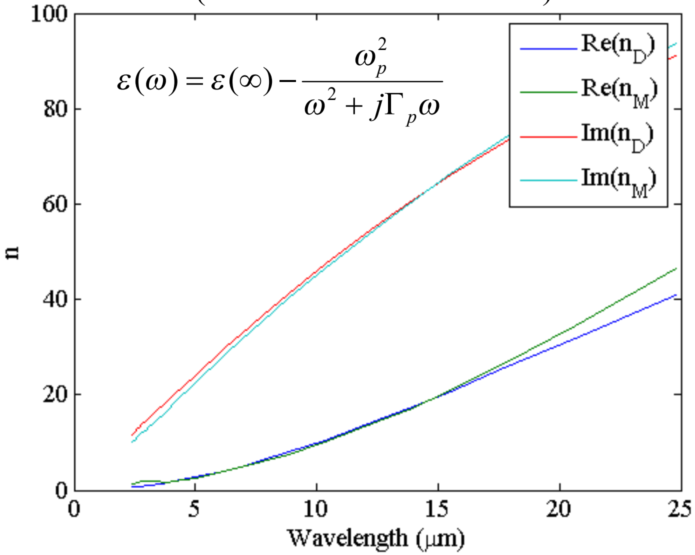
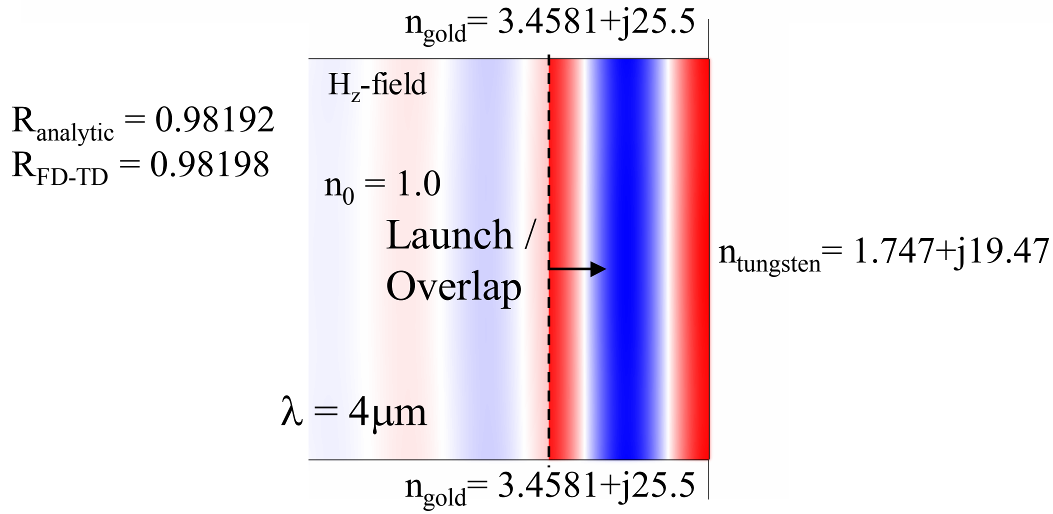
The Introduction of Metals

Tungsten Drude Model
(Measured Data from Palik)



Example: Reflection from Closed Metal Waveguide



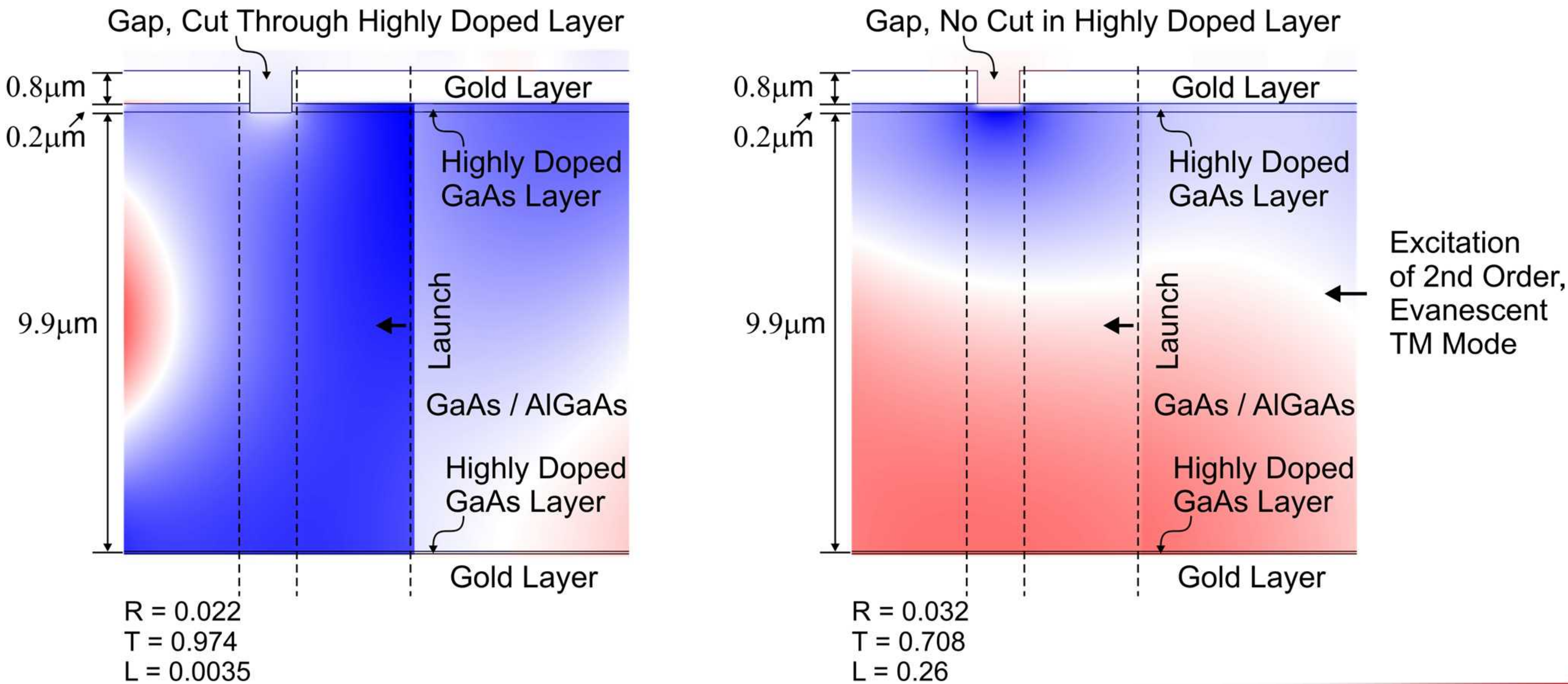
How do we implement metals

- Metals introduced by adding a terms for the current densities J_x, J_y, and J_z
- Note: Frequency dependent refractive index and conductivity
  - Dispersion accounted for by implementing the Drude Model
- Drude Model Accurately Models Complex Refractive Index in Mid-to-Long IR
- Analytic & FD-TD Reflection Coefficients Nearly Identical (0.98192 vs. 0.98198)

Simulation in the Terahertz Domain

Simulation of cut in contact of a Terahertz Quantum Cascade Laser

- ❑ Question: Do you cut through the highly doped GaAs layer or not?
- ❑ Intuition (Optics): Leaving highly doped GaAs layer intact will minimize radiation
- ❑ Answer: Leaving the highly doped GaAs layer intact can cause massive losses
- ❑ Why?



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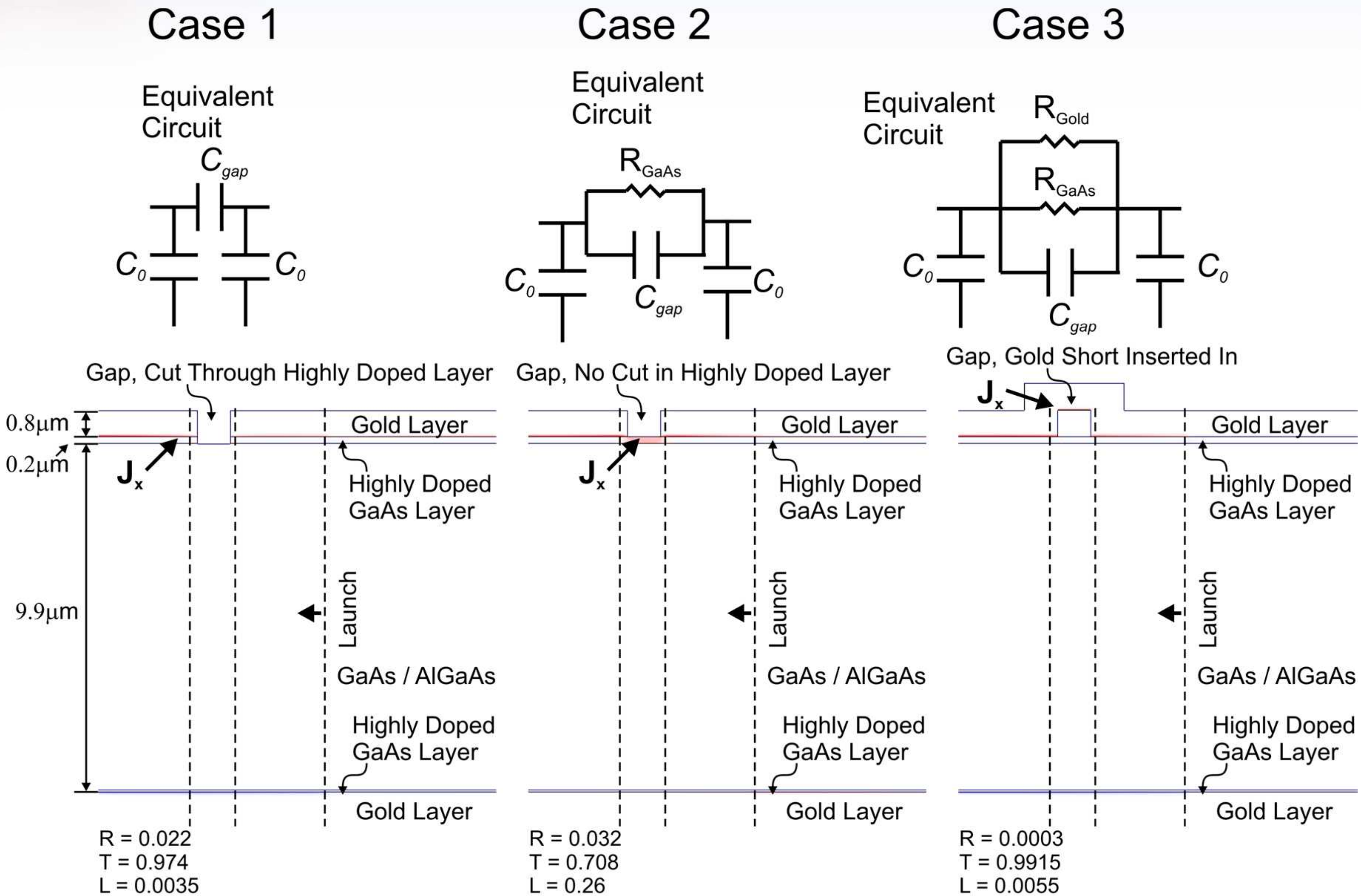
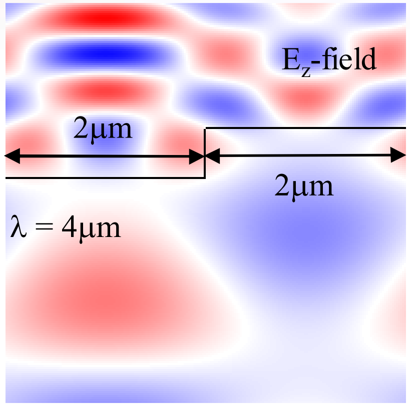
Well . . . Circuit Theory, Look at Jx



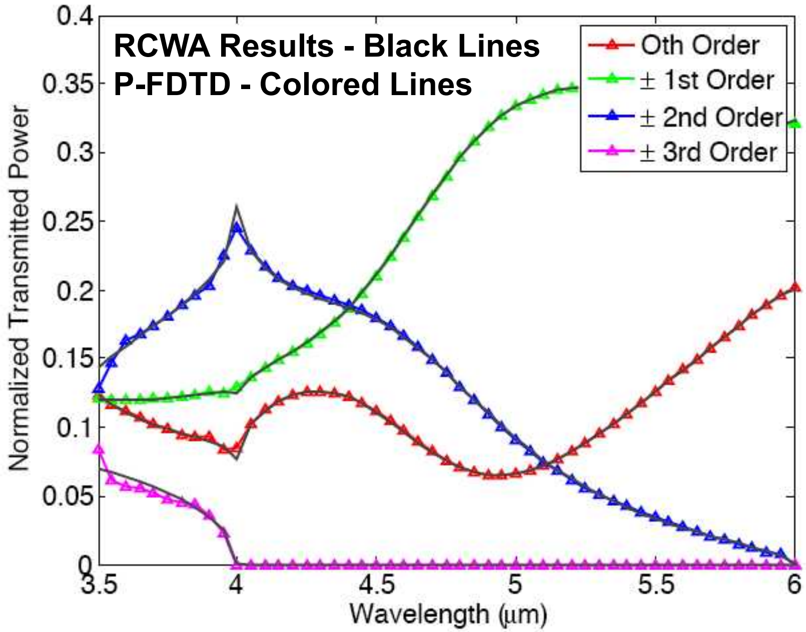
Note: Jx is depicted in Red and Blue

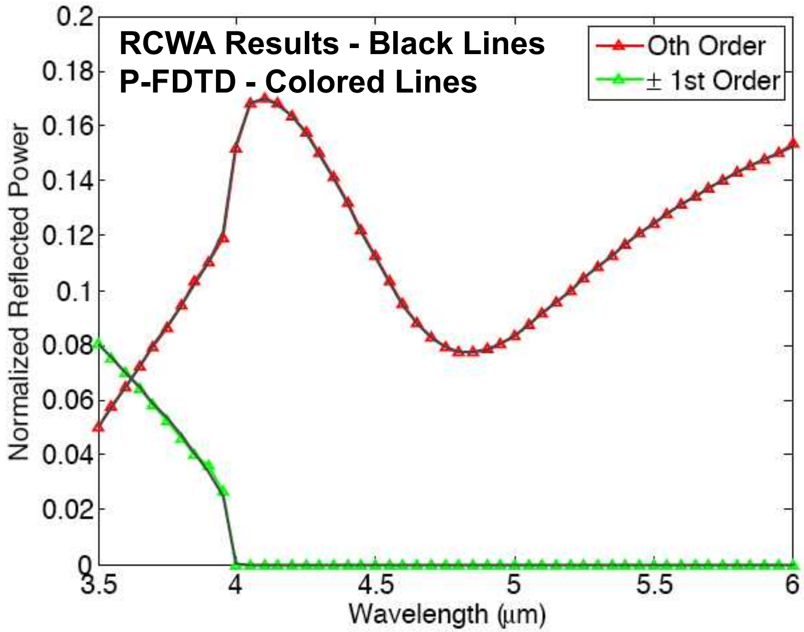
Periodic FD-TD



Periodic Boundary Conditions Introduced

- Normal incidence is straightforward
- Off-normal incidence requires substitution of variables that complicates the code a bit
- Agreement between RCWA and P-FDTD quite good

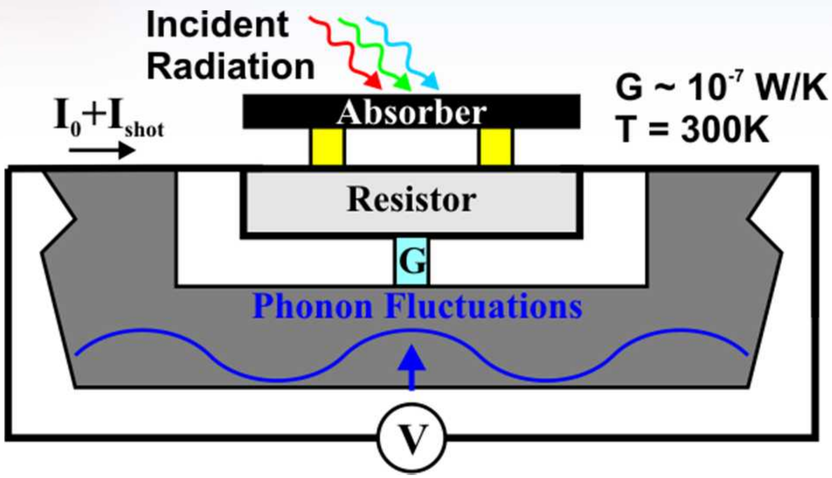




A Multi-Physics Problem: Thermal Microphotonic Focal Plane Array (TM-FPA) for Uncooled Thermal Imaging

Michael R. Watts, Michael J. Shaw, Gregory N. Nielson, Jeremy B. Wright, and Frederick B. McCormick

Limits to Room Temperature Bolometric Detection



ΔT 0.02/K

$$S(t) = S_0 \frac{P_{abs}}{G} \frac{dR/dT}{R}$$

Scale Factor

$$\frac{S(t)}{S_0 P_{abs}} = \frac{\Delta V}{V} = 2\times10^{-7}/pW$$

Bolometric Detection: Detect change in resistance due change in temperature

- ❑ Despite great strides in past decades, bolometric performance has plateaued
- ❑ **Non-ideal thermal detector: Dissipating power in sensor, inducing temperature change**

Fundamental Limits

- ❑ Shot Noise: (1) Measurement of current/voltage, and (2) induced thermal fluctuations
- ❑ Johnson Noise (Thermal Electron Fluctuations)

  $NEP = \sqrt{4k_B TP} = 4\times10^{-12} W/\sqrt{Hz},\ P = 1mW$
- ❑ Phonon Noise (Thermal Phonon Fluctuations)

  $NEP = \gamma\sqrt{4k_B GT} = 7\times10^{-13} W/\sqrt{Hz}$ ← **Fundamental Limit**

Practical Limits

- ❑ Best bolometers achieve NEP > $2\cdot10^{-11}$ W/√Hz (NETD ~ 30mK)
- ❑ **Perturbing measurement / small scale factor make bolometers susceptible to Johnson, 1/*f*, etc.**

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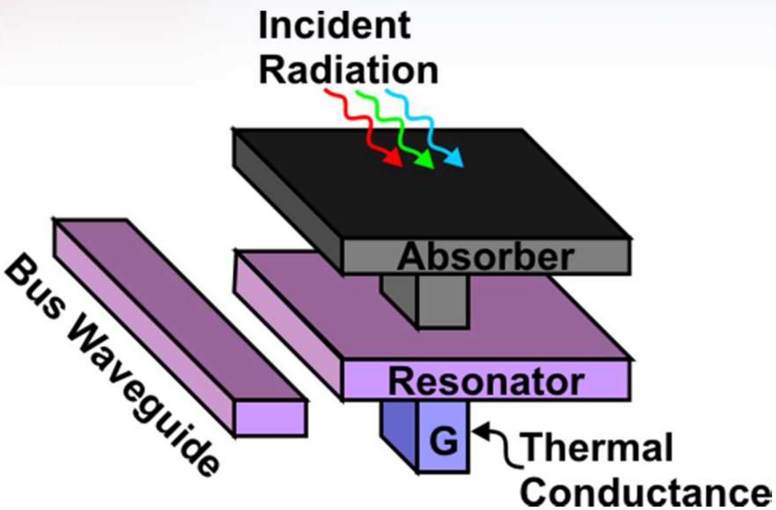
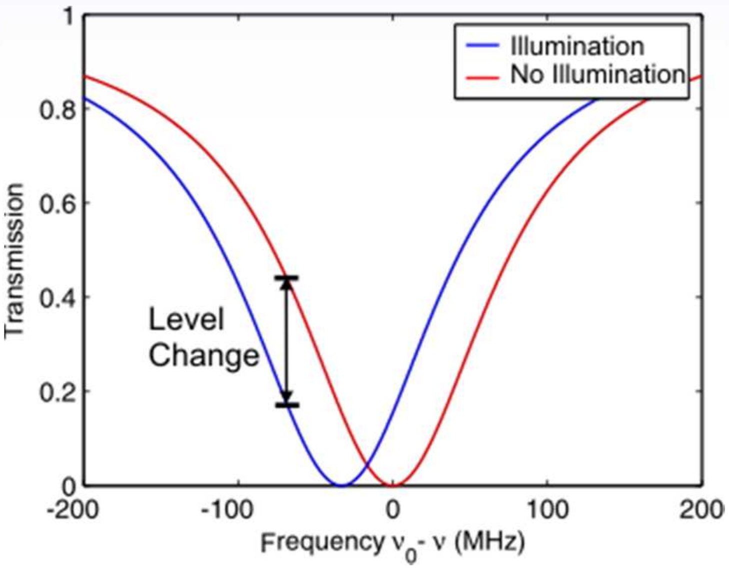
Thermo-Microphotonic Detection





Scale Factor of the T-O Approach

DC Level, Slope, ΔT

$$S(t) = \frac{S_0}{2}\frac{2}{\Delta\nu}\frac{d\nu}{dT}\frac{P_{abs}}{G} \Rightarrow \frac{S(t)}{S_0 P_{abs}} = \frac{Q}{G}\frac{dn}{ndT}$$

$$\frac{d\nu}{dT} = \frac{d\nu}{dn}\frac{dn}{dT} \approx \frac{\nu}{n}\frac{dn}{dT}$$

For Q = 10^6, and G = 10^{-8} W/K in Si

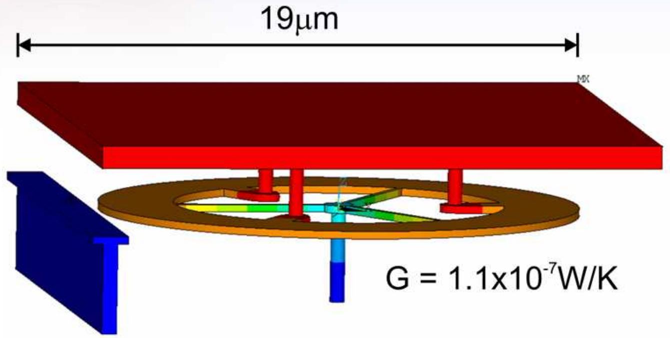
$$\frac{S(t)}{S_0 P_{abs}} = \frac{\Delta V}{V} \approx 6\times 10^{-3} / pW$$

~30,000X Larger than bolometric approaches

Noise Limitations

- ❑ No Johnson noise
- ❑ Large scale factor min. impact of shot noise
- ❑ Fundamentally, limited only by Phonon Noise
- ❑ Measurement does not perturb sensor
- ❑ No metal paths back to substrate

Simulation of a Multiphysics Problem

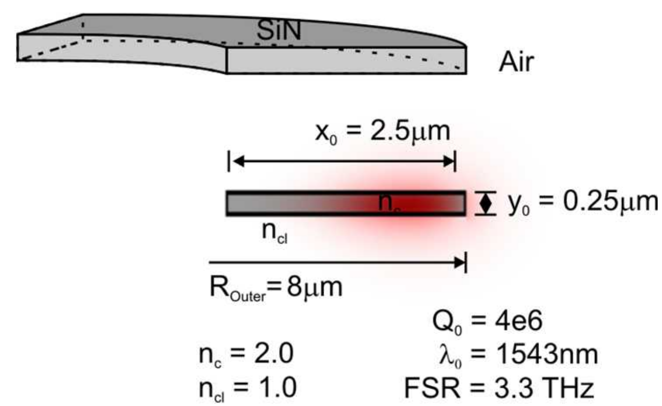


Thermal Design in Silicon Nitride

- ❑ Silicon nitride (200nm wide) tethers to minimize ***G***
- ❑ ANSYS FEM predicts ***G*** = 1.1×10^{-7} W/K
- ❑ Thermal Time Constant $\tau \approx 2$ ms
- ❑ Corresponding Phonon ***NEP*** = 7×10^{-13} W/√Hz

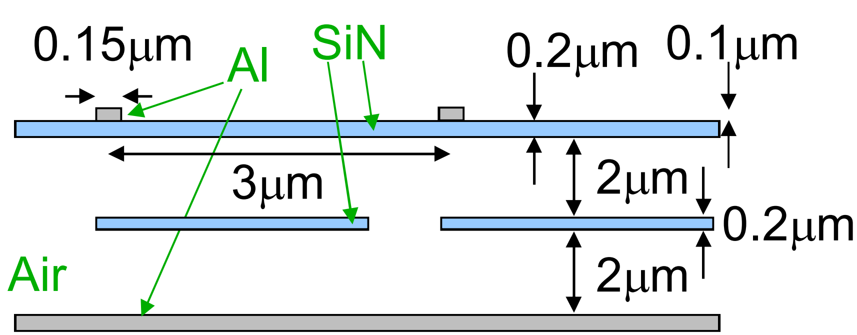
Microphotonic Design Considerations

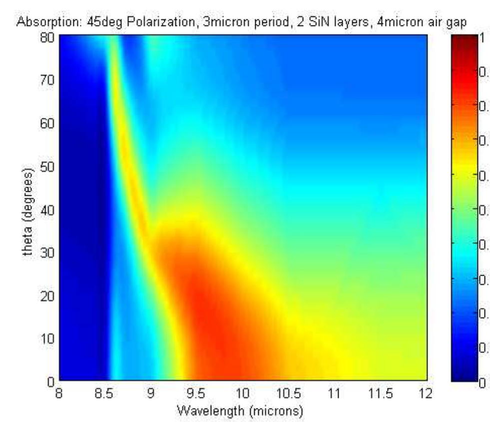
- ❑ Sufficiently small bend radii (R = 8μm)
- ❑ High-Q (>10^5) demonstrated in SiN (M. Shaw, *Sandia*)
- ❑ Sufficiently large thermo-optic response (Δf ~ 2 GHz/K)
- ❑ No significant nonlinearities



Antenna / Absorber Design (RCWA Analysis)

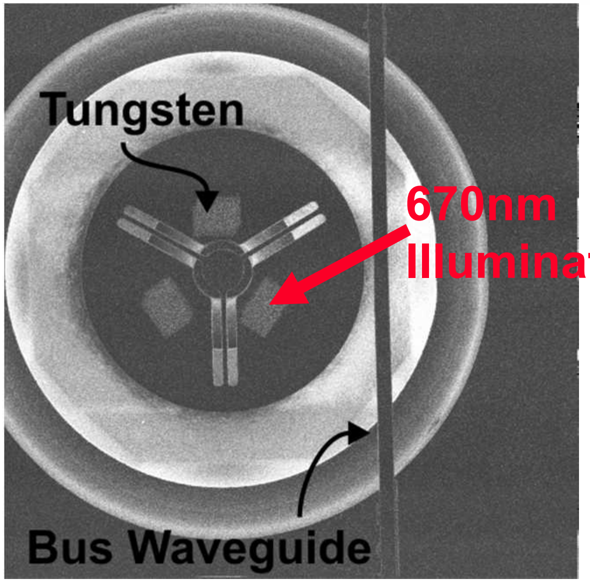
- ❑ Fortunately, silicon nitride absorbs from 9-12μm



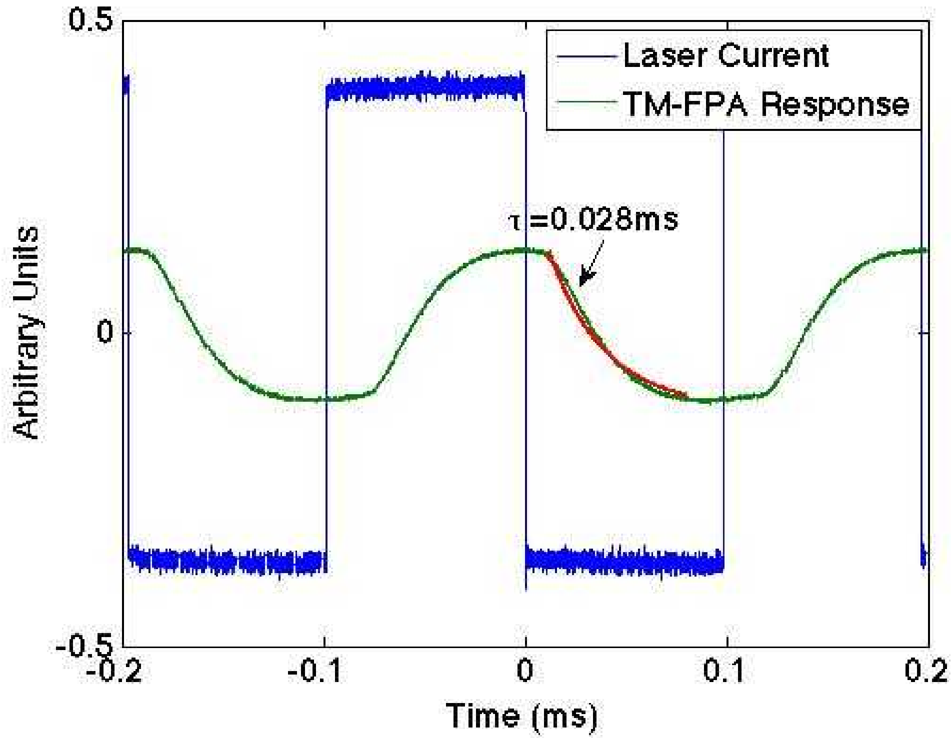


Initial Experimental Results

FIB Image of SiN Suspended Disk with Deposited Tungsten



Response to Illuminations by 670nm Laser



Preliminary Results

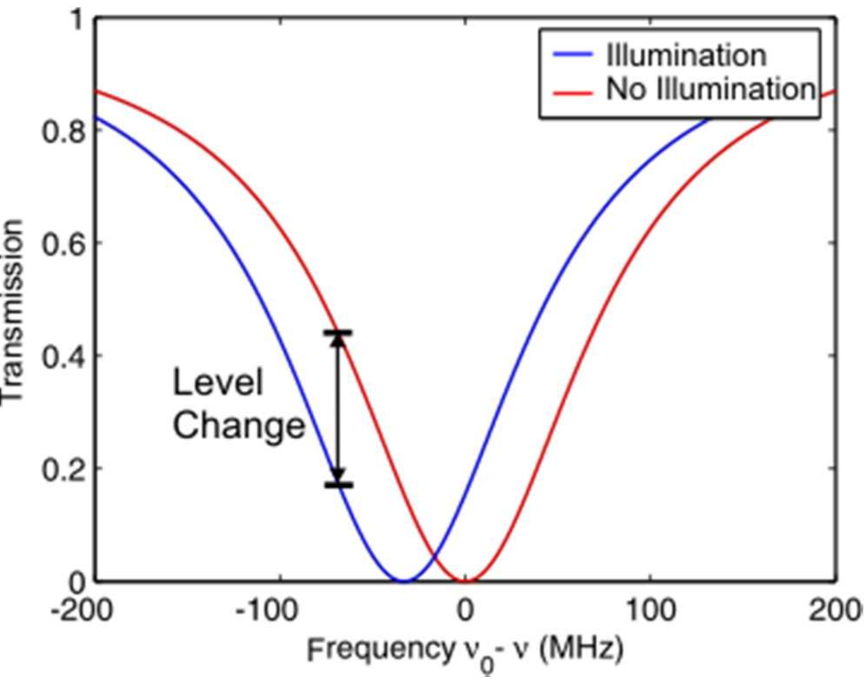
- ❑ Correct sign on thermo-optic shift
- ❑ Time Constant of ~0.028ms indicating a conductivity of G ~ 6×10^{-6} (Limited by Air)
- ❑ Not yet prepared to comment on Signal-to-Noise Ratio

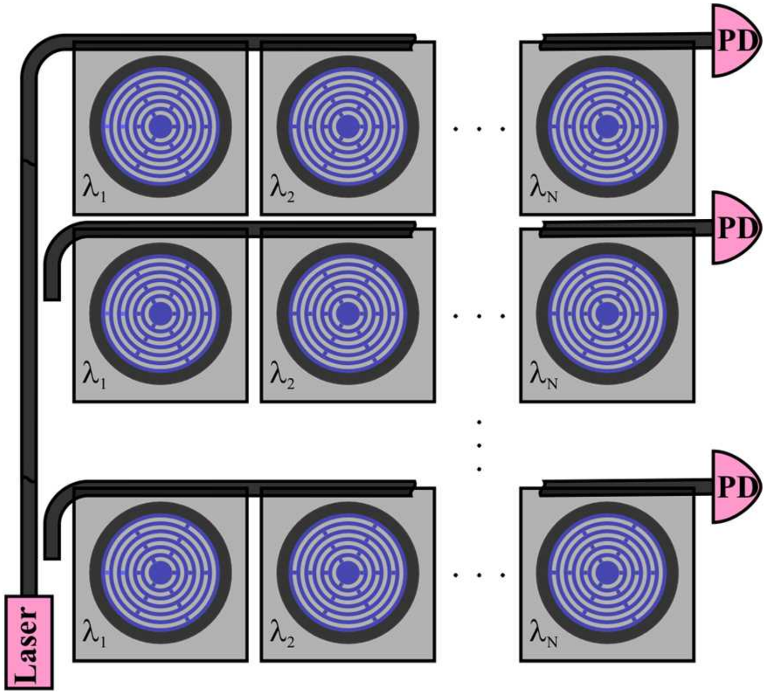
TM-FPA on a Large Scale

Like any Focal Plane Array, there is a desire to reach Millions of Pixels

- Approach: Use a WDM-based readout
- Is this reasonable?
- How do we model this in various states?
- Certainly, some challenges lie ahead to deal with complex VLSI microphotonic systems

Many Partially Overlapping Resonances





Summary and Conclusions

Design Approach

- Coupled Mode Theory for used for intuition
- 3D FD-TD / EME for electromagnetic simulations
- Transfer Matrix Method for large scale problems

Matching Numerical Models with Experiment

- Quite good on passive devices
- Active / multiphysics devices - not yet there
  - All domains simulated independently - very much imperfect
  - Quantum fluctuations not captured

Future Needs

- Need for multiphysics codes (electromagnetic, thermal, mechanical, electrical etc.)
  - Nice to see a time domain code with all effects captured & statistical noise sources
- Need for object oriented transfer matrix code for VLSI with device library capability