



Design and Simulation of a Hybrid Silicon/Electro-optic Polymer Modulator

Kjersti Kleven and Scott T. Dunham

Department of Electrical Engineering

University of Washington

21 September 2005

Outline

- Motivation
- Resonant Cavity Structure
- Previous Work
- Hybrid Waveguide Analysis
- Simulation Method
- Device Analysis
- Conclusions

Motivation

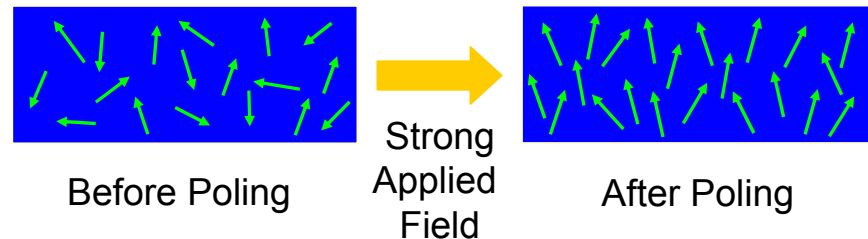
- Our aim is to design a modulator with:
 - Large modulation depth
 - Small device size
 - High speed
 - Low loss
 - Low drive voltage

Motivation

- This is achieved by combining the benefits both silicon and EO polymers
 - Benefits of Silicon
 - Low loss
 - High index of refraction
 - Manufacturability
 - Benefits of EO Polymer
 - Large electro-optic coefficient
 - Fast response

EO Polymer Overview

- Newly developed EO polymers exhibit a very large change in index of refraction under applied field^[1,2]
 - The achievable change in the index of refraction is related to the degree of chromophore alignment of the film achieved during poling



- The EO polymer considered for this analysis is AJL8^[2]
 - $n = 1.6$ at $\lambda = 1.55\mu\text{m}$
 - $r_{33} = 50$ to 150pm/V
 - Loss = 0.5 to 2 dB/cm

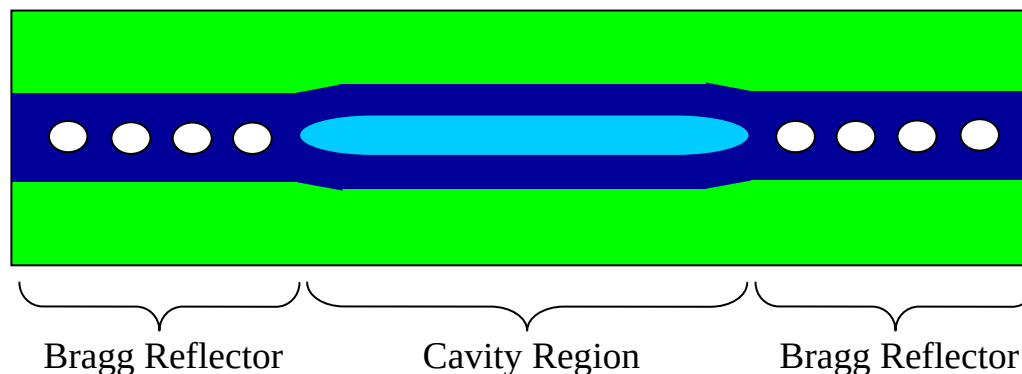
$$\Delta n = -\frac{n^3 r_{33} V_a}{2d}$$

[1] L. Dalton et al, *IEEE J. Select. Topics Quantum Electron.*, Vol 7, 826–835, 2001.

[2] J. Luo, A.K-Y. Jen, et al, *Proc. SPIE*, Vol 5351, 36–43, 2004.

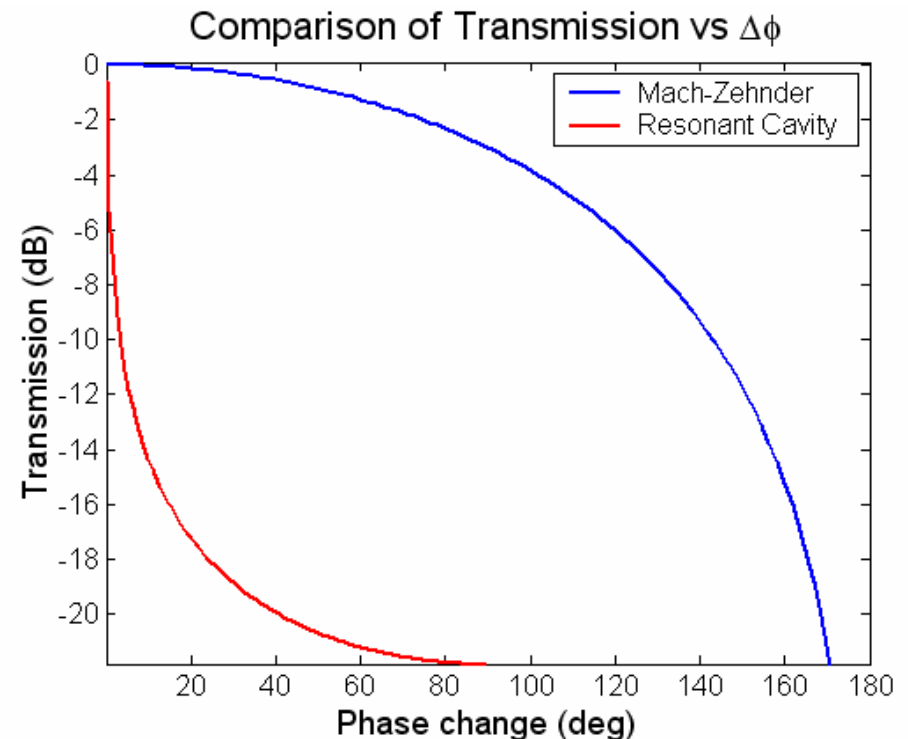
Resonant Cavity Structure

- The focus of this design is the resonant cavity structure
 - Series of defects creates a Bragg reflector
 - Resonant cavity breaks periodicity of reflector and allows for transmission at the resonant wavelength



Modulator Structures

- Required phase shift for resonant cavity is much smaller than for Mach-Zehnder
 - Allows for much shorter device length and lower applied voltages for full modulation



Overview of Current Devices

Author	Type	Material	Length	X-ratio/ ModDep	V _a (V)	V _π -L (V-cm)	Speed
Liu et. al. ^[3]	MZ	Silicon	2.5mm	16 dB	7.7	2	Medium
Barrios et. al. ^[4]	RC	Silicon	20μm	53%	3.7	0.00074	Slow
Rabiei et. al. ^[5]	μR	Polymer	1.5mm	50%	16	2.4	Medium
Wooten et. al. ^[6]	MZ	LiNbO ₃	~2cm	15-20dB	~5	~10	Medium
S. Lee et. al. ^[7]	MZ	Polymer	20mm	18 dB	4.5	0.9	Fast
M. Lee et. al. ^[8]	MZ	Polymer	2cm	20.7 dB	11.3	22.6	Very Fast
This Work	RC	Polymer /Silicon	25 μm - 35 μm	70–90%	1-2	0.0006	Fast

[3] *Nature*, Vol. 427, 12 February 2004

[4] *IEEE Photon. Tech. Lett.*, Vol. 16, February 2004

[5] *J. of Lightwave Tech.*, Vol. 20, November 2002

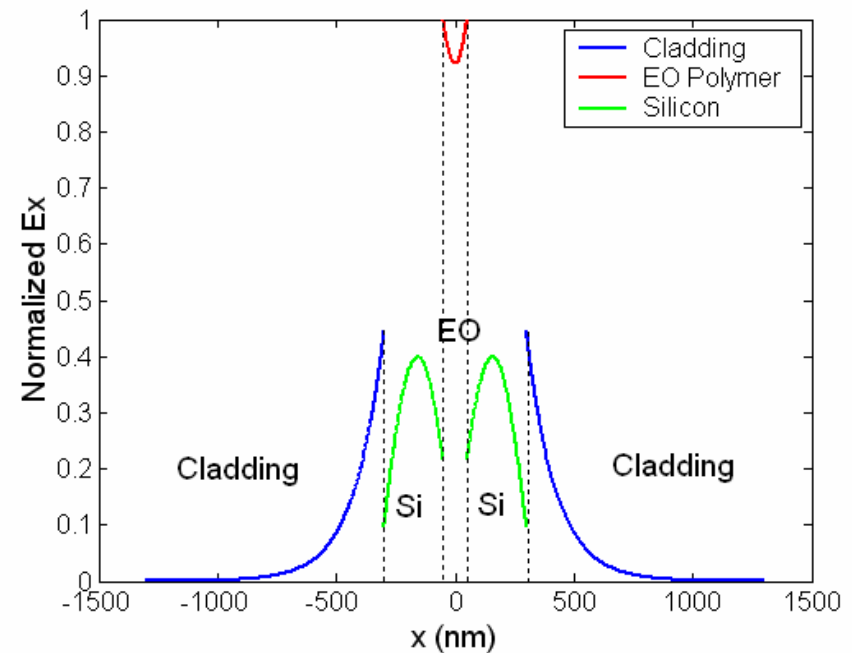
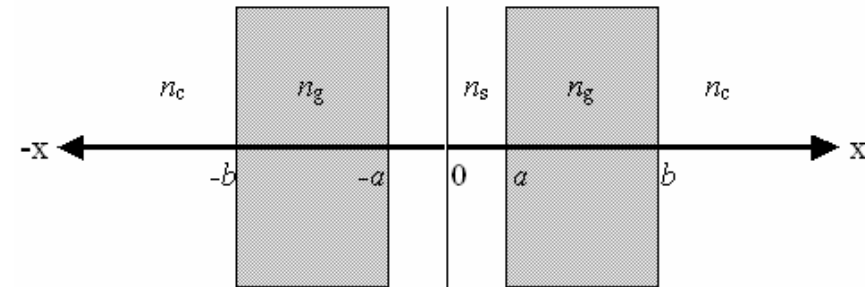
[6] *IEEE J. of Select. Topics Quantum Electron.*, Vol. 6, Jan. 2000

[7] *IEEE J. Quantum Electron.*, Vol. 36, May 2000

[8] *Science*, Vol. 298, Nov. 2002

Hybrid Waveguide

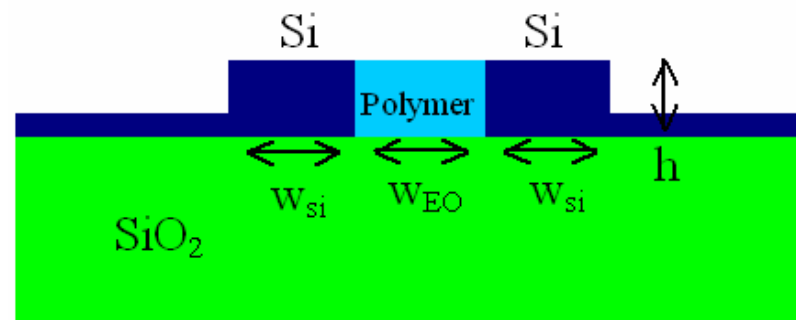
- The hybrid waveguide structure confines light in the low index region^[9]
 - Requirements:
 - $n_s < n_g$
 - Width of core is small
 - Width of ridge is small
 - Satisfy the boundary conditions from Maxwell's Equations at both interfaces
 - Results in a transcendental equation for β



[9] V. Almeida, et al., *Optics Lett.* Vol. 29, June 2004

Hybrid Waveguide

- For modulator application, want a large change in propagation constant
- Design parameters that can be varied include:
 - h
 - W_{eo}
 - W_{si}



Hybrid Waveguide

- An effective index approach was then used to estimate the achievable $\Delta\beta$

$$N_{\text{hybrid}} = \frac{\beta}{k_o}$$

$$V_{eq} = k_o h \sqrt{N_{\text{hybrid}}^2 - N_{L1}^2}$$

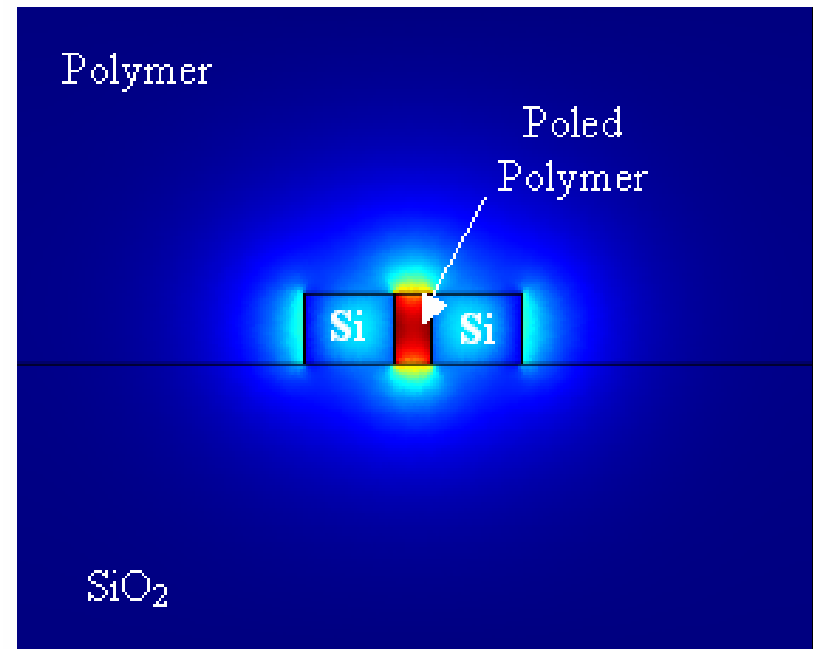
$$V = \frac{1}{\sqrt{1-b}} \left[a \tan\left(\frac{b}{1-b}\right) + a \tan\left(\sqrt{\frac{b+a}{1-b}}\right) \right]$$



$$\beta_{\text{eff}} = k_o \sqrt{N_{L1}^2 + b_{eq} (N_{\text{hybrid}}^2 - N_{L1}^2)}$$

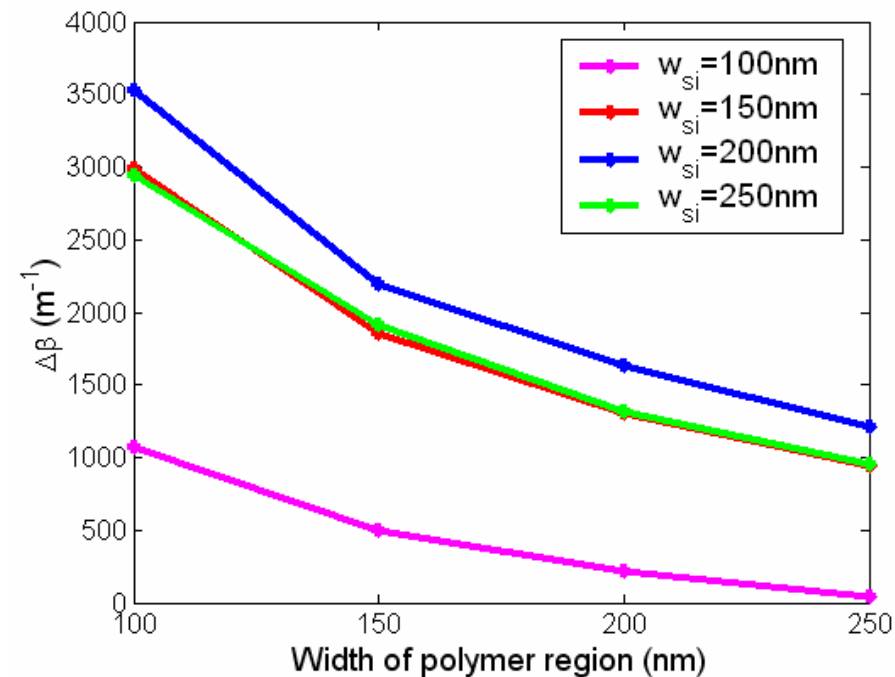
Hybrid Waveguide

- FEMLAB was also used to compare the effective index approach to a 2D modal analysis
 - Longer simulation times
 - Field profile similar to 1-D

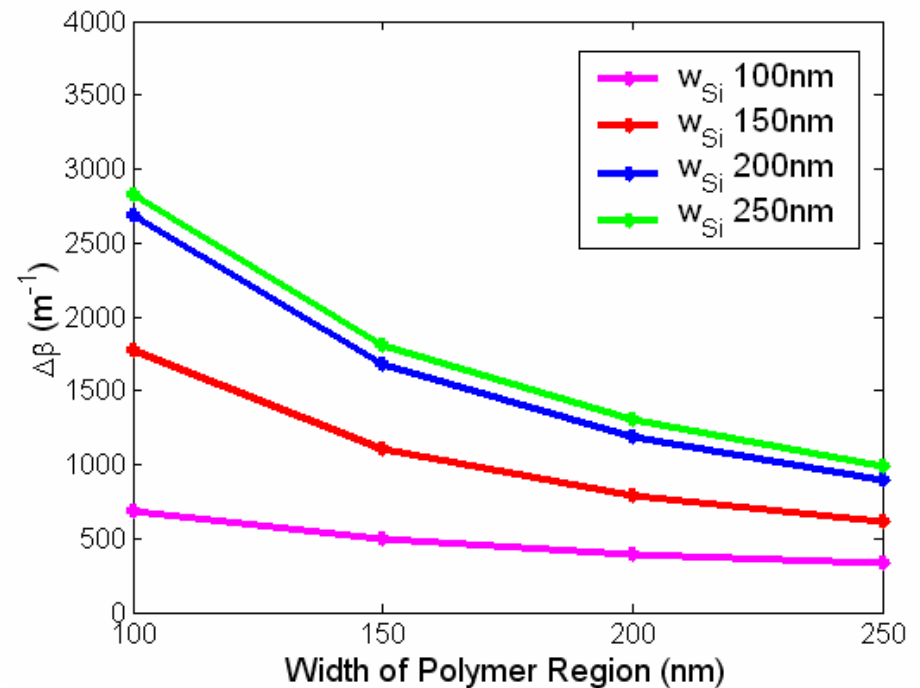


Hybrid Waveguide

- Comparison between effective index and FEMLAB showed substantial differences in $\Delta\beta$



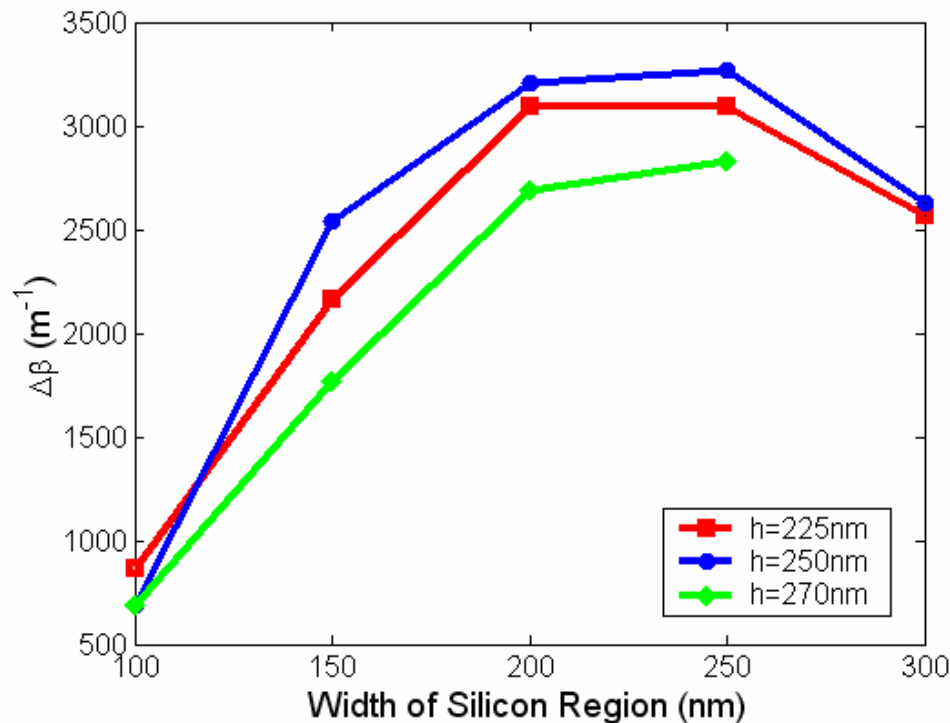
Effective Index



FEMLAB

Hybrid Waveguide

- Variation of the height of the hybrid waveguide shows an optimum for various silicon widths

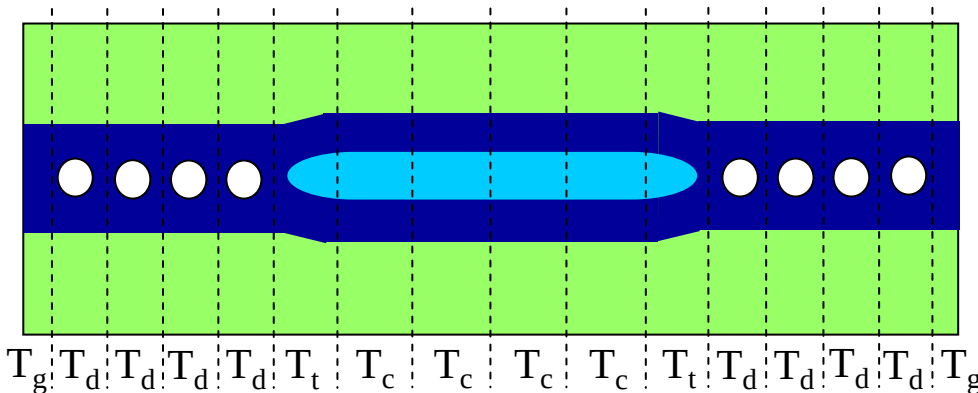


Modulator Simulation

- 3-D simulation of structure required due to:
 - High operating frequencies
 - Complex nature of structure
 - Small device dimensions
- 3-D simulation is very computationally expensive!

Modulator Simulation

- The resonant cavity modulator has a large amount of periodicity in the device structure
- This allows a cascade matrix approach to be used to reduce simulation times^[10]
 - Each section simulated individually
 - Cascade matrix (T) from each section then used to model entire structure

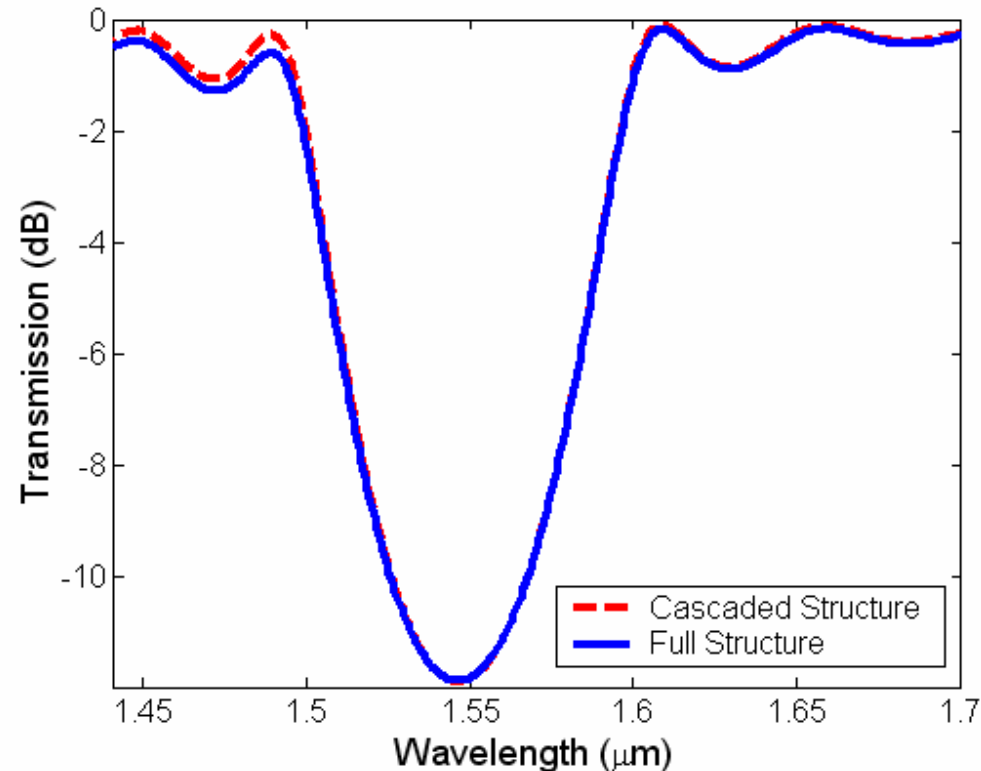


$$\vec{T} = \vec{T}_g \vec{T}_d \vec{T}_d \vec{T}_d \vec{T}_d \vec{T}_t \vec{T}_c \vec{T}_c \vec{T}_c \vec{T}_c \vec{T}_t \vec{T}_d \vec{T}_d \vec{T}_d \vec{T}_d \vec{T}_g$$

[10] Kearns and Beatty, *Basic Theory of Waveguide Junctions and Introductory Microwave Network Analysis*, Pergamon Press, Oxford, London, 1967

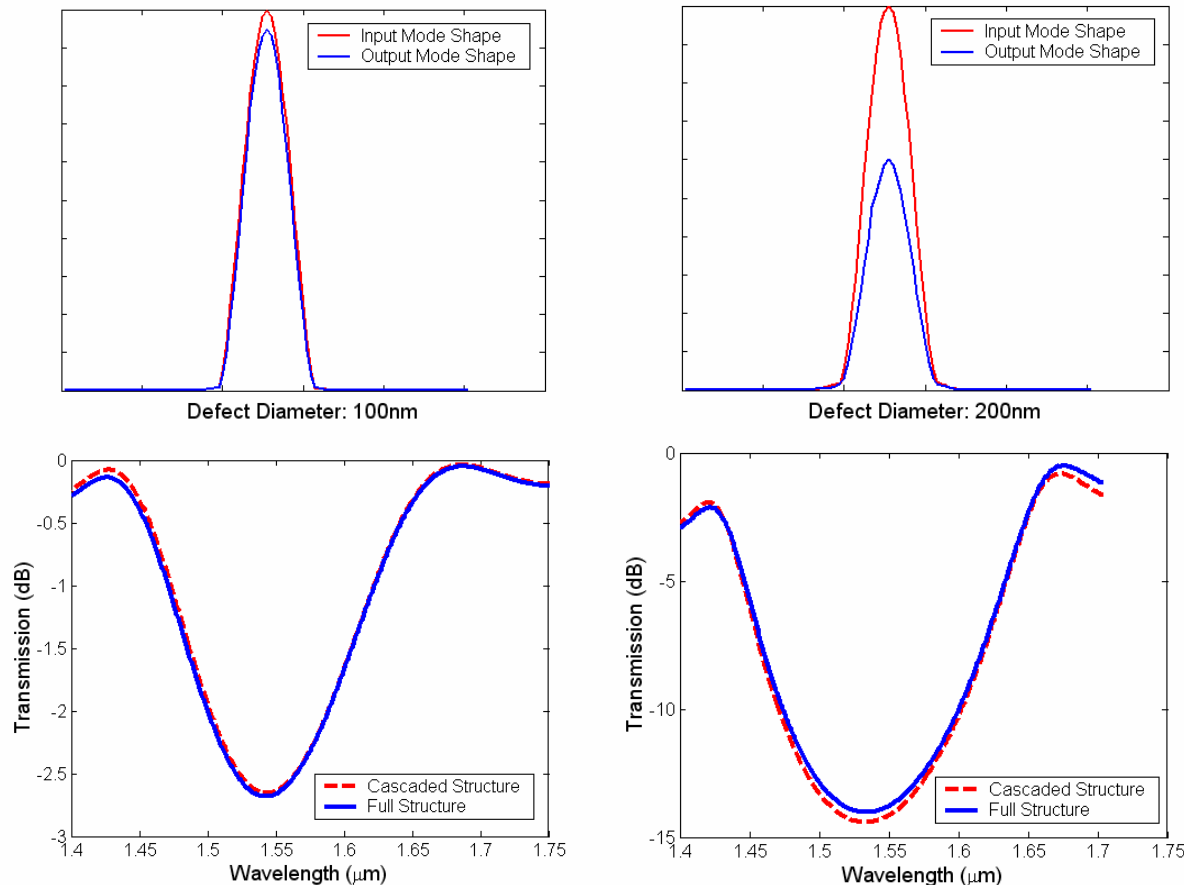
Modulator Simulation

- Excellent agreement between the full simulation and the cascade approach
- Significant savings in computation time
 - Full structure: 17.5 hours
 - Single period: 22 minutes
- Simulation times scale at $\sim n^{2.5}$



Modulator Simulation

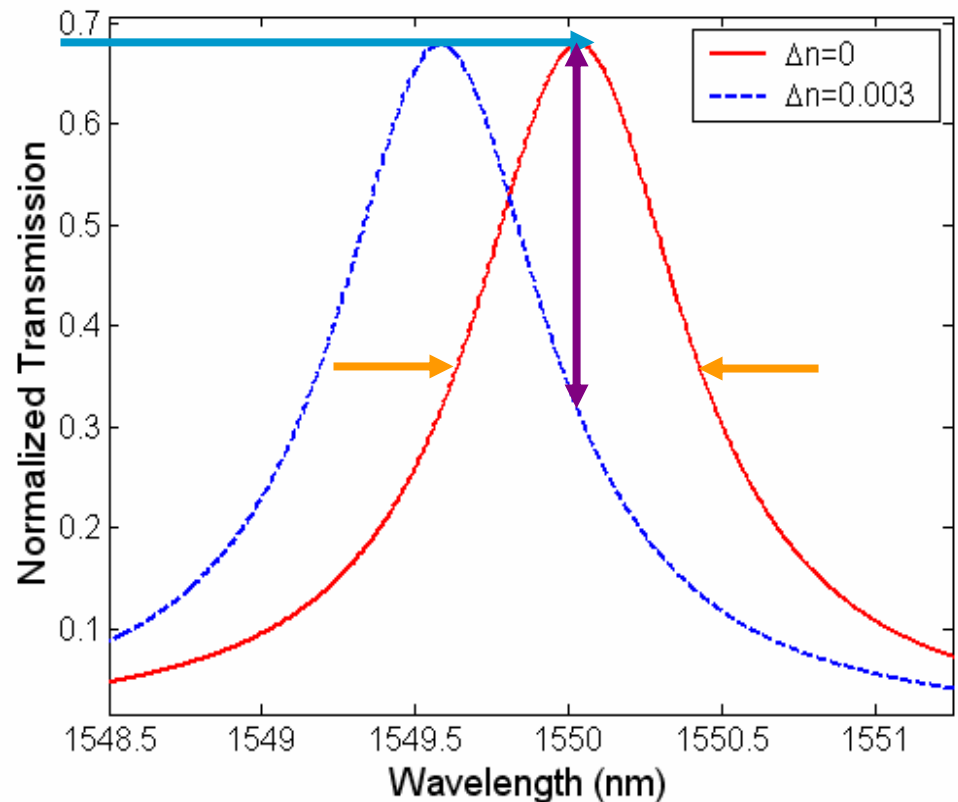
- Comparison of the mode shapes can be used to predict if the cascade approach will work



Device Analysis

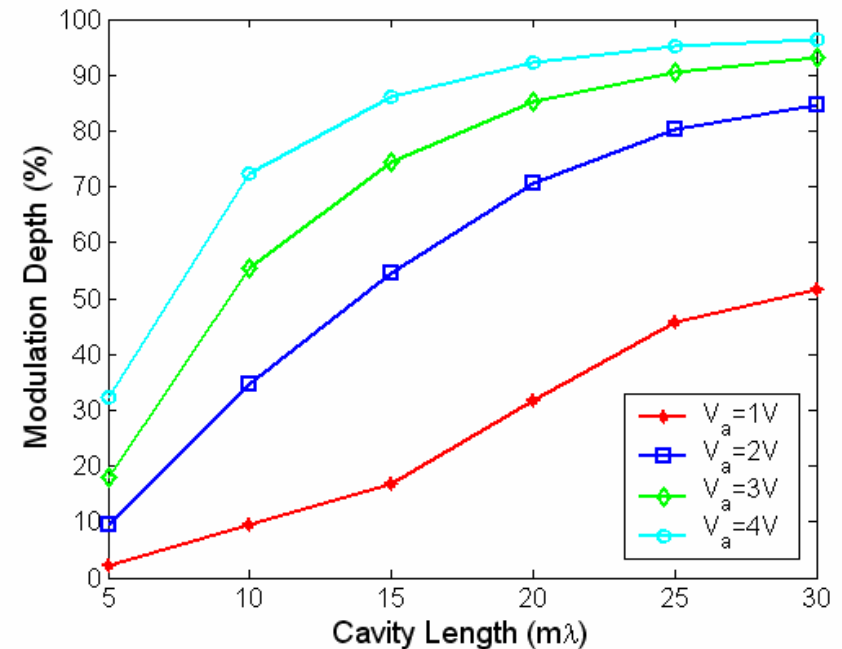
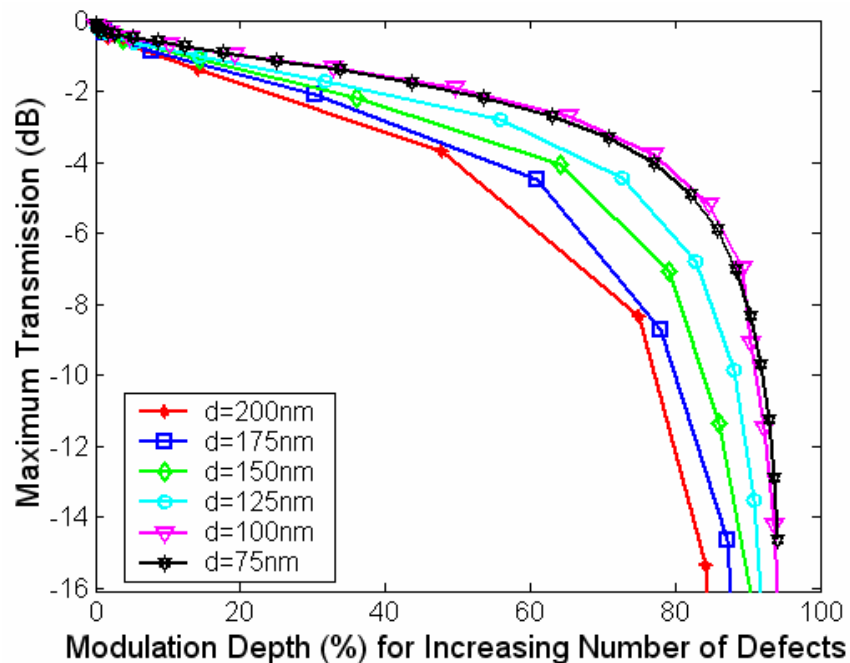
- Resonant cavity structure allows for design trade-offs among:

- Modulation depth
- FWHM
- Max. transmission
- Device length
- Applied voltage



Device Analysis

- There is clearly a limit to useful additional defects
- Many parameters of the design that can be varied depending upon the application



Conclusions

- Significant reduction in simulation times due to the cascade matrix approach
 - Allows for fast optimization of device and flexibility in the design
- Hybrid structure reduces required V_a
- Simulations show large modulation depth, narrow FWHM, moderate transmission, and short device length possible with the resonant cavity structure

Acknowledgements

- National Science Foundation Center on Materials and Devices for Information Technology Research (CMDITR), DMR-0120967
- National Science Foundation Graduate Research Fellowship
- Nanotechnology Modeling Lab members at the University of Washington
- Jingdong Luo and MDITR members of the Jen Group at UW
- Rhys Lawson and Susan Soggs from the Dalton Group at UW