A Comparison of Optical Modulator Structures Using a Matrix Simulation Approach

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Outline

- Motivation
- Resonant Cavity Modulator
- Microring Resonator Modulator
- Modeling Approach
- Results

Modulator Design Goals

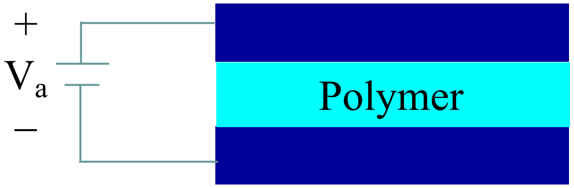
- Intended for future integrated optics and DWDM applications
  - Primarily CMOS-compatible
  - Low drive voltage
  - Large response
  - High-speed modulation
  - Compact structure
  - Narrow linewidths
- Often difficult to simultaneously achieve these design goals
- Modeling is challenging due to small dimensions and complex nature of the devices
  - Often requires full 3D simulation for accurate propagation characteristics
  - Very computationally expensive

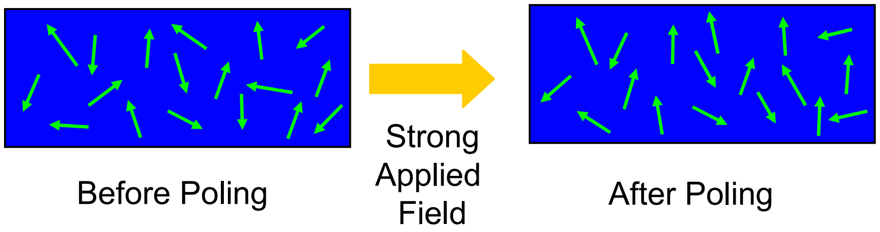
Material Options

- Silicon
  - Low loss
  - Highly manufacturable
- Electro-optic polymer
  - Very fast response
  - Large change in index of refraction under applied field
    - The achievable change in the index of refraction is related to the degree of chromophore alignment of the film achieved during static electrode poling

$$\Delta n = -\left[8.8\text{x}10^{-22}\,\Delta N_e + 8.5\text{x}10^{-18}\left(\Delta N_h\right)^{0.8}\right]$$

$$\frac{\Delta n}{\Delta T} = +1.86\times10^{-4}\,K^{-1}$$





  - The EO polymer parameters considered in this analysis were:
    - n = 1.6 at λ = 1.55μm
    - r_{33} = 100pm/V
    - Loss = 1 dB/cm

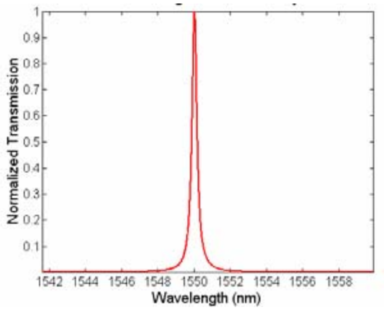
$$\Delta n = -\frac{n^3 r_{33} V_a}{2d}$$

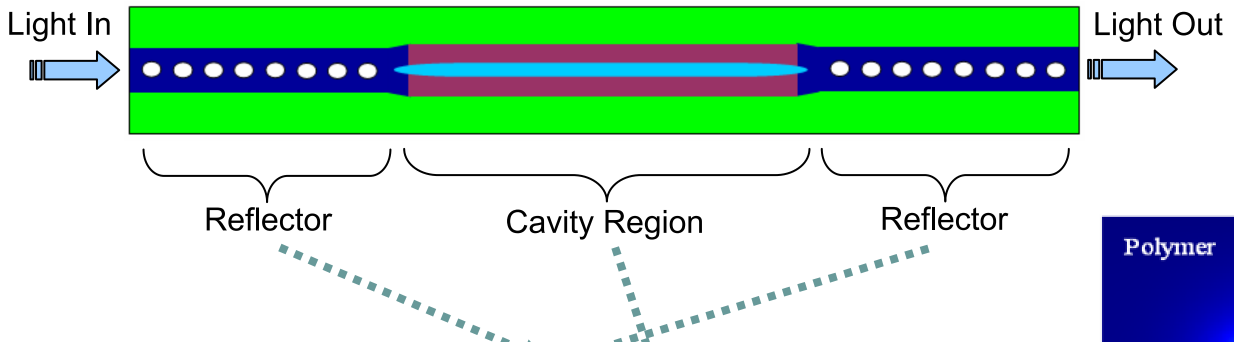
  - Recent developments have shown significant improvements in EO response
    - Dalton et al. have demonstrated r_{33} = 300pm/V and glass transition temperatures of 130°C [1]

[1] Dalton et al., *Proc. SPIE*, vol. 5935, 2005

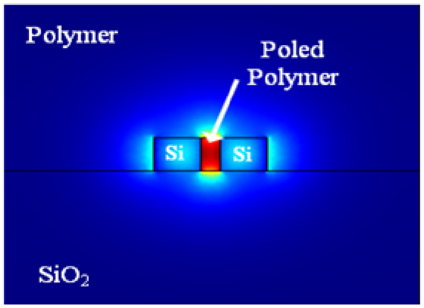
Basic Structures

- Fabry-Perot cavity is one option for an optical modulator structure
  - Series of holes creates a Bragg reflector
  - Resonant cavity breaks the periodicity of the reflector and allows for transmission at the resonant wavelength
    - Hybrid slot waveguides strongly confines light in narrow low-index region
    - Electro-optic polymer in slot waveguide can provide active material for modulation
    - Silicon ridges can be used as integrated electrodes, significantly reducing the necessary applied voltages





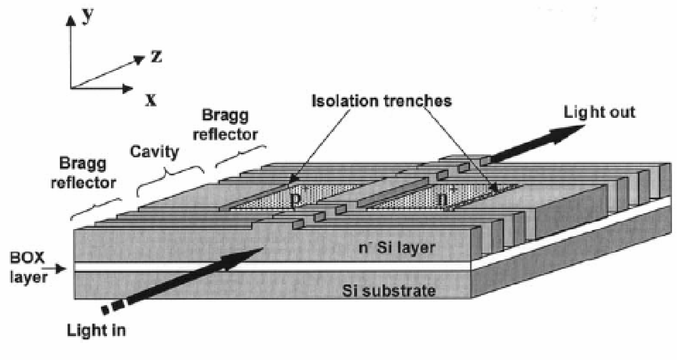
$$T = \frac{(1-R)^2}{1+R^2-2R\cos(\varphi)}$$



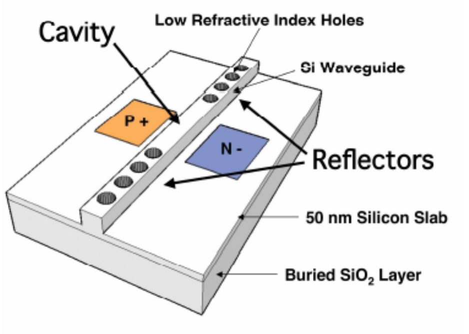
E-field in Hybrid Slot Waveguide

Current Resonant Cavity Modulators

- A FP structure in silicon using free carrier dispersion effects was demonstrated by Barrios et al.[2]
  - A very short device length: only 20μm
  - FWHM of 1.54nm
  - Modulation depth of 53%



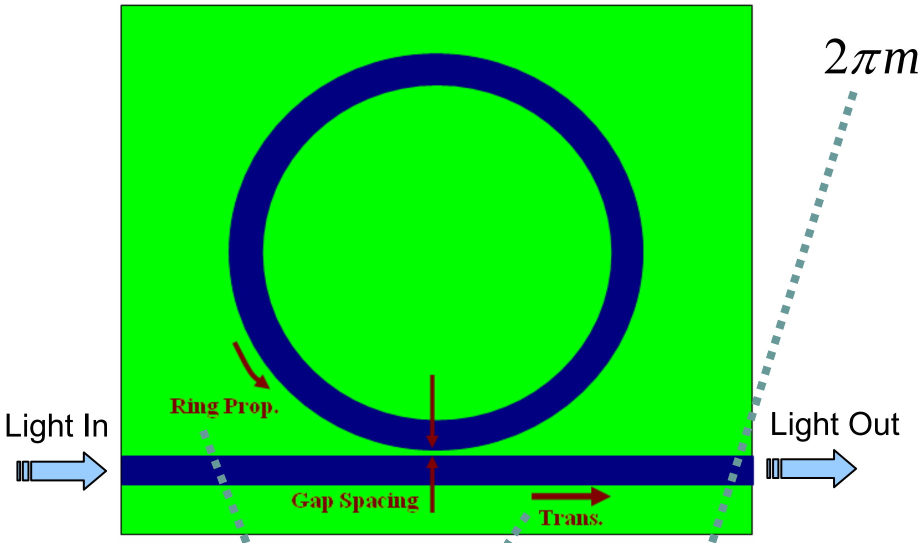
- Compact PBG modulator with p-i-n junction[3]
  - Device length 6μm
  - Modulation depth of 5.87dB
  - Demonstrated modulation at 250Mb/s
  - FWHM of 6.19nm



[2] Barrios et al., *IEEE Photon. Technol. Lett.*, vol. 16, Feb. 2004
[3] Schmidt et al., *Optics Express*, vol. 15, March 2007

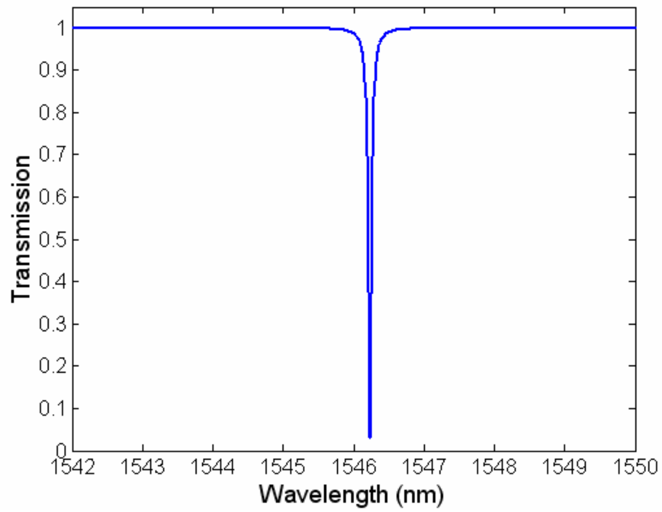
Basic Structures

- Microring resonator
  - Light of resonant wavelengths couples into the ring and can result in a sharp extinction ratio in the transmission spectrum



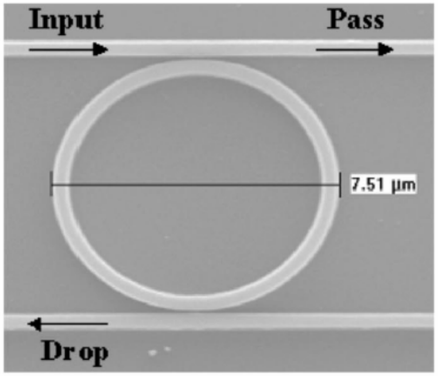
$$2\pi m = \beta L$$

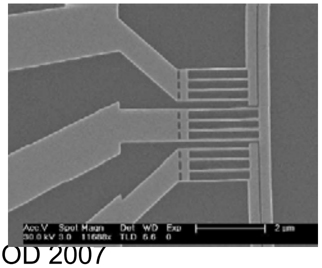
$$T = \frac{\alpha^2 + t^2 - 2\alpha t \cos(\beta L)}{1 + \alpha^2 t^2 - 2\alpha t \cos(\beta L)}$$

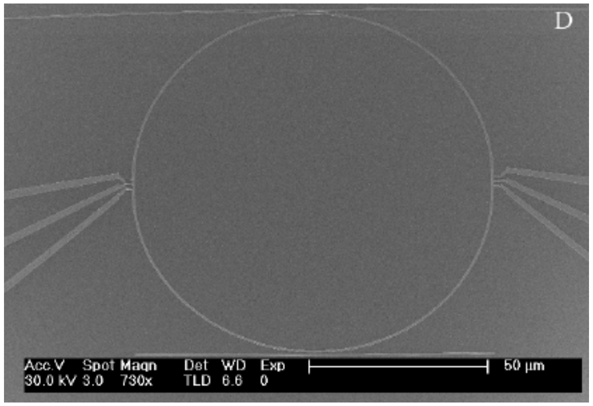


Current Microring Resonators/Modulators

- A very compact silicon MRR in SOI has been demonstrated by Miao et al.[4]
  - Drop port transmission of 81%
  - FWHM of 1.43nm for a diameter of 7.5µm
  - No modulation demonstrated
- High-speed all-polymer MRR modulator[5]
  - ALJ8/APC EO polymer demonstrated 28GHz modulation
  - Ring diameter of 2mm, resulted in FWHM of 0.03nm
- A hybrid EO polymer/silicon slot waveguide MRR modulator was recently demonstrated[6]
  - 100µm ring diameter
  - 20V required for 5dB modulation depth



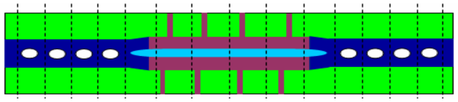


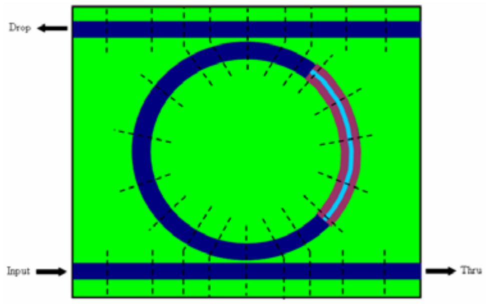


[4] Miao et al., *J. Microlith, Microfab.*, vol. 4, Apr. 2005
[5] Tawaza et al., *J. Lightwave Technol.*, vol. 24, Sept. 2006
[6] Baehr-Jones et al., *Optics Express*, vol. 13, July 2005

Modeling Approach

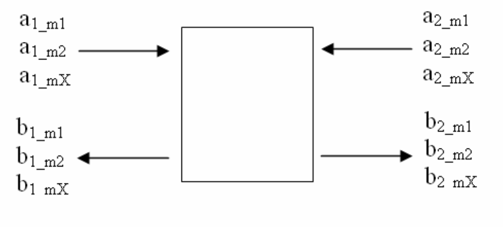
- Use a cascading matrix approach for full 3D modeling of optical modulators[7]
  - Needs to include propagation through straight waveguide(s) as well as coupling into and out of the separate ring waveguide for microring designs





  - Simulation of each unique section
    - *m* is the number of modes and *p* is the number of ports
    - $\mathbf{b}_{(1\,\mathrm{x}\,mp)} = \mathbf{S}_{(mp\,\mathrm{x}\,mp)}\,\mathbf{a}_{(1\,\mathrm{x}\,mp)}$
  - Scattering matrices from each section are organized into a diagonal matrix, from input to output, with N_{tot} being the total number of sections

$$\begin{bmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \\ \vdots \\ \mathbf{b}_{N_{tot}} \end{bmatrix} = \begin{bmatrix} \mathbf{S}_1 & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{S}_2 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{S}_{N_{tot}} \end{bmatrix} \begin{bmatrix} \mathbf{a}_1 \\ \mathbf{a}_2 \\ \vdots \\ \mathbf{a}_{N_{tot}} \end{bmatrix}$$



[7] Glock et al., *IEEE Trans. Mag.*, vol. 38, 2002

Modeling Approach

- The coupling between the sections still needs to be included
  - First create a permutation matrix of the internal and external inputs

$$\begin{bmatrix}\mathbf{a}_1\\ \vdots \\ \mathbf{a}_{N_{tot}}\end{bmatrix} = \mathbf{M}_{Int}\begin{bmatrix}\mathbf{a}_{Int}\\ \mathbf{a}_{Ext}\end{bmatrix}$$

  - Then create another permutation matrix that specifies the output of one section as the input to another
    - Provides the coupling between the light input to the straight waveguide and the coupled ring waveguide

$$\begin{bmatrix}\mathbf{a}_{Int}\\ \mathbf{b}_{Ext}\end{bmatrix} = \mathbf{M}_{Bnd}\begin{bmatrix}\mathbf{b}_1\\ \vdots \\ \mathbf{b}_{N_{tot}}\end{bmatrix}$$

- Finally, want relationship between input at one end of straight waveguide and output at other end of straight waveguide
  - Combining above relationships gives:

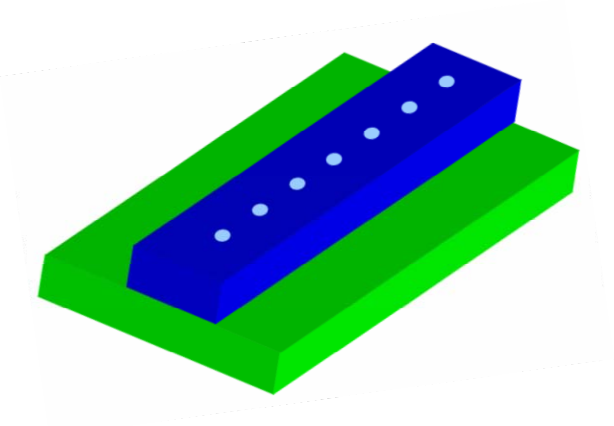
$$\begin{bmatrix}\mathbf{a}_{Int}\\ \mathbf{b}_{Ext}\end{bmatrix} = \mathbf{M}_{Bnd}\mathbf{S}_{Tot}\mathbf{M}_{Int} = \begin{bmatrix}\mathbf{T}_{11} & \mathbf{T}_{12}\\ \mathbf{T}_{21} & \mathbf{T}_{22}\end{bmatrix}\begin{bmatrix}\mathbf{a}_{Int}\\ \mathbf{a}_{Ext}\end{bmatrix}$$

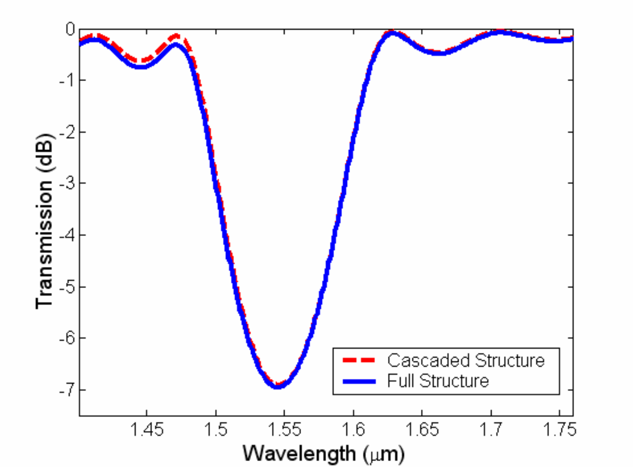
  - Eliminating internal coupling ($\mathbf{a}_{int}$) leads to final transmission matrix
    - Where the dimensions of $\mathbf{T}_{21}$ are (N_{Ext} x N_{Int}), $\mathbf{T}_{11}$, $\mathbf{I}$ are (N_{Int} x N_{Int}), $\mathbf{T}_{12}$ are (N_{Int} x N_{Ext}), and $\mathbf{T}_{22}$ are (N_{Ext} x N_{Ext})

$$\mathbf{b}_{Ext} = \left[\mathbf{T}_{21}\left(\mathbf{1} - \mathbf{T}_{11}\right)^{-1}\mathbf{T}_{12} + \mathbf{T}_{22}\right]\ \mathbf{a}_{Ext}$$

Simulation

- A full simulation of a 7-period DBR with 100nm holes spaced by 515nm was performed to compare this to the cascade matrix approach
  - Excellent agreement of transmission
  - Simulation times:
    - Full structure: 7 hours
    - Cascade structure: 30 minutes





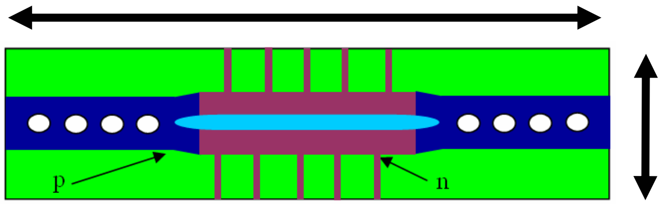
- Calculation of overlap integral can give a sense of accuracy of cascade matrix approach
  - Significant disturbances of the primary mode reduce this agreement

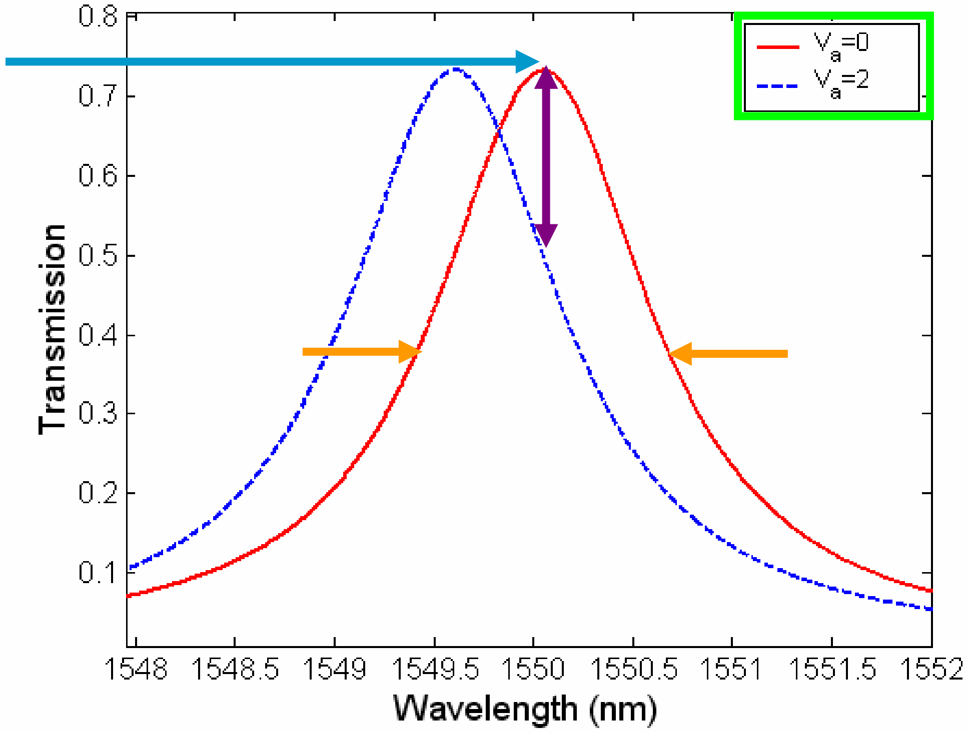
$$\eta = \frac{P_{out}}{P_{in}}$$

Section Length:	200nm	400nm	800nm	1000nm
Overlap (η) %:	82.64	86.76	89.51	90.92

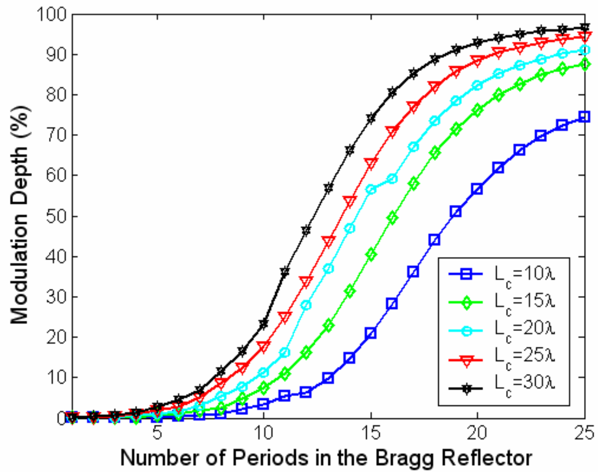
Design Parameters

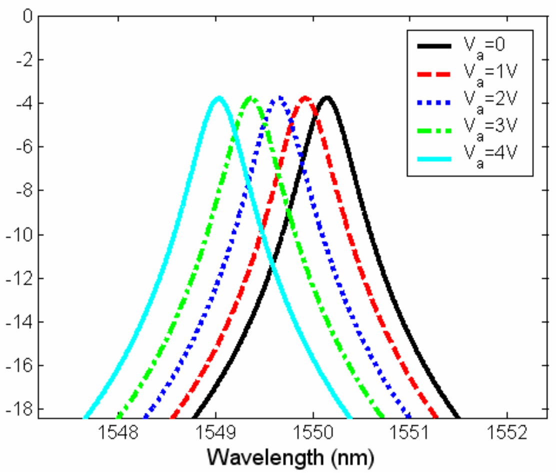
- Modulator structures allows for design trade-offs among:
    - Modulation depth
    - FWHM
    - Max. transmission
    - Applied voltage
    - Device length
    - Device width

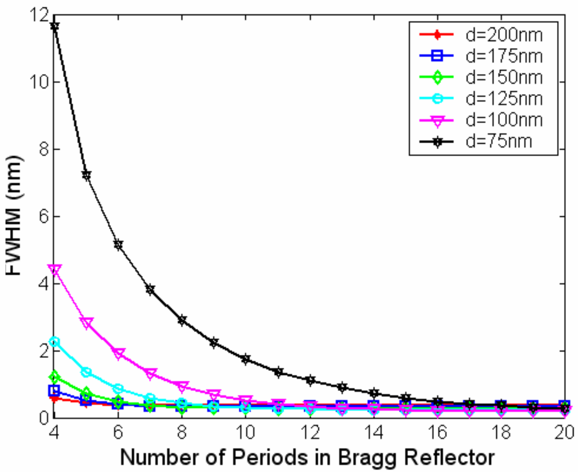


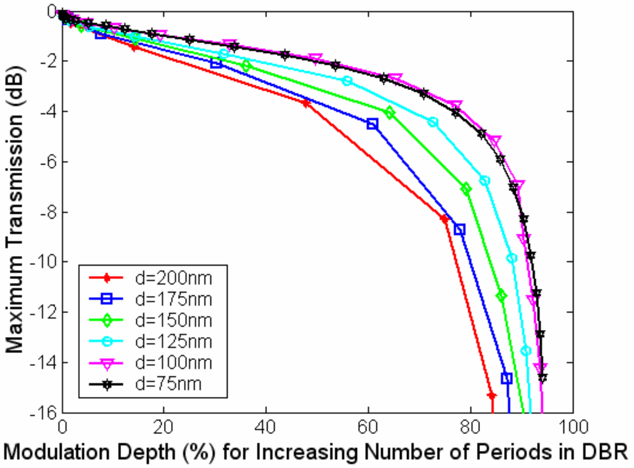


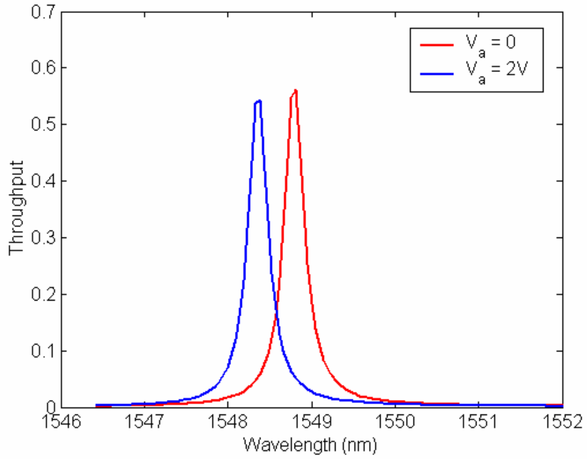
Results for Resonant Cavity Modulator







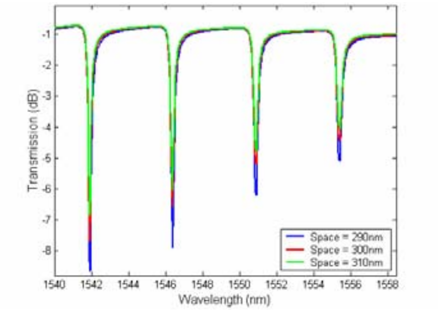




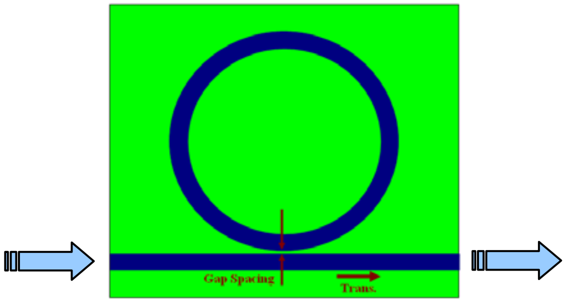
FHWM = 0.29nm
MD: 89%
Length: 40μm

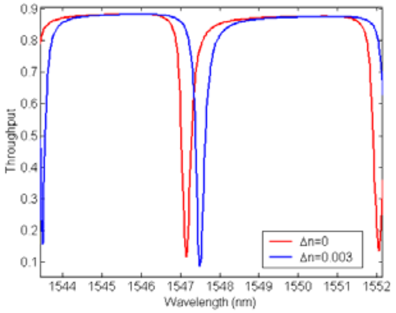
Results for 30μm Ring Resonator Modulator

- Single coupled ring resonator
  - Variations in gap spacing

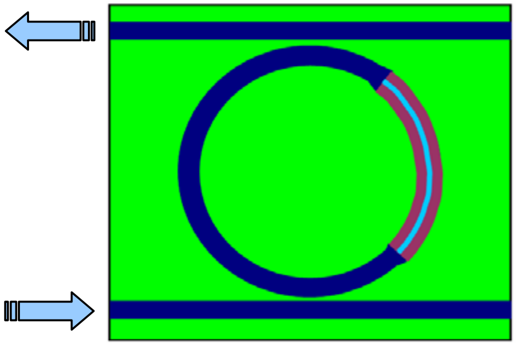


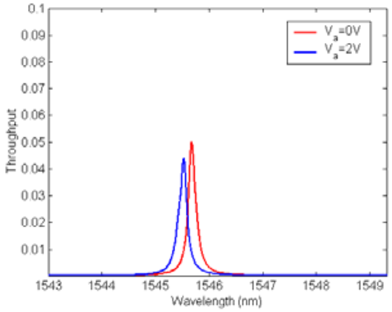
  - Index variation of 0.003
    - FWHM of 0.23nm
    - MD of 83%





- Two waveguides coupled to ring resonator with 25μm hybrid slot waveguide in ring waveguide
    - FWHM of 0.18nm
    - MD of 78%





Conclusions

- Full 3D simulation of resonant cavity and microring resonator modulators has been investigated
  - Drastic reduction in simulation times using cascade matrix approach
  - Good agreement between full simulation and matrix analysis

- Designed and simulated a hybrid silicon/EO polymer resonant cavity modulator
  - Simultaneously achieve a large modulation depth, low applied voltage, and compact device structure
  - CMOS compatible, with minimum feature size limited to 100nm to allow for the use of current photolithography techniques

- Investigated hybrid microring resonator modulator
  - Also has large response for small voltages, but design needs to be improved for higher throughput

- Future work will focus on further investigation of this modeling approach for optical modulators and other devices for integrated optics applications
  - Simulation of microring resonator modulator designs
  - Investigation of fabrication tolerances
  - Further analysis of hybrid silicon/EO polymer structures and multi-ring resonators

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