ECE 695 Numerical Simulations Lecture 11: Beam Propagation Method

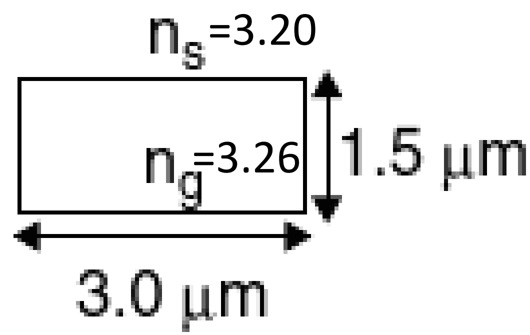
Prof. Peter Bermel

February 3, 2017

Outline

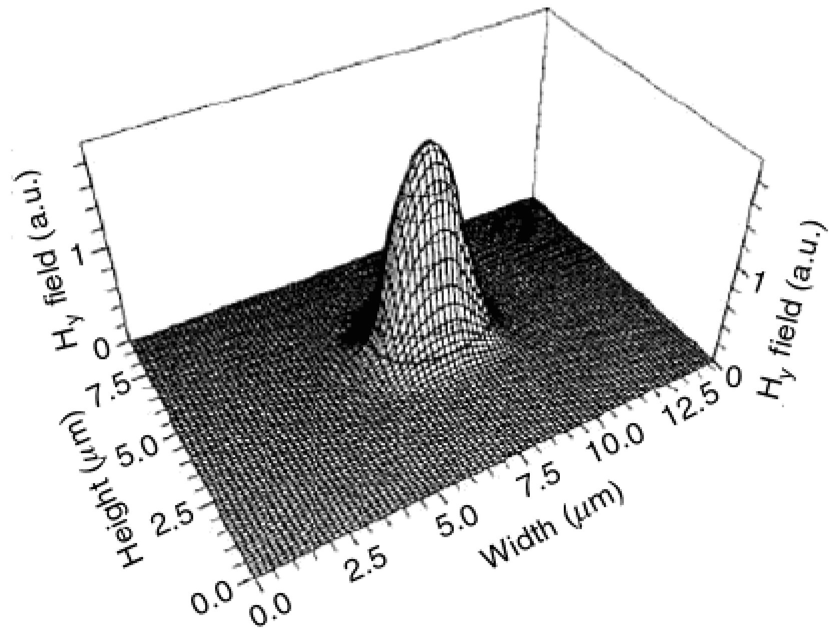
- Vectorial BPM Solver
- Tunable Photonic Crystal Fibers
- Electro-Optic Modulator
- Electro-Optic Switch

VBPM on a Waveguide: Problem Description



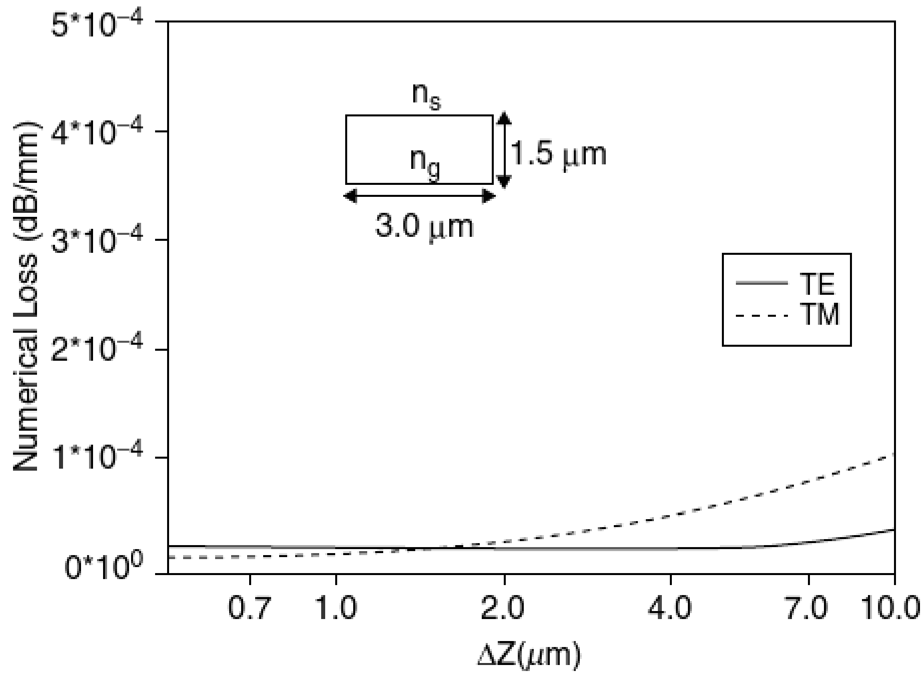
- Cross section defined above; $\lambda = 1.3\ \mu$m
- Propagation along z is semi-infinite
- Must grid space with first-order triangular elements in cross-sectional plane; choose PML to reduce reflections to 10^{-100}
- Will vary Δz for maximum effectiveness

VBPM on a Waveguide



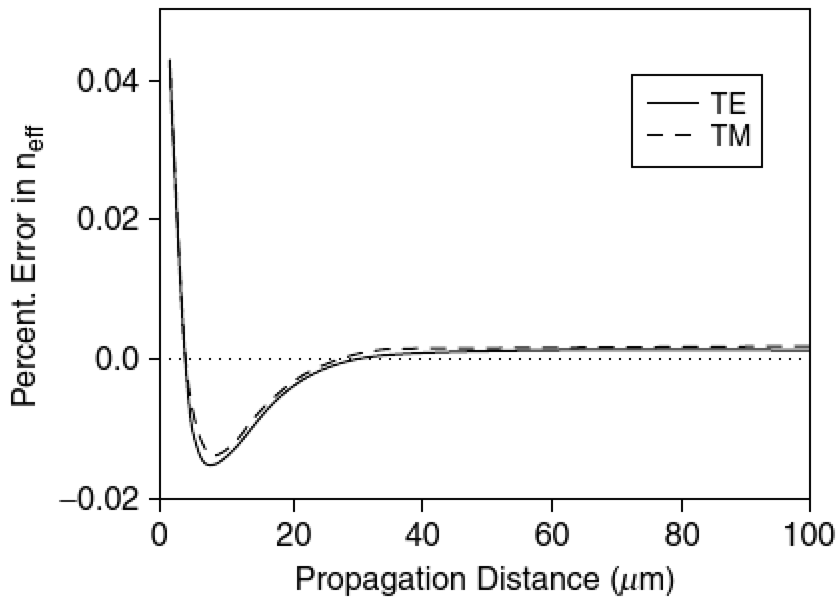
- Fundamental mode is calculated accurately with 12,800 first-order triangular elements

VBPM on a Waveguide



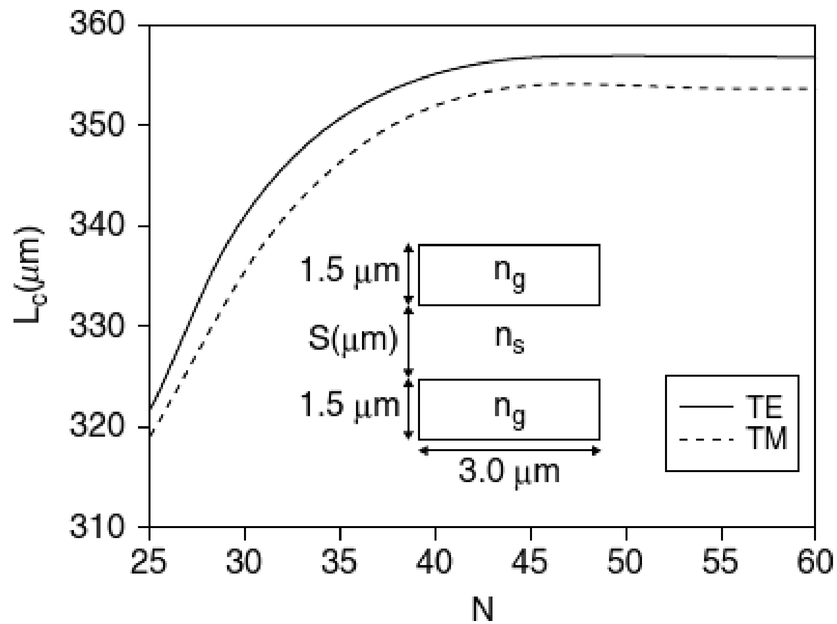
- Propagation step size in *Z*, known as ΔZ, should equal transverse dimensions for best accuracy

VBPM on a Waveguide: Longitudinal Imaginary Propagation



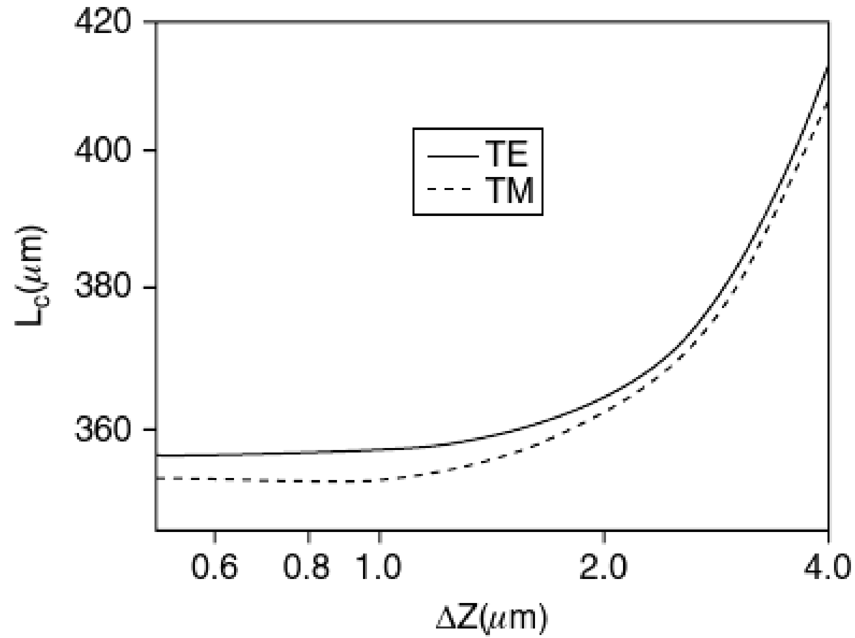
- With optimal step size, can solve the fundamental mode of both polarizations in a pretty modest number of steps!

VBPM on a Waveguide: Accuracy



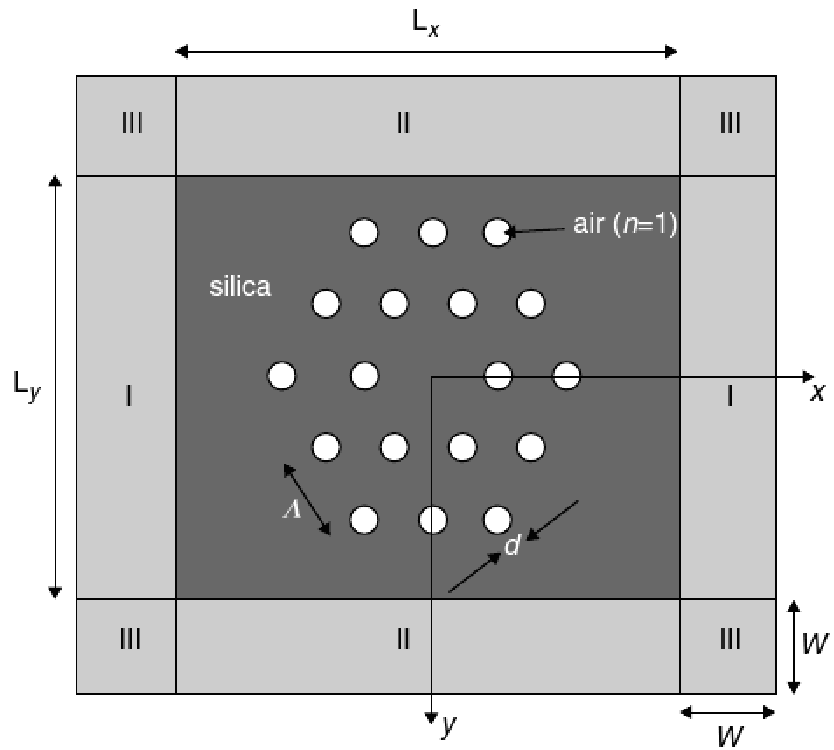
- Accuracy of calculation of waveguide coupling length as a function of mesh divisions *N*

VBPM on a Waveguide



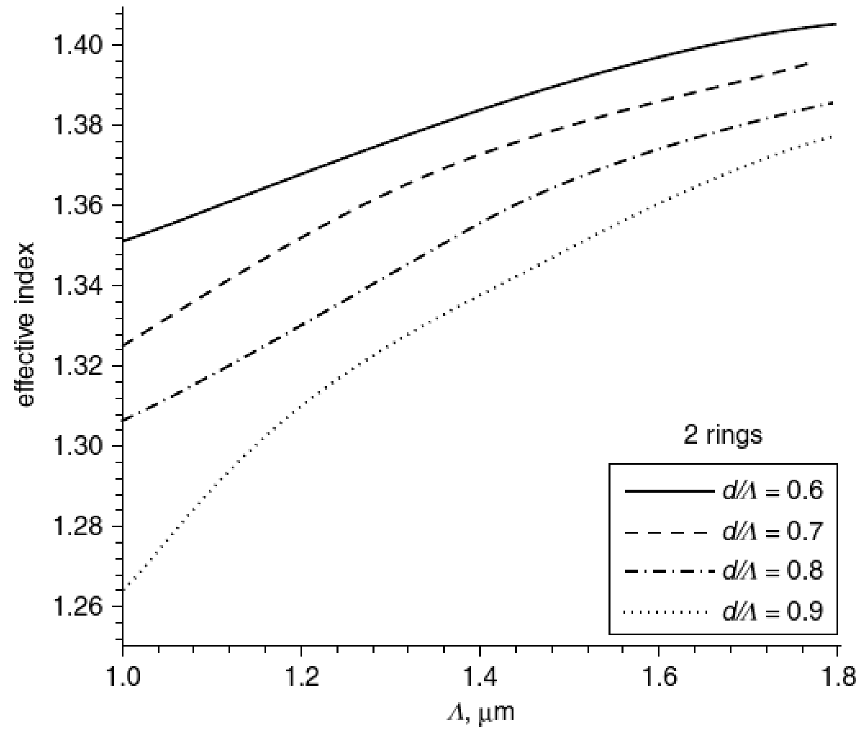
- Accuracy of coupling length as a function of ΔZ saturates below one wavelength

VBPM on a Photonic Crystal Fiber



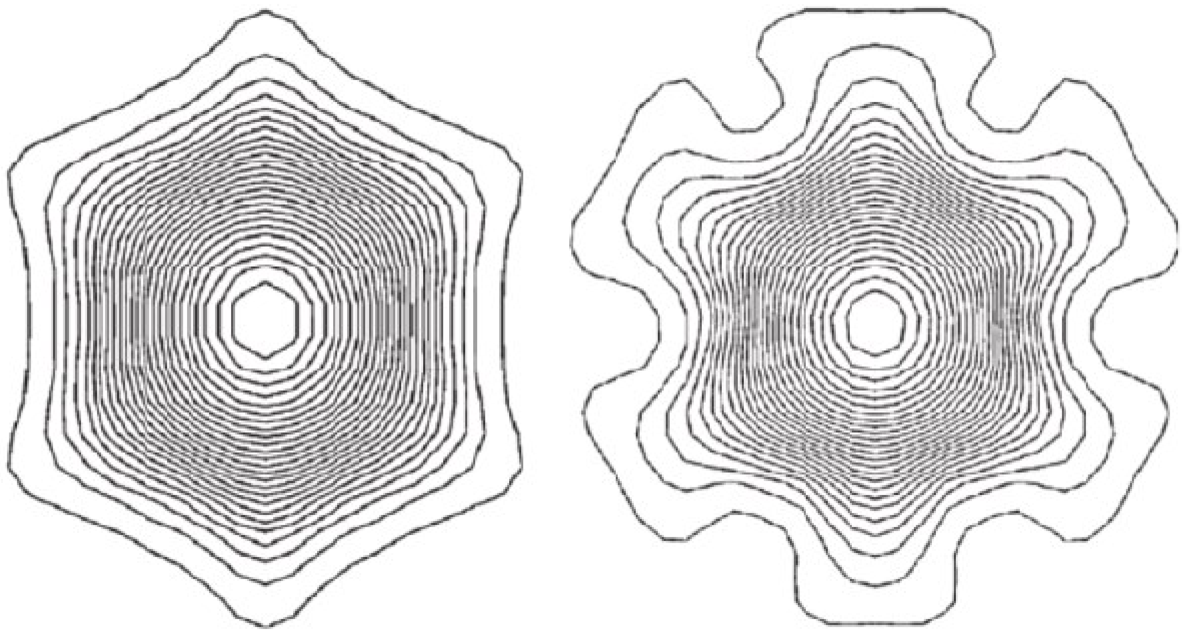
- Originally conceived of by P.J. Russell
- Confines light to core without total internal reflection!

VBPM on a PhC Fiber



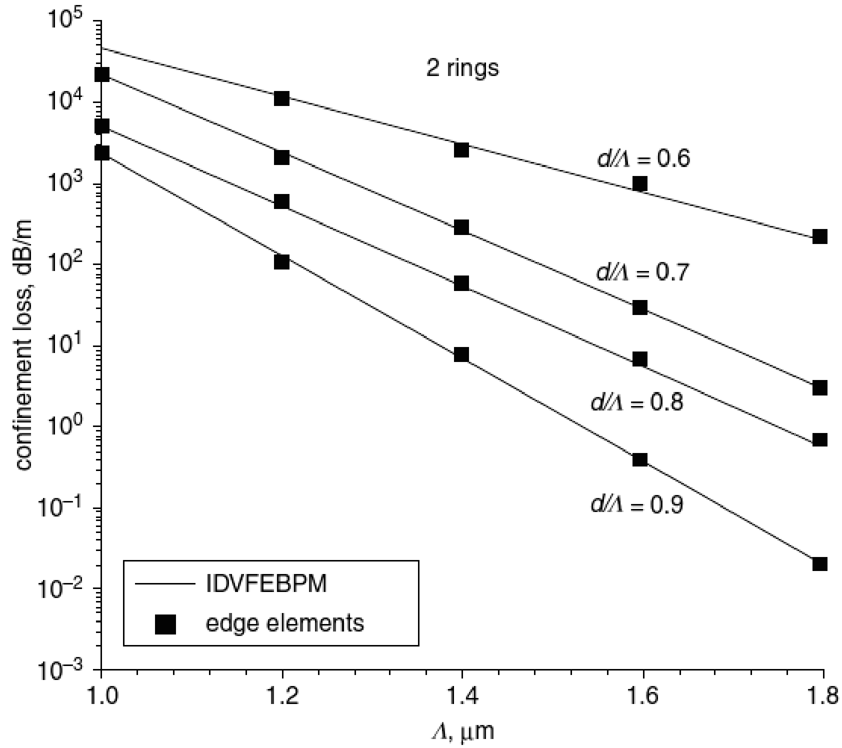
- Effective index vs. PhC period

VBPM on a PhC Fiber



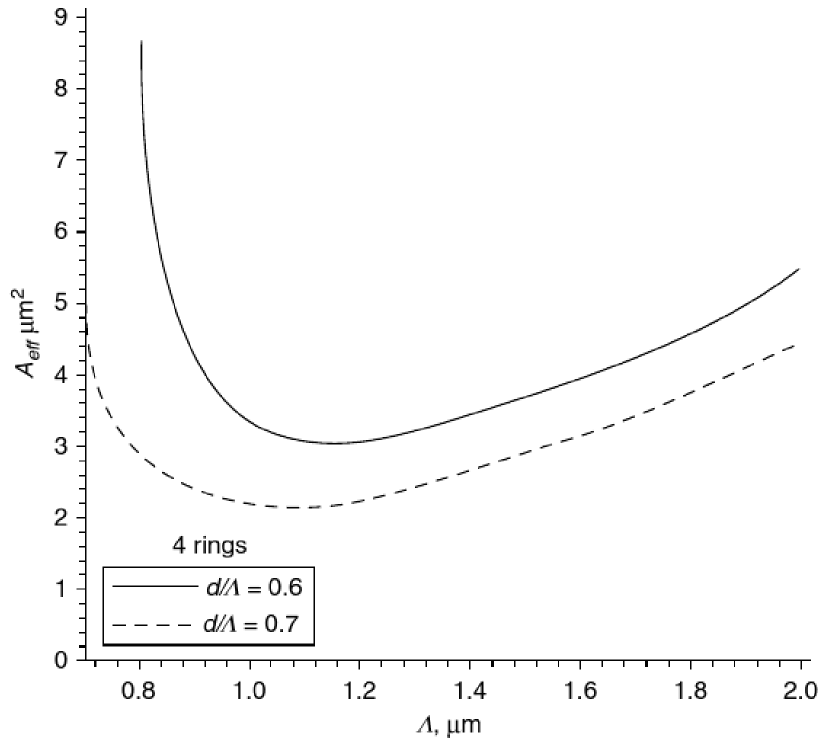
- H_y field distributions for the fundamental TE modes

VBPM on a PhC Fiber



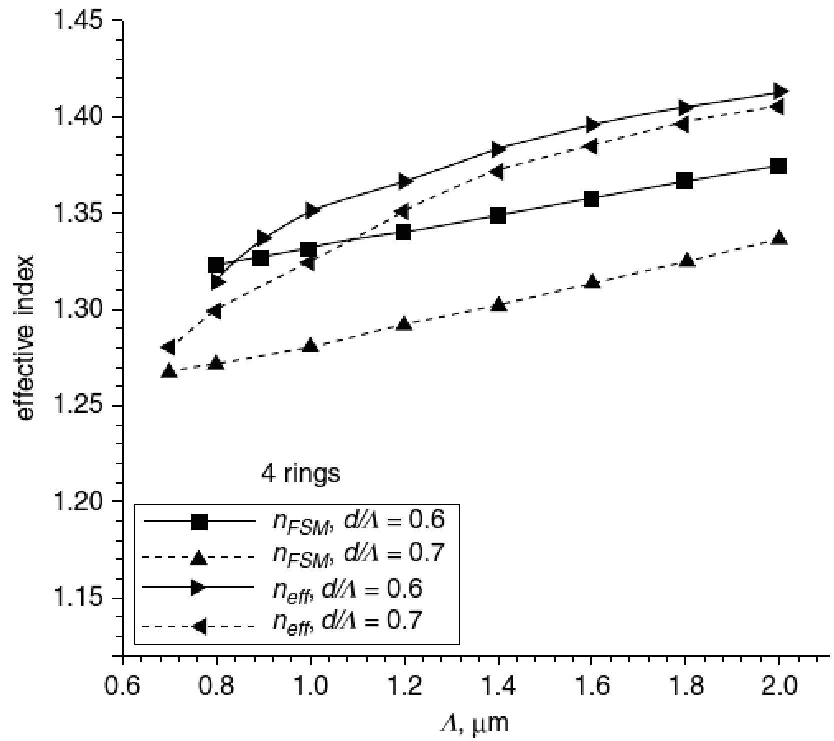
- Confinement loss decreases sharply as period Λ increases

VBPM on a PhC Fiber



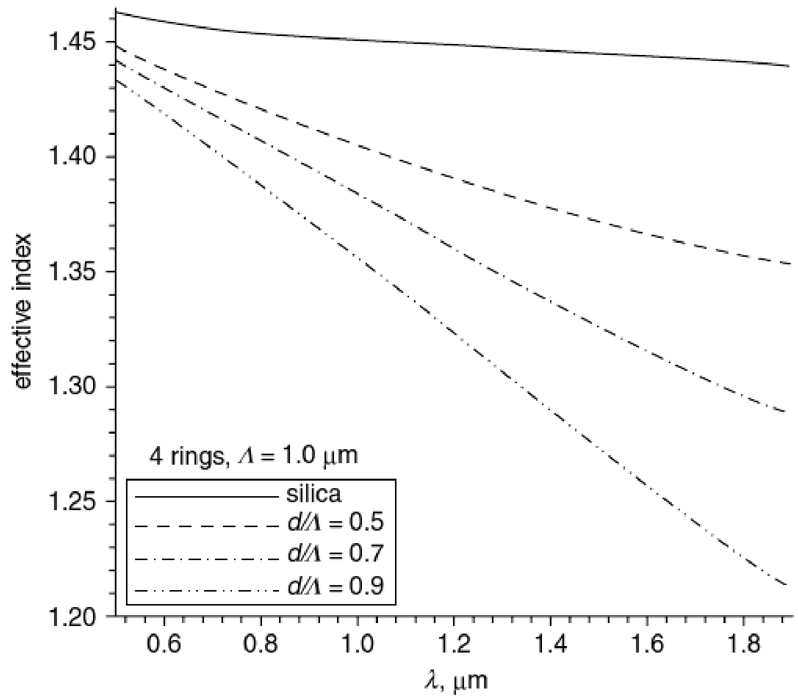
- Variation of the effective mode area with PhC period Λ

VBPM on a PhC Fiber



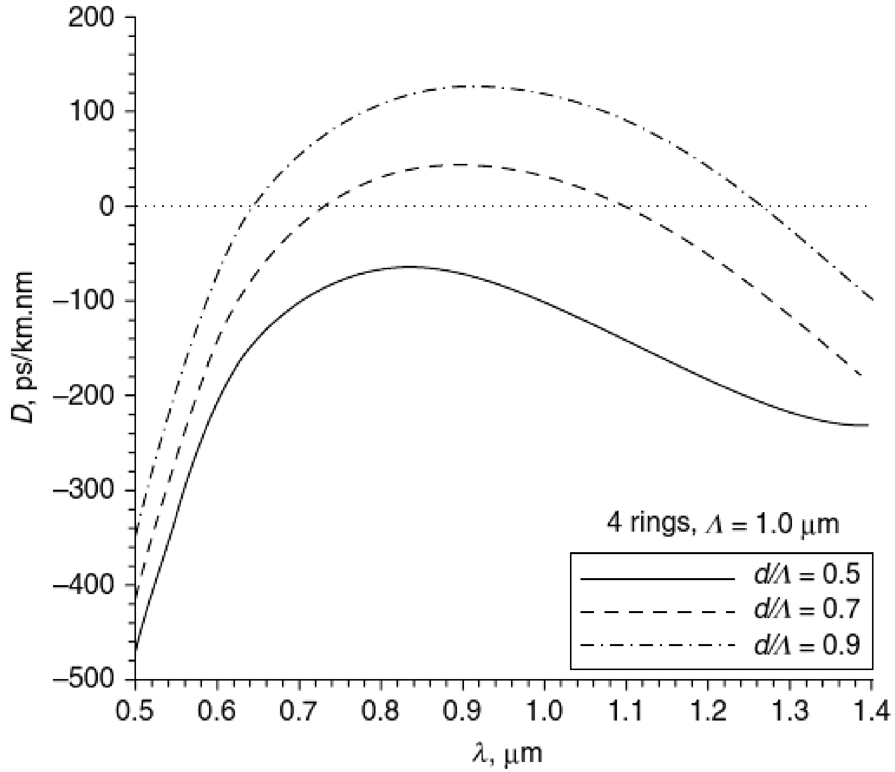
- Effective index increases modestly with increasing period Λ, indicating increased mode confinement

VBPM on a PhC Fiber



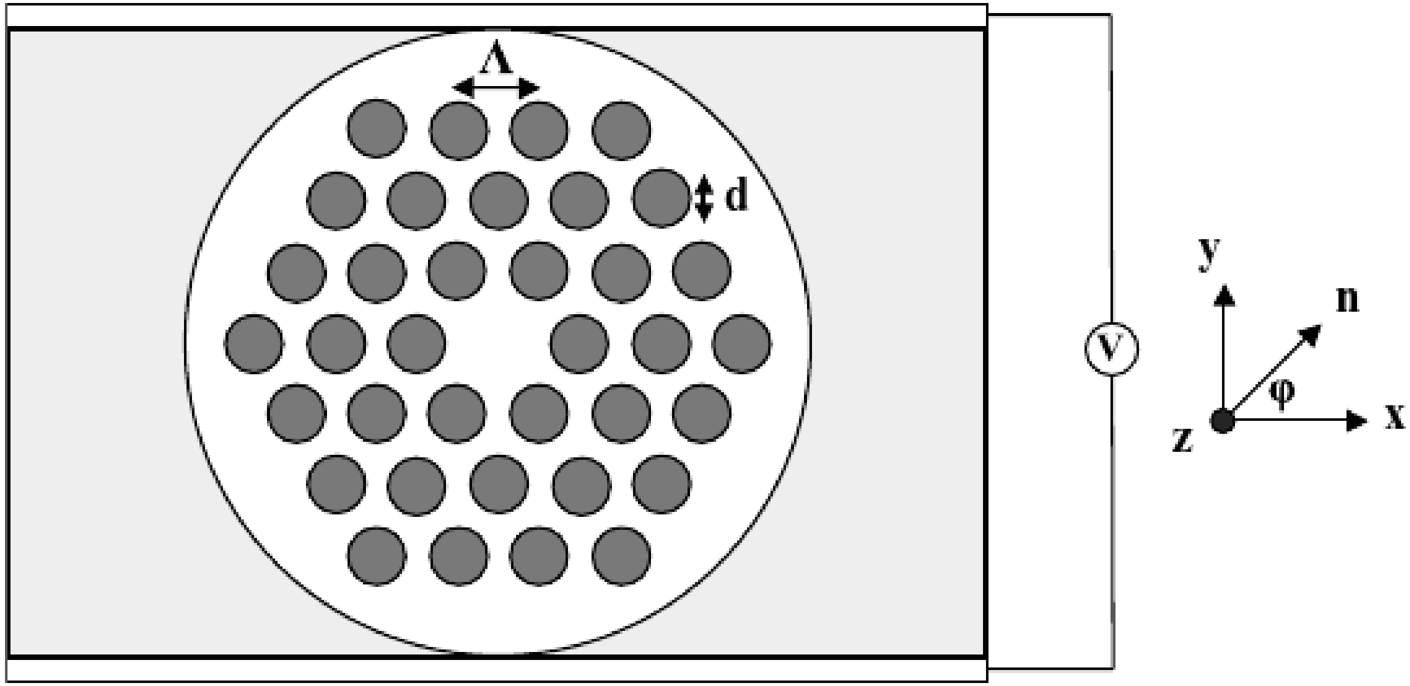
- Calculated dispersion relation (effective index versus wavelength) for a PhC Fiber

VBPM on a PhC Fiber



- Obtained dispersion $D = d^2k/d\omega^2$ from earlier data
- Note modest changes in parameters flip sign of *D*

Tunable PhC Fiber



S. Obayya, "Computational Photonics" (Wiley, 2010)

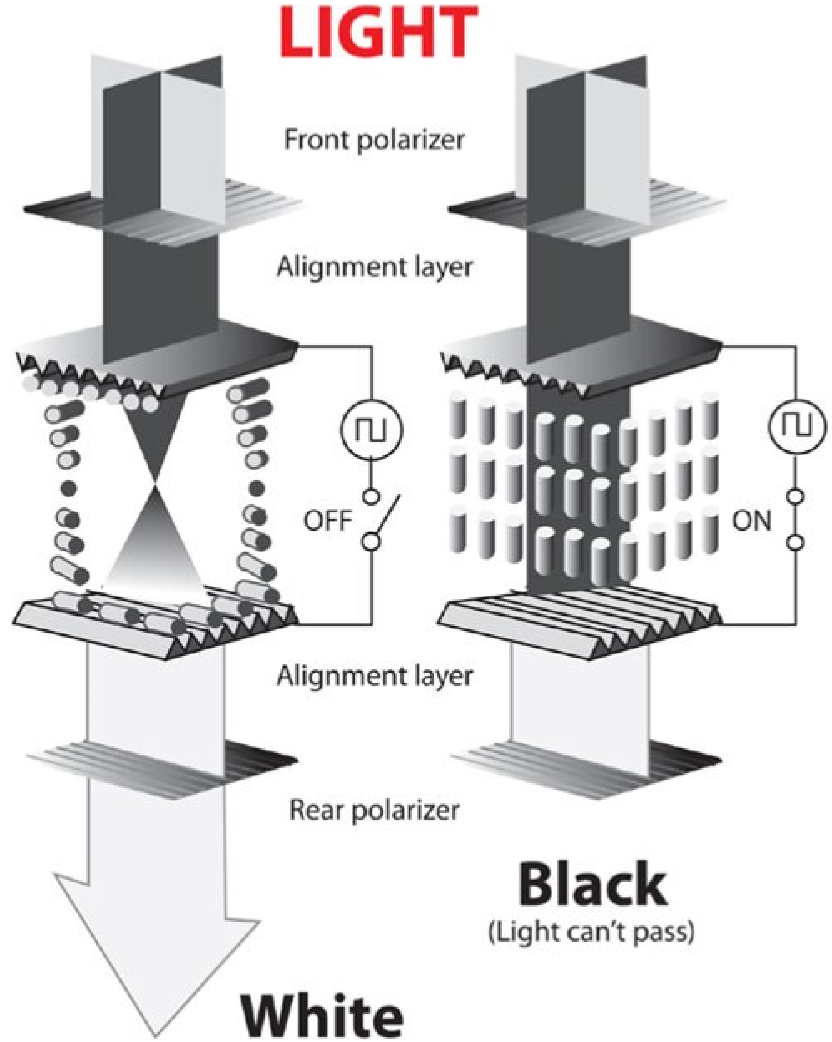
- Cross-section of a PhC fiber filled with electrostatically tunable liquid crystals

Liquid Crystals

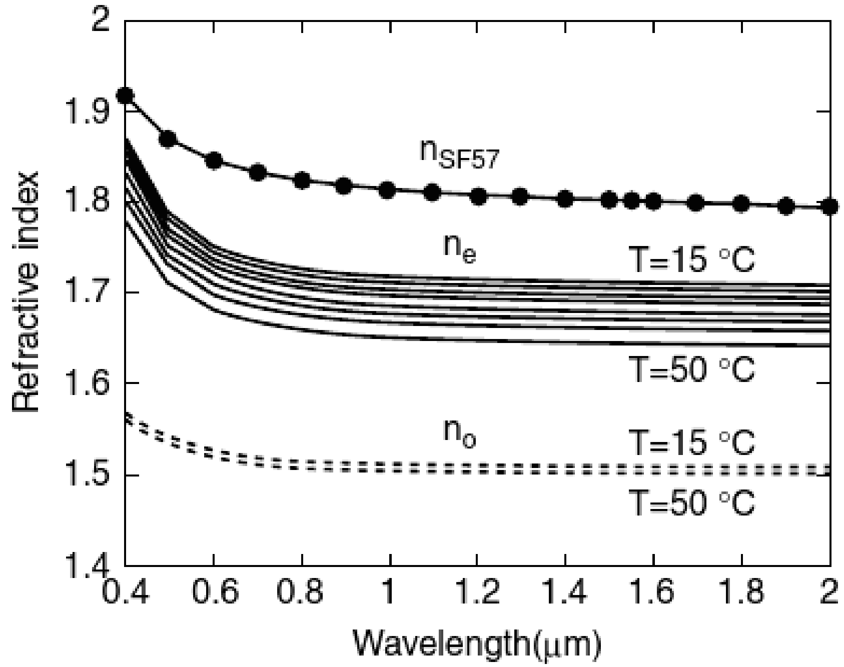
- Liquid crystals consist of many stiff molecules
- LC order in between that of liquids and crystals
- LCs have a uniaxial dielectric function:

$$\epsilon_{ij} = \epsilon_o + \delta\epsilon\, \hat{n}_i \hat{n}_j$$

- The director is oriented along applied electrostatic fields



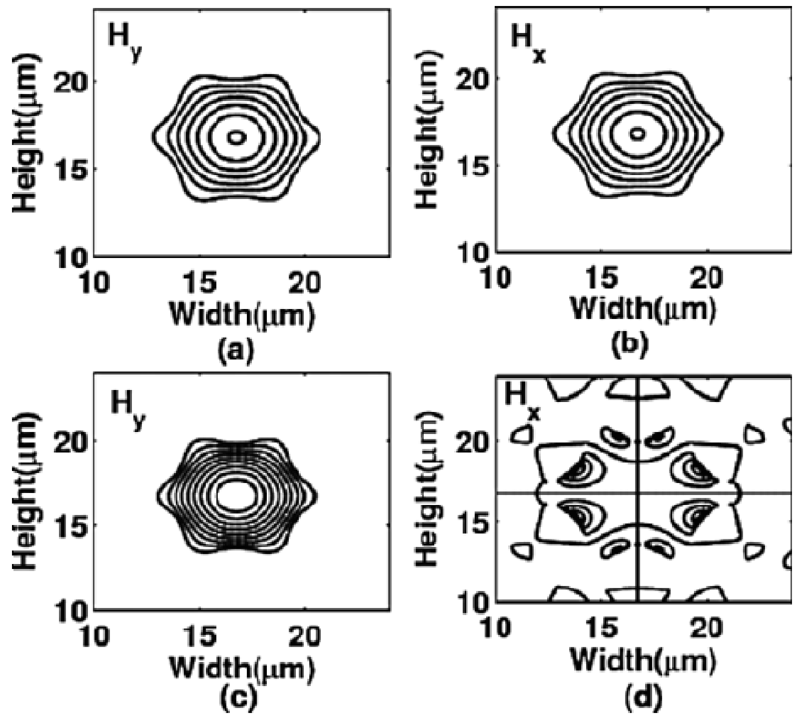
Tunable PhC Fiber



S. Obayya, “Computational Photonics” (Wiley, 2010)

- Variation of LC refractive indices both on and off-axis, consistent with normal dispersion

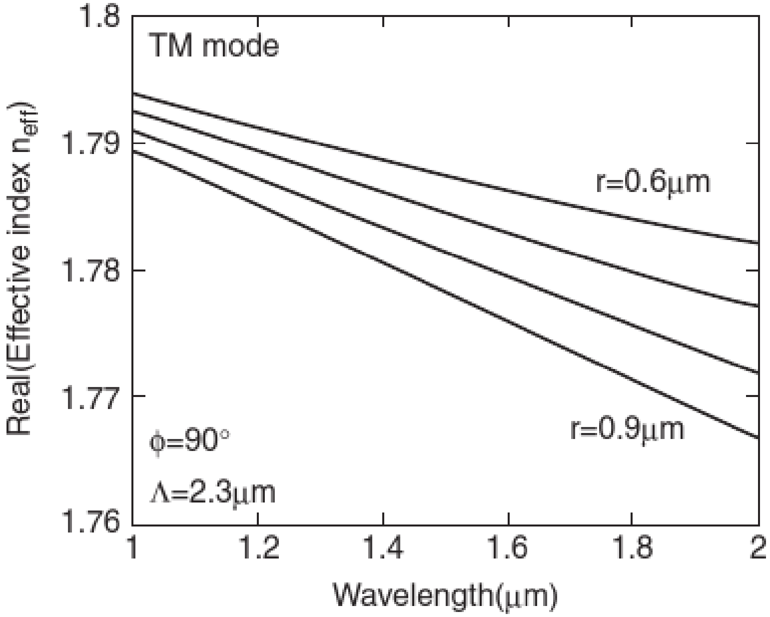
Tunable PhC Fiber

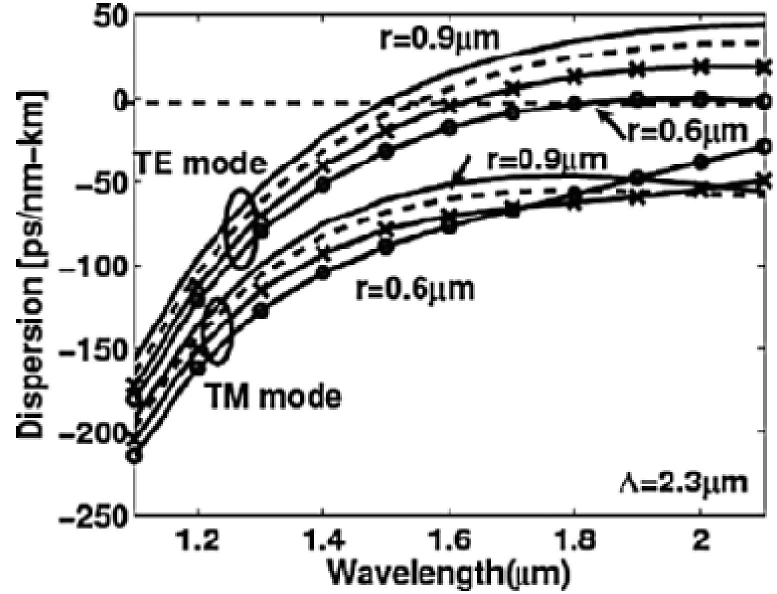


S. Obayya, "Computational Photonics" (Wiley, 2010)

- Dominant and non-dominant HE (quasi-TE) modes for tunable PhC fiber

Tunable PhC Fiber

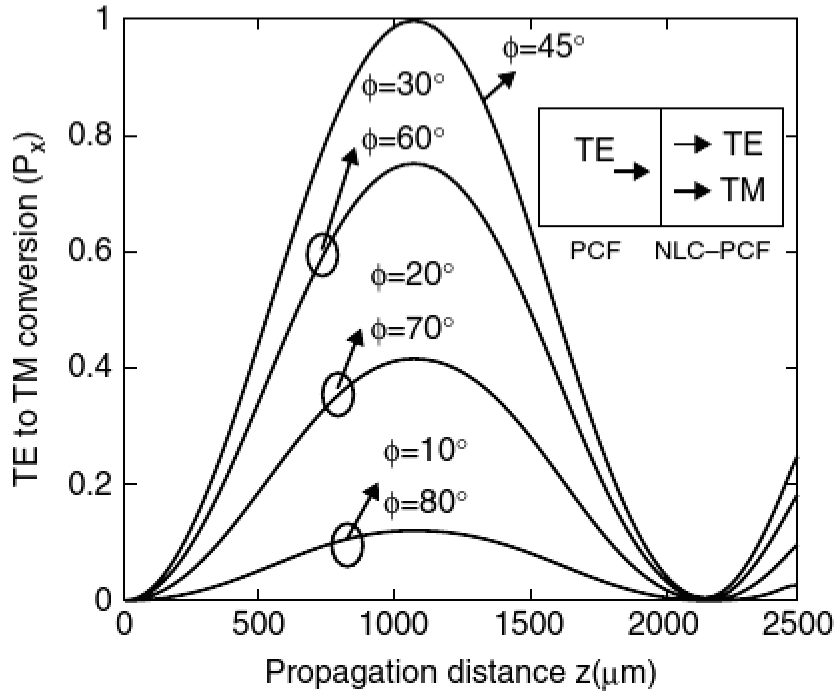




S. Obayya, "Computational Photonics" (Wiley, 2010)

- Wavelength dependence of the effective index (left) and dispersion (right)

Tunable PhC Fiber



S. Obayya, "Computational Photonics" (Wiley, 2010)

- Polarization conversion versus propagation distance Z

Electro-Optic Modulation

- The refractive index matrix for a Pockels medium subject to an external electric field in the xy-plane can be written as follows:

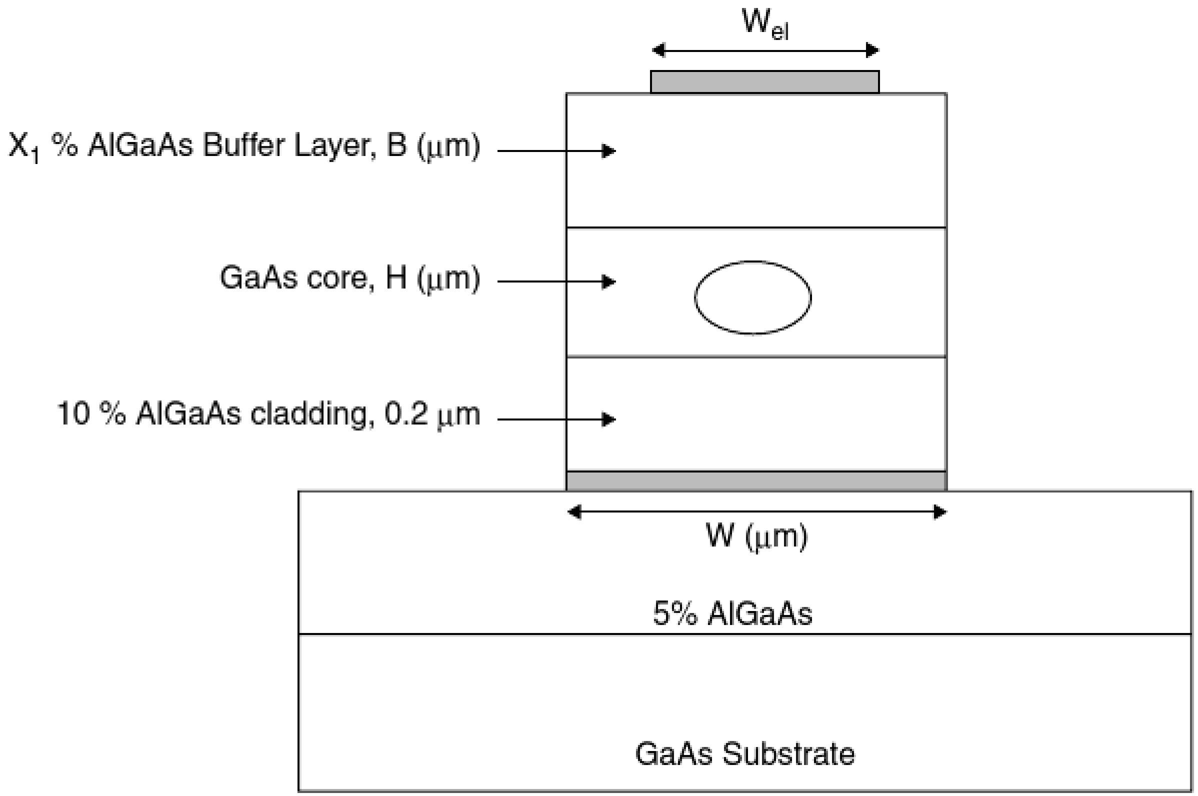
$$n = \begin{pmatrix} n_o + \delta n_{xx} & \delta n_{xy} & 0 \\ \delta n_{yx} & n_o & 0 \\ 0 & 0 & n_o - \delta n_{zz} \end{pmatrix}$$

- Where:

$$\delta n_{xx} = \delta n_{zz} = \frac{1}{2} n_o^3 \, r_{41} E_y$$

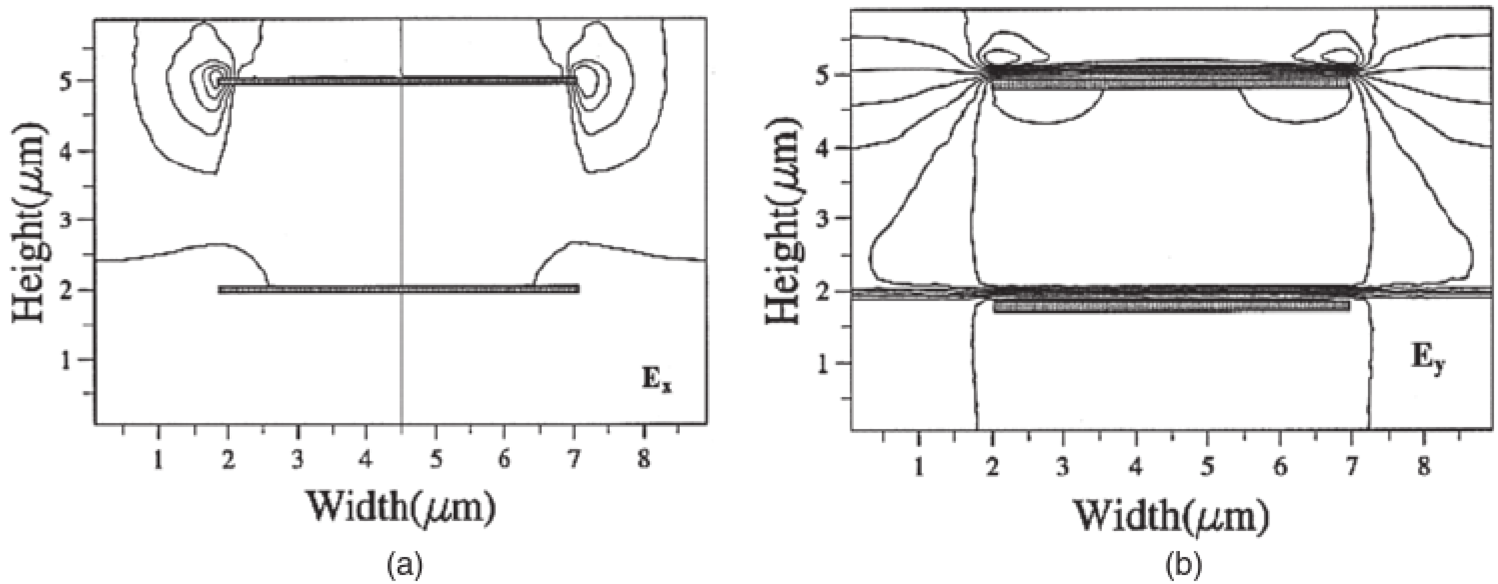
$$\delta n_{xy} = \delta n_{yx} = \frac{1}{2} n_o^3 \, r_{41} E_x$$

Electro-Optic Modulator



- Schematic diagram of the electro-optic modulator, made from epitaxial GaAs/AlGaAs layers

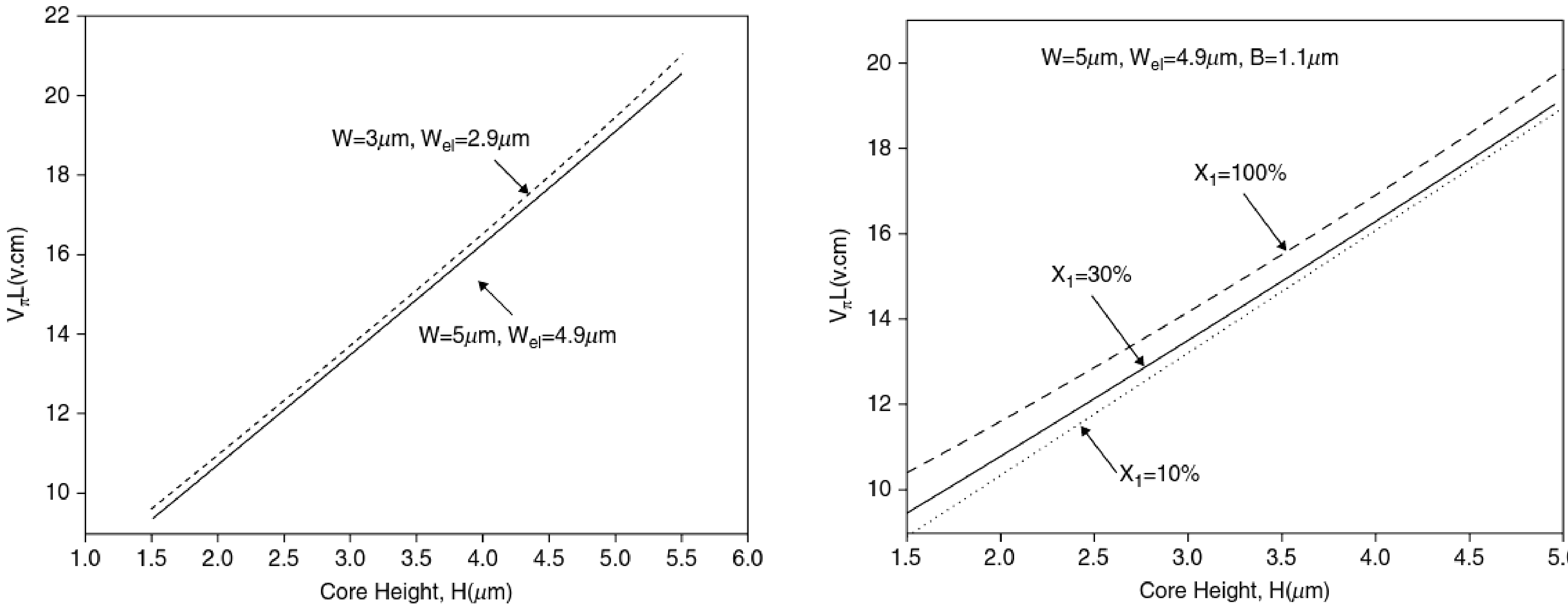
Electro-Optic Modulator



S. Obayya, "Computational Photonics" (Wiley, 2010)

- Electric modulation field distributions for Ex (left-hand side) and Ey (right-hand side)

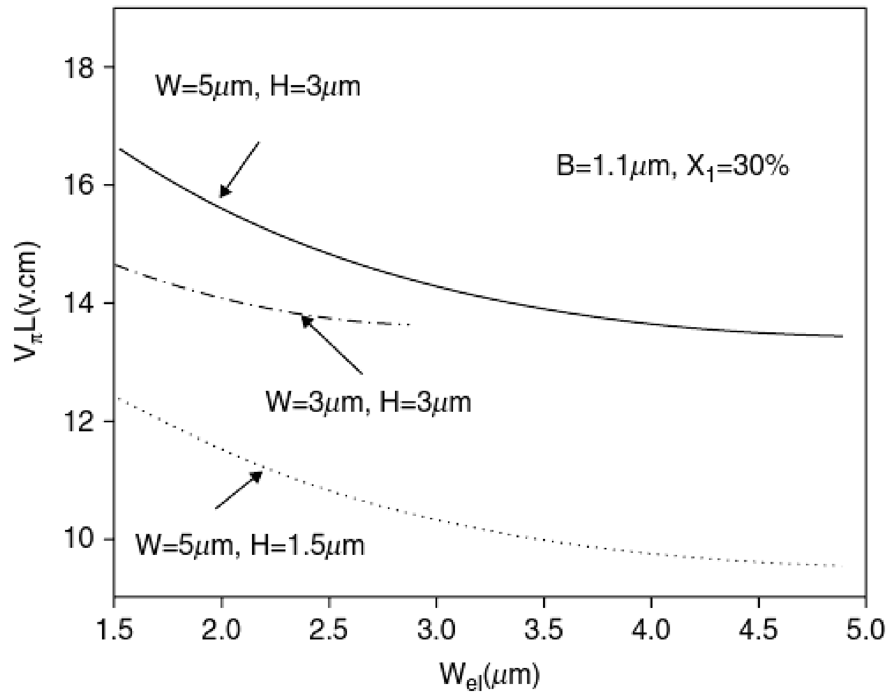
Electro-Optic Modulator



S. Obayya, “Computational Photonics” (Wiley, 2010)

- Key quantity $V_\pi L$, product of voltage and electrode separation necessary to create a π phase shift, is measured as a function of core height for a few designs

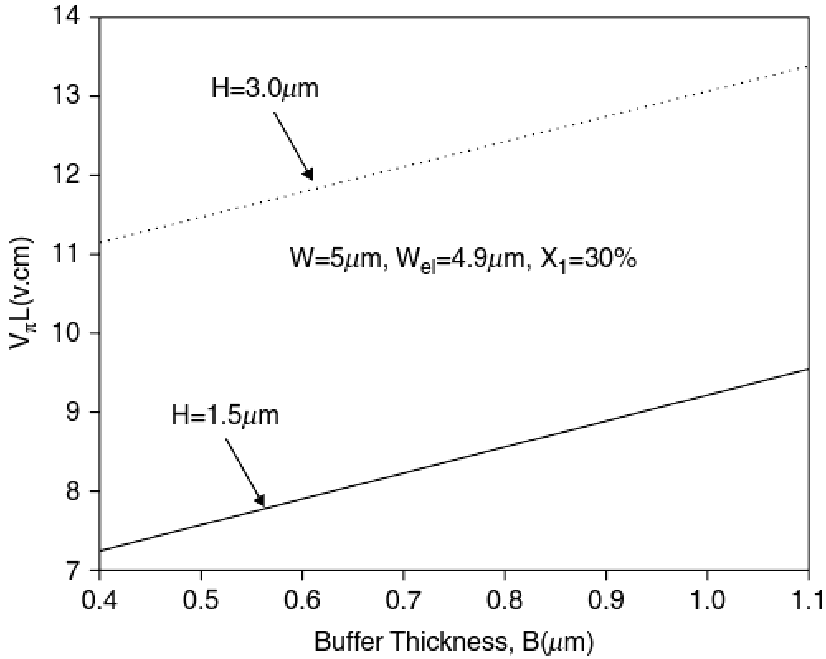
Electro-Optic Modulator

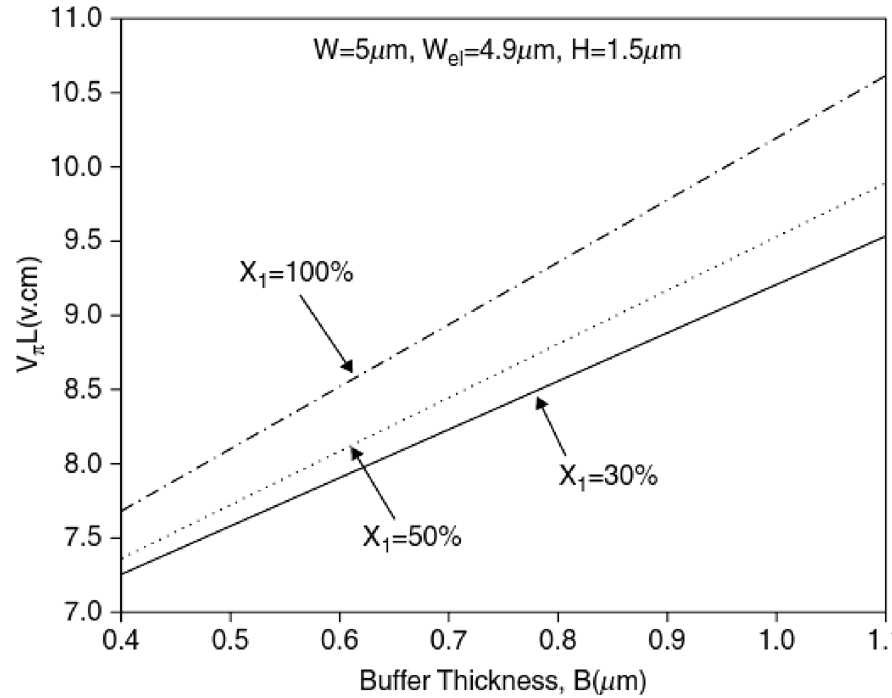


S. Obayya, "Computational Photonics" (Wiley, 2010)

- Here, $V_{\pi}L$ is measured as a function of core width for several designs – greater widths are more sensitive to voltage

Electro-Optic Modulator

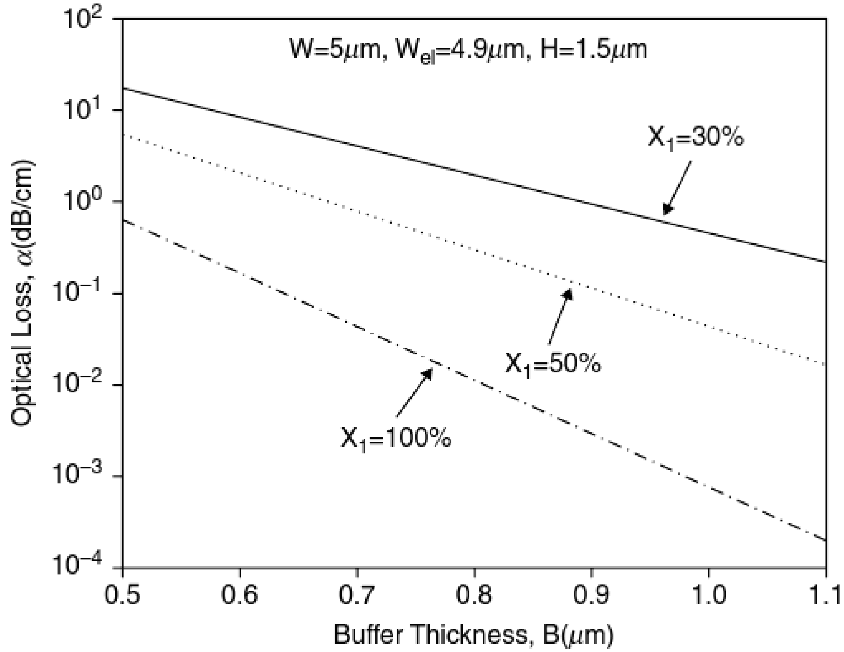




S. Obayya, "Computational Photonics" (Wiley, 2010)

- Here, $V_\pi L$ increases with buffer thickness, caused by diminishing field strength in the core region

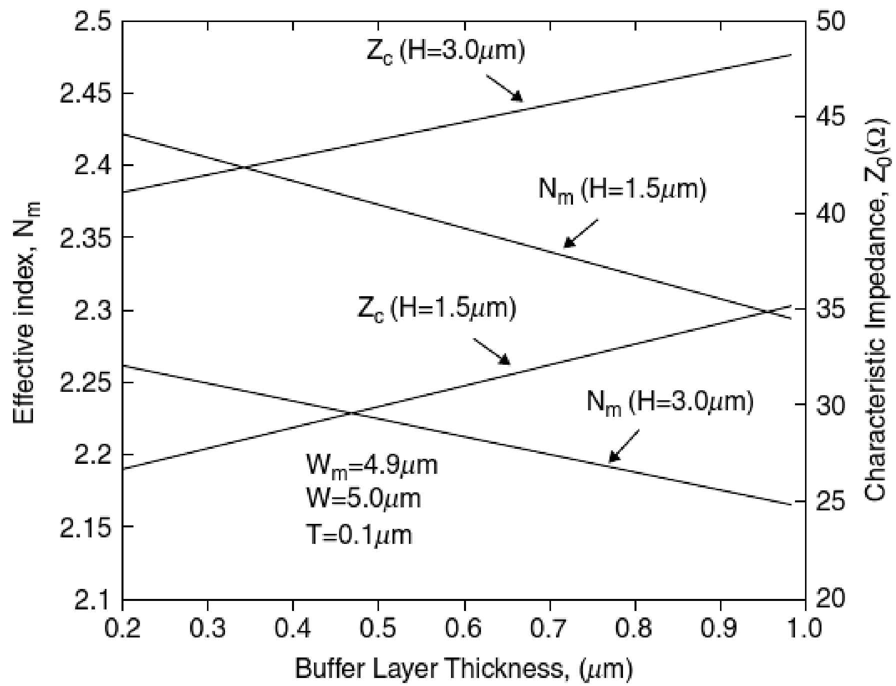
Electro-Optic Modulator



S. Obayya, “Computational Photonics” (Wiley, 2010)

- On the other hand, optical loss decreases with buffer thickness increases for similar reasons

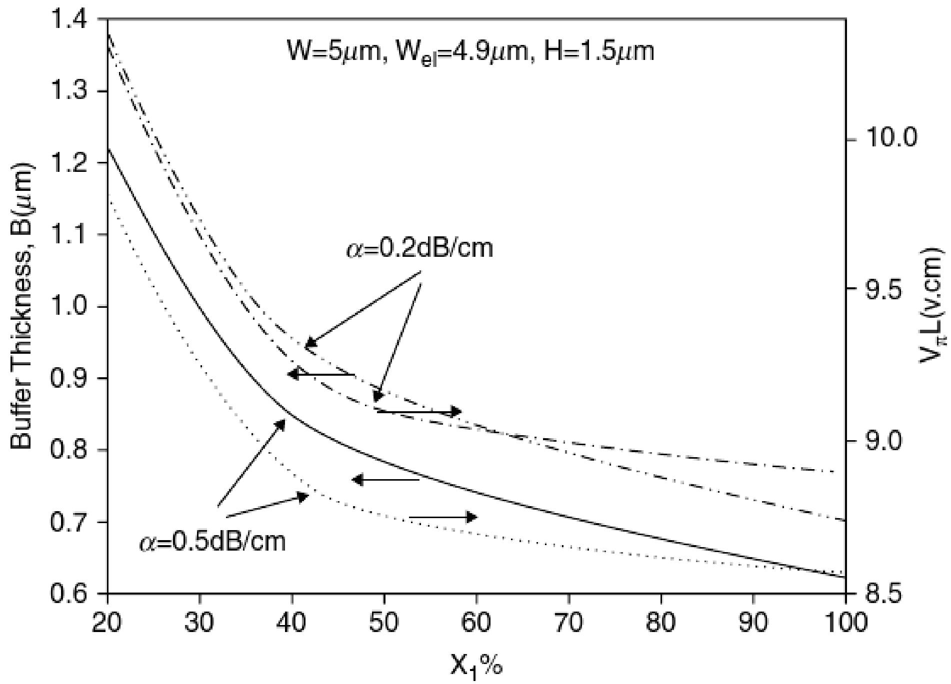
Electro-Optic Modulator



S. Obayya, "Computational Photonics" (Wiley, 2010)

- Effective impedance of microwaves and refractive index of IR signals cross over only at selected buffer thicknesses that vary greatly with core height

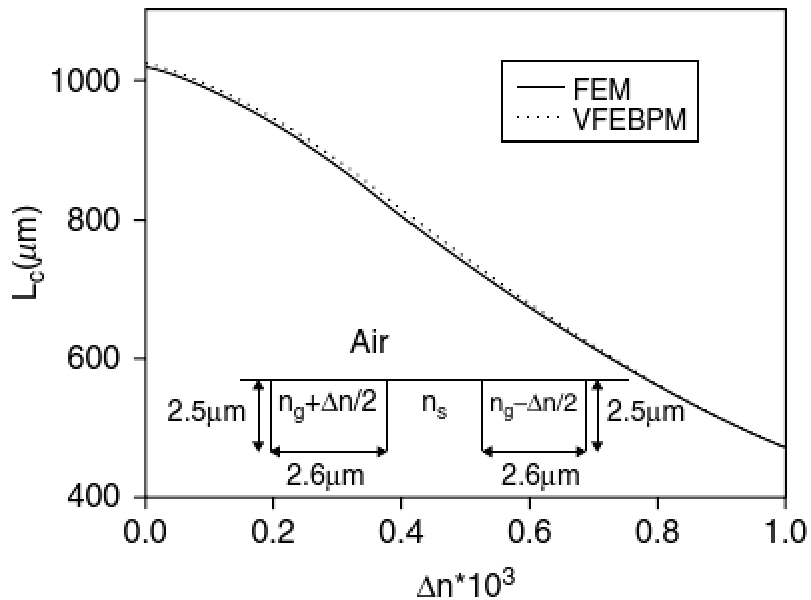
Electro-Optic Modulator



S. Obayya, "Computational Photonics" (Wiley, 2010)

- Here, the buffer thickness needed to achieve a given level of loss is calculated as a function of Al doping concentration X_f

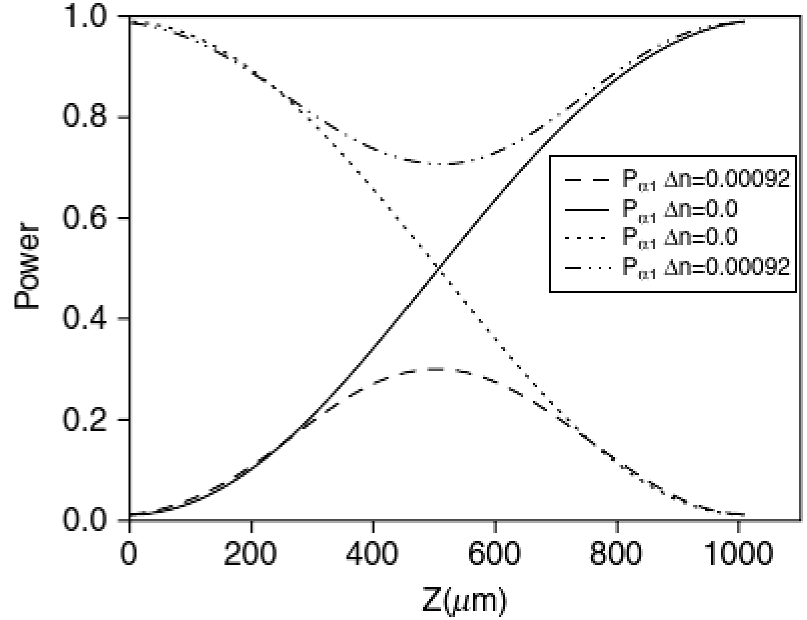
Electro-Optic Switch



S. Obayya, "Computational Photonics" (Wiley, 2010)

- Coupling length required for power transfer decreases as a function of EO index tuning

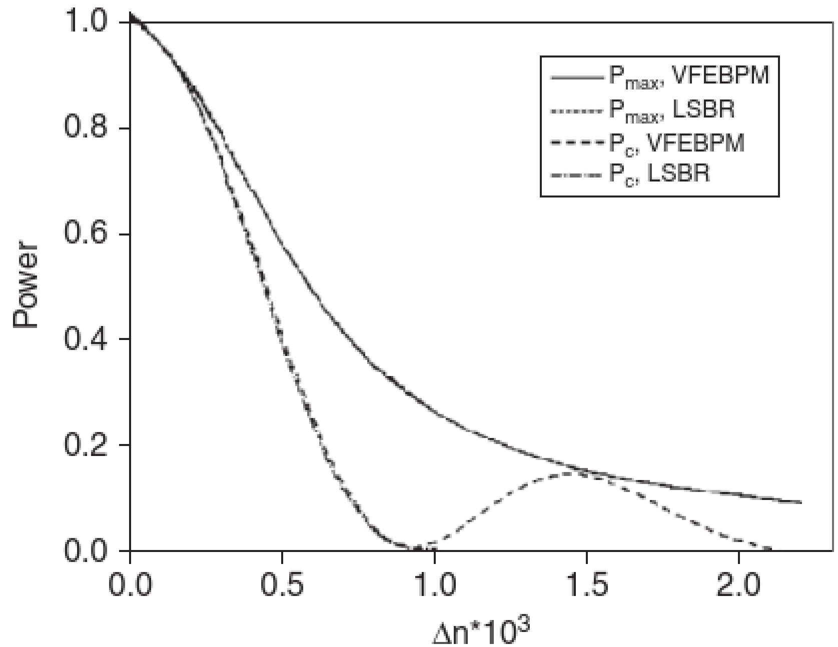
Electro-Optic Switch



S. Obayya, “Computational Photonics” (Wiley, 2010)

- Power transferred as a function of position for waveguides both with and without EO tuning

Electro-Optic Switch



S. Obayya, "Computational Photonics" (Wiley, 2010)

- Variation of output and maximum power transfer as a function of EO index tuning

Next Class

- We will cover other FEM applications in heat transfer and electronic transport