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Is naïve building-block integration in strained glass PLC optimal?

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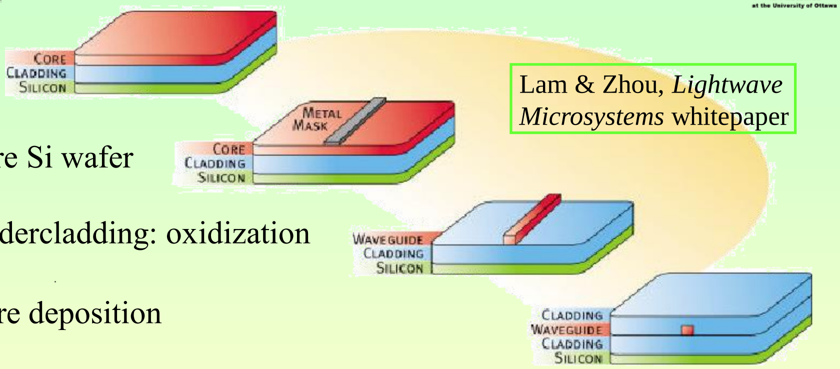
Outline

To address our question, we shall require…

… a wafer-level perspective of buried-core glass waveguiding

- building the system: fabrication, materials, a "first look"
- detailed treatment: math & meshing (FEM)
- metrics & symmetries
    - waveguiding: isotropic & anisotropic
- integration – one step up
    - answering the question
    - device impact
- closing thoughts

Wafer Fabrication Process



Lam & Zhou, *Lightwave Microsystems* whitepaper

Bare Si wafer

Undercladding: oxidization

Core deposition

Pattern the core layer - lithography

Etch away extraneous material

Uppercladding deposition

Material Parameters

Material	Thickness (µm) t	Young's modulus (GPa) E	Poisson's ratio υ	Thermal expansion coefficient (10^{-6}/K) α
BPSG	23	65	0.17	3.43
SiO$_2$	13	72.5	0.17	0.55
Si	650	130	0.28	3.9
SiO$_2$	15	72.5	0.17	0.55

Dominant effects: differential thermo-mechanical properties…

- break local symmetries
- couple across multiple length scales

Some light stretching exercises to warm up…

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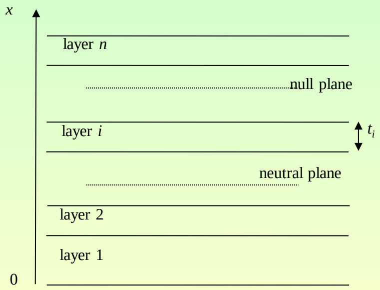
Structural Mechanics – *no waveguide*

Planar multilayers



$$\sigma_i(x) = E_i'\varepsilon_i(x), \quad E_i' = \left(\frac{E_i}{1-\nu_i}\right)$$

Biaxial stress

Biaxial modulus

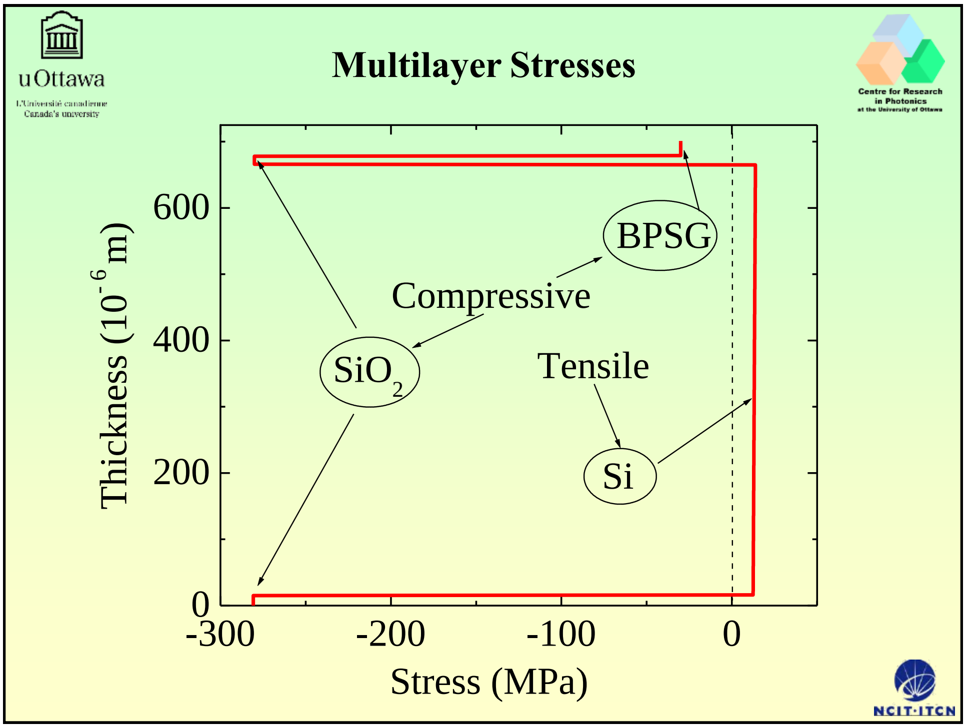
$$\varepsilon_{i,0} = -\int_{T_{ref}}^{T} \alpha_i(T)\,dT$$

Layer macro-strain (flat)

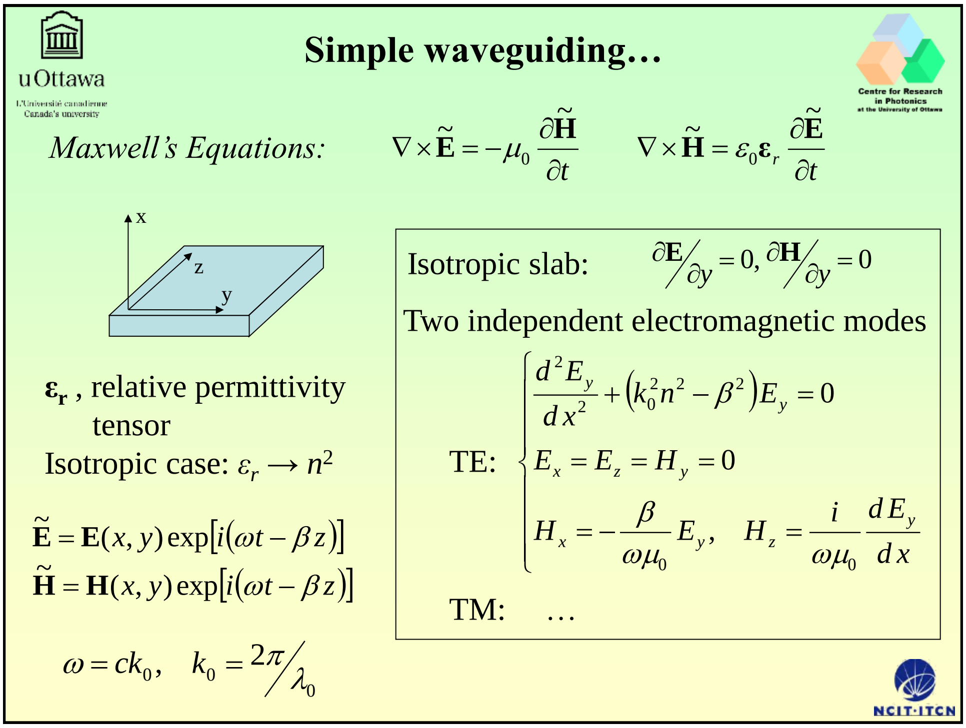
Weighted average strain

Wafer curvature

$$\sigma_i(x) = E_i'[(\varepsilon_{i,0} - \bar{\varepsilon}_0) + (x_N - x)K]$$



Multilayer Stresses



Simple waveguiding…

Maxwell's Equations: $\nabla\times\tilde{\mathbf{E}} = -\mu_0\dfrac{\partial\tilde{\mathbf{H}}}{\partial t}$ $\quad\nabla\times\tilde{\mathbf{H}} = \varepsilon_0\boldsymbol{\varepsilon}_r\dfrac{\partial\tilde{\mathbf{E}}}{\partial t}$

$\boldsymbol{\varepsilon}_\mathbf{r}$, relative permittivity tensor

Isotropic case: $\varepsilon_r \longrightarrow n^2$

$$\tilde{\mathbf{E}} = \mathbf{E}(x,y)\exp[i(\omega t-\beta z)]$$
$$\tilde{\mathbf{H}} = \mathbf{H}(x,y)\exp[i(\omega t-\beta z)]$$

$$\omega = ck_0,\quad k_0 = {2\pi}/{\lambda_0}$$

Isotropic slab: $\partial\mathbf{E}/\partial y = 0,\ \partial\mathbf{H}/\partial y = 0$

Two independent electromagnetic modes

$$\text{TE:}\quad\begin{cases}\dfrac{d^2E_y}{dx^2}+\left(k_0^2n^2-\beta^2\right)E_y = 0\\ E_x = E_z = H_y = 0\\ H_x = -\dfrac{\beta}{\omega\mu_0}E_y,\quad H_z = \dfrac{i}{\omega\mu_0}\dfrac{dE_y}{dx}\end{cases}$$

TM: …

…now the more serious **math**

"Oh, dear! Another tragic case of math anxiety!"

Structural Mechanics – *with waveguide*

Total strain:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_{el} + \boldsymbol{\varepsilon}_{th} + \boldsymbol{\varepsilon}_{in}$$

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{pmatrix} = \mathbf{a}\nabla\mathbf{u} - \boldsymbol{\gamma}$$

$$\mathbf{u} = (u_x, u_y, u_z)$$

Stress-strain relation:

$$\boldsymbol{\sigma} = \mathbf{D}\boldsymbol{\varepsilon}_{el}$$

$$\boldsymbol{\gamma} = \frac{E\alpha\Delta T}{1-2\nu}\mathbf{1}$$

$$\Delta T = T - T_{ref}$$

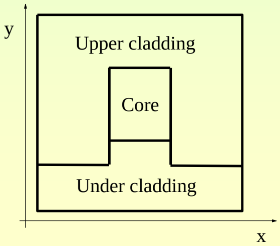
$$T_{ref} \sim 980^\circ C$$

Solve:

$$\rho\frac{\partial^2\mathbf{u}}{\partial t^2} - \nabla\cdot\boldsymbol{\sigma} = \boldsymbol{\kappa}$$

…under generalized plane strain

$$\varepsilon_z = e_0 + e_1 x + e_2 y$$

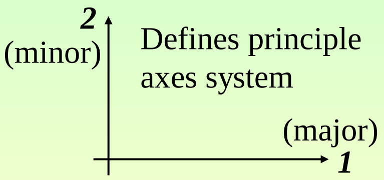


…not-so-simple waveguiding

Full-Vector Maxwell's Equation's $\nabla \times \left(\boldsymbol{\varepsilon}_r^{-1} \nabla \times \mathbf{H} \right) - k_0^2 \boldsymbol{\mu}_r \mathbf{H} = 0$

$\mathbf{H}(x, y, z) = \mathbf{H}_t(x, y) \exp(-i\beta z)$ *Perpendicular Hybrid Modes*

$\mathbf{H}_t = H_{major}\, \hat{\mathbf{a}}_1 + H_{minor}\, \hat{\mathbf{a}}_2$



Defines principle axes system

Relative permittivity tensor:

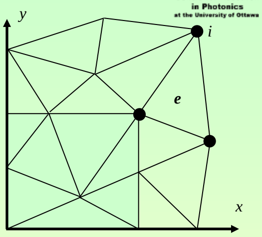
$$\boldsymbol{\varepsilon}_r = \begin{pmatrix} \left[n - C_1\sigma_x - C_2\left(\sigma_y + \sigma_z\right)\right]^2 & 2n\left(C_2 - C_1\right)\tau_{xy} & 0 \\ 2n\left(C_2 - C_1\right)\tau_{xy} & \left[n - C_1\sigma_y - C_2\left(\sigma_z + \sigma_x\right)\right]^2 & 0 \\ 0 & 0 & \left[n - C_1\sigma_z - C_2\left(\sigma_x + \sigma_y\right)\right]^2 \end{pmatrix}$$

Photoelastic constants of silica glass (N/m^2):

$$C_1 = 0.65 \text{ x } 10^{-12}, \quad C_2 = 4.2 \text{ x } 10^{-12}$$

The Finite element method – *"sort-of"*

Functional (scalar wave equation):



$$I[\phi] = \frac{1}{2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left[\left(\frac{\partial \phi}{\partial x} \right)^2 + \left(\frac{\partial \phi}{\partial y} \right)^2 - \left(k^2 n^2 - \beta^2 \right) \phi^2 \right] dxdy$$

$$\left\{ \phi_{pert}(x, y) = \phi(x, y) + \delta\eta(x, y), \quad \lim_{\delta \to 0} \left(\frac{\partial}{\partial \delta} I[\phi_{pert}] \right) = 0 \right\}$$

Approx. field in each element as: $\boldsymbol{\phi(x, y)} = p_0^e + p_1^e x + p_2^e y$

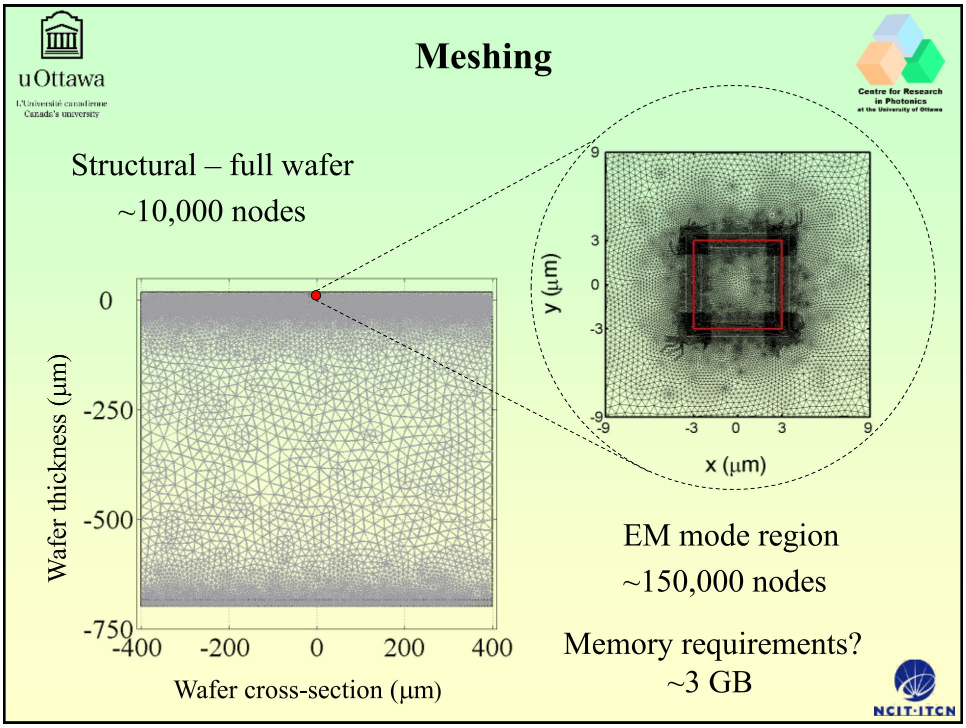
…calculate functional, , for each element, then: $I = \sum_{e=1}^{Z} I^e$

…obtain stationary condition: $\frac{\partial I}{\partial \phi_i} = \sum_{j=1}^{N} c_{ij}\, \phi_j = 0$

…in matrix form: $\mathbf{C}\{\phi\} = \{0\}$

Algebraic eigenvalue problem: $\mathbf{det(C)} = 0$

$$\longleftrightarrow (\mathbf{A} - \lambda \mathbf{I})\{\phi\} = 0$$

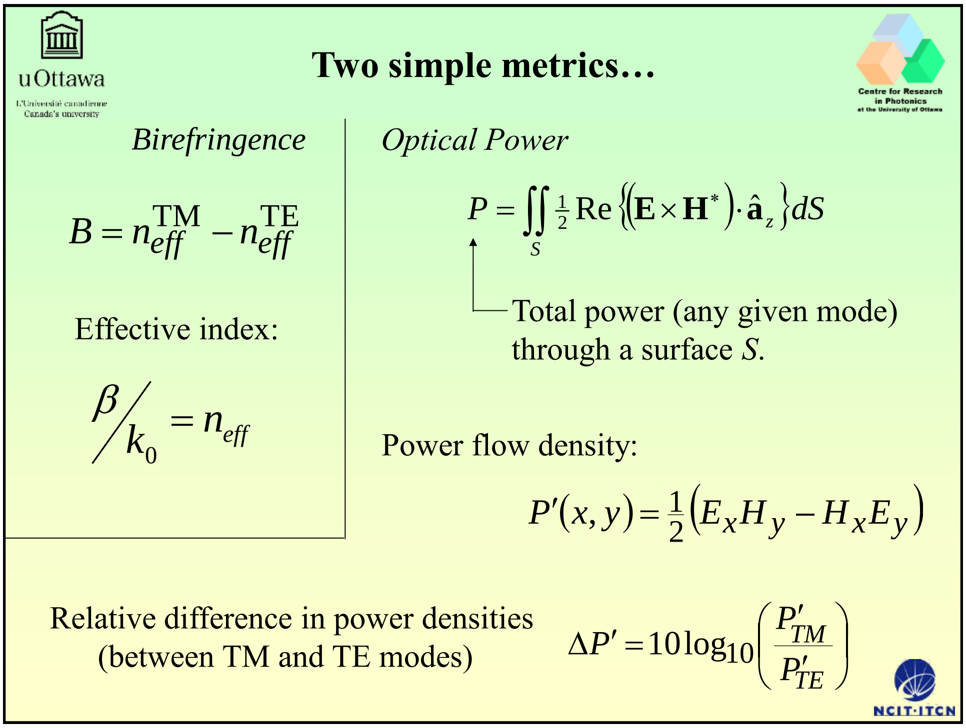


Meshing

Structural – full wafer
~10,000 nodes

EM mode region
~150,000 nodes

Memory requirements?
~3 GB



Two simple metrics…

Birefringence

$$B = n_{eff}^{\mathrm{TM}} - n_{eff}^{\mathrm{TE}}$$

Effective index:

$$\beta / k_0 = n_{eff}$$

Optical Power

$$P = \iint_S \tfrac{1}{2} \operatorname{Re}\left\{ \left(\mathbf{E} \times \mathbf{H}^* \right) \cdot \hat{\mathbf{a}}_z \right\} dS$$

Total power (any given mode) through a surface *S*.

Power flow density:

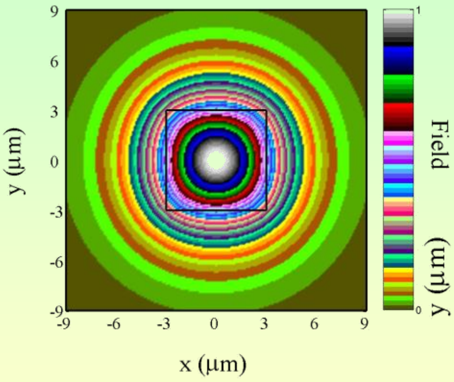
$$P'(x,y) = \tfrac{1}{2}\left(E_x H_y - H_x E_y \right)$$

Relative difference in power densities (between TM and TE modes)

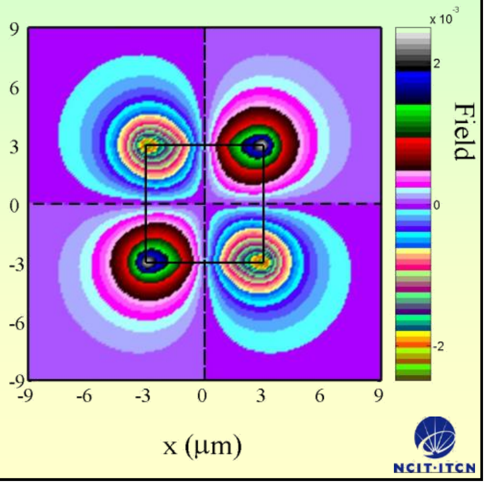
$$\Delta P' = 10 \log_{10}\left(\frac{P'_{TM}}{P'_{TE}} \right)$$

Simple symmetries – an isotropic waveguide

E-field: major component



E-field: minor component

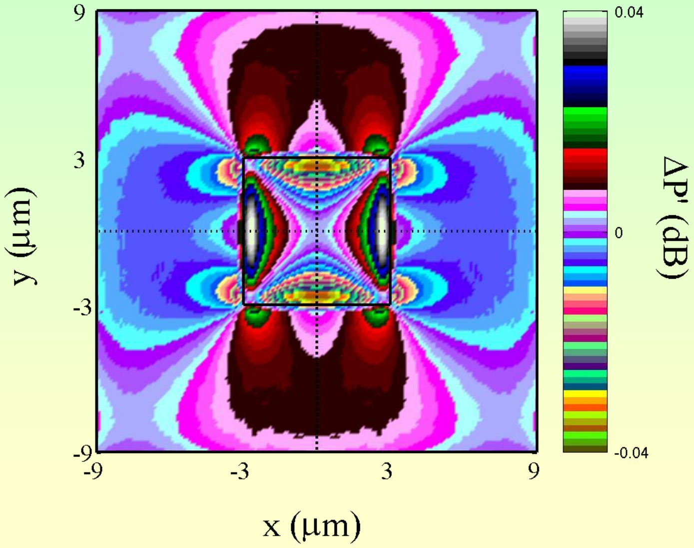


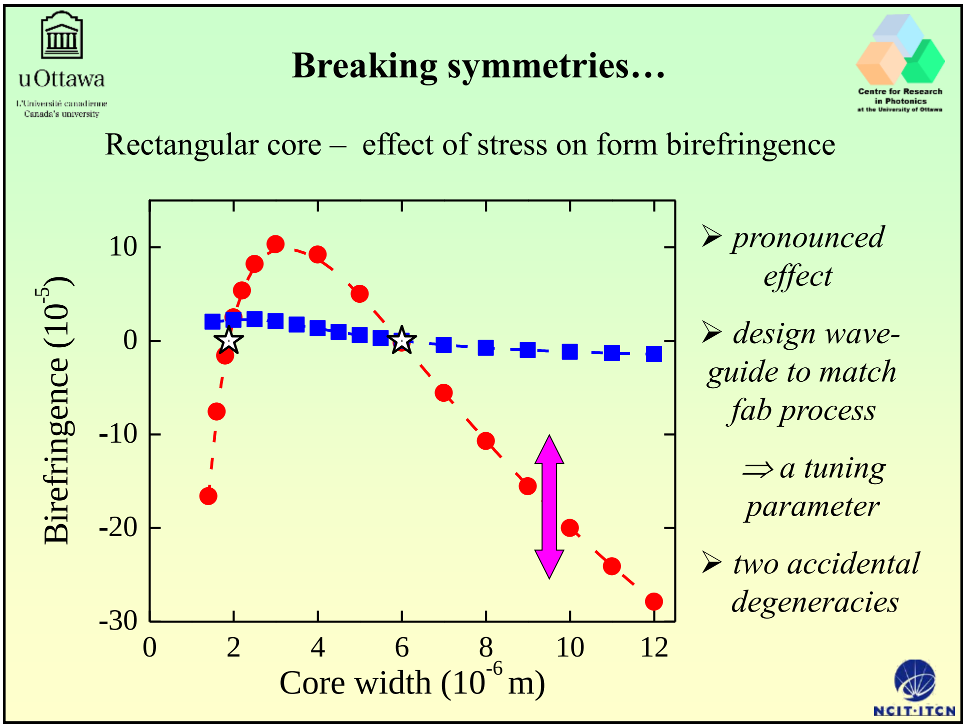
(6 x 6 core)

$n_{core} = 1.455$

$n_{clad} = 1.445$

…and its differential power density





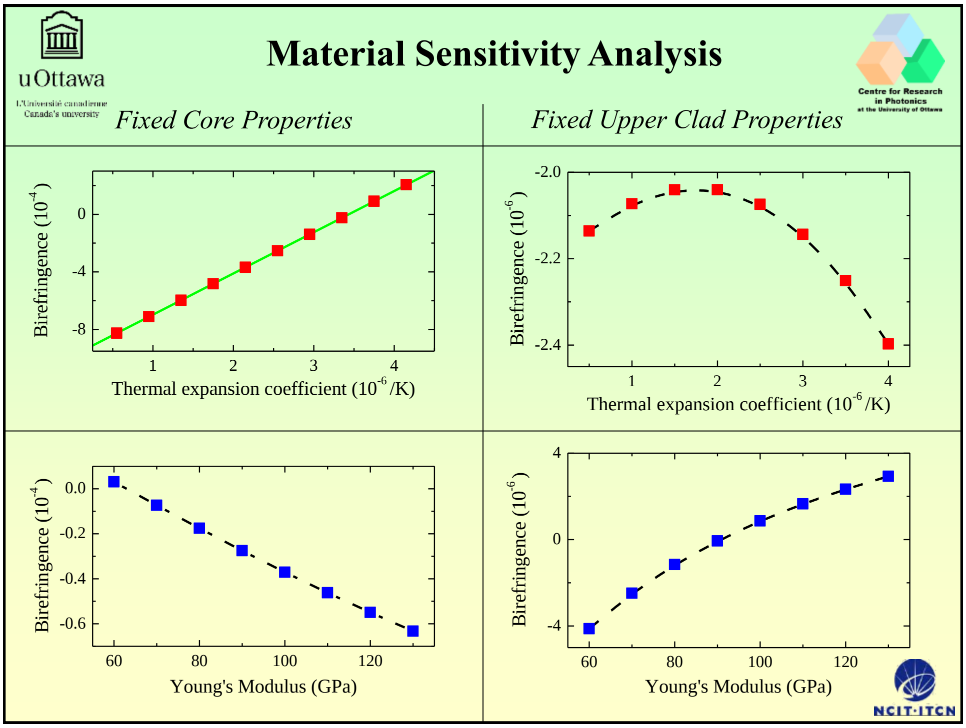
Breaking symmetries…

Rectangular core – effect of stress on form birefringence

- *pronounced effect*
- *design wave-guide to match fab process*

⇒ a tuning parameter

- *two accidental degeneracies*



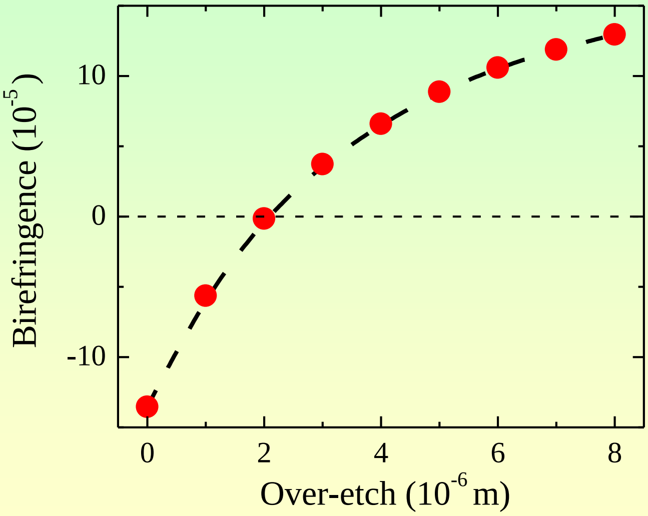
Material Sensitivity Analysis

Fixed Core Properties

Fixed Upper Clad Properties

Indirect symmetry-breaking

Isolated square-core waveguide



- *control the position of the neutral plane in fabrication…*

⇒ a "tuning" parameter

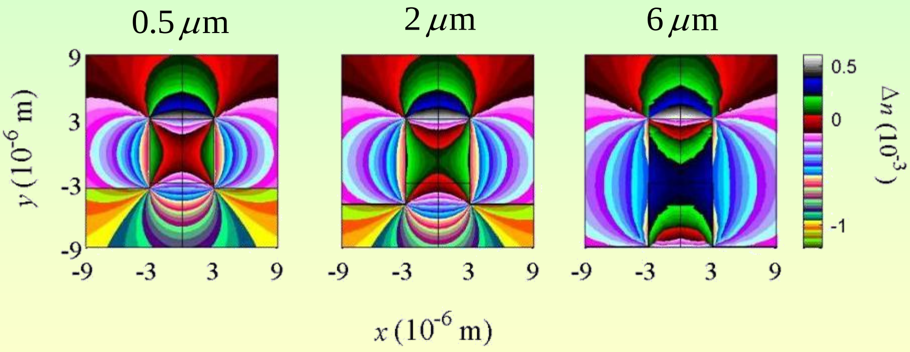
…exploit differential thermal expansion through layer thickness

Schriemer & Cada, IEEE J. Quantum Electron., vol. 40, 1131-1139 (Aug. 2004)

"Over-etch" tuning – physical origins

Material birefringence: $\Delta n = n_x - n_y = (C_2 - C_1)(\sigma_x - \sigma_y)$

Over-etch:


0.5 μm   2 μm   6 μm

What is the impact on the eigenvector?

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Minor field component

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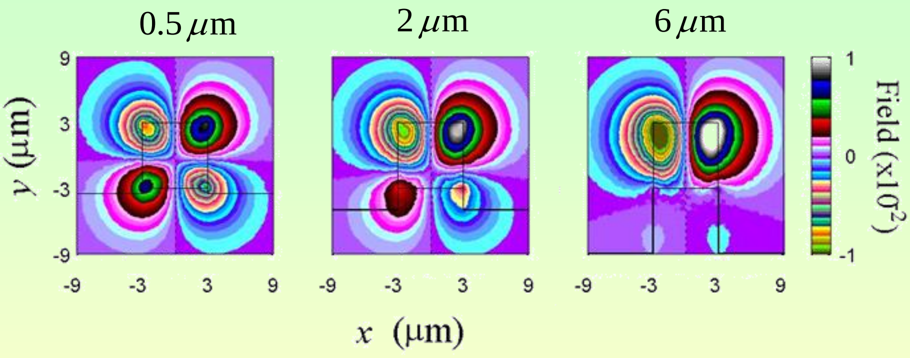

Symmetry-breaking of primarily geometrical origin…

…enhanced by field-pinning due to shear strains

(overwhelms nominal index discontinuities)

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Differential power densities

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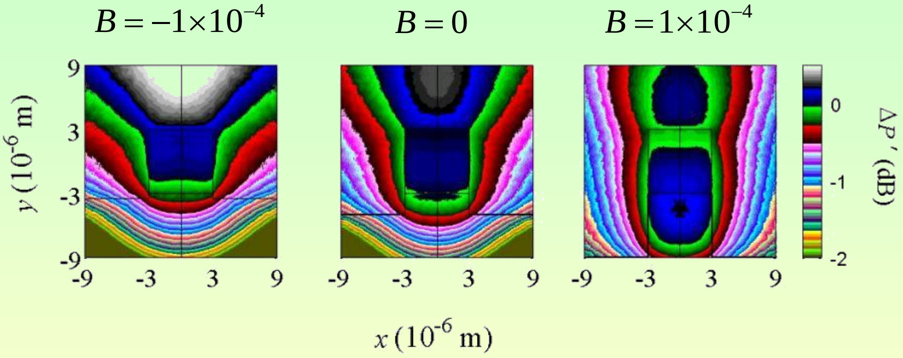

Fundamental reduction in symmetry…

- smoothly lifted with increasing stress
- control energy density with over-etch

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Component Integration…

What is it…from a *physics* perspective?

… a spatially-compact method of controlling interlinked power flow trajectories with minimal information loss

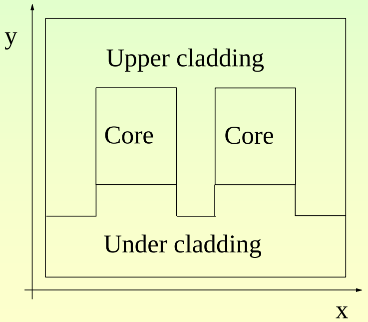
… symmetry-breaking across spatial & temporal length scales

The simplest example?

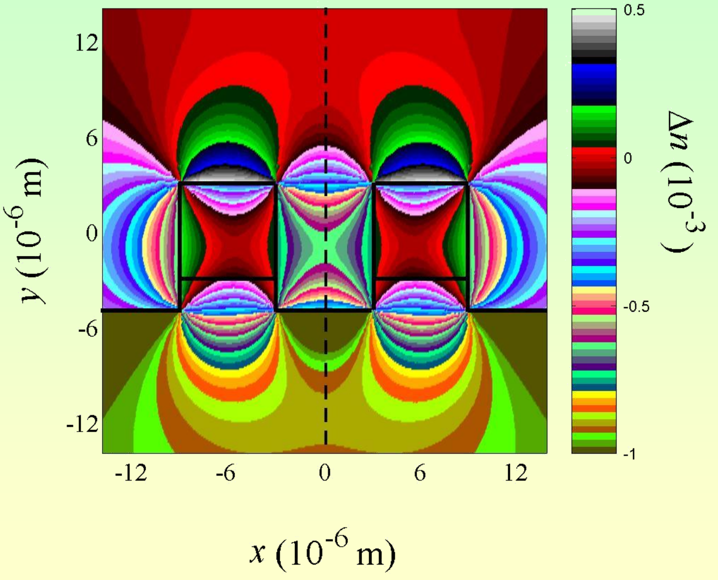
A *coupled* waveguide!

BUT: This discrete geometrical symmetry-breaking couples to a distributed material symmetry-breaking.

Is there a difference in optimal parameters?



Material birefringence



Optimize optical specifications

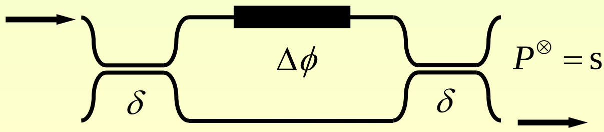
Consider supermodes of coupled waveguide…
…under “optimal” isolated waveguide process.

Critical coupling length: $L_c = \dfrac{\lambda_0}{2\Delta n}, \quad \Delta n = n_{even} - n_{odd}$
(…for TE & TM)

Building-block representation? An idealized directional coupler.

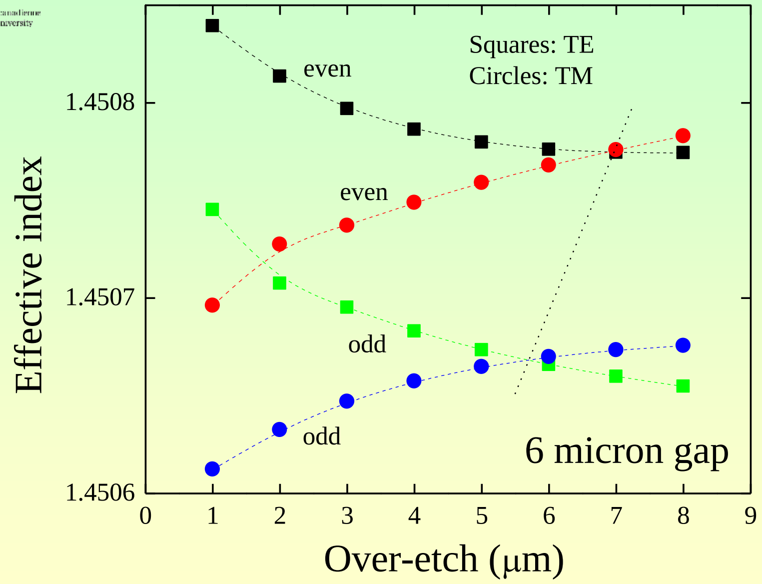
Is its operation “optimal” under the “isolated square waveguide” fab process?

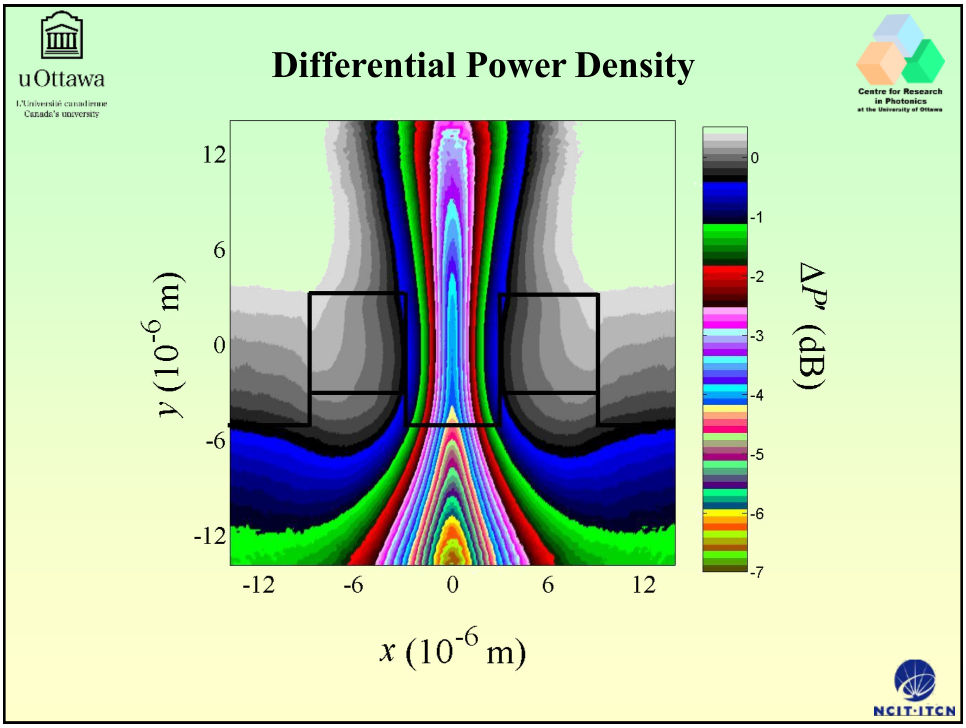
What is the device impact? Consider the VOA.



$$P^{\otimes} = \sin^2(2\delta)\cos^2\left(\tfrac{1}{2}\Delta\phi\right)$$

Supermode indices





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Differential Power Density

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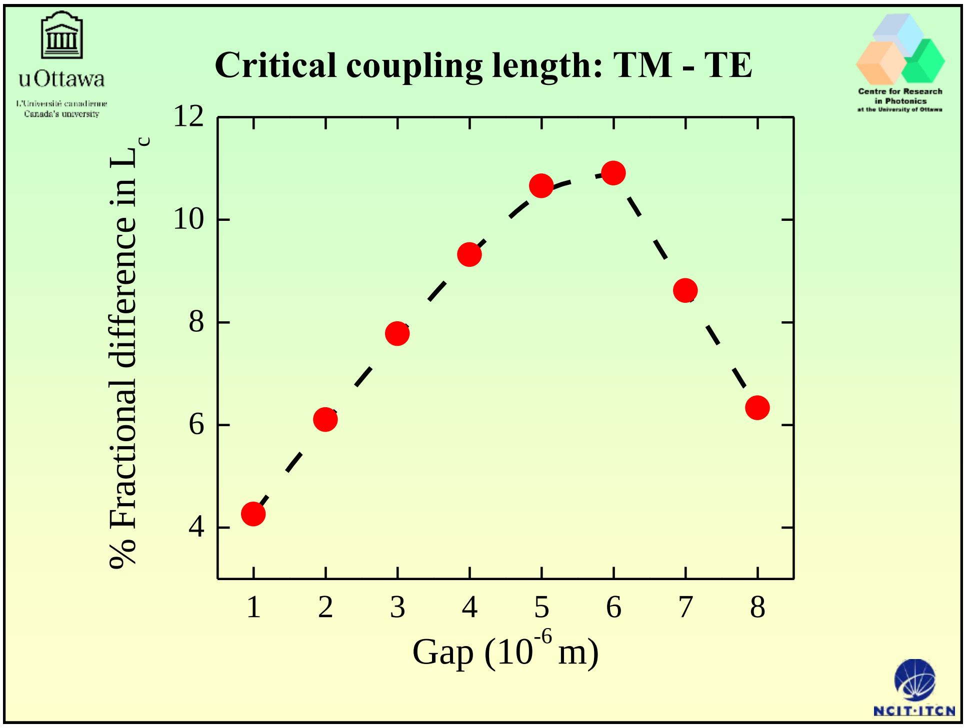

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Critical coupling length: TM - TE

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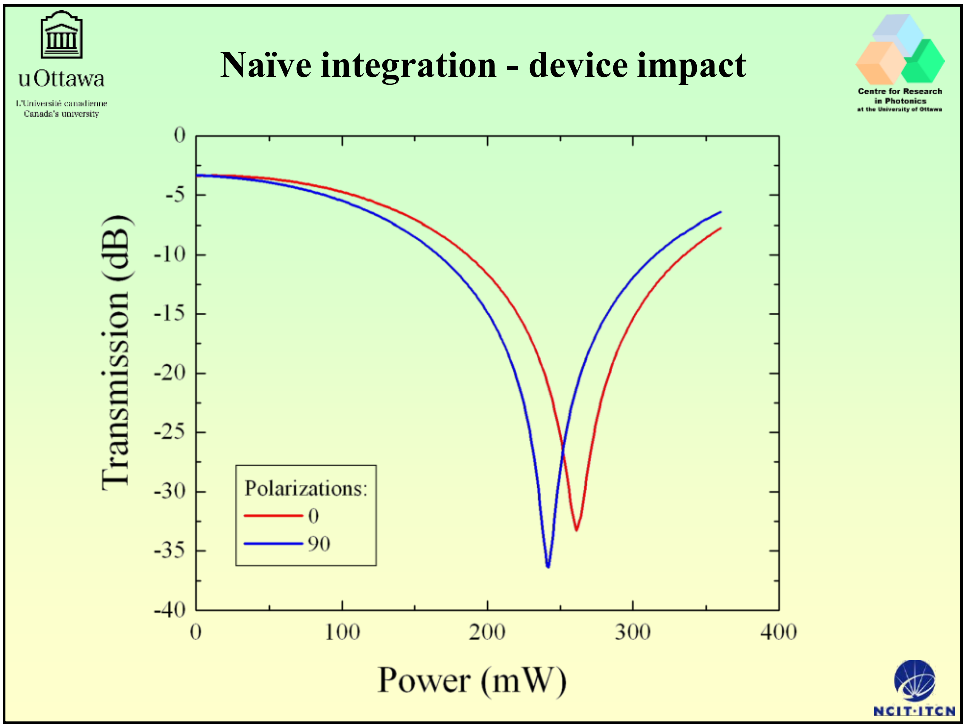

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Naïve integration - device impact

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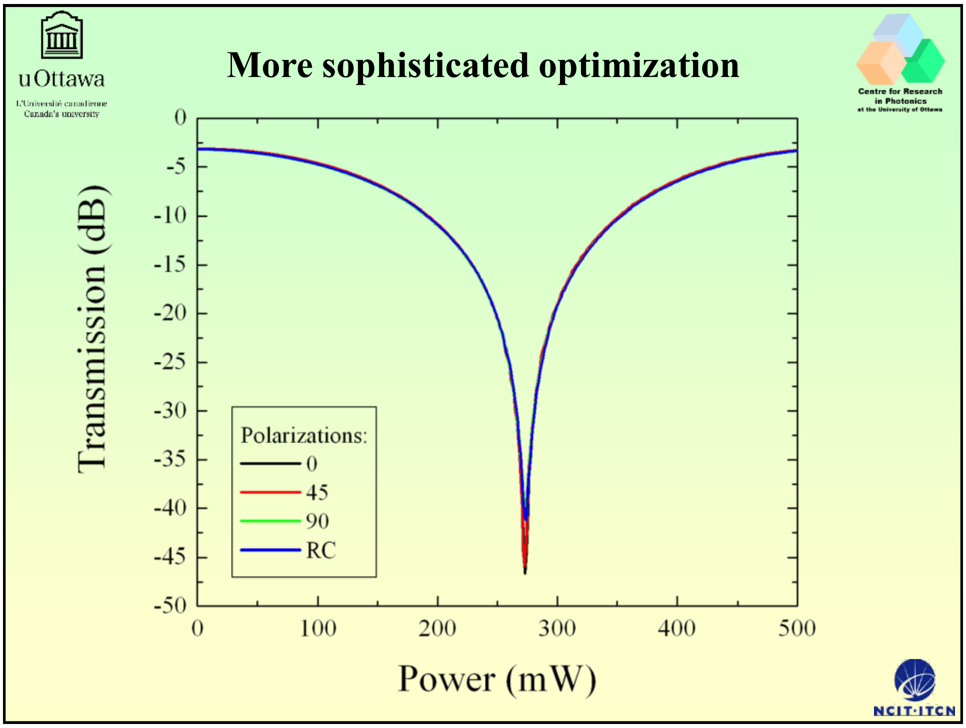

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More sophisticated optimization

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Closing thoughts

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- ➢ Naïve building block integration is NOT optimal

  …but integration may yet be achieved!
- ➢ Optimize within a “rich parameter space”
  - fab is digital
  - design is analogue
- ➢ Future prospects?
  - low-delta passive monolithic integration cannot meet current market cost points
  - high(er)-delta hybrid integration is the solution

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