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PENNSTATE

Electro-Optics Center

A Manufacturing Technology Center of Excellence

Implementation of a Paraxial Optical Propagation Method for Large Photonic Devices

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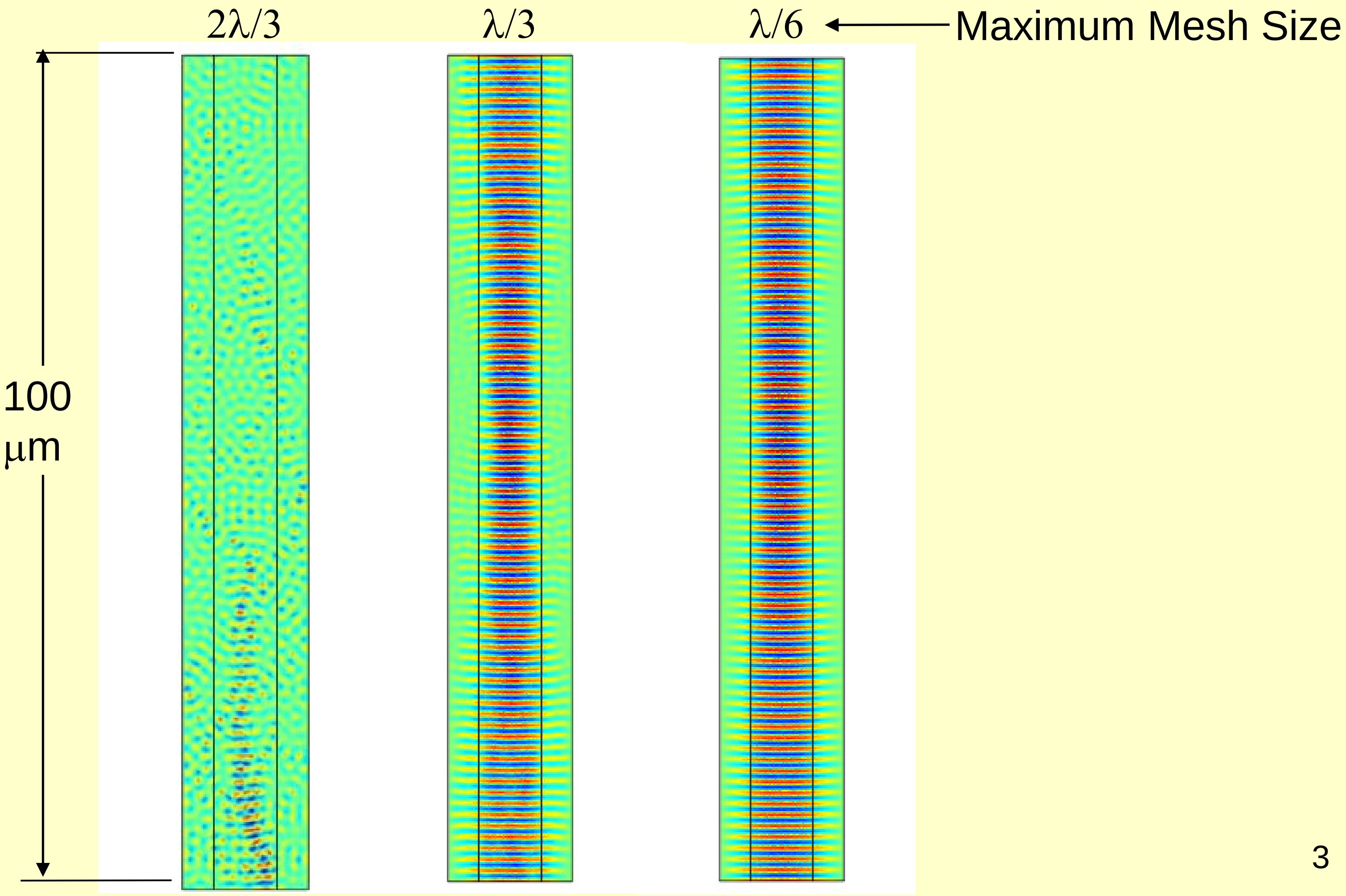
Outline

- Computational Limitations of EM Propagation Modes
- Review of Beam Propagation Methods
- Implementation of BPM-Like Mode in Comsol
- Representative Results

EM Modes Require Mesh Size <<λ



Beam Propagation Method

- Assume steady-state (time harmonic) oscillation

$$U(\mathbf{r},t)=U(\mathbf{r})\, e^{-i\omega t} \rightarrow \nabla^2 U+k^2 U = 0 \quad (k=2\pi n/\lambda)$$

- Assume propagation is primarily along the z-axis

$$U(\mathbf{r})= u(\mathbf{r})\, e^{ik0z} \rightarrow \nabla^2 u+2ik_0\, \partial u/\partial z+(k^2-k_0^2)\, u= 0$$

- Assume that the field varies slowly along the z-axis ($\partial^2 u/\partial z^2 \sim 0$)

$$\partial u/\partial z= i/2k\, [\nabla_{xy}^2 u+(k^2-k_0^2)\, u]$$
$$= in_0/(2k_0 n)\, \{\nabla_{xy}^2 u+k_0^2[(n/n_0)^2-1]\, u\}$$

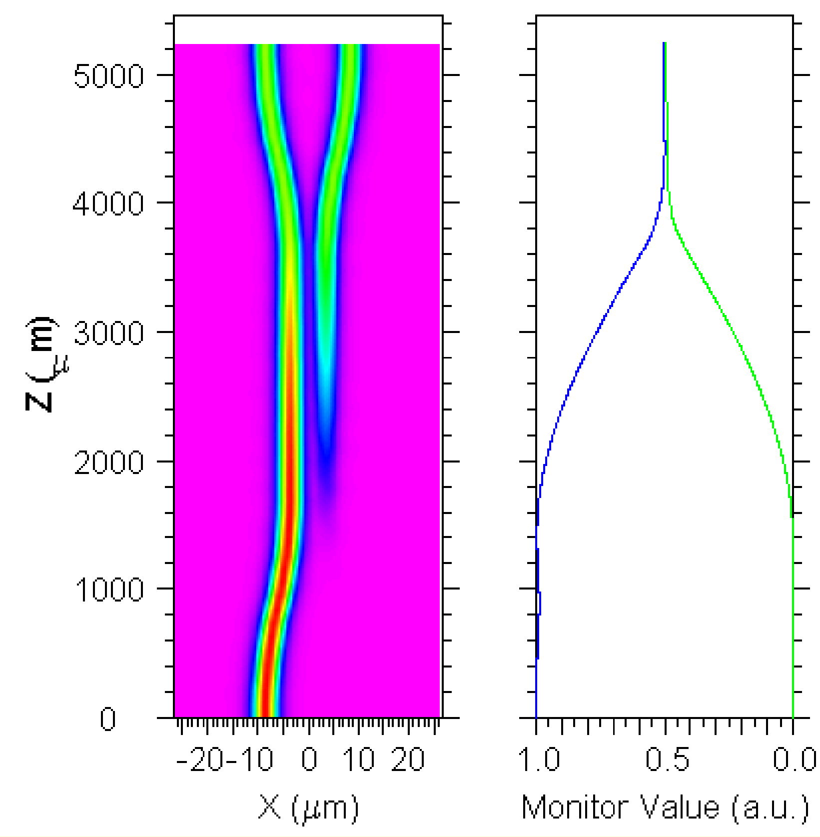
- Choose a form for the input field
- Field can then be "propagated" in the z-direction

Applications of BPM

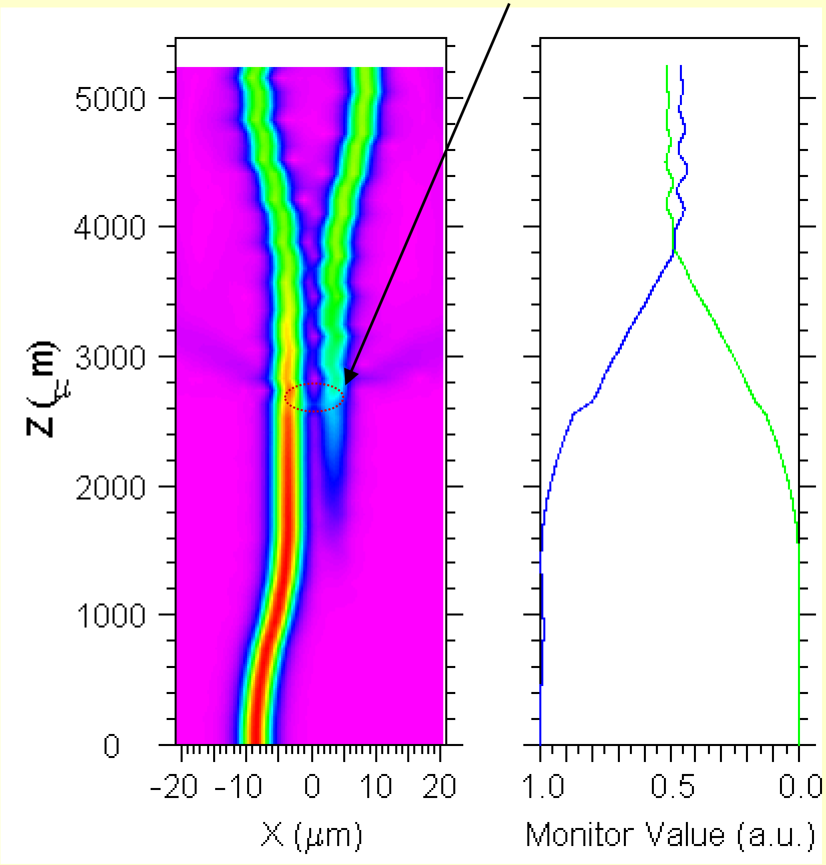
- Good for relatively large, waveguide-based devices
  - Couplers, splitters, interferometers, array waveguide gratings
- Not as good for high-index contrast systems
- Cannot handle systems with arbitrary propagation directions:
  - Photonic crystals (photonic band gaps)
  - Ring resonators
  - Tight bends
- Cannot do frequency mixing/nonlinear effects

BPM Example : 3 dB Coupler

Equal splitting between arms



Perturbation of refractive index

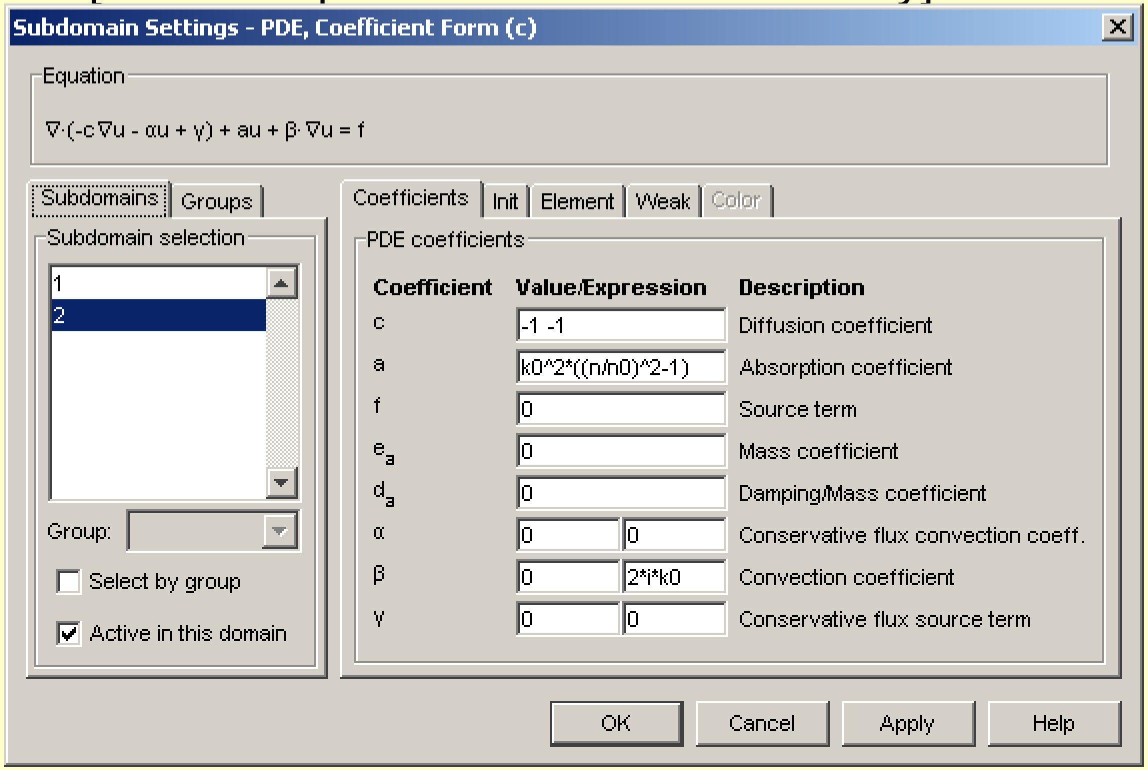


PDE Implementation of BPM-Like Mode

Recall the basic paraxial wave equation:

$$\nabla^2 u + 2ik_0\,\partial u/\partial z + k_0^2[(n/n_0)^2-1]\,u = 0$$

[No assumption of $\partial^2 u/\partial z^2 \sim 0$ necessary]



Equation

$\nabla\cdot(-c\nabla u - \alpha u + \gamma) + au + \beta\cdot\nabla u = f$

Subdomain selection

1
2

Group:

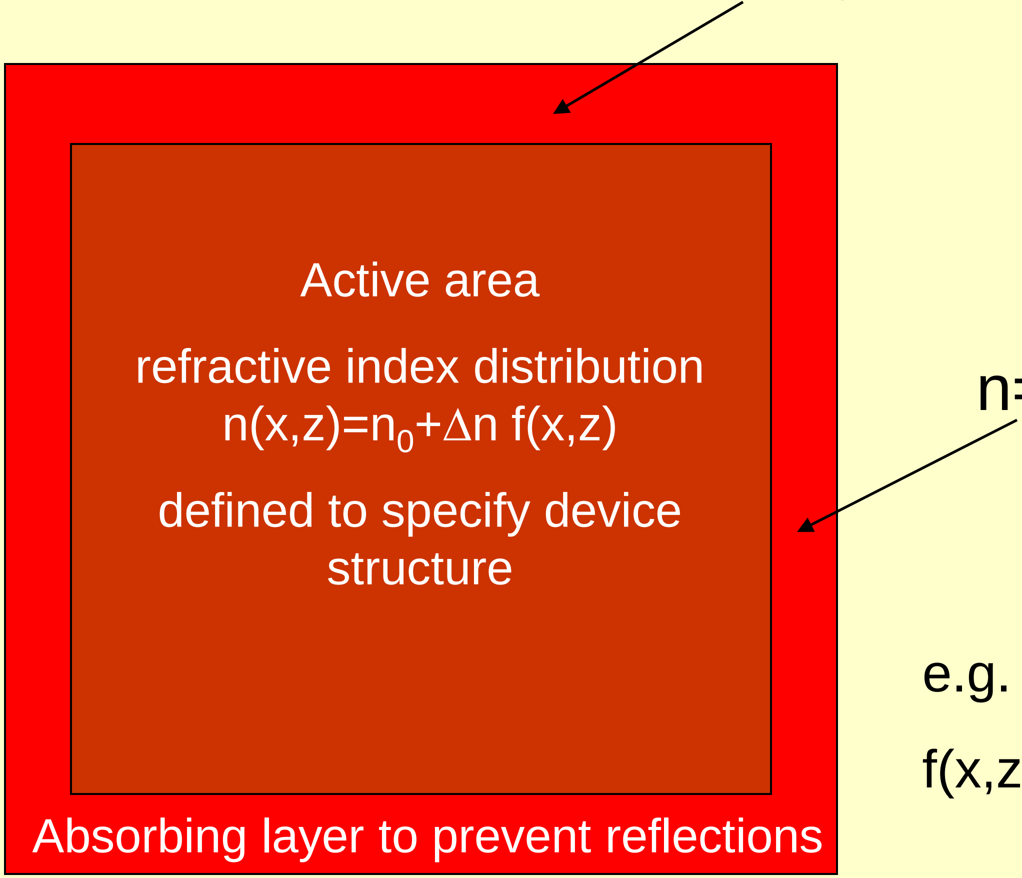
☐ Select by group

☑ Active in this domain

PDE coefficients

Coefficient	Value/Expression		Description
c	-1 -1		Diffusion coefficient
a	k0^2*((n/n0)^2-1)		Absorption coefficient
f	0		Source term
e_a	0		Mass coefficient
d_a	0		Damping/Mass coefficient
α	0	0	Conservative flux convection coeff.
β	0	2*i*k0	Convection coefficient
γ	0	0	Conservative flux source term

Geometry for 2D BPM-Like Mode



$n=n_0\ [1+ie^{(y-y0)/\Delta y}\ ]$

Active area

refractive index distribution
$n(x,z)=n_0+\Delta n\ f(x,z)$

defined to specify device structure

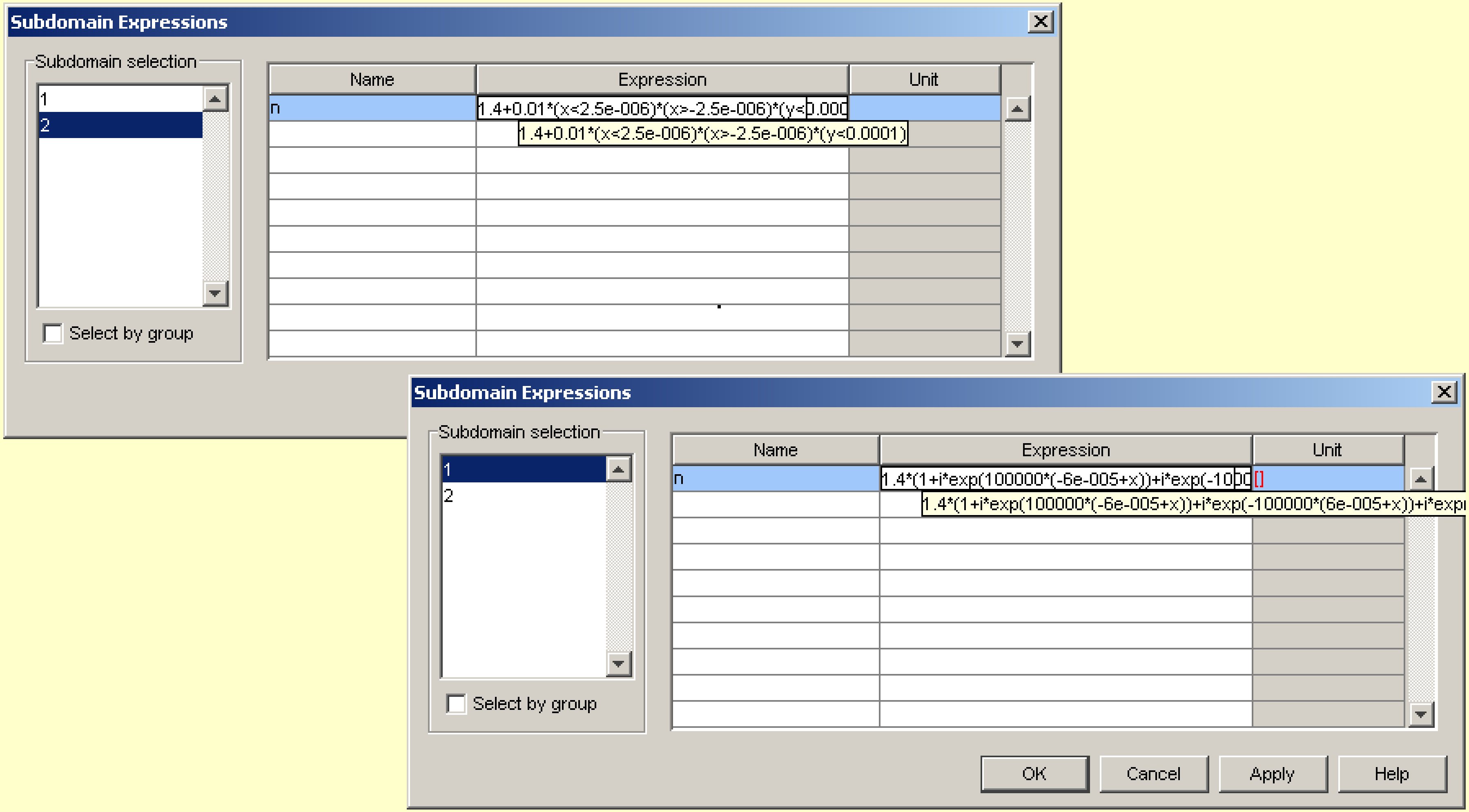
Absorbing layer to prevent reflections

$n=n_0\ [1+ie^{(x-x0)/\Delta x}\ ]$

e.g. step-index WG of width w:

f(x,z)=(x>-w/2)*(x<w/2)

Specification of Refractive Index Distribution



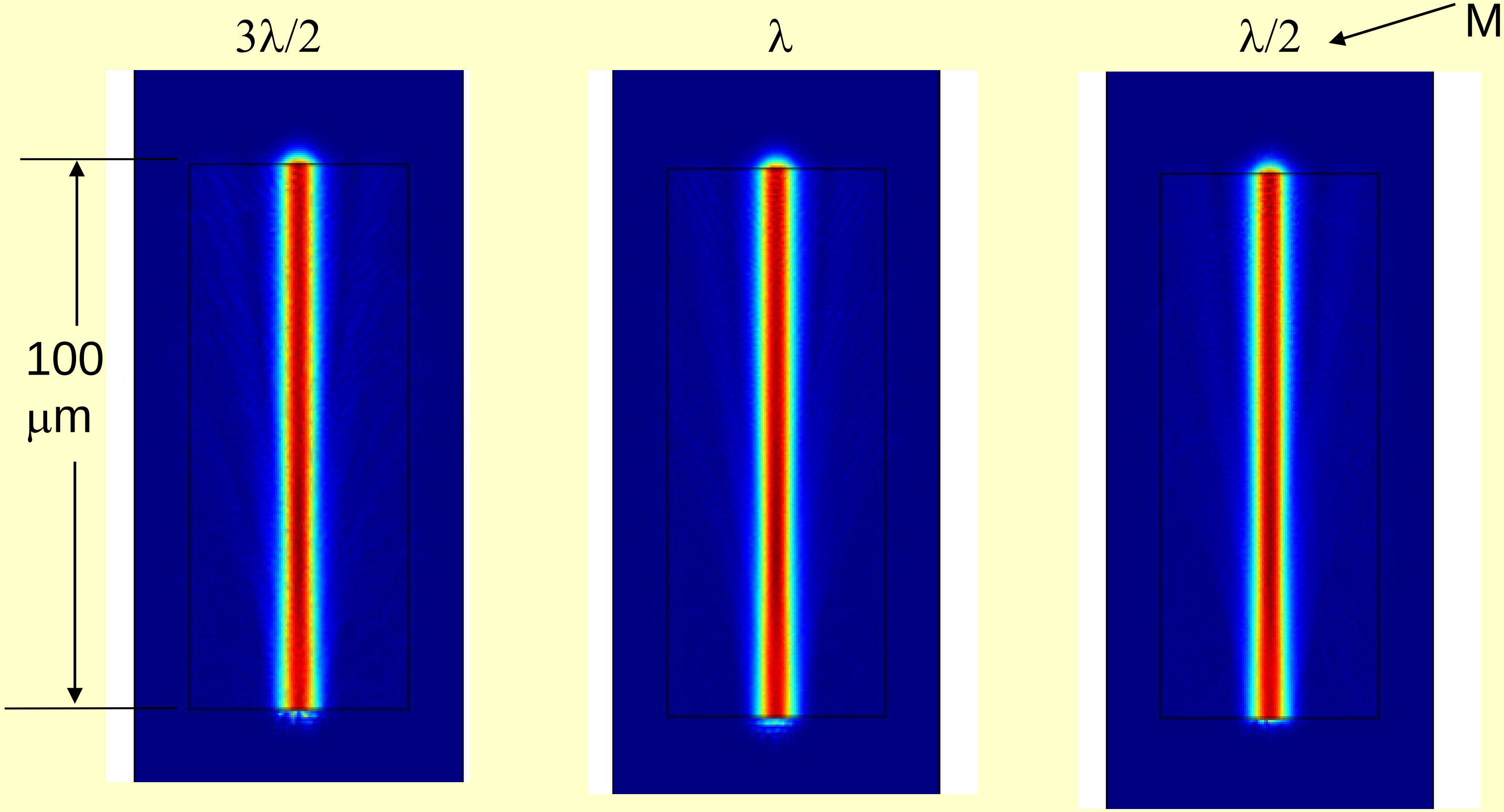
Name	Expression	Unit
n	1.4+0.01*(x<2.5e-006)*(x>-2.5e-006)*(y<0.000	

1.4+0.01*(x<2.5e-006)*(x>-2.5e-006)*(y<0.0001)

Name	Expression	Unit
n	1.4*(1+i*exp(100000*(-6e-005+x))+i*exp(-1000	[]

1.4*(1+i*exp(100000*(-6e-005+x))+i*exp(-100000*(6e-005+x))+i*expi

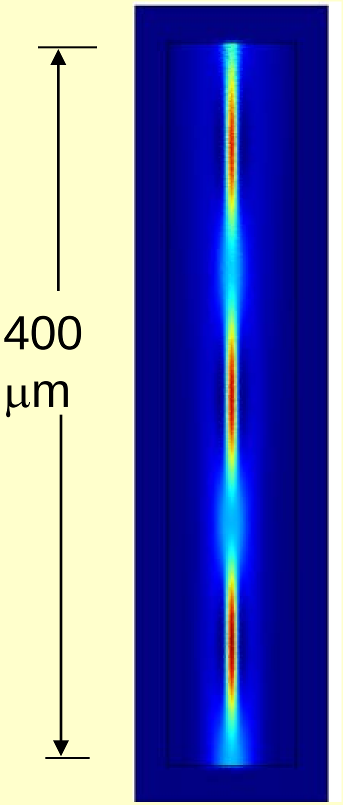
BPM-Like Mode Allows a Much Coarser Mesh



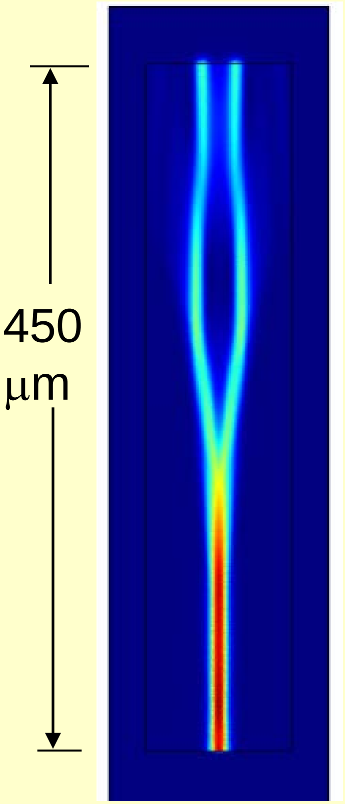
Maximum Mesh Size

Examples of 2D Models

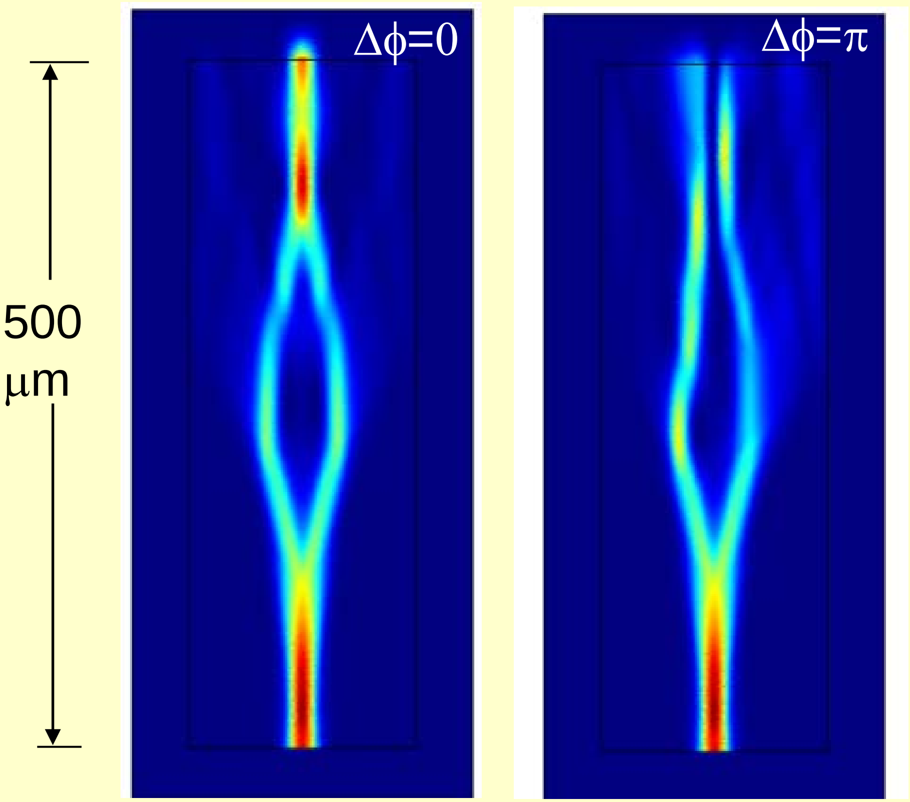
Graded-Index Waveguide



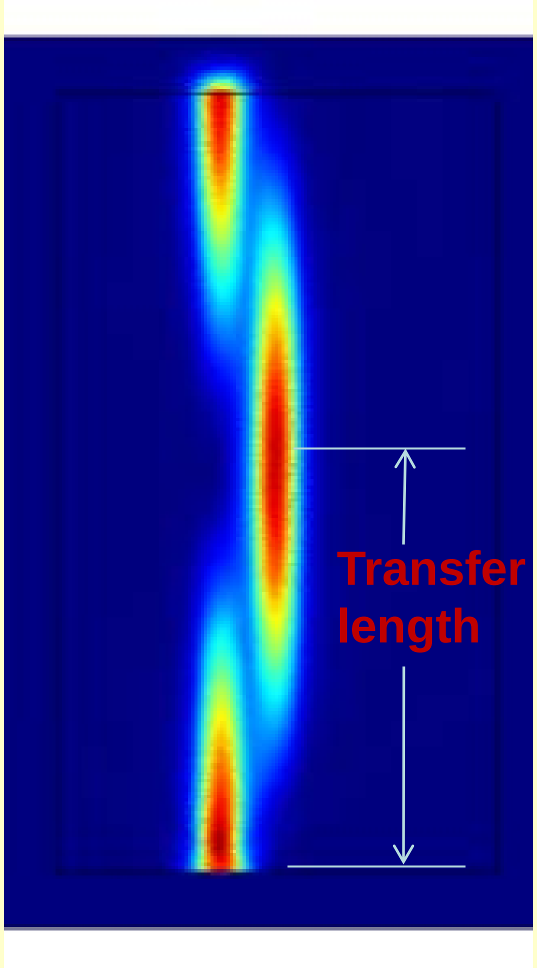
Y-splitter

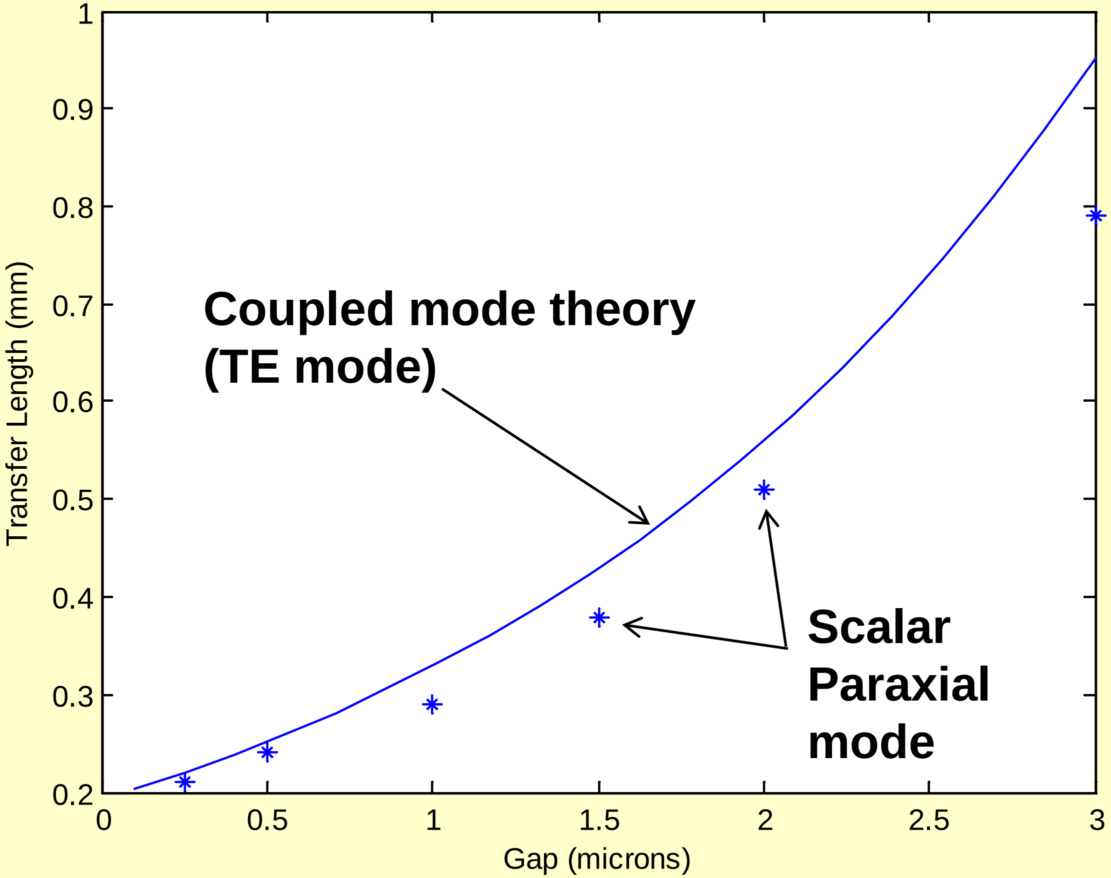


Mach-Zehnder Interferometer



Directional Coupler

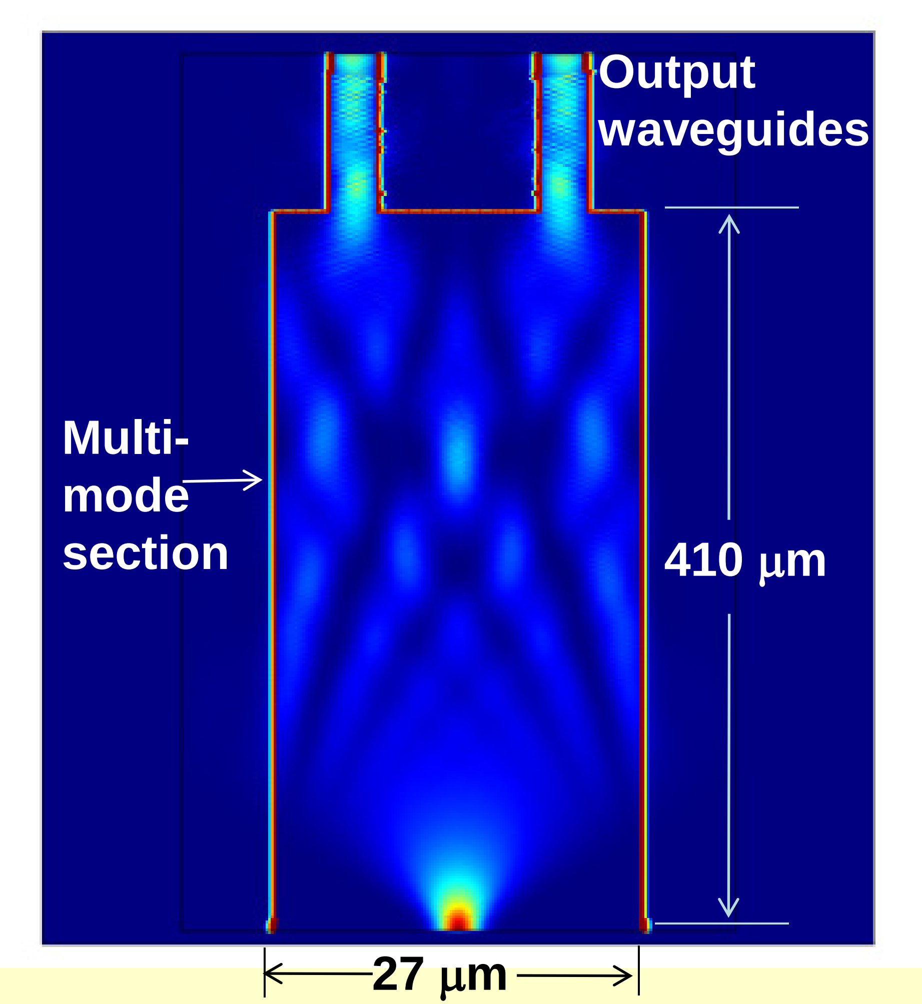




Coupled mode theory (TE mode)

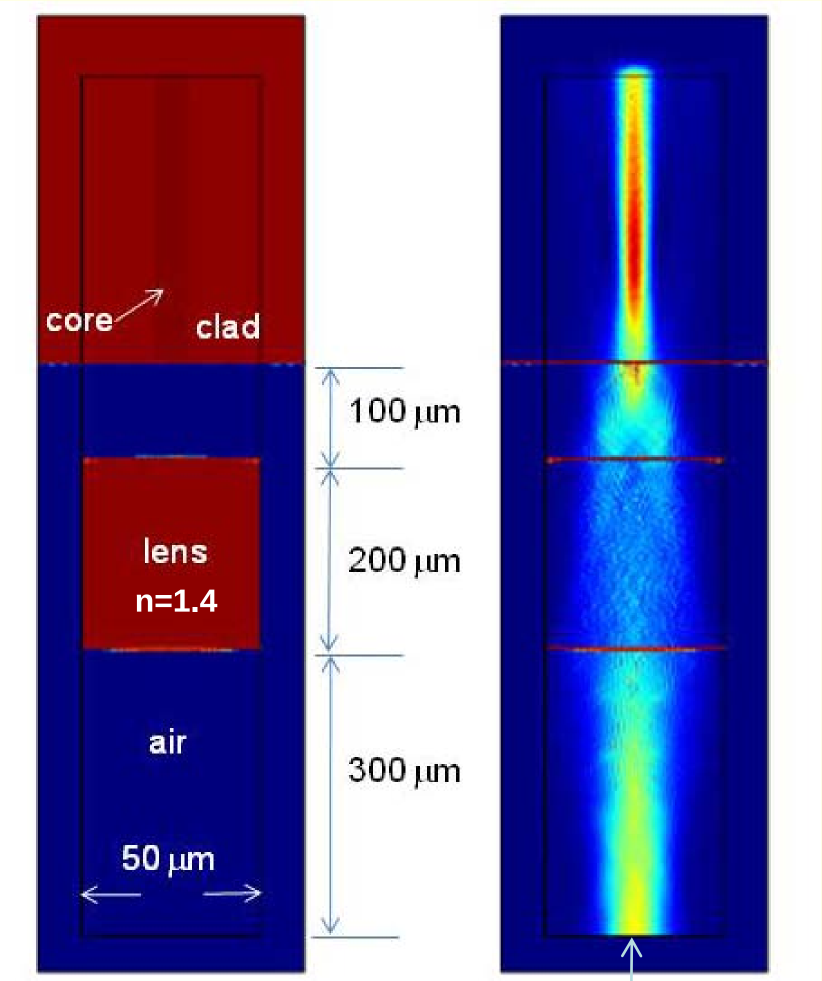
Scalar Paraxial mode

Multi-Mode Interference Splitter



- •According to theory, two-fold image occurs at L~400 μm for symmetrical excitation
- •Illustrates that the paraxial model (like BPM) accounts for reflections at moderate angles

Beam Coupling via a Circular Microlens



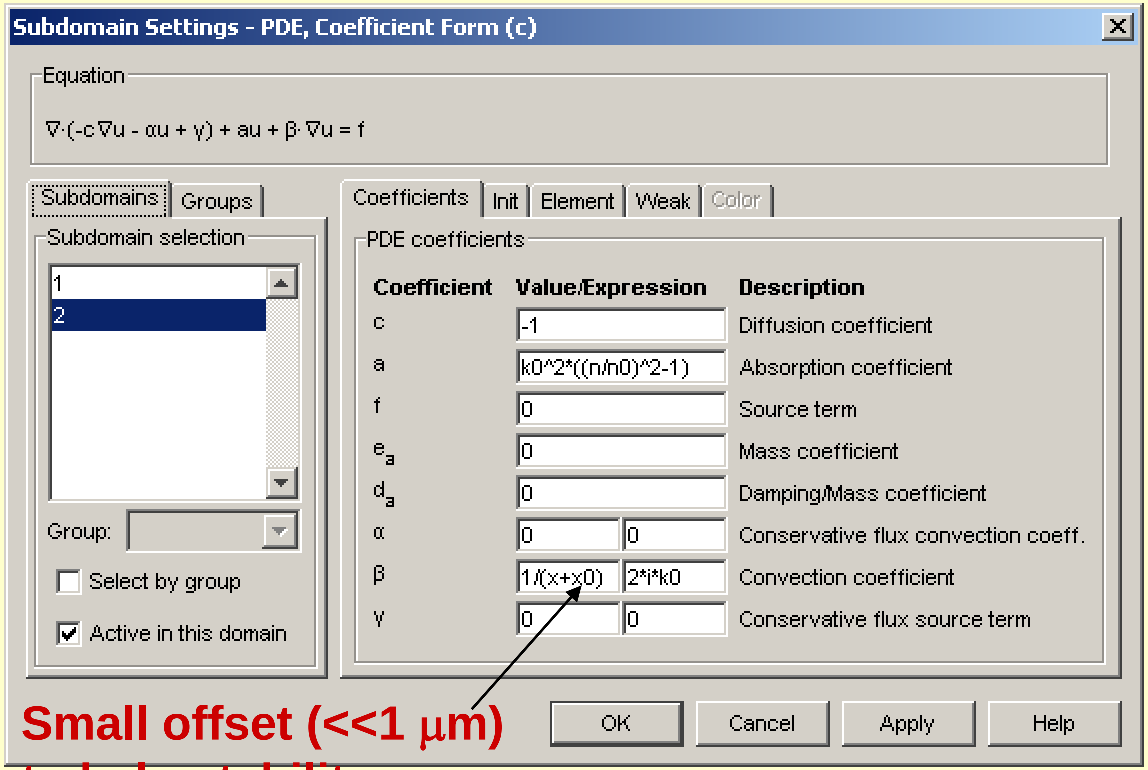
Gaussian beam input

- **High index contrasts makes this problem more challenging**
- **Reduced mesh was used (~0.45 λ)**
- **Field in low-intensity regions is somewhat grainy**
- **Focusing distance (~200 μm from center) agrees fairly well with focal length from geometrical optics (175 μm)**

Scalar Paraxial Mode with Axial Symmetry

Scalar Wave Equation in 2D, Cylindrical Coordinates:

$$\partial u^2/\partial z^2+(1/r)\partial(r\ \partial u/\partial r)/\partial r+2ik_0\partial u/\partial z+k_0^2[(n/n_0)^2-1]u= 0$$



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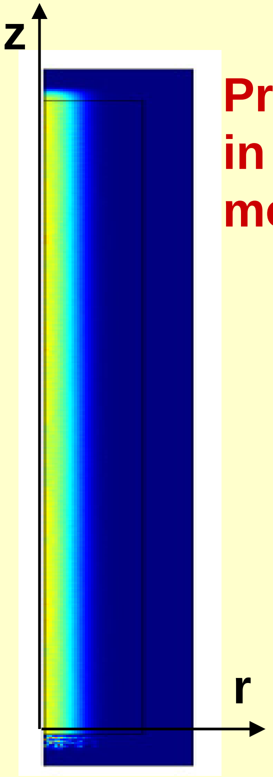
α	0	0	Conservative flux convection coeff.
β	1/(x+x0)	2*i*k0	Convection coefficient
γ	0	0	Conservative flux source term

Small offset (<<1 μm) to help stability



Propagation in single-mode fiber

Conclusions

- BPM-Like mode can be implemented easily in Comsol via a PDE mode
- Enables a much coarser mesh and therefore larger devices to be simulated
- Accounts for interference, evanescent wave coupling, refraction, glancing reflections, but not back reflections
- Can be integrated with thermal, RF and strain effects for complex devices

Thank You!

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