ECE 695
Numerical Simulations
Lecture 28: Finite-Difference Time Domain in MEEP

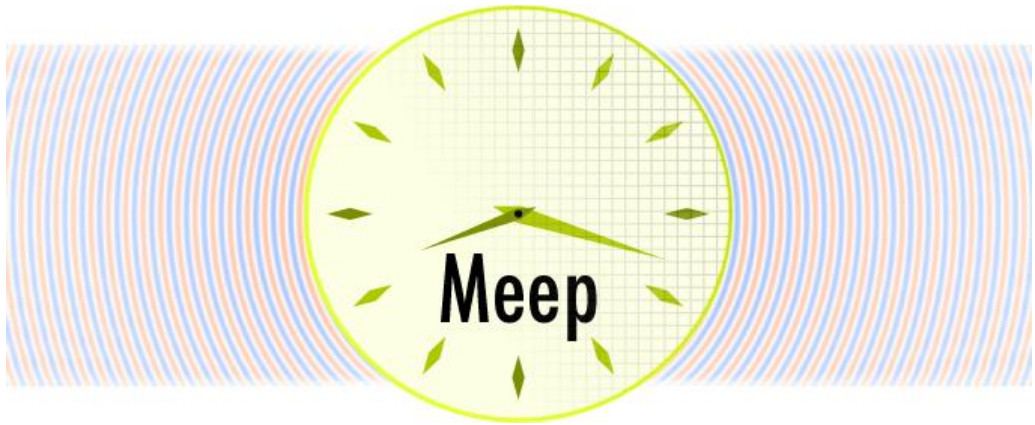
Prof. Peter Bermel

March 27, 2017

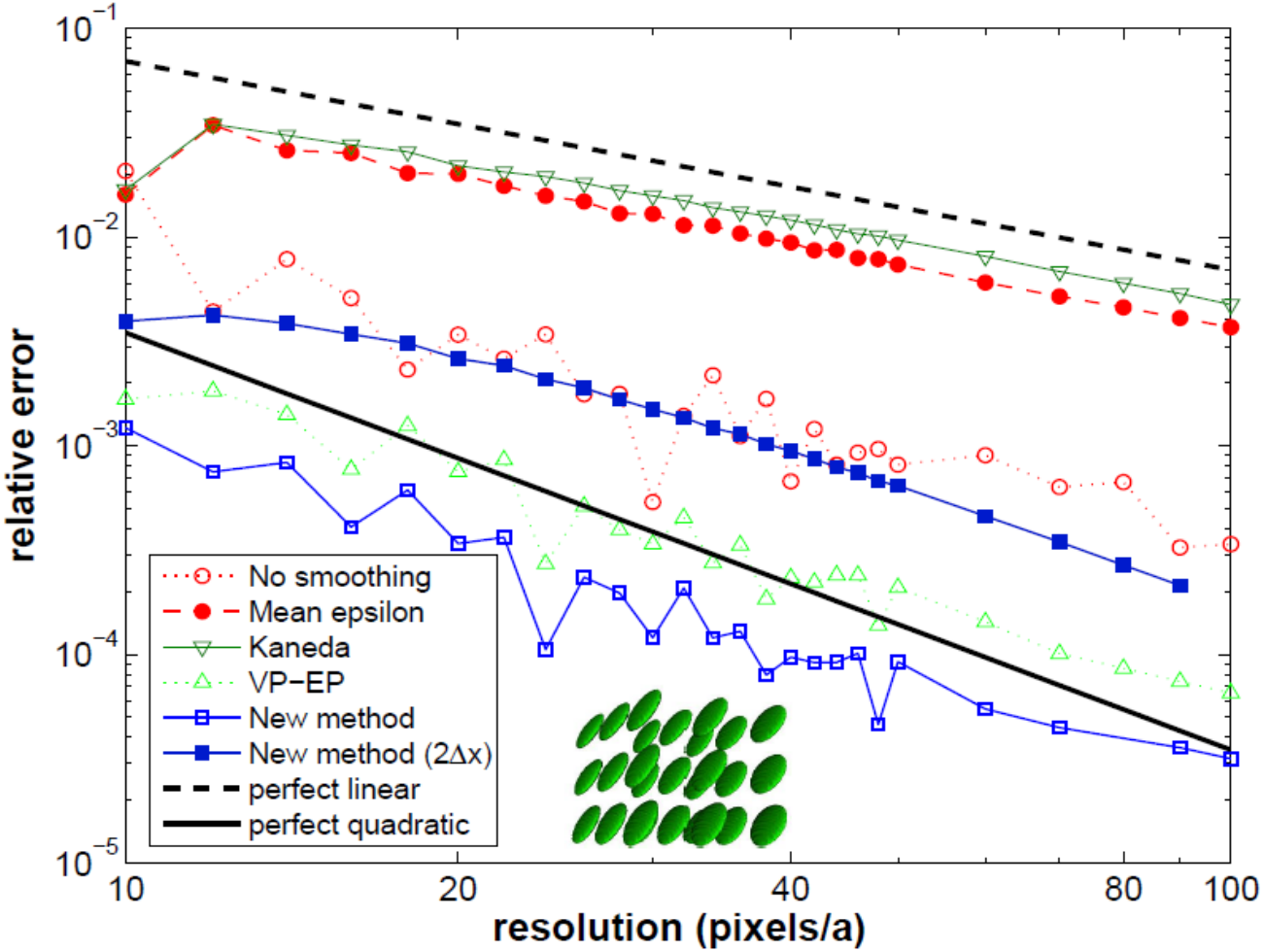
Recap: Special Features of MEEP

jdj.mit.edu/meep
nanohub.org/tools/meep

- Arbitrary dimensionality, boundary conditions
- Perfectly matched layers
- Subpixel averaging
- Symmetry and parallelization
- Fully programmable
- Nonlinear and saturable gain media
- Frequency-domain solver

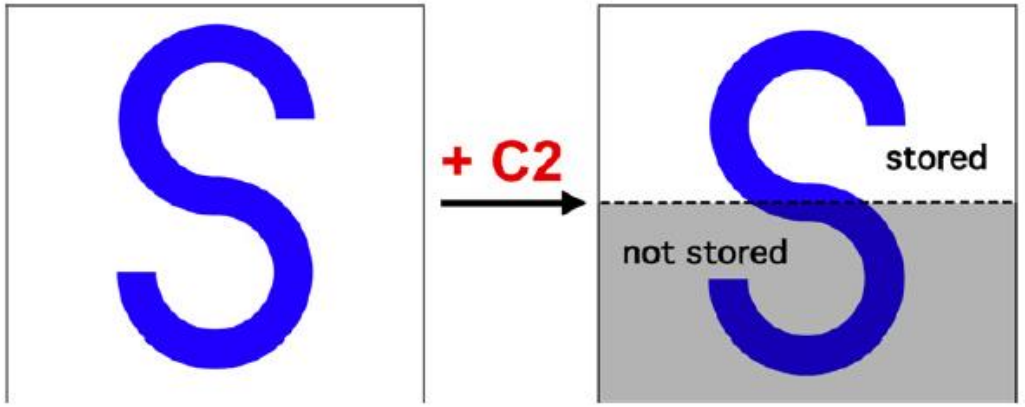


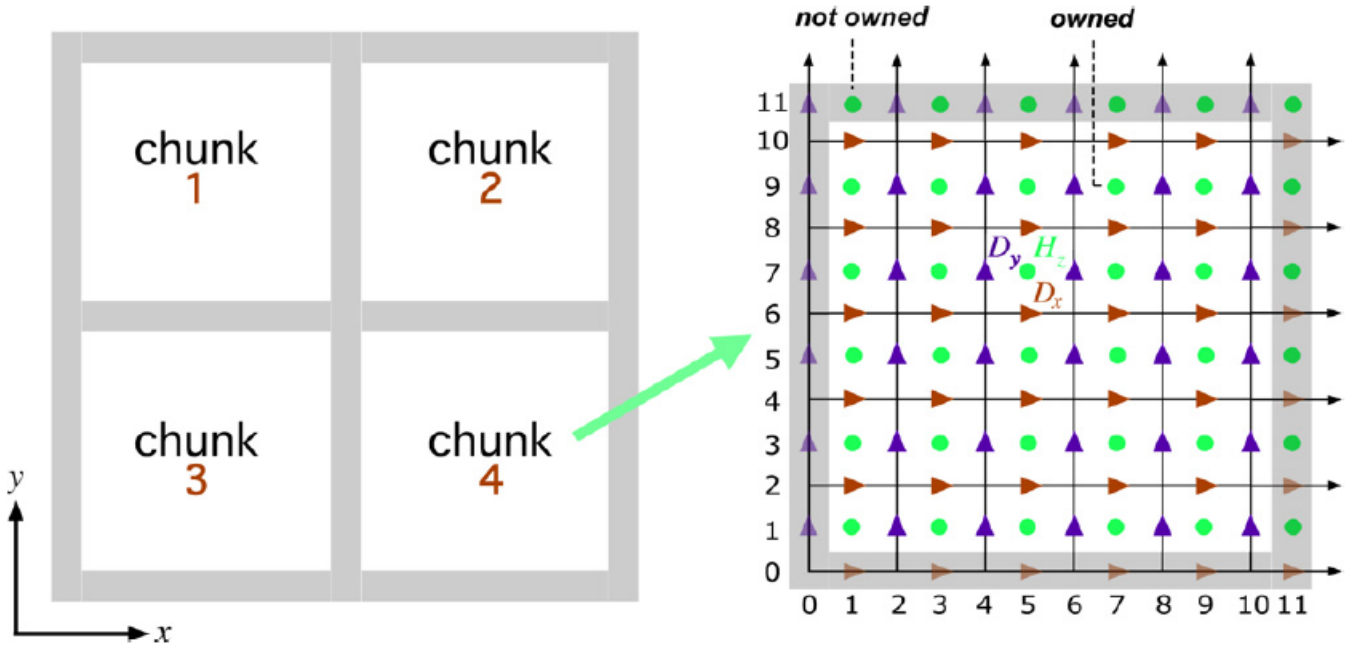
Subpixel Averaging



A. Farjadpour, D. Roundy, A. Rodriguez, M. Ibanescu, P. Bermel, J.D. Joannopoulos, S.G. Johnson, *Proc. SPIE* **6322**, 63220G (2006)

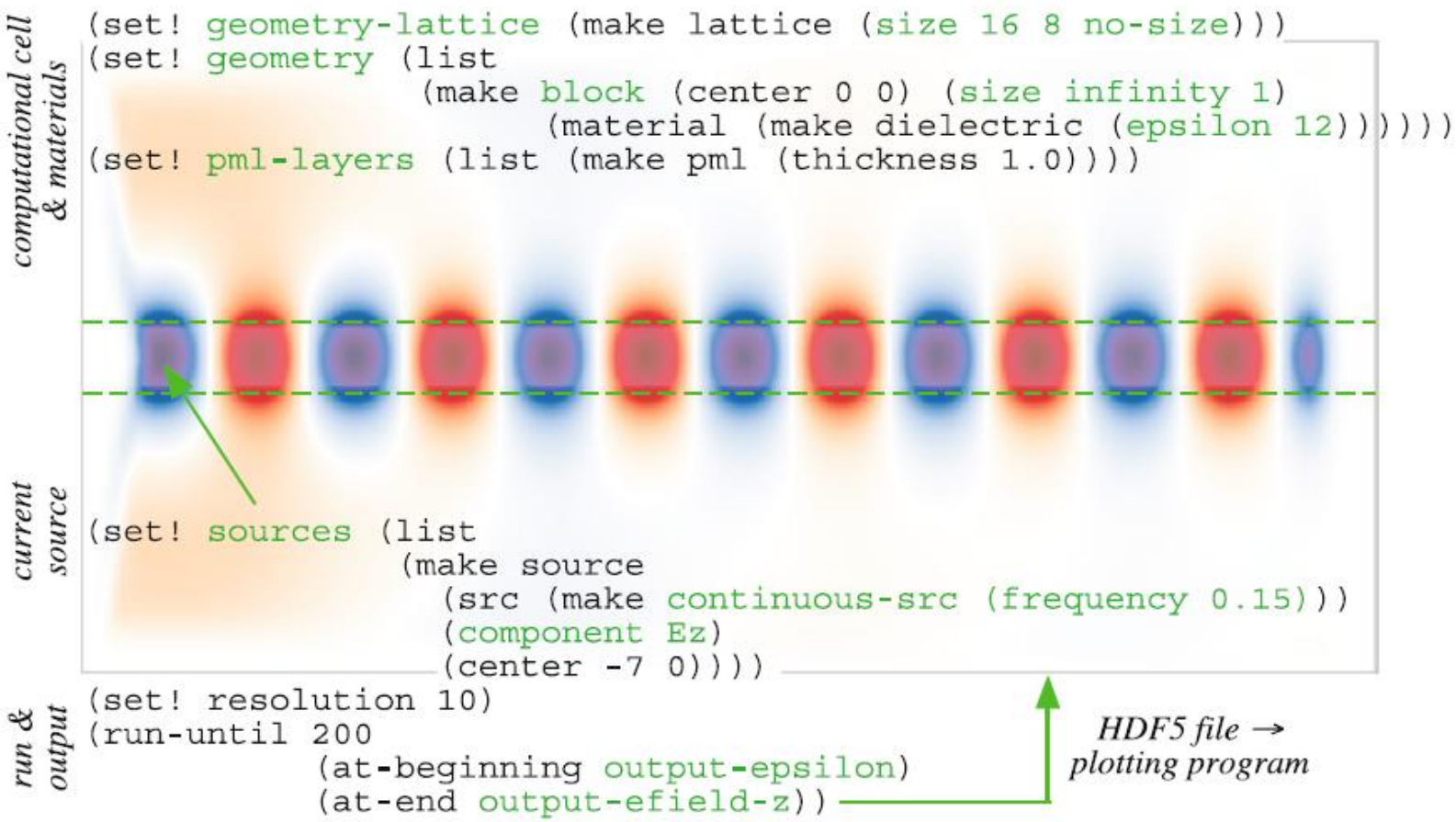
Symmetry and Parallelization





A. Farjadpour, D. Roundy, A. Rodriguez, M. Ibanescu, P. Bermel, J.D. Joannopoulos, S.G. Johnson, *Comput. Phys. Commun.* (2009)

Using the Scheme Interface



Outline

- MEEP Interfaces
- MEEP Classes
- Tutorial examples:
  - Waveguide
  - Bent waveguide
  - Multimode ring resonators
  - Isolating individual resonances
  - Kerr nonlinearities
  - Quantifying third-harmonic generation
- Random and correlated random textured structures

MEEP Interfaces

- C/C++ interface
  - Original interface developed
  - Executable compiled with MEEP library
  - Provides tremendous flexibility and speed
- Scheme interface
  - Most widely used interface
  - Built on Scheme and Libctl to make simple problems easy and hard problems soluble
  - Scripted and interpreted at runtime
- nanoHUB GUI
  - Reduces complexity of input at expense of flexibility

MEEP Classes

- Lattice: defines the size of the computational cell, when used
- Material-type: basic materials (3 choices)
  - Medium
  - Perfect-metal
  - Material-function
- Geometric-object: basic structures
  - Block
  - Cylinder
  - Sphere / Ellipsoid
  - Cone

MEEP Classes (Cont'd)

- Symmetry (3 choices)
  - Mirror-symmetry
  - Rotate2-symmetry
  - Rotate4-symmetry
- Pml: key properties
  - Thickness
  - Direction

MEEP Classes (Cont'd)

- Source (3 types):
  - Gaussian-src
  - Continuous-src
  - Custom-src
- Flux-region: used to calculate

$$P(\omega) = \int d\boldsymbol{A} \cdot [\boldsymbol{E}^*(\omega) \times \boldsymbol{H}(\omega)]$$

- Flux-region properties include:
  - Center
  - Size
  - Direction
  - Weight

Run Functions

- Run-until
- Run-sources
- Run-sources+
- Stop-when-fields-decayed
- (run-k-point T k)

Selected Step functions

- Output-epsilon
- Output-efield-z
- Output-tot-pwr
- (output-png component h5topng-options)

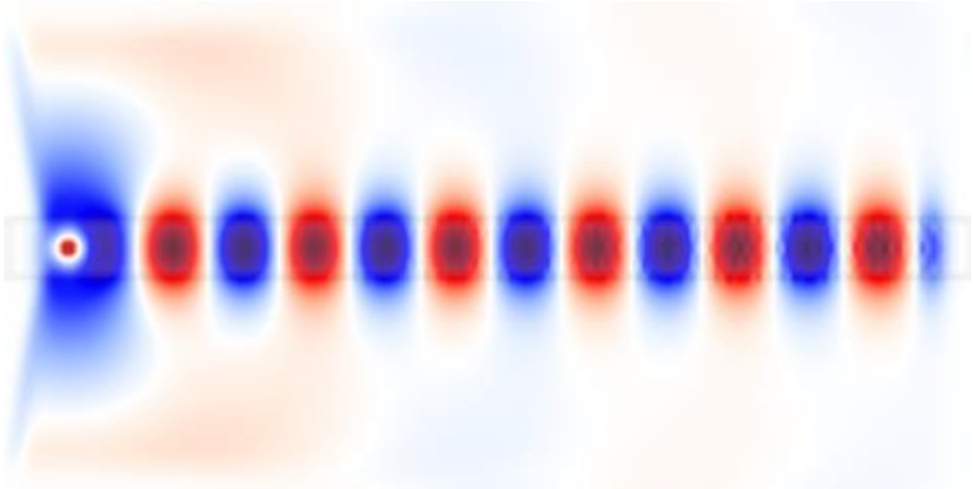
Example: Index-Guided Waveguide

```
(set! geometry-lattice (make lattice (size 16 8 no-size)))
(set! geometry (list (make block (center 0 0) (size infinity 1 infinity) (material (make dielectric (epsilon 12))))))
(set! sources (list (make source (src (make continuous-src (frequency 0.15))) (component Ez) (center -7 0))))
(set! pml-layers (list (make pml (thickness 1.0))))
(set! resolution 10)
(run-until 200 (at-beginning output-epsilon) (at-end output-efield-z))
```

Example: Index-Guided Waveguide

- Dielectric function is as expected:

- Ez field propagates nicely along waveguide as expected:



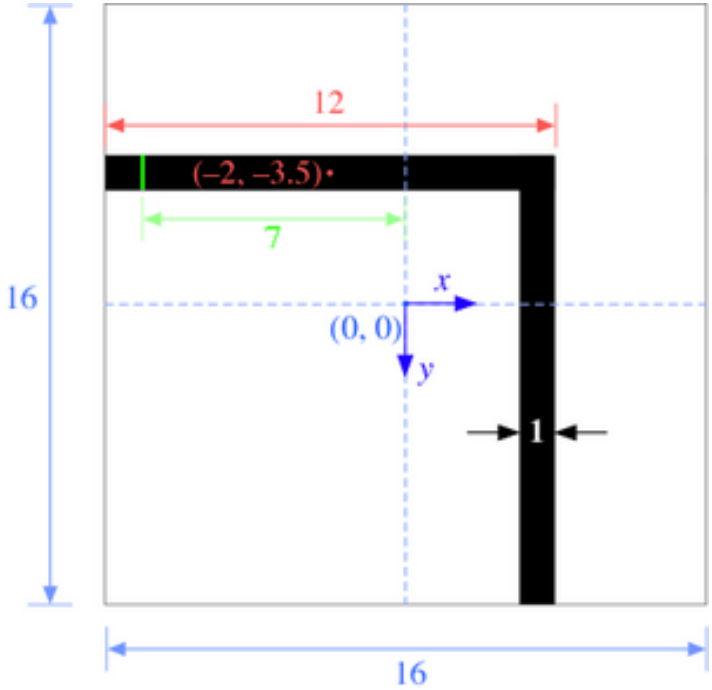
Example: Index-Guided Bend

(set! geometry-lattice (make lattice (size 16 16 no-size)))

(set! geometry (list (make block (center -2 -3.5) (size 12 1 infinity) (material (make dielectric (epsilon 12)))) (make block (center 3.5 2) (size 1 12 infinity) (material (make dielectric (epsilon 12))))))

(set! resolution 10)

- Resulting geometry (as shown on right):



Example: Index-Guided Bend

```
(set! pml-layers (list (make pml (thickness 1.0))))
(set! sources (list (make source (src (make continuous-src (wavelength (* 2 (sqrt 12))) (width 20))) (component Ez) (center -7 -3.5) (size 0 1))))
(run-until 200 (at-beginning output-epsilon) (to-appended "ez" (at-every 0.6 output-efield-z)))
```

Example: Index-Guided Bend

- Can create movie from this (as shown below):

Example: Index-Guided Bend

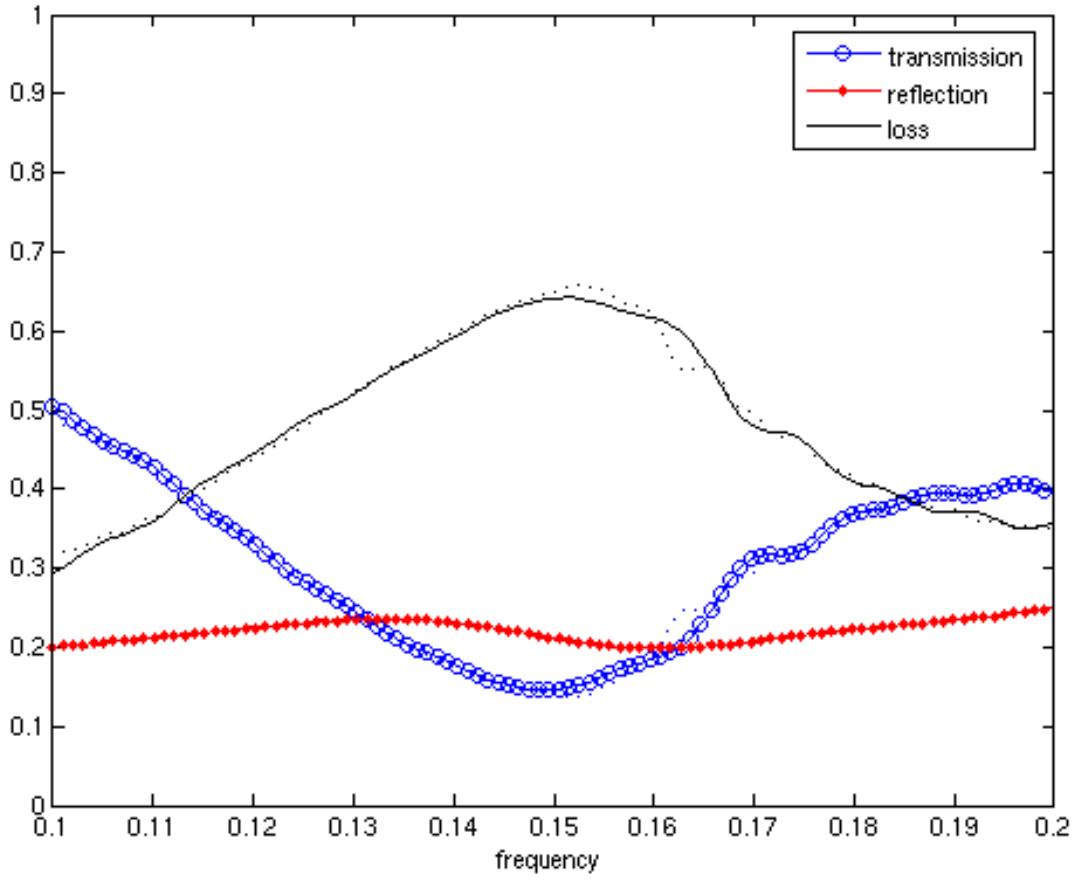
```
(define-param no-bend? false)
(set! geometry (if no-bend?
  (list (make block (center 0 wvg-ycen)
          (size infinity w infinity)
          (material (make dielectric (epsilon 12)))))
  (list (make block (center (* -0.5 pad) wvg-ycen)
         (size (- sx pad) w infinity)
         (material (make dielectric (epsilon 12))))
        (make block (center wvg-xcen (* 0.5 pad))
         (size w (- sy pad) infinity)
         (material (make dielectric (epsilon 12)))))))
```

Example: Index-Guided Bend

```
(define-param nfreq 100)
(define trans ; transmitted flux
  (add-flux fcen df nfreq
      (if no-bend?
        (make flux-region
          (center (- (/ sx 2) 1.5) wvg-ycen) (size 0 (* w 2)))
        (make flux-region
          (center wvg-xcen (- (/ sy 2) 1.5)) (size (* w 2) 0)))))
(define refl ; reflected flux
  (add-flux fcen df nfreq
      (make flux-region
        (center (+ (* -0.5 sx) 1.5) wvg-ycen) (size 0 (* w 2)))))
```

Example: Index-Guided Bend

Transmission, reflection, and loss spectrum for the bend



Ring Resonators

- Ring resonators are essentially index-guided waveguides bent in on themselves
- Discrete resonant frequencies induced by periodicity
- Free spectral range between modes varies inversely with ring radius
- Radiative losses decay exponentially with ring radius

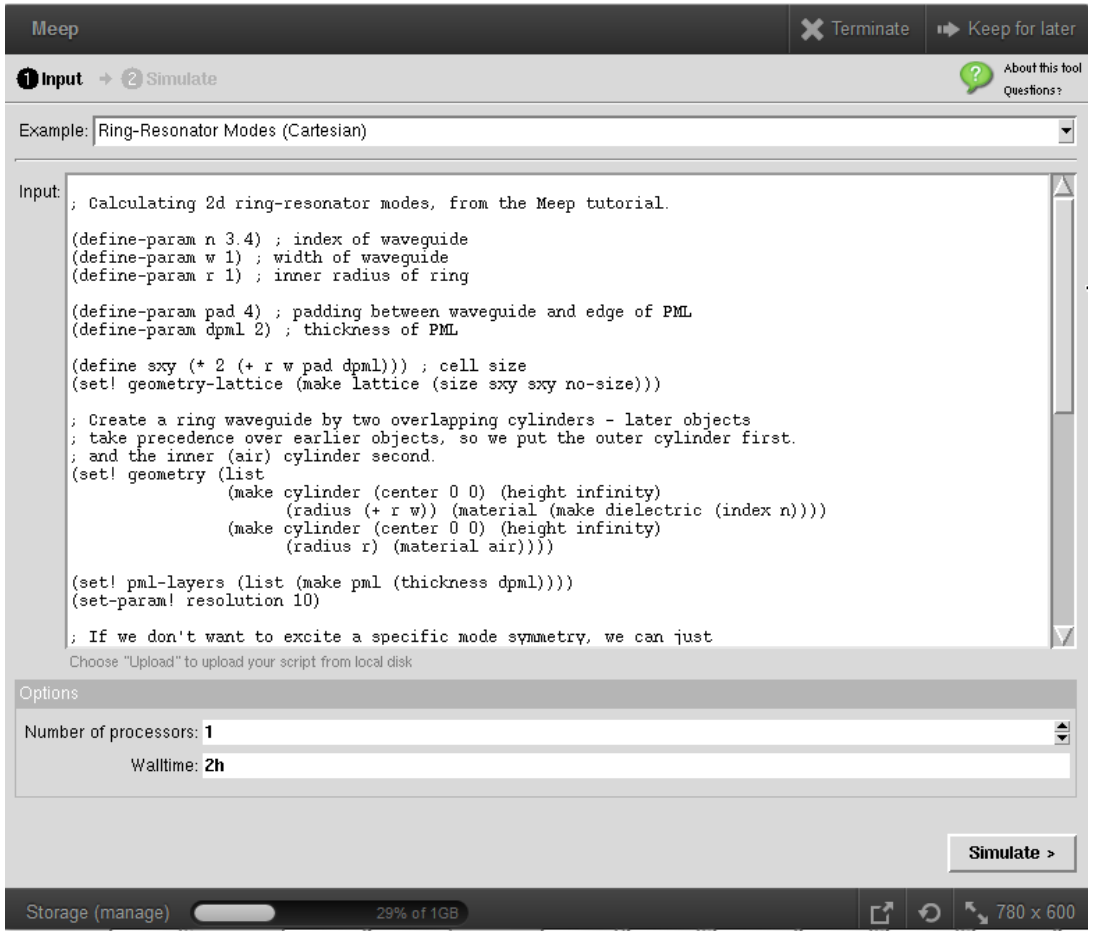
Ring Resonators

```
(define-param n 3.4) ; index of waveguide
(define-param w 1) ; width of waveguide
(define-param r 1) ; inner radius of ring
(define-param pad 4) ; padding from waveguide
(define-param dpml 2) ; thickness of PML
(define sxy (* 2 (+ r w pad dpml))) ; cell size
(set! geometry-lattice (make lattice (size sxy sxy no-size)))
(set! geometry (list (make cylinder (center 0 0) (height infinity)
                        (radius (+ r w)) (material (make dielectric (index n))))
                     (make cylinder (center 0 0) (height infinity)
                        (radius r) (material air))))
(set! pml-layers (list (make pml (thickness dpml)))) (set-param!
resolution 10)
```

Ring Resonators

```
(define-param fcen 0.15) ; pulse center frequency
(define-param df 0.1)  ; pulse width (in frequency)
(set! sources (list (make source (src (make gaussian-src
(frequency fcen) (fwidth df))) (component Ez) (center (+ r 0.1)
0))))
(run-sources+ 300 (at-beginning output-epsilon) (after-sources
(harminv Ez (vector3 (+ r 0.1)) fcen df)))
```

Ring Resonators



Can also access this example on MEEP tool:

https://nanohub.org/tools/meep

Ring Resonators

- Filter diagonalization (harminv) extract resonant frequencies and decay rates:

$$f(t) = \sum_{k=1}^{N} a_k e^{-j\omega_k t - \Gamma_k t}$$

- Where: $Q_k = \omega_k / 2\Gamma_k$
- Raw output:

harminv0:, frequency, imag. freq., Q, |amp|, amplitude, error harminv0:, 0.118101575043663, -7.31885828253851e-4, 80.683059081382, 0.00341388964904578, -0.0030502290529417 5-0.0015332140295640 4i, 1.02581433904604e-5

harminv0:, 0.14716255552815 4, -2.32636643253225e-4, 316.29272471914, 0.028645766390816 5, 0.019312788201646 9-0.021156468136141 3i, 7.32532621851082e-7

harminv0:, 0.175246750722663, -5.22349801171605e-5, 1677.48461212767, 0.00721133215656089, -8.12770506086109e-4-0.00716538314235085i, 1.82066436470489e-7

Ring Resonators

- Add the following to ring.ctl:

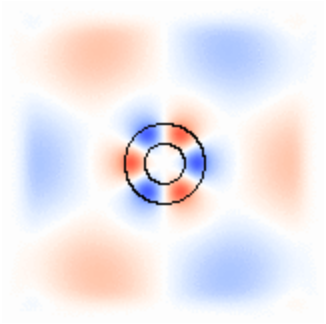
```
(run-until (/ 1 fcen) (at-every (/ 1 fcen 20) output-efield-z))
```

- Run the following from command line:

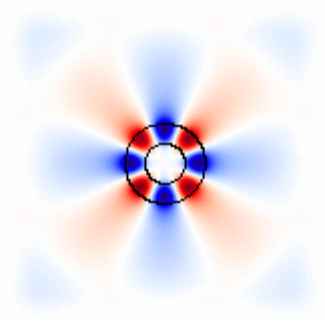
```
unix% meep fcen=0.118 df=0.01 ring.ctl
unix% meep fcen=0.147 df=0.01 ring.ctl
unix% meep fcen=0.175 df=0.01 ring.ctl
unix% h5topng -RZc dkbluered -C ring-eps-000000.00.h5 ring-ez-*.h5
unix% convert ring-ez-*.png ring-ez-0.118.gif
```

Ring Resonators

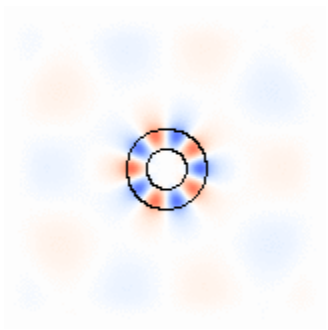
- End result is to create movies of single ring resonator modes:



$\omega = 0.118\ (2\pi c/a)$
$Q = 81$



$\omega = 0.147\ (2\pi c/a)$
$Q = 316$



$\omega = 0.175\ (2\pi c/a)$
$Q = 1682$

Next Class

- Next time: we will continue finite-difference time domain techniques
- Suggested reference: S. Obayya's book, Chapter 5, Sections 4-6