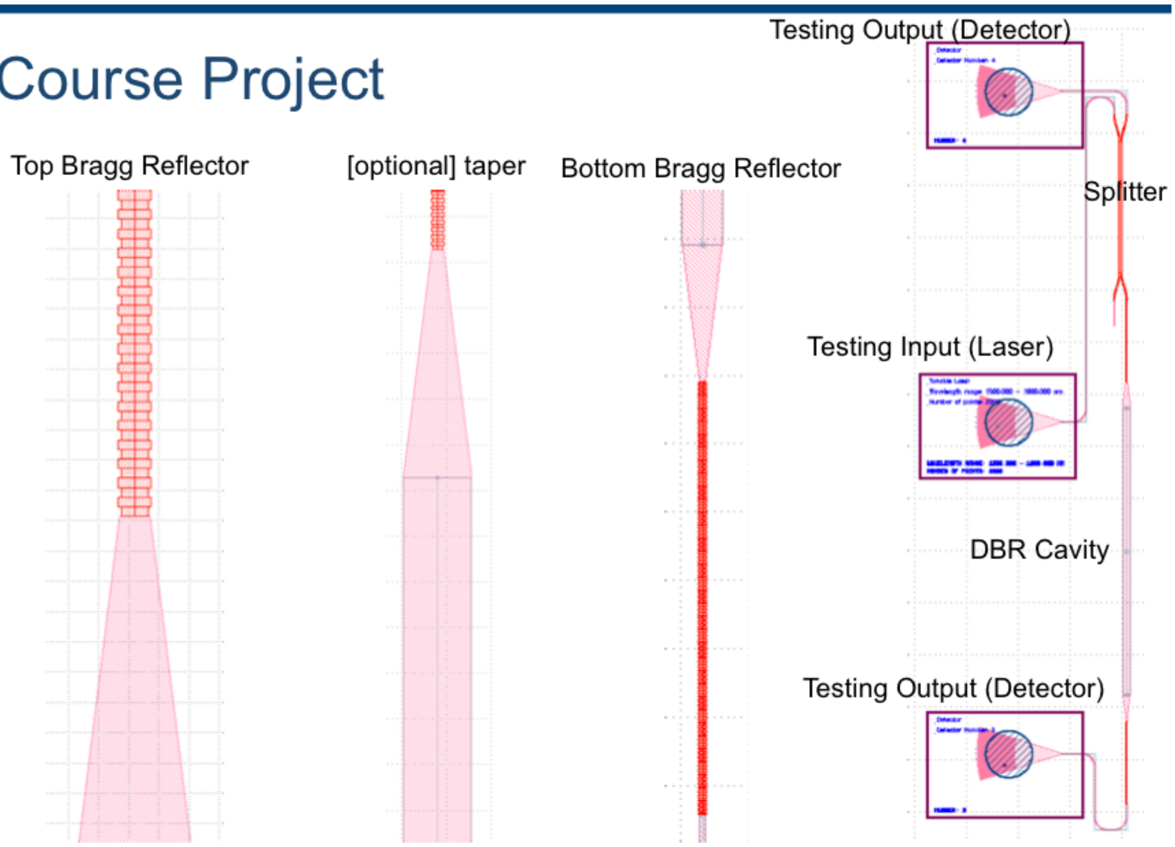
Bragg Grating = Mirror

<u>Basic Design</u>

(FP Cavity)

Bragg $\longrightarrow$ Waveguide $\longrightarrow$ Bragg Grating

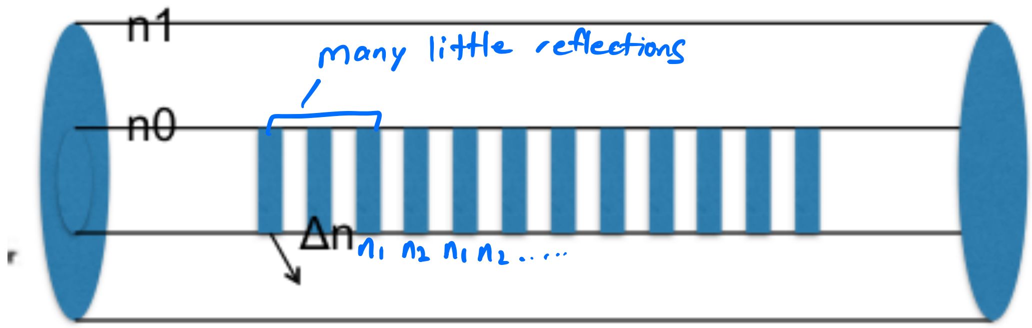
Our Course Project



What are Bragg gratings?

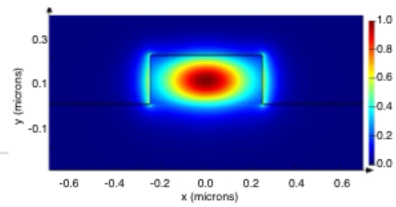
- Excellent optical filters
  - can be designed for many different shapes;
    - narrow vs. broadband
  - wide control of spectral shape
    - thanks to choices in Δn, period, # periods (N)
- Numerous applications
  - lasers – mirrors
    - N = 3-30 for VCSELs
    - N = 100 - 1000s for DFB or DBR lasers
  - filters for communications – in fibres
  - sensors

Fiber Bragg Grating

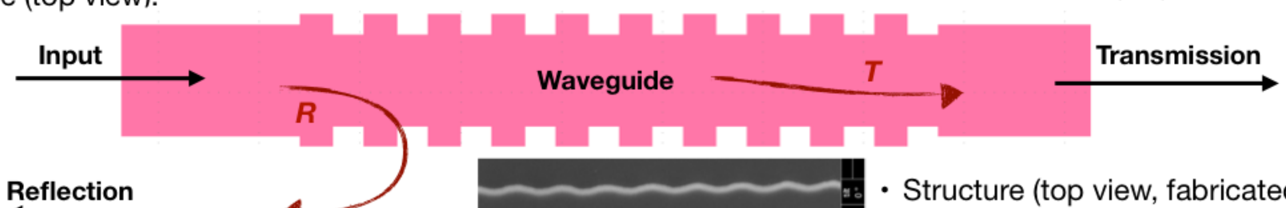


Waveguide Bragg grating

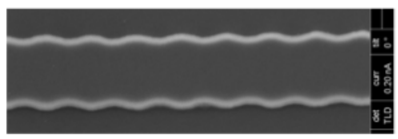
- Structure (side view):



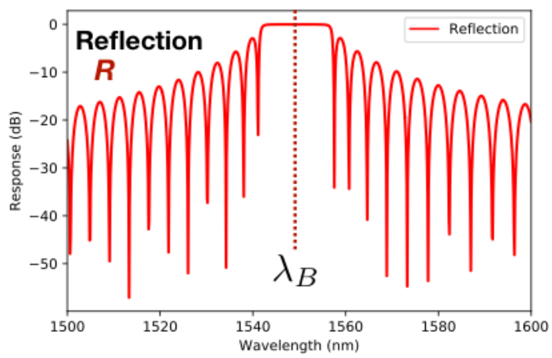
- Structure (top view):

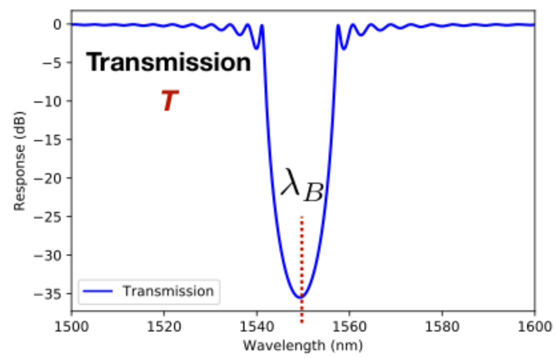


- Structure (top view, fabricated)



- Performance





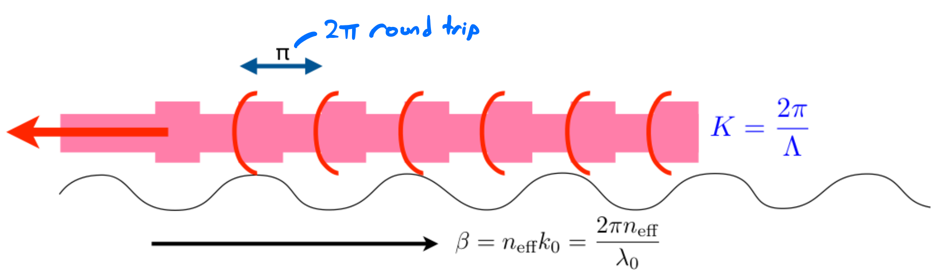
Waveguide Bragg grating – operating wavelength

- Phase matching condition:

$$\beta \cdot 2\Lambda = 2\pi \cdot M$$

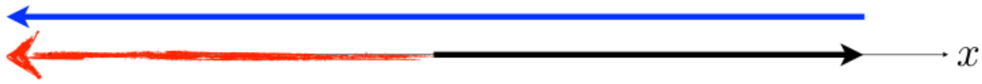
- M is the grating order

- Propagation constant X grating period is equal to a 360° (or multiple) phase shift
  - Optical wavelength inside the grating matches 2X period
- Namely, constructive interference from each period, where light has to travel 2 * Period



- Bragg condition – Wave vector matching:

$$K = \frac{2\pi}{\Lambda}$$ Grating, M=1



$$\beta_{\text{left}} = n_{\text{eff}} \cdot k_0 = \frac{2\pi}{\lambda_0} n_{\text{eff}}$$

waveguide propagation constant (backwards)

$$\beta_{\text{right}} = n_{\text{eff}} \cdot k_0 = \frac{2\pi}{\lambda_0} n_{\text{eff}}$$

waveguide propagation constant (forward)

$$\beta_{\text{right}} - K = -\beta_{\text{left}}$$

- We can find the Bragg wavelength: $\boxed{\lambda_B = 2 n_{\text{eff}} \Lambda}$

Uniform Bragg grating

- Can have nearly 100% reflectivity over a band
  - R depends on # of gratings, and grating strength (kappa). From Coupled Mode Theory (optional):

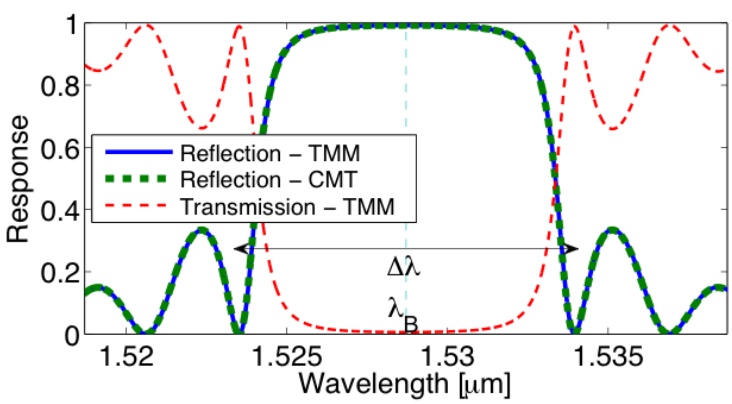
$$R_{peak} = \tanh^2(\kappa L)$$

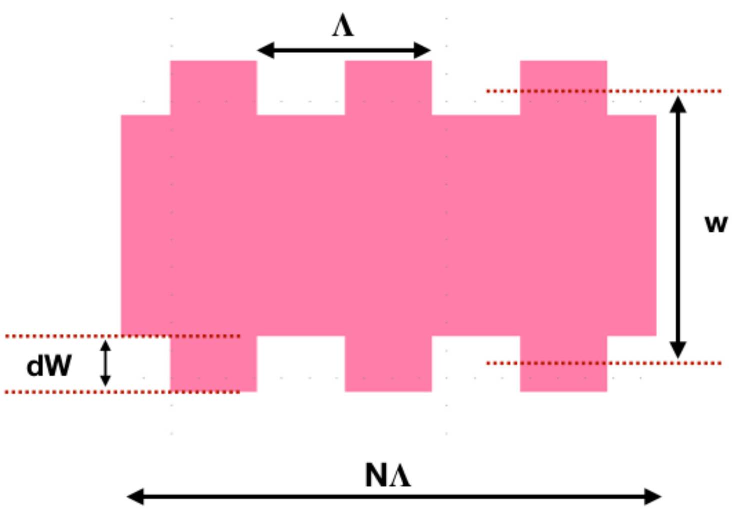
kappa

  - Bandwidth depends mainly on kappa:

$$\Delta\lambda = \frac{\lambda_B^2}{\pi n_g}\sqrt{\kappa^2 + (\pi/L)^2}$$

- Kappa is coupling coefficient





- Parameters
  - Λ: Grating period
  - w: width of the waveguide
  - dW: corrugation width
  - Type: Rectangular or sinusoidal
  - N: number of grating periods

- Calculation of the optical transmission spectrum for a uniform grating, from coupled-mode theory:

$$r = \frac{-i\kappa \sinh(\gamma L)}{\gamma \cosh(\gamma L) + i\Delta\beta \sinh(\gamma L)} \tag{4.29}$$

with

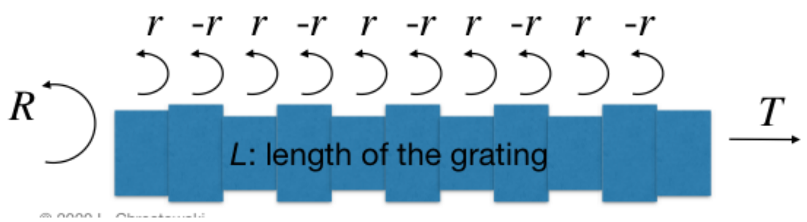
$$\gamma^2 = \kappa^2 - \Delta\beta^2 \tag{4.30}$$

Here, $\Delta\beta$ is the propagation constant offset from the Bragg wavelength:

$$\Delta\beta = \beta - \beta_0 << \beta_0 \tag{4.31}$$

and κ is often defined as the coupling coefficient of the grating and can be interpreted as the amount of reflection per unit length. Kappa

$$\beta = \frac{2\pi n_{\mathrm{eff}}}{\lambda} - i\frac{\alpha}{2}$$



Relate r & t to kappa found from experiments or FDTD

$$\boxed{\kappa = \frac{2r}{\Lambda} = \frac{2}{\Lambda}\frac{\Delta n}{2n_{\mathrm{eff}}}} = \frac{2\Delta n}{\lambda_B}, \quad \Delta n = \kappa\lambda_B/2$$

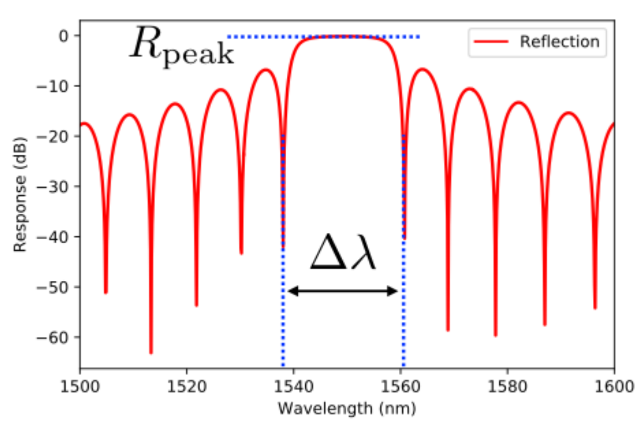
- Coupled-mode theory predicts the peak reflectivity

$$R_{peak} = \tanh^2(\kappa L)$$

- and the bandwidth (defined here as the 1st-nulls bandwidth, not the 3-dB bandwidth)

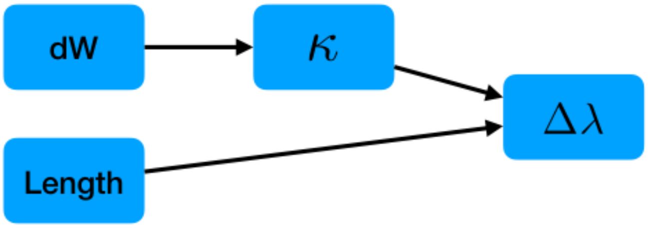
$$\Delta\lambda = \frac{\lambda_B^2}{\pi n_g}\sqrt{\kappa^2 + (\pi/L)^2}$$

- **How do we find κ (kappa), the coupling coefficient?**
  - Experiments
  - Simulations

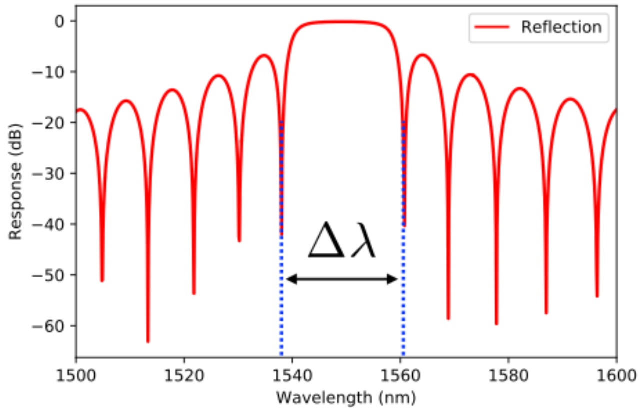


Finding Kappa :

- Relationship between physical parameters, model parameters, and performance parameters:



$$\Delta\lambda = \frac{\lambda_B^2}{\pi n_g}\sqrt{\kappa^2 + (\pi/L)^2}$$



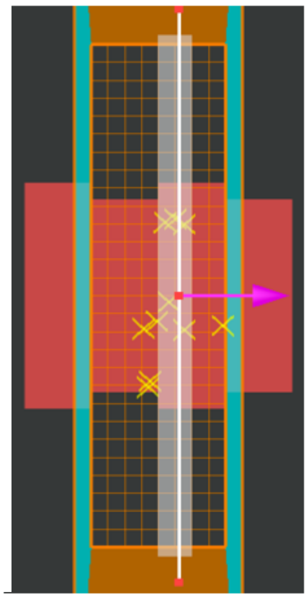
- We need a method of finding the model and performance parameters from the physical parameters
  - Experiments
  - Simulations
    - **Band-structure calculation through 3D-FDTD**
    - CMT-based perturbation analysis
    - Δneff eigenmode approach

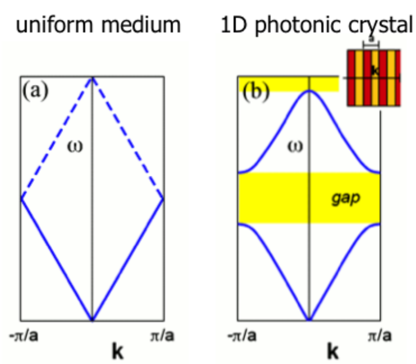
- Simulation steps:
  - Draw the structure
  - Define a unit cell
  - Bloch boundary conditions: simulates an infinitely-long grating
  - Set k (wave vector)
  - Excitation source
  - Use time-domain monitors and calculate the optical spectrum
  - Find peaks in the spectrum: these correspond to the 1st-null bandwidth
  - Find Kappa from the bandwidth

$$\Delta\lambda = \frac{\lambda_B^2}{\pi n_g}\sqrt{\kappa^2 + (\pi/L)^2}$$

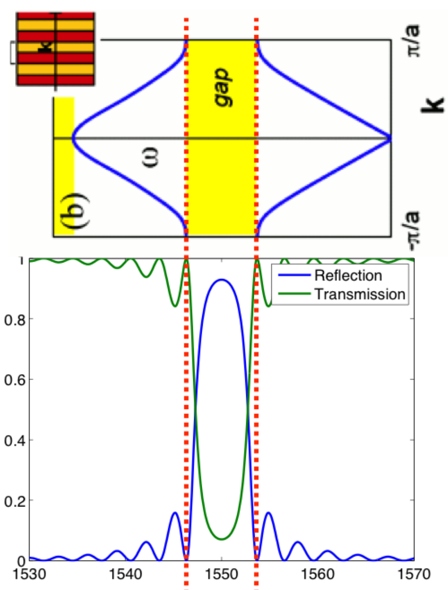
    - and where L is infinity
  - The grating coupling coefficient is:

$$\kappa = \pi n_g \frac{\Delta\lambda}{\lambda_B^2}$$

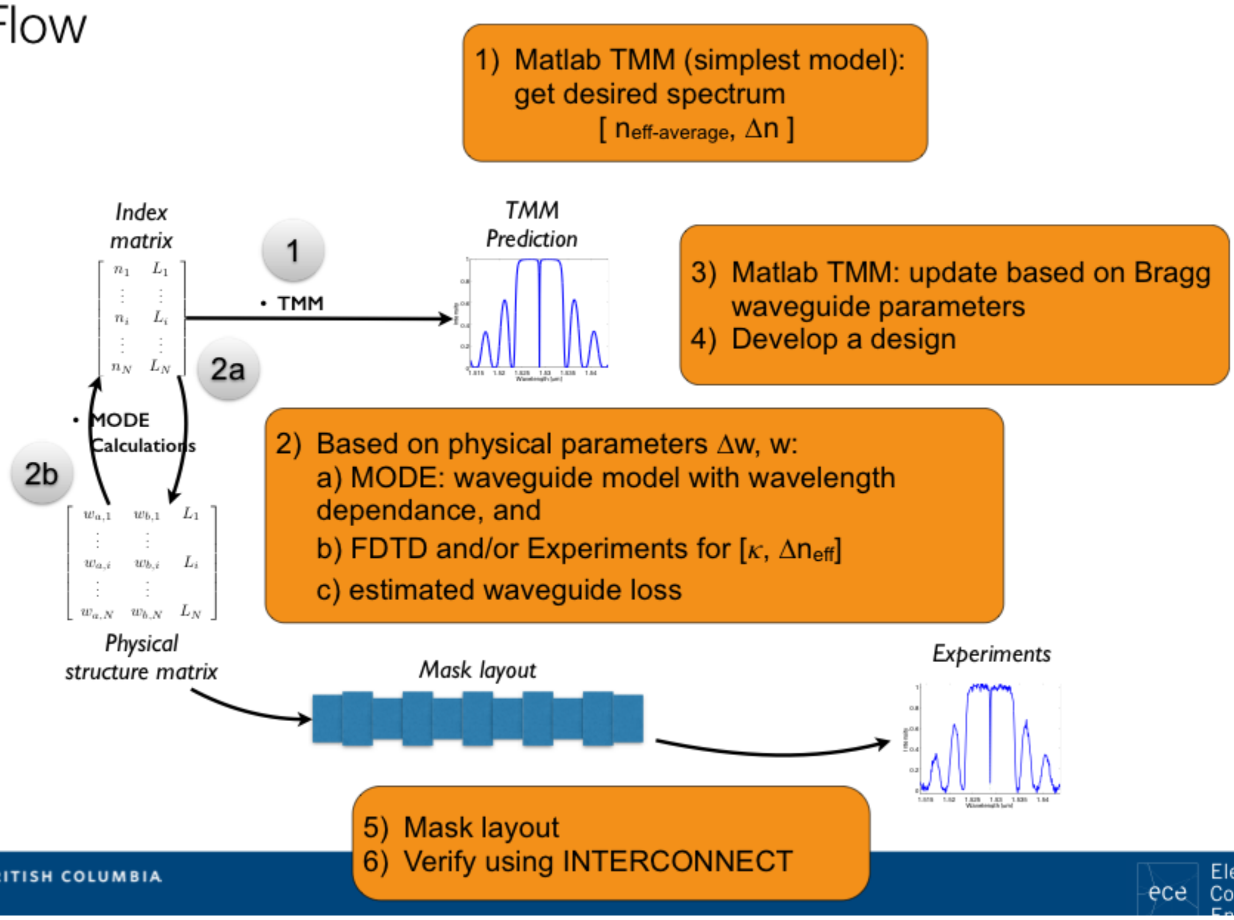




- Photonic crystals devices have band gaps in which there are no propagating solutions
- The size and location of the gap will give us the center wavelength and bandwidth of the Bragg grating



Design Flow



Transfer Matrix Method – Bragg grating

- 1) Use the definition of coupling coefficient (= reflections per unit length), and the normal incidence Fresnel reflection coefficient, to find an equivalent Δn:

$$\kappa = \frac{2r}{\Lambda} = \frac{2}{\Lambda}\frac{\Delta n}{2n_{\text{eff}}} = \frac{2\Delta n}{\lambda_B}, \quad \Delta n = \kappa\lambda_B/2$$

  - Use this Δn value in TMM

- 2) Use a wavelength-dependant waveguide model for the effective index, n_{eff}:

$$n_{\text{eff}} = n_1 + n_2\,(\lambda - \lambda_0) + n_3\,(\lambda - \lambda_0)^2$$

  - e.g. strip waveguide parameters (do this for 1.31 μm wavelength):

$$\lambda_0 = 1.55, n_1 = 2.4445, n_2 = -1.12733, n_3 = -0.033342$$

  - Waveguide dispersion has a big impact on the spectrum of the waveguide Bragg grating

- Construct arbitrary non-uniform structures: Fabry-Perot cavities, etc.

Maximum theoretically possible Q

- Quality factor definition:

$$Q = \omega \cdot \tau_p, \qquad \tau_p^{-1} = \alpha \frac{c}{n_g}$$

– Group Velocity

where ω is the angular frequency, and α is the total power loss in m^{-1} including **propagation loss and mirror loss**.

  - What if you had no mirror loss? What would R be?

- Thus,

$$Q = 2\pi \frac{c}{\lambda} \frac{n_g}{c} \frac{1}{\alpha} = 2\pi \frac{n_g}{\lambda \cdot \alpha}$$

- This is the Q given the total "distributed" optical losses