Si Photonics

Lecture 8 : Optical Fiber

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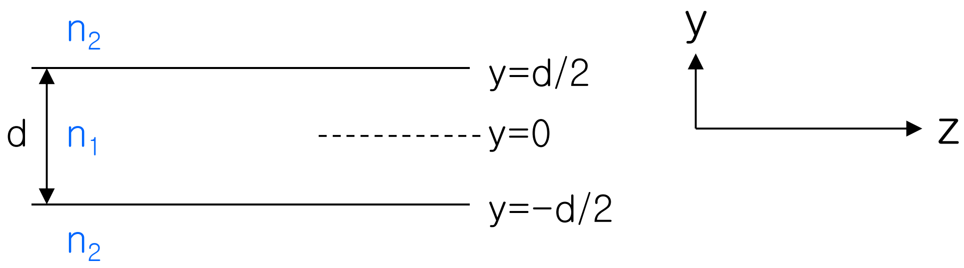
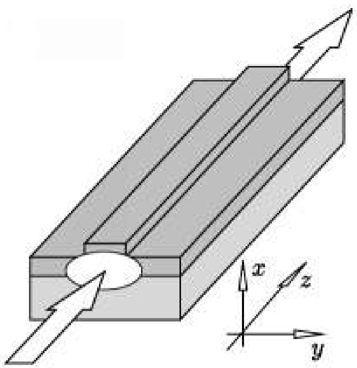
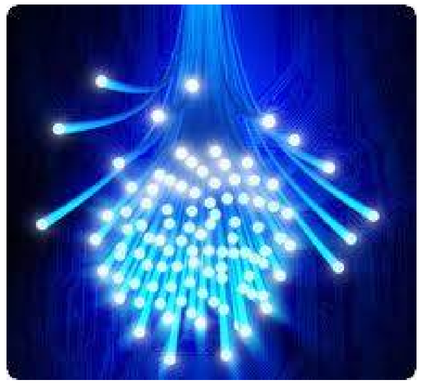
Lecture 8: Optical Fiber

3-layer dielectric waveguide



Practical dielectric waveguides





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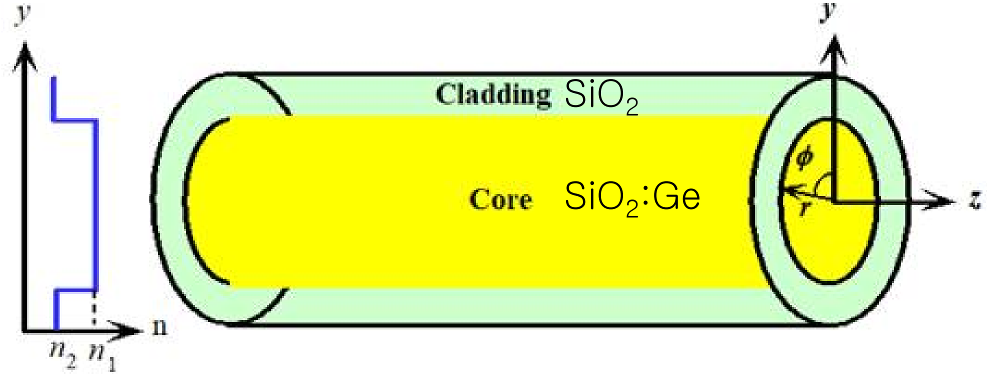
Optical Fiber: Circular dielectric waveguide made up of silica (SiO_2)



Cladding diameter: ~150 μm

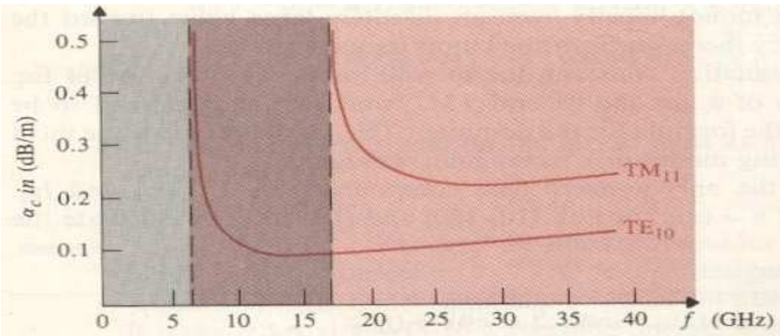
Core diameter: ~10 μm for single-mode fiber

10's of μm for multi-mode fiber

What is special about silica fiber?

- Extremely low loss: 0.2dB/km
- Can be very long: 100's of km

Loss in rectangular metal waveguide



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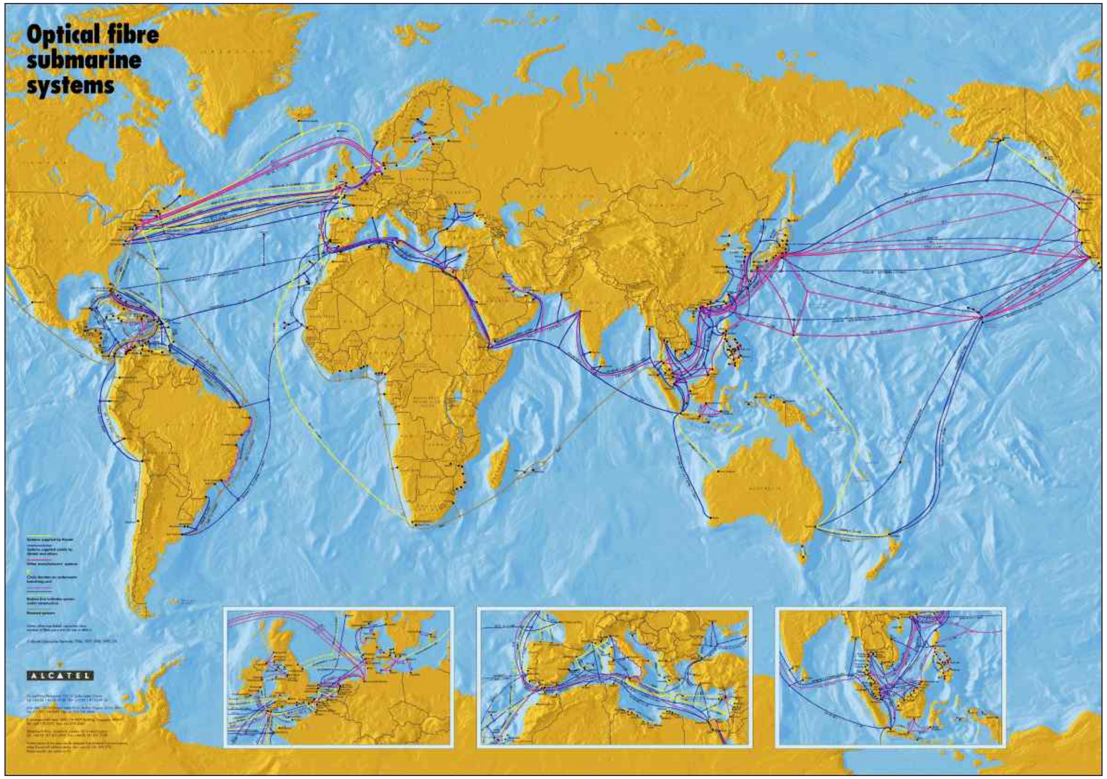
Basis for Global Optical Communication Networks



Total undersea fiber length: ~0.5 billion km (>700 round trips between earth and moon)

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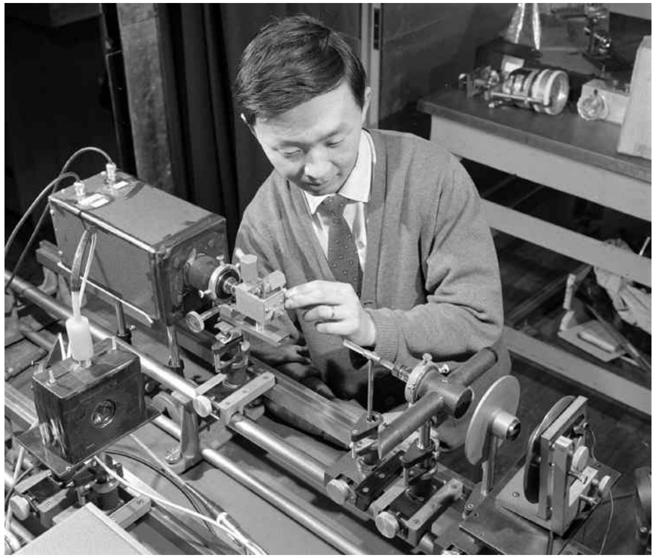

Charles K. Kao (1993~2018)

2009 Nobel Prize in Physics

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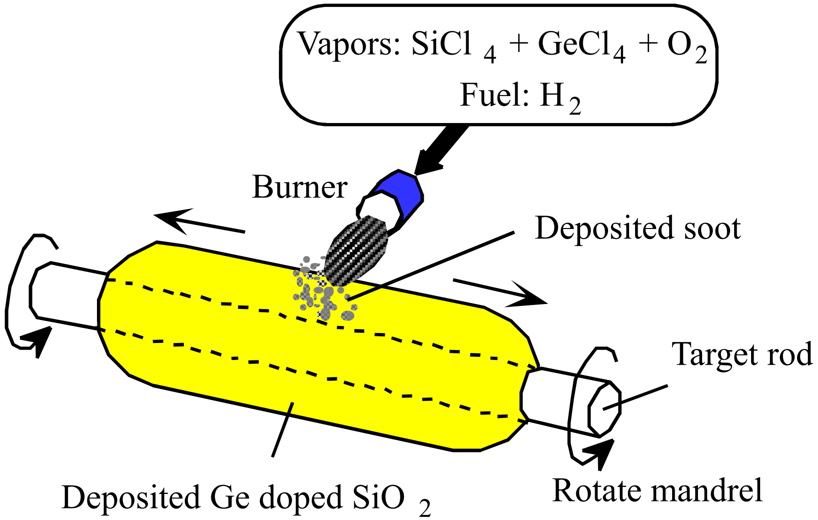
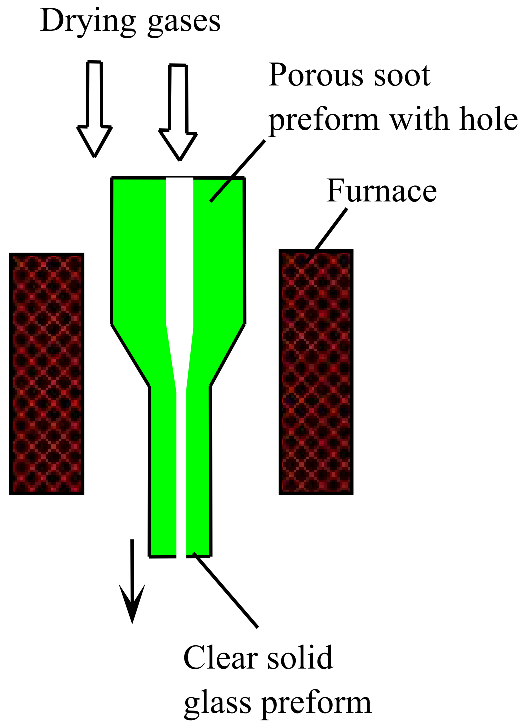
How to make silica optical fiber





$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$

$GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2$

Sintering at 1400-1600 deg C

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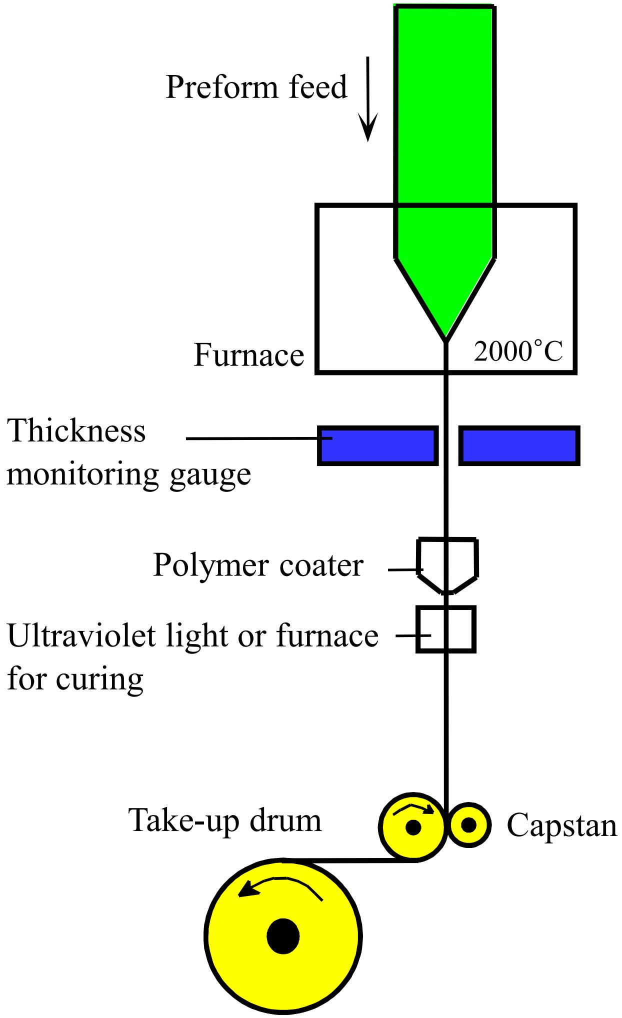

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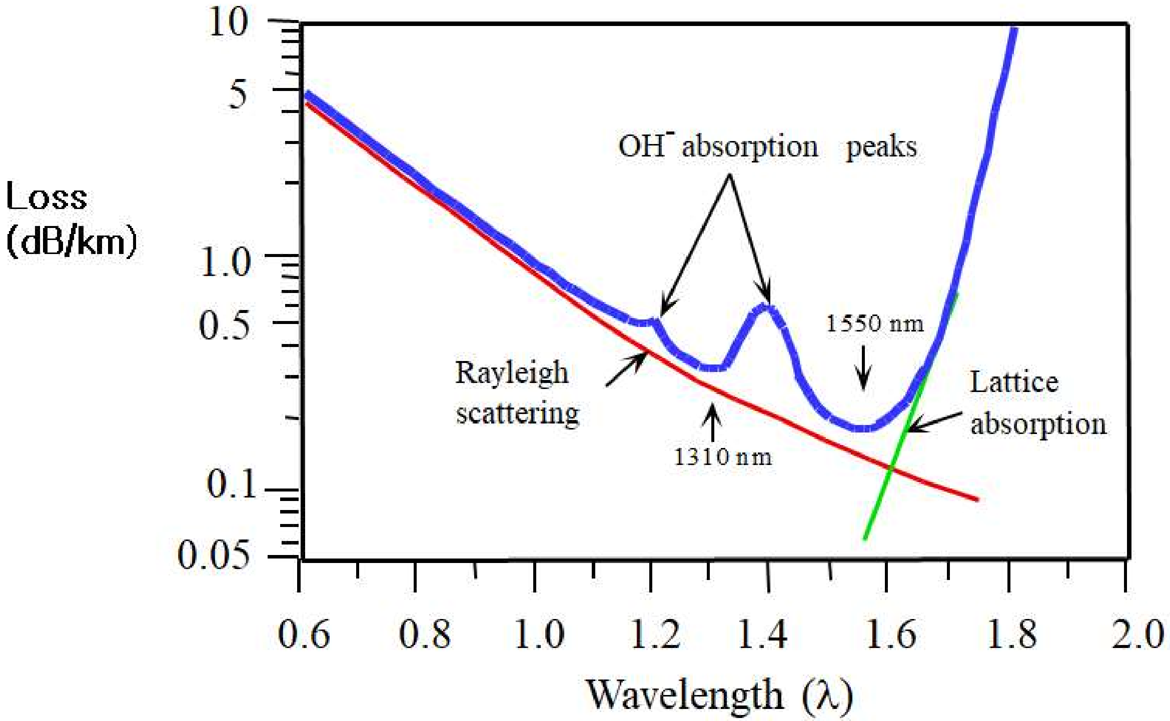
Loss in fiber



Minimum loss at 1.55μm

1.55μm for long-distance optical communication

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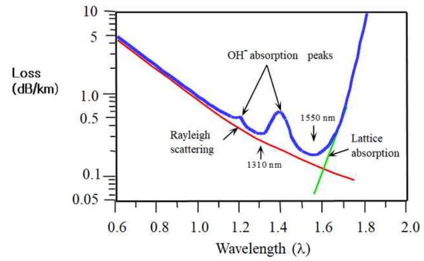
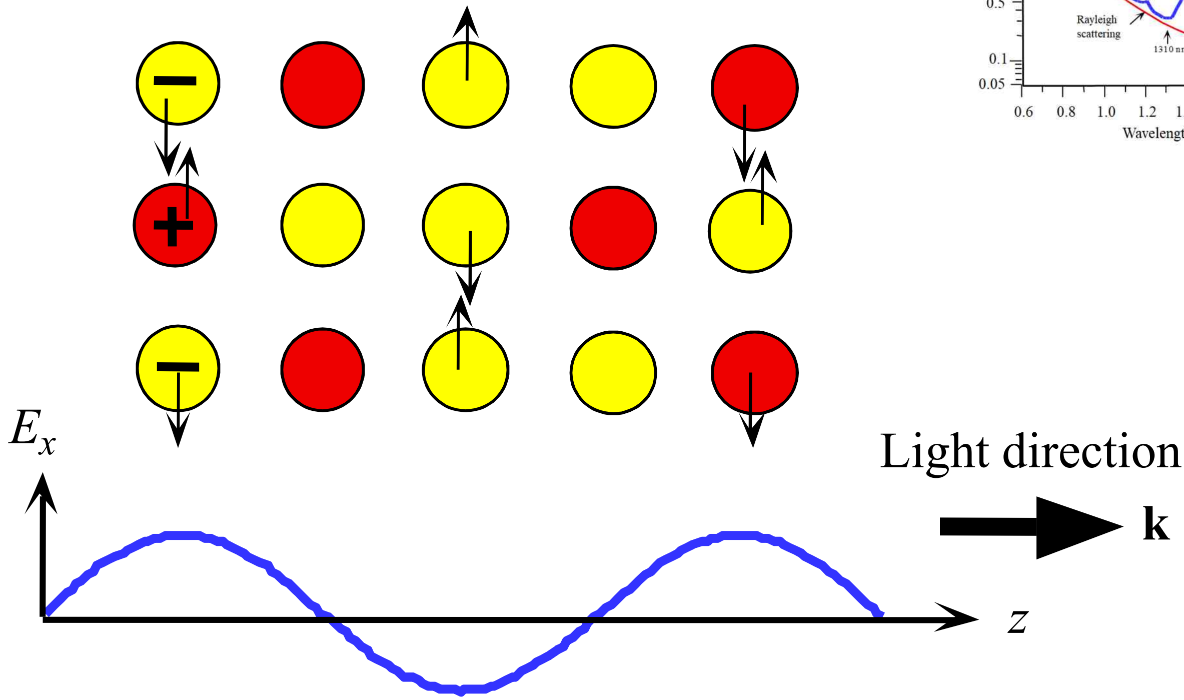
Lattice Absorption:
EM waves cause vibration of ions inside fiber.
Peak absorption occurs at around λ= 9 μm in Silica fiber.





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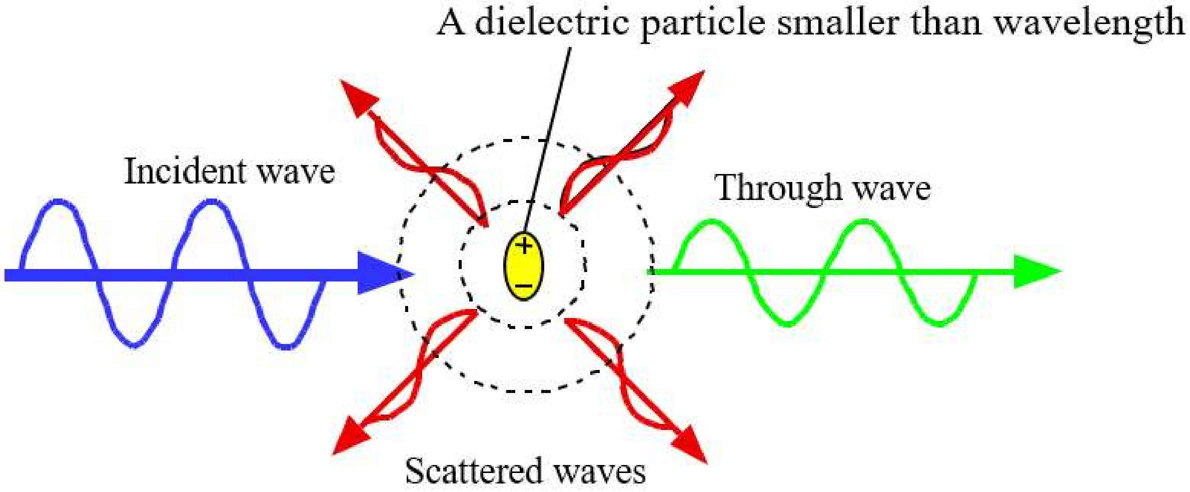
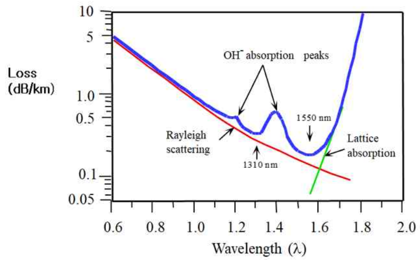
Rayleigh scattering
A small portion of EM waves get directed away from small dielectric particles due local fluctuation of fiber refractive index.
More scattering with smaller wavelength (inversely proportional to λ^3).





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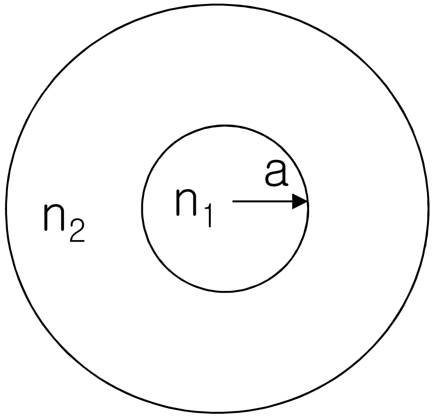
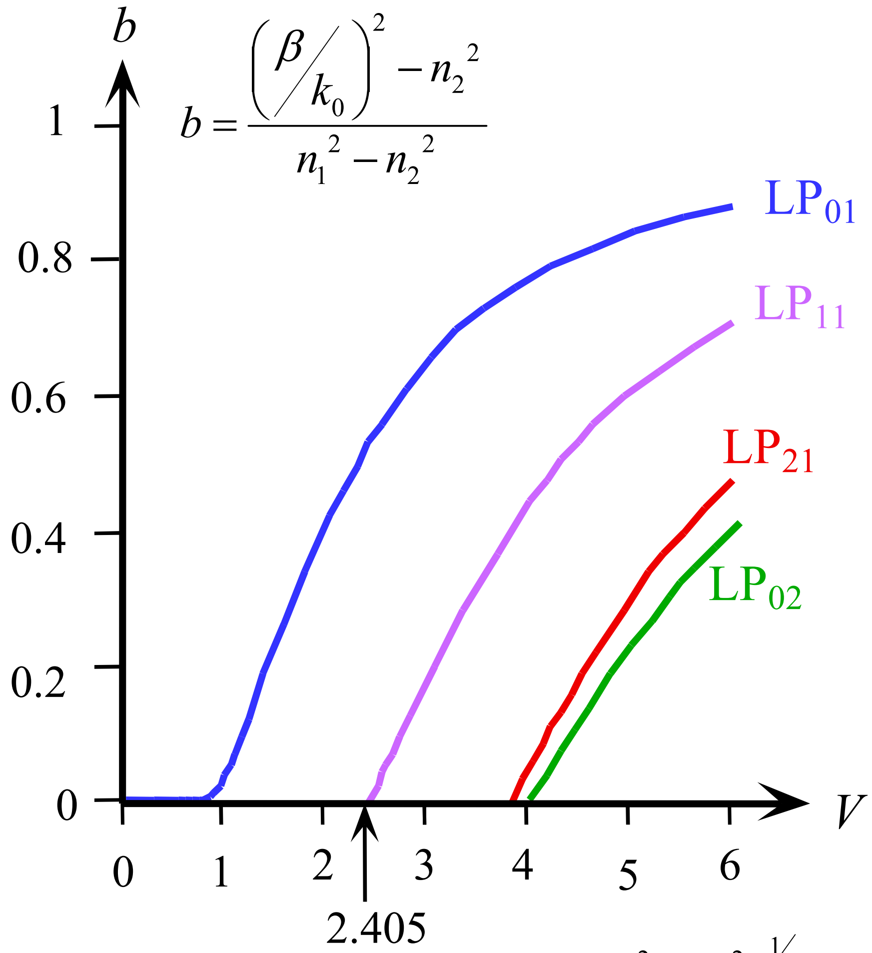


Solve for guided modes in (r, φ, z) coordinate

With an approximation, LP (linearly polarized) mode solutions are obtained

$$E_{LP} = E_{lm}(r,\phi)\,\mathrm{e}^{-j\beta_{lm}z}$$

$$LP_{lm} \text{ mode}$$



$$b = \frac{\left(\beta/k_0\right)^2 - n_2^{\,2}}{n_1^{\,2} - n_2^{\,2}}$$

$$V = k_0 a (n_1^{\,2} - n_2^{\,2})^{1/2}$$

(a : fiber core radius)

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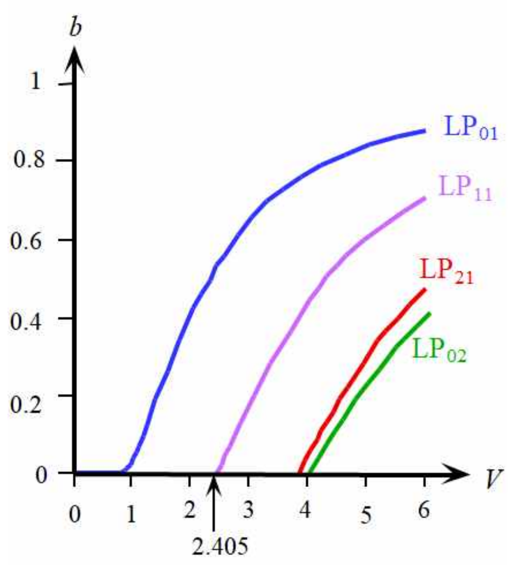
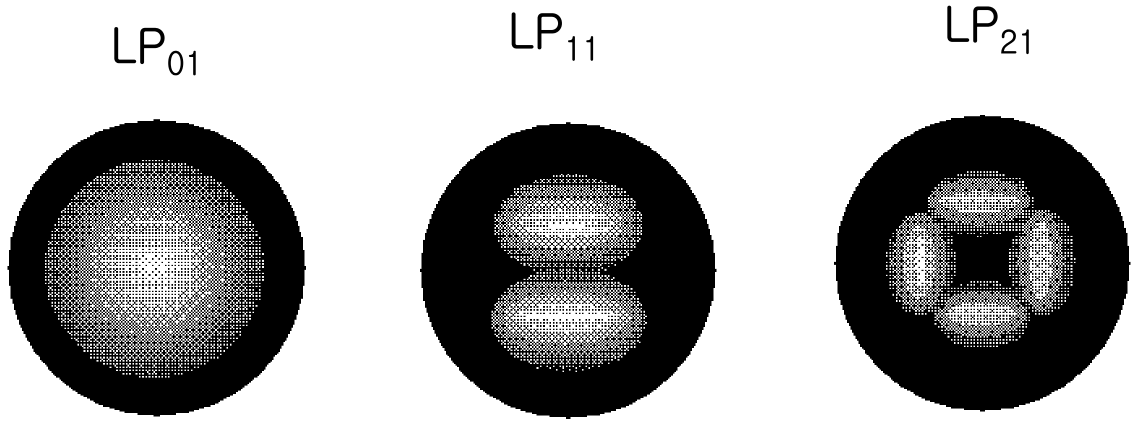
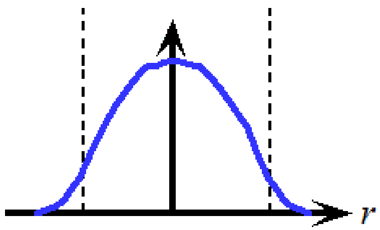


LP_{lm}





m: the number of peaks along r

2l: the number of peaks along ϕ

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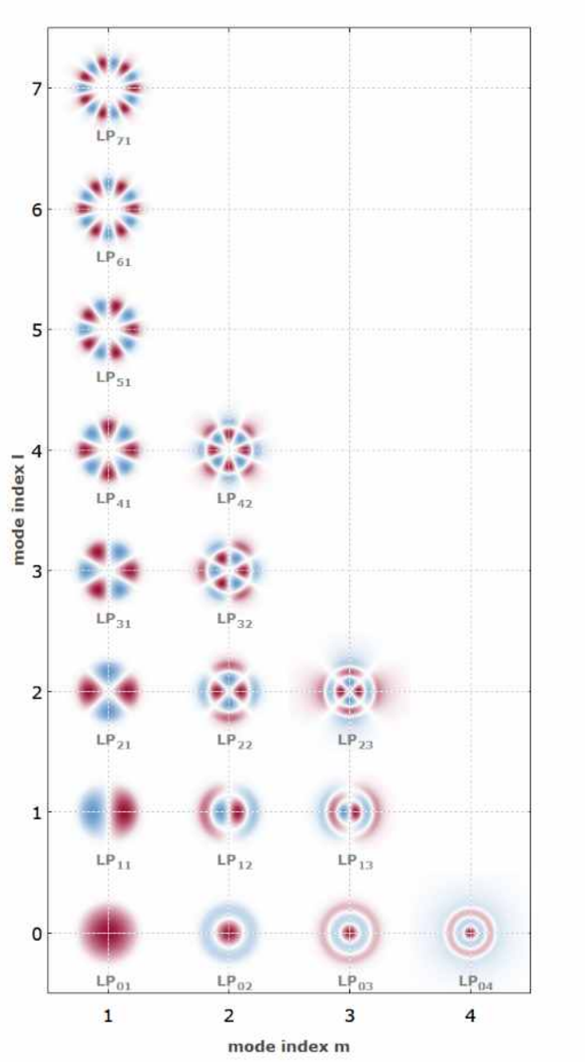

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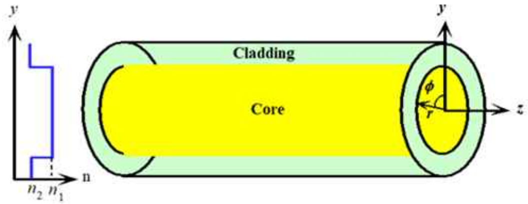
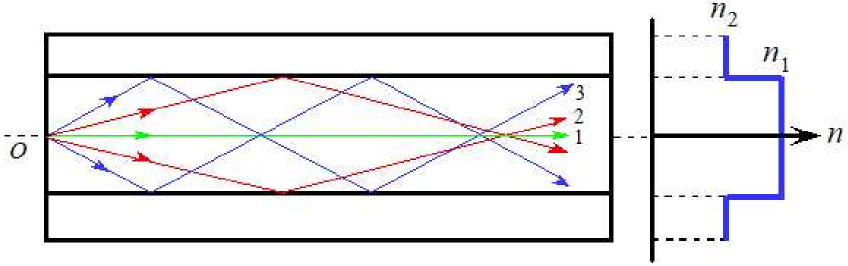
Single-mode fiber vs Multi-mode fiber



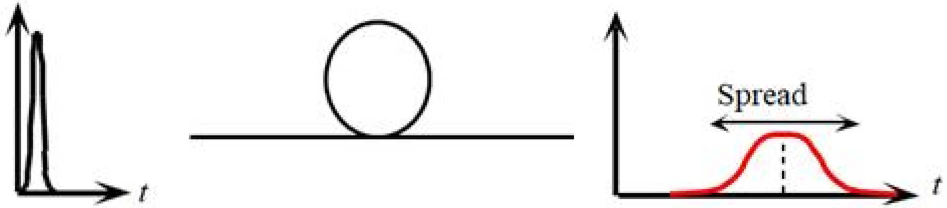
Core diameter: ~10 μm for single-mode fiber
10's μm for multi-mode fiber



Each mode has its own group velocity

$$(v_g = \frac{\partial \omega}{\partial \beta})$$

Multi-mode fiber suffers from modal dispersion



Spread determined by
group velocity differences and distance

➔ Transmission data rate limited

➔ Single-mode fiber for high-speed, long-distance optical communication

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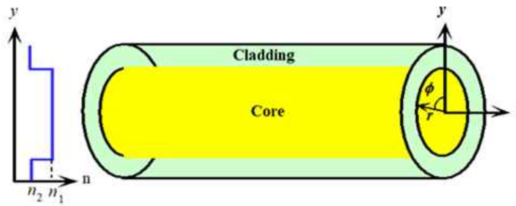
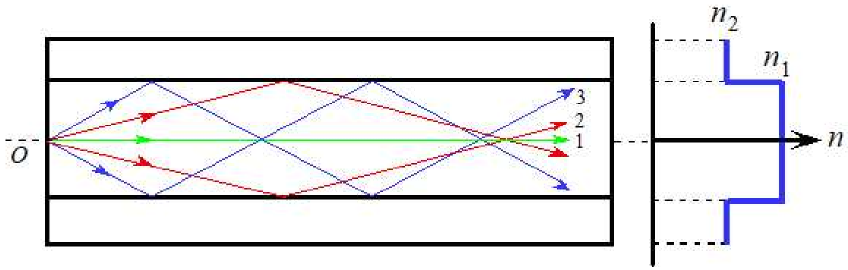
Single-mode fiber vs Multi-mode fiber



Core diameter: ~10 μm for single-mode fiber
10's μm for multi-mode fiber



➔ Single-mode fiber for high-speed, long-distance optical communication

Single-mode fiber has higher packaging cost

➔ Multi-mode fiber for short-distance optical communication

λ=1.55μm not required   λ=0.85 μm often used for cost effectiveness

Light source at 0.85 μm (VCSEL) is very cheap

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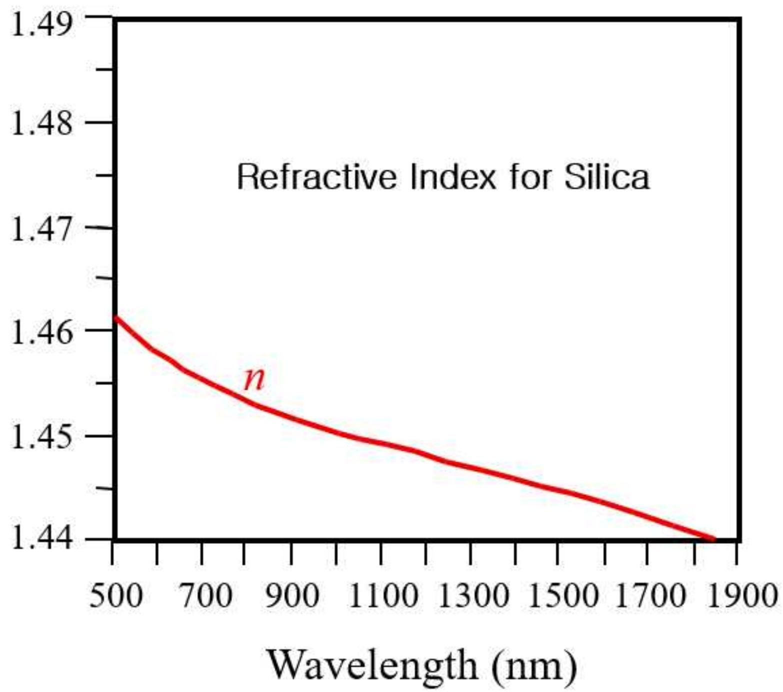
Single mode fiber also has small but non-zero dispersion

- Material (or chromatic) dispersion:

Refractive index of any material depends on wavelength (frequency)



➔ Group velocity depends on frequency (wavelength)

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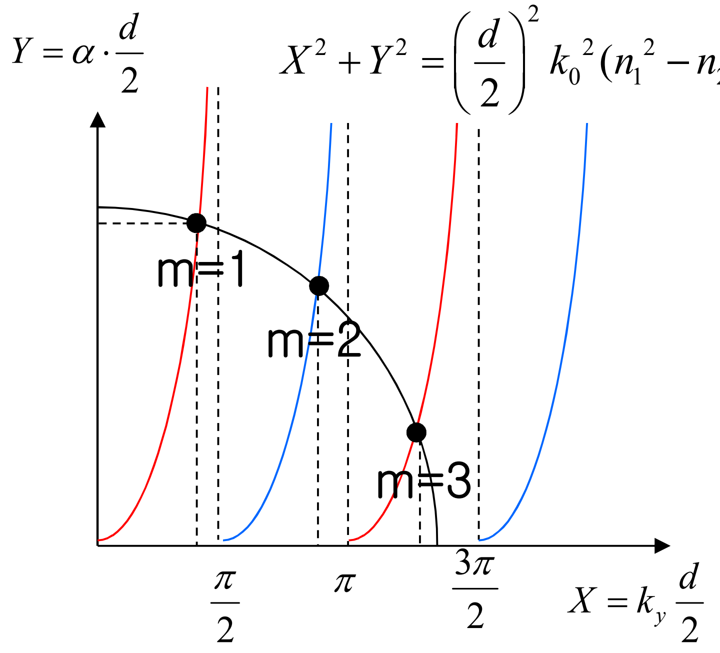
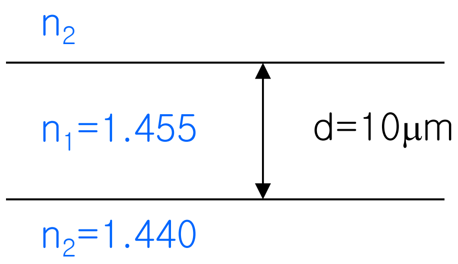
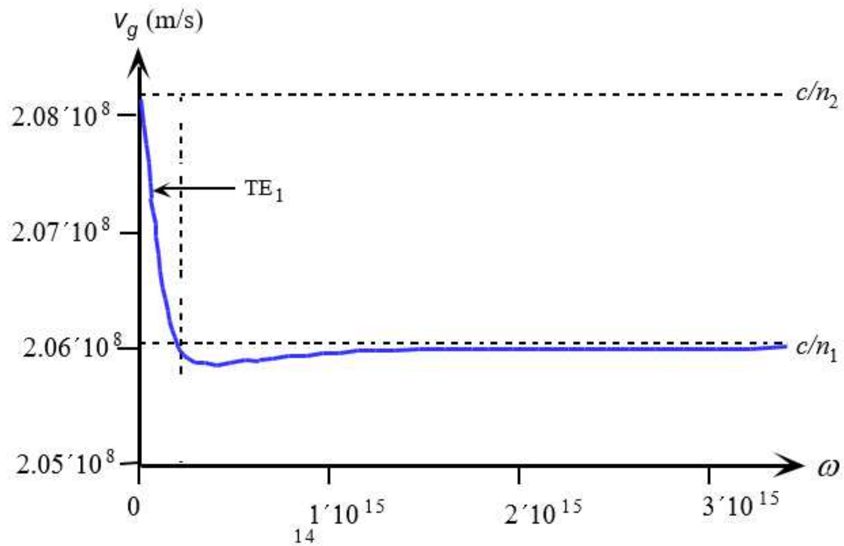
Single mode fiber also has small but non-zero dispersion

- Waveguide dispersion

  Even if refractive index does not change, v_g depends on frequency (wavelength)







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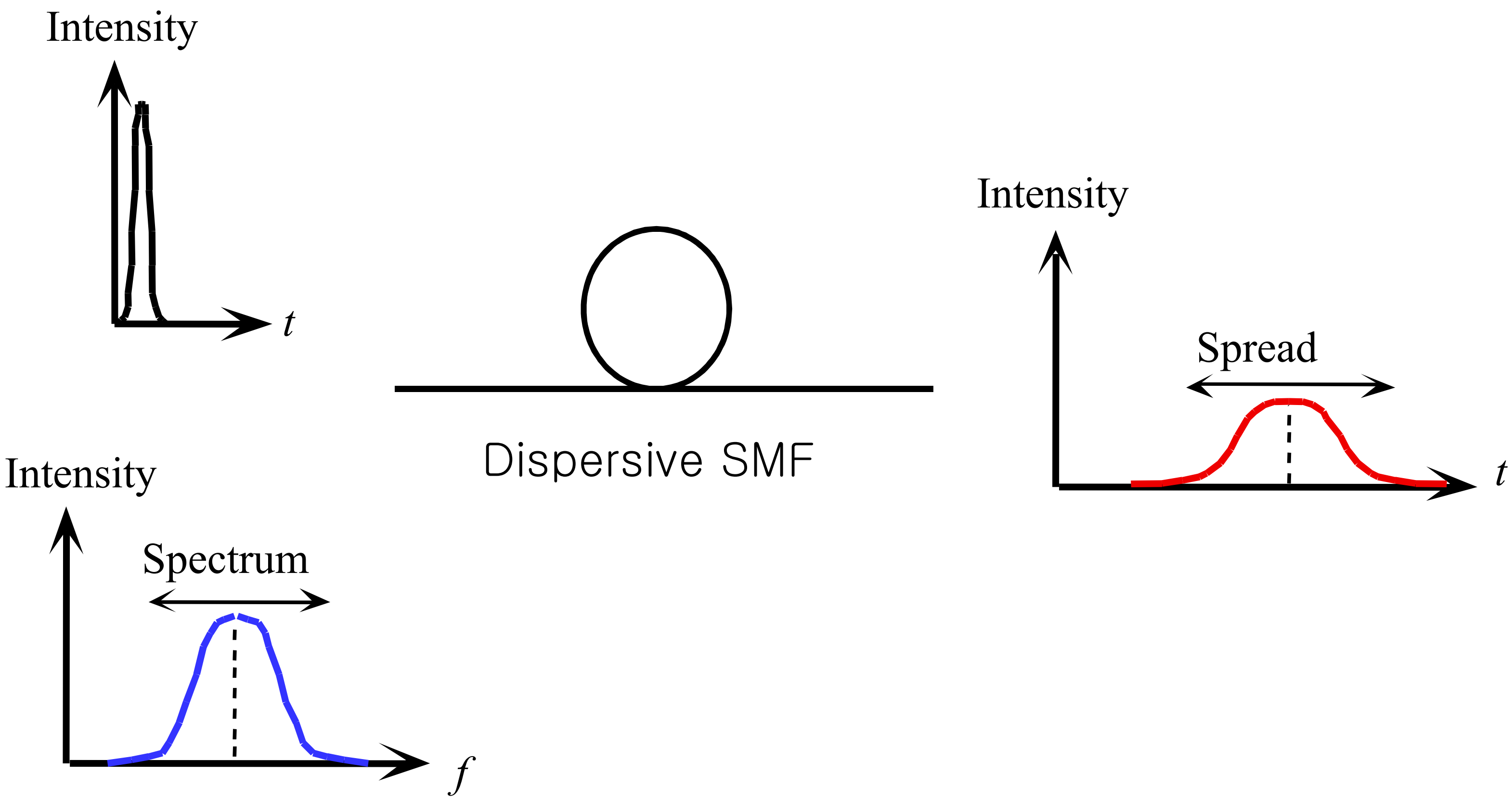
Dispersion in single-mode waveguide: Group velocity depends on frequency

➔ Limitation on data rate and transmission distance



Dispersion exists because β is not not linear with ω

Mathematically,

$$\beta(\omega_0+\omega)=\beta(\omega_0)+\left.\frac{\partial\beta}{\partial\omega}\right|_{\omega_0}\cdot\omega+\frac{1}{2}\left.\frac{\partial^2\beta}{\partial\omega^2}\right|_{\omega_0}\cdot\omega^2+\bullet\bullet\bullet$$

$$\approx\beta(\omega_0)+\beta_1(\omega_0)\cdot\omega+\frac{1}{2}\beta_2(\omega_0)\cdot\omega^2$$

$$=\beta(\omega_0)+\frac{1}{v_g(\omega_0)}\cdot\omega+\frac{1}{2}\frac{\partial}{\partial\omega}\left.\left(\frac{1}{v_g}\right)\right|_{\omega_0}\cdot\omega^2$$

In Silica fiber, $\beta_2\sim -20\ \mathrm{ps}^2/\mathrm{km}$ at λ=1.5μm

With $\beta_2<0$, v_g increases as ω increases

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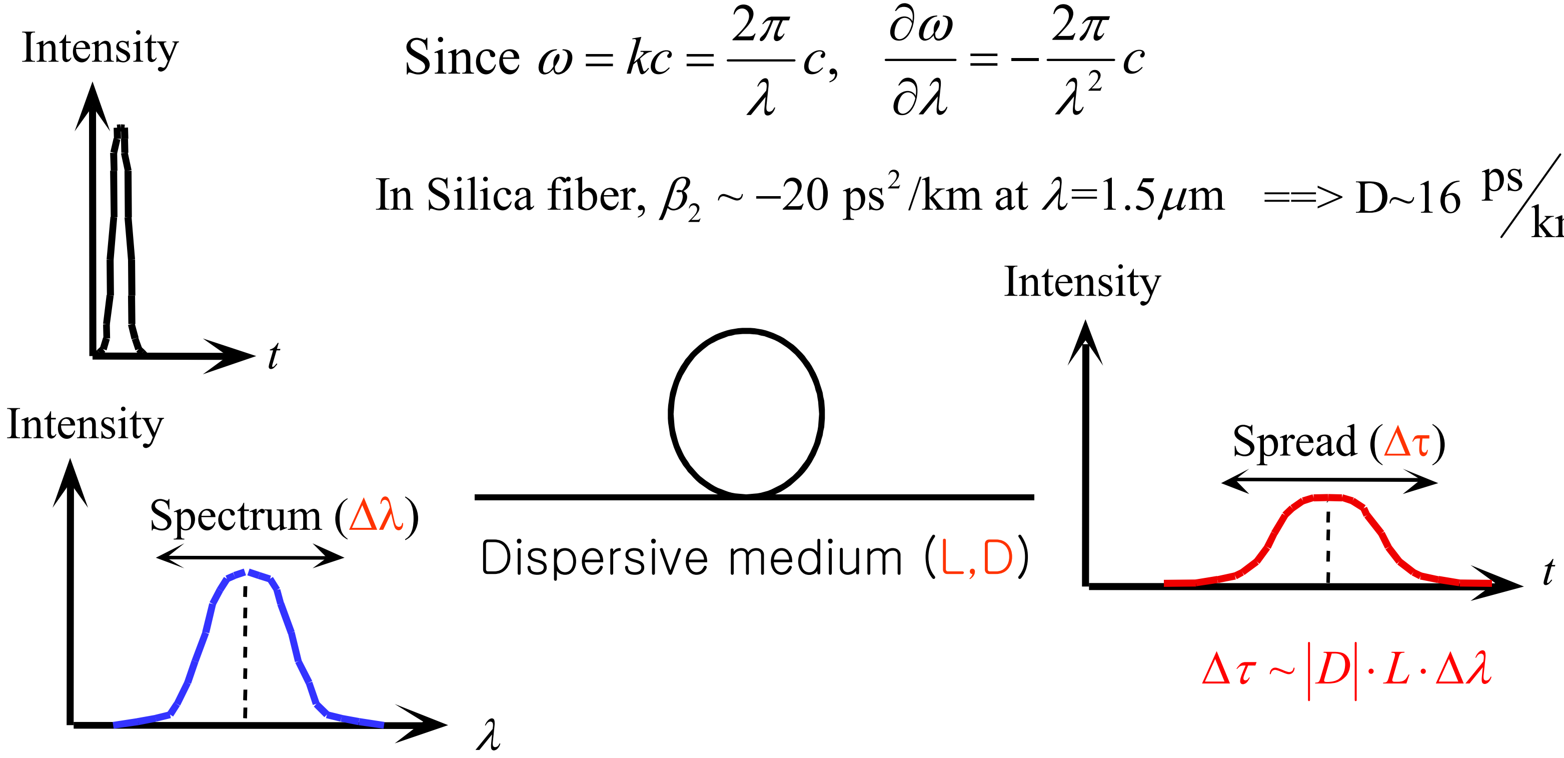
Often, dispersion parameter D is used.

$$D = \frac{\partial \beta_1}{\partial \lambda} = \frac{\partial \omega}{\partial \lambda}\frac{\partial \beta_1}{\partial \omega} = \frac{\partial \omega}{\partial \lambda}\beta_2 = -\frac{2\pi}{\lambda^2}c\beta_2$$

Since $\omega = kc = \frac{2\pi}{\lambda}c, \quad \frac{\partial \omega}{\partial \lambda} = -\frac{2\pi}{\lambda^2}c$

In Silica fiber, $\beta_2 \sim -20\ \mathrm{ps}^2/\mathrm{km}$ at λ=1.5μm ==> D~16 $\mathrm{ps}/\mathrm{km}\cdot\mathrm{nm}$



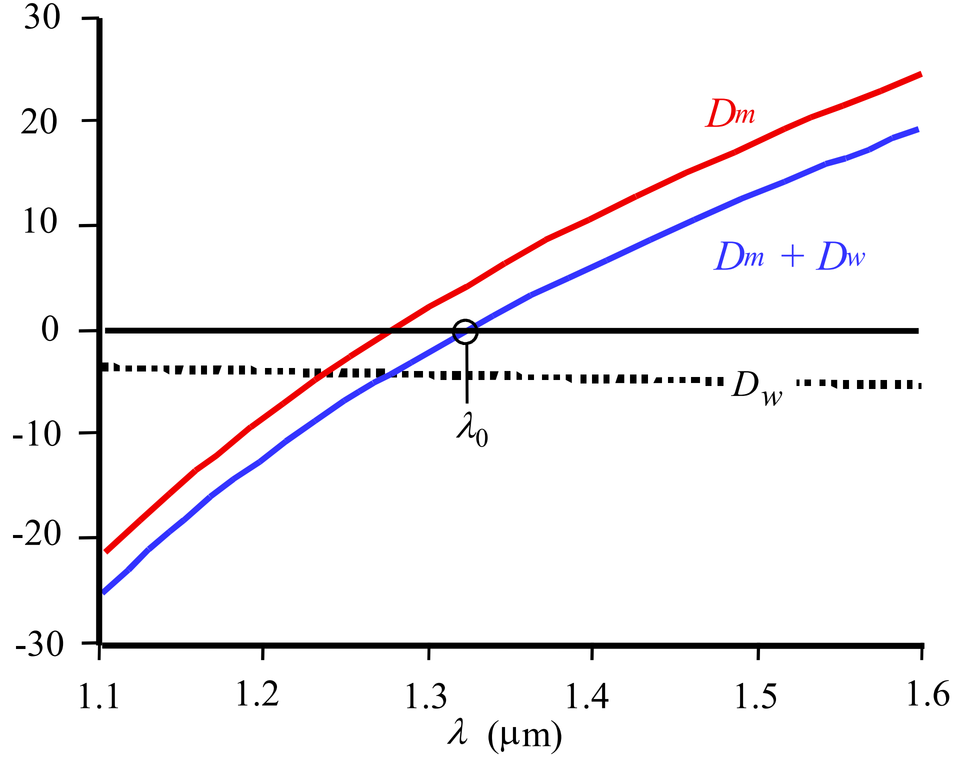
$\Delta\tau \sim |D| \cdot L \cdot \Delta\lambda$

Dispersion coefficient, D, for silica fiber with a=4.2μm

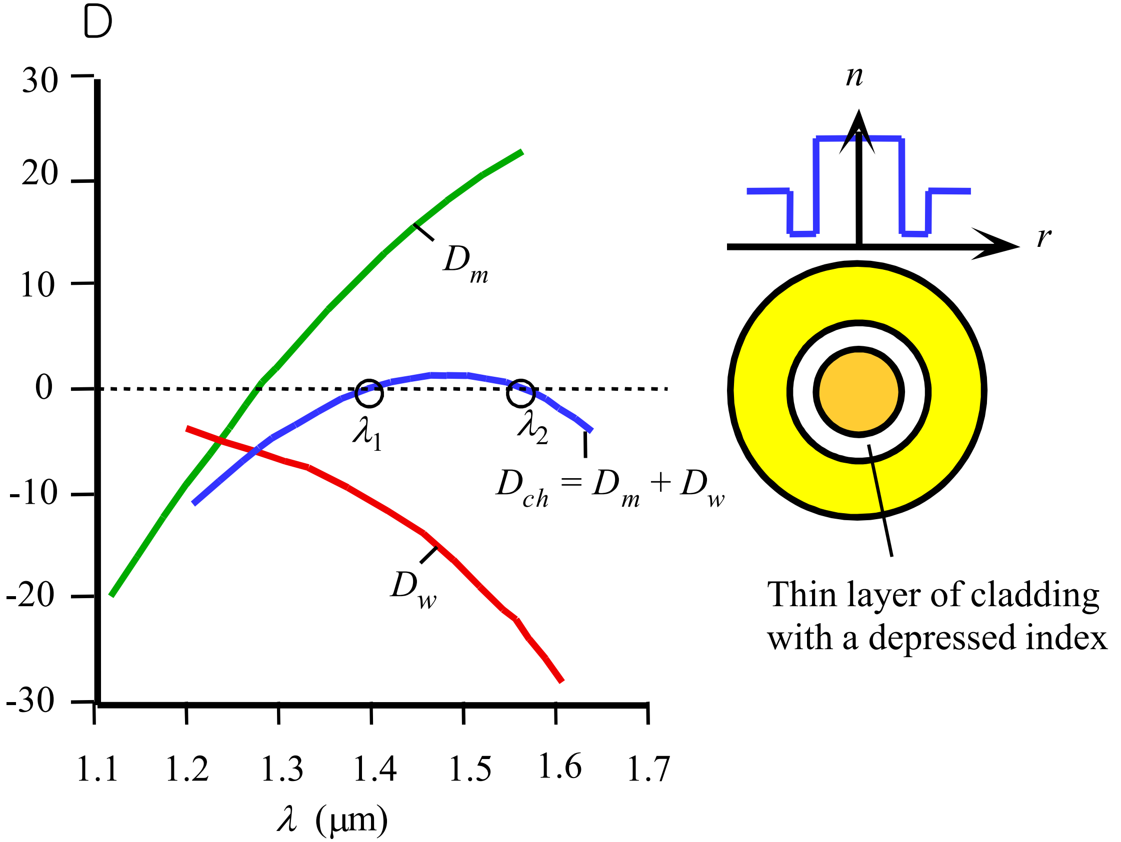
D_m: material (chromatic) dispersion only

D_w: waveguide dispersion only

D_m+D_w: total dispersion



It is possible to control D by changing waveguide structure
(Dispersion Flattened Fiber)



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Homework:

A fiber has its core refractive index given as $n_1(z) = n_0 + \Delta n \sin[(2\pi/d) z)$ as shown below.

$$n_2 = 1.497$$

$$n_1 = 1.5 + \Delta n \cdot \sin(\frac{2\pi}{d} Z),\ \text{core radius: } 5\mu\text{m}$$

(a) Using the fiber b-V diagram given in the lecture notes, determine the approximate value of the effective index for the fundamental guided mode. For this problems, assume $\Delta n = 0$, the cladding layer is infinitely thick and λ=1.5μm.

(b) With a very small amount of Δn so that the effective index of the guided mode does not change from the value obtained in (a), the fiber can reflect light having a specific wavelength of 1.5μm. Determine the numerical value d (with its unit) so that the reflection efficiency is highest.

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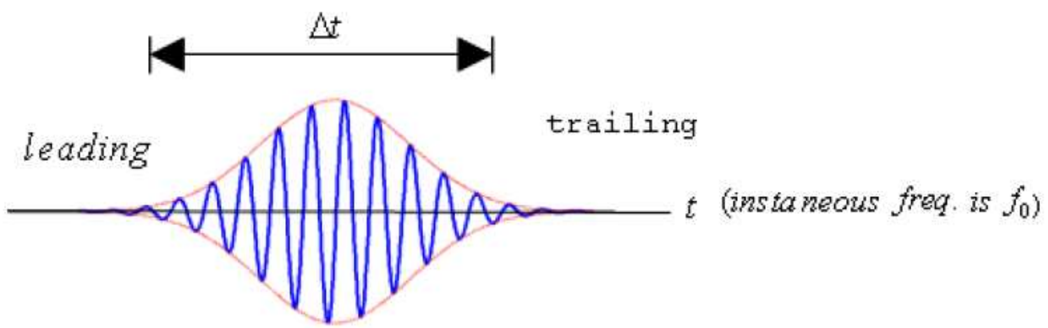
Homework

The time-domain profile of an E-field for an optical pulse is sketched below.

Assume the carrier frequency is f_0 and the envelop has a Gaussian shape.



(a)(10) Sketch the frequency-domain spectrum (f>0 only) of the E-field pulse. Clearly indicate important features of your sketch.

(b)(10) The pulse has propagated in a fiber with a positive dispersion parameter (D>0). Sketch the resulting time-domain profile of the E-field pulse. Clearly indicate important features of your sketch.