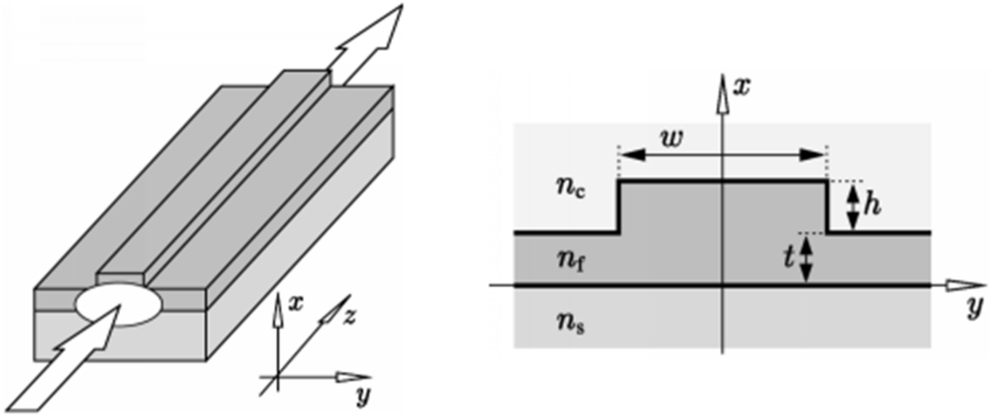
Lect. 17: Optical Fiber

3-dimentioanl dielectric waveguide?

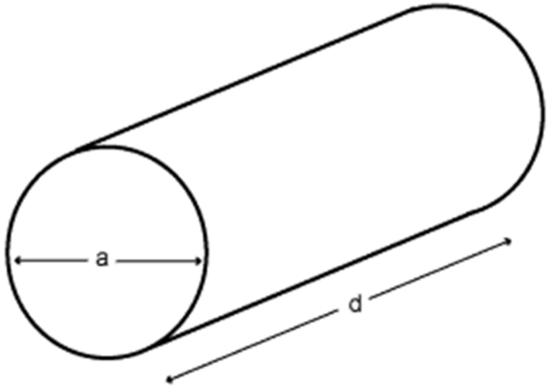


planar waveguide

- Analysis very complicated
- Contains the same qualitative features

➔ TE, TM modes, cut-off frequency, …

- Design Exercise 2



circular waveguide

➔ Optical fiber

circular w

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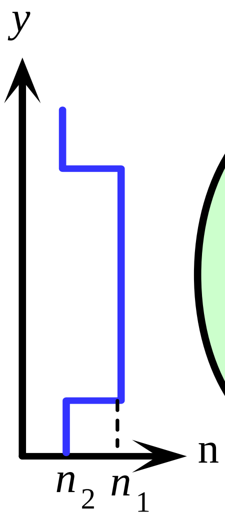
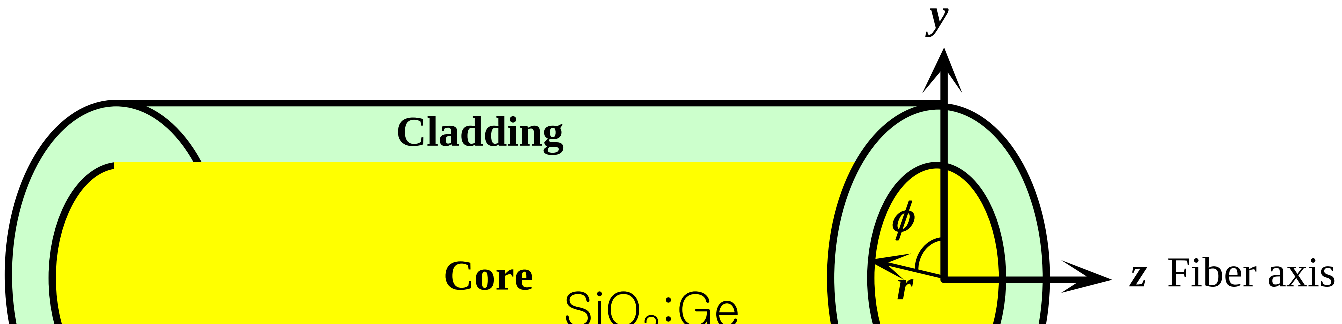
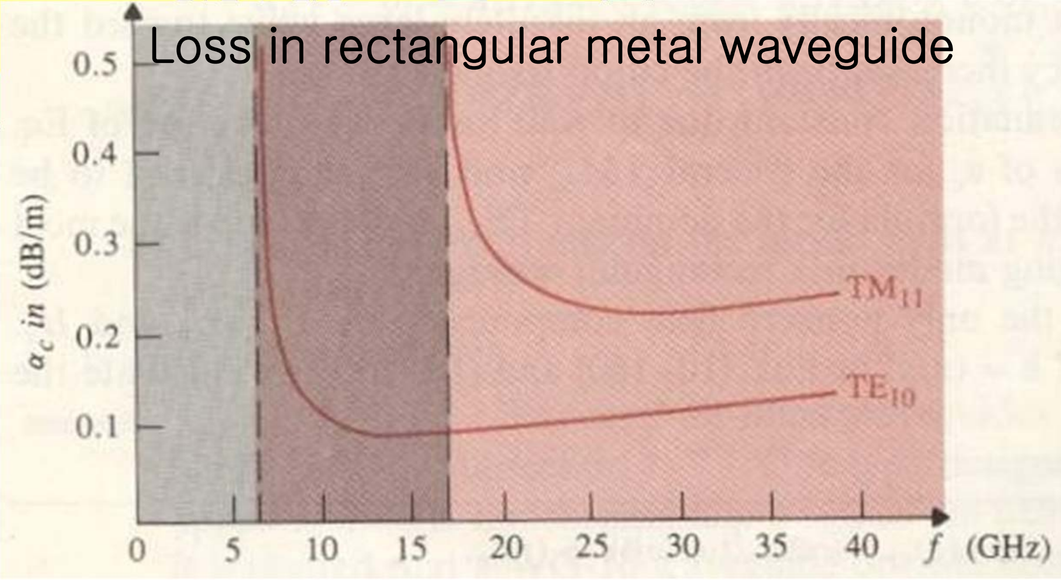
Optical Fiber: Circular dielectric waveguide made of silica (SiO_2)







Loss in rectangular metal waveguide

What is special about fiber?

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

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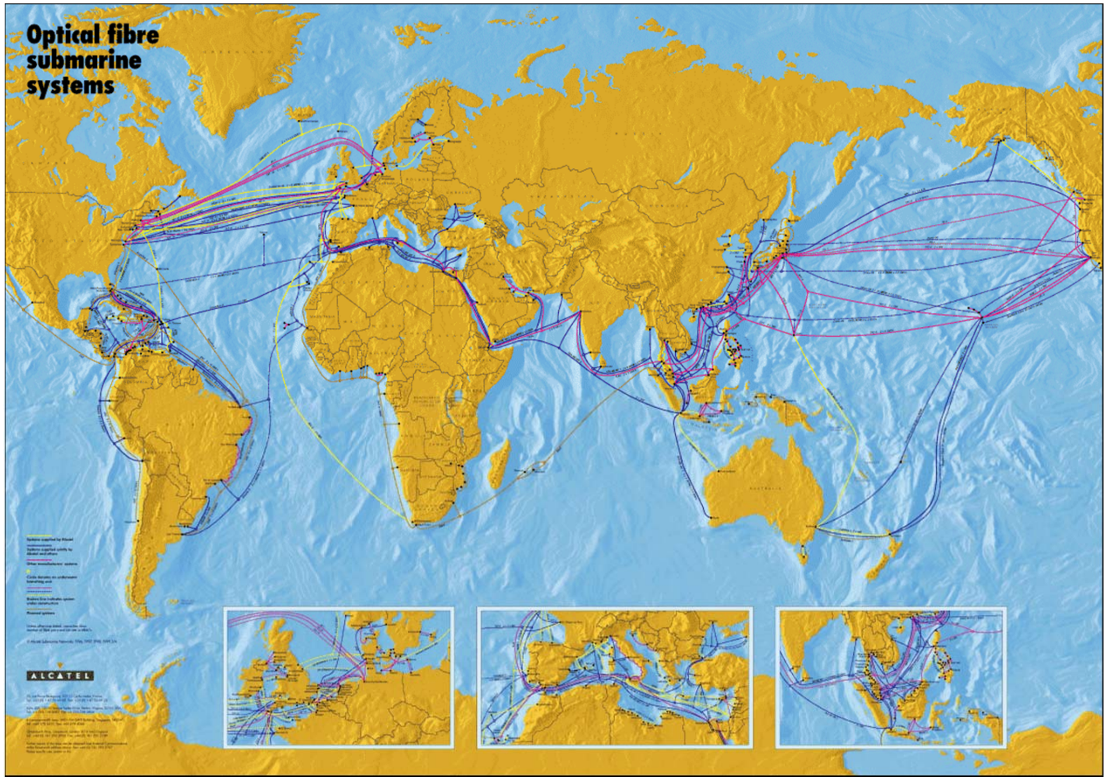
Optical Communication Networks



Total undersea fiber length: 0.4 billion km (628 round trips between earth and moon)

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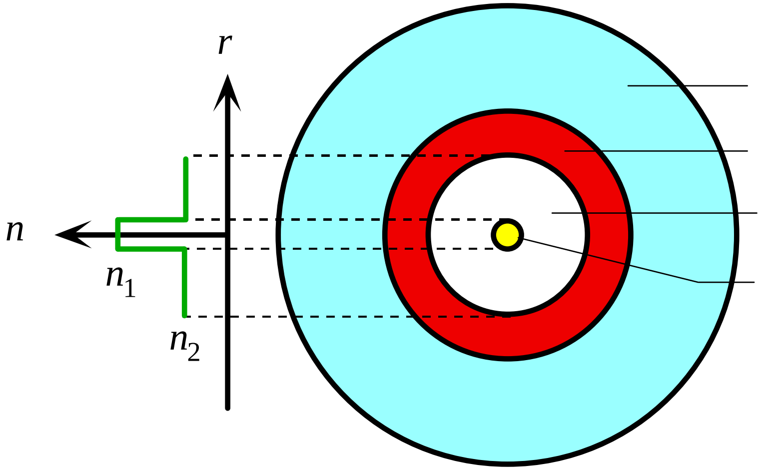

Buffer tube: d = 1mm

Protective polymerinc coating

Cladding: d = 125 - 150 μm

Core: d = 8 - 10 μm for single-mode fiber

(For multi-mode fiber, d: several tens of μm)

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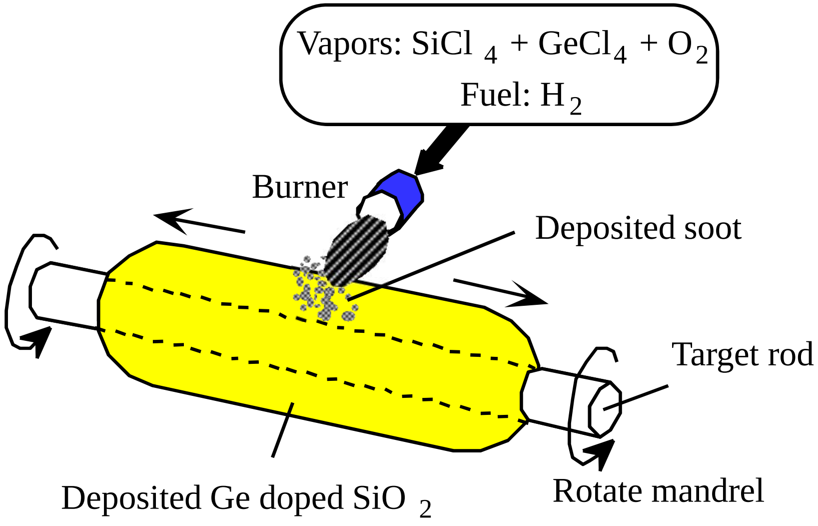
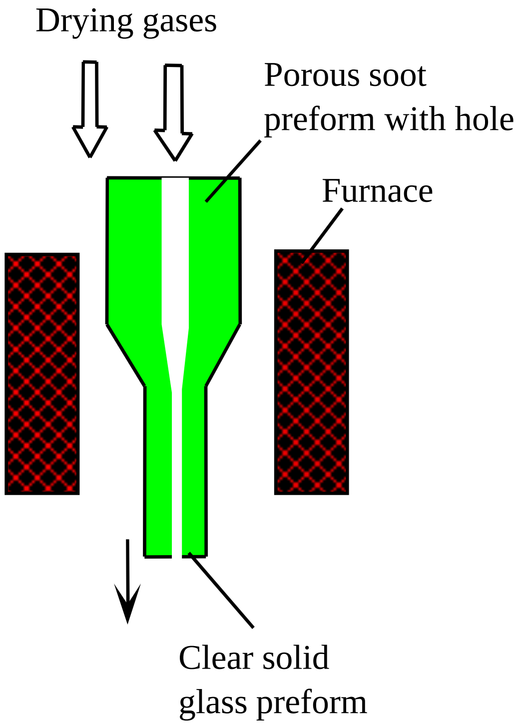


$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$

$GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2$



Sintering at 1400−1600 deg C

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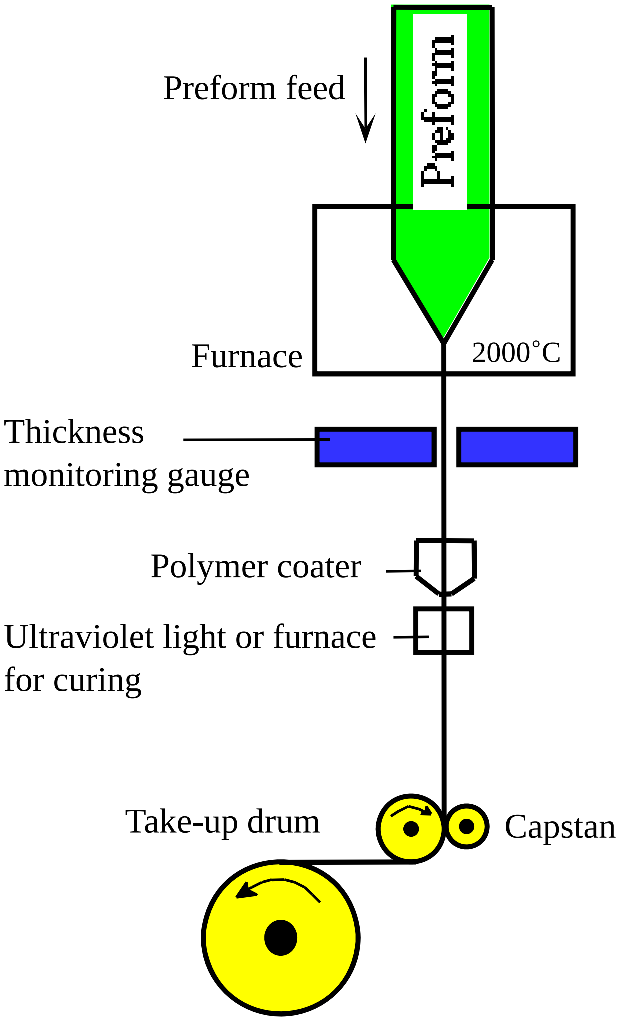

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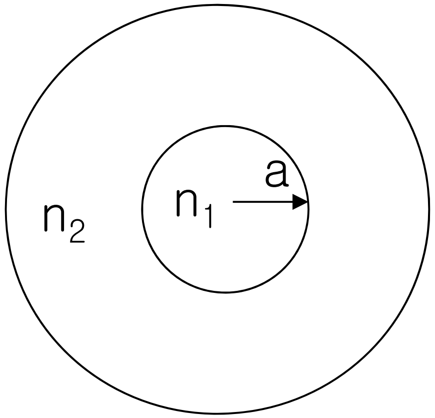
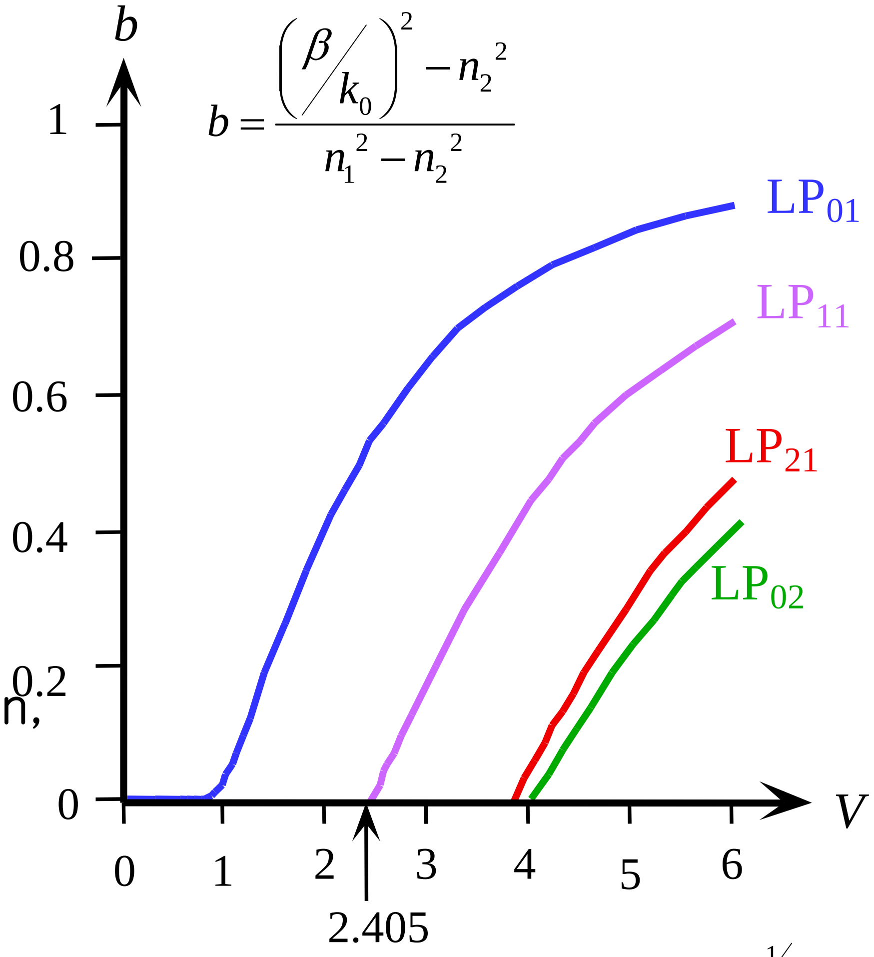


Solving for guided modes for circular dielectric waveguide problem in (r, θ, z) coordinate is very complicated.

It can be shown that with a little approximation, LP (linearly polarized) mode solutions are obtained

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


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

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

(a : fiber core radius)

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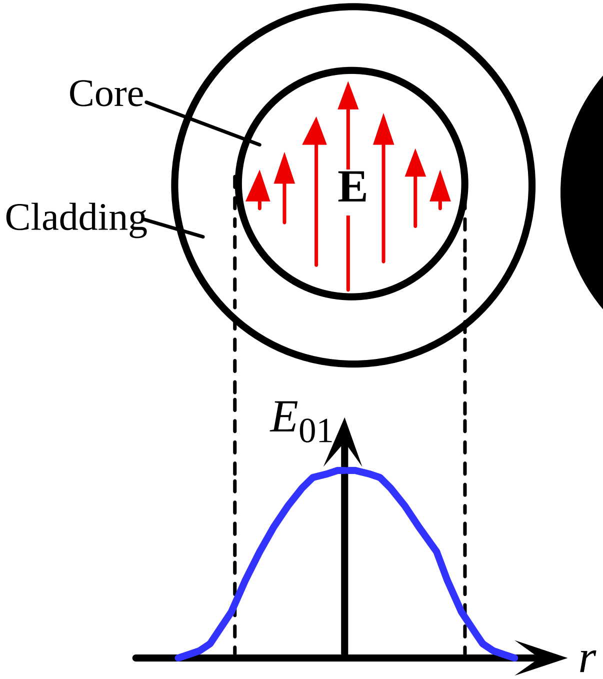
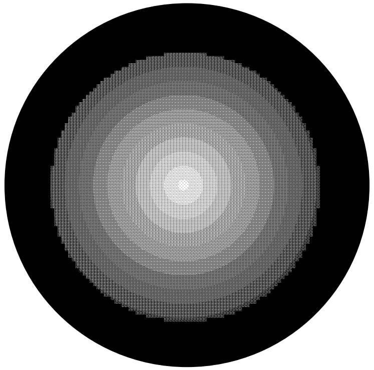
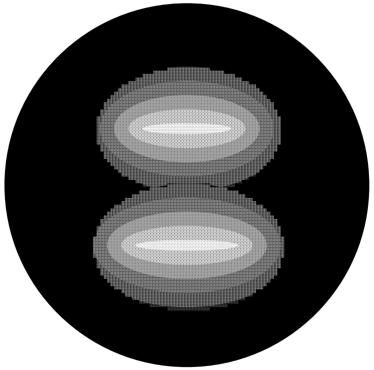


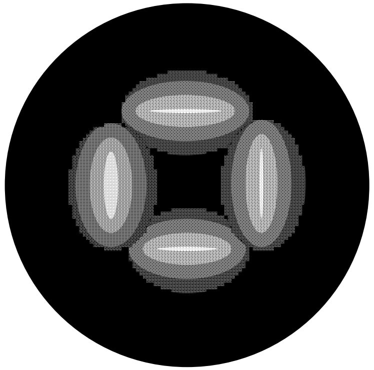
(a) The electric field of the fundamental mode



(b) The intensity in the fundamental mode LP_{01}



(c) The intensity in LP_{11}



(d) The intensity in LP_{21}

For LP_{lm} mode,
m represents the number of peaks along r,
2l represents the number of peaks along ϕ

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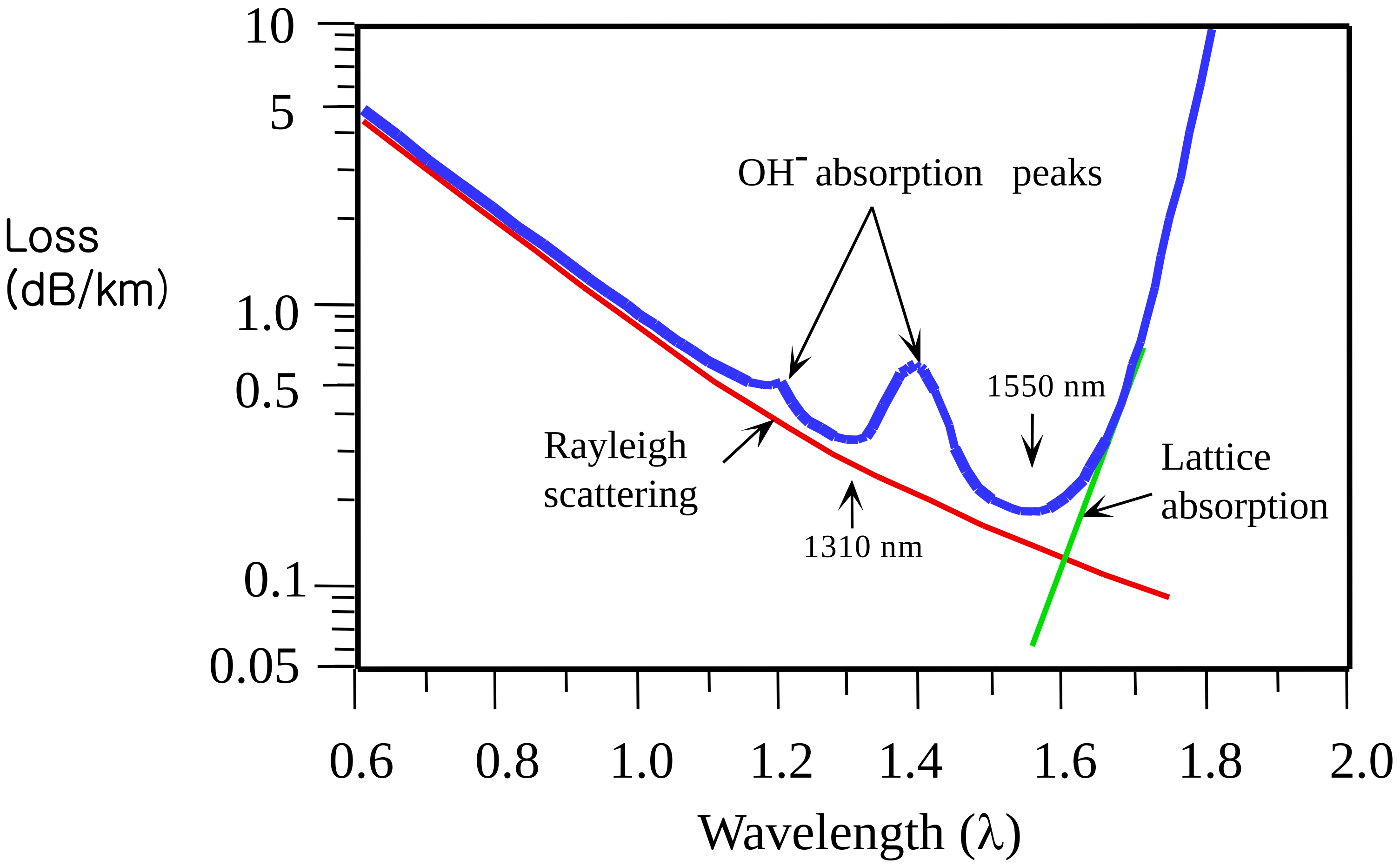
Loss in fiber



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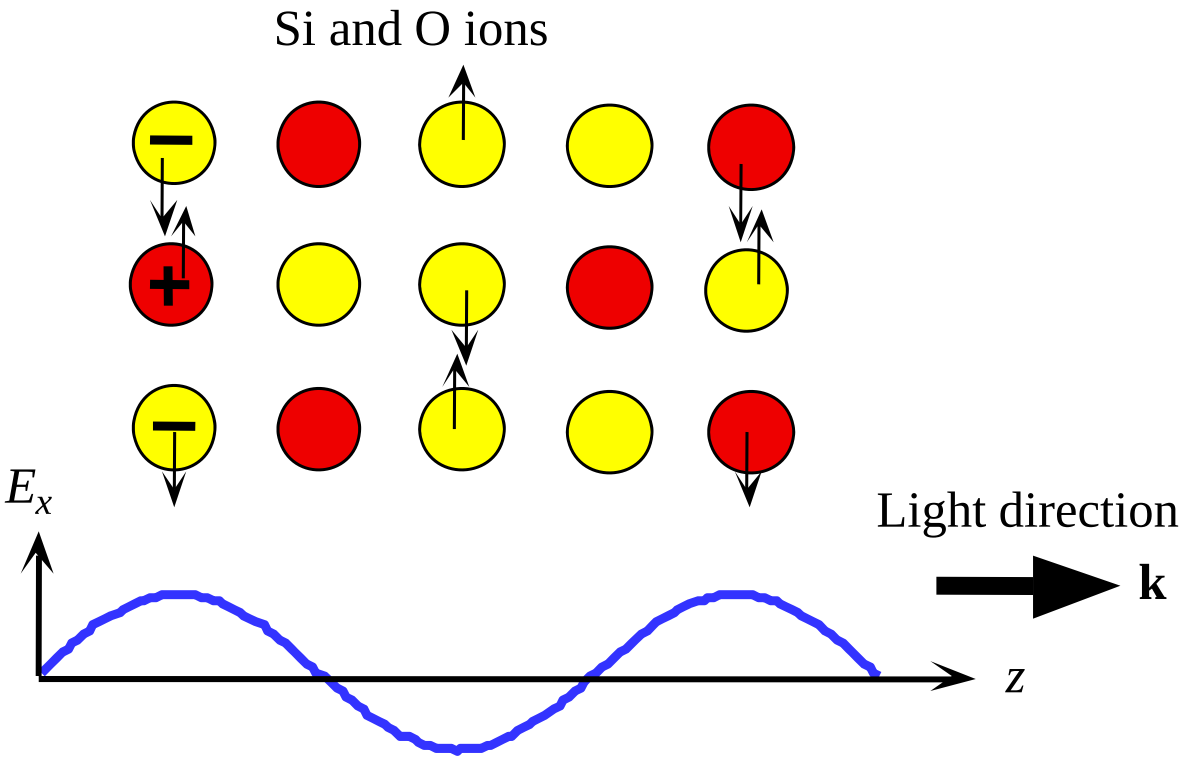
Lattice Absorption:
EM waves cause vibration of ions inside fiber.
Peak absorption occurs at around λ= 9 μm in Silica fiber.



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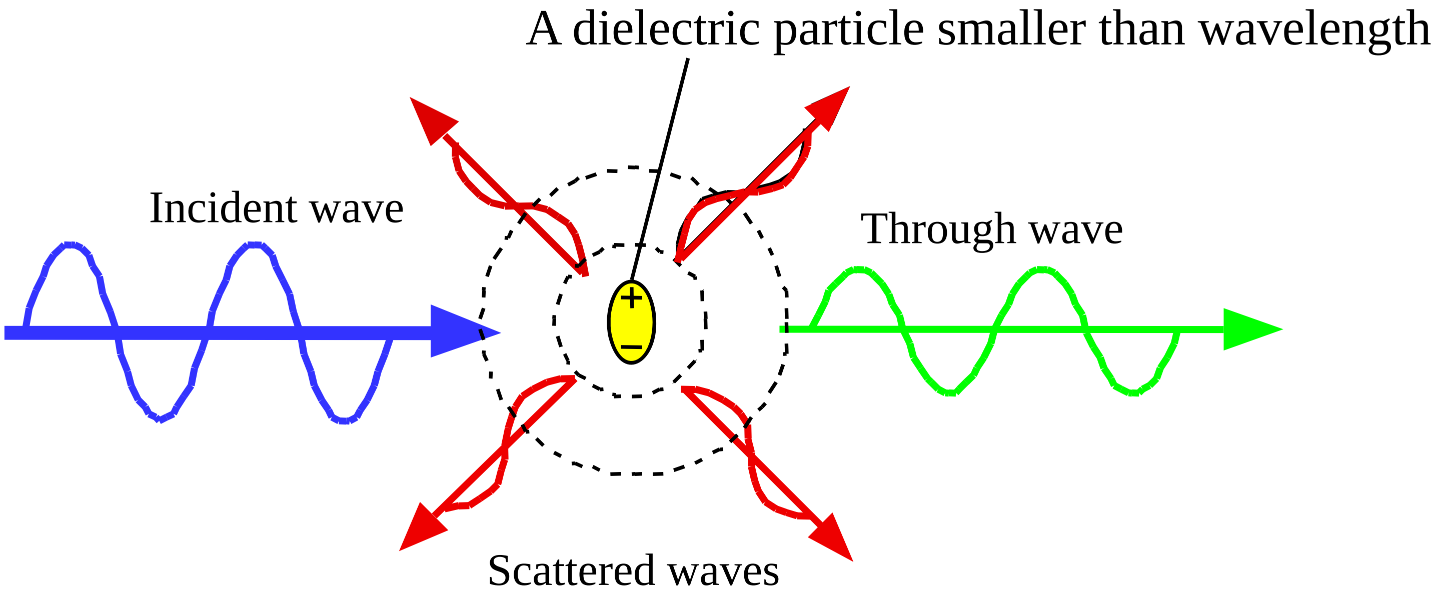
Rayleigh scattering
A small portion of EM waves get directed away from small dielectric particles due local fluctuation of fiber refractive index.
More scattering with smaller wavelength (inversely proportional to λ^3).



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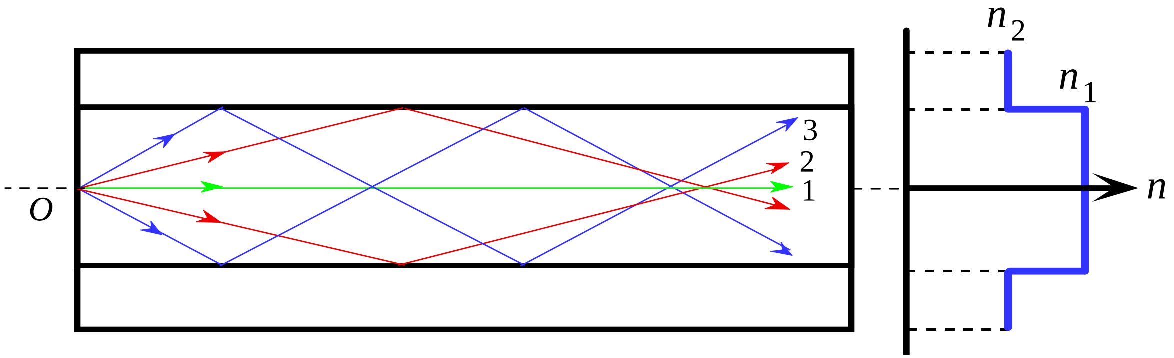
Dispersion in Fiber

- Multi-Mode Fiber: Modal Dispersion



Each mode has its own group velocity (Group index: $n_g = c/v_g$)

If a light pulse is decomposed into many modes,
the pulse gets dispersed (broadened) after propagation

Prevention: Use single mode fiber!

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But single mode fiber also has small but non-zero dispersion

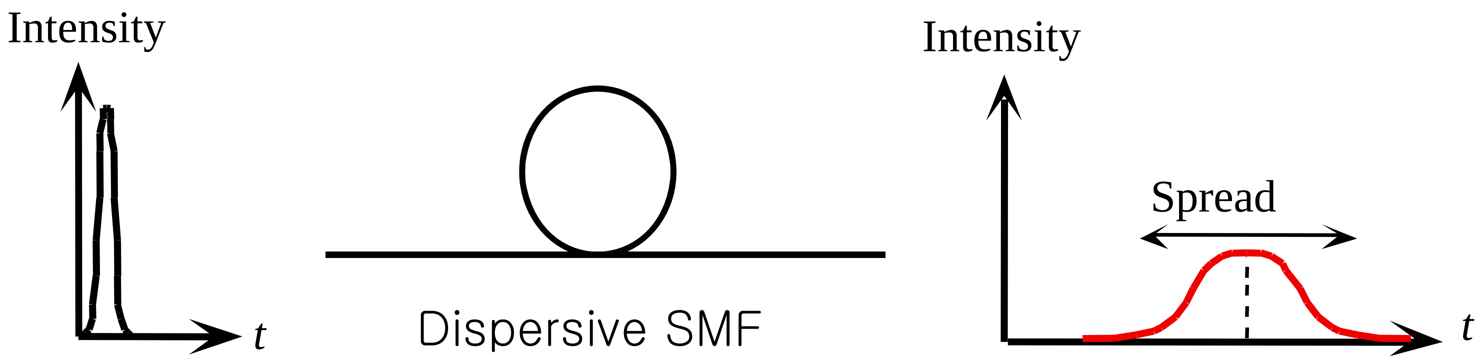
- Waveguide dispersion

Waveguide solution depends on wavelength

- Material (or chromatic) dispersion:

Refractive index of any material depends on wavelength (frequency)

➔ v_g for SMF depends on wavelength(frequency)



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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 $\lambda=1.5\mu\mathrm{m}$

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

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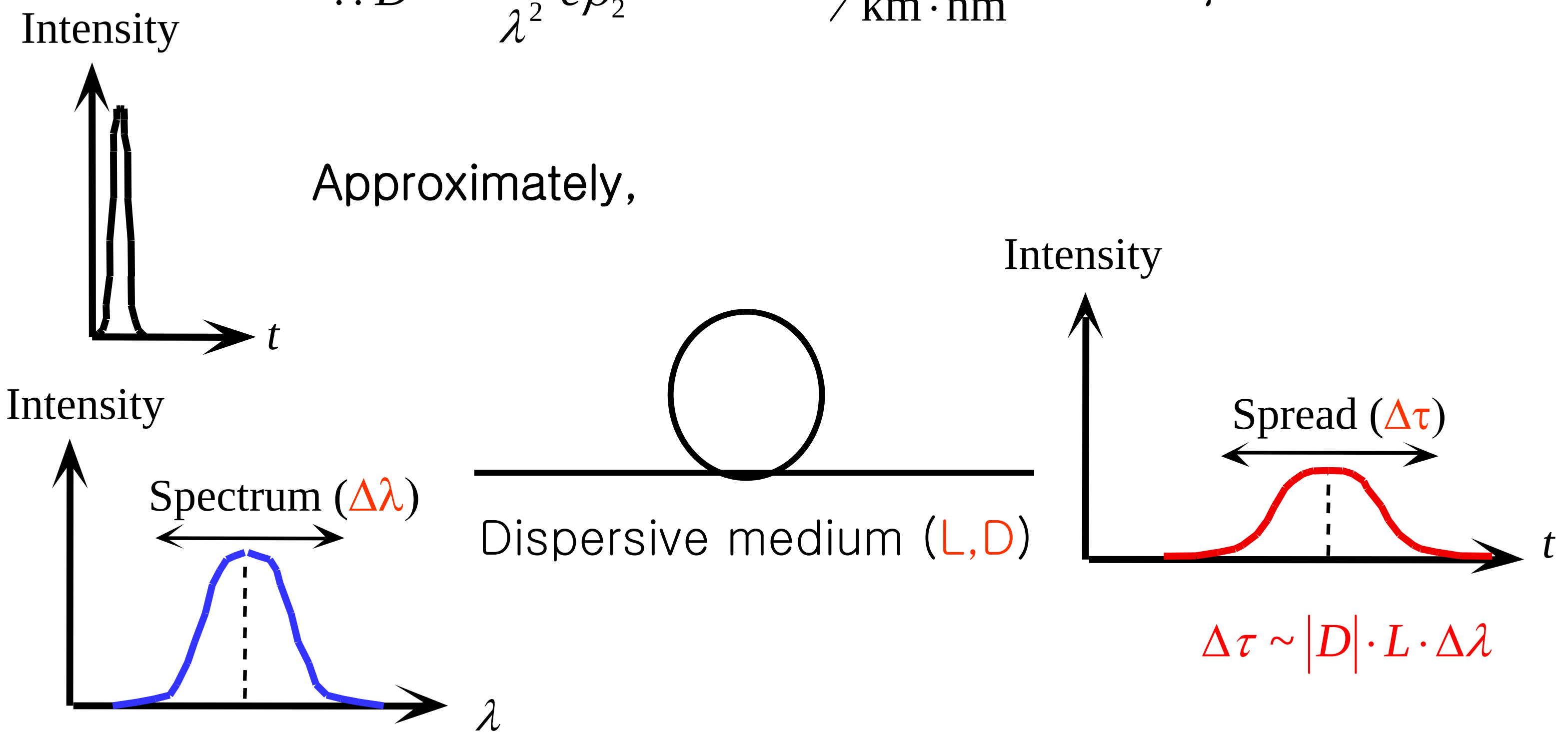
Often, dispersion parameter D is used.

$$D = \frac{\partial \beta_1}{\partial \lambda} = \frac{\partial \omega}{\partial \lambda}\frac{\partial \beta_1}{\partial \omega} = \frac{\partial \omega}{\partial \lambda}\beta_2 \qquad \frac{\partial \omega}{\partial \lambda} = -\frac{2\pi}{\lambda^2}c \quad (\because\ \omega = kc = \frac{2\pi}{\lambda}c)$$

$$\therefore D = -\frac{2\pi}{\lambda^2}c\beta_2 \qquad \mathrm{D}\sim 16\ {}^{\mathrm{ps}}\!/_{\mathrm{km\cdot nm}} \ \text{at}\ \lambda = 1.5\mu m$$

Approximately,



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

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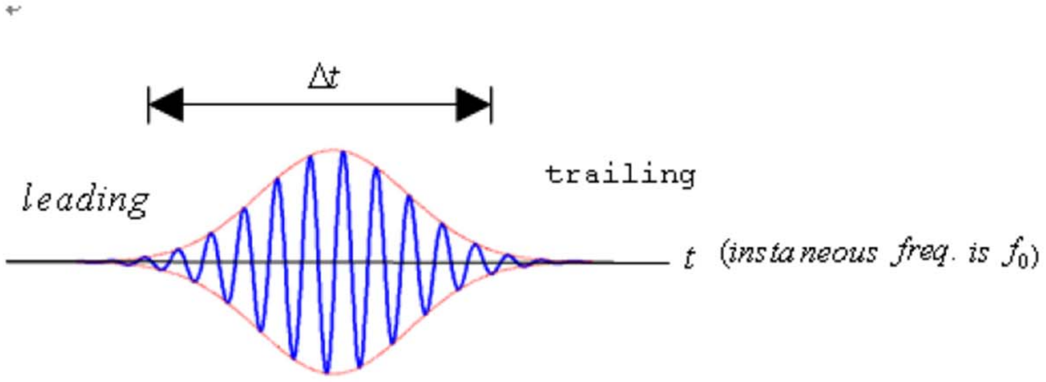
Homework

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.