Lecture 7: Optical waveguides

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Types of guiding structures:

- Planar waveguides (integrated optics)
- Fibers (communications)

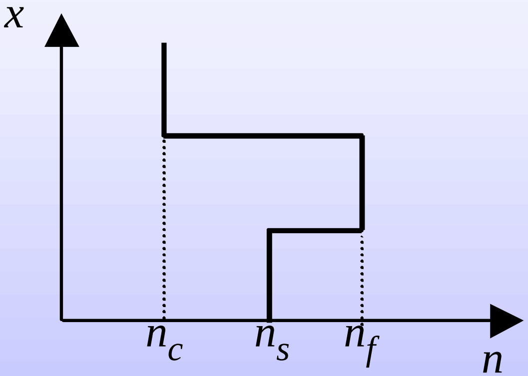
Theory:

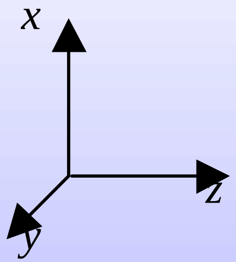
- Rays and field approach
- Various shapes and index profiles

Attenuation and dispersion

Coupling of light into the waveguide

Homogeneous planar waveguide

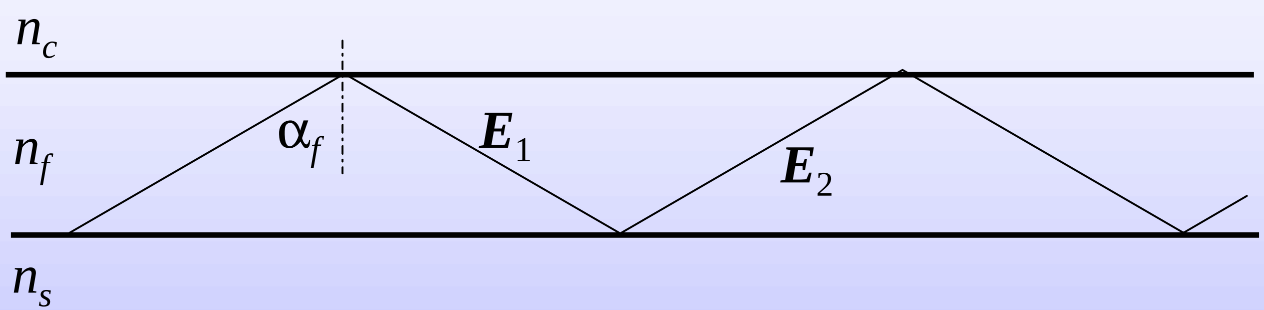




Series of total internal reflections (angle of incidence α_f):

$$\sin\alpha_f > \frac{n_s}{n_f} > \frac{n_c}{n_f}$$

Transverse resonance condition



$$E_1 = E_{10} \exp\left(i\omega t - ikn_f\,(-x\cos\alpha_f + z\sin\alpha_f)\right)$$

$$E_2 = E_{20} \exp\left(i\omega t - ikn_f\,(x\cos\alpha_f + z\sin\alpha_f)\right)$$

$$E_1(x=h)\,e^{i\delta_c} = E_2(x=h)$$

$$E_2(x=0)\,e^{i\delta_s} = E_1(x=0)$$

→ Phase change during total reflection

Waveguide equation

Continuity of $\boldsymbol{E}_1$ and $\boldsymbol{E}_2$ lead to:

$$\exp\left(-2ikn_f h\cos\alpha_f + i\delta_c + i\delta_s\right) = 1$$

Waveguide dispersion equation:

$$2kn_f h\cos\alpha_f = \delta_c + \delta_s + 2\pi m$$

Solution numeric or graphic

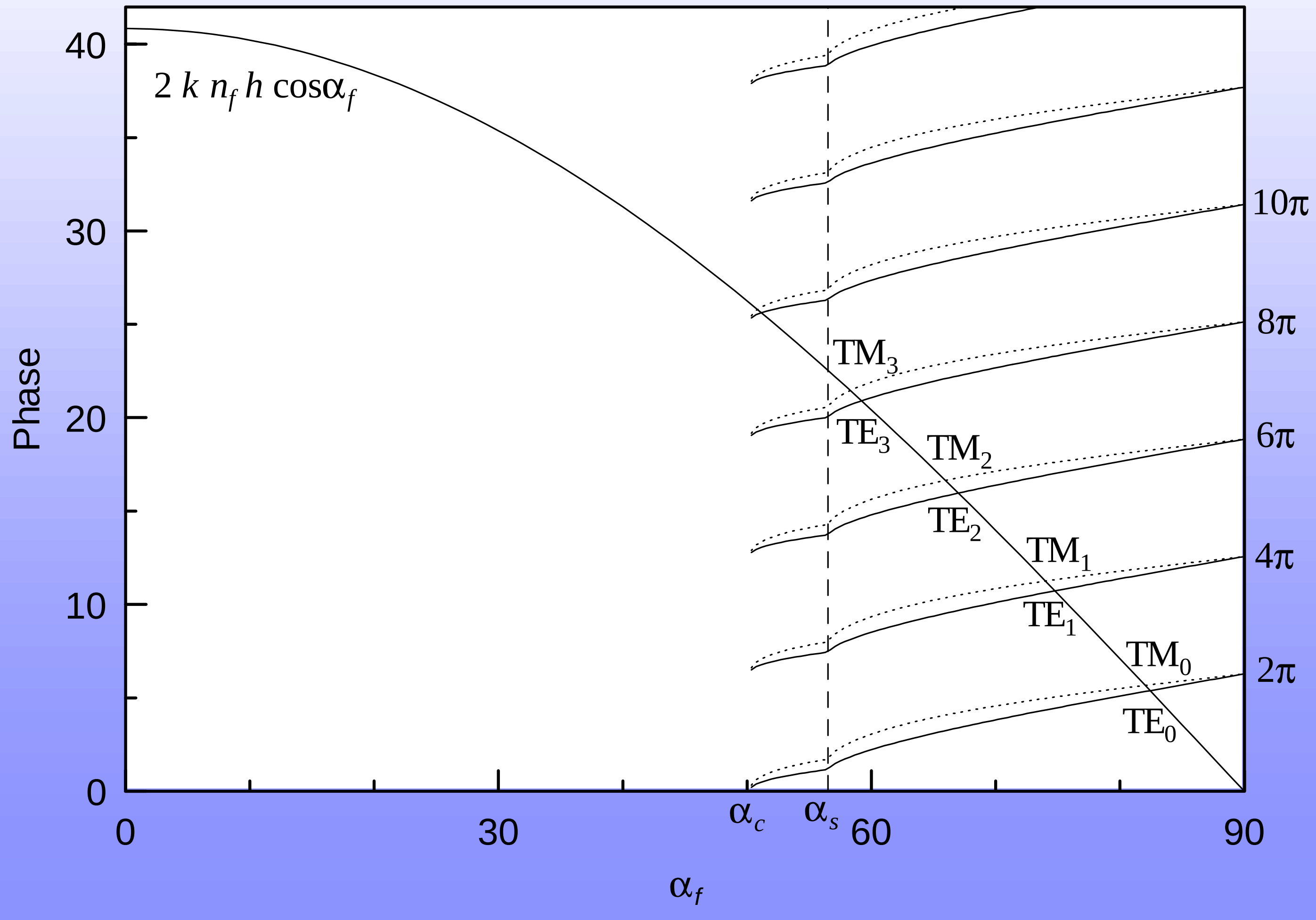
kh increase $\rightarrow$ number of modes increase

symmetric waveguide $\rightarrow$ at least one guided mode

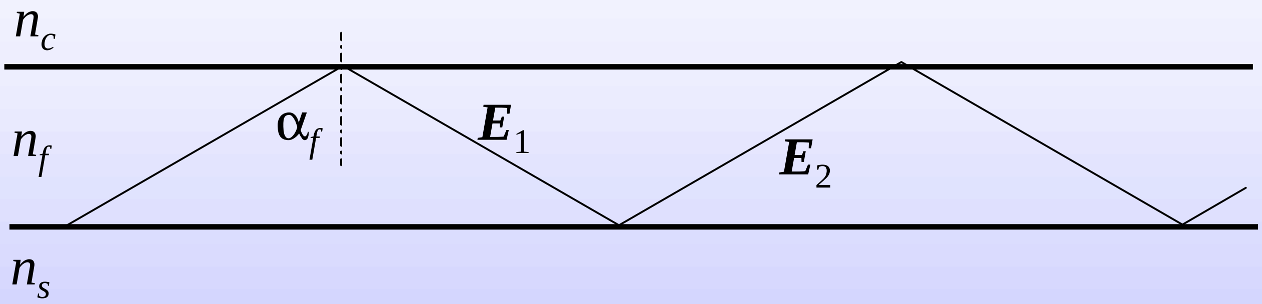
non-symmetric waveguide, small kh $\rightarrow$ no guided mode

Graphic solution

Graphic solution of the waveguide equation



Longitudinal propagation



Longitudinal propagation constant:

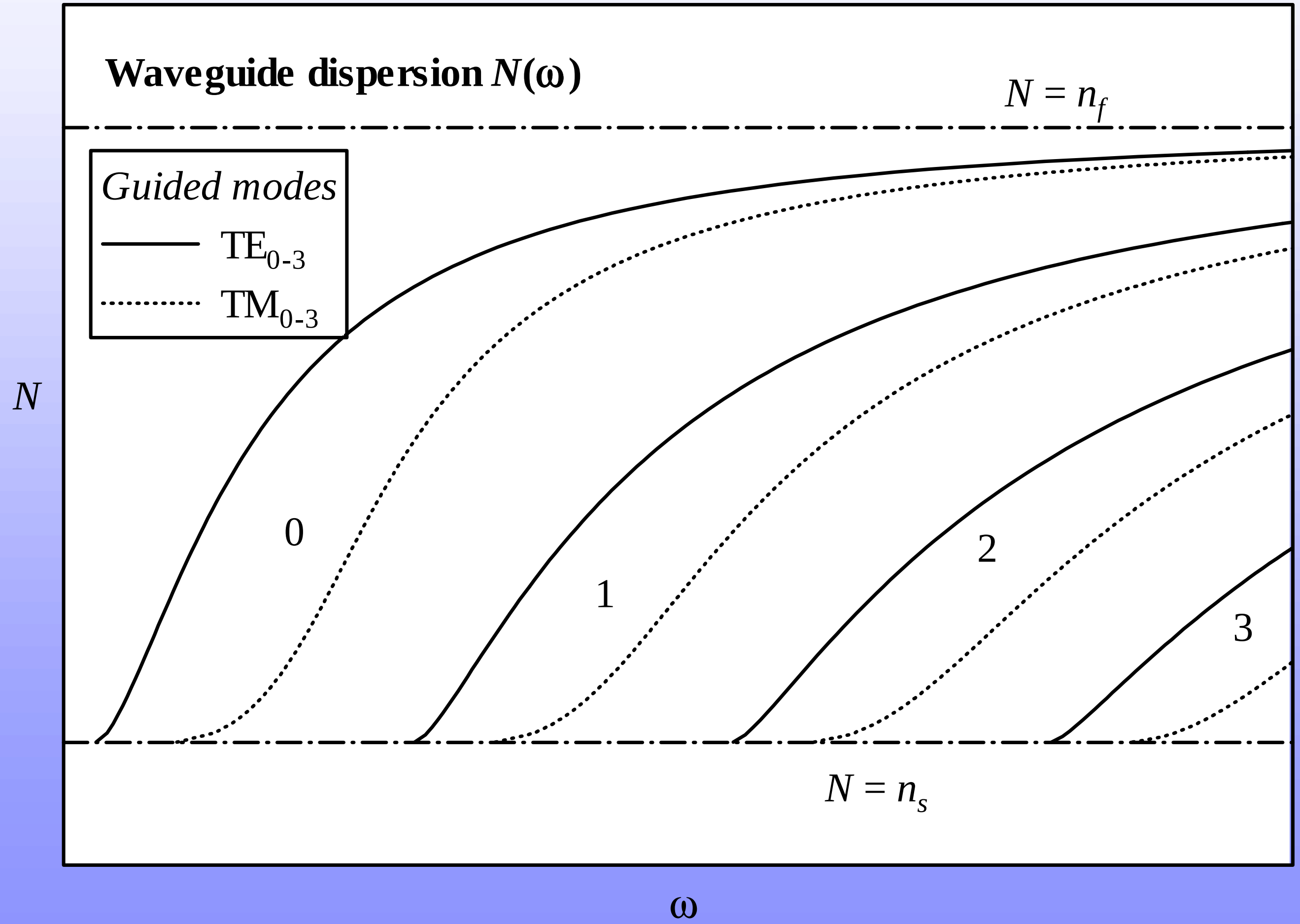
$$\beta = kn_f \sin\alpha_f = \frac{\omega}{c} n_f \sin\alpha_f(\omega)$$

Effective refractive index:

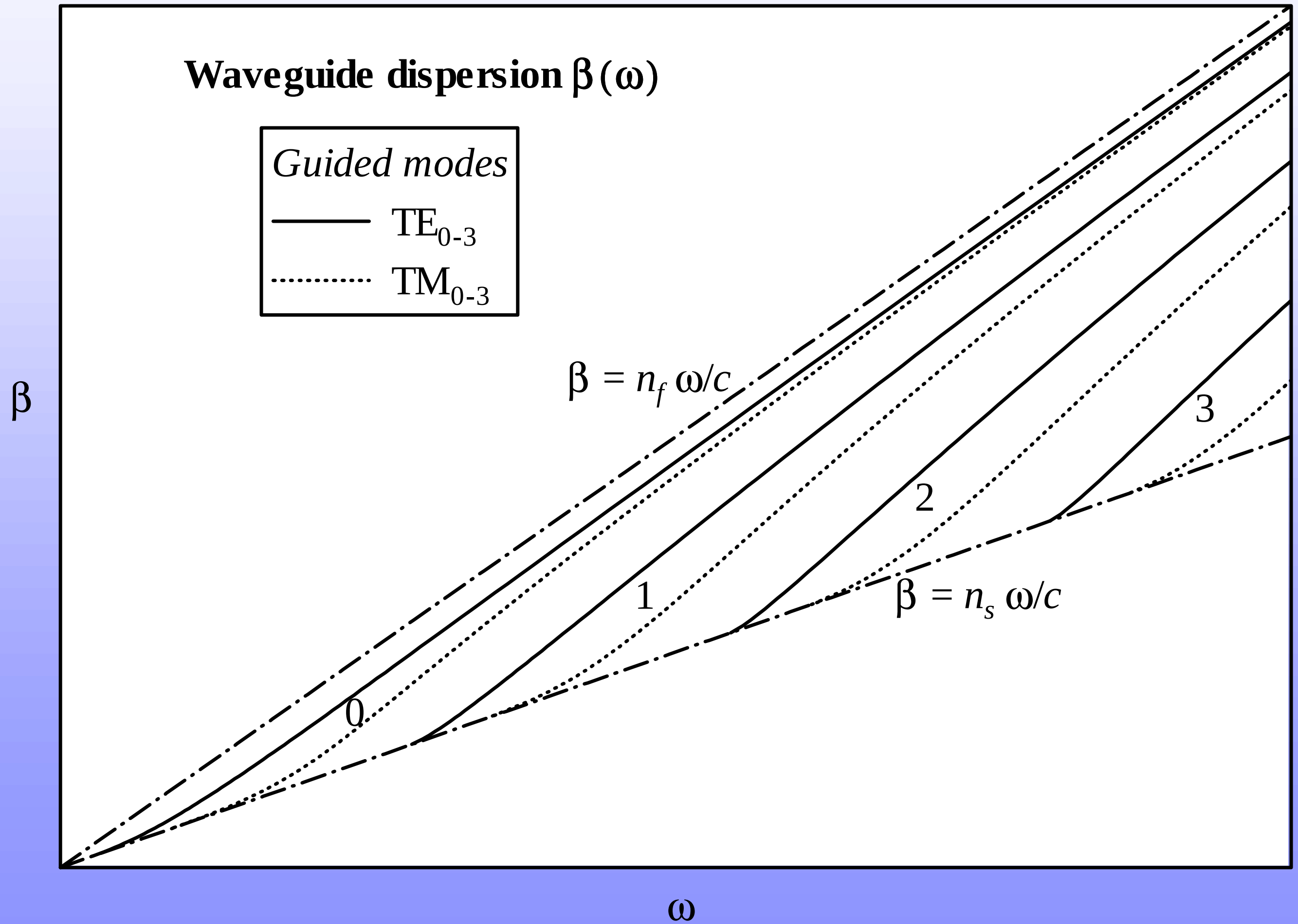
$$N = \frac{\beta}{k} = n_f \sin\alpha_f$$

Waveguide dispersion curves: $\beta(\omega)$ or $N(\omega)$

Waveguide dispersion



Waveguide dispersion

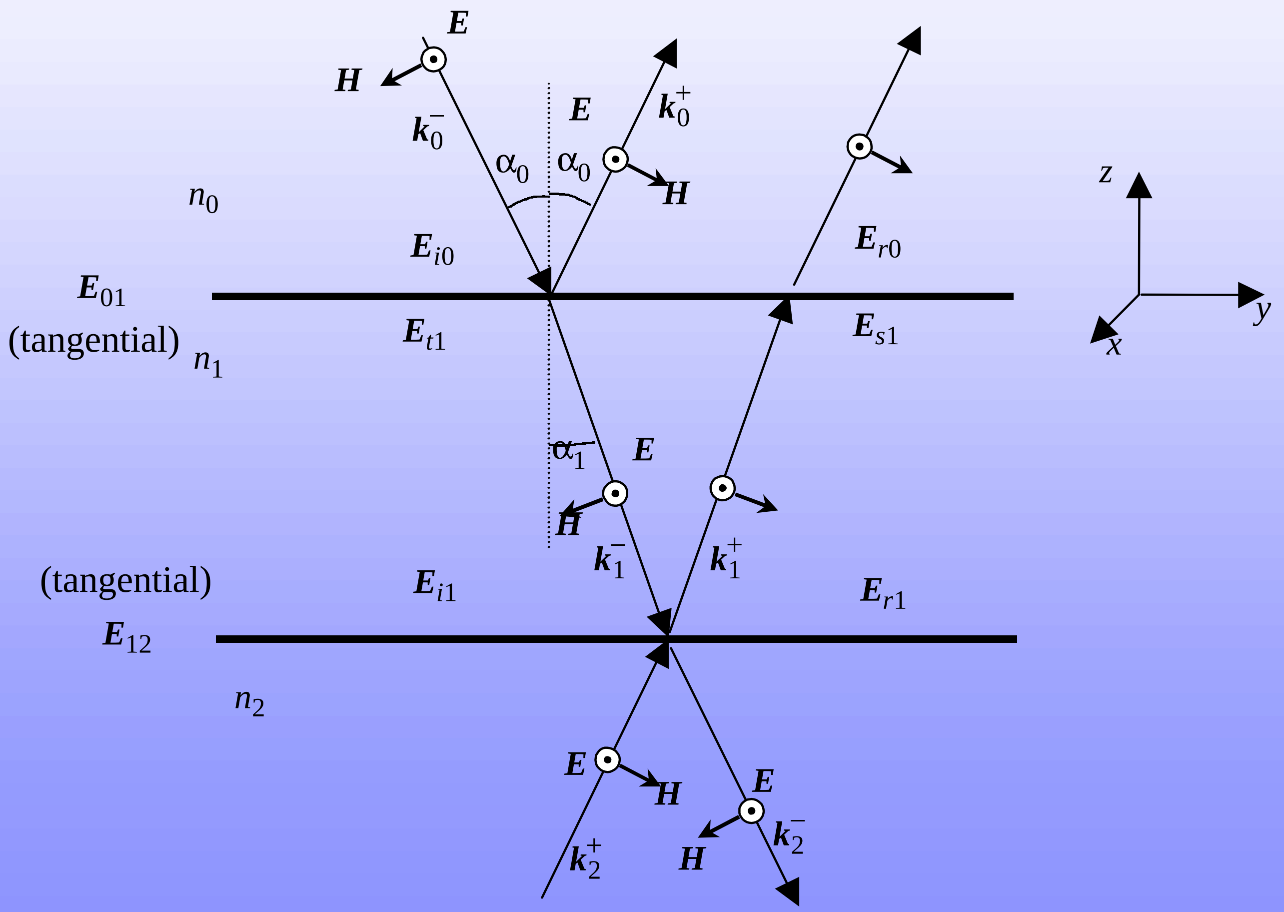


Wave approach to waveguides

Linear combinations of the basis functions should satisfy the continuity conditions at the interfaces

- One-dimensional planar waveguide: harmonic plane waves
- Rectangular waveguide: analytic solution does not exist
- Circular waveguide: Bessel functions
- Circular waveguide with parabolic *n*-profile: Gaussian beams

Planar waveguide



Attenuation in waveguides

Mechanisms:

- Intrinsic

  Residual absorption (SiO_2, impurities: OH^-)

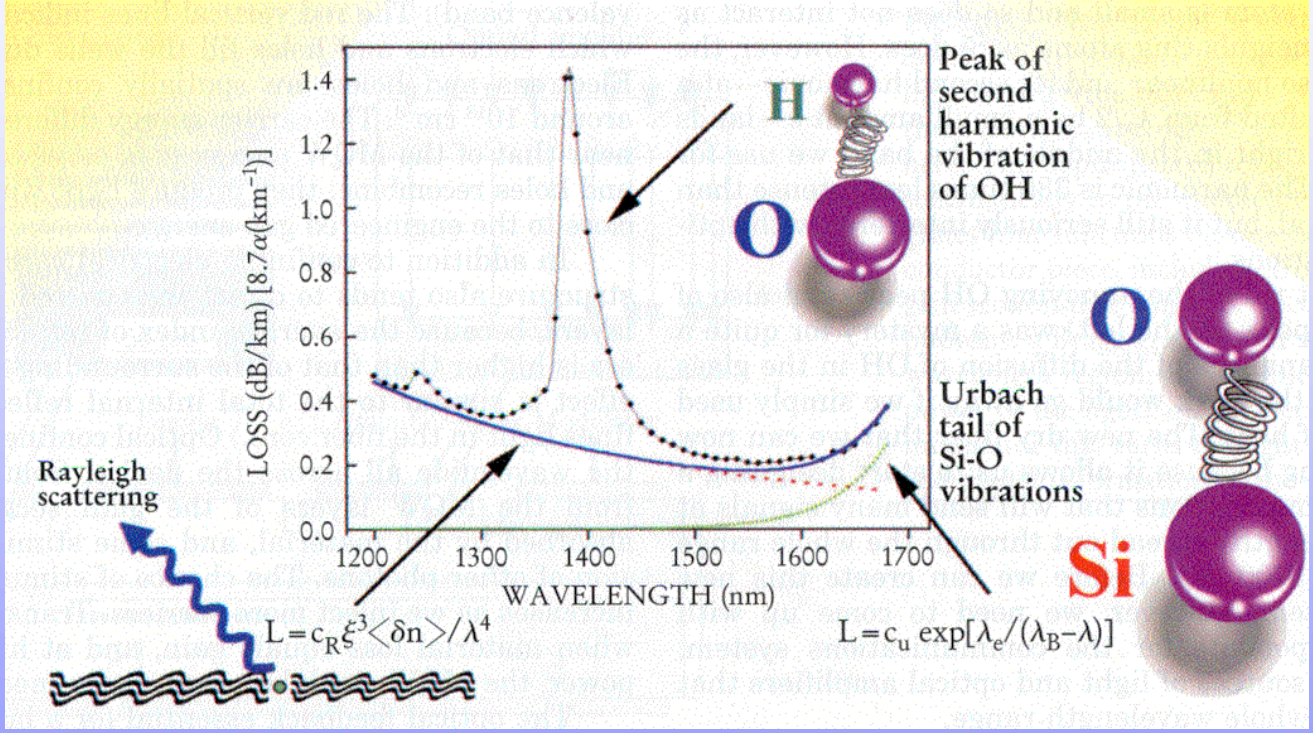
  Rayleigh scattering (proportional to ω^4)

- Extrinsic
  - Large inhomogeneities (fabrication of the fiber)
  - geometrical irregularities (curvature, surface defects…)
  - Losses at the fiber input and output (Fresnel reflection, aperture...)

SiO_2 fibers: 0.2 dB/km with $\lambda = 1.55$ µm

$$\alpha[\mathrm{dB}] = 10 \log\left(\frac{I_1}{I_2}\right)$$

Attenuation in waveguides



Dispersion

Broadening of pulse during the propagation (limits the rate of the information transfer)

1. Modal dispersion (tens of ns per km)

$$\frac{\Delta\tau_1}{L} = \frac{N_{max}}{c} - \frac{N_{min}}{c} \approx \frac{n_f - n_s}{c}$$

Single mode fibers, gradient index profile

2. Material dispersion (hundreds of ps per km)

$$\frac{\Delta\tau_2}{L} = -\frac{\lambda}{c}\frac{d^2 n_f}{d\lambda^2}\Delta\lambda$$

It vanishes for SiO_2 at 1.27 μm

3. Waveguide dispersion (*N* depends on ω)

$$\frac{\Delta\tau_3}{L} = -\frac{\lambda}{c}\frac{d^2 N}{d\lambda^2}\Delta\lambda$$

(tens of ps per km)