Guided waves and optical fibres

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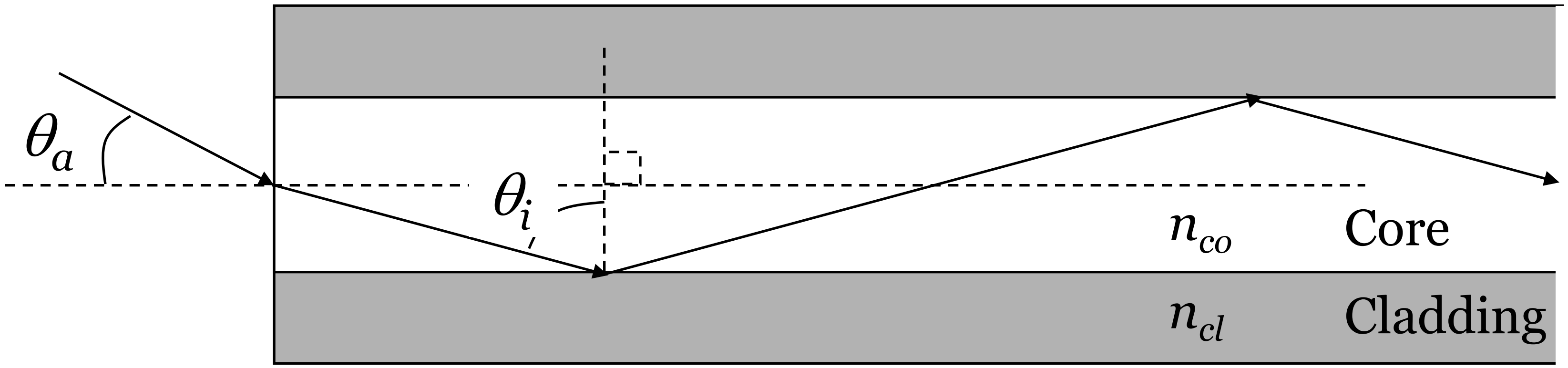
Optical Waveguides



- **Total Internal Reflection**

$$\theta_i > \theta_c = \sin^{-1}\left(\frac{n_{cl}}{n_{co}}\right)$$

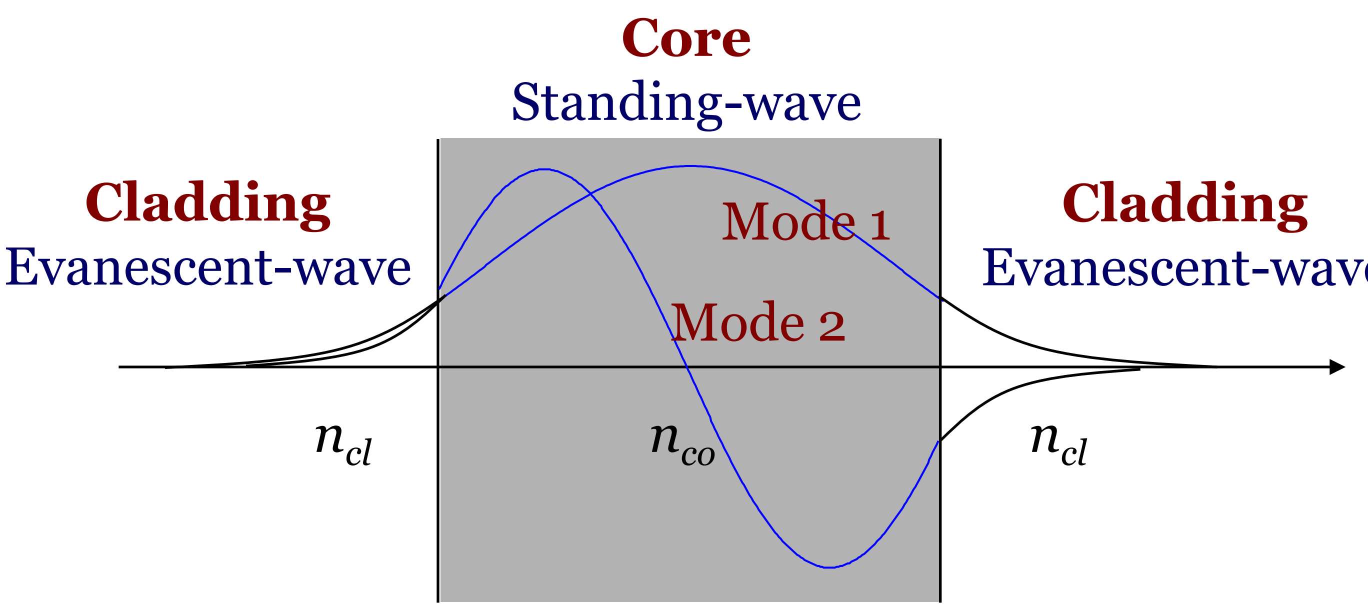
If the incident angle is greater than θ_c

- **Numerical Aperture**

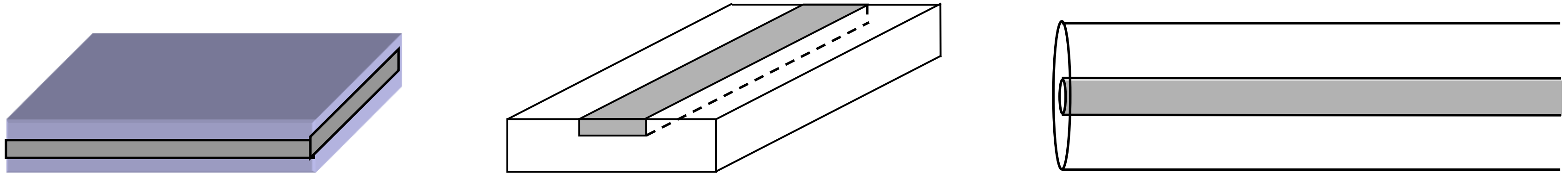
$$NA = n_o \sin\theta_a \approx \theta_a = \sqrt{n_{co}^2 - n_{cl}^2}$$

Optical Waveguides

❑ Quantized Mode State



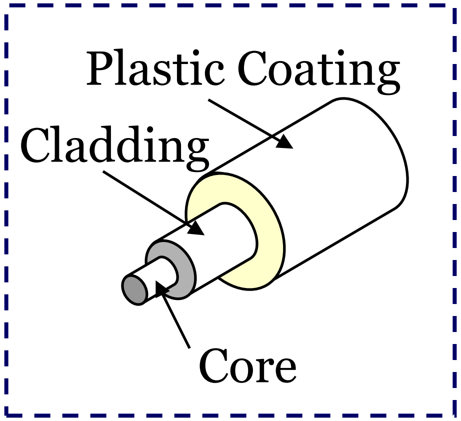
■ **Planar W/G** ■ **Channel W/G** ■ **Circular W/G**



Optical Fibers

- A flexible optically transparent fiber, as of glass or plastic, through which light can be transmitted by successive internal reflection

- **Structure of Optical Fiber**



Optical Fiber Fabrication

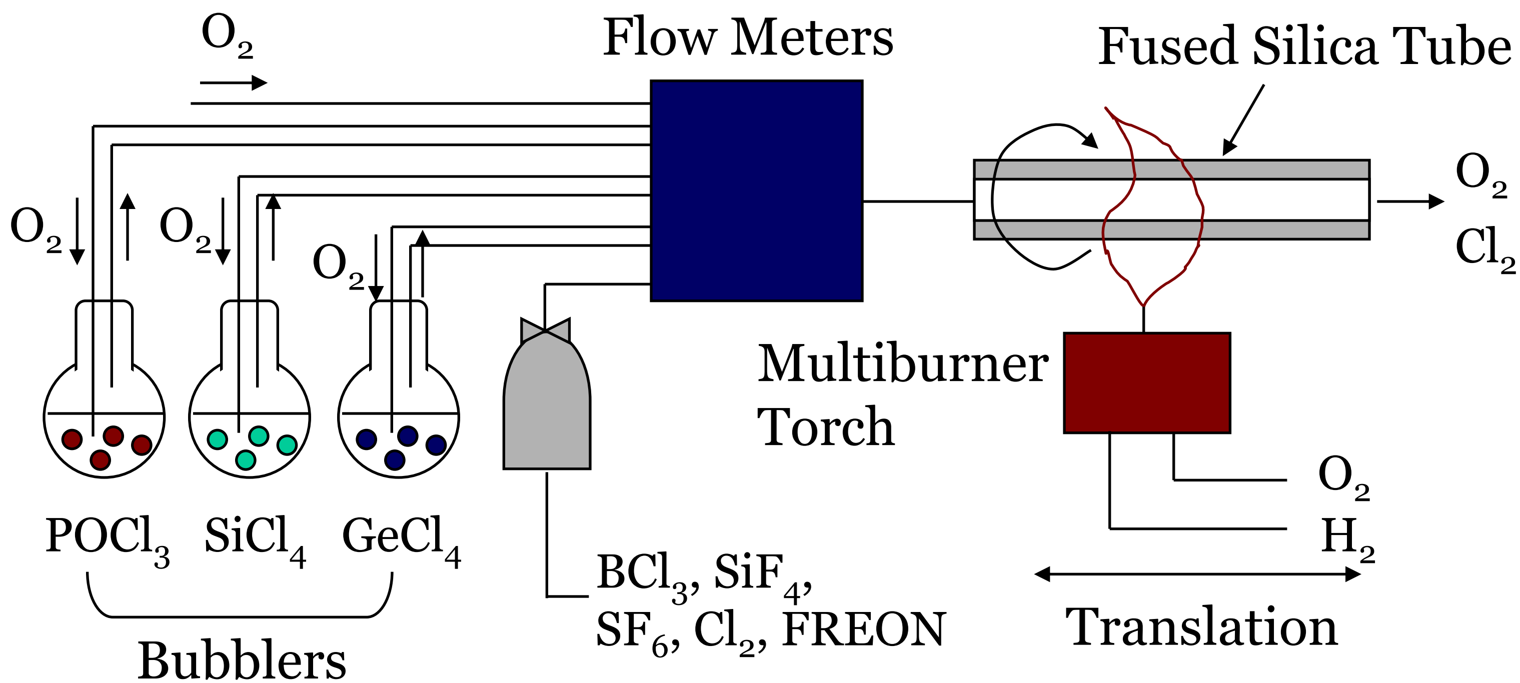
- **Double Crucible** Directly drawing
- **Rod in Tube** Preform and drawing

Preform Fabrication

❑ Deposition Techniques

- Modified chemical vapor deposition (MCVD)
- Plasma-enhanced modified chemical vapor deposition (PMCVD)
- Outside vapor deposition (OVD)
- Axial vapor deposition (AVD)

Preform Fabrication by MCVD

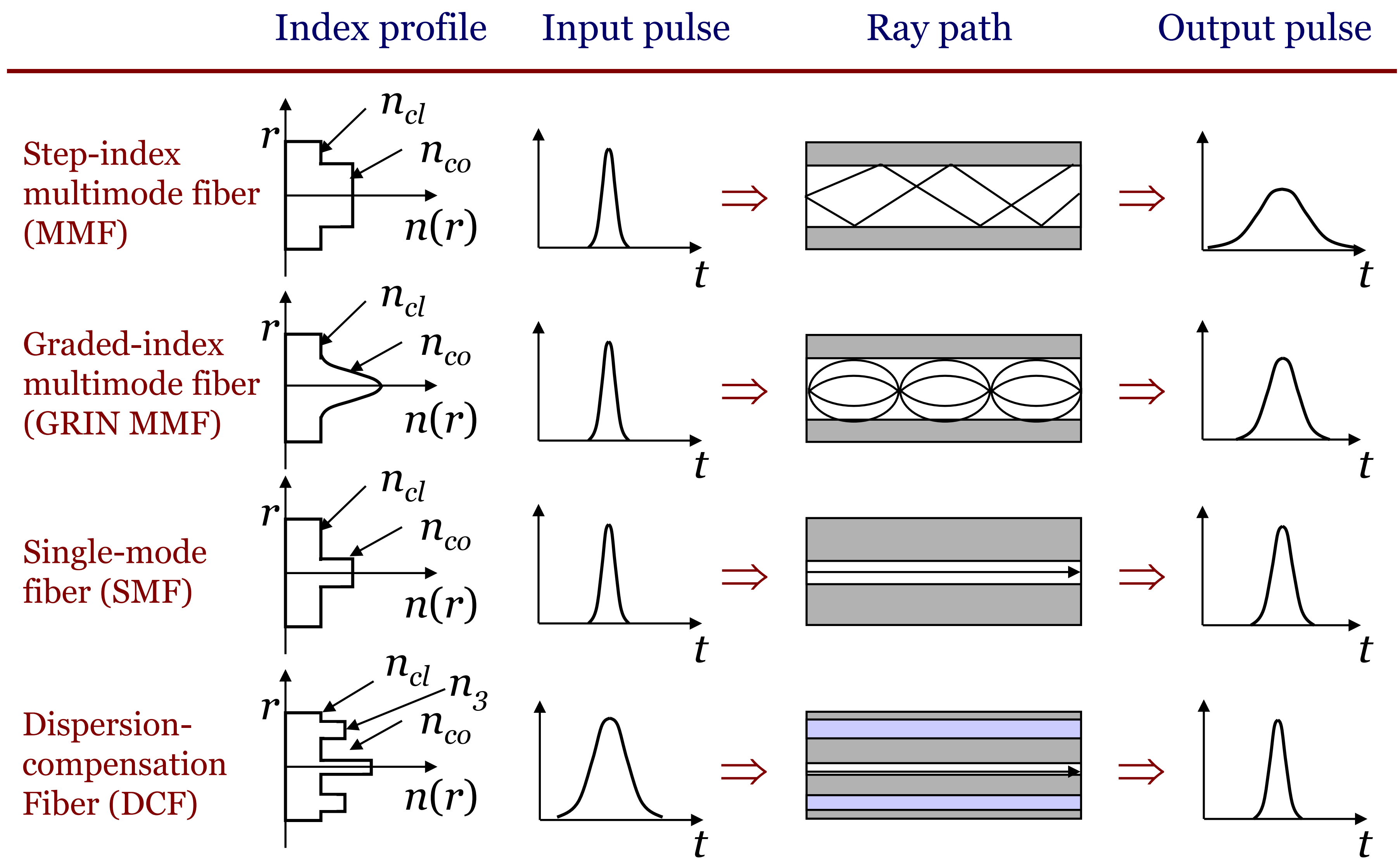


- Dopants:
  GeO_2, P_2O_5, $ErCl_3$, Nd_2O_3

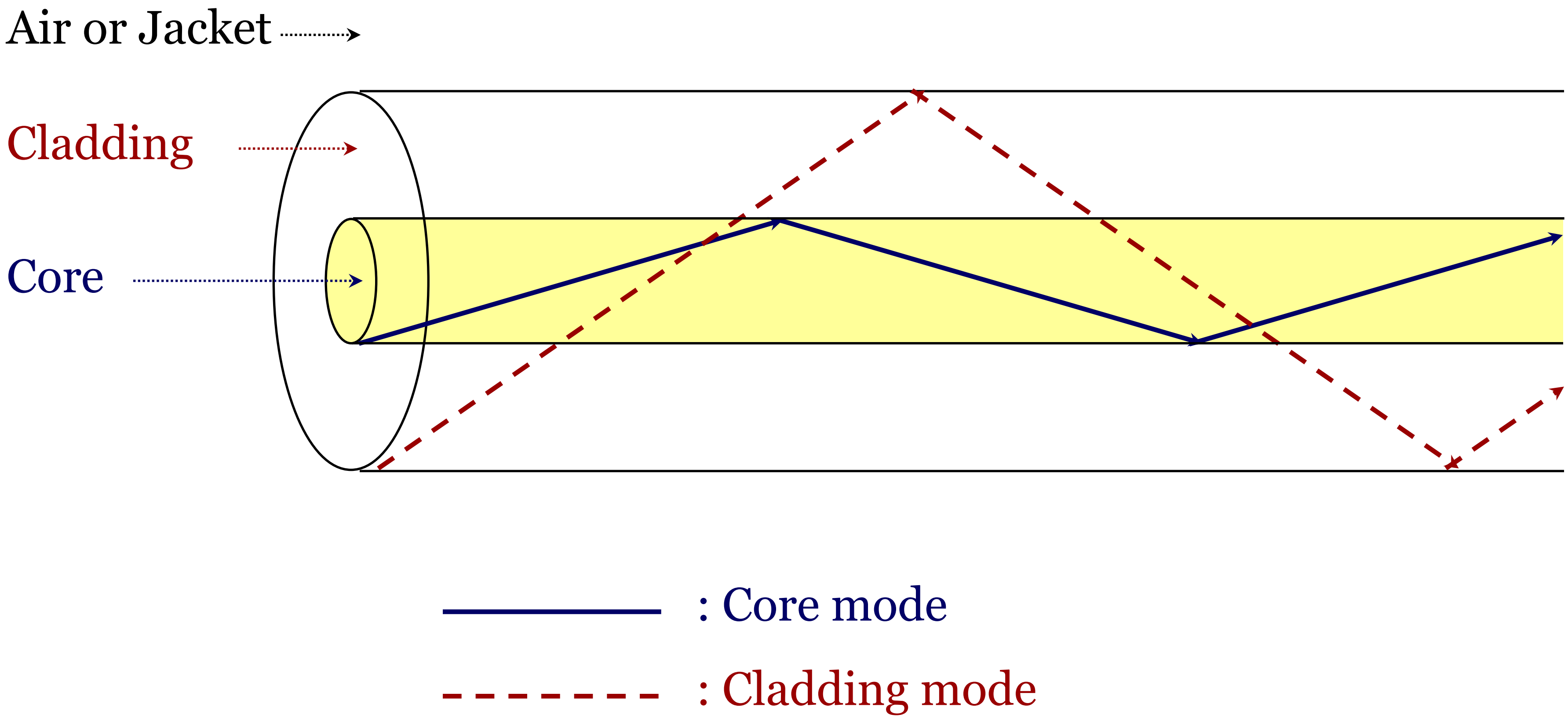
Drawing and Spooling

- **Procedure**
  - Drawn from the Preform
  - Quality checked
  - Coated for protection
  - Stored on a spool

Optical Fibers



Single-Mode Fiber



Core Mode

❑ Mode Expansion

Core $(r \le r_{co})$	Cladding $(r \ge r_{co})$
$E_z = a_{co} J_\nu (h_{co} r)$	$E_z = a_{cl} K_\nu (h_{cl} r)$
$H_z = b_{co} J_\nu (h_{co} r)$	$H_z = b_{cl} K_\nu (h_{cl} r)$
$\rightarrow E_r, E_\phi, H_r, H_\phi$	$\rightarrow E_r, E_\phi, H_r, H_\phi$
$where\;\; h_{co} = \sqrt{k_o^2 n_{co}^2 - \beta^2}$	$where\;\; h_{cl} = \sqrt{\beta^2 - k_o^2 n_{cl}^2}$

$note : \exp[i(\omega t - \beta z + \nu\phi)]$: omitted

- Continuity condition of tangential fields at $r = r_{co}$

  $\Rightarrow$ **Core-bounded mode**

Exact Core Mode

❑ Mode Expansion

Core $(r \le r_{co})$	Cladding $(r_{co} < r \le r_{cl})$	Air $(r > r_{cl})$
$E_z = a_{co} J_\nu(h_{co} r)$	$E_z = a_{cl} K_\nu(h_{cl} r) + c_{cl} I_\nu(h_{cl} r)$	$E_z = a_{ai} K_\nu(h_{ai} r)$
$H_z = b_{co} J_\nu(h_{co} r)$	$H_z = b_{cl} K_\nu(h_{cl} r) + d_{cl} I_\nu(h_{cl} r)$	$H_z = b_{ai} K_\nu(h_{ar} r)$
$\rightarrow E_r, E_\phi, H_r, H_\phi$	$\rightarrow E_r, E_\phi, H_r, H_\phi$	$\rightarrow E_r, E_\phi, H_r, H_\phi$
$where\ \ h_{co} = \sqrt{k_o^2 n_{co}^2 - \beta^2}$	$where\ \ h_{cl} = \sqrt{k_o^2 n_{cl}^2 - \beta^2}$	$where\ \ h_{ai} = \sqrt{\beta^2 - k_o^2 n_{ai}^2}$

$note : \exp[i(\omega t - \beta z + \nu\phi)]$: omitted

■ Continuity condition of tangential fields at $r = r_{co}$, $r = r_{cl}$

$\Rightarrow$ **Core-bounded mode**

Cladding Mode

❑ Mode Expansion

Core $(r \le r_{co})$	Cladding $(r_{co} < r \le r_{cl})$	Air $(r > r_{cl})$
$E_z = a_{co} J_\nu (h_{co} r)$	$E_z = a_{cl} J_\nu (h_{cl} r) + c_{cl} Y_\nu (h_{cl} r)$	$E_z = a_{ai} K_\nu (h_{ai} r)$
$H_z = b_{co} J_\nu (h_{co} r)$	$H_z = b_{cl} J_\nu (h_{cl} r) + d_{cl} Y_\nu (h_{cl} r)$	$H_z = b_{ai} K_\nu (h_{ar} r)$
$\rightarrow E_r, E_\phi, H_r, H_\phi$	$\rightarrow E_r, E_\phi, H_r, H_\phi$	$\rightarrow E_r, E_\phi, H_r, H_\phi$
$where\ \ h_{co} = \sqrt{k_o^2 n_{co}^2 - \beta^2}$	$where\ \ h_{cl} = \sqrt{k_o^2 n_{cl}^2 - \beta^2}$	$where\ \ h_{ai} = \sqrt{\beta^2 - k_o^2 n_{ai}^2}$

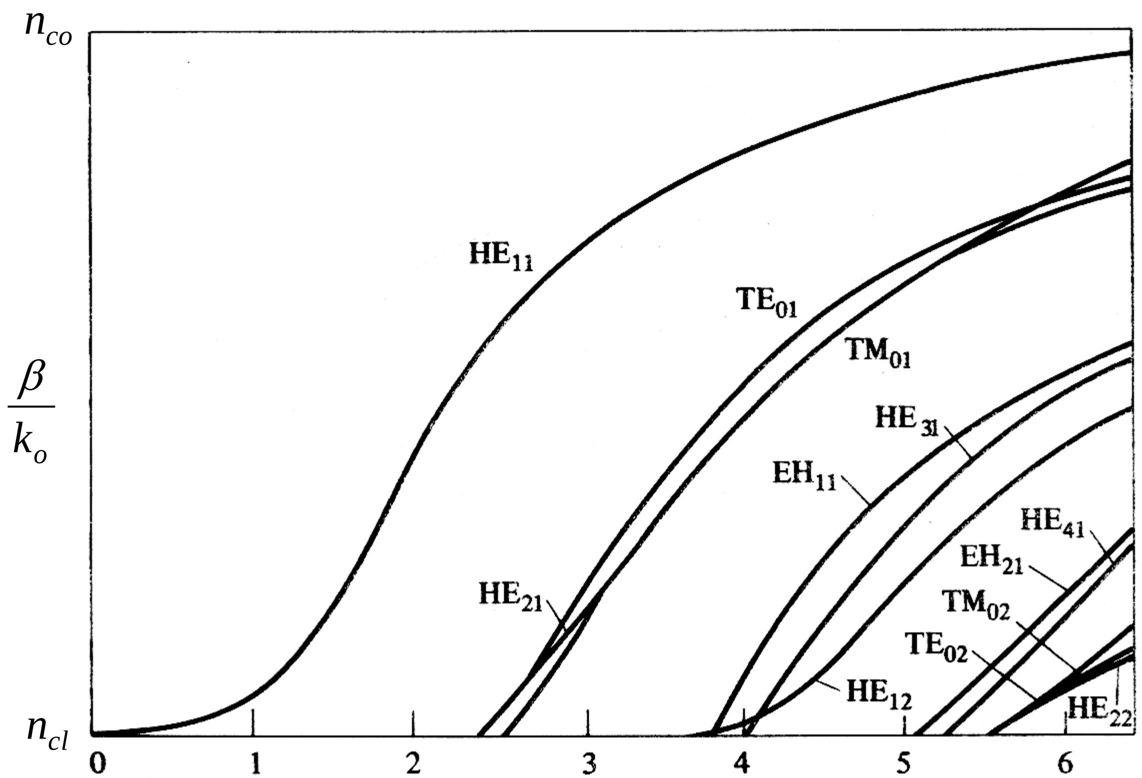
$note : \exp[i(\omega t - \beta z + \nu\phi)]$: omitted

- Continuity condition of tangential fields at $r = r_{co}$, $r = r_{cl}$

  $\Rightarrow$ **Cladding-bounded mode**

Effective Index of Core Mode

- As a function of V parameter



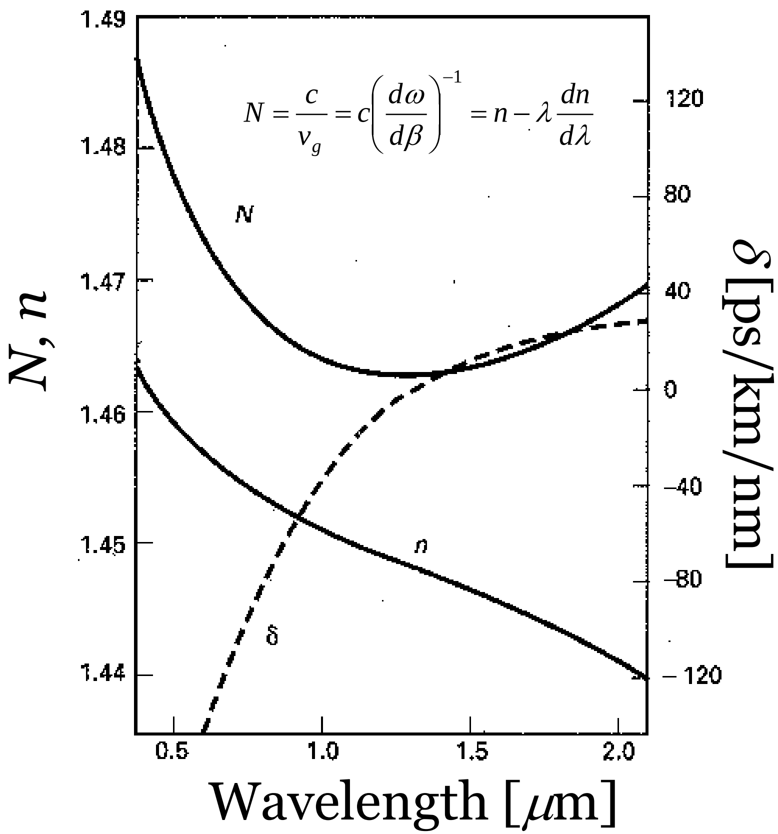
$$V = \frac{2\pi r_{co}}{\lambda}\sqrt{n_{co}^2 - n_{cl}^2}$$

Source: Optical Electronic in Modern Communications, A. Yariv

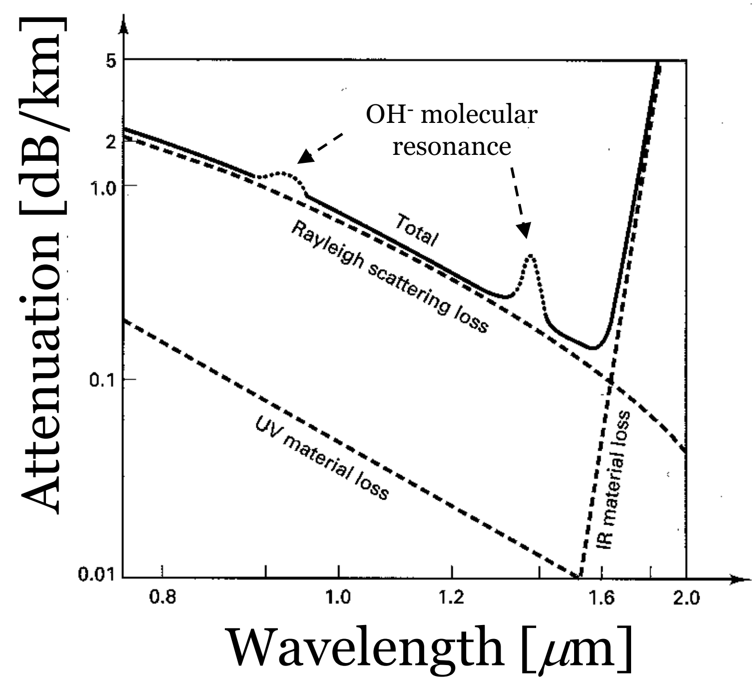
- $V < 2.405 \Rightarrow$ **Single-mode operation**

Dispersion and Attenuation in SMF

- Dispersion and Attenuation vs. Wavelength



- 1.3 μm: Zero dispersion
- 1.5 μm: Minimum loss



Source: Nonlinear Fiber Optics, G. P. Agrawal

Attenuation in SMF

❑ Causes of Attenuation

- Absorption
  - Intrinsic absorption: ultraviolet and infrared
  - Absorption by impurities: OH^- and transition metal
  - Absorption by atomic defects
- Scattering
  - Rayleigh scattering prohibits the use of wavelength below 0.8 μm, which is proportional to $1/\lambda^4$.
- Geometrical effects
  - Bending loss

Typically, the attenuation in SMF is 0.2 dB/km.

Dispersion in SMF

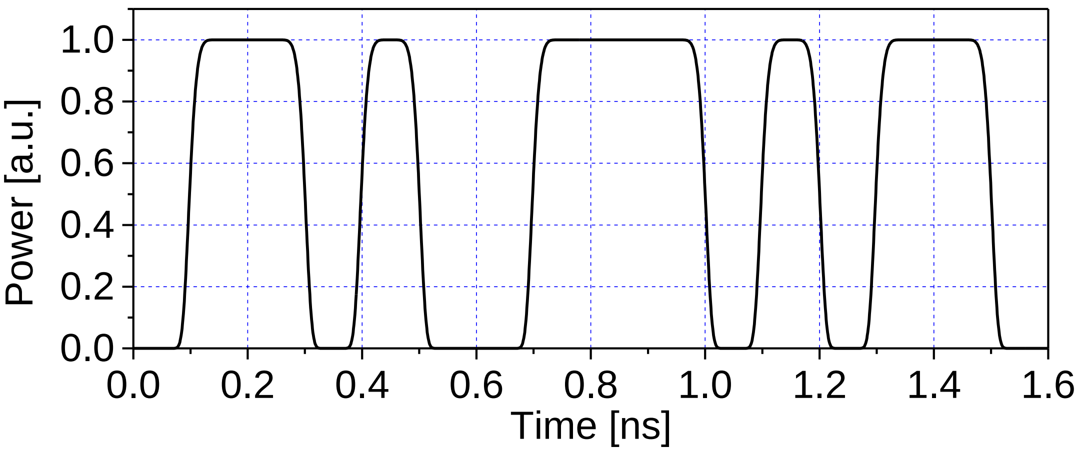
❑ Types of Dispersion

- Intermodal dispersion
  Pulse spreading in multimode fiber
- Intramodal dispersion
  Material dispersion
  Waveguide dispersion: usually *smaller* than material dispersion
    Short wavelength: The effective index is close to n_{core}.
    Long wavelength: The effective index is close to $n_{cladding}$.
    Recall V parameter!

Dispersion is a problem in fiber communications: It eventually limits the *bandwidth* of the fiber.

Data Transmission in SMF

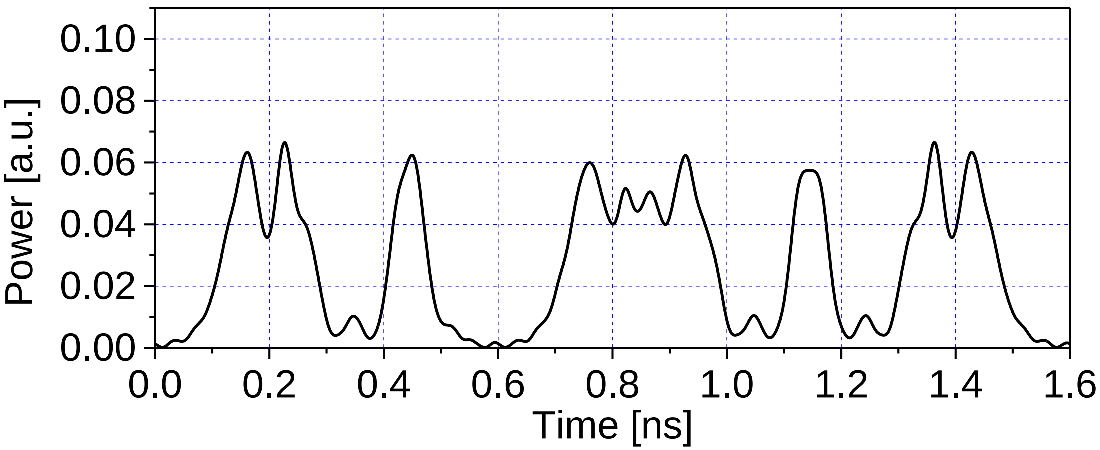
■ Initial Optical Pulses (10 Gbps, 0 dBm)



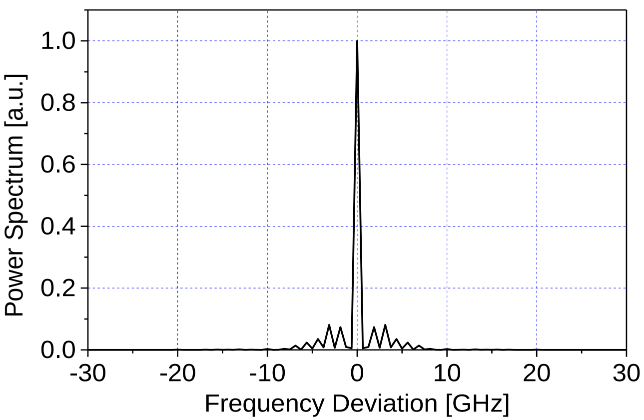
■ Group velocity dispersion (GVD)
⇒ Frequency chirp

■ Nonlinear effect
⇒ Four-wave mixing (FWM)

■ After 50-km Transmission



■ Power Spectrum



Nonlinearities in Fibers

❑ Stimulated Raman Scattering (SRS)

A stimulated effect in which the energy from a photon incident on a molecule delivers parts of its energy to mechanical vibration of the molecule and part into reradiated light (*Stokes light*) of longer wavelength than the incident light

❑ Stimulated Brillouin Scattering (SBS)

A stimulated effect (highly directional) due to interaction between the traveling light wave, composed of photons, and *a traveling sound wave* that it induces, which can be considered as composed of quantum sound particles, *phonons*

❑ Four-Wave Mixing (FWM)

Third-order cross-product of electric field.

$f_i - f_j - f_k \Rightarrow$ frequency mixing, interfering effect in WDM