Nonlinear Optical Engineering

Introduction
(NFO 5th ed: 1.1 ~ 1.4)

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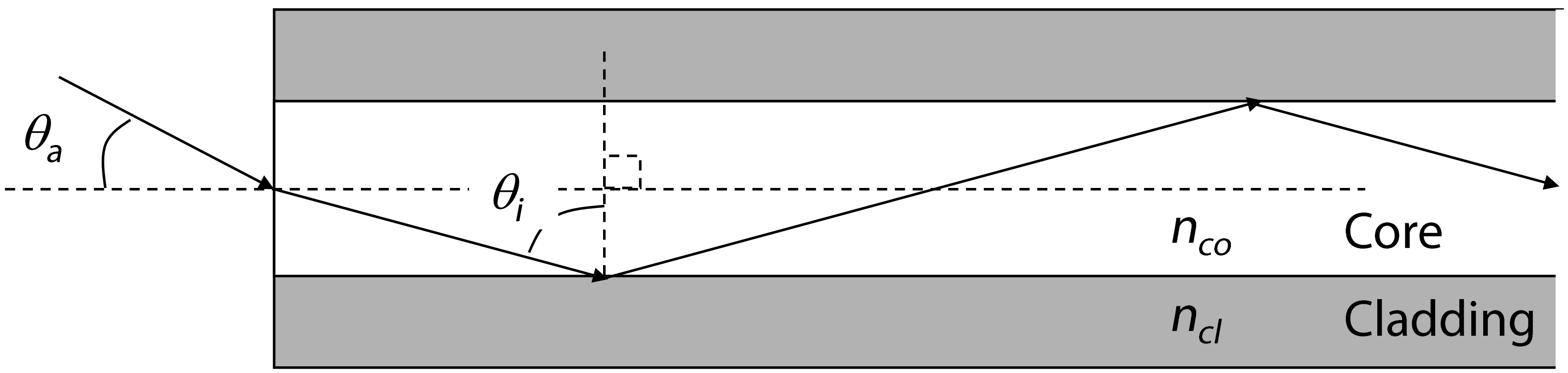
Total Internal Reflection



Total internal reflection:

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

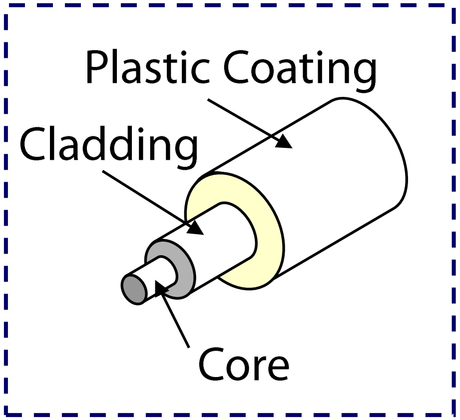
Numerical aperture:

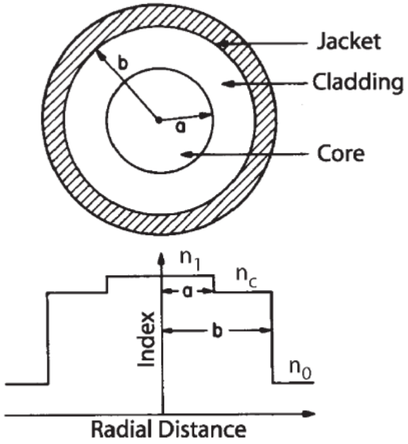
$$NA = n_o \sin\theta_a \approx \theta_a = \sqrt{n_{co}^2 - n_{cl}^2}$$

Optical Fibers

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

Geometry of an Optical Fiber:





G. P. Agrawal, Nonlinear Fiber Optics, 5th ed.

Fabrication of Optical Fibers

Double crucible:

$\rightarrow$ Direct drawing

Rod in tube:

$\rightarrow$ Preform and drawing

Fabrication of Fiber Preforms

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

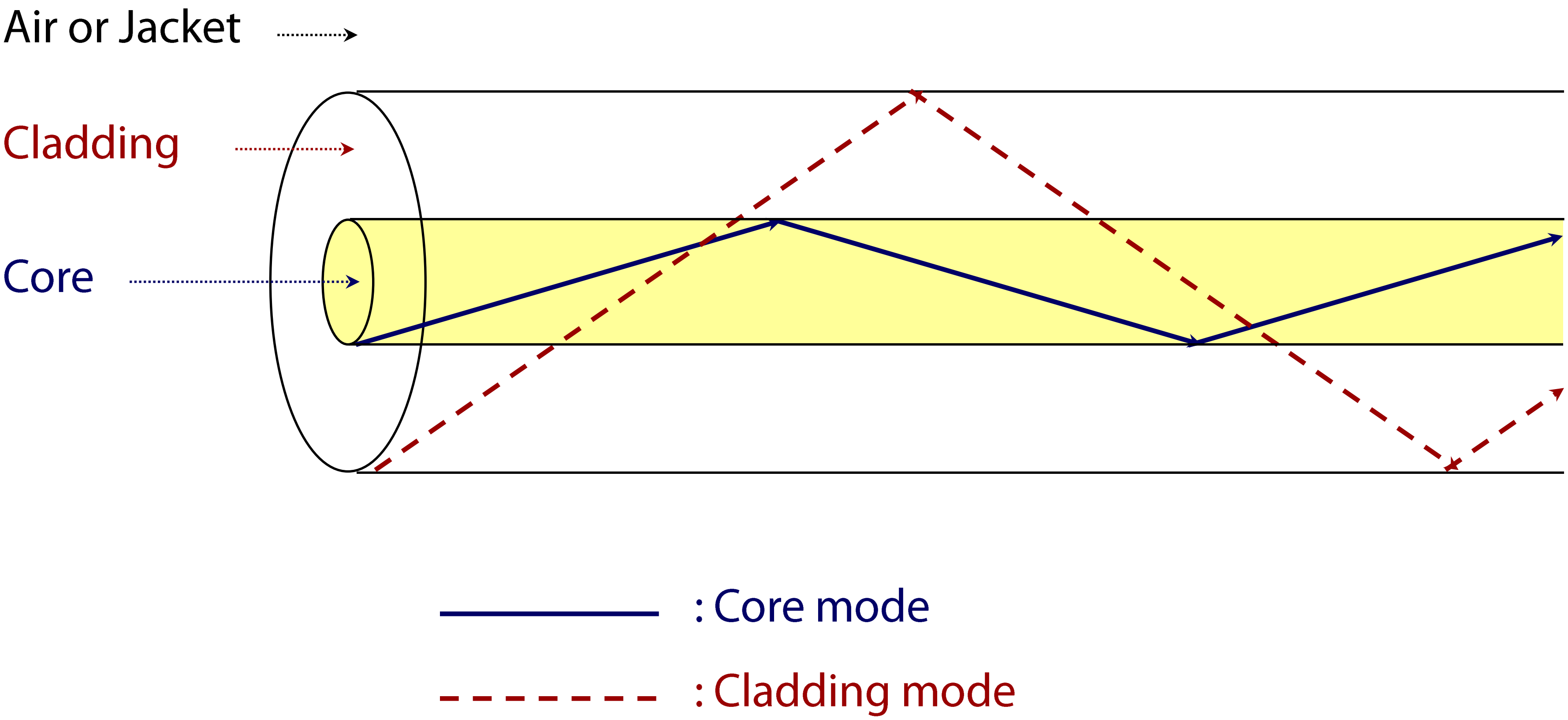
MCVD: Modified chemical vapor deposition

Dopants: GeO_2, P_2O_5, $ErCl_3$, Nd_2O_3

Fiber Drawing and Spooling

Procedure:
- Drawing from preform
- Quality checking
- Coating for protection
- Spooling

Single-Mode Fiber



Core Mode

Mode expansion:

$$Core\ (r \le r_{co})$$

$$E_z = a_{co} J_\nu (h_{co} r)$$
$$H_z = b_{co} J_\nu (h_{co} r)$$
$$\rightarrow E_r, E_\phi, H_r, H_\phi$$
$$where\ \ h_{co} = \sqrt{k_o^2 n_{co}^2 - \beta^2}$$

$$Cladding\ (r \ge r_{co})$$

$$E_z = a_{cl} K_\nu (h_{cl} r)$$
$$H_z = b_{cl} K_\nu (h_{cl} r)$$
$$\rightarrow E_r, E_\phi, H_r, H_\phi$$
$$where\ \ h_{cl} = \sqrt{\beta^2 - k_o^2 n_{cl}^2}$$

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

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

$\rightarrow$ Core-bounded mode

Exact Core Mode

Mode expansion:

Core $(r \le r_{co})$

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

Cladding $(r_{co} < r \le r_{cl})$

$$E_z = a_{cl} K_\nu (h_{cl} r) + c_{cl} I_\nu (h_{cl} r)$$
$$H_z = b_{cl} K_\nu (h_{cl} r) + d_{cl} I_\nu (h_{cl} r)$$
$$\rightarrow E_r, E_\phi, H_r, H_\phi$$
$$where \;\; h_{cl} = \sqrt{k_o^2 n_{cl}^2 - \beta^2}$$

Air $(r > r_{cl})$

$$E_z = a_{ai} K_\nu (h_{ai} r)$$
$$H_z = b_{ai} K_\nu (h_{ar} r)$$
$$\rightarrow E_r, E_\phi, H_r, H_\phi$$
$$where \;\; h_{ai} = \sqrt{\beta^2 - k_o^2 n_{ai}^2}$$

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

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

$\rightarrow$ Core-bounded mode

Cladding Mode

Mode expansion:

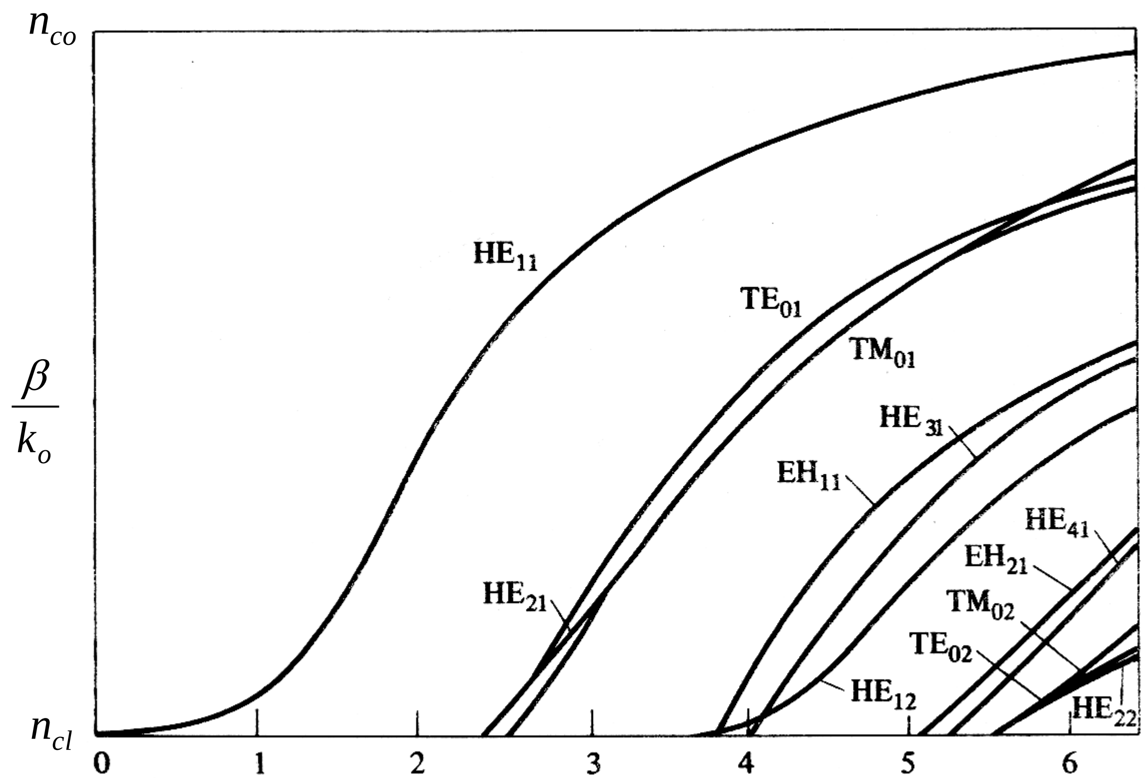
Core $(r \le r_{co})$	Cladding $(r_{co} < r \le r_{cl})$	Air $(r > r_{cl})$
$E_z = a_{co} J_\nu (h_{co} r)$	$E_z = a_{cl} J_\nu (h_{cl} r) + c_{cl} Y_\nu (h_{cl} r)$	$E_z = a_{ai} K_\nu (h_{ai} r)$
$H_z = b_{co} J_\nu (h_{co} r)$	$H_z = b_{cl} J_\nu (h_{cl} r) + d_{cl} Y_\nu (h_{cl} r)$	$H_z = b_{ai}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



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

Source: Optical Electronic in Modern Communications, A. Yariv

Single-mode operation:

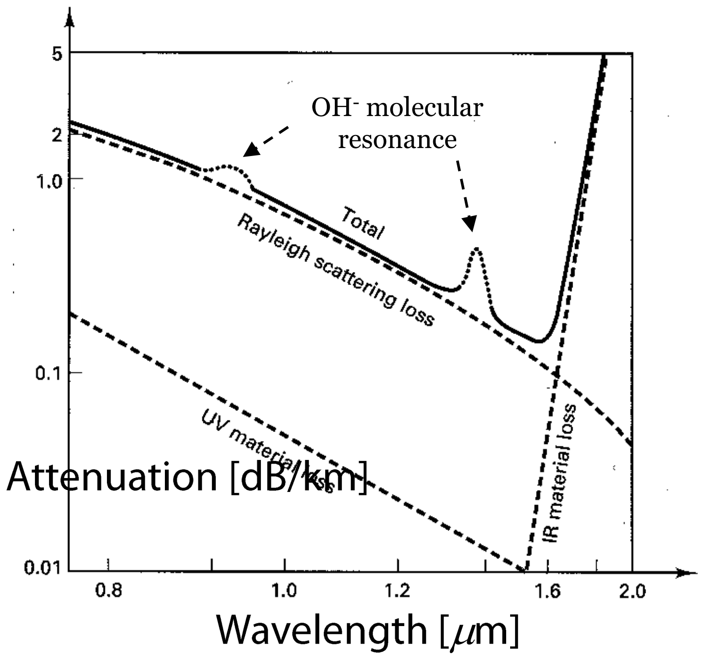
$\rightarrow V < 2.405$

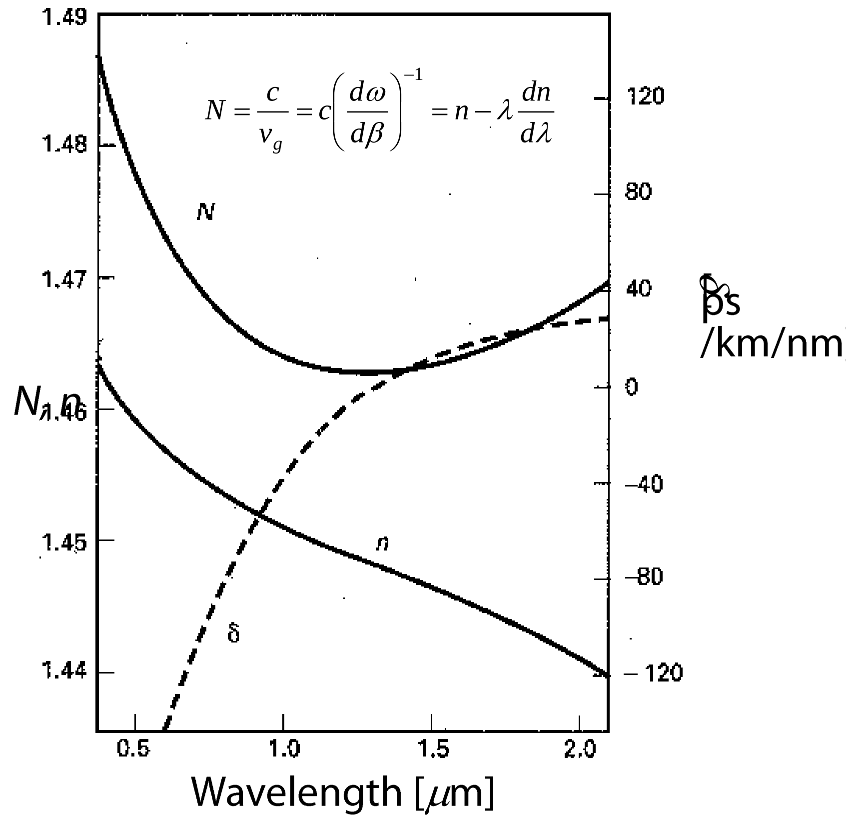
Attenuation and Dispersion in SMF

Attenuation and dispersion 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: In particular for below 0.8 μm
- Geometrical effects:
  - Bending loss

Typical attenuation in SMF: 0.2 dB/km

Dispersion in SMF

Types of dispersion:

- Intermodal dispersion:

  Pulse spreading in multimode fiber

- Intramodal dispersion (Chromatic dispersion):

  Material dispersion

  Waveguide dispersion: usually *smaller* than material dispersion

  Short wavelength: Effective index is close to n_{core}.

  Long wavelength: Effective index is close to $n_{cladding}$.

  → *Recall V parameter!*

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

Polarization-mode dispersion:

Modal birefringence:

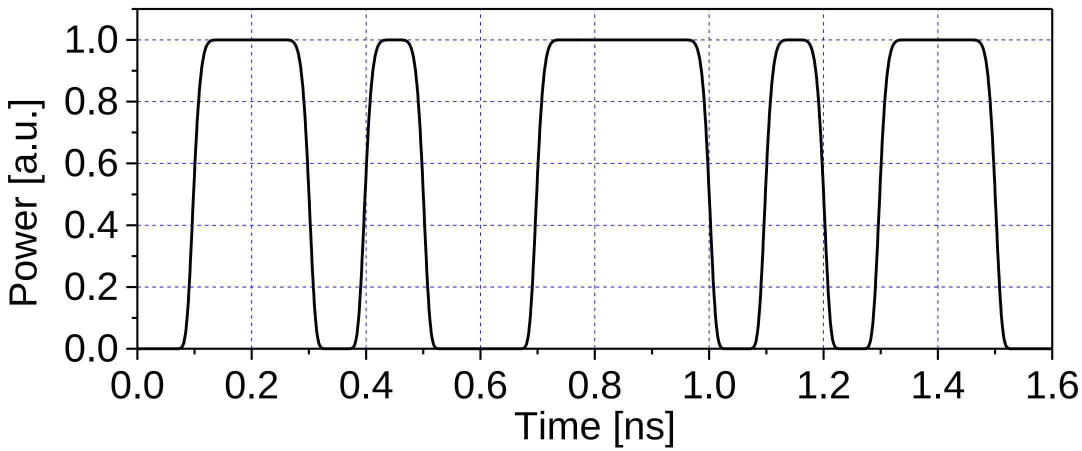
$$\rightarrow B_m = \frac{|\beta_x - \beta_y|}{k_0} = |n_x - n_y|$$

Beat length:

$$\rightarrow L_B = \frac{2\pi}{|\beta_x - \beta_y|} = \frac{\lambda}{B_m}$$

Data Transmission in SMF

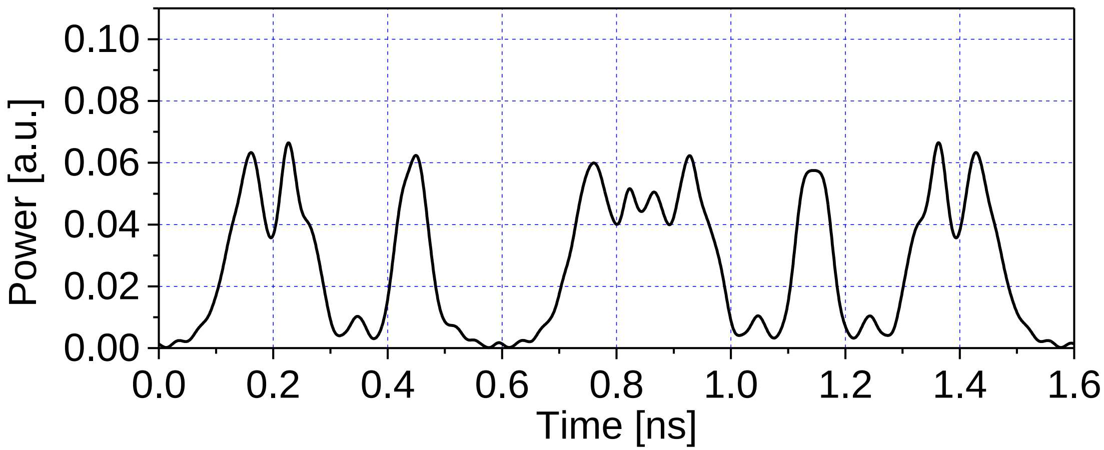
Initial optical pulses (10 Gbps, 0 dBm):



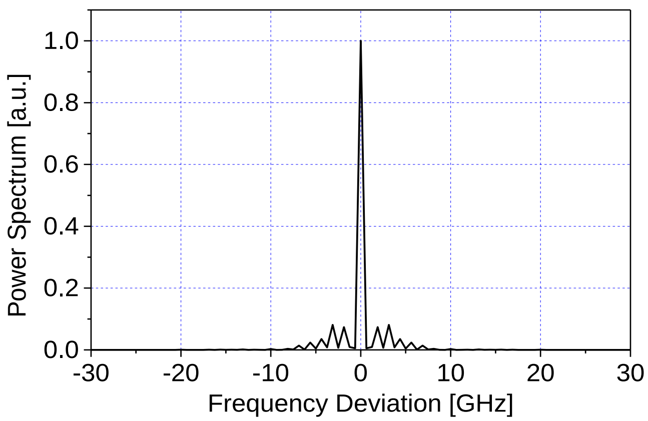
Group velocity dispersion:
→ Frequency chirp

Nonlinear effect:
→ SPM/XPM/FWM/SRS/SBS

After 50-km Transmission:



Power spectrum:



Nonlinearities in Fibers

Nonlinear response of optical media:

$$\mathbf{P} = \varepsilon_o \chi \mathbf{E} = \varepsilon_o \left(\chi^{(1)} \cdot \mathbf{E} + \chi^{(2)} : \mathbf{EE} + \chi^{(3)} \vdots \mathbf{EEE} + \cdots \right)$$

← Anharmonic motion of bound electrons

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 parts 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*

Parametric process:

Third-order product of electric fields

Four-wave mixing (FWM) or harmonic generation