Nonlinear Optical Effects in Fibers

• NLO effects are manifested as attenuation, phase shifts, or wavelength conversion effects, and become stronger with increasing light intensity. The glass materials usually used for fibers exhibit very small “intrinsic” nonlinearities.

• Nevertheless, the magnitude with which a nonlinear effect manifests itself is proportional to 3 factors: the size of the nonlinearity, the intensity of the radiation (light), and the interaction length.

• Because of the latter 2 factors, esp. the interaction length (limited normally by focusing geometries and by attenuation), optical fibers can manifest extremely strong nonlinear behavior, which can limit the BL products for optical communication applications.
Dominant Nonlinear Optical Effects in Telecom Fibers

Nonlinear optical effects → Stimulated Brillouin scattering
    - Stimulated "inelastic" light scattering
    - Stimulated Raman scattering
        - Self-phase modulation
        - Cross-phase modulation
Nonlinear phase modulation
Four-wave mixing

Note that all the above effects are due to 3rd order nonlinearities, since 2nd order NLs are negligible in centrosymmetric media (the glass materials used to make fibers are nearly-perfectly isotropic, thus they are centrosymmetric)
Stimulated Brillouin Scattering

Energy conservation: \( \Omega = \Omega_p - \Omega_s \)

Momentum conservation: \( k_A = k_p - k_s \)

Dispersion relation: \( |k_A| = \Omega / v_A \)

The acoustic frequency: \( \Omega = |k_A| v_A = 2 v_A |k_p| \sin(\theta / 2) \)

\( \theta = 0 : \) \( \Omega = 0 \)

\( \theta = \pi : \) \( \Omega = \Omega_B = 2 v_A |k_p| \)

The Brillouin shift: \( \nu_B = \Omega_B / 2\pi = 2 \bar{n} v_A / \lambda_p \)

For \( \lambda_p = 1.55 \mu m \) \( v_A = 5.96 km / s \) \( \bar{n} = 1.45 \) \( \nu_B = 11.1 GHz \)
Stimulated Brillouin Scattering

The feedback process is governed by:

\[
\begin{align*}
\frac{dI_p}{dz} &= -g_B I_p I_s - \alpha_p I_p \\
\frac{dI_s}{dz} &= g_B I_p I_s - \alpha_s I_s
\end{align*}
\]

\(I_p\) and \(I_s\) are the intensity of the pump and Stokes fields, \(g_B\) is the SBS gain, and \(\alpha_p\) and \(\alpha_s\) account for fiber losses.

If the acoustic waves decay as \(\exp(-t / T_B)\),

The Brillouin gain is frequency dependent

\[
g_B(\Omega) = \frac{g_B(\Omega_B)}{1 + (\Omega - \Omega_B)^2 T_B^2}
\]

The peak value of Brillouin gain is depends on various material parameters such as the density and the elasto-optic coefficient.

For Silica fibers \(g_B \approx 5 \times 10^{-11} \text{m/} W\)
Stimulated Brillouin Scattering

Brillouin-gain spectra measured using a 1.525-µm pump for three fibers with different germania doping: (a) silica-core fiber; (b) depressed-cladding fiber; (c) dispersion-shifted fiber.

The threshold power: $$g_B P_{th} L_{eff} / A_{eff} \approx 21$$

$$L_{eff} = [1 - \exp(-\alpha L)] / \alpha$$

$$A_{eff} = \pi w^2$$

$$P_{th} \sim 5\,mW$$

- SBS gain bandwidth of silica fiber is larger than that of bulk silica
- A part of this increase is due to the guided nature of acoustic modes in optical fibers
- Most of the increase can be attributed to variations in the core diameter along the fiber length.
- The difference of SBS gain bandwidth between fibers can exceed 100MHz
- Typical value ~50MHz for wavelength near 1.55 µm
Stimulated Raman Scattering

Spontaneously Scattered waves ($\Omega_R$)  
Beating term ($\Omega_O$)  
Molecular oscillations ($\Omega_O$)

Pump ($\Omega_p$)  

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$I_p$ and $I_s$ are the intensity of the pump and Stokes fields, $g_R$ is the SRS gain, and $\alpha_p$ and $\alpha_s$ account for fiber losses.

For Silica fibers:

$g_R \approx 1 \times 10^{-13} \text{ m/W @1\mu m}$

$g_R \approx 6 \times 10^{-13} \text{ m/W @1.55\mu m}$
Stimulated Raman Scattering

- SRS gain bandwidth of silica fiber exceeds 10 THz
- The broadband and multi-peak nature of the spectrum is due to the amorphous nature of glass
- The maximum gain occurs when the Raman shift is about 13 THz.

Raman gain spectrum of fused silica at $\lambda_p = 1 \, \mu m$

The threshold power:

$$g_R P_{th} L_{eff} / A_{eff} \approx 16$$

$$L_{eff} = [1 - \exp(-\alpha L)] / \alpha$$

$$A_{eff} = \pi w^2$$

$$P_{th} \approx 16 \alpha (\pi w^2) / g_R$$

$$P_{th} \approx 500 \, mW$$
**Stimulated Light Scattering**

**SBS and SRS**

**Similarity:**
- Inelastic scattering
- Frequency shifted down (lower energy)
- Grows exponentially

**Difference:**
- SBS occurs only in the backward direction whereas SRS can occur in both directions
- Frequency shift about ~ 10 GHz for SBS, ~ 13 THz for SRS
- The Brillouin gain spectrum is extremely narrow (bandwidth < 100 MHz) compared with the Raman-gain spectrum (bandwidth > 20 THz)
- SBS acoustic phonon, SRS optical phonon
Self-Phase Modulation

Physics origin of nonlinearity:

\[ n' = n + \bar{n}_2 \left( P / A_{\text{eff}} \right) \]

\( \bar{n}_2 \) is the nonlinear-index coefficient, \( \sim 2.6 \times 10^{-20} \, \text{m}^2 / \text{W} \)

The propagation constant is power dependent:

\[ \beta' = \beta + k_0 \bar{n}_2 P / A_{\text{eff}} = \beta + \gamma P \]

\[ \gamma = 2\pi \bar{n}_2 / (A_{\text{eff}} \lambda) \]

Nonlinear phase shift:

\[ \phi_{NL} = \int_0^L (\beta' - \beta)dz = \int_0^L \gamma P_{in} \exp(-\alpha z)dz = \gamma P_{in} L_{\text{eff}} \]
Self-Phase Modulation

- In practice, time dependence of $P_{in}$ makes $\phi_{NL}$ vary with time
- SPM leads to frequency chirping of optical pulses
- The frequency chirp is proportional to the derivative $dP_{in}/dt$, and depends on the pulse shape

SPM-induced frequency chirp for Gaussian (dashed curve) and super-Gaussian (solid curve) pulse
Cross-Phase Modulation

In DWDM systems, the nonlinear phase shift for a specific channel depends not only on the power of that channel but also on the power of other channel, the phase shift for the jth channel:

$$\phi_j^{NL} = \gamma L_{eff} (P_j + 2 \sum_{m \neq j} P_m)$$

The worst case:

$$\phi_j^{NL} = (\gamma / \alpha)(2M - 1)P_j$$

Enlarging $A_{eff}$ helps reduce the fiber nonlinearity considerably
Four-Wave Mixing

If three optical fields with carrier frequencies $\omega_1$, $\omega_2$, and $\omega_3$ copropagate inside the fiber simultaneously, $\chi^{(3)}$ generates a fourth field whose frequency $\omega_4$, is related to other frequencies:

$$\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$$

The most troublesome case:

$$\omega_4 = \omega_1 + \omega_2 - \omega_3$$

The phase mismatch when four waves propagate in the same direction:

$$\Delta = \beta(\omega_3) + \beta(\omega_4) - \beta(\omega_1) - \beta(\omega_2)$$

Modern DWDM systems avoid FWM by using the technique of dispersion management.
Birefringence

Birefringence is acquired when the degeneracy between the orthogonally polarized fiber modes is removed.

The degree of birefringence is

\[ B = \left| \bar{n}_x - \bar{n}_y \right| \]

\( \bar{n}_x \) and \( \bar{n}_y \) are the mode indices for the orthogonally polarized fiber modes.

Birefringence leads to a periodic power exchange between the two polarization components. The period is called beat length:

\[ L_B = \lambda / B \]

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Polarization state is arbitrary in a conventional fiber.

Polarization-preserving fiber is produced by intentionally introducing a large amount of birefringence.

Typically, $B \sim 10^{-4}$

State of polarization in a birefringent fiber over one beat length. Input beam is linearly polarized at 45° with respect to the slow and fast axes.
Spot Size

The field distribution is often approximated by a Gaussian function:

\[ E_x = A \exp(-\rho^2 / \omega^2) \exp(i\beta z) \]

Where, \( \omega \) is the field radius and is referred to as the spot size.

\( \omega / a \) depends on V parameter; the value for 1.2 < V < 2.4 can be determined by:

\[ \omega / a \approx 0.65 + 1.619V^{-3/2} + 2.879V^{-6} \]

Confinement factor:

\[
\Gamma = \frac{P_{\text{core}}}{P_{\text{total}}} = \frac{\int_0^a |E_x|^2 \rho d\rho}{\int_0^\infty |E_x|^2 \rho d\rho} = 1 - \exp \left( - \frac{2a^2}{\omega^2} \right)
\]
Spot Size

(a) Normalized spot size $\omega/a$ as a function of the $V$ parameter obtained by fitting the fundamental fiber mode to a Gaussian distribution; (b) quality of fit for $V=2.4$

➤ Most telecommunication single-mode fibers are designed to operate in the range $2<V<2.4$
Fiber Loss

Power attenuation inside an optical fiber is governed by

\[ \frac{dP}{dz} = -\alpha P \]

Where, \( \alpha \) is the field radius and \( P \) is the optical power.

The output power is determined

\[ P_{out}(L) = P_{in} \exp(-\alpha L) \]

Relation between units of dB/km and 1/m

\[ \alpha (dB / km) = -\frac{10}{L} \log_{10} \left( \frac{P_{out}}{P_{in}} \right) = 4.343\alpha \]

Fiber loss:

1. Material Absorption
2. Rayleigh Scattering
3. Waveguide Imperfection
4. Bending
Fiber Loss

Two main sources:

- Material absorption
- Rayleigh scattering

Spectral loss profile of a single-mode fiber. Wavelength dependence of fiber loss for several fundamental loss mechanisms is also shown.
Material Absorption

Material absorption:

(1) Intrinsic material absorption

The electronic and vibrational resonances associated with SiO$_2$

(a) Electronic resonance $\lambda < 0.4\mu$m

(b) Vibrational resonance $\lambda > 7\mu$m

(2) Extrinsic material absorption

The electronic and vibrational resonances associated with impurities

(a) Transition-metal (Fe, Cu, Co, Ni, Mn, and Cr)

(b) OH ion

(c) Dopants (GeO$_2$, P2O$_5$, and B2O$_3$)
Rayleigh Scattering

- Rayleigh scattering is a fundamental loss mechanism arising from local microscopic fluctuations in density.

\[ \alpha_R = \frac{C}{\lambda^4} \]

Where, \( C \) is in the range 0.7-0.9(dB/km)-\( \mu m^4 \),

- At 1.55\( \mu m \), \( \alpha_R = 0.12-0.16 \text{ dB/km} \)
Waveguide Imperfections

• Mie scattering induced by the imperfections at the core-cladding interface (random core-radius variations)

• In practice, such variation can be kept below 1%, and the resulting scattering loss is typically below 0.03 dB/km
Bending Loss

• Bending is another source of scattering loss

• The bending loss is proportional to $\exp\left(-\frac{R}{R_c}\right)$

• For single-mode fibers, $R_c = 0.2 - 0.4\mu m$ typically, and the bending loss is negligible ($<0.01 \, dB/km$) for bend radii $R > 5 \, mm$

• Macrobending loss are negligible in practice since macroscopic bends exceed $R = 5 \, mm$

• Microbending loss could be large in the cable
Optical Fiber Manufacturing

- Fiber Materials
- Design Issues
- Fabrication Methods
- Cables and Connectors
Fiber Materials

Requirements in selecting materials for optical fibers:

1. It must be possible to make long, thin, flexible fibers from the material
2. The material must be transparent at a particular optical wavelength
3. Physically compatible materials that have slightly different refractive indices for the core and cladding must be available

✓ Oxide Glass Fibers
✓ Halide Glass Fibers
✓ Active Glass Fibers
✓ Chalcogenide Glass fibers
✓ Plastic Optical Fibers
Glass Fibers

Glass is made by fusing mixtures of metal oxides, sulfides, or selenides

Glass has a randomly connected molecular network

Glasses do not have well-defined melting points
Oxide Glass Fibers

• The most common oxide glass fiber is silica (SiO₂)

• Its refractive index is 1.458 @ 850nm

• Its refractive index can be easily modified by adding either fluorine or various oxides

Examples of fiber compositions:

(1) GeO₂-SiO₂ core; SiO₂ cladding
(2) P₂O₅-SiO₂ core; SiO₂ cladding
(3) SiO₂ Core; cladding
(4) Ge₂O₅-B₂O₃-SiO₂ core, P₂O₅-SiO₂ core cladding

Variation in refractive index as function of doping concentration in silica glass
Halide Glass Fibers

• The most common halide glass fiber is ZBLAN (ZrF₄, BaF₄, LaF₃, AlF₃, NaF)

• A lower-refractive-index cladding (ZHBLAN) is produced by partially replacing ZrF₄ by HaF₄

• Extremely low transmission losses at mid-infrared wavelengths (0.2-8µm) with the lowest loss being around 2.55 µm

• Potentially offers intrinsic minimum losses of 0.01-0.001dB/km

<table>
<thead>
<tr>
<th>Molecular composition of a ZBLAN fluoride glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>ZrF₄</td>
</tr>
<tr>
<td>BaF₄</td>
</tr>
<tr>
<td>LaF₃</td>
</tr>
<tr>
<td>AlF₃</td>
</tr>
<tr>
<td>NaF</td>
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</tbody>
</table>
Active Glass Fibers

• Incorporating rare-earth elements (atomic numbers 57-71) into a normally passive glass gives the resulting materials new optical and magnetic properties

• Amplification, attenuation, and phase retardation can be performed in active glass fibers

• Commonly used materials for fiber lasers and amplifiers: Erbium, Neodymium, Ytterbium, Holmium,
Chalcogenide Glass Fibers

• Contain at least one chalcogen element (S, Se, or Te) and typically one other element such as P, I, Cl, Br, Cd, Ba, Si, or Tl for tailoring the thermal, mechanical, and optical properties of the glass

• High optical nonlinearity

• Long interaction length

• As$_2$S$_3$ is one of the most well-known materials (core: As$_{40}$S$_{58}$Se$_2$, cladding: As$_2$S$_3$)

• Loss typically range around 1 dB/m
Plastic Optical Fibers

• High-bandwidth graded-index polymer optical fibers (POFs) meet the growing demand for delivering high-speed services directly to the workstation

• The core of FOPs are either polymethylmethacrylate (PMMA POF) or perfluorinated polymer (PFP POF)

• Larger optical signal attenuations than glass fibers

• Tough and durable

<table>
<thead>
<tr>
<th>Sample characteristics of PMMA and PFP polymer optical fibers</th>
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<tbody>
<tr>
<td>Characteristic</td>
</tr>
<tr>
<td>Core diameter</td>
</tr>
<tr>
<td>Cladding diameter</td>
</tr>
<tr>
<td>Numerical aperture</td>
</tr>
<tr>
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<tr>
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</table>
Several index profiles used in the design of single-mode fibers. Upper and lower rows correspond to standard and dispersion-shifted fibers, respectively.
Fiber Fabrication

• Outside Vapor-Phase Oxidation
• Vapor-Phase Axial Deposition
• Modified Chemical Vapor Deposition
• Plasma-Activated Chemical Vapor Deposition
• Double-Crucible Method
Basic steps in preparing a preform by the OVPO process. (a) Bait rod rotates and moves back and forth under the burner to produce a uniform deposition of glass soot particles along the rod; (b) profiles can be step or graded index; (c) following deposition, the soot preform is sintered into a clear glass preform; (d) fiber is drawn from the glass preform.
Modified Chemical Vapor Deposition

GeCl₄ + O₂ → GeO₂ + 2Cl₂
4POCl₃ + 3O₂ → 2P₂O₃ + 6Cl₂

Schematic of MCVD
Plasma-Activated Chemical Vapor Deposition

Schematic of PCVD process
Vapor-Phase Axial Deposition

Apparatus for the VAD process
Double-Crucible Method

Double-crucible arrangement for drawing fibers from molten glass
Fiber Drawing

Apparatus used for fiber drawing

Schematic of a fiber-drawing apparatus
Cables and Connectors

Typical designs for light-duty fiber cables

Typical designs for heavy-duty fiber cables
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