3.2.3.2 Stimulated Raman Scattering

The transformation of a small fraction power from the incident light to the scattered light is called the spontaneous Raman scattering. This phenomenon was discovered by C. V. Raman in 1928 [6]. In general, the frequencies of the scattering light are different from those of the incident light by an amount defined by the vibrational levels of the medium.

The spontaneous Raman scattering is a weak process to some extent. For example, if the light is propagated through a medium with a volume of 1 cm^3 only one part of the million of the incident light will be scattered into the Stokes frequency. However, if an intense laser source is incident on a molecular medium there is a high scattering component can occur and more than 10% of the incident power is transferred to the scattering components [7]. This type of nonlinear scattering was discovered in 1962 and called the SRS phenomenon [8].

Basic Concept

The SRS is an important nonlinear phenomenon that can convert the optical fibers into wideband Raman amplifiers and tunable Raman fiber lasers. It can also strongly limit the WDM communication system performance by relocating fraction of power from one wavelength to another [9]. In SRS nonlinear phenomenon, the incident light works as a pump source and called the RPP, and the transmitted power known as the residual Raman pump power (R-RPP). The scattering components which shifted to lower frequencies (red-shift) are known as Stokes waves, and those shifted to higher frequencies (blue-shift) are called anti-Stokes waves [64, 79].

The origin of the Stokes wave generation lies in the energy exchange between the photons and the material molecules. The quantum mechanical energy diagram for Raman scattering is shown in Figure 3.3. In the Stokes generation process, the incident photon of frequency v_P excites a molecule from the ground state to the virtual state. Then, this molecule returns to the vibrational state and releasing a Stokes photon of frequency v_S.

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Since, the energy between the virtual state and the vibrational level is smaller than the energy between the ground and the virtual states, as a results the $\nu_S < \nu_P$. On the contrary, in the anti-Stokes process, the excitement molecule will be within the vibrational level. Hence, the frequency of the anti-Stokes signal is higher than the incident photon $\nu_A > \nu_P$.

Furthermore, the intensity of the Stokes waves is many orders of magnitude higher than the intensity of the anti-Stokes waves. This is due to the anti-Stokes process requires the vibrational state to be initially populated with a phonon of right energy and momentum. In what follows the anti-Stokes process was ignored as it plays an insignificant role in Raman amplification.

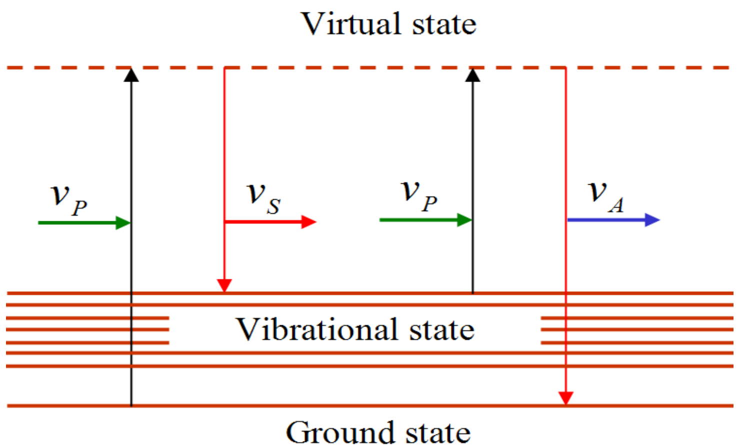

Figure 3.3: Quantum-mechanical energy diagram for Raman scattering.

Using the same criteria as those specified for the Brillouin scattering threshold given in (**Equation 3.5**), it may be shown that the threshold optical power for SRS P_R in a long single-mode fiber is given by:

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB}$$ **(Equation 3.6)**

Example 3.3

A long SMF has an attenuation of 0.5 dB km^{-1} when operating at a wavelength of 1.3 μm. The fiber core diameter is 6 μm and the laser source bandwidth is 600 MHz. Compare the threshold optical powers for SBS and SRS within the fiber at the wavelength specified.

Solution:

The threshold optical power for SBS is given by (**Equation 3.5**) as:

$$P_d = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB}\, v$$

$$= 4.4 \times 10^{-3}\, 6^2\, 1.3^2\, 0.5 \times 0.6$$

$$= 80.3\ \mu\mu$$

The threshold optical power for SRS may be obtained from (**Equation 3.6**), where:

$$P_R = 5.9 \times 10^{-2} d^2 \lambda\, \alpha_{dd}$$

$$= 5.9 \times 10^{-2}\, 6^2\, 1.3\ \ 0.5$$

$$= 1.38\ \mu$$

3.2.4 Bending Losses

Bending losses occur whenever an optical fiber undergoes a bend of finite radius of curvature. Fiber can be subject to two types of bends:

a) Macroscopic bends having radii that are large compared to the fiber diameter,for example, such as occur when a fiber cable turns a corner.

b) Microscopic bends of the fiber axis that can arise when the fibers are incorporated into cables.

The minimum bend radius it has a particular importance in the handling of fiber optic cables, which are often used in telecommunications. The minimum bending radius will vary with different cable designs. The manufacturer should specify the minimum radius to which the cable may safely be bent during installation.

The minimum bend radius is in general also a function of tensile stresses, e.g., during installation, while being bent around a sheave while the fiber or cable is under tension. If no minimum bend radius is specified, one is usually safe in assuming a minimum long-term lower-stress radius **not less than 15 times** the cable diameter.

Optical fibers suffer radiation losses at bends or curves on their paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy to be radiated from the fiber. An illustration of this situation is shown in **Figure 3.4**. The part of the mode which is on the outside of the bend is required to travel faster than that on the inside so that a wavefront perpendicular to the direction of propagation is maintained. Hence, part of the mode in the cladding needs to travel faster than the velocity of light in that medium. As this is not possible, the energy associated with this part of the mode is lost through radiation. The loss can generally be represented by a radiation attenuation coefficient which has the form:

$$\alpha_r = C_1 \exp(-C_2 R) \qquad \textbf{(Equation 3.7)}$$

where R is the radius of curvature of the fiber bend and C_1, C_2 are constants which are independent of R. Furthermore, large bending losses tend to occur in multimode fibers at a critical radius of curvature R_{CMMF} which may be estimated from:

$$R_{CMMF} = \frac{3 n_1^2 \lambda}{4\pi (n_1^2 - n_2^2)^{\frac{3}{2}}} \qquad \textbf{(Equation 3.8)}$$

It may be observed from the expression given in (**Equation 3.8**) that potential macrobending losses may be reduced by:

(a) Designing fibers with large relative refractive index differences;

(b) Operating at the shortest wavelength possible.

The above criteria for the reduction of bend losses also apply to SMF, the critical radius of curvature for a SMF R_{CSMF} can be estimated as:

$$R_{CSMF} = \frac{20\lambda}{(n_1 - n_2)^{\frac{3}{2}}} \left(2.748 - 0.996\frac{\lambda}{\lambda_c}\right)^{-3} \qquad \textbf{(Equation 3.9)}$$

where λ_c is the cutoff wavelength for the SMF.

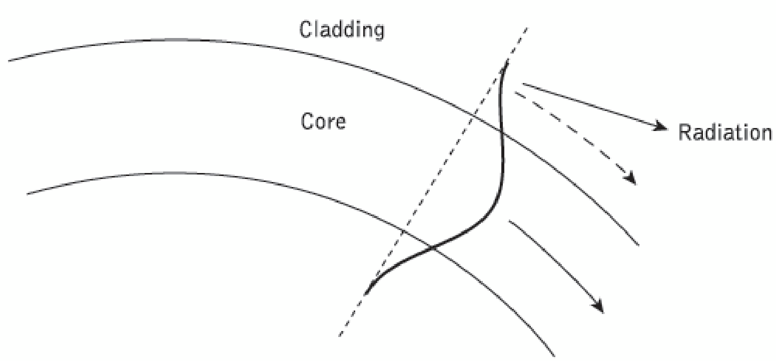

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Figure 3.4: An illustration of the radiation loss at a fiber bend.
The part of the mode in the cladding outside the dashed arrowed line may be required to travel faster than the velocity of light in order to maintain a plane wavefront. Since it cannot do this, the energy contained in this part of the mode is radiated away.

Example 3.4

Two step index fibers exhibit the following parameters: **(a)** MMF with a core refractive index of 1.5, a relative refractive index difference of 3% and an operating wavelength of 0.82 μm;

(b) an 8 μm core diameter SMF with a core refractive index the same as (a), a relative refractive index difference of 0.3% and an operating wavelength of 1.55 μm. Estimate the critical radius of curvature at which large bending losses occur in both cases.

Solution:

(a) The relative refractive index difference is as:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

Hence:

$$n_2^2 = n_1^2 - 2n_1^2\Delta = 2.25 - 2 \times 2.25 \times 0.03 = 2.115$$

Using (**Equation 3.8**) for the multimode fiber critical radius of curvature:

$$R_{CS} = \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{\frac{3}{2}}} = \frac{3 \times 2.25 \times 0.82 \times 10^{-6}}{4\pi \times (0.135)^{\frac{3}{2}}} = 1.2\ \mu m$$

(b) R_{CS} =34 mm

3.3 Dispersion

Next to the fiber loss, the capacity of information transmission is an important consideration in designing a fiber-optic communication system. **The dispersion of the fiber essentially determines the maximum bit rate or modulation frequency that can be attained. There are three types of dispersion** [12]:

1. Mode dispersion (MD).
2. Chromatic dispersion (CD).
   a. Material dispersion
   b. Waveguide dispersion
3. Polarization mode dispersion (PMD)

Variation in propagation time among different modes creates **mode dispersion**. If the source were perfectly monochromatic, then mode dispersion would be the only dispersion with which to contend. In reality, all sources, especially when modulated, emit light over a spread of optical frequencies, and the frequency spread of the source leads to other types of dispersion.

The variation in propagation time due to the wavelength dependence of the refractive index creates **material dispersion**. The wavelength dependence of the propagation pattern causes **waveguide dispersion**.

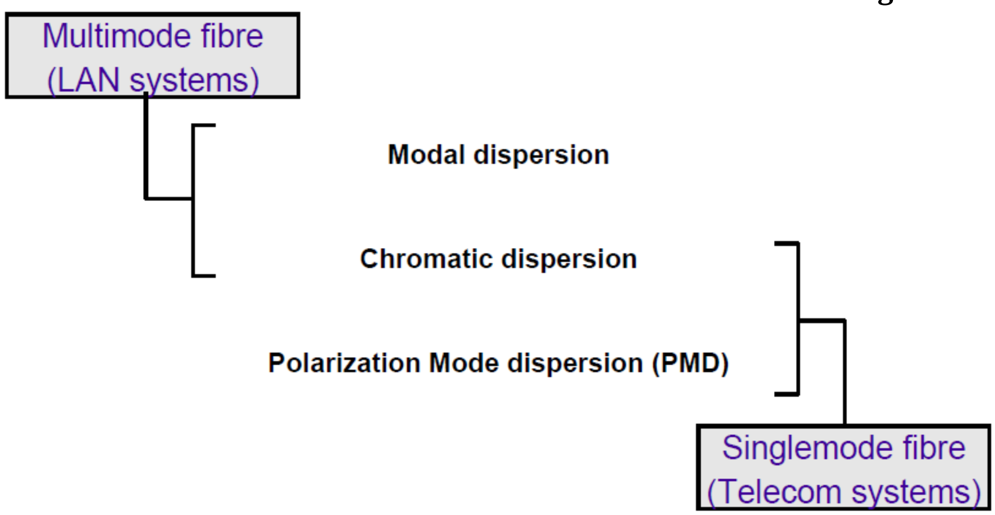

Figure 3.5: Dispersion in an optical fiber.

3.3.1 Mode Dispersion (MD)

Using the ray theory model, the fastest and slowest modes propagating in the step index fiber may be represented by the axial ray and the extreme meridional ray (which is incident at the core–cladding interface at the critical angle φc) respectively. The paths taken by these two rays in a perfectly structured step index fiber are shown in Figure 3.8. The delay difference between these two rays when traveling in the fiber core allows estimation of the pulse broadening resulting from intermodal dispersion within the fiber. As both rays are traveling at the same velocity within the constant refractive index fiber core, then the delay difference is directly related to their respective path lengths within the fiber. Hence the time taken for the axial ray to travel along a fiber of length L gives the minimum delay time T_{Min} and: We now derive an approximate measure of the time spread due to intermodal dispersion.

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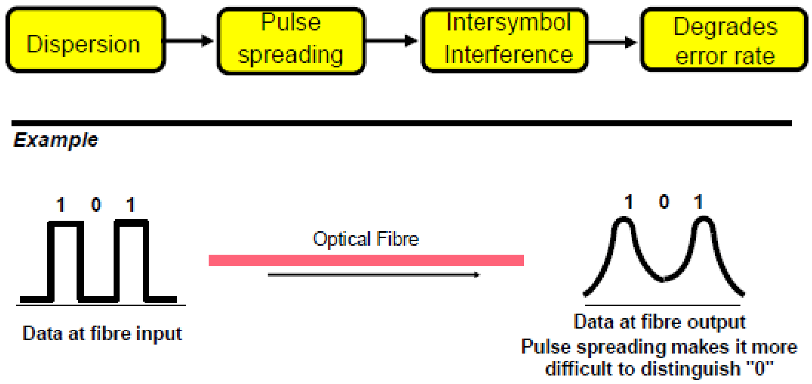

Figure 3.6: Why dispersion is a problem

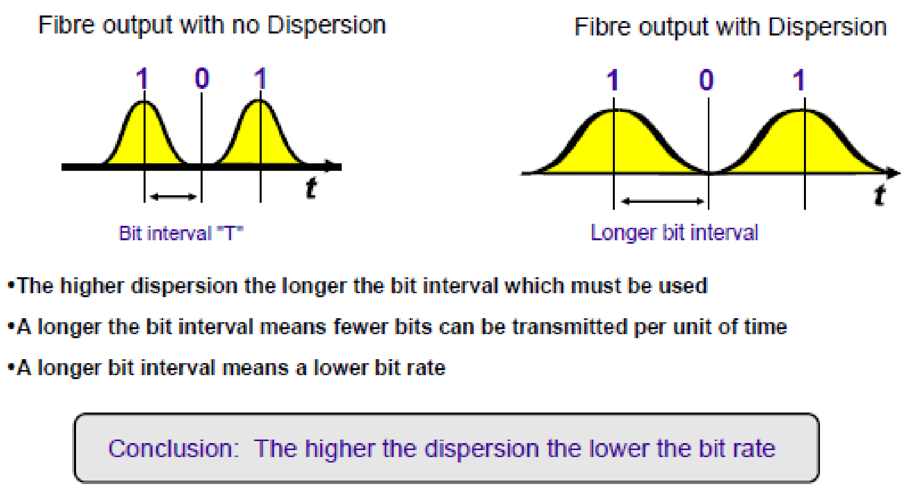

Figure 3.7: Dispersion and Bit Rate.

•Assume:

- Step index fibre
- An impulse-like fibre input pulse
- Energy is equally distributed between rays with paths lying between the axial and the extreme meridional

•What is the *difference in delay* for the two extremes over a linear path length L?

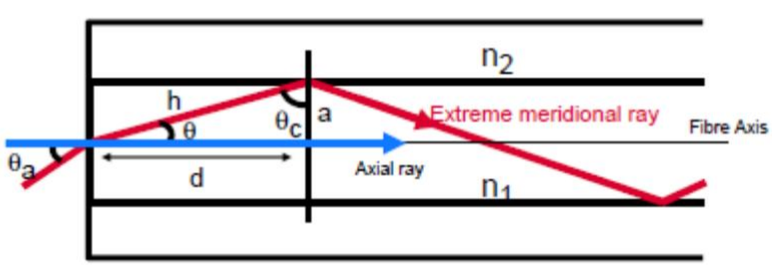

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Figure 3.8 The paths taken by the axial and an extreme meridional ray in a perfect multimode step index fiber.

Transmission distance = L

T_{max} = Transmission time for extreme meridional ray

T_{min} = Transmission time for axial ray

Delay difference $\delta t = T_{max} - T_{min}$

$$T_{min} = \frac{\text{Distance}}{\text{Velocity}} = \frac{L}{(c/n_1)} = \frac{Ln_1}{c}$$

To find T_{max} realise that the ray travels a distance h but only travels a distance d toward the fibre end (d<h). So if the fibre length is L then the actual distance travelled is:

$$\frac{h.L}{d}$$

$$T_{max} = \frac{Ln_1}{c\cos\theta}$$ Using simple trigonometry

Using Snell's law: $\sin\theta_c = \frac{n_2}{n_1} = \cos\theta$

$$T_{max} = \frac{Ln_1^2}{cn_2}$$

$$\text{Delay difference } \delta t = T_{max} - T_{min} = \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c}$$

$$\delta T_s = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right) \simeq \frac{Ln_1\Delta}{c}$$

How large can δT be before it begins to matter? That depends on the bit rate used. A rough measure of the delay varies δa that can be tolerated at a bit rate of B b/s is half the bit period 1/2B s. Thus intermodal dispersion sets the following limit:

$$[illegible]\, a = \frac{L\,(N [illegible]}{[illegible]2[illegible])^2} < \frac{1}{2d}$$

[illegible] [illegible]1

The capacity of an optical communication system is frequently measured in terms of the bit rate–distance product. If a system is capable of transmitting (x Mb/s over a distance of y km),

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it is said to have a bit rate-distance product of xy (Mb/s)-km. The intermodal dispersion constrains the bit rate-distance product of an optical communication link to be:

$$BL < \frac{n_2}{n_1^2}\frac{c}{\Delta}$$

For example, if $\Delta = 0.01$ and $n_1 = 1.5 (\approx n_2)$, we get $BL < 10$ (Mb/s)-km. This limit is plotted in Figure 3.9.

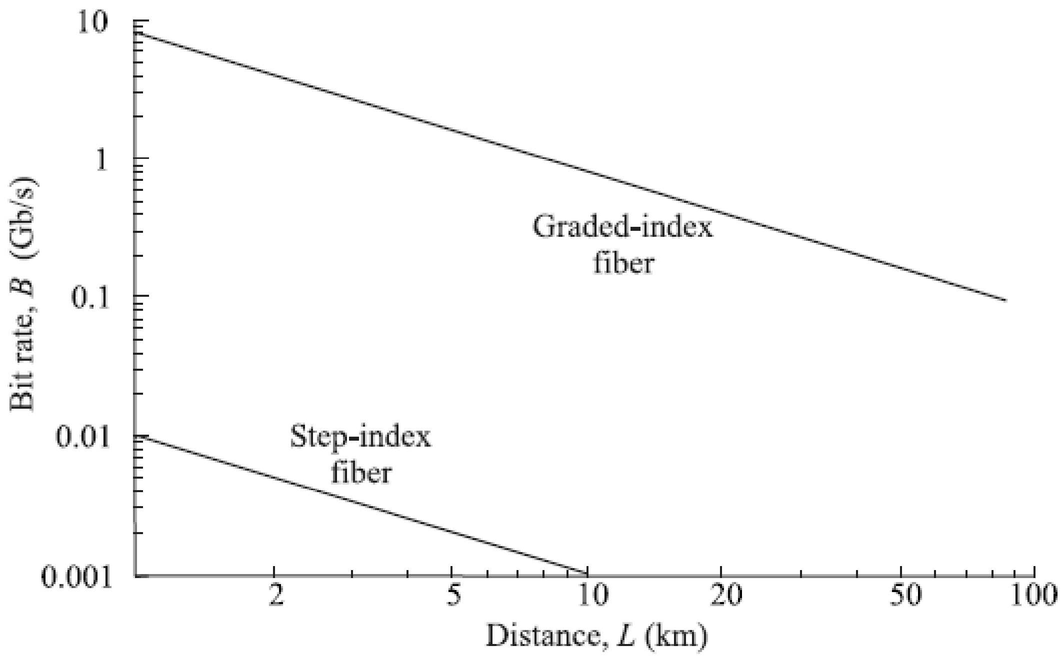

Figure 3.9: Limit on the bit rate–distance product due to intermodal dispersion in a step-index and a graded-index fiber. In both cases, $\Delta = 0.01$ and n1 = 1.5.

- BW get smaller as fibre length L increases
- High NA fibres have lower bandwidths, eg plastic fibre has high NA: Poor bandwidth
- Lowering NA to improve bandwidth makes source coupling more difficult as the acceptance angle decreases

Example 3.5

A 6 km optical link consists of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate:

(a) The delay difference between the slowest and fastest modes at the fiber output;

(b) The rms pulse broadening due to intermodal dispersion on the link;