Module 4 : Third order nonlinear optical processes

Lecture 33 : Consequences of the Stimulated Scattering in Optical Communication

Objectives

In this lecture we will

- Discuss broad band Raman amplifiers;
- Harmful effects of
  (a) Stimulated Raman Stokes scattering.
  (b) Stimulated Brillouin scattering and remedies for optical communication systems.

Raman Amplifiers:

we have seen that the interaction of the intense optical field with optical phonons in solids leads to stimulated Raman scattering. As explained earlier in lecture #29, in this process through nonlinear coupling, energy is transferred from the pump field to the signal field at the Stokes frequency resulting in the amplification of the latter.

Optical fibers are made of amorphous fused silica glass. Consequently, the vibrational frequencies of the molecules broaden and overlap to form a very broad spectral profile.
Thus the glass fibers can provide Raman gain at extended frequency range (typically 1-10THz) for wideband signal amplification. Under the assumption of constant pump intensity one can see from equation (29.36), the power of the Stokes wave at frequency ω_s after propagating a distance *L* through the Raman active medium will be

$$P_s(L) = P_s(0)\exp\left[g_s^{'}\left|E_p(0)\right|^2 L\right]$$

$$= P_s(0)\exp\left[g_s^{'}\frac{P_p}{A}L\right] \qquad (33.1)$$

where P_p is the pump power.

It should be noted that the gain, $g_s = \frac{\omega_s}{n_s c}\operatorname{Im}\chi_R^{(3)}(\omega_s)$ scales linearly with frequency. Since in optical fibers the propagation losses occur for various reasons, one has to add a damping term in the coupled differential equations (29.31) and (29.32) for the Stokes and the pump fields.
The resulting equations for the field evolution thus will be

$$\frac{dI_s}{dz} = g_s^{'} I_p I_s - \alpha_s I_s \qquad (33.2)$$

and

$$\frac{dI_p}{dz} = -\frac{\omega_p}{\omega_s} g_s^{'} I_p I_s - \alpha_p I_p \qquad (33.3)$$

where α_p and α_s are the absorption coefficients for the Stokes and the pump light. If the pump depletion due to stimulated Raman scattering is neglected then I_p varies with propagation due to its absorption only

$$I_p(z) = I_0 e^{-\alpha_p z} \qquad (33.4)$$

Substituting (33.4) in (33.2) and integrating

$$I_s(L) = I_s(0)\, e^{\left(g_s^{'} I_0 L_e - \alpha_s L\right)} \qquad (33.5)$$

where L_e is the effective length given by

$$L_e = \frac{\left[1-\exp\left(-\alpha_p L\right)\right]}{\alpha_p} \tag{33.6}$$

We define Raman threshold power as that pump power at which the Stokes wave power at the end of the fiber is comparable to pump power. Since the gain profile is almost Lorenzian, the threshold condition will be satisfied if the exponent in equation (33.5) is 16.

$$P_c = \frac{16A}{g_s' L_e} \tag{33.7}$$

Example:

For the following typical parameters given for the single mode fiber at $\lambda = 1.55\mu m$, $A = 70\mu m^2$, L= 20km

and $g = 7\times10^{-14} m/W$, the critical power will be $P_c = 800mW$

A typical Raman amplifier arrangement is shown in figure 33.1.

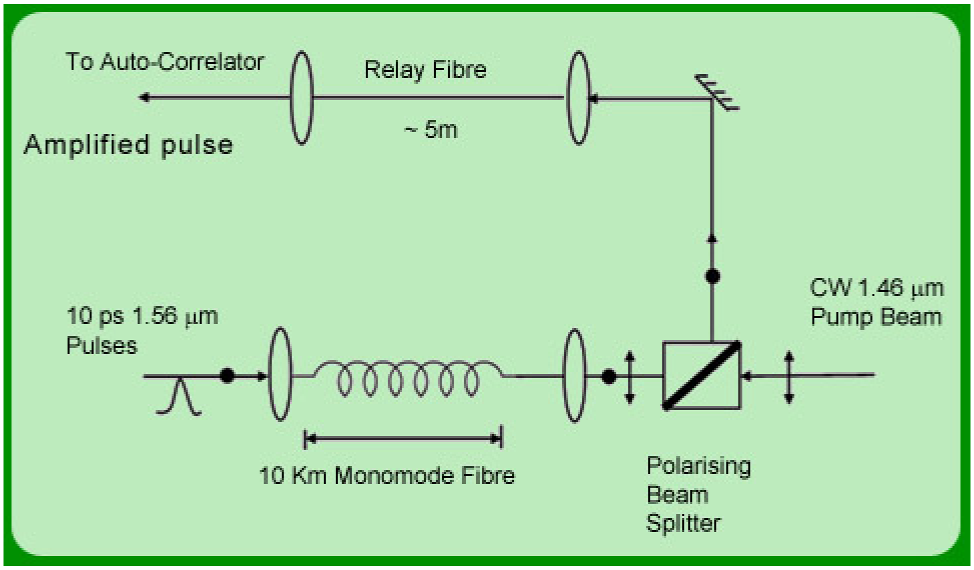

Figure 33.1

A 1460 mm pump laser is coupled to the amplifier fiber through a polarization coupler at one end. From the other end of the fiber the signal at $\lambda_s = 1.55\mu m$ is launched which get amplified as it propagates. Amplified signal is out coupled from the second port of the polarization coupler. With a powerful laser, one can amplify signal in several channels simultaneously. Also, there is no limit on communication speed- very small Δt allowed.

Harmful effects of SRS:

SRS process can adversely affect the wavelength division multiplex(WDM) communication by transferring energy from short wavelength channels to the long wavelength channels. This increases the inter-channel cross-talk. The tolerable limit of SRS induced cross-talk is 1%. This would imply

$$\frac{P_s(L)}{P_s(0)} = \exp\left(g_s' P_p \frac{L}{A}\right) = 1.01 \tag{33.8}$$

$\Rightarrow$

$$g_s' P_p \frac{L}{A} = 0.01 \tag{33.9}$$

$\Rightarrow$ to avoid the harmful effect of the cross talk the exponent value of 16 in the expression (33.5) should be limited to 0.01. Thus $P_c \sim 1mW$ should not exceed. Another important precaution to observe is to avoid the channel separations just equal to maximum Raman gain window. This would suggest the channel separation to be 500 cm^{-1}. This restricts the maximum realizable information carrying capacity of WDM communication system.

SBS effects:

In SBS light scattering is caused by the acoustic phonons. Typically acoustic phonon frequency ranges from 1-10 GHz. Therefore, the frequency shifts in SBS are much smaller than those in SRS. We have shown that SBS takes place only in backward direction.
Taking the fiber losses into account, the equations (32.22) and (32.23) for the spatial evolution are modified as

$$\frac{\mathrm{d}I_b}{\mathrm{d}z} = -g_b^{'} I_p I_b + \alpha I_b \tag{33.10}$$

and

$$\frac{\mathrm{d}I_p}{\mathrm{d}z} = -g_b^{'} I_p I_b + \alpha I_p \tag{33.11}$$

since $\omega_b \approx \omega_p$, we can take $\alpha_b \approx \alpha_p \equiv \alpha$

For undepleted pump, we can neglect the first term in equation (33.11) so that

$$I_p\left(z\right) = I_p\left(0\right)\mathrm{e}^{-\alpha z} \tag{33.12}$$

Substituting it back in the equation(33.10), one can write

$$I_b\left(0\right) = I_b\left(L\right)\mathrm{e}^{\left(\left(g_b^{'} Pp Le / A\right) - \alpha L\right)} \tag{33.13}$$

where

$$L_e = \frac{\left[1 - \exp\left(-\alpha_p L\right)\right]}{\alpha_p} \tag{33.14}$$

is the effective interaction length. SBS gain in glass fibers can be more than two orders of magnitude larger than SRS. We can define the critical power for SBS on the lines of SRS.

$$P_c = \frac{21A}{g_b^{'} L_e} \tag{33.15}$$

Example: Consider Billouin line width $\Delta\omega_b \approx 100MHz$; $\lambda = 1 \cdot 55\mu m$; $g_b^{'} = 5^{x}10^{-11} m / W$; $A = 50\mu m^2$; $L_e = 20km$; $P_c = 1mW$ $\Rightarrow$ SBS is a dominant nonlinear process in optical fibers and it can affect the optical communication system much more strongly and adversely than SRS. It causes

1. significant signal loss;
2. produce multiple frequency shifts. of course it is not so produce multiple frequency shifts. Of course, it is not so severe an effect as SRS in WDM communication;
3. creates a very strong backward wave which causes feedback in to the laser source and can damage it.

These deleterious effects can be overcome by raising the SBS threshold by broadening the signal spectrum

Recap

In this lecture we have

- Discussed the broad band fiber Raman amplifiers.

Harmful effects of
(a) Stimulated Raman Stokes scattering.
(b) Stimulated Brillouin scattering and remedies for optical communication systems.