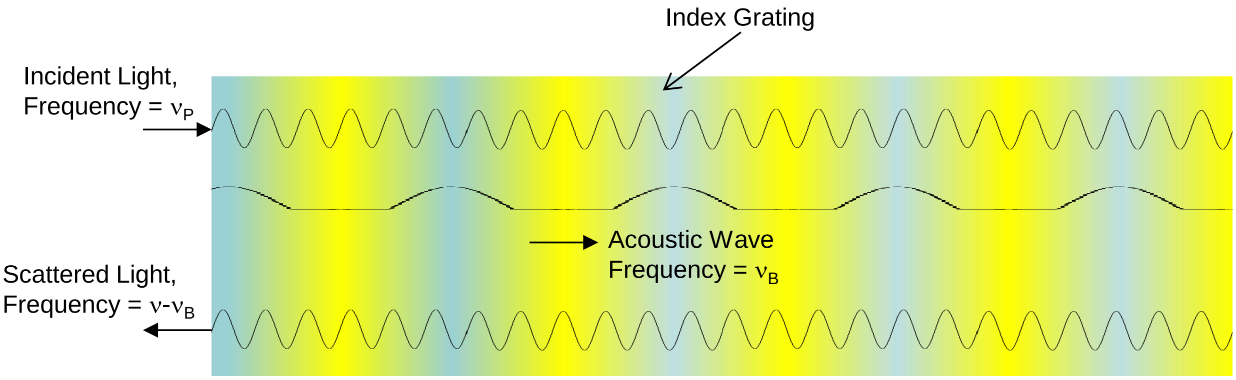
OPTI 500F, Take Home Exam

Stimulated Brillouin Scattering

You may use class notes and other reference material.

Due May 10, 2012



Stimulated Brillouin Scattering (SBS) is a nonlinear optical effect that limits the amount of forward-traveling optical power than can be used for an optical communication link.

Stimulated Brillouin Scattering – The Basic Idea

The mechanism for SBS, as discussed in Professor Garmire's nonlinear optics lecture and illustrated above, is as follows: Light of frequency ν_P (p for "pump") is incident on a material medium. The light is scattered backwards off an index grating created by a random, thermally-generated phonon (acoustic wave) of frequency ν_B in the medium. The forward-going incident wave and backward-going scattered wave interfere to create an intensity pattern in the material. Through the process of electrostriction, the optical intensity pattern creates a density pattern that propagates in the forward direction as an acoustic wave that also has a frequency ν_B. This acoustic wave creates a corresponding index grating through the density dependence of the refractive index that enhances the original grating; so that, once initiated, the process reinforces itself.

Impact on DWDM Communication Systems

The frequency of the Doppler-shifted, scattered light is

$$\nu_S = \nu_P - \nu_B,$$

Not all phonons have exactly the same frequency. Lifetime broadening of the phonon line means that phonon frequency is in the approximate range of

$$\nu_B = \nu_{B0} \pm \frac{\Delta\nu_B}{2}$$

$$\text{with } \nu_{B0} = \frac{n v_S}{\pi\lambda_0} \text{ and } \Delta\nu_B = \frac{1}{\pi\tau_{ph}},$$

where n is the refractive index of the medium, v_s is the velocity of sound, λ_0 is the optical wavelength, and τ_{ph} is the lifetime of a phonon.

1. *Calculate the Doppler shift, in Hertz, due to a phonon in the center of the frequency range, for light with λ_0 = 1550 nm in silica optical fiber with n = 1.45 and v_s = 5940 m/s.*

This value is small enough so that the SBS effect is confined to a single channel in a DWDM (dense wavelength division multiplexed) optical communication link, where wavelengths are separated by 50-200 GHz.

Comparison with Stimulated Raman Scattering

2. *Calculate the phonon frequency spread in optical fiber, in Hertz, given a photon lifetime of 9.4 nanoseconds.*

Stimulated Brillouin Scattering and Stimulated Raman Scattering (SRS) both arise from the interaction of light with material vibrations, but this calculation shows an important way in which they differ. The range of vibrational frequencies involved in SBS is 1,000,000 times smaller than the range for SRS.

This means SBS cannot be used to simultaneous amplify multiple DWDM wavelengths.

The SBS Threshold

An SBS threshold power has been defined that is has been widely used to estimate at what input power the SBS scattered light becomes comparable to the input light, and a problem:

$$P_{th} = 21\frac{A_{eff}1.5}{g_{B0}L_{eff}}\left(1+\frac{\Delta\nu_P}{\Delta\nu_B}\right),$$

where the factor of 1.5 means that we have assumed unpolarized light, A_{eff} is the effective fiber core area that takes into account the spread of the optical mode into the cladding, $\Delta\nu_P$ is the spread of frequency components in the input (pump) light, g_{B0} is the peak SBS gain coefficient, and L_{eff} is the effective fiber length

$$L_{eff} = \frac{1-\exp(\alpha L)}{\alpha},$$

where L is the fiber length.

3. *Calculate the SBS threshold power for a narrow band source ($\Delta\nu_P << \Delta\nu_B$) and a 100-meter-long optical fiber with α = 4.6 x 10^{-5} m^{-1} (equivalent to a loss of 0.2 dB/km), an effective core area A_{eff} = 50 μm2, and an SBS gain coefficient g_{B0} = 4.1 x 10^{11} m/W.*

The SBS threshold is very low – about 1000 times smaller than for Raman Scattering. An analysis has shown that the threshold is about 4 times higher for the modulated light in high date rate optical communication links.

SBS Gain and the Interaction Length

The Brillouin scattered optical power grows according to the expression

$$P_S(L) = P_S(0)\exp\left(g_B(\Delta\nu_S)\frac{P_P}{A_{eff}}L\right),$$

where P_P is the optical power in the incident light beam, A_{eff} is the "effective area" for the optical mode in the fiber, and the SBS gain coefficient g_B is

$$g_B(\Delta\nu_S) = g_{B0}\frac{\left(\frac{\nu_B}{2}\right)^2}{(\Delta\nu_S)^2 + \left(\frac{\Delta\nu_B}{2}\right)^2},$$

where $\Delta\nu_S = \nu_S - (\nu_P - \nu_{B0})$.

Notice that g_B is related to the conventional gain coefficient g through the relation

$$g = g_B\frac{P_P}{A_{eff}},$$

which is why g_B and g_{B0} have units of m/W. This last relationship shows the reason for defining g_B. The conventional gain coefficient g depends on the power in the incident wave, while g_B depends only on material properties.

4. *Find the peak gain coefficient g with 50 μm^2 for the effective area of the optical mode in the fiber threshold input power you calculated in 3.*
5. *Find the length of fiber that is required to give an overall SBS gain of 10.*

The long interaction length that can be achieved in optical fibers is required for significant SBS at these optical powers.