Problem Set 12
Nonlinear Optics (NLO)

Due: 13. July 2016

1) Stimulated Raman Scattering

Stimulated Raman scattering (SRS) is an important nonlinear effect that can e.g. be used for broadband fiber amplifiers. However, in wavelength-division multiplexing (WDM) systems, SRS can also reduce the performance, as it causes an energy transfer (crosstalk) between different channels.

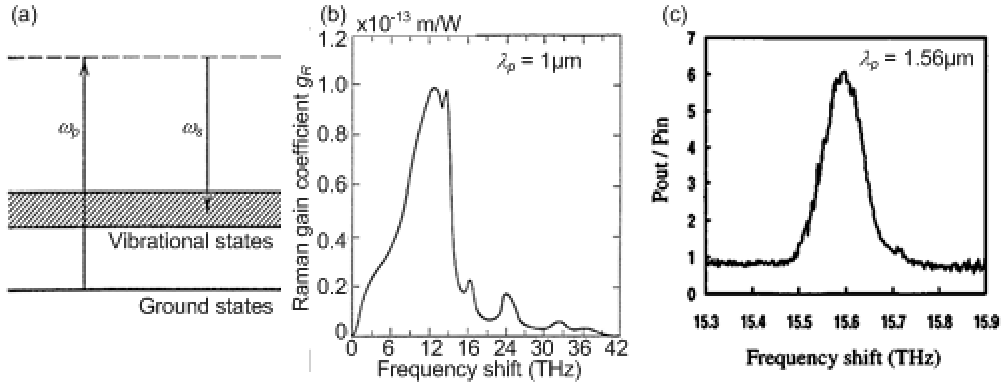

Figure 1: (a) Energy-level representation of SRS. **(b)** Raman gain spectrum in a fused-silica fiber for a pump wavelength of 1000 nm [1]. **(c)** Raman gain spectrum in a silicon-on-insulator waveguide for a pump wavelength of 1557.4 nm [2]. Note that on the vertical axis in (b) and (c) two different quantities have been measured and therefore the numbers are not comparable.

Raman effect

1. Explain the Raman effect using your own words and relate your explanation to Figure 1. What is the difference between spontaneous and stimulated Raman scattering?

2. The Raman gain spectra of fused-silica and crystalline silicon are depicted in Figure 1(b) and (c). Explain the differences. How are they related to the material structure?

Stimulated Raman scattering

The nonlinear interaction of a continuous pump wave with the Stokes wave in a fiber is described by the following set of coupled differential equations:

$$\frac{dI_s}{dz} = g_R I_p I_S - \alpha_s I_S \qquad (1)$$

$$\frac{dI_p}{dz} = -\frac{\omega_p}{\omega_s} g_R I_p I_S - \alpha_p I_p \, , \qquad (2)$$

where I_p and I_S are the intensities of pump and Stokes waves at frequencies ω_p and ω_S respectively. The quantity g_R denotes the Raman gain coefficient and α_p and α_S describe the fiber losses.

3. Show that the total number of photons of the pump and the Stokes wave is conserved in the absence of fiber losses ($\alpha_p = \alpha_s = 0$).

4. Solve the coupled differential equations under the assumption that the power of the pump wave is not significantly depleted by SRS ($I_S << I_p$, undepleted-pump approximation). Neglect the corresponding term in Eq. (2).

5. Calculate the Raman gain factor $G_A = \frac{I_s(L)}{I_s(0)e^{-\alpha_s L}}$ for a fiber amplifier of length $L = 1000\,\mathrm{m}$. Assume that both the pump and the Stokes wave experience a propagation loss of $\alpha = 0.2\,\mathrm{dB/km}$. To do this, take the maximum value of the Raman gain coefficient from Figure 1(b) and assume an input pump power of $P_{in} = I_P A_m = 240\,\mathrm{mW}$, where $A_m = 10\,\mu\mathrm{m}^2$ denotes the effective modal cross section. Can the gain factor be increased arbitrarily by increasing the length of the fiber?

   Hint: The fiber propagation loss in dB/m has to be converted into linear units by [1]

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

6. Even if no light at the Stokes wavelength is coupled into the fiber, a strong Stokes signal can build up from spontaneously emitted Stokes photons that are subsequently amplified by SRS. What is the consequence for the transport of high optical powers over a single-mode fiber, e.g. in a WDM system?

7. Explain three major differences between Raman and Brillouin scattering.

References

[1] G. P. Agrawal, '*Fiber-optic communications systems*', John Wiley & Sons, 2002.

[2] T. K. Liang and H. K. Tsang, '*Efficient Raman amplification in silicon-on-insulator waveguides*', Appl. Phys. Lett., Vol. 85, No. 16, 2004

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