Nonlinear Optical Engineering

Stimulated Raman Scattering (1)
(NFO 5th ed: 8.1)

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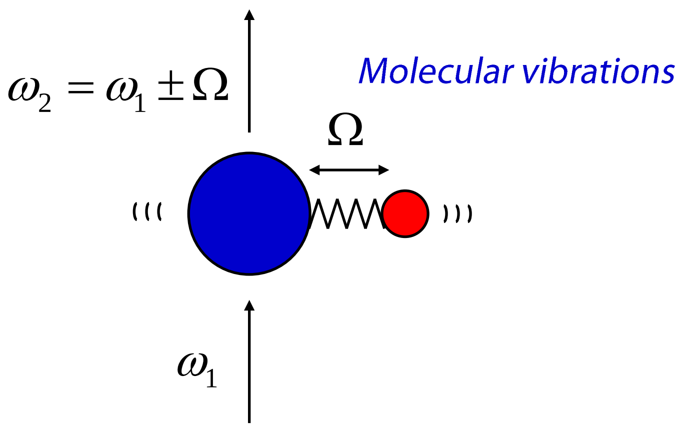
Basic Concepts (1)

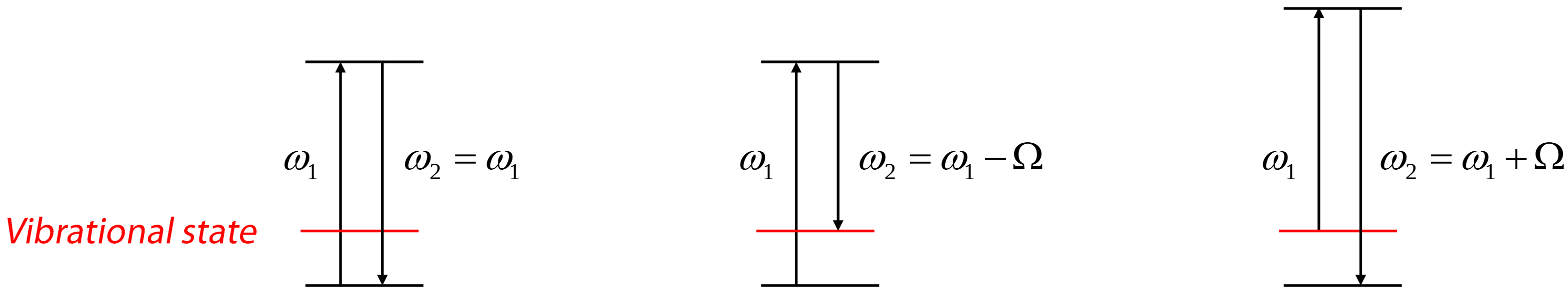
Discovery of Raman scattering:

$\rightarrow$ C. V. Raman in 1928

Inelastic scattering $\leftrightarrow$ molecular vibrations



Does every kind of molecule tend to vibrate?



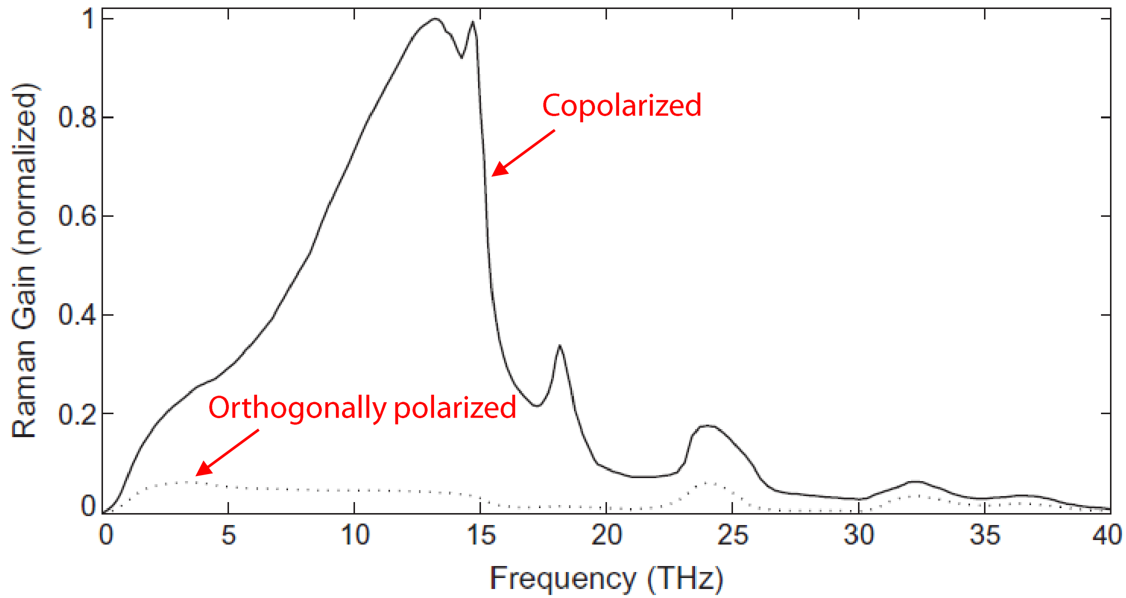
Elastic scattering:
Rayleigh scattering

Inelastic scattering:
Stokes scattering

Inelastic scattering:
Anti-Stokes scattering

Basic Concepts (2)

Raman-gain spectrum:



G. P. Agrawal, Nonlinear Fiber Optics, 5th ed.

Initial growth of the Stokes wave:

$$\rightarrow \frac{dI_s}{dz} = g_R I_p I_s \qquad \leftarrow g_R \sim 10^{-13}\ \text{m/W}, \quad \Omega_R \sim 13.2\ \text{THz}$$ ← For silica

Basic Concepts (3)

Raman threshold:

Coupled equations in the CW case:

$$\rightarrow \frac{dI_s}{dz} = g_R I_p I_s - \alpha_s I_s$$

$$\rightarrow \frac{dI_p}{dz} = -\frac{\omega_p}{\omega_s} g_R I_p I_s - \alpha_p I_p$$

In the absence of losses:

$$\rightarrow \frac{d}{dz}\left(\frac{I_s}{\omega_s} + \frac{I_p}{\omega_p}\right) = 0$$

For non-depleted pump:

$$\rightarrow \frac{dI_s}{dz} = g_R I_0 \exp(-\alpha_p z) I_s - \alpha_s I_s$$

$$\rightarrow I_s(L) = I_s(0)\exp(g_R I_0 L_{eff} - \alpha_s L) \quad \leftarrow L_{eff} = [1-\exp(-\alpha_p L)]/\alpha_p$$

Raman-gain spectrum:

$$\rightarrow P_s(L) = \int_{-\infty}^{\infty} h\nu \exp[g_R(\nu_p - \nu) I_0 L_{eff} - \alpha_s L] d\nu$$

$\leftarrow$ Method of steepest descent, assuming a Lorentzian gain profile

$$\rightarrow P_s(L) \approx P_{s0}^{eff} \exp[g_R(\nu_R) I_0 L_{eff} - \alpha_s L] \quad \leftarrow \nu_R = \nu_p - \nu_s$$

$$\leftarrow P_{s0}^{eff} = h\nu_s B_{eff}, \quad B_{eff} = \frac{\sqrt{\pi}}{2} \frac{\Delta\nu_{FWHM}}{[g_R(\nu_R) I_0 L_{eff}]^{1/2}} = \left(\frac{2\pi}{I_0 L_{eff}}\right)^{1/2} \left|\frac{\partial^2 g_R}{\partial \nu^2}\right|_{\nu=\nu_R}^{-1/2}$$

Basic Concepts (4)

Raman threshold:

Critical pump power:

$$\rightarrow P_s(L) = P_p(L) \equiv P_0 \exp(-\alpha_p L)$$

$$\rightarrow P_{s0}^{eff} \exp[g_R(\nu_R) I_0 L_{eff} - \alpha_s L] = P_0 \exp(-\alpha_p L) \quad \leftarrow I_0 = P_0 / A_{eff}, \quad \alpha_s \approx \alpha_p$$

$$\rightarrow P_{s0}^{eff} \exp[g_R(\nu_R) P_0 L_{eff} / A_{eff}] = P_0$$

$$\rightarrow \exp[g_R(\nu_R) P_0 L_{eff} / A_{eff}] = P_0 / P_{s0}^{eff}$$

$$\rightarrow \boxed{\frac{g_R P_0^{cr} L_{eff}}{A_{eff}} \approx 16} \quad \leftarrow \frac{P_0}{P_{s0}^{eff}} \approx 70 \text{ dB}$$

Basic Concepts (5)

Coupled amplitude equations:

Optical field:

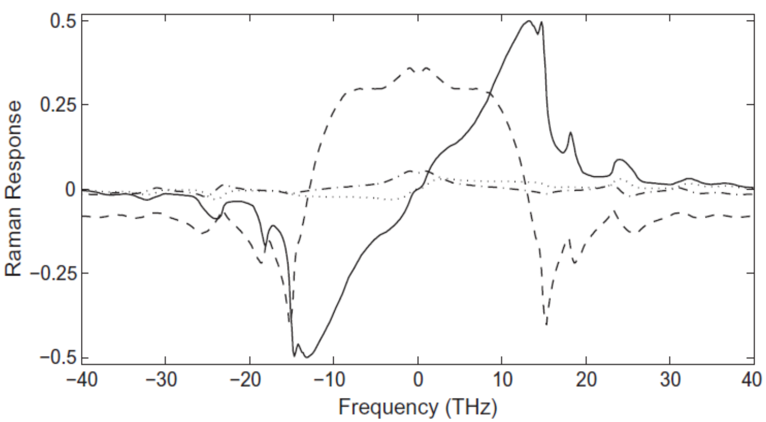
$$\rightarrow \mathbf{E}(\mathbf{r},t) = \tfrac{1}{2}\hat{x}\left\{A_p \exp[i(\beta_{0p}z-\omega_p t)] + A_s \exp[i(\beta_{0s}z-\omega_s t)]\right\} + c.c.$$

Coupled NLSE:

$$\rightarrow \frac{\partial A_p}{\partial z} + \frac{1}{v_{gp}}\frac{\partial A_p}{\partial t} + \frac{i\beta_{2p}}{2}\frac{\partial^2 A_p}{\partial t^2} + \frac{\alpha_p}{2}A_p = i\gamma_p(1-f_R)(|A_p|^2 + 2|A_s|^2)A_p + R_p(z,t)$$

$$\rightarrow \frac{\partial A_s}{\partial z} + \frac{1}{v_{gs}}\frac{\partial A_s}{\partial t} + \frac{i\beta_{2s}}{2}\frac{\partial^2 A_s}{\partial t^2} + \frac{\alpha_s}{2}A_s = i\gamma_s(1-f_R)(|A_s|^2 + 2|A_p|^2)A_s + R_s(z,t)$$

$$\leftarrow R_j(z,t) = i\gamma_j f_R A_j \int_{-\infty}^{t} h_R(t-t')\left[|A_j(z,t')|^2 + |A_k(z,t')|^2\right]dt'$$



$$+ i\gamma_j f_R A_k \int_{-\infty}^{t} h_R(t-t')A_j(z,t')A_k^*(z,t')\exp[\pm i\Omega(t-t')]dt'$$

$$\leftarrow j,k = p \text{ or } s, \quad j \neq k, \quad \Omega_R = \omega_p - \omega_s$$

$$\rightarrow R_j = i\gamma_j f_R\left[(|A_j|^2 + |A_k|^2)A_j + \tilde{h}_R(\pm\Omega_R)|A_k|^2 A_j\right]$$

$$\rightarrow \delta_R = f_R \,\mathrm{Re}[\tilde{h}_R(\Omega)], \quad g_j = 2\gamma_j f_R \,\mathrm{Im}[\tilde{h}_R(\Omega)]$$

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Basic Concepts (6)

Coupled amplitude equations:

Coupled NLSE:

$$\rightarrow \frac{\partial A_p}{\partial z} + \frac{1}{v_{gp}}\frac{\partial A_p}{\partial t} + \frac{i\beta_{2p}}{2}\frac{\partial^2 A_p}{\partial t^2} + \frac{\alpha_p}{2}A_p$$

$$= i\gamma_p\left[\left|A_p\right|^2 + (2+\delta_R - f_R)\left|A_s\right|^2\right]A_p - \frac{g_p}{2}\left|A_s\right|^2 A_p$$

$$\rightarrow \frac{\partial A_s}{\partial z} + \frac{1}{v_{gs}}\frac{\partial A_s}{\partial t} + \frac{i\beta_{2s}}{2}\frac{\partial^2 A_s}{\partial t^2} + \frac{\alpha_s}{2}A_s$$

$$= i\gamma_s\left[\left|A_s\right|^2 + (2+\delta_R - f_R)\left|A_p\right|^2\right]A_s + \frac{g_s}{2}\left|A_p\right|^2 A_s$$

For silica fibers: $\leftarrow f_R \approx 0.18$

Walk-off length:

$$\rightarrow L_W = T_0 / \left|v_{gp}^{-1} - v_{gs}^{-1}\right|$$