

Nonlinear Optical Engineering

Stimulated Raman Scattering (2) (NFO 5th ed: 8.2 ~ 8.3)

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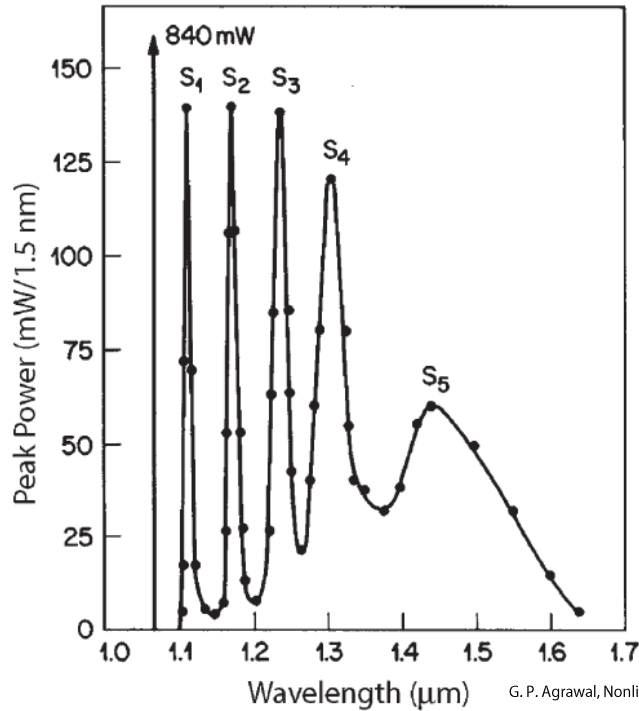
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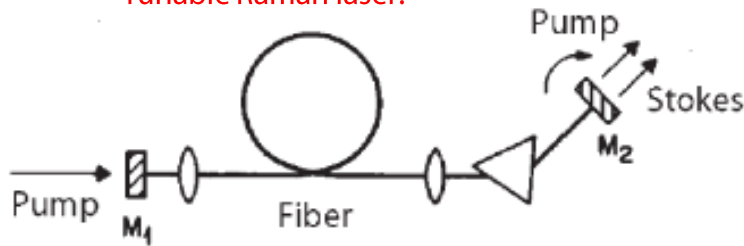
Quasi-Continuous SRS (1)

Single-pass Raman generation:



Raman fiber lasers:

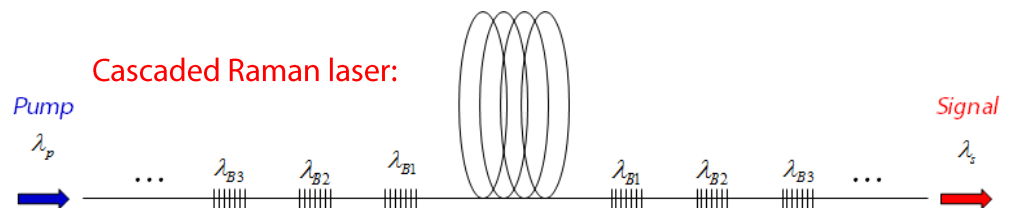
Tunable Raman laser:



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

Raman gain: $\rightarrow G = \exp[2g_R P_0 L_{eff} / A_{eff}] = \text{Cavity loss}$

Cascaded Raman laser:



Quasi-Continuous SRS (2)

Raman fiber amplifiers:

Amplification factor:

$$\rightarrow G_A = \exp[g_R P_0 L_{eff} / A_{eff}]$$

Recall:
$$\frac{dI_s}{dz} = g_R I_p I_s - \alpha_s I_s, \quad \frac{dI_p}{dz} = -\frac{\omega_p}{\omega_s} g_R I_p I_s - \alpha_p I_p$$

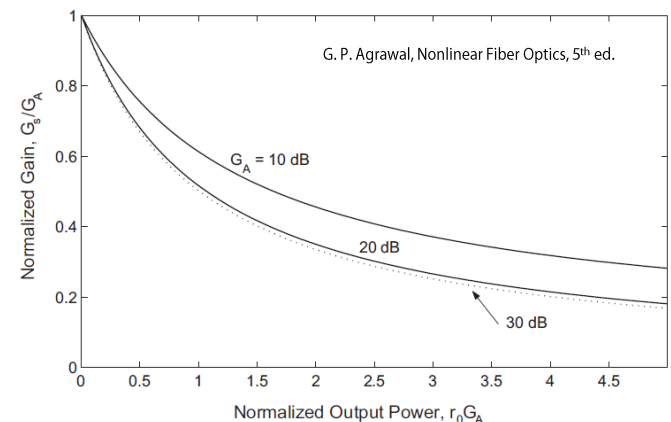
Coupled eqs.:

$$\rightarrow \frac{dF_s}{dz} = \omega_p g_R F_p F_s e^{-\alpha z}, \quad \frac{dF_p}{dz} = -\omega_p g_R F_p F_s e^{-\alpha z}$$

$$\rightarrow F_p(z) + F_s(z) = C$$

$$\rightarrow \frac{F_s(L)}{F_s(0)} = \left(\frac{C - F_s(L)}{C - F_s(0)} \right) \exp(\omega_p g_R C L_{eff})$$

$$\leftarrow I_j = \omega_j F_j \exp(-\alpha z)$$



Saturated gain:

$$\rightarrow G_s = \frac{I_s(L)}{I_s(0)} = \frac{F_s(L)}{F_s(0)} \exp(-\alpha L) = \left(\frac{C - F_s(L)}{C - F_s(0)} \right) \exp(\omega_p g_R C L_{eff} - \alpha L)$$

$$\rightarrow G_s = \frac{(1 + r_0) e^{-\alpha L}}{r_0 + G_A^{-(1+r_0)}}$$

$$\leftarrow C = F_p(0) + F_s(0)$$

$$\leftarrow r_0 = \frac{F_s(0)}{F_p(0)} = \frac{\omega_p}{\omega_s} \frac{P_s(0)}{P_0}$$

Quasi-Continuous SRS (3)

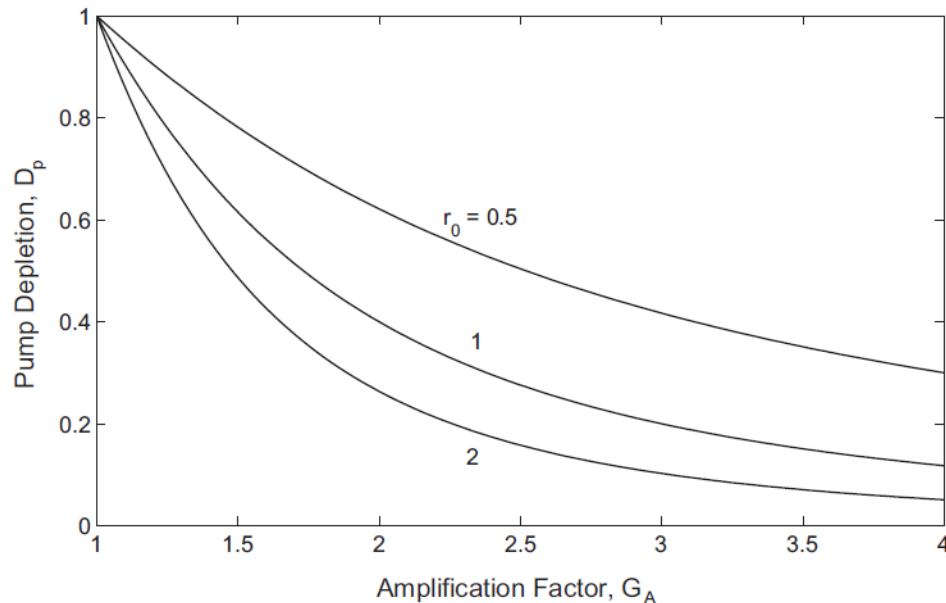
Raman-induced crosstalk:

Pump depletion factor:

$$\rightarrow D_p = \frac{I_p(L)}{I_p(0) \exp(-\alpha_p L)} = \frac{1+r_0}{1+r_0 G_A^{1+r_0}}$$

Power penalty:

$$\rightarrow \Delta = 10 \log(1/D_p) \quad [\text{dB}]$$



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

SRS with Short Pump Pulses (1)

Pulse-propagation equations:

Coupled NLSE:

$$\rightarrow \frac{\partial A_p}{\partial z} + \frac{i\beta_{2p}}{2} \frac{\partial^2 A_p}{\partial T^2} = i\gamma_p \left[|A_p|^2 + (2 - f_R) |A_s|^2 \right] A_p - \frac{g_p}{2} |A_s|^2 A_p$$

$$\rightarrow \frac{\partial A_s}{\partial z} - d \frac{\partial A_s}{\partial T} + \frac{i\beta_{2s}}{2} \frac{\partial^2 A_s}{\partial T^2} = i\gamma_s \left[|A_s|^2 + (2 - f_R) |A_p|^2 \right] A_s + \frac{g_s}{2} |A_p|^2 A_s$$

$$\leftarrow T = t - z / v_{gp}, \quad d = v_{gp}^{-1} - v_{gs}^{-1}$$

Scaling of parameters:

$$\rightarrow \beta_{2s} = \frac{\lambda_p}{\lambda_s} \beta_{2p}, \quad \gamma_s = \frac{\lambda_p}{\lambda_s} \gamma_p, \quad g_s = \frac{\lambda_p}{\lambda_s} g_p$$

Length scales:

$$\rightarrow L_D = \frac{T_0^2}{|\beta_{2p}|}, \quad L_W = \frac{T_0}{|d|}, \quad L_{NL} = \frac{1}{\gamma_p P_0}, \quad L_G = \frac{1}{g_p P_0}$$

SRS with Short Pump Pulses (2)

Nondispersive case:

Nondispersive and non-depleted pump assumption: $\rightarrow \beta_{2p} = \beta_{2s} = 0, \quad g_p = 0$

$$\rightarrow A_p(z, T) = A_p(0, T) \exp[i\gamma_p |A_p(0, T)|^2 z]$$

$$\rightarrow A_s(z, T) = A_s(0, T + zd) \exp\{[g_s / 2 + i\gamma_s(2 - f_R)]\psi(z, T)\}$$

$$\leftarrow \psi(z, T) = \int_0^z |A_p(0, T + zd - z'd)|^2 dz'$$

For a Gaussian pump pulse:

$$\rightarrow A_p(0, T) = \sqrt{P_0} \exp(-T^2 / 2T_0^2)$$

$$\rightarrow \psi(z, \tau) = [\text{erf}(\tau + \delta) - \text{erf}(\tau)](\sqrt{\pi} P_0 z / \delta) \quad \leftarrow \text{erf}(\tau) = \frac{2}{\sqrt{\pi}} \int_0^\tau e^{-t^2} dt$$

Seed pulse:

$$\rightarrow A_s(0, T) = (P_{s0}^{eff})^{1/2}$$

$$\leftarrow \tau = T / T_0, \quad \delta = zd / T_0 = z / L_W$$

Peak power of the Raman pulse:

$$\rightarrow P_s(L) = |A_s(L, 0)|^2 \approx P_{s0}^{eff} \exp(\sqrt{\pi} g_s P_0 L_W) \quad \leftarrow \tau = 0, \quad L / L_W \gg 1$$

$$\text{Recall: } \rightarrow P_{s0}^{eff} \exp[g_R(\nu_R) P_0 L_{eff} / A_{eff}] = P_0 \quad (\leftarrow CW)$$

Effective interaction length: $\rightarrow L_{eff} = \sqrt{\pi} L_W \approx T_{FWHM} / |d|$

SRS with Short Pump Pulses (3)

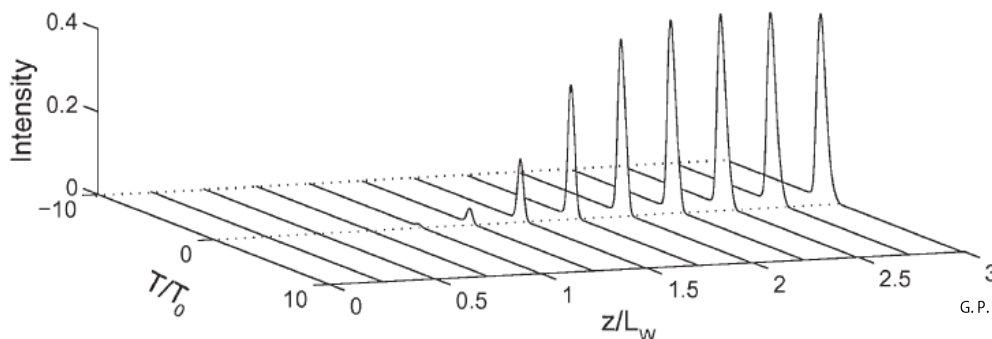
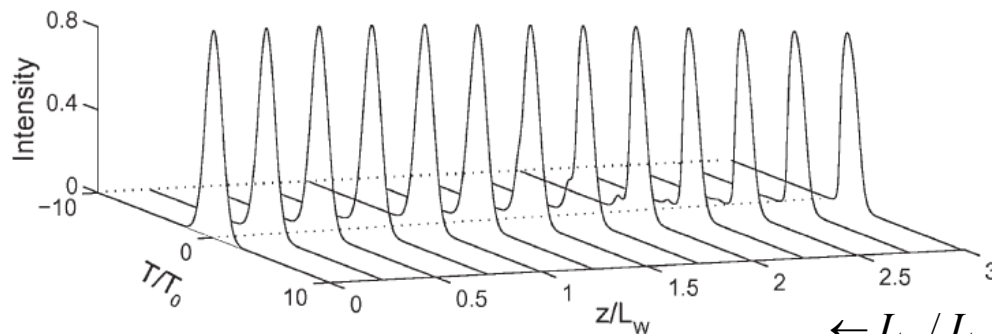
Effects of GVD:

Normalized variables: $\rightarrow z' = \frac{z}{L_W}, \quad \tau = \frac{T}{T_0}, \quad U_j = \frac{A_j}{\sqrt{P_0}}, \quad r = \frac{\lambda_p}{\lambda_s}$

Coupled NLSE:

$$\rightarrow \frac{\partial U_p}{\partial z'} + \frac{i}{2} \frac{L_W}{L_D} \frac{\partial^2 U_p}{\partial \tau^2} = i \frac{L_W}{L_{NL}} \left[|U_p|^2 + (2 - f_R) |U_s|^2 \right] U_p - \frac{L_W}{2L_G} |U_s|^2 U_p$$

$$\rightarrow \frac{\partial U_s}{\partial z'} + \frac{\partial U_s}{\partial \tau} + \frac{ir}{2} \frac{L_W}{L_D} \frac{\partial^2 U_s}{\partial \tau^2} = i \frac{rL_W}{L_{NL}} \left[|U_s|^2 + (2 - f_R) |U_p|^2 \right] U_s + \frac{rL_W}{2L_G} |U_p|^2 U_s$$



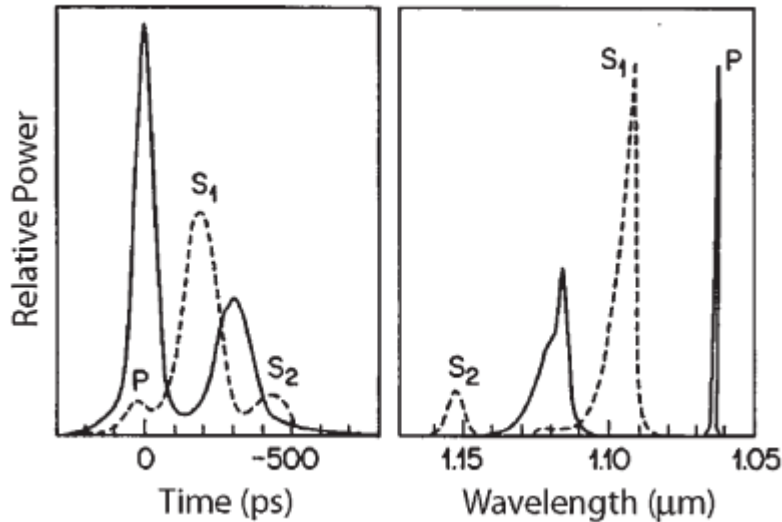
$$\leftarrow L_D / L_W = 1000, L_W / L_{NL} = 24, L_W / L_G = 12$$

$$\rightarrow \sqrt{\pi} g_s P_0 L_W \approx 21$$

SRS with Short Pump Pulses (4)

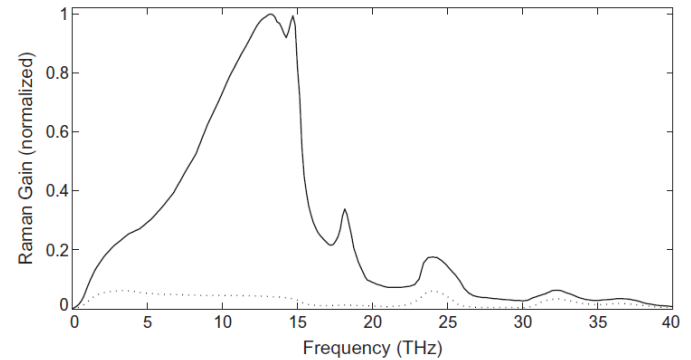
Synchronously pumped Raman lasers:

Temporal and spectral output of a Raman laser in the case of resonant (dashed) and single-pass (solid) operation:



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

Recall:



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