Nonlinear Optical Engineering

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

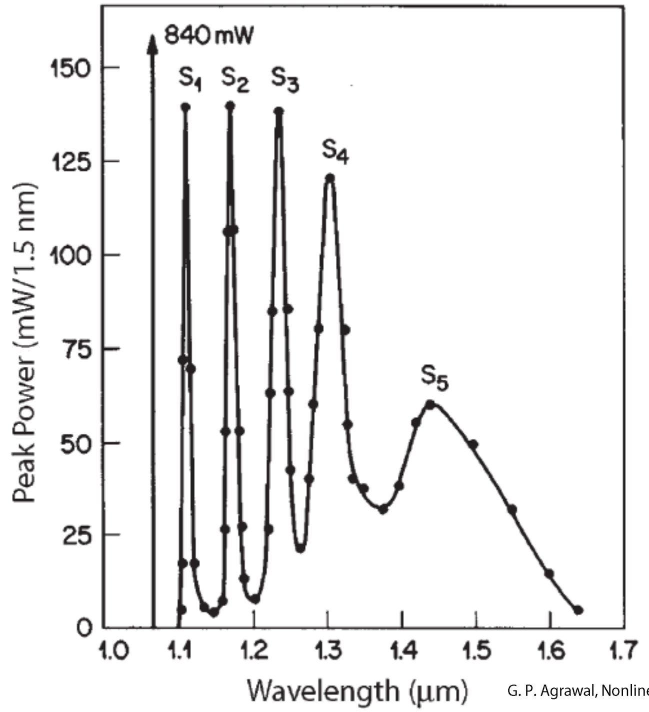
Yoonchan Jeong

School of Electrical Engineering, Seoul National University

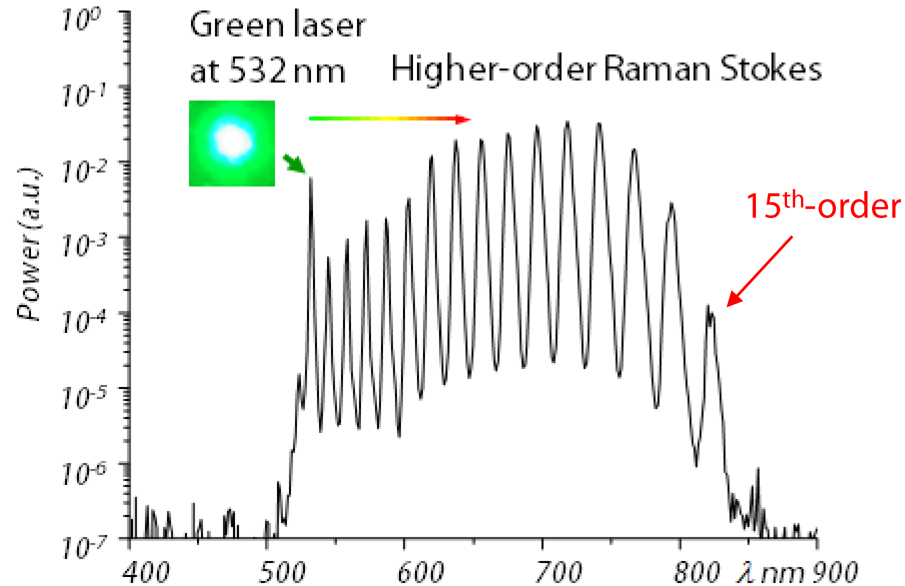
Tel: +82 (0)2 880 1623, Fax: +82 (0)2 873 9953
Email: yoonchan@snu.ac.kr

Quasi-Continuous SRS (1)

Single-pass Raman generation:



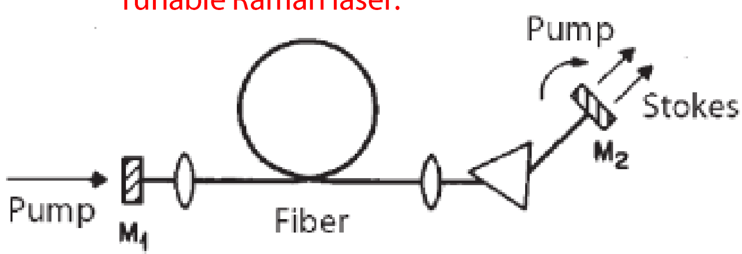
G. P. Agrawal, Nonlinear Fiber Optics, 5th ed.



Raman fiber lasers:

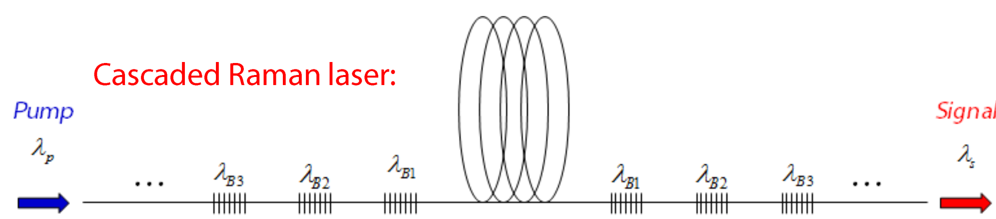
Raman gain: $\rightarrow G = \exp[2 g_R P_0 L_{eff} / A_{eff}] = Cavity\ loss$

Tunable Raman laser:



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

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

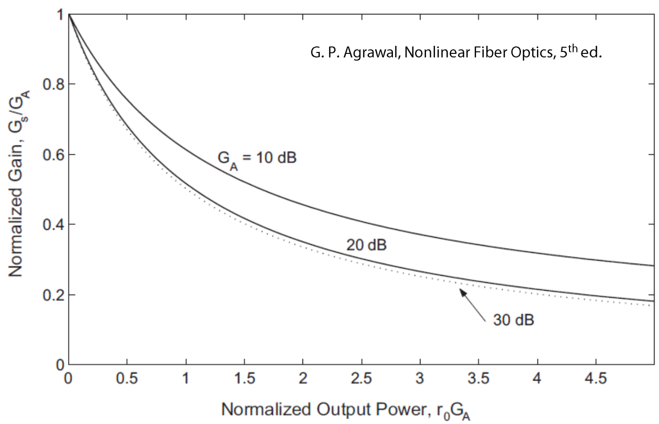
$$\leftarrow I_j = \omega_j F_j \exp(-\alpha z)$$

Coupled eqs.:

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

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

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



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)

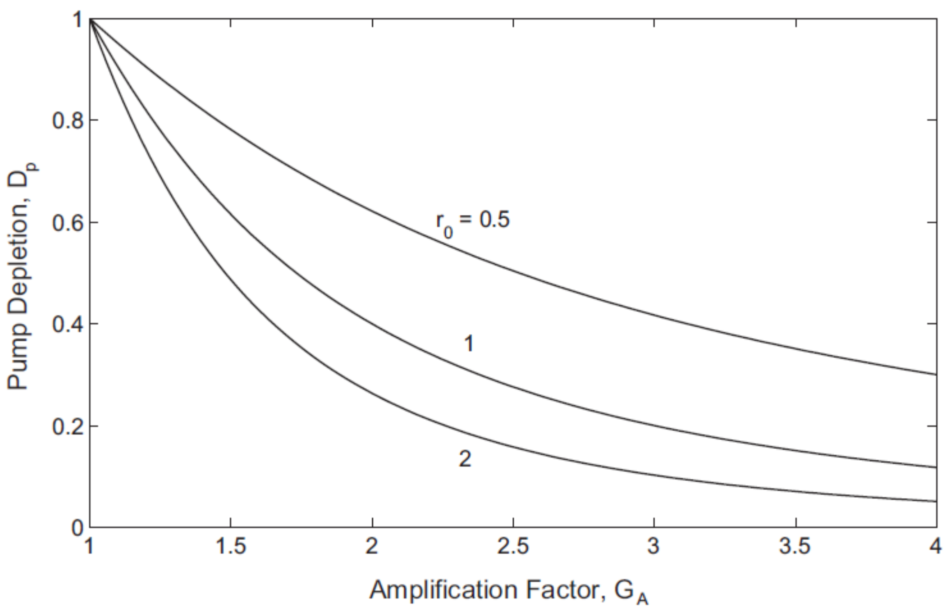
Raman-induced crosstalk:

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:

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



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

SRS with Short Pump Pulses (1)

Pulse-propagation equations:

Coupled NLSE:

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

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

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

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:

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

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:

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

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

Seed pulse:

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

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

Peak power of the Raman pulse:

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

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)

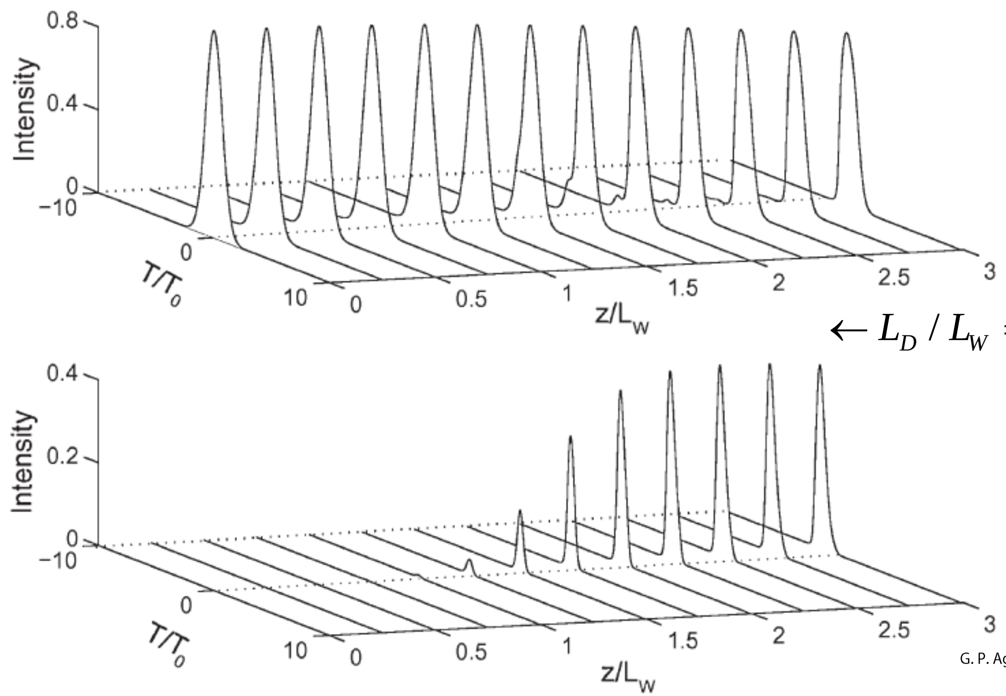
Effects of GVD:

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

Coupled NLSE:

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

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



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

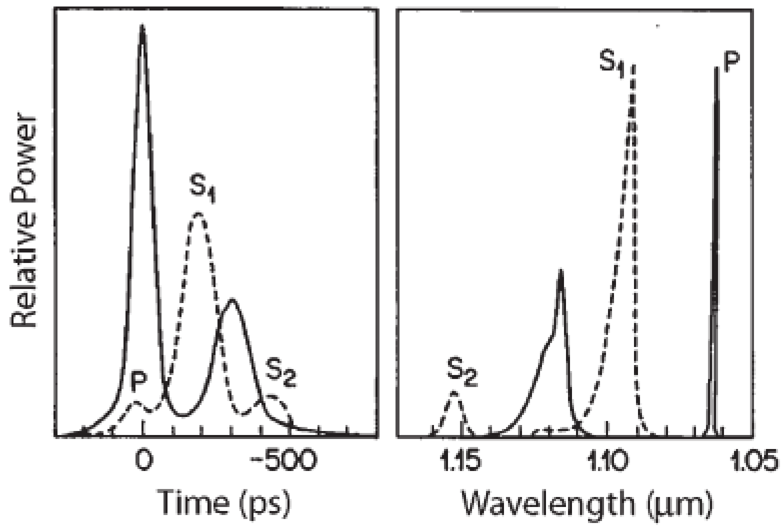
$\rightarrow \sqrt{\pi}\, g_s P_0 L_W \simeq 21$

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

SRS with Short Pump Pulses (4)

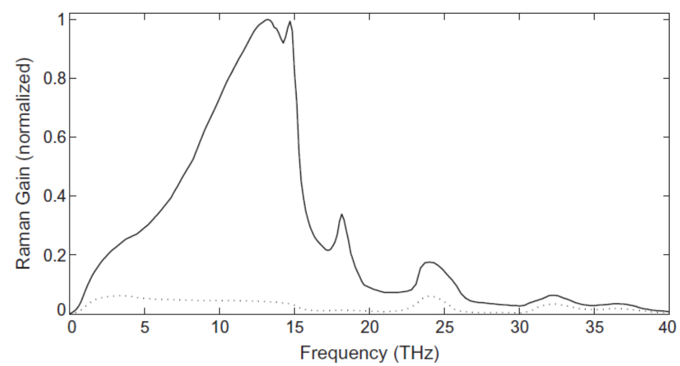
Synchronously pumped Raman lasers:

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:



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