Nonlinear optics

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Y.B. Band, Light and Matter, Wiley

R. W. Boyd, Nonlinear Optics, Academic Press, Latest Edition. In addition, course notes will be distributed.

G. P. Agrawal, Nonlinear Fiber Optics, Academic Press, 1995

Y. R. Shen, Principals of Nonlinear Optics, John Wiley and Sons, 1984

1. **Nonlinear optical media**
   Nonlinear/Linear optical media
   Harmonic oscillator
   Nonlinear Polarization
   Wave equation in a NL media

2. **Second-order nonlinearities**
   Second harmonic generation
   The electro-optic effect
   Three wave mixing
   Phase matching – TWM

3. **Coupled wave theory**
   SHG
   Frequency conversion
   Parametric amplification

4. **Third-order nonlinearities**
   Third-harmonic generation
   The optical Kerr effect
   - Self-phase modulation
   - Self focusing
   - Spatial solitons
   - Cross-phase modulation

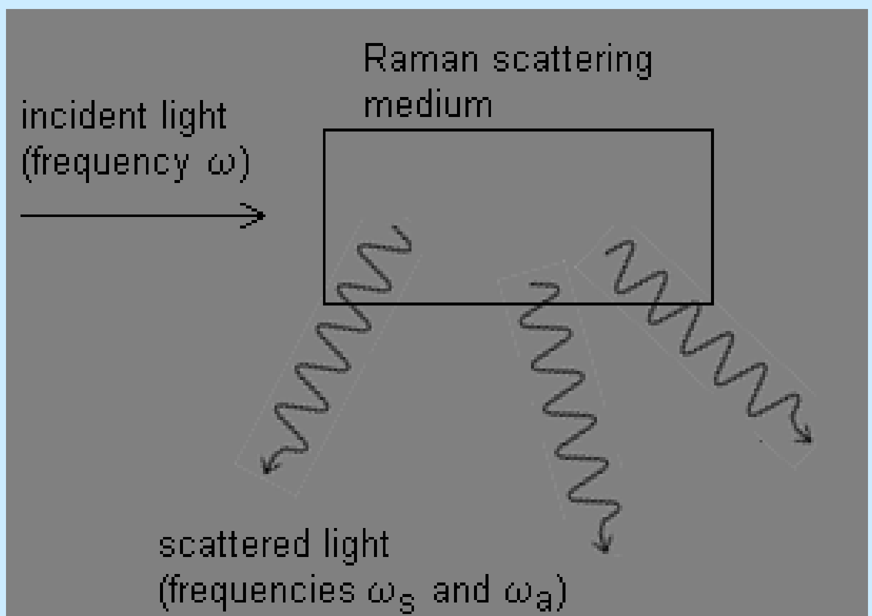
   Four-wave mixing
   Phase matching – FWM

5. **Solitons**

6. **Stimulated inelastic scattering**
   Raman
   Brillouin

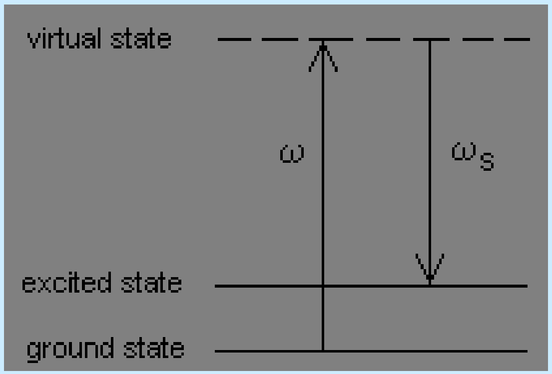
Spontaneous Raman scattering

- The spontaneous Raman effect was discovered by C.V. Raman in 1928
- Third order nonlinear effect
- A beam of light illuminating a sample (solid, liquid or gas) is scattered with down-shifted and up-shifted frequencies
- Lower frequencies – Stokes lines
- Higher frequencies – anti-Stokes lines

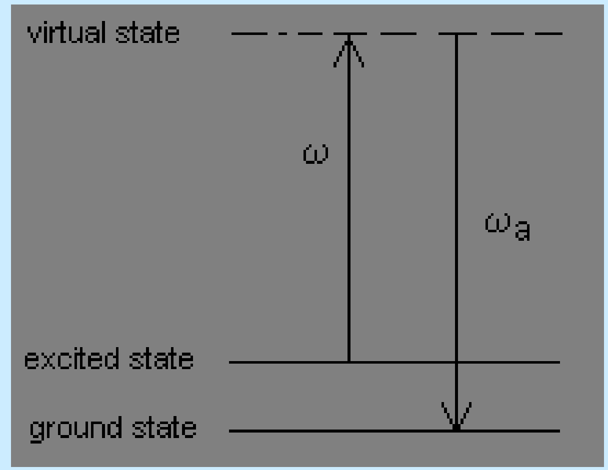


Spontaneous Raman scattering

- Energy level diagrams describing Raman scattering



Stokes scattering



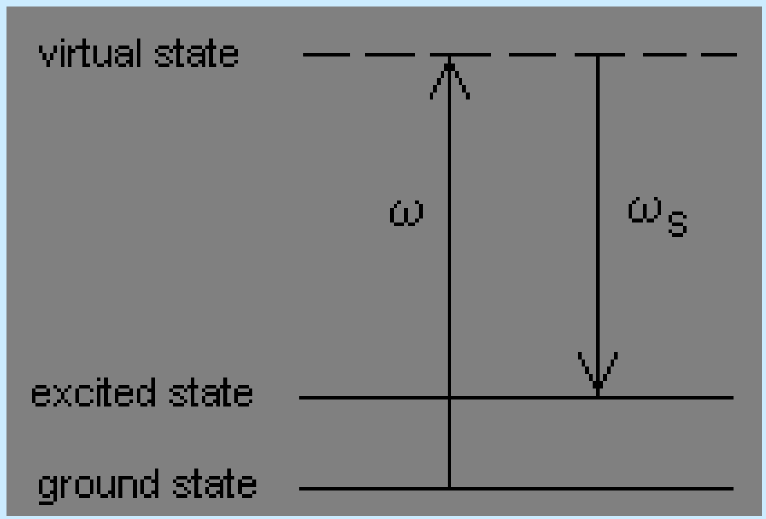
Anti-Stokes scattering

- The excited state can be a vibrational or rotational state that de-excite by phonon emission

- In thermal equilibrium the population of higher states is smaller than the ground state ➔ anti-Stokes lines are several orders of magnitude lower than the Stokes lines

Stimulated Raman scattering

- Spontaneous Raman scattering is a rather weak process
- Under excitation by an intense laser beam we can get **stimulated Raman scattering**



- Can be very efficient – more than 10% of the incident power can be converted to the Stokes frequency
- Can be used as a gain source

Raman gain

Self-phase modulation is expressed as given earlier

$$E_{SPM}(t) = E_{In}(t)e^{j\Delta\varphi(t)} \qquad \Delta\varphi = k_0 n_2 IL \qquad n_2 = \frac{3\chi^{(3)}\eta_0}{n^2\varepsilon_0}$$

The third-order nonlinear coefficient $\chi^{(3)}$ is complex-valued

$$\chi^{(3)} = \chi_R^{(3)} - j\chi_I^{(3)}$$

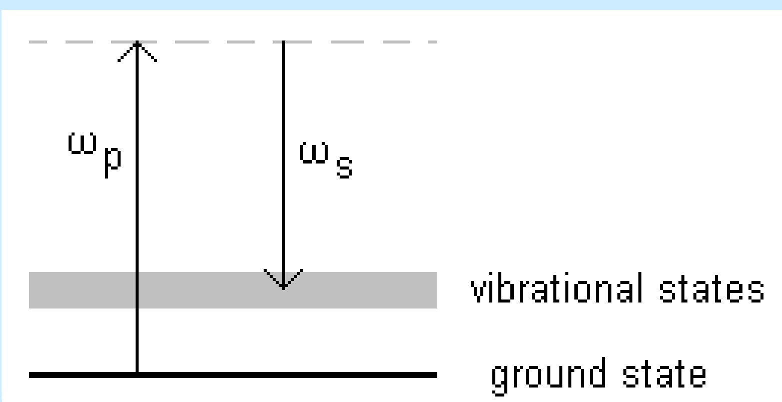
Using a non-zero $\chi_I^{(3)}$, we therefore get **gain (the Raman gain)**

$$E_{Raman}(t) = E_{In}(t)e^{\frac{1}{2}\gamma L} \qquad \gamma = \frac{12\pi\eta_0}{\varepsilon_0}\frac{\chi_I^{(3)}}{n^2}\frac{1}{\lambda_0 A}P$$

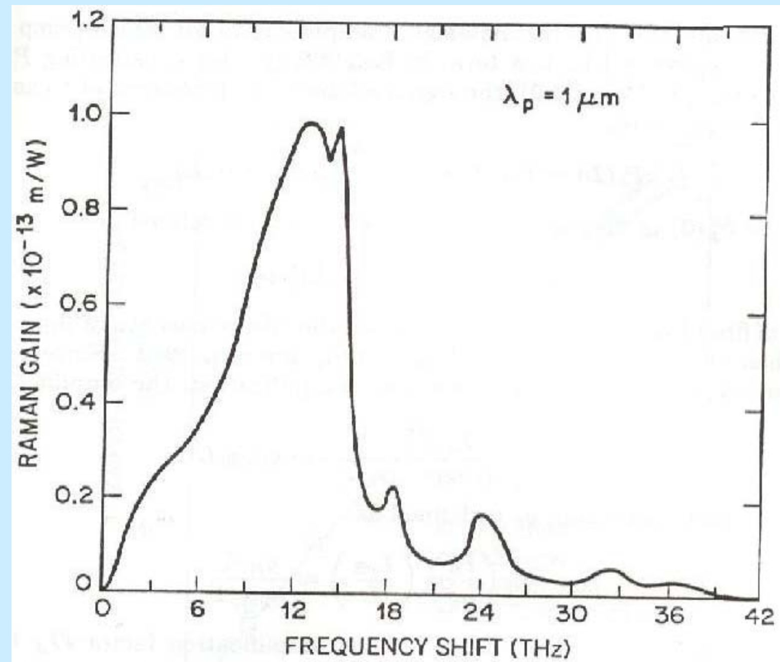
$$g = e^{\frac{1}{2}\gamma L}$$

Raman effect in silica

- In molecular gases ➔ discrete vibrational/rotational frequencies
- In silica ➔ molecular vibrational states generate a continuum



Raman gain spectrum for fused silica



Gain extends over a large frequency range ➔ can act as broadband optical amplifier

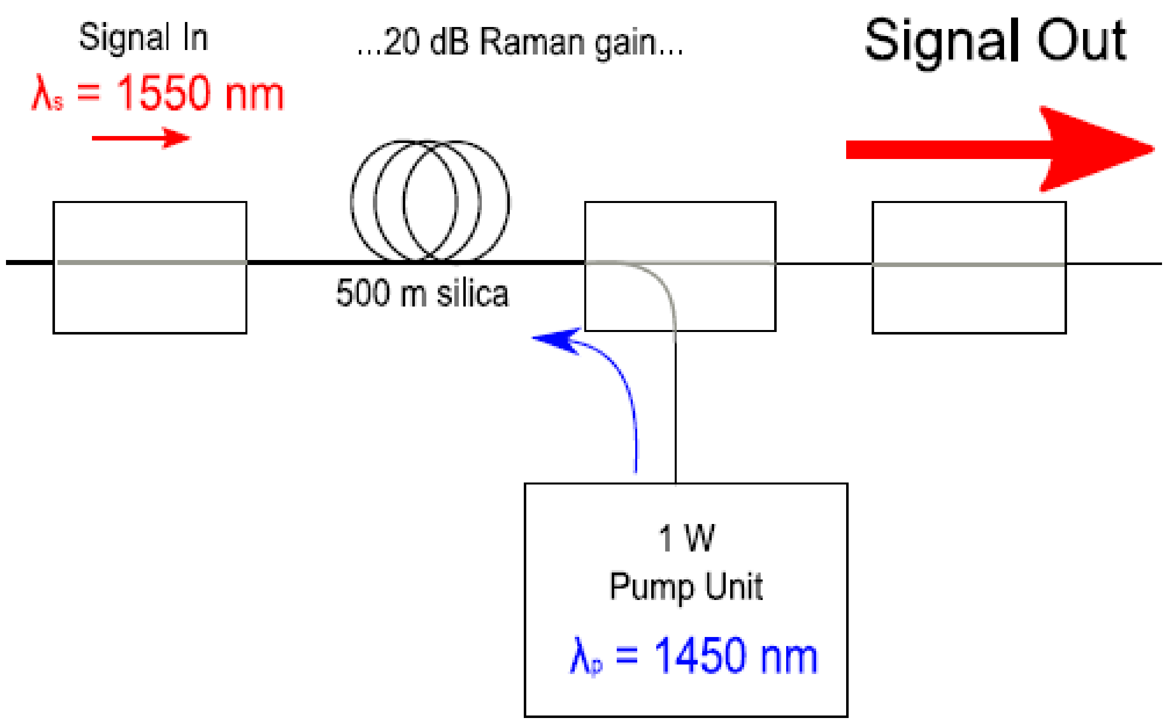
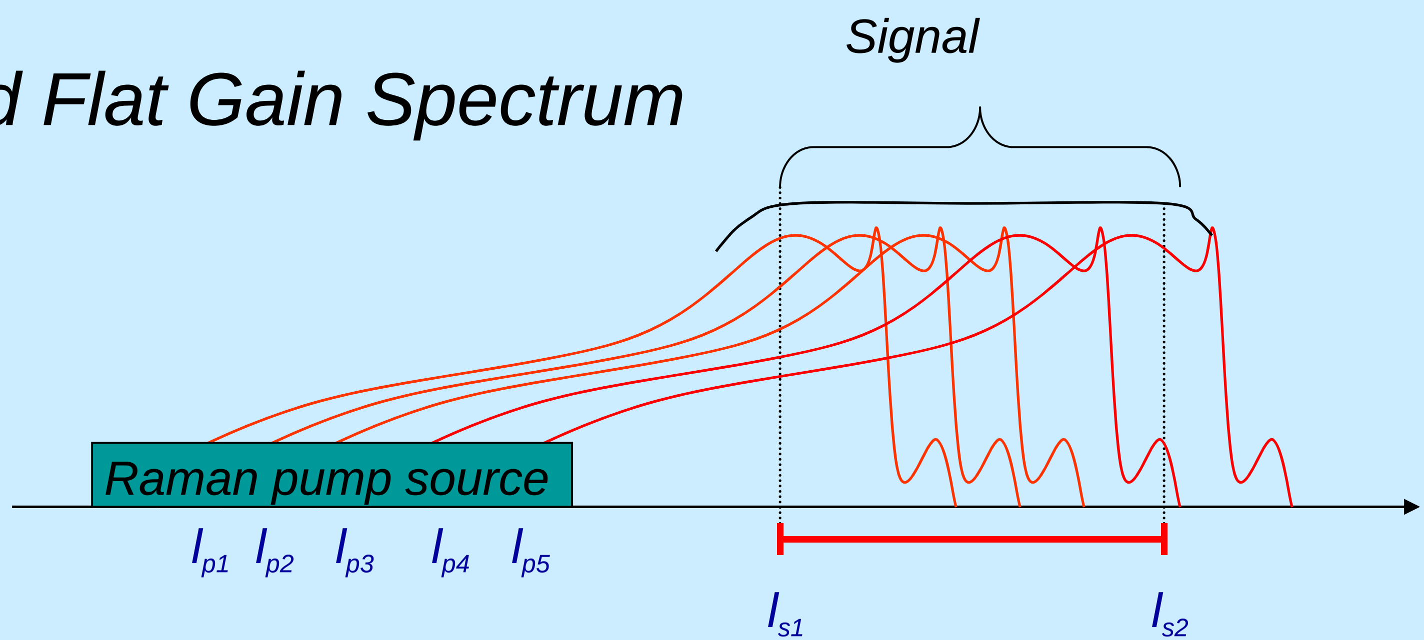


Figure 2.3: *Schematic illustrating Raman amplification through the transfer of energy from the pump beam to the signal beam, in a counterpropagating regime. In silica based systems, $\sim$ 500 m of fibre are necessary to amplify a signal 100 times, for 1 W pump units.*

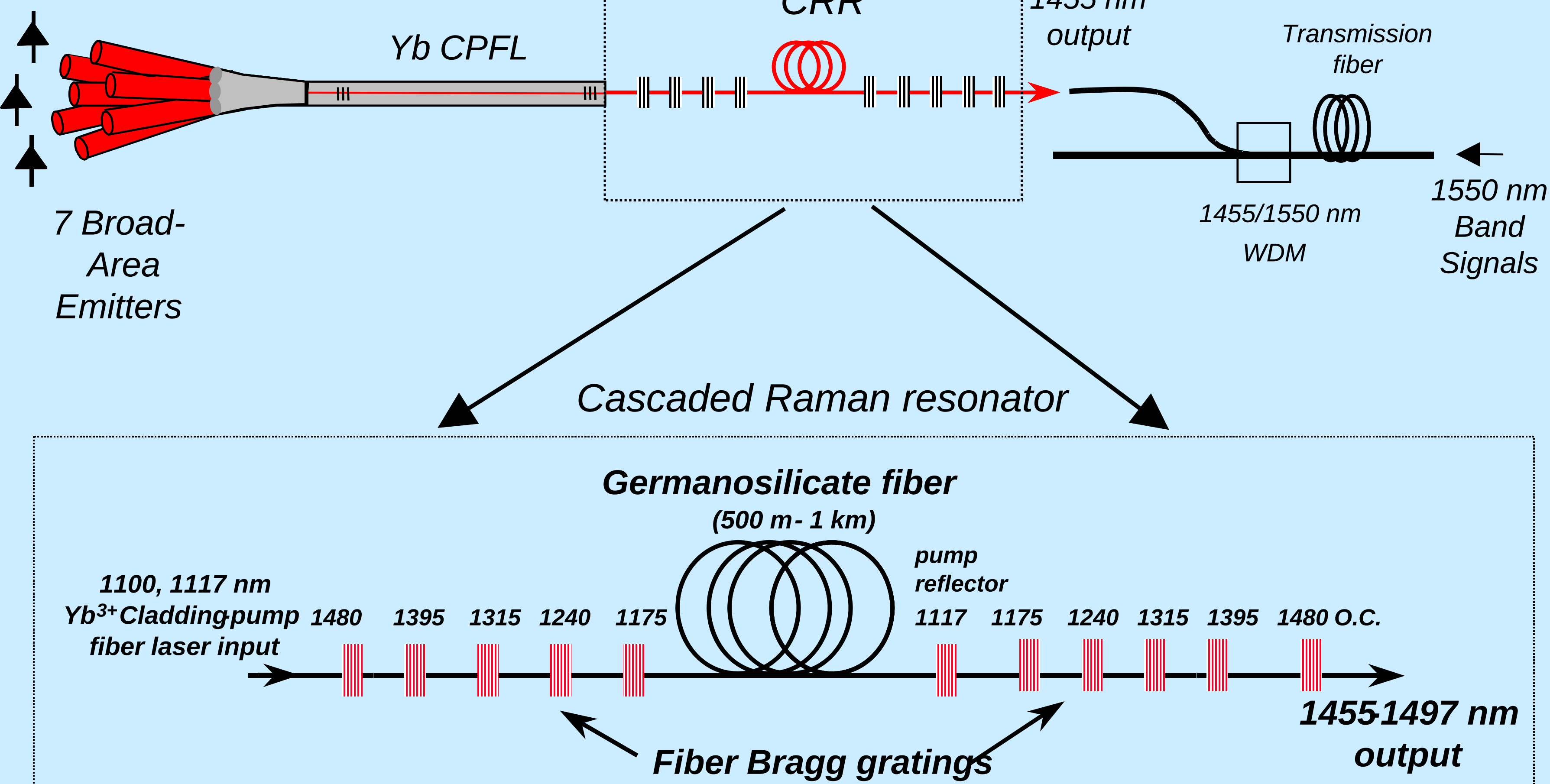
Multi-wavelength Raman Pump

Broad Flat Gain Spectrum



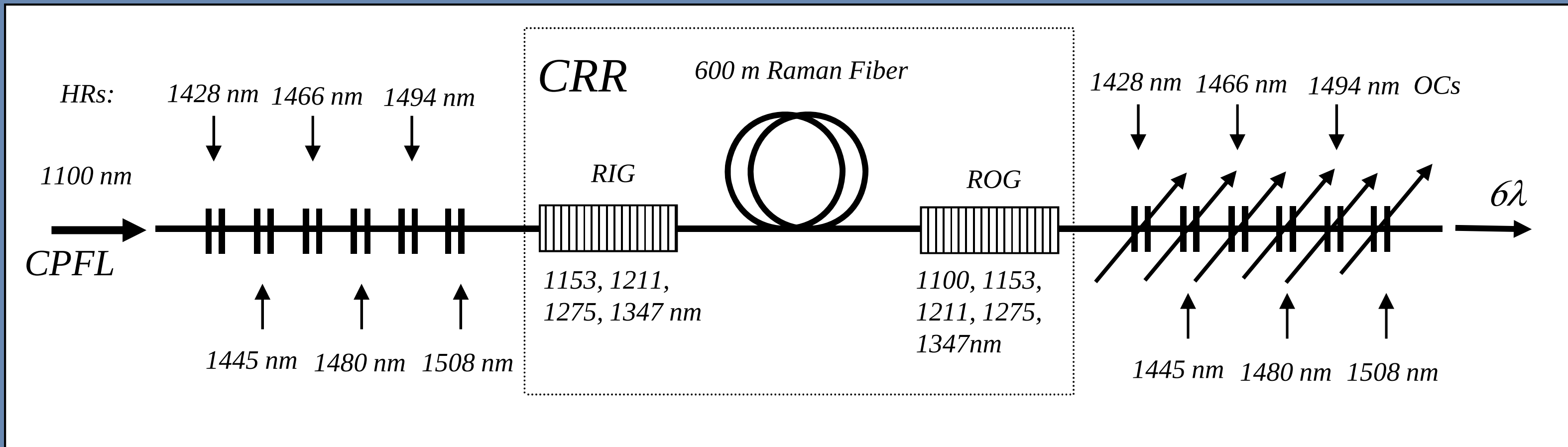
- Gain wavelength determined by pump wavelength
- Gain spectrum determined by pump distribution
- By combining different wavelengths obtain a flat Raman gain
- No loss filters needed

Cascaded Raman Resonators

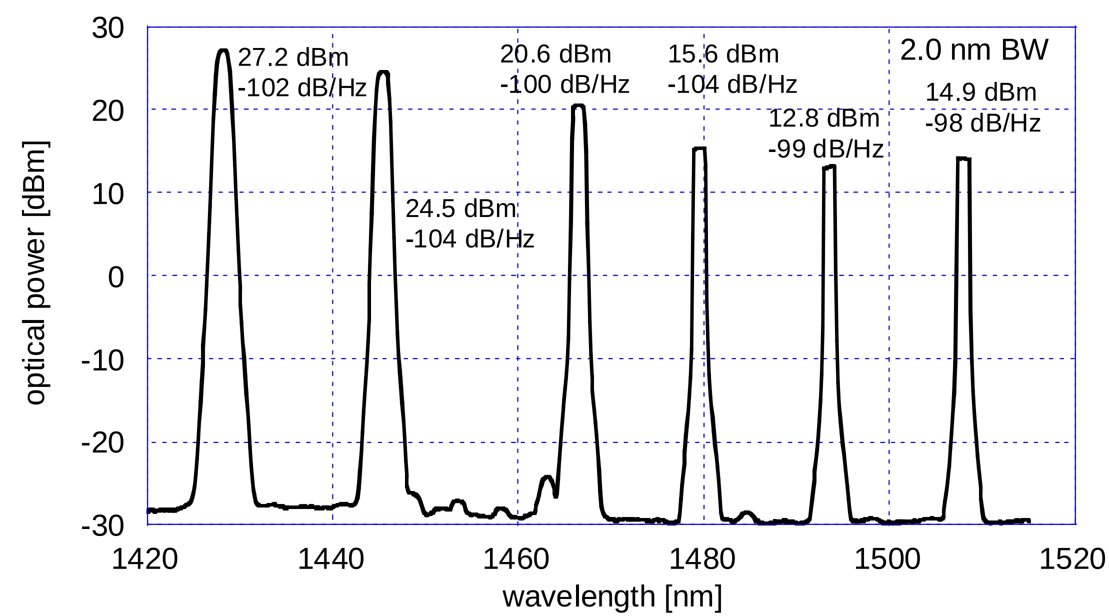


S. G. Grubb et al., "High power, 1.48 μm cascaded Raman laser in germanosilicate fibers", in OAA, paper SaA4 (1995).

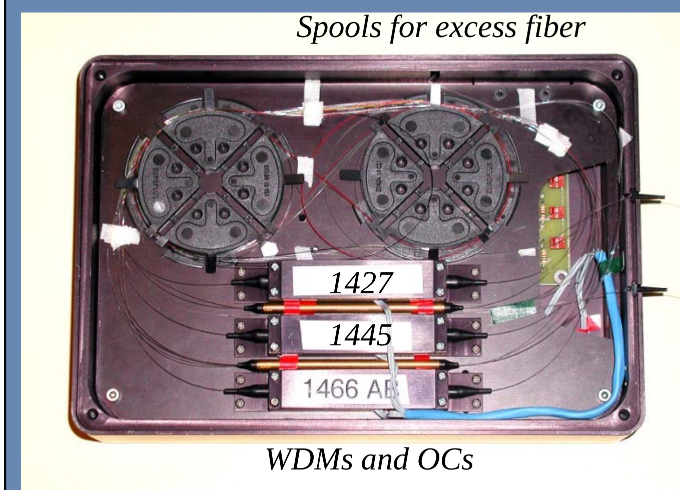
MULTIWAVELENGTH RAMAN FIBER LASER



Optical Power Spectrum



Prototype Device



Brillouin scattering

Bragg grating : constructive interference between waves in a medium with periodically varying refractive index

$$\vec{k}_{Pump} = \vec{k}_{Bragg} + \vec{k}_{Reflected}$$

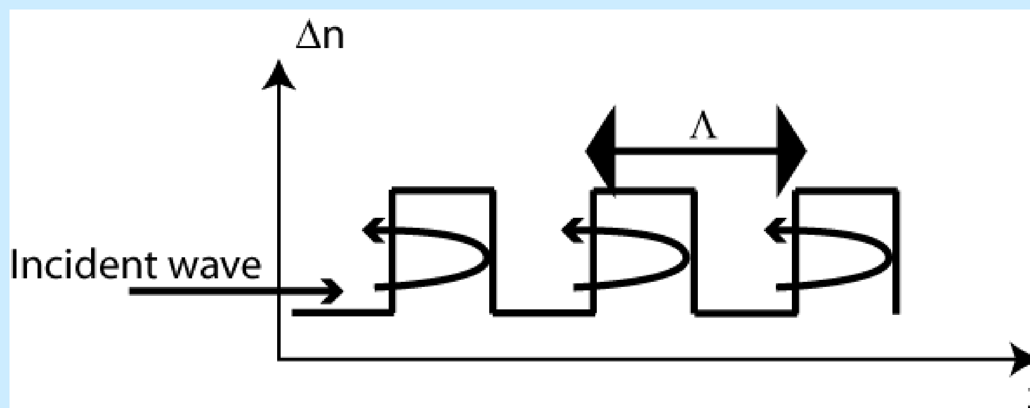
$$\omega_{Pump} = \omega_{Bragg} + \omega_{Reflected}$$

Momentum and energy conservation

$$\left|\vec{k}_{Bragg}\right| = 2\left|\vec{k}_{Pump}\right|$$

$$\frac{2\pi}{\Lambda} = 2\frac{2\pi n}{\lambda_{Pump}}$$

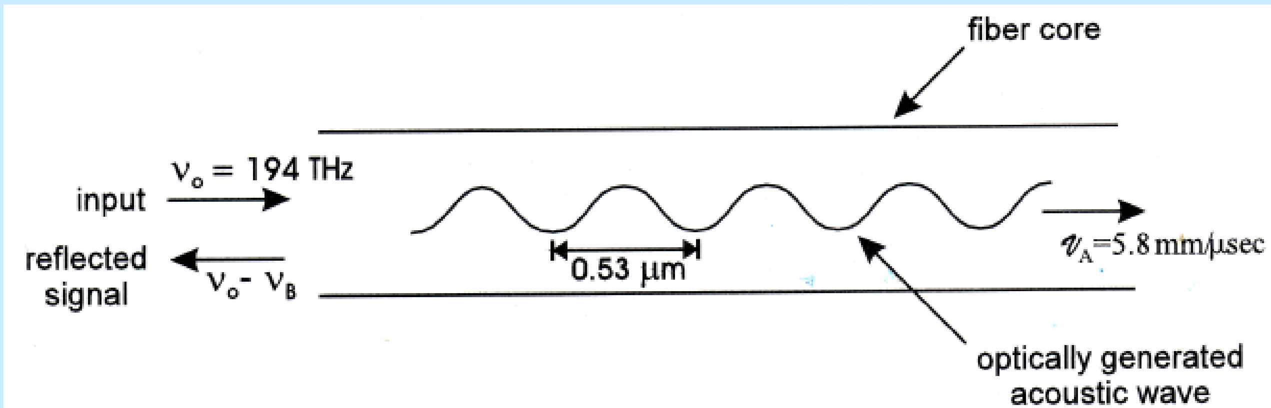
$$\boxed{\Lambda = \frac{\lambda_{Pump}}{2n}}$$



Condition of constructive interference (in reflexion) for the scattered waves

Brillouin scattering

Brillouin effect : Pump wave induces electrostriction, which in turn causes a periodic modulation of the refractive index--<u>acoustic phonons</u> form a Bragg grating moving at speed of sound.



$$\vec{k}_{Pump} = \vec{k}_{Acoustic} + \vec{k}_{Stokes}$$

$$\omega_{Pump} = \omega_{Acoustic} + \omega_{Stokes}$$

Momentum and energy conservation

$$\omega_{Acoustic} = \left|\vec{k}_{Acoustic}\right| v_{Acoustic} \approx 2\left|\vec{k}_{Pump}\right| v_{Acoustic}$$

Dispersion relation

$$\Delta f_{Brillouin} = \frac{\omega_{Acoustic}}{2\pi} \approx \frac{2nv_{Acoustic}}{\lambda_{Pump}}$$

Brillouin shift (~11 GHz)