Lecture 9 - Polarization Mode Dispersion and Fiber Nonlinearties

Polarization

- So called single mode fiber is not really single mode. There are two degenerate modes (for example, vertical and horizontal polarization).
- Fiber is in general birefringent due to core ellipticity or strain so the two polarizations travel at different velocities.
- The polarization evolves in time. The distance over which it repeats is the beat length (visible by looking at the fiber).

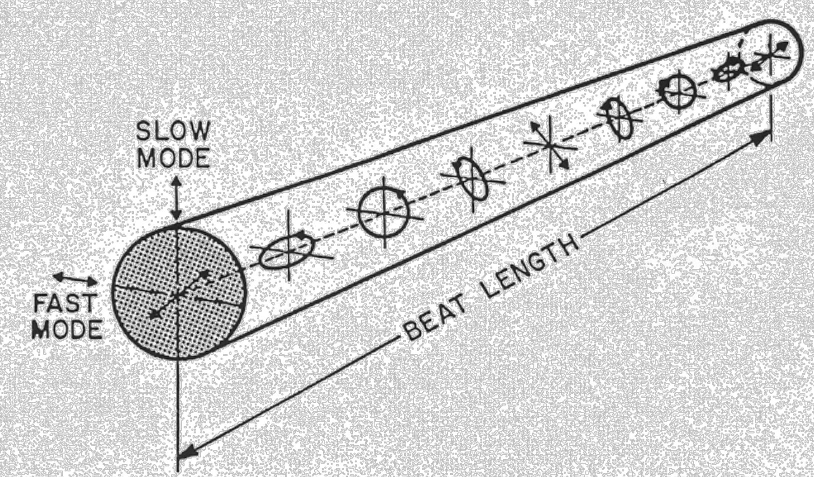
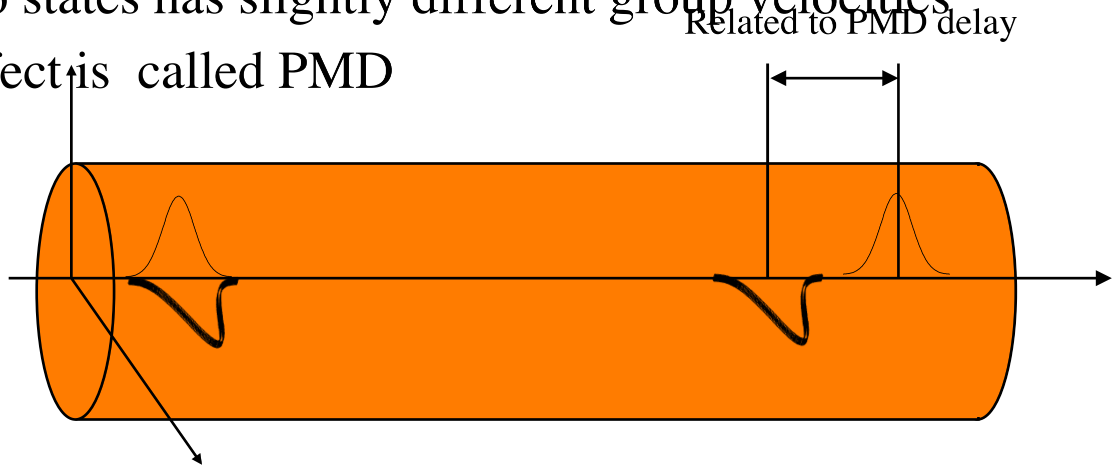


Figure 2.6: State of polarization in a birefringent fiber over one beat length. Input beam is linearly polarized at 45° with respect to the slow and fast axes.

Polarization Mode Dispersion (PMD)

- An input optical pulse is randomly coupled, along the fiber, with the two local orthogonal states of polarization
- The two states has slightly different group velocities
- This effect is called PMD



- PMD will broaden pulses in the same way other dispersion mechanisms do
- PMD changes instantly along fiber as a function of time, temperature and wavelength
- Power penalties associated with PMD are time varying

Poincare Sphere

- A way to represent all polarizations states.
- Equator: Linear polarization states
- Poles: Right and left circular polarization
- Half wave plates rotate around the pole.
- Quarter wave plates go through the poles,…

Poincare Sphere

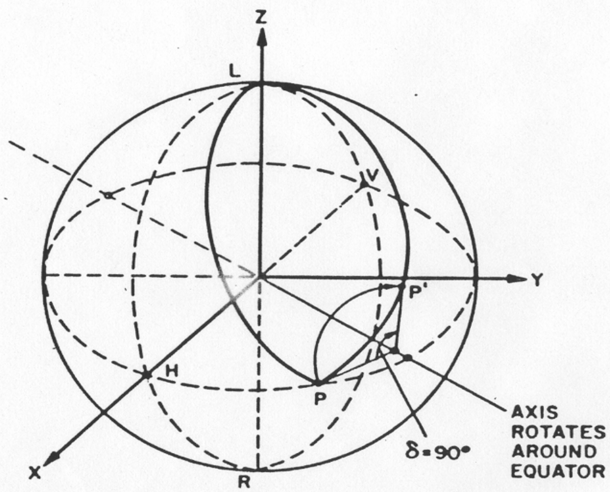


Fig. 1. On the Poincaré sphere, a quarterwave plate is characterized by a phase delay of 90° around a movable equatorial axis. The curve shown is for linear input polarization.

fringence of a quarterwave plate introduces a 90° phase difference between the principal SOPs. Figure 1 shows the effect on linear input polarization. This is a 90° rotation of the Poincaré sphere around an axis through

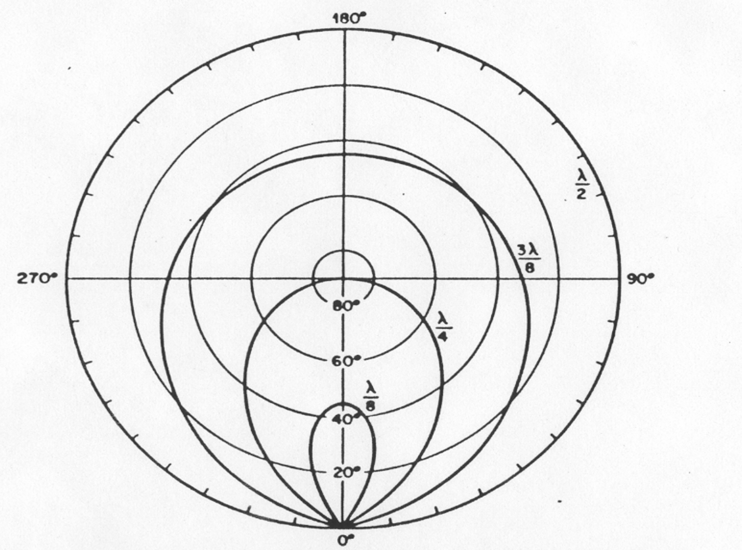


Fig. 2. Top view of the Poincaré sphere showing the effect of $\lambda/8$, $\lambda/4$, $(3\lambda)/8$, and $\lambda/2$ coils on linear horizontal input polarization. Note that this is not a perspective view. Twice the ellipticity, 2χ, is plotted radially inward. 2ψ is given by the angle around the perimeter. For 180° rotation of the wave plates, the locus shows a double loop, one in the upper hemisphere and one in the lower hemisphere.

Real Polarization Controllers

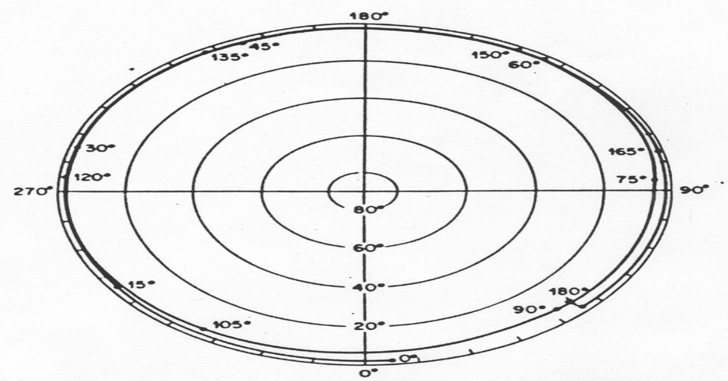


Fig. 4. Experimental 1.55-μm light in uncabled fiber for an approximate $\lambda/2$ coil (three turns of 1.1-cm radius) for linear horizontal input polarization. Data points are taken every 15° of rotation of the $\lambda/2$ coil up to a total of 180°.

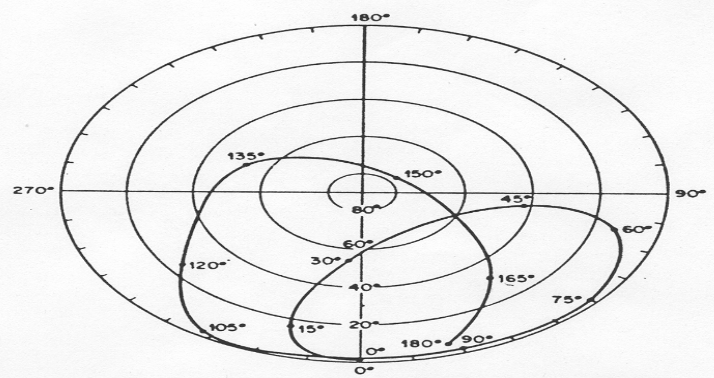


Fig. 5. Experimental 1.55-μm light in uncabled fiber for an approximate $\lambda/4$ coil (two turns of 1.3-cm diameter) for horizontal linear input polarization. Data points are taken every 15° of rotation of $\lambda/4$ coil up to a total of 180°.

PMD limit

- A (quite approximated) formula that shows the PMD limit is the following (see Optical Fiber Communications IIIa, I. Kaminov, T. Koch, Academic Press)

$$B^2 L \approx \frac{0.02}{PMD^2} \Rightarrow L_{\max} = \frac{0.02}{PMD^2 \cdot B^2}$$

	Bit rate = 10 Gbit/s	Bit rate = 40 Gbit/s
PMD=0.1 $ps/km^{0.5}$	L_{max}=20.000 Km	L_{max}=1250 Km
PMD=1 $ps/km^{0.5}$	L_{max}=200 Km	L_{max}=12.5 Km

- New fibers have PMD values of the order of 0.1 $ps/km^{0.5}$
  - PMD is an issue on ultra long distance only
- Installed fiber often have PMD values close to 1 $ps/km^{0.5}$
  - In these cases, PMD may be a fundamental issue even at 10 Gbit/s

Polarization Control

- Polarization maintaining fiber (or) Polarization preserving fiber:
  - If the index of the two directions is significantly different, then they do not couple
  - Deform the preform or
  - Introduce stress (bow tie or PANDA fiber)
- Single polarization fiber
  - Only one polarization is guided.

Polarization Dispersion

Time delay between the two polarization components

$$\Delta T = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right| = L\left|\beta_x - \beta_y\right| = L\Delta\beta$$

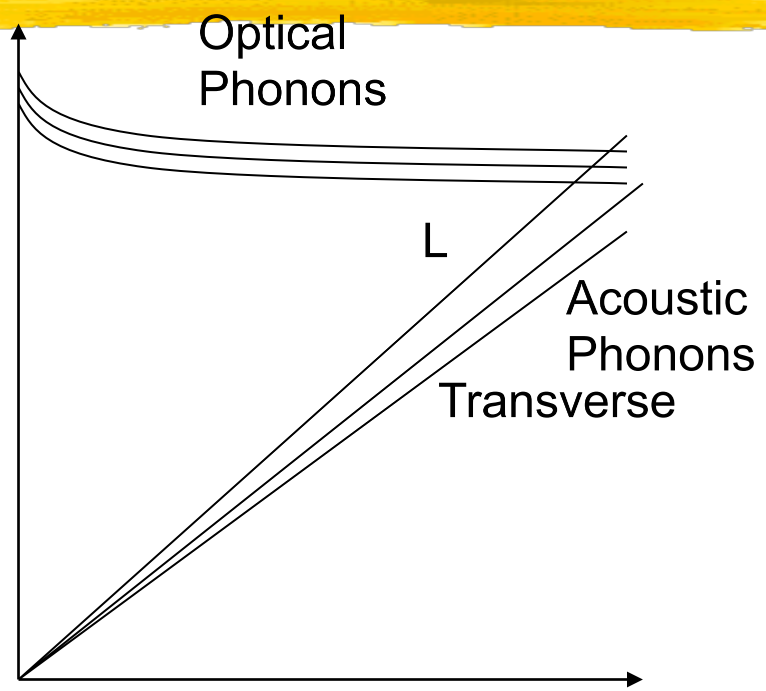
Random coupling between the two modes results in a growth
Which is not linear in L, but $L^{1/2}$ where D_p is the polarization mode dispersion.

$$\sigma_T = \left\langle \Delta T^2 \right\rangle^{1/2} = D_p\sqrt{L}$$

Old fiber was not well controlled in eccentricity, and has larger PMD than newer fiber.

Nonlinear Effects

- Raman scattering
  - Optical phonon process
  - Input ω_1
  - Output ω_1-ω_B
  - ω_B 2π 10-20 THz



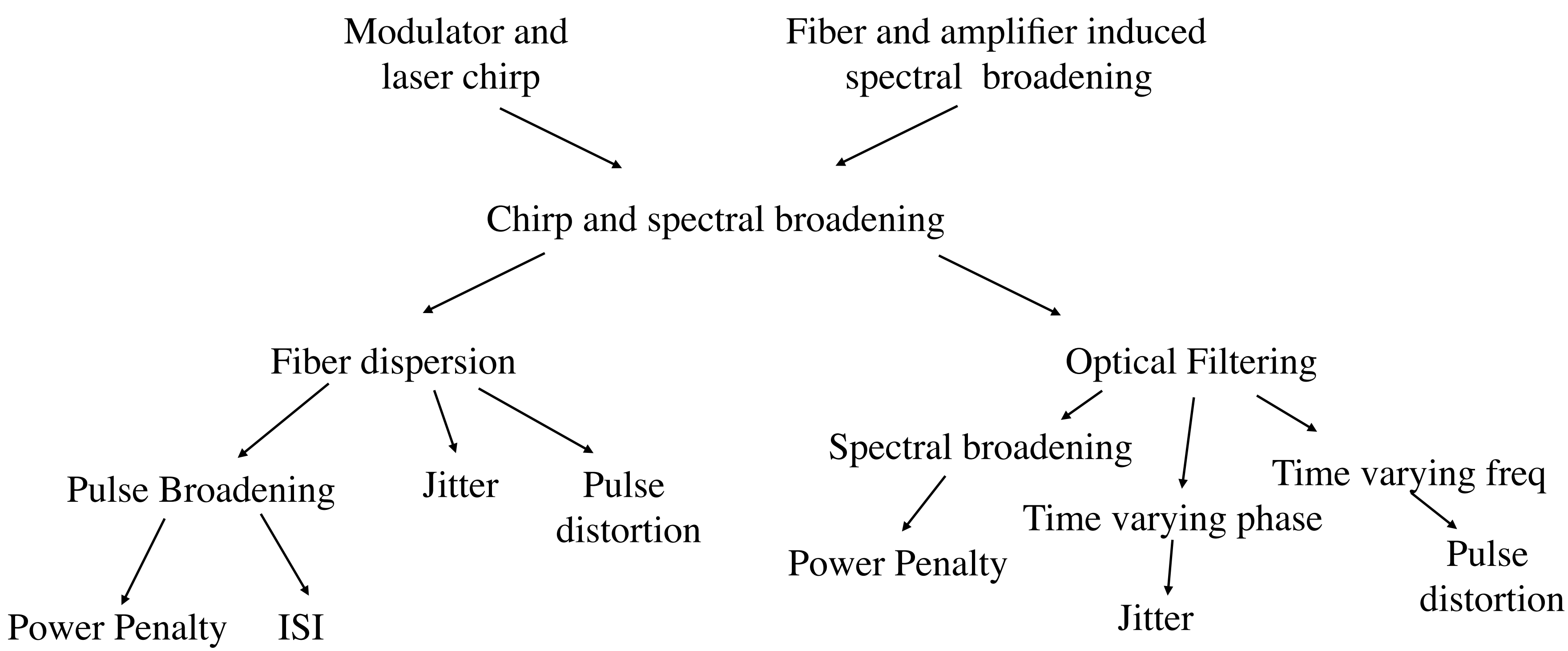
- Brillouin scattering
  - Acoustic phonon process
  - Input ω_1
  - Output ω_1-ω_B
  - Output opposite direction from input

Fiber Nonlinearities

- ⇨ In principle, we can continue to increase the optical power at the transmitter to overcome power penalties and limitations to SNR due to amplifier and receiver noise sources
  - ⇨ But ! We if we try to increase the optical power per channel too much, the signal will start to degrade due to distortion and crosstalk caused by nonlinearities in the fiber and amplifiers
  - ⇨ This means that the effective receiver sensitivity will be decreased or limited
  - ⇨ We have to limit the input power injected into the fiber in order to avoid nonlinearities
  - ⇨ The limits depend on the dominant nonlinear mechanism, the link and channel configurations and other link/network parameters

Spectral Power Penalty due to Modulation Chirp and Fiber and Amplifier Nonlinearities

We have already seen how modulation chirp can impart a time dependent frequency shift in the optical signal and produce spectral broadening. Later we will see how fiber and amplifier nonlinearities can produce this same effect.



Fiber Non-linearity Impairments

- There are several conditions where the optical power in the fiber can actually cause signal distortion or crosstalk with other optical wavelengths
  - Self-Phase Modulation (SPM)
  - Cross-Phase Modulation (CPM)
  - Four-Wave Mixing (FWM)

  → *Kerr Effects*

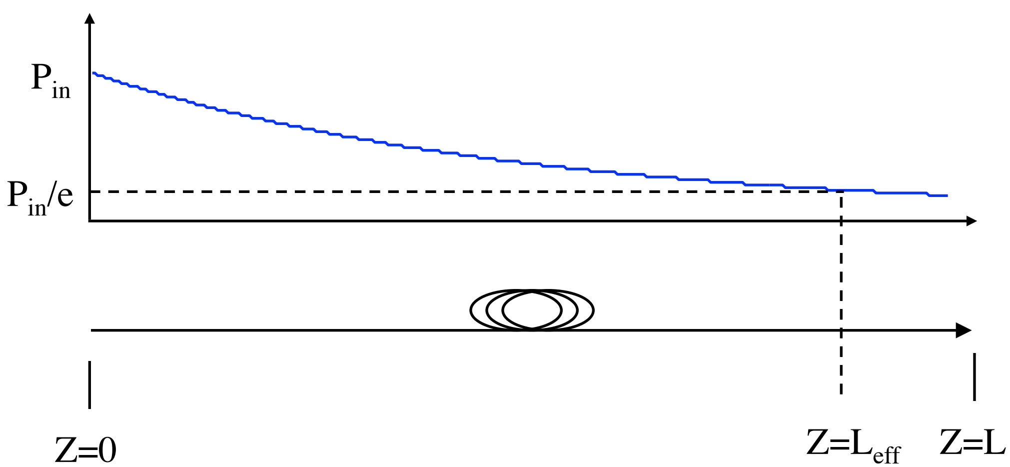
  - Stimulated Raman Scattering (SRS)
  - Stimulated Brillouin Scattering (SBS)

  → *Scattering Effects*

- In general, these effects limit the
  - Amount of power per wavelength that can be carried in the fiber
  - The number of wavelengths per fiber
  - The channel spacing between wavelengths per fiber
  - Bit rate per wavelength vs. number of wavelengths that can be supported

Effective Fiber Length

Any nonlinear effect depends strongly on the optical intensity within the fiber.
Therefore, fiber loss plays a role in how far along the fiber the nonlinearities occur



This result can also be interpreted as follows:
Fiber non-linear effects take place mostly in the first 25 km

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha}$$

$$L_{eff} \approx \frac{1}{\alpha}\,,\ \text{For large L}$$

$$L_{eff} \approx 25\ km \text{ for } L > 50\ km$$

Where L is the fiber length and α is the fiber attenuation factor.

Kerr Effects

$$\frac{\partial A}{\partial z} = -\alpha A + j\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial t^2} - \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial t^3} - j\gamma|A|^2 A$$

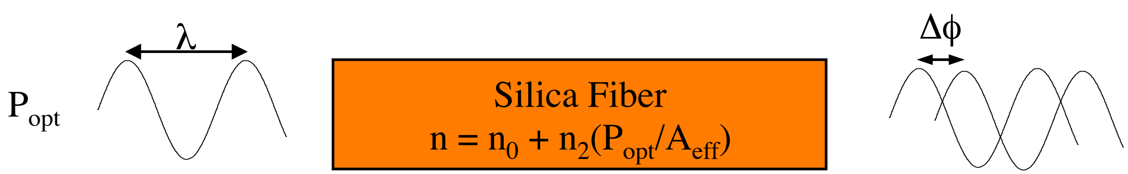
Kerr Effect term

- Optical power in the fiber (Silica) can alter the index of refraction
- All the resulting effects are generically called as "Kerr effects"
- In general, Kerr effect induces a phase modulation on the signal that is proportional to its instantaneous power level
- The phase modulation is then converted to amplitude modulation by fiber dispersion
- Though its apparent simplicity in the above equation, Kerr effects are very difficult to be studied analytically

Self-Phase Modulation (SPM)

Optical power in the fiber (Silica) can alter the index of refraction and therefore the phase of the optical signal via the nonlinear Kerr Optical effect:

Single Channel (SPM)



$$\delta\phi_{SPM} = \frac{5}{6}\frac{2\pi n_2}{\lambda}\frac{L_{eff}}{A_{eff}}\delta P_{opt}$$

$$\approx 0.035\left(\frac{4}{\omega(\mu m)}\right)^2 \delta P(mW),$$ for 1.55 μm and $\alpha = 0.25$ dB/km[1]

$$\delta P_{opt}(t) \Rightarrow \delta\phi(t) \Rightarrow \text{phase modulation} \Rightarrow \text{spectral broadening}$$

[1] A. R. Chraplyvy, IEEE JLT, Vol.. 8, No. 10, p. 1548, Oct. 1990.

Self-Phase Modulation

- SPM induces a spectral broadening
  - A fraction of the channel power may leak to adjacent channel
  - Some of the signal power may be blocked by the receiver filter
- The phase modulation is converted to amplitude modulation by dispersion
  - Eye diagram degradation
- SPM usually sets the limits in maximum launched power for single channel system
  - The limit is strongly dependent from dispersion and link length, but it is of the order of 8-10 dBm (per channel)
- In a WDM environment, it is usually NOT the most important effect
  - The other multichannel effect have a much lower threshold
- The SPM (and all other nonlinearities) has a strength that is inversely proportional to the fiber effective area Aeff
  - Large effective area fiber potentially reduces fiber nonlinear effects

Cross-Phase Modulation (XPM)

In multichannel propagation (WDM), the phase of a given channel can be affected by other channels in the fiber leading to XPM. The strength of this effect depends on the alignment of bits between channels and fiber dispersion (pulse walk-off).

Multi-Channel (XPM)

$$\delta\phi_{XPM} = 2\delta\phi_{SPM} = \frac{5}{3}\frac{2\pi n_2}{\lambda}\frac{L_{eff}}{A_{eff}}\delta P_{opt}, \text{ For 2 Channels}$$

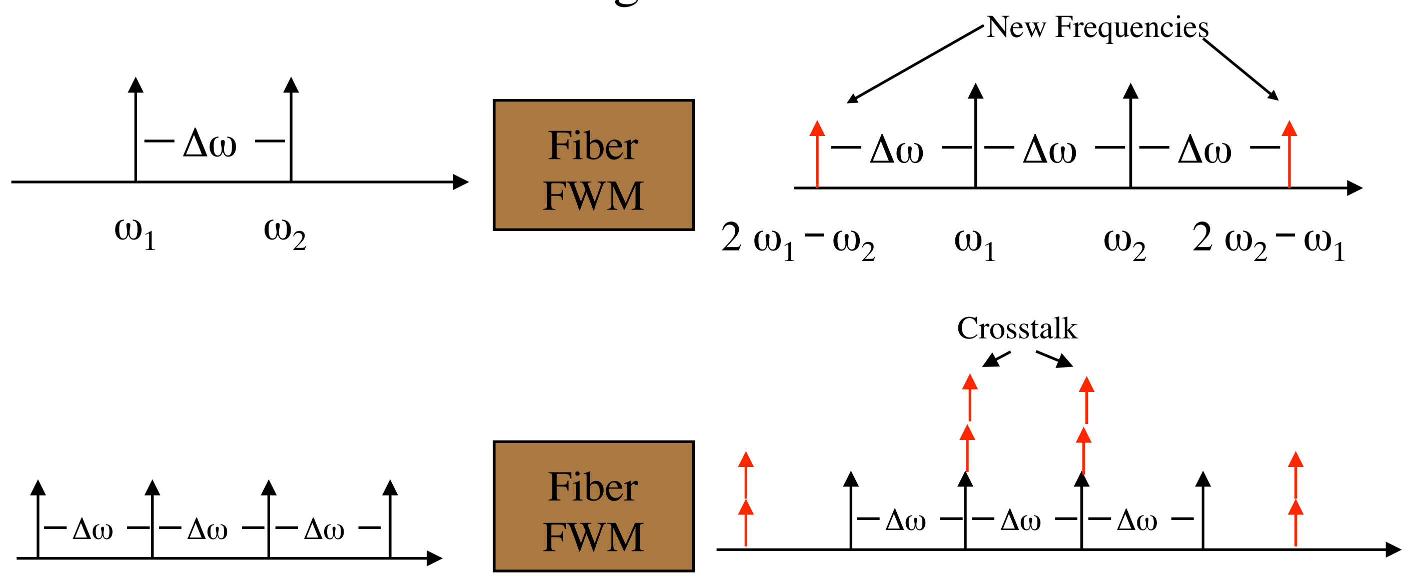
$$\delta\phi_{XPM} = \sum_{m=2}^{N}\delta\phi_{XPM}(m), \text{ For N channels}$$

- XPM combines in a very complex way with dispersion, due to the walk-off effect among bits in adjacent channels
- As a rule of thumb, the resulting XPM effect is inversely proportional to the (local) dispersion value $\propto 1/|D|$

1 A. R. Chraplyvy et. al., *IEEE JLT*, Vol. 2, No. 1, 1984.
2 A. R. Chraplyvy, *IEEE JLT*, Vol.. 8, No. 10, p. 1548, Oct. 1990.

Fiber Four-Wave Mixing (FWM)

- Four-wave mixing in optical fibers is a complicated process that produces nonlinear harmonics
- If the optical intensity, wavelength spacing, and fiber dispersion are right, two optical frequencies at ω_1 and ω_2 will generate light at two new frequencies $2\omega_1-\omega_2$ and $2\omega_2-\omega_1$.
- When more than two channels are present, these new frequencies can interfere as crosstalk with existing channels as shown below.



Fiber Four Wave Mixing

The power generated in a fourth (third) wavelength at frequency $\omega_{ijk} = \omega_i + \omega_j - \omega_k$ depends on the power in three (two) other wavelengths and is given by[1]

$$P_{\omega_{ijk}}(L) = \eta_{ijk} D \left(\frac{L_{eff}}{A_{eff}} \right)^2 P_i(\omega_i) P_j(\omega_j) P_k(\omega_k) e^{-\alpha_f L}$$

Where the FWM efficiency (η_{ijk}), the factor D and the phase mismatch $\Delta\beta$ are given by[1,2]

$$\eta_{ijk} = \frac{\alpha_f}{\alpha_f^2 + \Delta\beta_{ijk}^2} \left\{ 1 + 4 \frac{\exp(-\alpha_f L) \sin^2(\Delta\beta_{ijk} L/2)}{\left[1 - \exp(-\alpha_f L)\right]^2} \right\}$$

$$D = \frac{1024}{n^4 \lambda^2 c^2} d^2 \chi^{(3)2}, \text{ where d } = 3 \text{ for i = j, d = 6 for i} \neq \text{j}$$

$$\Delta\beta_{ijk} = \frac{2\pi\lambda^2}{c} \Delta f_{ik} \Delta f_{jk} \left[D(\lambda) + (\Delta f_{ik} + \Delta f_{jk}) \frac{\lambda^2}{2c} \frac{\partial D(\lambda)}{\partial \lambda} \right], \text{ where } \Delta f_{12} = |f_1 - f_2|$$

1 K. Inoue, *Optics Letters*, Vol. 17, No. 11 (1992)
2 N. Shibata, *IEEE J. Quantum Electronics*, Vol. 23, p. 1068 (1989)

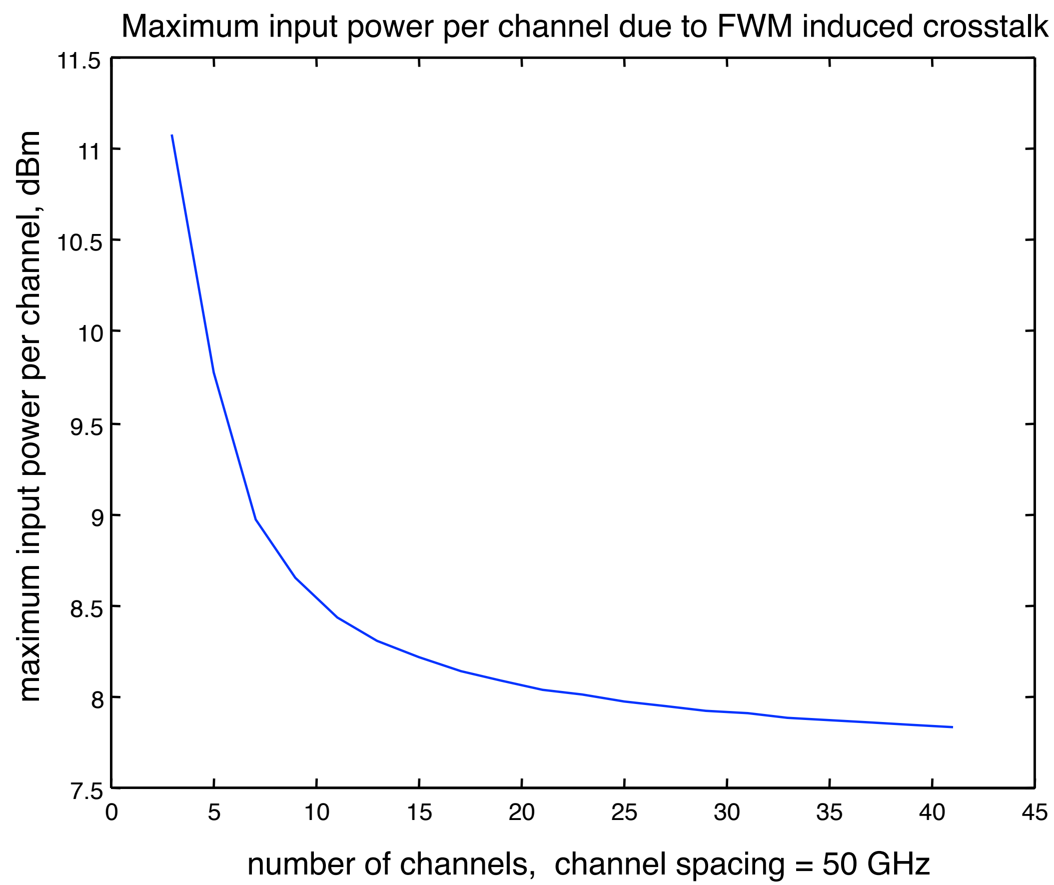
Fiber Four Wave Mixing

- XPM combines in a very complex way with dispersion, due to phase matching conditions
- As a rule of thumb, the resulting XPM effect is inversely proportional to the square of the (local) dispersion value

$$\propto 1/|D|^2$$

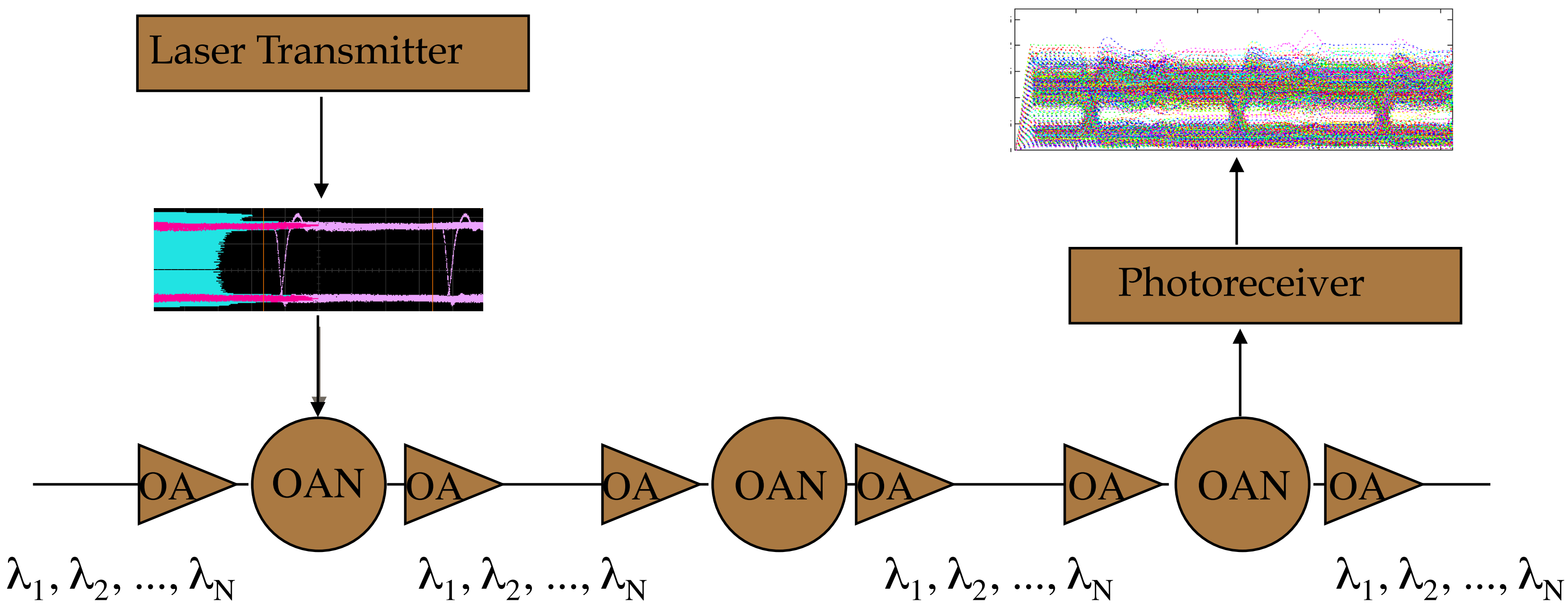
- The FWM effect is absolutely detrimental close to the zero dispersion wavelength (DS fibers), where dense WDM is virtually impossible
  - DS fiber have been intensively deployed in some countries (Japan, Mexico and Italy)
  - For these fibers, non-equally spaced channels are used, so to avoid FWM crosstalk

Fiber Four-Wave Mixing



FWM in EDFA Chains

- Modeled as multiwavelength fiber/amplifier chains



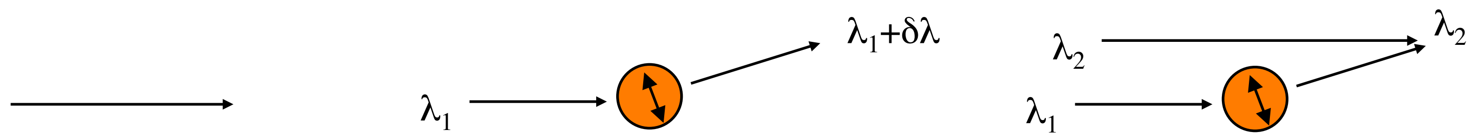
Summary on Kerr effects

- In today high-end DWDM transmission systems:
  - On DS fiber, FWM is the most relevant effect
  - On all other fibers, the final nonlinear limit is usually set by XPM
- The ways to reduce nonlinear effects are:
  - Increase the fiber effective area
  - Increase the fiber dispersion value (and use dispersion maps, as shown later)
  - Use of advanced modulation formats (RZ, CRZ, duobinary etc)

Raman Effects

- Raman effects have become relevant recently
  - As a detrimental effects: it takes place in recent systems with a very high number of WDM channels (>64 ch.)
    - It induces a tilt in the WDM comb, together with the aforementioned crosstalk effect
  - As a positive effect, for distributed Raman amplification
    - A strong pump at a lower wavelength is launched in a counter-propagating direction inside the fiber
    - A distributed amplification is obtained, as seen in a previous section
- Raman distributed amplification is an hot issue in optical transmission
  - The most recent "records" in transmission capacity have been obtained using Raman amplification

Stimulated Raman Scattering (SRS)



Optical signal at λ_1 propagates in fiber (glass)

Optical signals scatter off molecular vibrations (Optical Phonons) in the fiber. This results in a frequency shift to a longer wavelength

Energy couples between two different wavelengths with the shorter λ acting as an optical pump for the longer λ

New wavelengths can be generated up to 100 nm away from the original signal !

Single wavelength Degradation

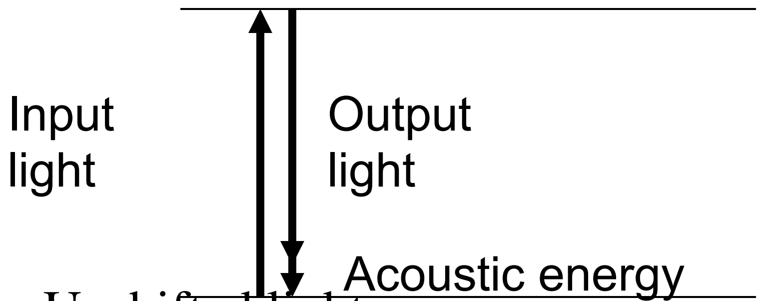
SRS will take power away from a single channel whose power exceeds threshold. The intensity in the scattered light grows exponentially with increasing power in the pump wavelength. The maximum power that can be injected into the a fiber with effect length L_{eff} such that SRS does not deplete more than 50% of the optical power is

$$P_{\max,SRS,1ch} = \frac{16bA_{eff}}{g_r L_{eff}}$$

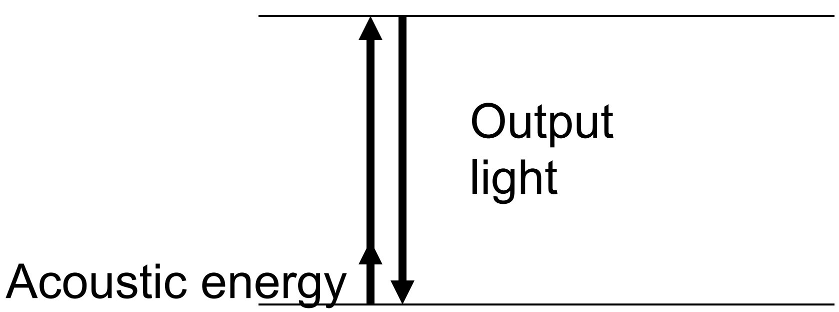
B = 1,2 for one or two polarization states
A_{eff} = effective core area for light in fiber
g_r = Raman gain

Raman Scattering

- Stokes Scattering-Downshifted light

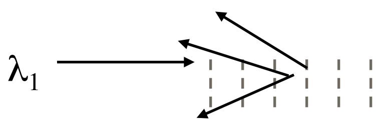


- Antistokes Scattering-Upshifted light
  - Intensity is orders of magnitude smaller than Stokes scattering

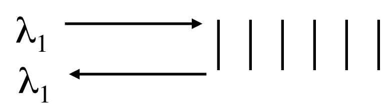


Stimulated Brillouin Scattering (SBS)

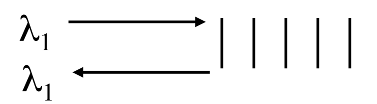
Similar to SRS, SBS involves scattering of optical waves (photons) from a vibration within the fiber. However, SBS involves scattering with sound waves (acoustic phonons) instead of molecular vibrations. The the optical waves scatter and are shifted to a new frequency that travels in the opposite direction (recall the Bragg grating !)



Optical signal is scattered efficiently at large angles and starts to create acoustic Bragg gratings within the fiber



At Threshold power a primary Bragg grating is matched to the original wavelength and reflects signal in backward direction at same wavelength



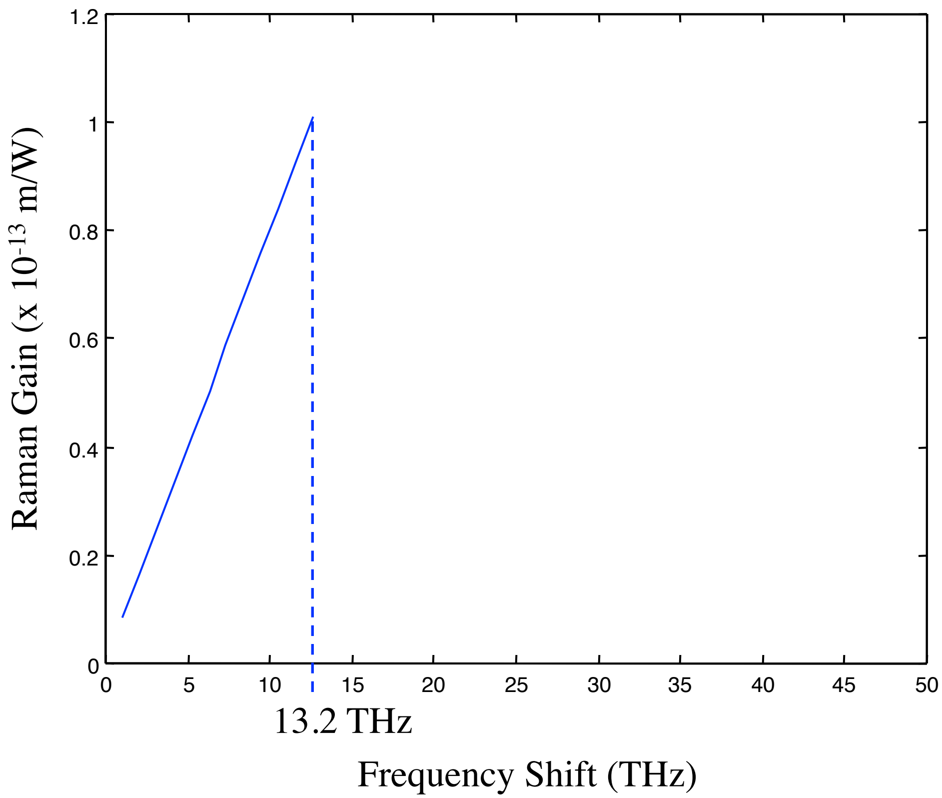
The forward and backward waves continue to couple through the grating and reinforce the existing grating

The wave scattered back is not exactly at the same wavelength, it is actually shifted by the Bragg frequency of around 20-50 MHz. The important point is that the power in the original signal has been depleted and sent in the opposite direction ! The maximum power injected per channel due to SBS is independent of the number of wavelengths due to the low gain-bandwidth (see next slide)

$$P_{SBS,\max} = \frac{21 b A_{eff}}{g_B L_{eff}}$$

SRS Gain

Raman Gain spectrum can be approximated by a triangular shape as a function of frequency shift from the original pump wavelength. Below is a commonly used spectral approximation for $\lambda_p = 1\ \mu$m. At $\lambda_p = 1.55\ \mu$m, the Raman gain peak is approximately 6.0 x 10^{-14} m/W.



Raman Gain

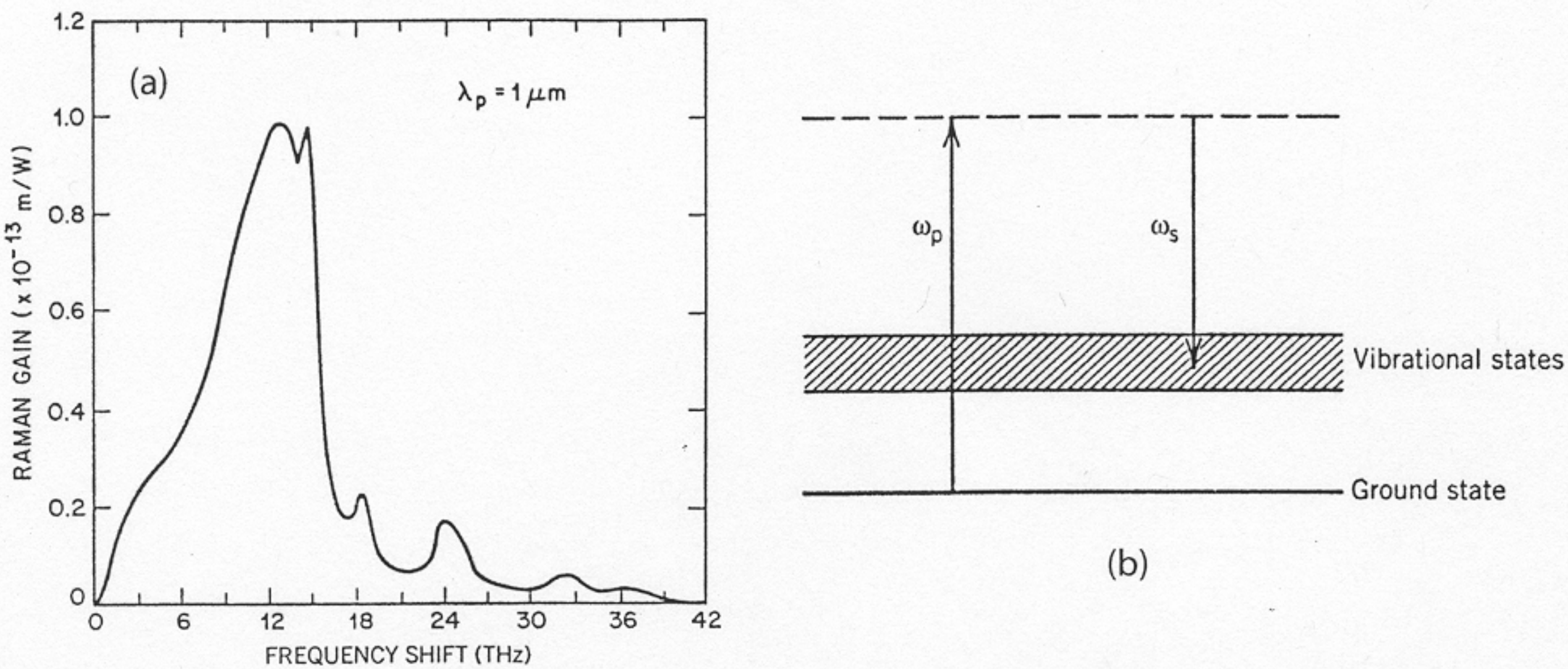


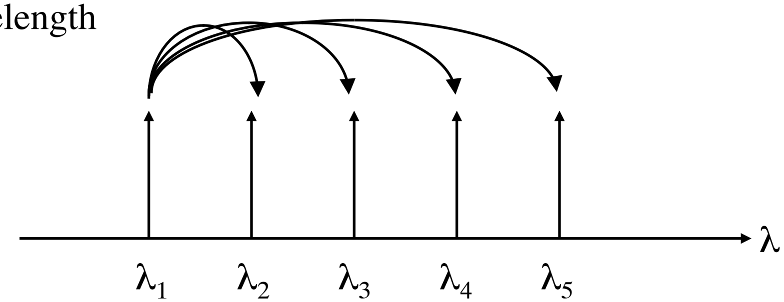
Figure 2.18: (a) Raman gain spectrum of fused silica at $\lambda_p = 1\ \mu$m and (b) energy levels participating in the SRS process. (After Ref. [75]; ©1972 AIP; reprinted with permission.)

Stimulated Raman Scattering (SRS)

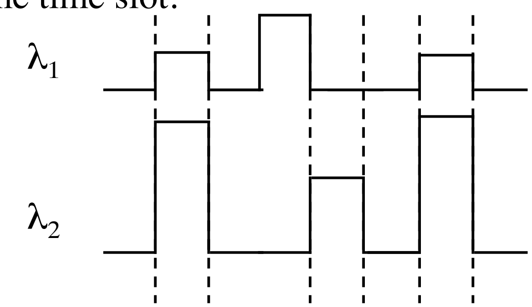
Multichannel Effects

When multiple wavelengths are present in the fiber, we run into a problem of crosstalk, where the higher frequency (shorter wavelength) channels act as optical pumps for the lower frequency (longer wavelength) channels.

Optical power transferred through SRS. Shown is power transferred from shortest wavelength



Bits modulated at shorter wavelength can be depleted when second wavelength has bit in same time slot.



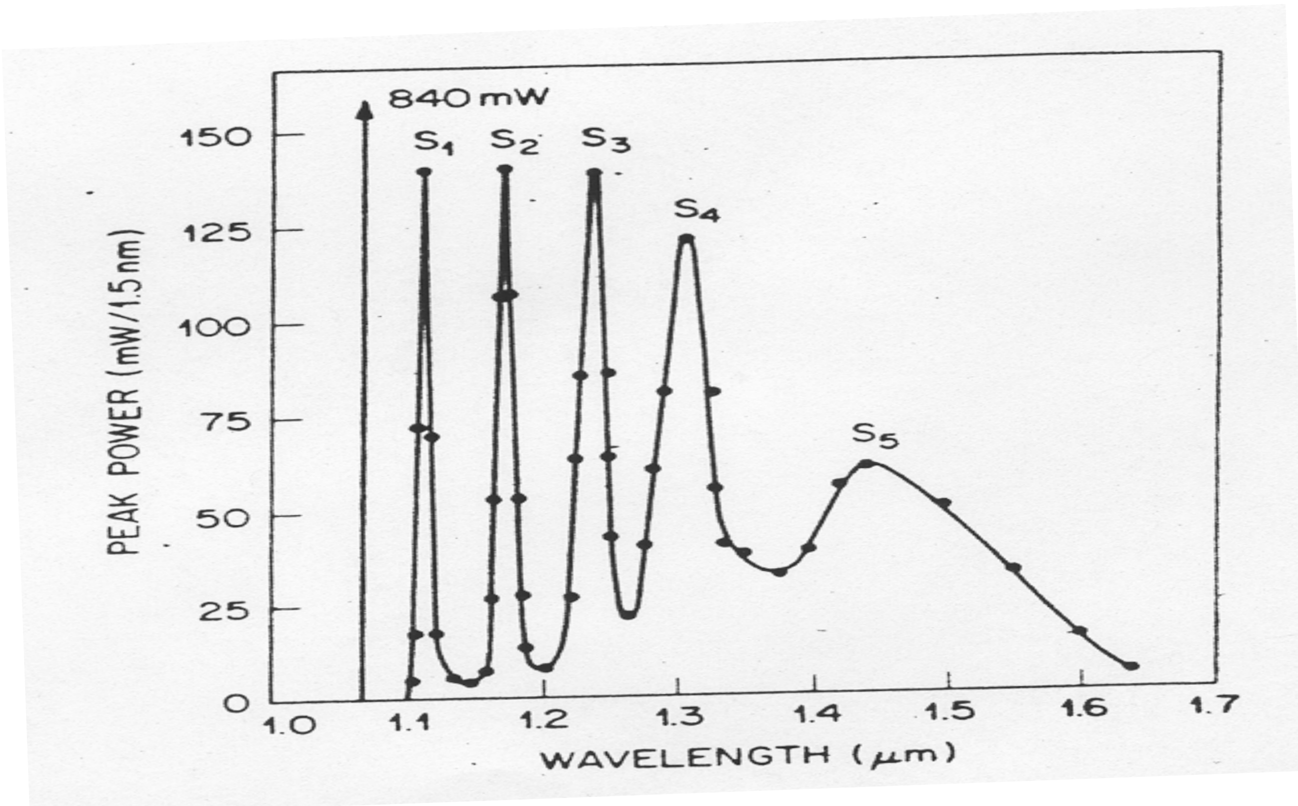
For an N wavelength system, with channel spacing Δf, assuming the shortest wavelength channel will degrade the most and that we want it to not decrease by more than 3dB, and power per channel is P_{ch}, the product of the total power and total occupied bandwidth are related by[1]

$$\left[NP_{ch}\right]\times\left[(N-1)\Delta f\right] < 500\ \mathrm{GHz}\cdot\mathrm{W}$$

[1] A. R. Chraplyvy, IEEE JLT, Vol.. 8, No. 10, p. 1548, Oct. 1990.

Multiple Stokes Lines

A high power pump generates first Stokes line, which pumps the second Stokes line, which pumps the third Stokes line, etc.

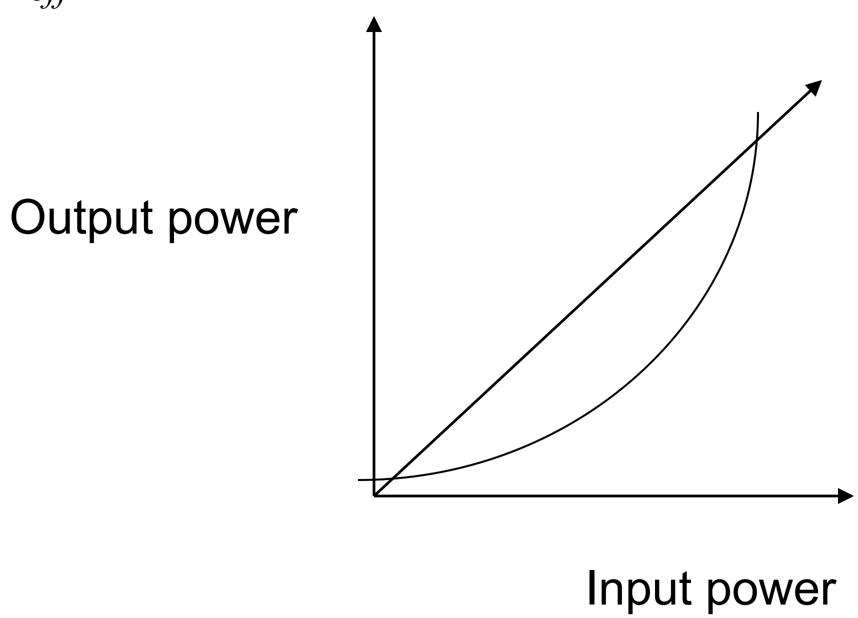


Raman Scattering

- We have discussed spontaneous Raman scattering
- There is also stimulated Raman scattering (SRS)
  - Important for amplifiers
  - Important for lasers
  - Important for optical communications (SRS is an important limit in DWDM systems.)

$$I_s(z) = I(0)\exp(g_R L_{eff} I_0 - \alpha z)$$

$$L_{eff} = (1 - \exp(-\alpha L))/\alpha$$



Raman Laser Threshold

Threshold defined by the input power where the output Raman power equals the pump power at the output

$$I_s(z) = I(0)\exp(g_R L_{eff} I_0 - \alpha z)$$

$$L_{eff} = (1 - \exp(-\alpha L))/\alpha$$

$$\frac{P}{P_0} = \exp\frac{P_0}{P_2} = \frac{1}{2}$$

$$P_0 \approx 16 P_2$$

$$g_R P_{th} L_{eff} / A_{eff} = 16$$

$$P_{th} = \frac{16 A_{eff}}{g_R L_{eff}}$$

For

$$A_{eff} = 50\mu m^2$$

$$g_R = 10^{-13} / mW$$

$$\alpha = 0.2 dB / km$$

$$P_{th} = 570 mW$$

SBS Gain

The optical power scattered in the back direction depend on the bit rate and modulation format[1]

For NRZ intensity modulation:

$$g = g_B \left\{ \tfrac{1}{2} - \frac{B}{4\Delta\upsilon_B}\left[1 - \exp\left(-\frac{\Delta\upsilon_B}{B}\right)\right]\right\}$$

For operation @ 1.55 μm $g_B \approx 5\text{x}10^{-9}$ cm/W
The gain-bandwidth is $\Delta\nu_B \leq 50\ MHz$ for silica fibers

- SBS effects may be detrimental whenever a sharp spectral peak is present in the signal spectrum, as in NRZ modulation
- SBS can be greatly suppressed introducing a small spurious modulation on the CW laser (dithering) that enlarge the spectral peak to more than $\Delta\nu_B = 50\ MHz$
- For the same reason, SBS is a single-channel effect

[1] A. R. Chraplyvy, IEEE JLT, Vol.. 8, No. 10, p. 1548, Oct. 1990.

Brillouin Differences

- Acoustic phonon, not optical phonon
- Shift is smaller (10 GHz, not 12 THz)
- Linewidth is narrower (100 MHz, not 5 THz)
- Output is opposite input
- Gain coefficient is 100 x larger than Raman.

Brillouin Gain

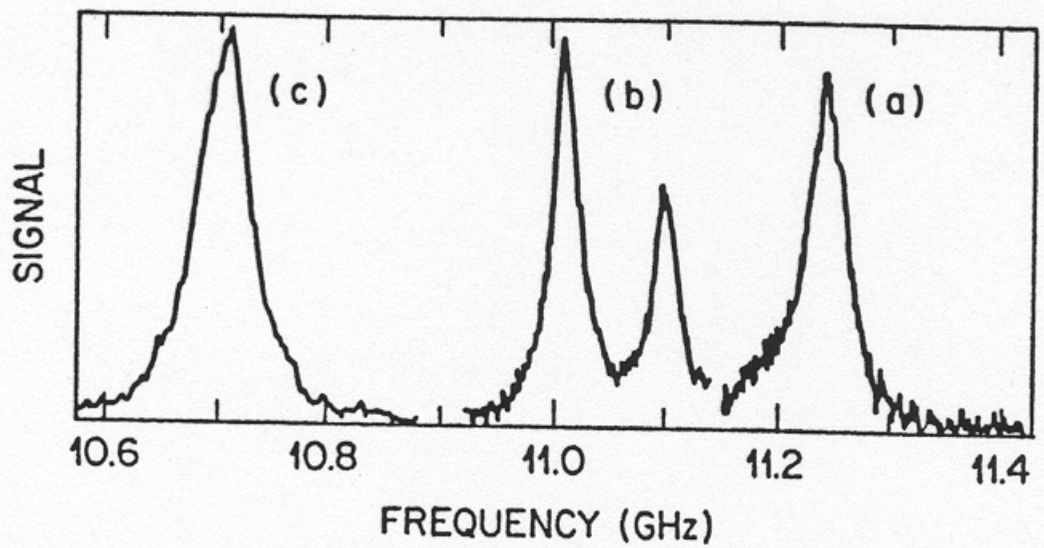


Figure 2.17: Brillouin-gain spectra measured using a 1.525-μm pump for three fibers with different germania doping: (a) silica-core fiber; (b) depressed-cladding fiber; (c) dispersion-shifted fiber. Vertical scale is arbitrary. (After Ref. [78]; ©1986 IEE; reprinted with permission.)

Brillouin Laser Threshold

Threshold defined by the input power where the output Brillouin power equals the pump power at the output.

$$I_s(z) = I(0)\exp(g_B L_{eff} I_0 - \alpha z)$$

$$L_{eff} = (1 - \exp(-\alpha L))/\alpha$$

$$\frac{P}{P_0} = \exp\frac{P_0}{P_2} = \frac{1}{2}$$

$$g_B P_{th} L_{eff} / A_{eff} = 21$$

$$P_{th} = \frac{21 A_{eff}}{g_B L_{eff}}$$

For

$$A_{eff} = 50\mu m^2$$

$$g_B = 5 \bullet 10^{-11} / mW$$

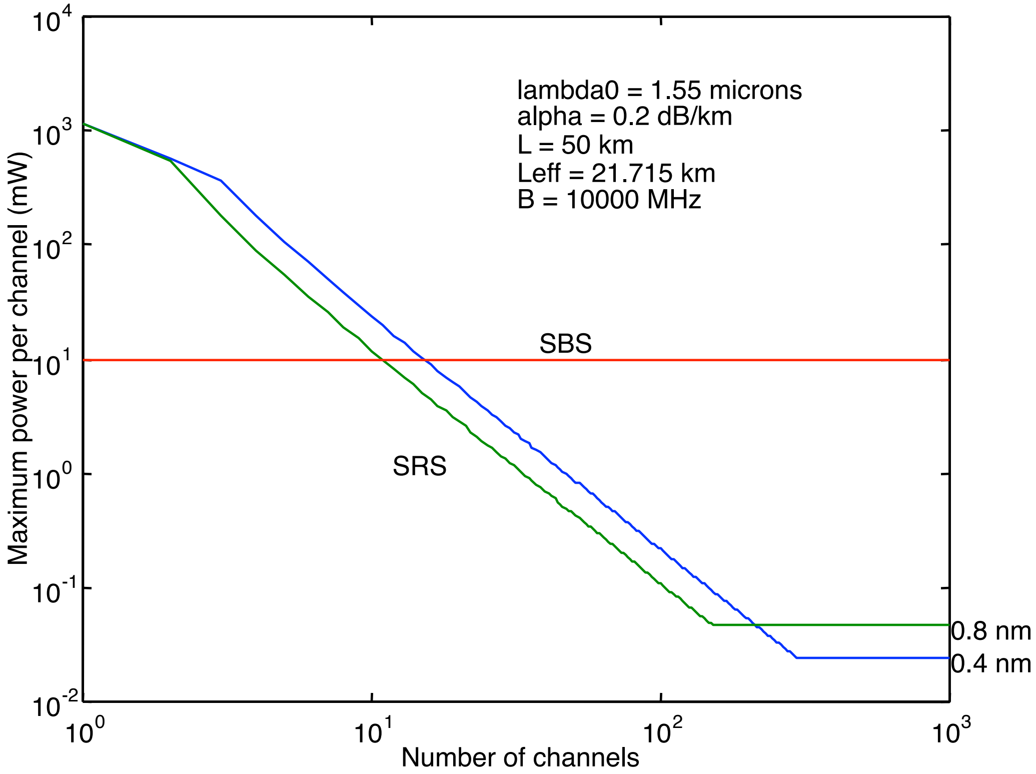
$$\alpha = 0.2 dB / km$$

$$P_{th} = 1mW$$

Brillouin Lasing Solution

- Brillouin scattering is a problem for narrow line sources.
- The solution is to chirp the pump laser, the effective power at a particular frequency is smaller.

SRS and SBS



lambda0 = 1.55 microns
alpha = 0.2 dB/km
L = 50 km
Leff = 21.715 km
B = 10000 MHz
SBS
SRS
0.8 nm
0.4 nm
Maximum power per channel (mW)
Number of channels
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{0}
10^{1}
10^{2}
10^{3}

Fiber Nonlinear Effects Summarized

- Various techniques can be applied to reduce the effects of fiber nonlinearities:
  - Phase modulation on at the transmitter can reduce effects of SBS
  - Careful placement of wavelengths within the ITU grid can reduce the effects of FWM
  - Design of special fibers with large area effective cores reduce the optical intensity (Corning)
  - Design of fibers with low (2ps/nm-km) dispersion but not zero dispersion can greatly reduce effects of fiber FWM (Truewave optimized for 10 Gbps)