Fiber Nonlinearities and Their Impact on Transmission Systems

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Outline

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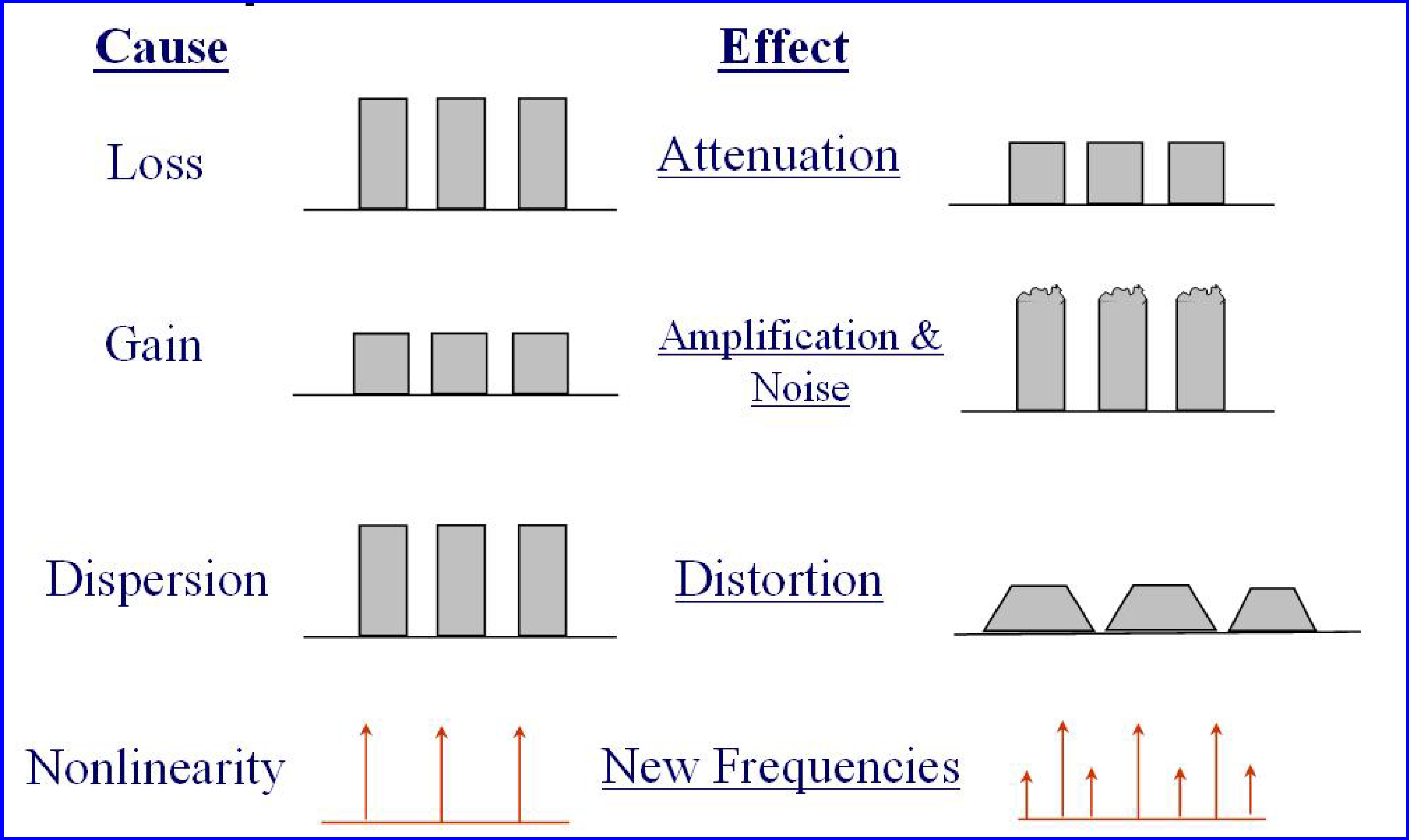
- An Overview of Fiber Nonlinearities
- Stimulated Brillouin Scattering (SBS)
- Self-Phase Modulation (SPM)
- Cross-Phase Modulation (CPM)
- Four-Photon Mixing (FPM)
- Dispersion Management
- Modulation Instability (MI)
- Stimulated Raman Scattering (SRS)
- Scaling Nonlinearities
- Summary

Introduction

- Fiber nonlinearities becomes a problem when several channels coexist in the same fiber (WDM=Wavelength Division Multiplexing)
- Interactions between propagating light and the fiber can lead to interference, distortion, or excess attenuation of the optical signals
- Nonlinear effects are determined by the total and per channel OA output power

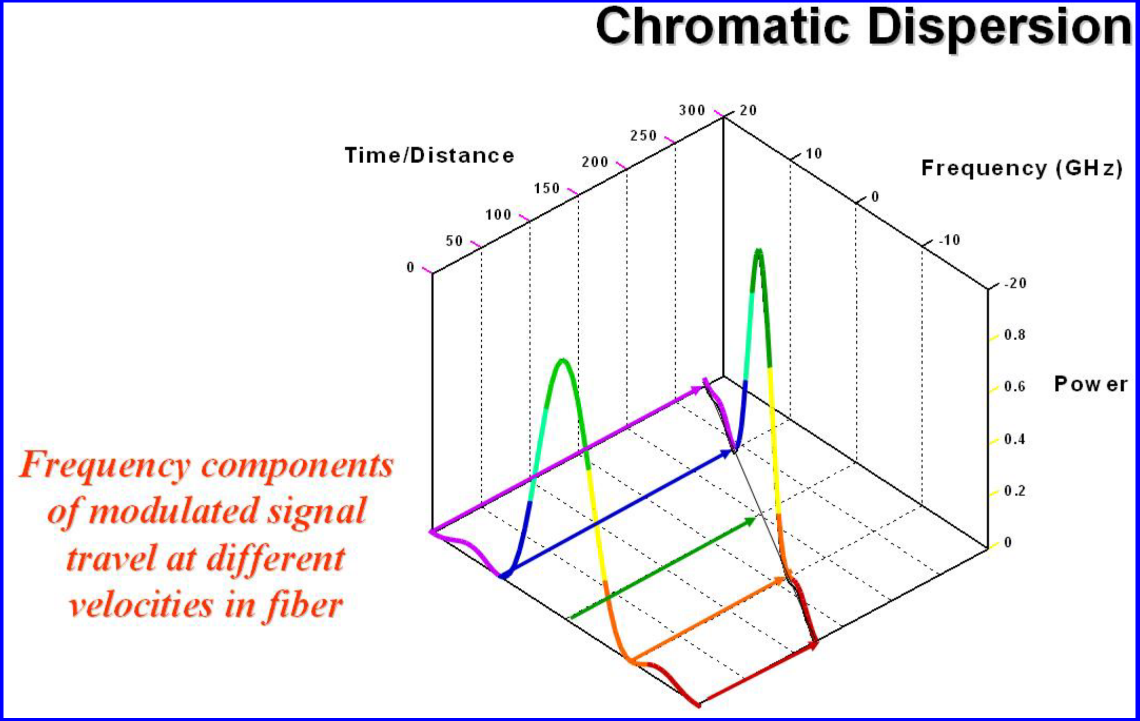
Introduction



Cause	Effect
Loss	Attenuation
Gain	Amplification & Noise
Dispersion	Distortion
Nonlinearity	New Frequencies

Introduction

- **Chromatic dispersion: Frequency components of modulated signal travel at different velocities in fiber**



Chromatic Dispersion

Frequency components of modulated signal travel at different velocities in fiber

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An Overview of Fiber Nonlinearities

- **The nonlinearities in silica fibers can be divided into two categories:**
  1. Stimulated scattering (Brillouin and Raman), gives rise to intensity dependent gain or loss
  2. Effects arising from the nonlinear index of refraction. Gives rise to an intensity dependent phase of the optical field leading to distortion, cross modulation, etc.

An Overview of Fiber Nonlinearities

- **Nonlinear interactions between two signals in a fiber can be expressed by the change in the electric field of one of the signals caused by the other**

  $$E_1(z + dz) = E_1(z)\exp[(-\alpha / 2 + ik)dz + gP_2(z)dz / 2A_e]$$

  Where α is the loss coefficient, g is the frequency-dependent gain coefficient of the nonlinear process, and A_e is the effective area of the fiber
- **For more complex situations the nonlinear Schrödinger equation needs to be solved**

An Overview of Fiber Nonlinearities

- **g is real => gain or loss. Parametric interaction between photons and phonons**
  - Stimulated Brillouin scattering
  - Stimulated Raman scattering
- **g is imaginary => phase modulation. Modulation of refractive index by light intensity fluctuation**
  - Self phase modulation (SPM)
  - Cross phase modulation (CPM)
  - Four-photon mixing (FPM)

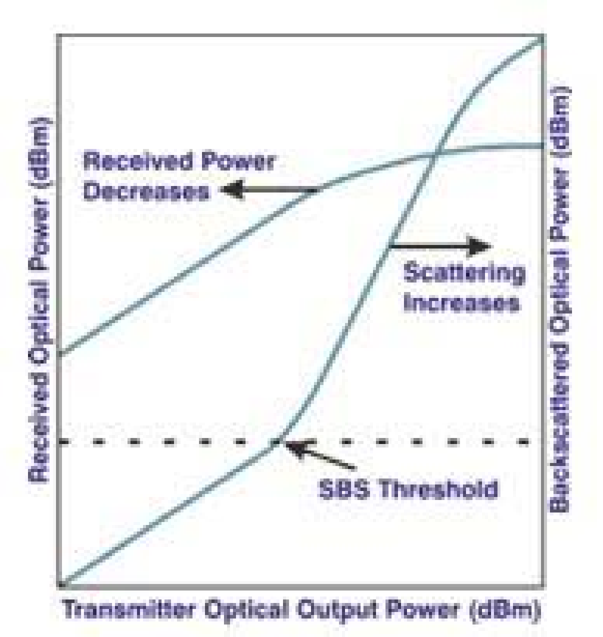
Stimulated Brillouin Scattering (SBS)

- SBS is caused by interaction of light with sound waves
- Sound waves in glass cause a variation in the index of refraction
- A strong wave traveling in one direction provides narrow band gain for light traveling in the opposite direction
- The reflected wave experiences a Doppler shift of about 20MHz in glass

Stimulated Brillouin Scattering (SBS)

- **SBS occurs when the incident light is of sufficiently high intensity (a few mW)**
- **The SBS threshold is defined as the input power at which the scattered power grows as large as the input power**
- **System impact:**
  - When signal power is transferred in a backward direction it can deplete the forward traveling signal
  - The transmitted power grows linearly with input power for low input powers, but saturates for higher input powers (gain compression)
  - This limiting behavior is also accompanied by a dramatic increase in intensity noise

Stimulated Brillouin Scattering (SBS)



SBS threshold effects

Self-Phase Modulation (SPM)

- **The refraction index of silica is weakly intensity dependent**

$$n = n_1 + n_2 \cdot \frac{P}{A_e}$$

- **n_2=2.6x$10^{-20}$$m^2$/W for silica fibers**
- **The nonlinear refraction index results in a phase change for the propagating light**

$$\Phi_{NL} = \gamma P L_e$$

- **γ is the nonlinear coefficient. The phase change becomes significant when the power times the length of the system equals 1W-km**

$$\gamma = \frac{2\pi n_2}{\lambda A_e}$$

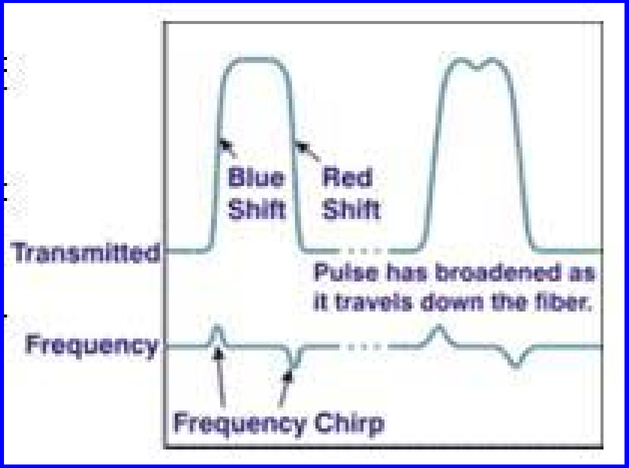
Self-Phase Modulation (SPM)

- SPM occurs when an intensity-modulated signal travels through a fiber
- The signal is broadened in frequency domain by

$$\Delta B = \gamma L_e \frac{dP}{dt}$$

- SPM can be used to compensate for positive chromatic dispersion (pulse narrowing)

Self-Phase Modulation (SPM)



Effects of SPM on a pulse

Cross-Phase Modulation (CPM)

- CPM is very similar to SPM
- CPM arises from intensity fluctuations from other channels present in a WDM system
- When two pulses travel down the fiber both will cause a change in refractive index as the optical power varies
- If these two pulses happen to overlap, they will introduce distortion into each other

Cross-Phase Modulation (CPM)

- The frequency shift caused by CPM is given by

$$\Delta B = 2\gamma L_e \frac{dP}{dt}$$

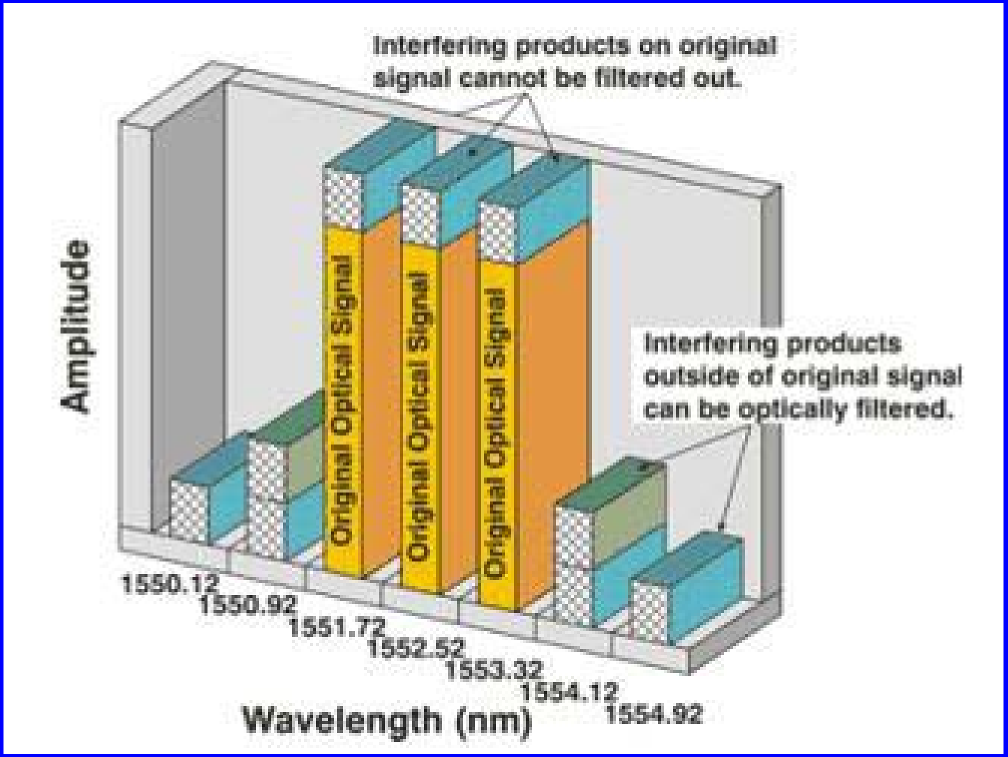
- Since CPM is an interaction between channels, the presence of chromatic dispersion means that pulses from interfering channels will not remain superimposed on the pulses in the channel of interest

Four-Photon Mixing (FPM)

- FPM is a third-order nonlinearity caused by the nonlinear refractive index of the fiber
- Example: If two signals with the frequencies f_1 and f_2 are traveling in the fiber, two new cross products will appear, $2f_1-f_2$ and $2f_2-f_1$. (Compare with IM3 and IP3 for electrical circuits)
- The number of interfering products increase rapidly with the number of signals (N) as $\frac{1}{2}(N^3-N^2)$

Four-Photon Mixing (FPM)

- **For signals with equal channel-spacing the interfering signals will fall on top of the original ones. They cannot be removed by any means.**

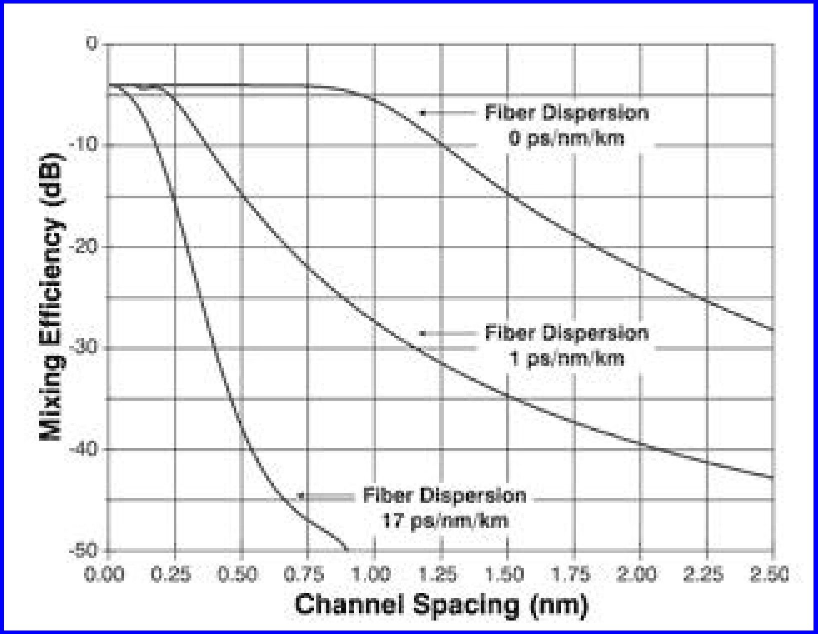


Interfering products on original signal cannot be filtered out.

Interfering products outside of original signal can be optically filtered.

Four-Photon Mixing (FPM)

- Channel spacing strongly influences the magnitude of the FPM products, the further apart the better
- Mixing efficiency is inversely proportional to the fiber dispersion, more dispersion means less FPM



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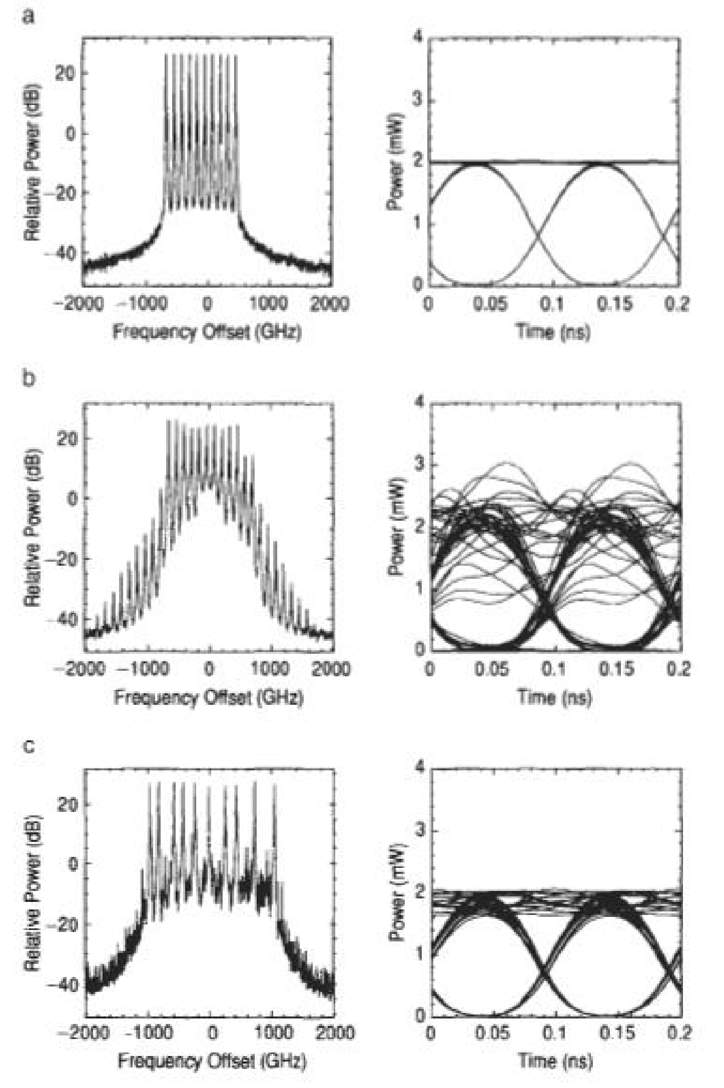
Four-Photon Mixing (FPM)

- **a) System input power spectrum and eye diagram**
- **b) System output, equally spaced channels**
- **c) System output, unequally spaced channels**



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Four-Photon Mixing (FPM)

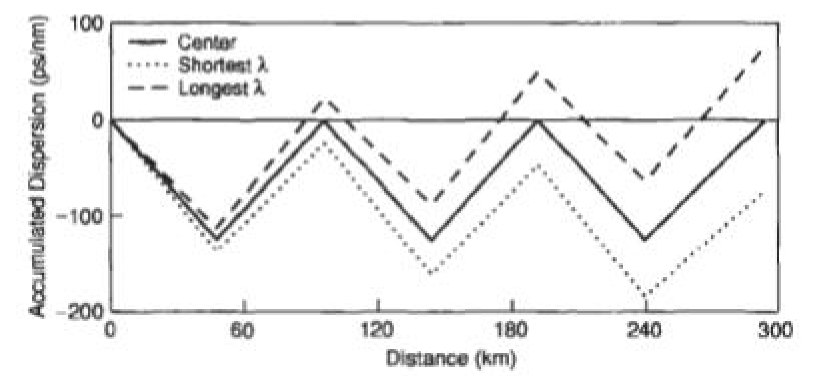
- Dispersion management and unequal channel spacing are used for FPM suppression
- Both these techniques are perfectly compatible and can preferably be used together

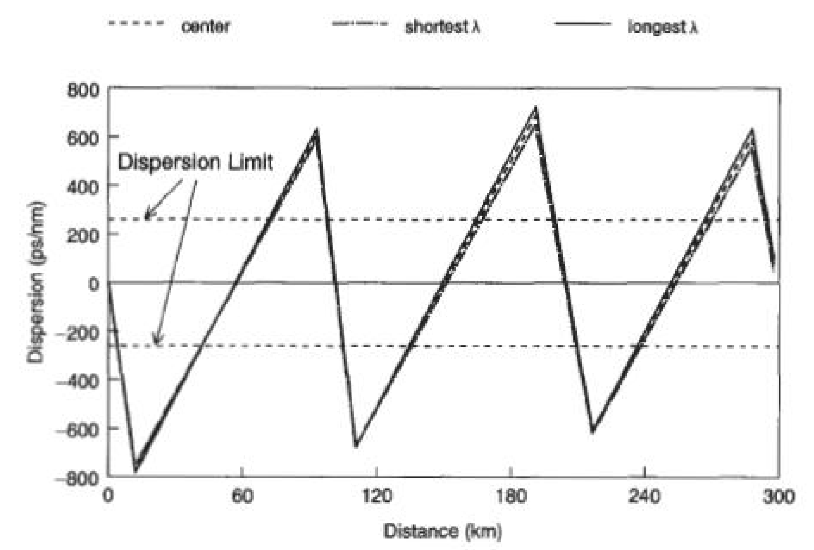
Dispersion Management

- **Fiber chromatic dispersion plays a schizophrenic role in WDM systems**
  - On the one hand, it is the bane of short optical pulses
  - On the other hand it is a useful tool to suppress FPM
- **Dispersion management ensures that no fiber in the transmission path has a dispersion-zero wavelength close to the signal wavelength**
- **However, the total accumulated dispersion between transmitter and receiver should be near zero**

Dispersion Management

- **Dispersion map for shortest and longest wavelength:**
  - Upper case: The spread in accumulated dispersion arises from the positive slope of dispersion in all fibers
  - Lower case: Conventional fiber compensated by dispersion-compensating fiber (DCF) with negative dispersion



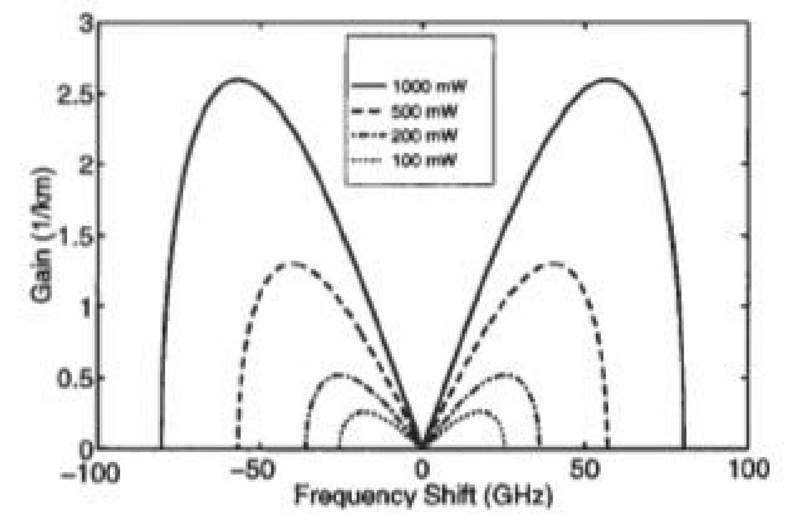


Modulation Instability (MI)

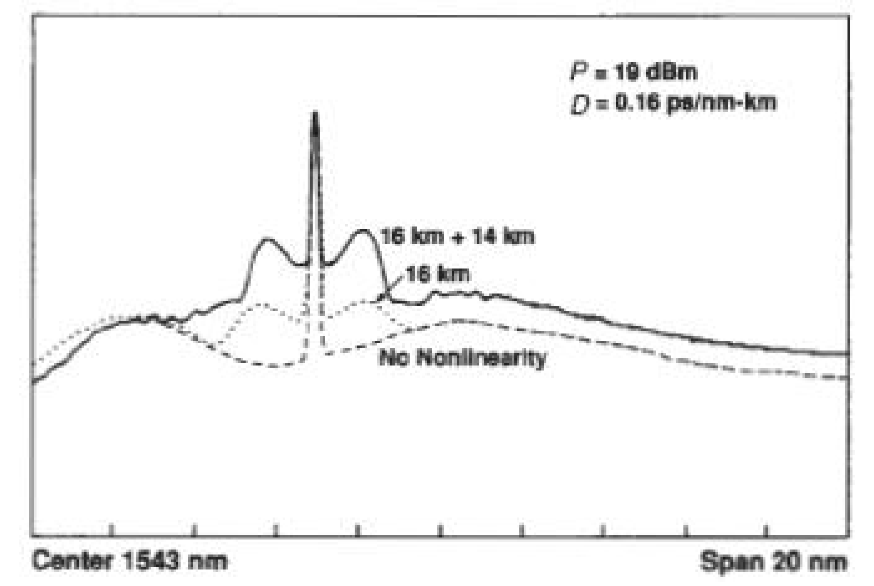
- **MI can be described in two ways:**
  - In time domain it can be viewed as pulse breakup or soliton formation
  - In the frequency domain, MI can be described in terms of parametric gain, or FPM phase matched by SPM producing exponential gain for the mixing products

Modulation Instability (MI)

- Modulation instability gain coefficient versus frequency



- Effect of parametric gain when transmitting a signal through a fiber

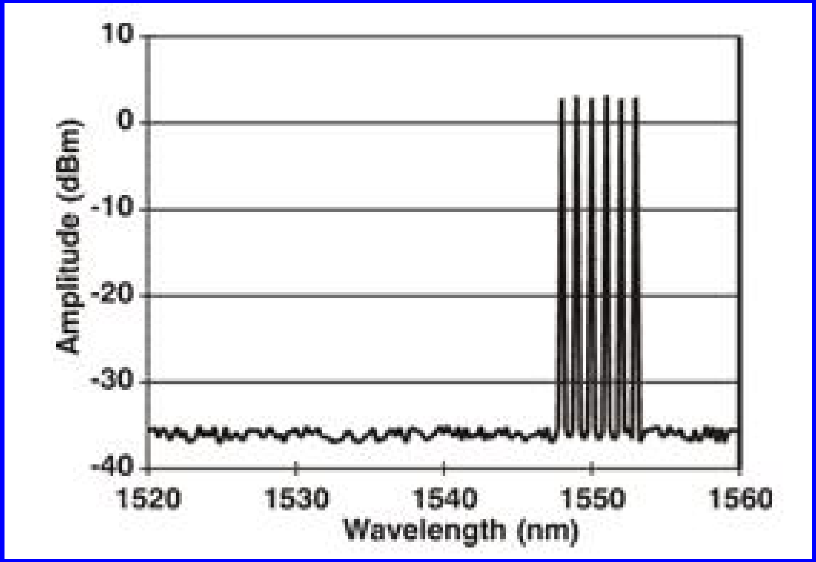


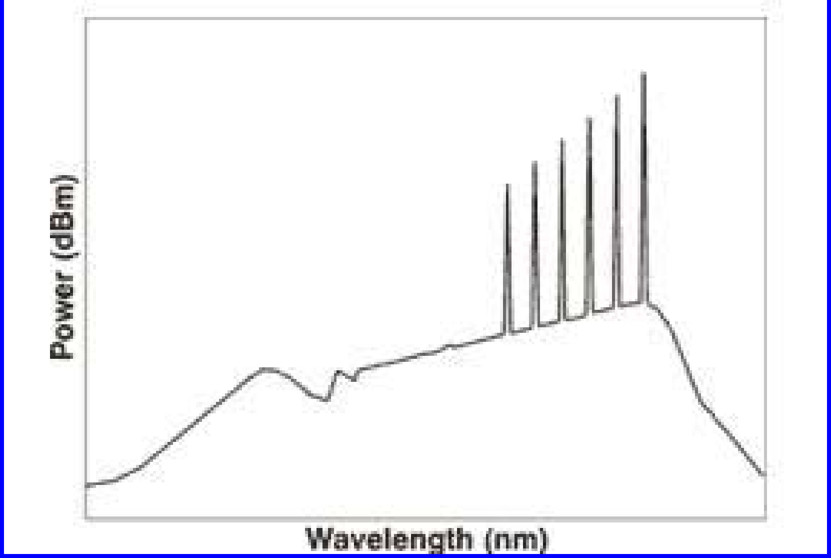
Stimulated Raman Scattering (SRS)

- SRS is a nonlinear parametric interaction between light and molecular vibrations
- SRS is similar to SBS, but its threshold is close to 1W nearly 1000 times higher than for SBS
- SRS can couple different channels in a WDM system and give arise to cross talk

Stimulated Raman Scattering (SRS)

- **The effect of SRS is usually first seen as that the shorter wavelength channels are robbed of power, and that power feeds the longer wavelength channels**





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Scaling Nonlinearities

- Issues of scaling of nonlinearities. Assume two systems described in the table below

	S1 10x10Gb/s	S2 20x5Gb/s
Number of channels	10	20
Bit rate per channel	10Gb/s	5Gb/s
Power per channel	P_1	$P_1/2$
Channel spacing	1nm	0.5nm
Dispersion map	$D_1(l)$	$D_2(l)=4D_1(l)$

Scaling Nonlinearities

- Since the power per channel for S_2 is lower, S_2 is less affected by the ”single-channel” nonlinearities SBS and SRS
- The power of neighboring channels is less for S_2 and thereby S_2 is less affected by CPM
- S_2 are less affected by FPM. S_1 has higher power and the mixing products generated by channels far away rapidly decreases, leading to the same number of ”relevant” mixing products for S_1 and S_2
- Since S_1 and S_2 have the same total power and bandwidth the SRS effect is the same for both systems

Scaling Nonlinearities

- The intuition that ”multi-channel” nonlinearities would affect S_2 more than S_1 because of the larger number of channels is wrong
- From a fiber nonlinearity point of view, 20 5Gb/s channels is a better choice than 10 10Gb/s channels to achieve a 100Gb/s system.

Summary

- **Two categories of nonlinearities**
  - Stimulated scattering (SBS, SRS)
  - Nonlinear index of refraction => distortion, cross modulation etc (SPM, CPM, FPM)
- **“Single-channel” nonlinearities:**
  - SBS
  - SPM
- **“Multi-channel” nonlinearities:**
  - CPM
  - FPM
  - SRS

Summary

- From a fiber nonlinearity point of view, 20 5Gb/s channels is a better choice than 10 10Gb/s channels to achieve a 100Gb/s system.
- Fiber nonlinearities represent the fundamental limiting on the amount of data that can be transferred on a single fiber
- There are several techniques to reduce the effects from fiber nonlinearities
- Maximizing the effective fiber area is the most common approach to reduce the fiber nonlinearities