

Fiber Nonlinearities

Nonlinearity effects arose as optical fiber data rates, transmission lengths, number of wavelengths, and optical power levels increased. The only worries that plagued optical fiber in the early day were fiber attenuation and, sometimes, fiber dispersion; however, these issues are easily dealt with using a variety of dispersion avoidance and cancellation techniques. Fiber nonlinearities present a new realm of obstacle that must be overcome. These nonlinearities previously appeared in specialized applications such as undersea installations. However, the new nonlinearities that need special attention when designing state-of-the-art fiber optic systems include stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), four wave mixing (FWM), self-phase modulation (SPM), cross-phase modulation (XPM), and intermodulation. Fiber nonlinearities represent the fundamental limiting mechanisms to the amount of data that can be transmitted on a single optic fiber. System designers must be aware of these limitations and the steps that can be taken to minimize the detrimental effects of fiber nonlinearities.

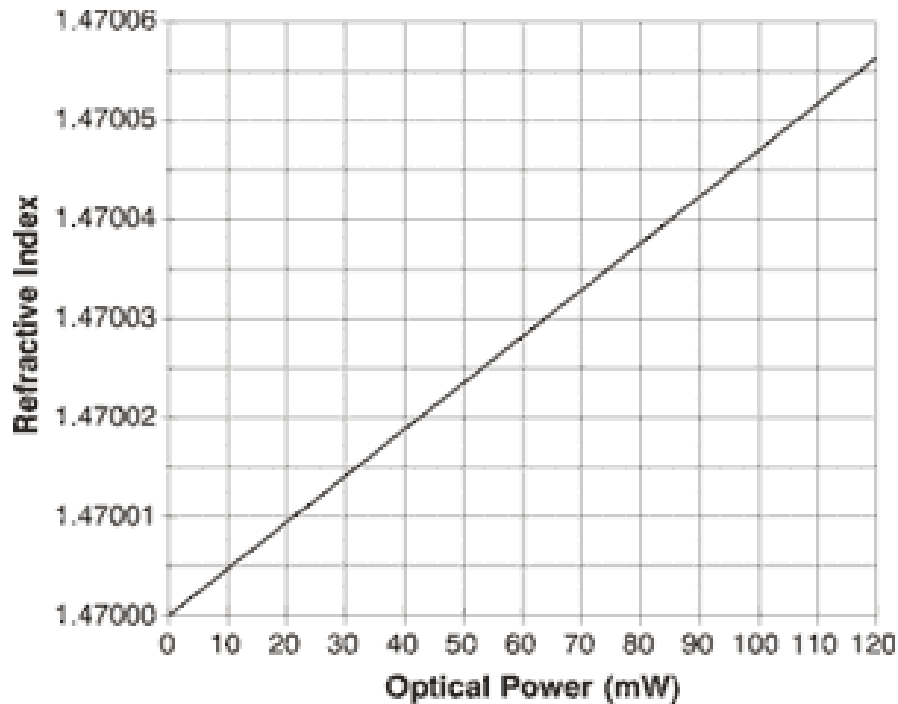
Causes of Nonlinearities

Fiber nonlinearities arise from two basic mechanisms. The most detrimental mechanism arises from the refractive index of glass being dependent on the optical power going through the material. The general equation for the refractive index of the core in an optical fiber is:

$n = n_0 + n_2 \cdot P/A_{\text{eff}}$ Where: n_0 = The refractive index of the fiber core at low optical power levels. n_2 = The nonlinear refractive index coefficient ($2.35 \times 10^{-20} \text{ m}^2/\text{W}$ for silica). P = The optical power in Watts. A_{eff} = The effective area of the fiber core in square meters.

The equation shows that minimizing the amount of power, P , launched and maximizing the effective area of the fiber, A_{eff} , eliminates the nonlinearities produced by refractive index power dependence. Minimizing the power goes against the current approach to eliminating the detrimental effects; however, maximizing the effective area remains the most common approach in the latest fiber designs. Figure 1 depicts the relationship of the refractive index of silica versus optical power. The magnitude of the change in the refractive index is relatively small; this only becomes important because the interaction length in a real fiber optic system can be hundreds of kilometers. SPM, XPM, FWM, and intermodulation nonlinearities result from the power dependent refractive index of silica.

Figure 1 - The Refractive Index of Silica versus Optical Power

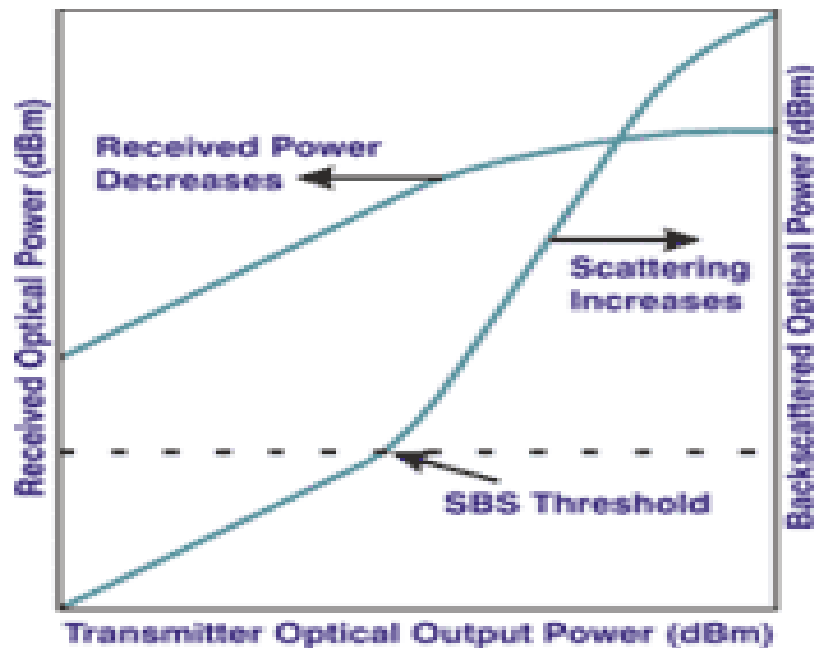


Stimulated Brillouin Scattering

The second mechanism that cause fiber nonlinearities is the scattering phenomena, which product SBS and SRS. Stimulated Brillouin Scattering (SBS) sets an upper limit on the amount of optical power that can be usefully launched into an optical fiber. When the SBS threshold for optical power is exceeded, a significant amount of the transmitted light is redirected back to the transmitters. In addition to causing a saturation of optical power in the receiver, problems also arise with backreflection in the optical signal, and noise that degrades the BER performance. It is particularly important to control SBS in high-speed transmission systems the use external modulators and continuous wave (CW) laser sources. It should be noted that 1550 nm CATV signals in the high-speed transmitters often possess the characteristics that trigger the SBS effect. Brillouin scattering is the time-varying electric fields within a fiber interacting with the acoustic vibrational modes of the fiber material which in turn scatter the incident light. Stimulated Brillouin Scattering is when the source of the high intensity electric fields is the incident lightwave. The periodic variation in in the refractive index, caused by the high power incident lightwave, cases backreflection similar to the effect of Bragg gratings. An increasing portion of light is backscattered because of the increasing optical level beyond the SBS threshold. This creates an upper limit to the power levels that can be carried over the fiber. Figure 2 illustrates this phenomenon. As the launch power is increased above the threshold, there is a dramatic increase in the amount of backscattered light. Wavelength (the threshold is lower at 1550 nm than 1310 nm) and the linewidth of the transmitter, among other parameters, govern the precise threshold

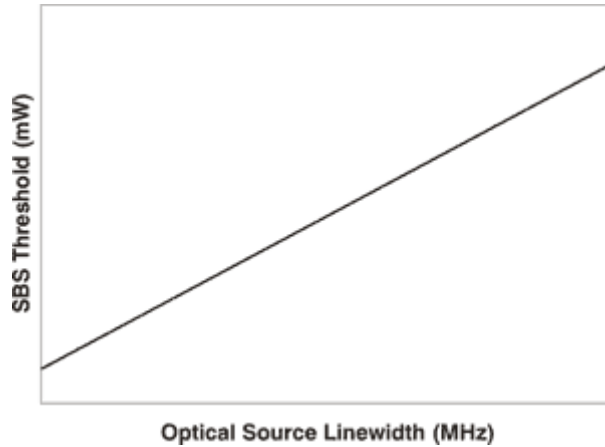
for the onset of the SBS effect. Values of +8 to +10 dBm are typical for direct modulated optical sources operating at 1550 nm over standard single-mode fiber.

Figure 2 - SBS Threshold Effects



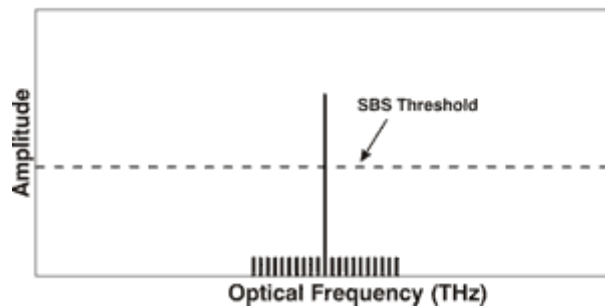
The SBS threshold is strongly dependent on the linewidth of the optical source with narrow linewidth sources having considerably lower SBS thresholds. Extremely narrow linewidth lasers (e.g. less than 10 MHz wide), often used in conjunction with external modulators, can have SBS thresholds of +4 to +6 dBm at 1550 nm. Figure 3 illustrates how the SBS threshold increases proportionally as the optical linewidth increases. Broadening the effective spectral width of the optical source minimizes SBS. Externally modulating the transmitter provides one way to broadening the linewidth. This involves adding a small AC modulation signal to the DC current source used drive to laser. This broadens the spectral linewidth of the transmitter and increases the threshold for the onset of SBS. This option also increases the dispersion susceptibility of the transmitter, primarily a concern when operating at 1550 nm over non dispersion-shifted single-mode fiber. Practical implementations of SBS suppression circuitry based on laser drive dithering can increase the SBS threshold by 5 dB.

Figure 3 - SBS Threshold versus Source Linewidth



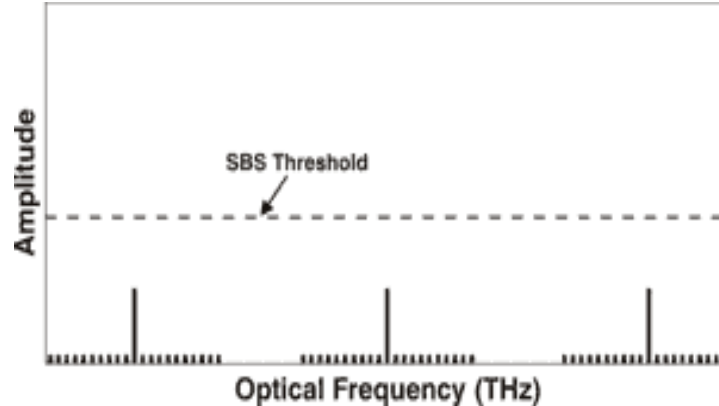
Phase dithering the output of the external modulator provide another common means of increasing the SBS threshold. In this case, a high frequency signal, usually twice that of the highest frequency being transmitted, is imposed onto both output legs of the external modulator. This modulates the phase of the light, effectively spreading out the spectral width. Figure 4 shows the optical spectra of an VSB/AM transmitter without phase dithering. The central carrier exceeds the SBS threshold, causing serious system degradation.

Figure 4 - Optical Spectrum without Phase Modulation



In Figure 5, a high frequency dither signal has been applied to the phase modulation input of the external modulator. It can be seen that all of the lines are now comfortably below the SBS threshold. This technique can raise the SBS threshold optical power by about 10 dB.

Figure 5 - Optical Spectrum with Phase Modulation



Adding EDFAs to a signal path greatly decrease the SBS threshold. The SBS threshold for a system containing N amplifiers is the threshold without amplifiers in mW divided by N . This can result in very low SBS thresholds that can seriously impair system performance.

Stimulated Raman Scattering

Stimulated Raman Scattering (SRS) is much less of a problem than SBS. Its threshold is close to 1 Watt, nearly a thousand times higher than SBS. But real systems are being deployed with EDFAs having optical output powers of 500 mW (+27 dBm), and this will only go higher. A fiber optic link that includes three such optical amplifiers will reach this limit since the limit drops proportionally by the number of optical amplifiers in series. SRS can cause scattering like SBS, but usually the effect first seen is that the shorter wavelength channels are robbed of power, and that power feeds the longer wavelength channels. This is similar to the operation of EDFAs where a 980 nm pump wavelength provides the energy that amplifies the signals in the longer wavelength, 1550 nm, region.

Figure 6 - Six Channel DWDM Transmitted Optical Spectrum

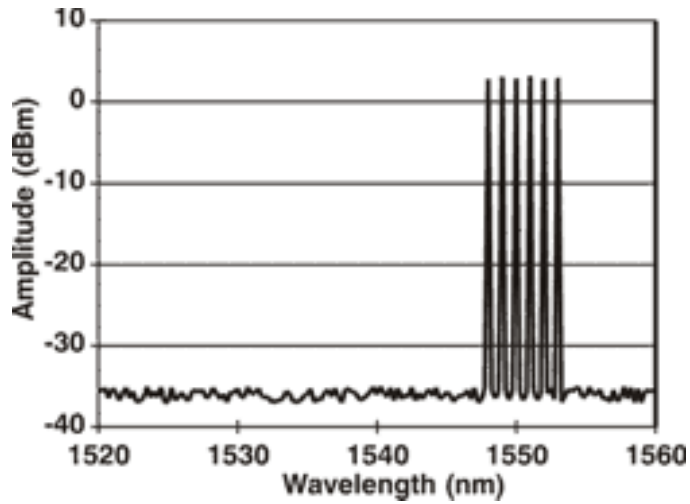
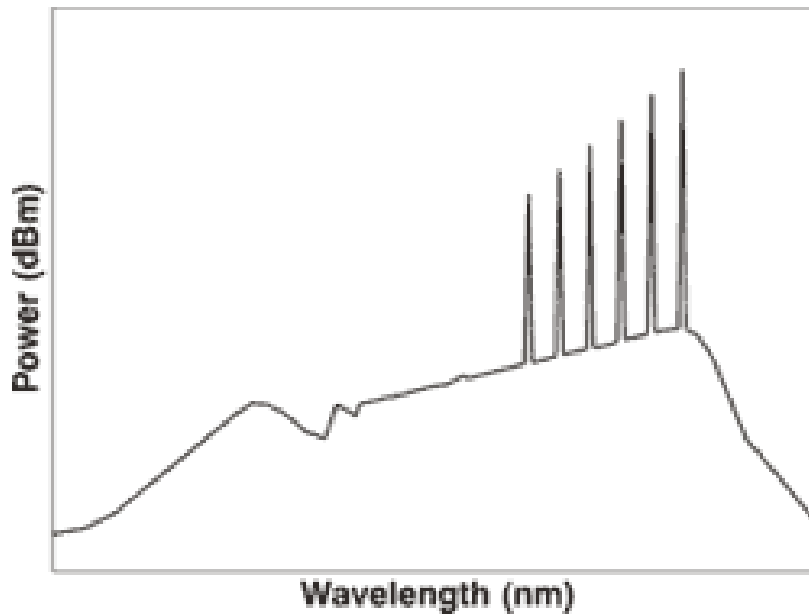


Figure 6 shows the typical transmit spectrum of a six-channel DWDM system. Note that all of the six wavelengths have identical amplitudes. These signals are all in the 1550 nm window. Figure 7 illustrates the SRS effect. It can be seen that the short wavelength channels have a much smaller amplitude compared to the longer wavelength channels. Plain silica fiber can provide similar gain using the Raman gain mechanism. Raman amplifiers are only now becoming mainstream additions to long-haul telecommunications system.

Figure 7 - SRS Effect on Six Channel DWDM Transmitted Optical Spectrum



Four Wave Mixing

Usually only systems that carry a number of simultaneous wavelengths, such as DWDM systems, exhibit four wave mixing (FWM). Caused by the nonlinear nature of the refractive index of the optical fiber itself, the FWM effect is similar to composite triple beat (CTB) distortion observed in CATV systems. CTB is also caused by nonlinearity, this time in the electrical amplifier chain or one of the optical components, usually the laser. CTB, like FWM, is classified as a third-order distortion phenomenon. Third-order distortion mechanisms generate third-order harmonics in systems with one channel. In multichannel systems, third-order mechanisms generate third-order harmonics and a gamut of cross products. These cross products cause the most problems since they often fall near or on top of the desired signals. Consider a simple three-wavelength (λ_1 , λ_2 , and λ_3) system that is experiencing FWM distortion. In this simple system, nine cross products are generated near λ_1 , λ_2 , and λ_3 that involve two or more of the original wavelengths. Note that there are additional products generated, but they fall well away from the original input wavelengths. Let us assume that the input wavelengths are $\lambda_1 = 1551.72$ nm, $\lambda_2 = 1552.52$ nm, and $\lambda_3 = 1553.32$ nm. The interfering wavelengths that are of most concern in our hypothetical three wavelength system are: $\lambda_1 + \lambda_2 - \lambda_3 = 1550.92$ nm $\lambda_1 - \lambda_2 + \lambda_3 = 1552.52$ nm $\lambda_2 + \lambda_3 - \lambda_1 = 1554.12$ nm $\lambda_1 - \lambda_2 + \lambda_3 = 1552.52$ nm $2\lambda_1 - \lambda_3 = 1550.12$ nm $2\lambda_3 - \lambda_1 = 1554.92$ nm $\lambda_2 + \lambda_3 - \lambda_1 = 1554.12$ nm $2\lambda_2 - \lambda_1 = 1553.32$ nm $2\lambda_3 - \lambda_2 = 1554.12$ nm It can be seen that three of the interfering products fall right on top of the original three signals. The remaining six products fall outside of the original three signals. These six can be optically filtered out. Because the three interfering products that fall on top of the original signals are mixed together, they cannot be removed by any means. Figure 8 shows the results graphically. The three tall solid bars are the three original signals. The shorter cross-hatched bars represent the nine interfering products. The number of interfering products increases as $\frac{1}{2} \cdot (N^3 - N^2)$ where N is the number of signals.

Figure 8 - FWM Products for a Three Wavelength System

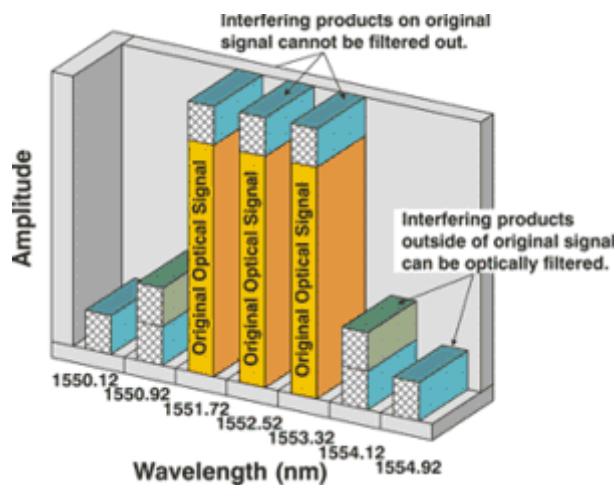
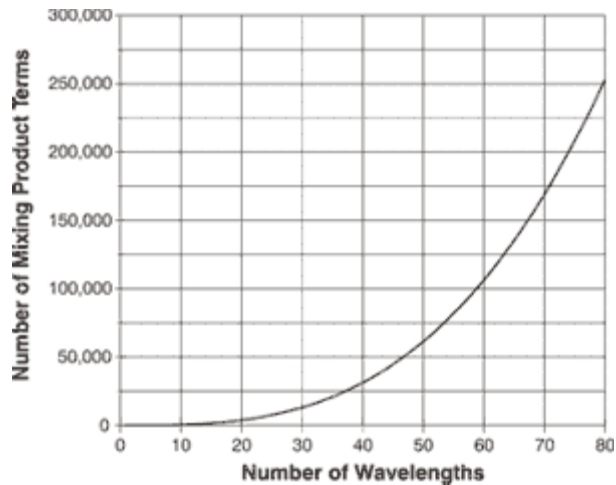


Figure 9 shows that the number of interfering products rapidly becomes a very large number. Since there is no way to eliminate products that fall on top of the original

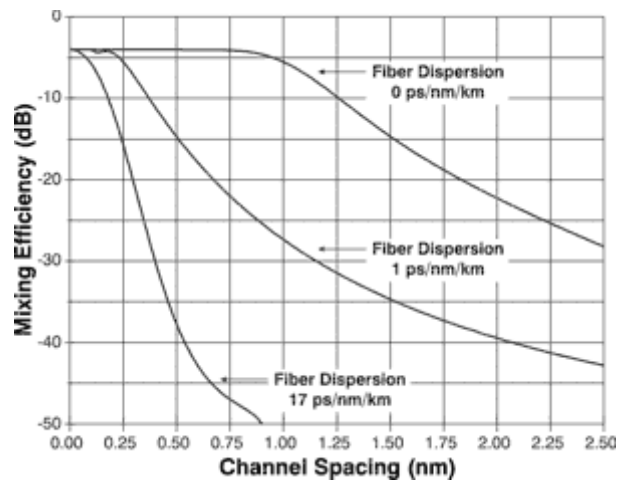
signals, the only hope is to prevent them from forming in the first place.

Figure 9 - FWM Products versus Channel Count



Two factors strongly influence the magnitude of the FWM products, referred to as the FWM mixing efficiency. The first factor is the channel spacing; mixing efficiency increases dramatically as the channel spacing becomes closer. Fiber dispersion is the second factor, and mixing efficiency is inversely proportional to the fiber dispersion, being strongest at the zero-dispersion point. In all cases, the FWM mixing efficiency is expressed in dB, and more negative values are better since they indicate a lower mixing efficiency. Figure 10 shows the magnitude of FWM mixing efficiency versus fiber dispersion and channel spacing. If a system design uses NDSF with dispersion of 17 ps/nm/km and the minimum recommended International Telecommunication Union (ITU) DWDM spacing of 0.8 nm, then the mixing efficiency is about -48 dB and will have little impact. On the other hand, if a system design uses DSF with a dispersion of 1 ps/nm/km and a non-standard spacing of 0.4 nm, then the mixing efficiency becomes -12 dB and will have a severe impact on system performance, perhaps making recovery of the transmitted signal impossible. The data presented in Figure 3.34 is for a given optical power level, fiber length, wavelength and so on. The magnitude of the mixing efficiency will vary widely as these parameters vary. The data presented is intended to illustrate the principles only.

Figure 10 - FWM Mixing Efficiency in Single-mode Fibers



Modulation

Self-phase Modulation

Figure 11 - Effects of SPM on a Pulse

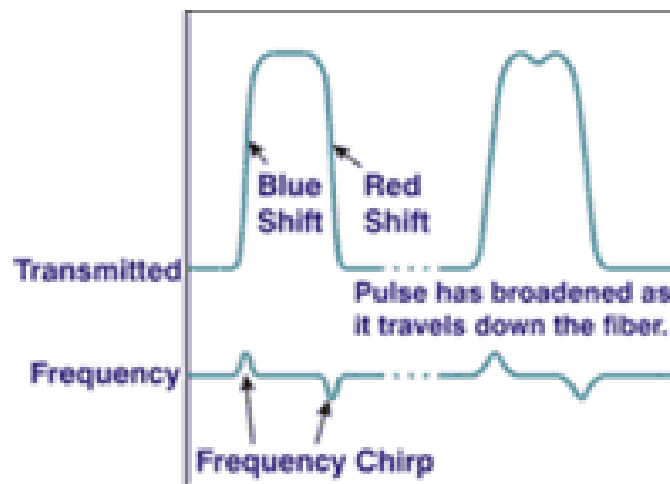


Figure 11 illustrates self-phase modulation. Like FWM, self-phase modulation (SPM) is due to the power dependency of the refractive index of the fiber core. It interacts with the chromatic dispersion in the fiber to change the rate at which the pulse broadens as it travels down the fiber. Whereas increasing the fiber dispersion will reduce the impact of FWM, it will increase the impact of SPM. As an optical pulse travels down the fiber, the leading edge of the pulse causes the refractive index of the fiber to rise, resulting in a blue shift. The falling edge of the pulse decreases the refractive index of the fiber

causing a red shift. These red and blue shifts introduce a frequency chirp on each edge which interacts with the fiber's dispersion to broaden the pulse.

Cross-phase Modulation

Cross-phase modulation (XPM) is very similar to SPM except that it involves two pulses of light, whereas SPM needs only one pulse. In XPM, two pulses travel down the fiber, each changing the refractive index as the optical power varies. If these two pulses happen to overlap, they will introduce distortion into the other pulses through XPM. Unlike, SPM, fiber dispersion has little impact on XPM. Increasing the fiber effective area will reduce XPM and all other fiber nonlinearities. **Intermodulation (Mixing)** Intermodulation is fairly similar to SPM and XPM. Consider the case where two laser light sources are transmitting light through the fiber. Again as the optical power in each light wave peaks and drops, the refractive index of the fiber changes accordingly. Now the two different light sources have different frequencies f_1 and f_2 . As the refractive index changes in concert with frequencies f_1 and f_2 , new frequencies, $2 \cdot f_1 - f_2$ and $2 \cdot f_2 - f_1$, appear. This is similar in many ways to the FWM nonlinearity.

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