The Effects of Fiber Nonlinearities

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BACKGROUND

In the early days of fiber optics, actually just a decade or two ago, optical fiber was simple. Everyone assumed that fiber had infinite bandwidth and would meet mankind's communication needs into the foreseeable future. As the need arose to send information over longer distances, the fiber community developed additional wavelength windows that would allow longer and longer transmission. The third window, 1550nm, seemed to be the ultimate answer, With losses of only 0.2dB/km, it seemed adequate for any imaginable application. Millions of kilometers of fiber were installed around the world creating a high-speed communication network that would surely last for years.

But then a few years ago, the Internet happened and simultaneously demand for lots of video channels exploded. The old days of sending 140 Mb/s over a 50 km fiber length were long gone. A lot more bandwidth was required, and fast! Back to the laboratories. Some researchers felt that terabit data rates were possible over fiber. Theory confirmed that conjecture, but could conventional electronics keep up? So far the answer has been an emphatic no. It appears that electronics will be up to 40 Gb/s data rates, but not much more. But fiber could support additional types of multiplexing beyond purely electronic schemes such as TDM (Time Division Multiplexing). It could also support transmission of many different colors or wavelengths of light.

The next big event was the development of affordable DWDM (Dense Wavelength Division Multiplexing) technology the last few years. Now suddenly, ten, twenty or even 80 or more simultaneous data streams could be combined onto a single fiber, each being transmitted at a slightly different color of light. The impact of DWDM on the telephony, video and data communications industries will be staggering. Now existing fibers can be used to carry up to two orders of magnitude more data than they could even a few years ago.

ROAD BUMPS

As the data rate on optical fiber increased and transmission lengths increased and the number of wavelengths increased and the optical power levels increased, a whole host of nonlinear fiber effects, just laboratory curiosities a few years earlier, suddenly became very important. In the early days of fiber, one had to worry most about fiber attenuation and to some extent fiber dispersion. As the fiber performance envelope stretched, dispersion became more important, but is generally well understood and can be dealt with using a variety of techniques. What is less well known are a host of optical fiber nonlinearities that have previously not been seen in field deployments other than specialized applications such as undersea installations. Fiber nonlinearities that now must be considered in designing state-of-the-art fiber optic systems include SBS (Stimulated Brillouin Scattering), SRS (Stimulated Raman Scattering), FWM (Four Wave Mixing), SPM (Self-Phase Modulation), XPM (Cross Phase Modulation) and Intermodulation (Mixing).

Why are all of these nonlinearities now so important? Because they represent the fundamental limiting mechanisms to the amount of data that can be transmitted on a single optical fiber. It is important that system designers be aware of these limitations and also be aware of steps that can be taken to minimize the detrimental effects of fiber nonlinearities.

FIBER DESIGNS

Single-mode (SM) fiber has gone through a continuing evolution for several decades now. Each new advance has been spurred by a newly discovered limitation of older fiber types in the field. The earliest SM fibers to be widely deployed were non dispersion-shifted fibers in the early 1980's. These fibers were initially intended for use near 1310nm, the second window in optical fiber. (The first window near 850nm was used almost exclusively for multimode fiber applications.) In order to optimize the fiber's performance in the 1310nm window, the fiber dispersion was designed to be very close to zero near that wavelength. That gave the fiber very low dispersion and consequently very high potential bandwidth. As optical fiber became more widespread and the need arose for more bandwidth and distance, the third window near 1550nm was exploited to provide a second SM wavelength. The 1550nm region offered much lower attenuation (0.2dB/km at 1550nm vs. 0.5dB/km at 1310nm), but it had quite a bit of dispersion (17ps/nm•km) which seriously limited bandwidth. This could be overcome by using more narrow line width lasers. Because non-dispersion-shifted fiber (NDSF) represents the majority of all installed SM fiber, laser manufacturers rushed to make laser line width more narrow to allow higher data rates to be transmitted. Laser manufacturers were also being pushed to provide ever higher output powers. While 1 mW lasers were the upper limit just a decade ago, laser manufacturers now routine provided 10mW output powers and higher. We will see later that these trends exposed several of the fiber nonlinearities we are going to discuss later.

Since the 1550nm region, the third window, seemed to have so many advantages compared to the 1310nm window, fiber manufacturers responded with a new fiber design, dispersion-shifted fiber (DSF), that moved the zero dispersion point to the 1550nm region. This seemed like a great leap forward, now the lowest optical attenuation and the zero dispersion points coincided in the 1550nm region. Surely this would be the ultimate optical fiber design. Some additional variations were also produced, the dispersion-flattened type being the most notable. Dispersion-flattened fiber was designed to have low dispersion in the 1310nm and 1550nm windows. However, there was a nasty surprise waiting for those who installed DSF several years ago and now want to convert their systems to have DWDM capabilities. It won't work! It turns out that there are tremendous nonlinearities in optical fiber near the zero dispersion point. There nonlinearities cannot be compensated for in any practical way, DSF simply can't be used for DWDM. It turns out that NDSF works quite well for DWDM applications, one just has to manage the dispersion introduced by this fiber.

Optical fiber manufacturers are responding with new fiber designs to address the market's need for aggressive DWDM. Most of these fibers are classified as non-zero dispersion-shifted fiber (NZ-DSF). The goal here was to make the dispersion low in the 1550nm region, but not zero, thus avoiding some of the nastiest nonlinearities. The latest generation of optical fibers have focused primarily on three performance parameters:

1) Increase the effective area of the optical fiber. This reduces the effects of some nonlinearities since the optical power is spread out over a larger area, reducing the impact of nonlinearities.

2) Shift the zero dispersion point near the 1550nm window, but guarantee that it falls <u>outside</u> of the 1550nm window. This avoids the nasty nonlinearities that lurk near the zero dispersion point.

3) Reduce the remaining absorption peaks in the fiber so that the second and third windows effectively merge together to form one large window, the "2-3" window and allow a fourth window from 1565nm to 1620nm to be utilized.

Corning and Lucent Technologies have led the push with new optical fiber designs to address the multitude of nonlinear effects that show up in today's advanced DWDM system designs. Corning offers a new fiber called LEAF® (large effective area fiber). It has a larger effective area to minimize some types of nonlinearities and has the zero dispersion wavelength shifted to 1570nm to minimize other nonlinear effects associated with DWDM. Lucent Technologies offers several varieties of Truewave® fiber that have similar characteristics.

FIBER NONLINEARITIES

Fiber nonlinearities arise from two basic mechanisms. The first, and most serious, is the fact that the refractive index of glass is dependent on the optical power going through the material. The general equation for the refractive index of the core in an optical fiber is:

$$n = n_0 + n_2 * P/A_{eff}$$

where n_0 is the refractive index of the fiber core at low optical power levels.

n_2 is the nonlinear refractive index coefficient. It is equal to 2.35×10^{-20} m^2/W for silica.

P is the optical power in Watts

A_{eff} is the effective area of the fiber core in square meters.

The equation shows that two strategies for minimizing nonlinearities due to refractive index power dependence are to minimize the amount of power, P, that is launched and to maximize the effective area of the fiber, A_{eff}. Obviously, minimizing P is counter to the current trend. We can, however, maximize A_{eff} with no other bad effects. Several of the latest fiber designs have focused on maximizing A_{eff}.

Figure 1 shows the relationship of the refractive index versus optical power. It can be seen that the magnitude of the change in refractive index is relatively small. It becomes important since the interaction length in a real fiber optic system can be hundreds of kilometers.

The power dependent refractive index of silica gives rise to the SPM, XPM and FWM nonlinearities.

The second mechanism for generating nonlinearities in fiber are scattering phenomena. These mechanisms give rise to SBS and SRS described later.

In this paper, we will examine the five most common fiber nonlinearities being encountered in today's system designs.

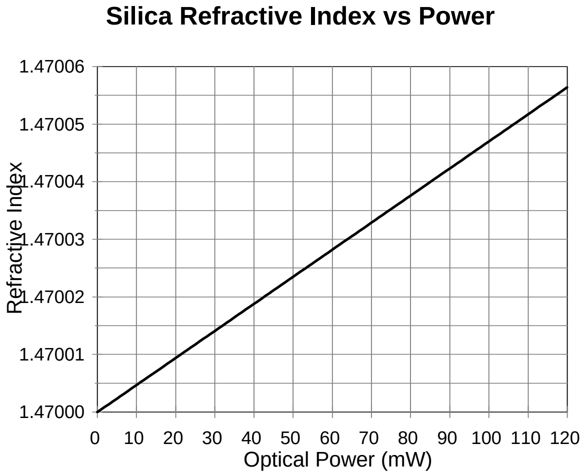

Figure 1 - Refractive Index of Silica vs. Optical Power

SBS (Stimulated Brillouin Scattering)

Stimulated Brillouin Scattering (SBS) is a fiber non-linearity that imposes an upper limit on the amount of optical power that can be usefully launched into an optical fiber. The SBS effect has a threshold optical power. When the SBS threshold is exceeded, a significant fraction of the transmitted light is redirected back toward the transmitter. This results in a saturation of optical power that reaches the receiver, as well as problems associated with optical signals being reflected back into the laser. The SBS process also introduces significant noise into the system, resulting in degraded BER performance. As a result, controlling SBS is particularly important in high speed transmission systems employing external modulators and CW laser sources. It is also of vital importance to the transmission of 1550nm-based CATV transmission, since these transmitters often have the very characteristics that trigger the SBS effect.

SBS is caused when time-varying electric fields within a fiber can interact with the acoustic vibrational modes of the fiber material to scatter incident light. This is known as Brillouin scattering. When the source of the high intensity electric fields is the incident light wave, the effect is known as SBS. The high power incident light wave actually causes the refractive index of the fiber to vary periodically causing back-reflection, similar to the effect of Bragg gratings in optical fiber.

As the input optical level increases beyond the SBS threshold, an increasingly larger portion of the light is back-scattered, creating 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. The precise threshold for the onset of the SBS effect depends on a number of system parameters including wavelength (the threshold is lower at 1550nm than 1310nm) and line width of transmitter. Values of +8 to +10dBm are typical for direct modulated optical sources operating in

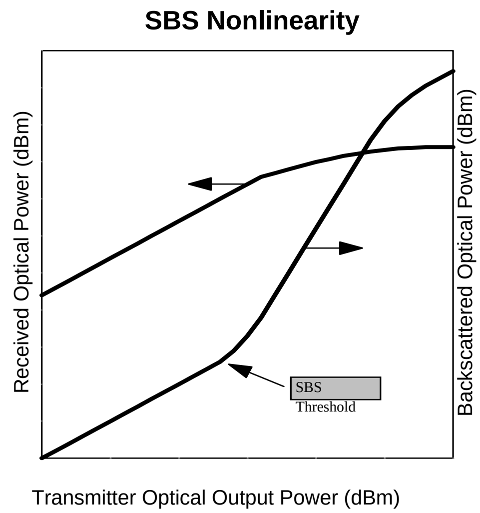

Figure 2 - SBS Threshold Effects

the 1550nm transmission window over standard single-mode fiber.

The SBS threshold is strongly dependent on the line width of the optical source, with narrow line width sources having considerably lower SBS thresholds. Extremely narrow line width lasers (e.g. less than 10 MHZ wide) are often used in conjunction with external modulators. These can have SBS thresholds of +4 to +6dBm at 1550nm. The SBS threshold increases proportionally as the optical source line width increases as shown in Figure 3. The most effective method of minimizing SBS is to broaden the effective spectral width of the optical source. An approach for line width broadening is to externally modulate the transmitter, while spreading out the line width by adding a very small AC modulation signal to the DC current source used to drive the laser itself. This will broaden the

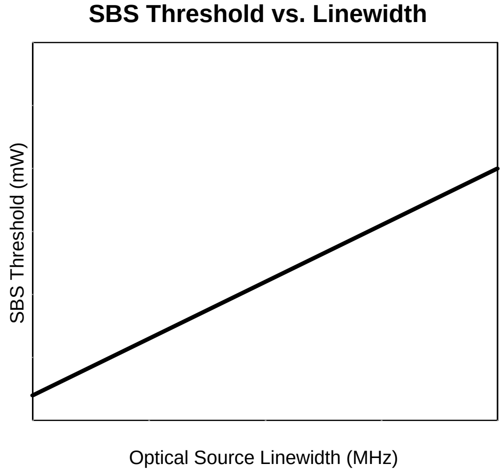

Figure 3 - SBS Threshold vs. Line width

spectral line width of the transmitter and increase the threshold for onset of SBS. This option also increases the dispersion susceptibility of the transmitter. This is primarily an concern when operating at 1550nm over non dispersion-shifted single-mode fiber. Practical implementations of SBS suppression circuitry based on laser drive dithering can increase the SBS threshold by 5dB.

Another common means increasing the SBS threshold is to phase dither the output of external modulator. 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 AM-VSB transmitter without phase dithering. The central carrier exceeds the SBS threshold, causing serious system degradation. 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 by about 10dB.

The other factor to consider is that the SBS threshold is even lower when a number of EDFA's are in the signal path. 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 thresholds that can seriously impair system performance.

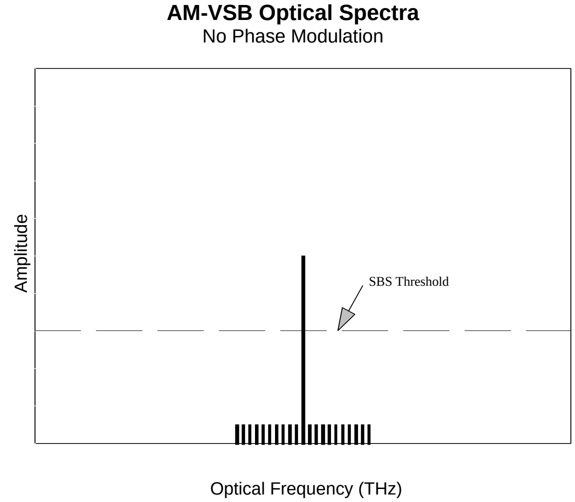

Figure 4 - Optical Spectrum - No Phase Modulation

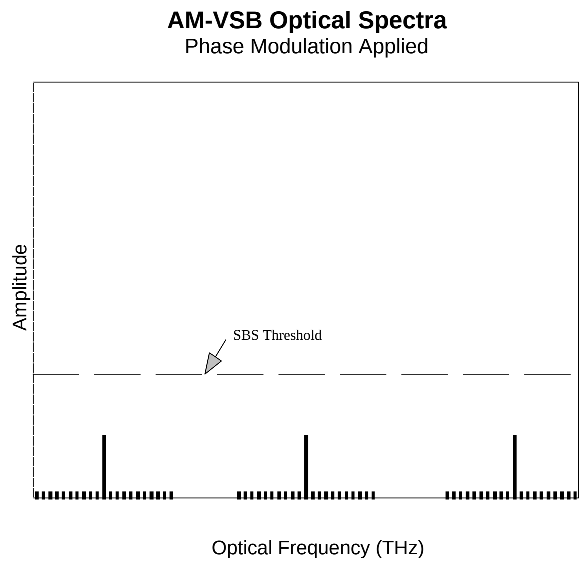

Figure 5 - Optical Spectrum with Phase Modulation

SRS (Stimulated Raman Scattering)

Stimulated Raman Scattering (SRS) is much less of a problem than SBS. Its threshold is close to 1Watt, nearly a thousand times higher than SBS. But, real systems are being deployed with EDFA's having optical output powers of 200mW and this will just go higher. So, a fiber optic link that includes five 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 that is seen first 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 EDFA's where a 980nm pump wavelength is used to provide energy that is used to amplify the signals in the 1550nm range. Currently EDFA's use a special Erbium doped fiber to provide this gain mechanism. Plain silica fiber can provide similar gain using the Raman gain mechanism. There is considerable talk that the next generation of EDFA's will be Raman type, rather than Erbium type.

Figures 6 and 7 show what would happen to six wave-

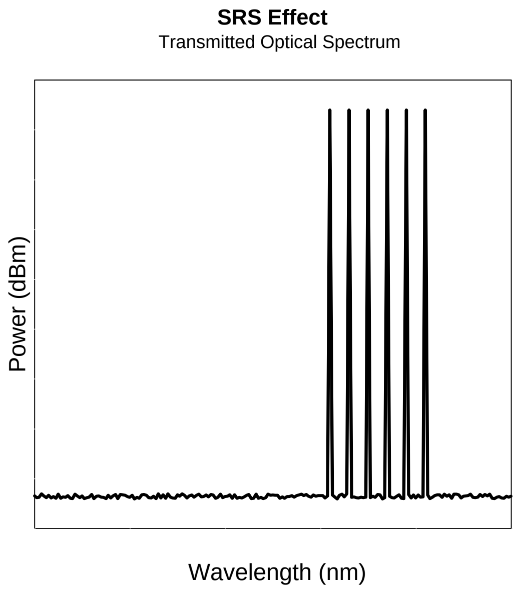

Figure 6 - Transmitted Optical Spectrum

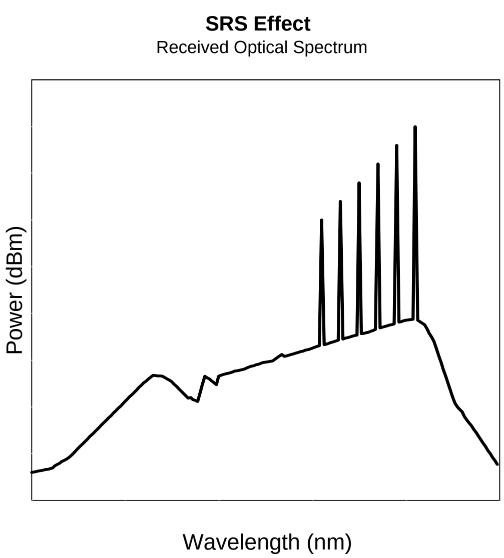

Figure 7 - SRS Effect Seen at Receiver Input

lengths that are transmitted through a series of optical amplifiers and long intermediate lengths of fiber. It can be seen in figure 5 that the six carriers initially have identical levels. In figure 6, it can be seen that the short wavelength channels have much smaller amplitude compared to the longer wavelength channels. This is the SRS effect.

FWM (Four Wave Mixing)

FWM is an effect that usually only shows up in fiber optic transmission systems that carry lots of simultaneous wavelengths, such as a DWDM system. It is caused by the nonlinear nature of the refractive index of the optical fiber itself. The FWM effect is very similar to composite triple beat (CTB) distortion that is 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 harmonics in single signal systems. In multi-channel systems, third-order mechanisms generate third harmonics and a whole range of cross products. It is the cross products that cause the most problems since they fall near or on top of the desired signals.

Consider a simple three wavelength (λ_1, λ_2 & λ_3) system that is experiencing FWM distortion. In this simple system, nine cross products are generated near λ_1, λ_2 & 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. Lets assume that the input wavelengths are λ_1 = 1551.72nm, λ_2 = 1552.52nm & λ_3 = 1553.32nm. The interfering wavelengths that are of most concern in our hypothetical three wavelength system are:

$\lambda_1 + \lambda_2 - \lambda_3$ = 1550.92nm
$\lambda_1 - \lambda_2 + \lambda_3$ = 1552.52nm
$\lambda_2 + \lambda_3 - \lambda_1$ = 1554.12nm
$2\lambda_1 - \lambda_2$ = 1550.92nm
$2\lambda_1 - \lambda_3$ = 1550.12nm
$2\lambda_2 - \lambda_1$ = 1553.32nm
$2\lambda_2 - \lambda_3$ = 1551.72nm
$2\lambda_3 - \lambda_1$ = 1554.92nm
$2\lambda_3 - \lambda_2$ = 1554.12nm

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. The three interfering products that fall on top of the original signals cannot be removed by any means. They are mixed together and can no longer be separated. Figure 8 shows the results graphically. The three tall solid bars are the three original signals. The shorter cross-hatched bars

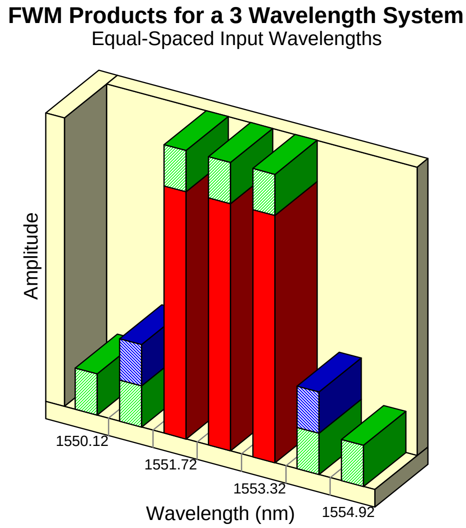

Figure 8 - FWM Products for a 3 Wavelength System

represent the nine interfering products. The number of interfering products increases as $½*(N^3-N^2)$. Figure 9 shows that this rapidly becomes a very large number. Since there is no way to eliminate products that fall on

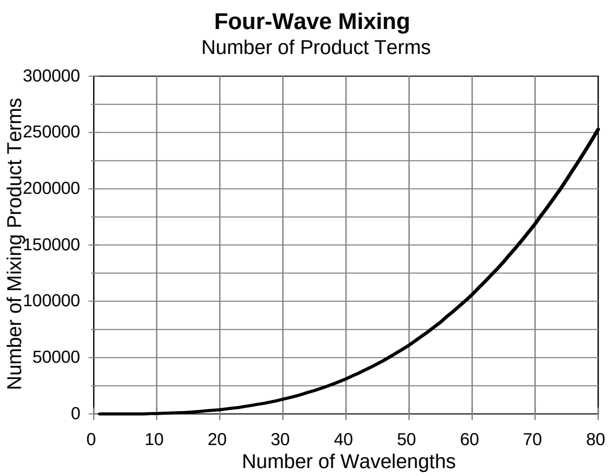

Figure 9 - FWM Products vs Channel Count

top of the original signals, our only hope is to prevent them from forming in the first place.

There are two factors that strongly influence the magnitude of the FWM products. This is referred to as the FWM mixing efficiency. It is expressed in dB. More negative values are better as they indicate lower mixing efficiency. The first factor is the channel spacing. Mixing efficiency increases dramatically as the channel spacing becomes closer. The second factor is the amount of dispersion in the fiber. Mixing efficiency is inversely proportional to the fiber dispersion, being strongest at the zero dispersion point. Figure 9 shows the magnitude of FWM mixing efficiency versus fiber dispersion and channel spacing. If your system design uses NDSF with dispersion of 17ps/nm•km and the minimum recommended ITU spacing of 0.8nm, then the mixing efficiency is about -48dB and will have little impact. On the other hand, if your system design uses DSF with a dispersion of 1ps/nm•km and non-standard spacing of 0.4nm, then the mixing efficiency becomes -12dB and will have a severe impact on system performance, perhaps making recovery of the transmitted signal impossible. The data presented in figure 10 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 in intended to illustrate the principles only.

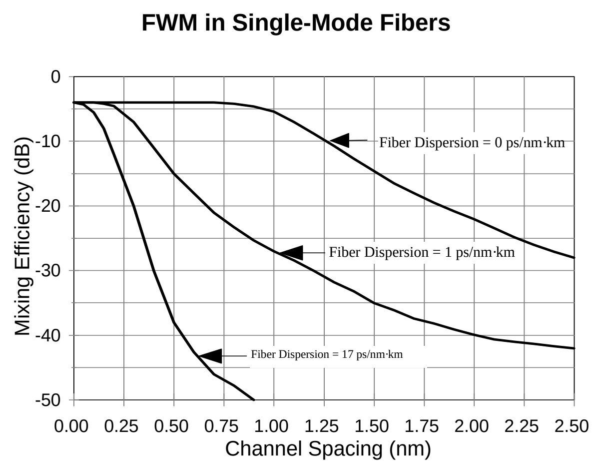

Figure 10 - FWM Mixing Efficiency in SM Fibers

SPM (Self-Phase Modulation)

Like FWM, SPM is a phenomenon that 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 causing 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. Figure 11 shows how this phenomenon works.

Demonstration of SPM

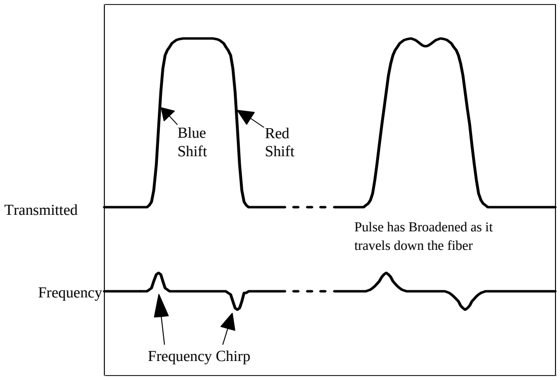

Figure 11 - Demonstration of SPM

XPM (Cross Phase Modulation)

Cross phase modulation is very similar to SPM except that it involves two pulses of light, whereas SPM needs only one pulse. In XPM, two pulses each travel down the fiber 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 improve 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, $2*f_1 - f_2$ and $2*f_2 - f_1$, appear. This is similar in many ways to the FWM nonlinearity.

CONCLUSION

Fiber nonlinearities raise the complexity of fiber optic system design to a new plateau. This paper has reviewed the key effects. Fiber nonlinearities present serious challenges to state-of-the-art DWDM system designs. There are several new fiber designs that reduce the impact of these nonlinearities. However, the unfortunate reality for many systems is that the fiber has been in the ground for a decade or more, so steps must be taken to use less than optimal fibers.

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QUICK SUMMARY CHART OF FIBER NONLINEARITIES

SBS

- SBS is caused by an interaction between the incident light wave and the acoustical vibration modes in the fiber material itself.
- The SBS threshold is directly proportional to the fiber area. Dispersion-shifted fiber have smaller areas, thus a lower threshold.
- Fiber designs with larger effective areas have a higher SBS threshold.
- The SBS threshold is directly proportional to the laser line width. Direct modulation, dithering of a CW laser or phase modulation of an external modulator all increase the effective line width, raising the threshold.
- Narrow line width laser sources in the 1550nm region without countermeasures can encounter SBS at optical powers of only +5dBm (3 mW).
- Countermeasures (dithering of the CW laser drive and phase modulating the output) can increase the SBS threshold in the 1550nm region to about +16dBm (40 mW).
- SBS limits the amount that light that reaches the receiver.
- Above the SBS threshold, backscattered light increases dramatically as does noise reaching the receiver.
- The SBS threshold is lower at longer wavelengths.
- For a system consisting of a chain of N optical amplifiers, the SBS threshold will drop by a factor of N.

SRS

- The SRS threshold power is about +30dBm (1 Watt).
- SRS limits the amount that light that reaches the receiver above the threshold.
- Below the SRS threshold, the SRS effect can rob power from shorter wavelength channels and feed that power to longer wavelength channels.
- For a system consisting of a chain of N optical amplifiers, the SRS threshold will drop by a factor of N.
- Fiber designs with larger effective areas have a higher SRS threshold.

FWM

- FWM is a phenomenon that arises from the nonlinearity of the refractive index of the optical fiber.
- FWM is a third order distortion mechanism. It is very similar to CTB (composite triple beat) distortion in the CATV realm.
- FWM becomes worse as the fiber dispersion drops. It is worst at the zero dispersion point. Higher chromatic dispersion results in less FWM.
- FWM is worst in WDM channel designs where the spacing is equal. (Equal channel spacing is, unfortunately, the case in standardized DWDM designs.)
- FWM is worse as wavelengths are spaced closer together.
- Fiber designs with larger effective areas have a higher SBS threshold.

SPM

- SPM causes a frequency chirp on the rising and falling edges of an optical pulse, broadening the pulse.
- SPM effects a single light pulse traveling down the fiber.
- SPM acts along with chromatic dispersion to broaden pulses.
- Higher chromatic dispersion results in less SPM.
- Fiber designs with larger effective areas have a higher SPM threshold.

XPM

- XPM causes multiple pulses traveling down the fiber to interact through their mutual effect on the refractive index of the fiber.
- XPM causes pulses to become distorted as they interact.
- Fiber dispersion has little effect on XPM.
- Fiber designs with larger effective areas have a higher XPM threshold.

Intermodulation (Mixing)

- Intermodulation is similar to XPM except that it causes new frequency components to appear that are cross products of the original frequencies.