

NONLINEAR EFFECTS AND ITS IMPACT ON MULTICHANNEL SYSTEMS

Mrs. Gurjit Kaur

Department of Electronics & Communication Engg, U.I.E.T.,
Panjab University, Chandigarh (India)

Arvind Kumar Sharda

M.E. (Student), Department of Electronics & Communication Engg, U.I.E.T.,
Panjab University, Chandigarh
arvshi007@rediffmail.com

Abstract – The basic aim of this paper is to provide an insight about various nonlinear effects that have to be taken into consideration while deploying high-bit-rate multiwavelength systems such as the WDM (Wavelength Division Multiplexing) systems.

Index Terms: Wavelength Division Multiplexing, Raman Scattering, Brillouin Scattering, Self Phase Modulation, Cross Phase Modulation, Four Wave Mixing, All Optical Wavelength Conversion.

I. INTRODUCTION

In optical communication systems the term nonlinearity refers to the dependence of the system on power of the optical beam/s being launched into the fiber cable. Nonlinear effects in optical fibers have become an area of academic research and of great importance in the optical fiber based systems. Several experiments in the past have shown that the deployment of high-bit-rate multiwavelength systems together with optical amplifiers creates major nonlinear effects such as SRS, SBS, SPM, XPM and FWM.

The system design engineers should not deploy high-bit-rate (>10Gbit/s per channel) multiwavelength systems without considering the nonlinear effects and their impact on these systems. We will also see various advantages and disadvantages of the above mentioned nonlinear effects in order to decide whether they affect the performance of these systems in a positive way or a negative way [1].

Nonlinearities in optical fibers originate due to the third order susceptibility (X^3). The real part of the equation gives us SPM, XPM and FWM while the imaginary part of the equation gives us SBS and SRS. The nonlinear effects depend on the transmission length of the optical fiber. The longer the optical fiber, the more the light interacts with the fiber material and the greater the nonlinear effects. On the other hand, if the power decreases while the light travels along the optical fiber, the effects of nonlinearity diminish.

II. WDM SYSTEMS

In fiber-optic communications, WDM is a technology which multiplexes multiple optical carrier signals on a single

optical fiber by using different wavelengths (colours) of laser light to carry different signals. This allows for a multiplication in capacity, in addition to enabling bidirectional communications over one strand of fiber.

The term wavelength-division *multiplexing* is commonly applied to an optical carrier (described by its wavelength), whereas frequency-division multiplexing typically applies to a radio carrier (described by frequency). However, since wavelength and frequency are inversely proportional, and since radio and light are both forms of electromagnetic radiation, the two terms are equivalent.

Most WDM systems operate on single mode fiber optical cables, which have a core diameter of 9 μm . Certain forms of WDM can also be used in multi-mode fiber cables (also known as premises cables) which have core diameters of 50 or 62.5 μm .

WDM systems are divided in different wavelength patterns, *conventional* or *coarse* and *dense* WDM. Conventional WDM systems provide up to 16 channels in the 3rd transmission window (C-band) of silica fibers around 1550 nm. DWDM uses the same transmission window but with denser channel spacing. Channel plans vary, but a typical system would use 40 channels at 100 GHz spacing or 80 channels with 50 GHz spacing. Some technologies are capable of 25 GHz spacing (sometimes called ultra dense WDM). New amplification options (Raman amplification) enable the extension of the usable wavelengths to the L-band, more or less doubling these numbers.

A WDM system mainly consists of the following components: transmitter (consisting of laser source, data source, modulators), receivers (consisting of photodiodes and filters), optical combiners, optical splitters and optical fiber cable. A simple WDM system can be seen in Fig. 1.

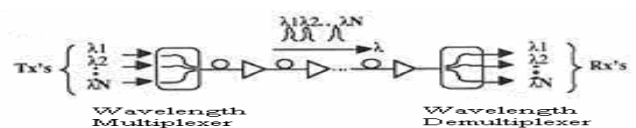


Fig. 1: Wavelength Division Multiplexing System

In a simple WDM system (Fig. 1), each laser must emit light at a different wavelength, with all the lasers_ light multiplexed together onto a single optical fiber. After being transmitted through a high bandwidth optical fiber, the combined optical signals must be demultiplexed at the receiving end by distributing the total optical power to each output port and then requiring that each receiver selectively recover only one wavelength by using a tunable optical filter. Each laser is modulated at a given speed, and the total aggregate capacity being transmitted along the high-bandwidth fiber is the sum total of the bit rates of the individual lasers. An example of the system capacity enhancement is the situation in which ten 2.5-Gbps signals can be transmitted on one fiber, producing a system capacity of 25 Gbps.

This wavelength-parallelism circumvents the problem of typical optoelectronic devices, which do not have bandwidths exceeding a few giga hertz unless they are exotic and expensive. The speed requirements for the individual optoelectronic components are, therefore, relaxed, even though a significant amount of total fiber bandwidth is still being utilized.

III. STIMULATED SCATTERING

When the optical power of the signal being transmitted through the fiber cable is increased then nonlinear scattering or stimulated scattering takes place. Stimulated scattering is transferring energy from the incident wave to another. In this case scattered wave at lower frequency (longer wavelength) with small energy difference is released in the form of phonons. Phonons are analogous to photons but only differ from it in terms of quantum properties. These scattered waves are also referred to as stokes waves. We can also say that stimulated scattering is another form of attenuation mechanism since the incident wave loses its energy during this process [1].

Stimulated scattering has three major components: Threshold power (P_{th}), gain (g), and the range of frequencies (Δf), within which scattering process is effective. (P_{th}) is the power of incident light at which the loss due to stimulated scattering is half over the fiber's length, L . The intensity of scattering light grows exponentially when the power of incident light exceeds (P_{th}). Gain (g), refers to the peak gain of the stimulated scattering at the given wavelength. Two major types of stimulated scattering are:

A. Stimulated Raman Scattering (SRS)

SRS scattered light moves mostly forward and the phonons associated with this process are optical in nature. Scattering of light takes place from vibrating silica molecules of the core of the fiber.

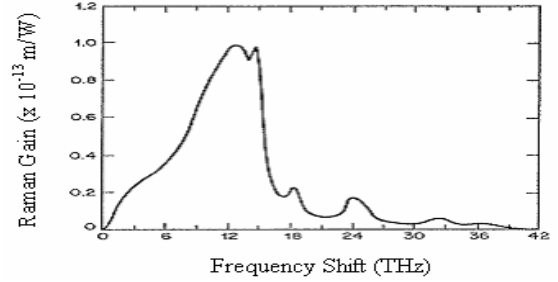


Fig. 2. Plot for Raman Gain Versus Frequency shift.

From Fig. 2 it is clear that Raman gain extends over 40 THz and is maximum around 13 THz. SRS is governed by two important equations:

$$\frac{dI_p}{dz} = -g_R I_s - \alpha_p I_p, \quad \frac{dI_s}{dz} = -g_R I_p - \alpha_s I_s \quad (1)$$

If we neglect pump depletion $I_s \ll I_p$, pump power decays exponentially, and the Stokes beam satisfies the following equation:

$$\frac{dI_s}{dz} = g_R I_0 e^{-\alpha_p z} I_s - \alpha_s I_s \quad (2)$$

The above equation has the solution as follows:

$$I_s(L) = I_s(0) \exp\left(g_R I_0 L_{eff} - \alpha_s L\right), \text{ where} \\ L_{eff} = \left[1 - \exp(-\alpha_p L)\right] / \alpha_p \quad (3)$$

SRS can also act as an amplifier if pump wavelength is chosen suitably. Even in the absence of source power stokes beam can buildup if the pump power is large enough. Spontaneous Raman scattering provides the foundation to this buildup. The buildup process is equivalent to injecting one photon per mode into the fiber [2], [4], [11].

Raman threshold is defined as the input pump power at which stokes power becomes equal to the pump power at the fiber output:

$$P_s(L) = P_p(L) \equiv P_0 \exp(-\alpha_p L) \quad (4)$$

- i. *Advantages of SRS:*
 - a. Raman amplifiers are a boon for WDM systems.
 - b. Can be used in the entire 1300–1650nm range.
 - c. Erbium-doped fiber amplifiers limited to ~40nm.
 - d. Distributed nature of amplification lowers noise.
 - e. Likely to open new transmission bands.
- ii. *Disadvantages of SRS:*
 - a. Raman gain introduces interchannel crosstalk in WDM systems.
 - b. Interchannel crosstalks can be reduced by lowering channel powers but it limits the number of channels.

B. Stimulated Brillouin Scattering (SBS):

SBS scattered light moves backward and the phonons associated with it are acoustic in nature. It becomes a stimulated process when the input power exceeds the threshold level. For long fibers threshold power is approximately 5 mW.

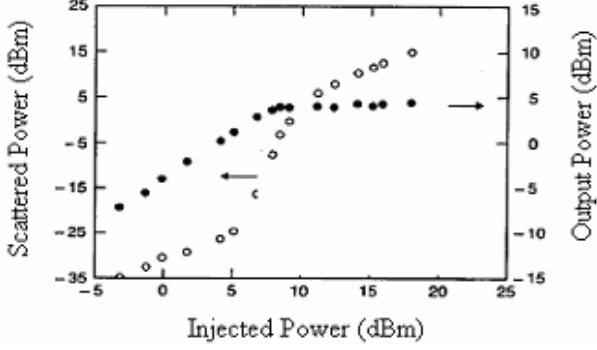


Fig. 3 Plot for scattered power versus injected power versus output power.

From the Fig. 3 it is clear that most of the power is reflected backward when the SBS threshold level is reached. Pump produces density variations through electrostriction, resulting in an index grating which generates Stokes wave through Bragg diffraction.

i. *Advantages of SBS:*

- a. SBS provides strong nonlinear optical interaction between light and acoustic waves.
- b. The temperature dependence of the Brillouin shift can be used for temperature and pressure sensing.
- c. Brillouin scattering can be used for optical phase conjugation.
- d. Brillouin gain can also be used for operating a Brillouin fiber laser.

ii. *Disadvantages of SBS:*

- a. Brillouin scattering is technically limited to the detection of quasiparticles with frequencies below about 500 GHz.
- b. SBS is a phenomenon to be avoided because it limits the amount of optical power that can be transmitted through a fiber. This is because SBS generates index gratings that reflect light in those portions of the optical signal spectrum that exceed a certain power threshold.

III. *Nonlinear Refractive Effects:*

An optical effect is called nonlinear if its parameters depend on light intensity (power). Higher order dispersion, strictly speaking does not fall into this category but the effects that we are going to consider next do fall under this category [1].

Nonlinearities stem from the dependence of the refractive index and attenuation on the intensity of light. Thus, one may talk about dispersion and attenuation nonlinearities but,

in nonlinear world, attenuation affects dispersion and vice-versa. Three major nonlinear effects due to refractive index variations are discussed below:

A. *Self Phase Modulation (SPM)*

SPM can be defined as nonlinear phase modulation of a beam caused by its own beam via the Kerr effect. While traveling in a medium, an ultra short pulse of light will produce a varying refractive index due to the Kerr effect. This variation in the refractive index of the medium induces phase shift in the pulse and hence producing change in the pulse's frequency spectrum [14].

The intensity of ultra short pulse with Gaussian shape and constant phase is given by the expression:

$$I(t) = I_0 \exp\left(-\frac{t^2}{\tau^2}\right) \quad (5)$$

The intensity at any point in the medium rises and falls producing a time varying refractive index:

$$\frac{dn(I)}{dt} = n_2 \frac{dI}{dt} = n_2 I_0 \frac{-2t}{\tau^2} \exp\left(-\frac{t^2}{\tau^2}\right) \quad (6)$$

The phase change per unit optical power is given the following proportionality constant:

$$\gamma_{SPM} = \frac{2\pi}{\lambda} n_2 L \left(\frac{\pi}{2} w_2\right)^{-1} = \frac{4n_2 L}{\lambda w^2} \quad (7)$$

i. *Advantages of SPM:*

- c. Modulation instability can be used to produce ultra short pulses at high repetition rates.
- d. SPM can be used for fast optical switching.
- e. It has been used for passive mode locking.
- f. Responsible for the formation of optical solitons.

ii. *Disadvantages of SPM:*

- g. SPM-induced spectral broadening can degrade performance of a lightwave system.
- h. Modulation instability often enhances system noise.

B. *Cross Phase Modulation (XPM):*

XPM can be defined as a process in which intensity of one beam traveling in a nonlinear medium (Kerr medium) effects the phase of another beam. Consider two optical fields propagating simultaneously. Nonlinear refractive index seen by one wave depends on the intensity of the other wave as:

$$\Delta n_{NL} = n_2 \left(|A_1|^2 + b|A_2|^2 \right) \quad (8)$$

Nonlinear phase shift is given by:

$$\varphi_{NL} = (2\pi L / \lambda) n_2 [I_1(t) + bI_2(t)] \quad (9)$$

An optical beam modifies not only its own phase but also of other co-propagating beams (XPM). XPM induces nonlinear

coupling among overlapping optical pulses. Fiber dispersion affects the XPM considerably. Pulses belonging to different WDM channels travel at different speeds. XPM occurs only when pulses overlap [4], [5].

XPM leads to interaction of pulses in the medium. This allows measurement of intensity of one beam by keeping a track of phase change of other beam. XPM can be used to synchronize two mode locked lasers using the same gain medium.

- i. *Advantages of XPM:*
 - i. Nonlinear Pulse Compression.
 - j. Passive mode locking
 - k. Ultra fast optical switching.
 - l. Demultiplexing of OTDM channels.
 - m. Wavelength conversion of WDM channels.
- ii. *Disadvantages of XPM:*
 - n. XPM leads to interchannel crosstalk in WDM systems.
 - o. It can produce amplitude and timing jitter.

C. Four Wave Mixing (FWM):

Assuming just two input frequency components ν_1 and ν_2 (with $\nu_2 > \nu_1$) which travel across the fiber optic cable, after interaction in a non linear medium, creates sidebands for each of the input waves. In effect, two new frequency components are generated: $\nu_3 = \nu_1 - (\nu_2 - \nu_1) = 2\nu_1 - \nu_2$ and $\nu_4 = \nu_2 + (\nu_2 - \nu_1) = 2\nu_2 - \nu_1$ as shown in Fig. 4.



Fig. 4: FWM components

In general, for N wavelengths launched into a fiber, the number of generated mixing products or sidebands (excluding the original wavelengths) is given as

$$M = \frac{(N^3 - N^2)}{2}$$

given by $\eta = \left[\frac{n_2}{A_{eff} D (\Delta \lambda)^2} \right]^{\frac{1}{2}}$, where n_2 is the core

refractive index, A_{eff} is the effective area, D is the dispersion, and $\Delta \lambda$ is the channel spacing.

FWM is a nonlinear effect arising from a third-order optical nonlinearity, as is described with a $\chi^{(3)}$ coefficient. It can occur if at least two different frequency components propagate together in a nonlinear medium such as e.g. an optical fiber.

Assuming just two input frequency components ω_1 and ω_2 (with $\omega_2 > \omega_1$), we obtain a refractive index modulation at the difference frequency, which again creates sidebands for each of the input waves in the figure below. In effect, two new frequency components are generated: $\omega_3 = \omega_1 - (\omega_2 - \omega_1) = 2\omega_1 - \omega_2$ and $\omega_4 = \omega_2 + (\omega_2 - \omega_1) = 2\omega_2 - \omega_1$ [10].

FWM is also present if only three components interact. In this case the term $f_0 = f_1 + f_1 - f_2$ couples three components thereby generating Degenerate four wave mixing.

In bulk media, phase matching may also be achieved by using appropriate angles between the beams. FWM in fibers is strongly related to self-phase modulation and cross-phase modulation: all these effects originate from the Kerr nonlinearity and differ only in terms of degeneracy of the involved waves. If one likes, one may even see self- or cross-phase modulation as a kind of degenerate four-wave mixing.

FWM can have important deleterious effects in optical fiber communications, particularly in the context of wavelength division multiplexing where it can cause cross-talk between different wavelength channels, and/or an imbalance of channel powers. One way to suppress this is avoiding equidistant channel spacing.

FWM can transfer data to a different wavelength. A continuous wave pump beam is launched into the fiber together with the signal channel. Its wavelength is chosen half-way from the desired shift. FWM transfers the data from signal to the idler beam at the new wavelength.

- i. *Advantages of FWM:*
 - p. Parametric amplification.
 - q. Optical phase conjugation.
 - r. Demultiplexing of OTDM channels.
 - s. Wavelength conversion of WDM channels.
 - t. Supercontinuum generation.
- ii. *Disadvantages of FWM:*
 - u. FWM leads to interchannel crosstalk in WDM systems.
 - v. It generates additional noise and degrades system performance.

IV. WAVELENGTH CONVERSION TECHNOLOGIES:

Wavelength converter is simply a device for converting the injected signal light from one wavelength to another. An ideal wavelength converter is a single input/output device that converts the wavelength of a channel appearing on its input port to a different value at its output port, but otherwise leaves the optical signal unchanged. Wavelength converters may be separated into two categories: those

based on optical-gated effects, and those that use wavelength mixing, referred to as "coherent converters".

Optically gated converters typically operate on a single input signal and are not transparent to bit rate and modulation format, whereas the wavelength mixing converters operate transparently on multiple signals within a broad band of wavelengths. Within this latter category, devices based on four-wave mixing and difference frequency generation (also referred to as "three-wave mixing") are known.

Wavelength conversion is a process by which the data on one wavelength can be transferred to another wavelength. There are three most important conversion technology types.

In case of OE-EO type configuration speed is limited by the electronic circuitry used. The speed of this configuration is approximately 10 GB/s.

In case of Gating type configuration used for XGM and XPM waveform obtained is chirped and inverted. While in case of nonlinear optical loop mirror (NOLM) configuration there is a need for synchronization of the signals. The speed for XGM and XPM configurations is approximately 40 GB/s while for NOLM it is in Tb/s.

In case of coherent type configuration for difference wavelength generation (DFG) phase matching is complex. While for configuration involving FWM phase matching is a lot easier. The speed in case of both configurations is in TB/s [13].

One of the reasons for this is the strong demand for wavelength division multiplexing (WDM) communication systems. If we could convert a signal to a desired wavelength in a transmission bandwidth, it can be used to perform add drop multiplexing (ADM) and an optical cross connect using the wavelength domain in WDM systems. This enables us to realize highly flexible and reconfigurable communication systems.

The wavelength conversion technologies can also be used to perform demultiplexing of very high-bit-rate time domain signals by converting each bit to different wavelengths. The most important characteristics desired of wavelength converters using parametric conversion are high conversion efficiency and broad bandwidth.

V. CONCLUSION:

Optical fibers exhibit a variety of nonlinear effects. Nonlinear effects are feared by telecom system designers because they can affect system performance adversely. Presence of these non linear effects in the optical fiber communication systems like WDM systems can adversely

effect the communication between two receiving ends. That is it can lead to transference of wrong or incorrect data to the receiving end due to interchannel mixing if the sideband wavelengths generated due to FWM coincide with the original wavelengths carrying data.

These nonlinear effects can be managed through proper system design. There are many ways by which these nonlinear effects can be reduced. However, nonlinear effects are also useful for many device and system applications: optical switching, soliton formation, wavelength conversion, broadband amplification, demultiplexing, etc. New kinds of fibers have been developed for enhancing nonlinear effects. We have seen how the various nonlinear effects originate and studied various advantages and disadvantages of these nonlinear effects.

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