Nonlinear Effects and its Impact on WDM Systems in Optical Fiber Communication

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Abstract – **Optical nonlinearities give rise to many ubiquitous effects in optical fibers. These effects are interesting in themselves and can be detrimental in optical communications. This paper provides a deep insight about various nonlinear effects that have been taken into consideration while implementing high-bit-rate multiwavelength systems such as the WDM (Wavelength Division Multiplexing) systems.**

Keywords- **Wavelength Division Multiplexing(WDM), Stimulated Raman Scattering(SRS),Stimulated Brillion Scattering(SBS), Self Phase Modulation(SPM), Cross Phase Modulation(XPM), Four Wave Mixing(FWM).**

I. INTRODUCTION

In optical communication systems the term nonlinearity refers to the dependence of the system on power of the optical beams being launched into the fiber cable. Nonlinear effects in optical fibers have become an area of academic research. Several experiments in the past have been shown that the deployment of high-bit-rate multiwavelength systems along with optical amplifiers creates major non linear effects such as SRS, SBS, SPM, XPM and FWM[1].

The system design engineers should not deploy high-bit-rate (>10Gbit/s per channel) multiwavelength systems such as WDM without considering the nonlinear effects and their impact on these systems. This paper will also show 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 [2].

Nonlinearities in optical fibers originate due to the third order susceptibility (χ^3). The real part of the equation gives us SPM, XPM and FWM .The nonlinear effects depend on the transmission length of the optical fiber. The longer the optical fiber, more light will interact with the fiber material and greater will be the nonlinear effects. On the other hand, if the power decreases while the light travels along with 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 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, whereas frequency-division multiplexing typically applies to a radio carrier. However, since wavelength and frequency are inversely proportional, and since radio and light are both forms of electromagnetic radiation, the two terms are equivalent.

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

In a simple WDM system (Fig. 1), each laser must emit light at a different wavelength, with all the laser's 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[4].

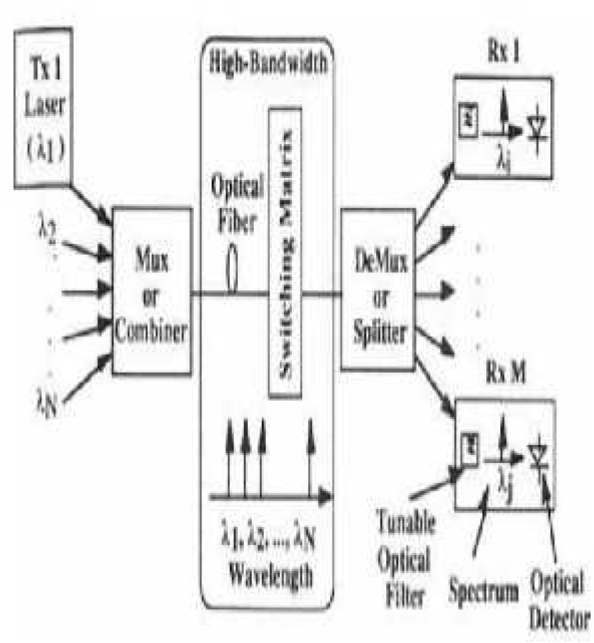

Fig 1: Simple WDM system[3]

(i) Advantages of WDM

- Huge bandwidth
- Enhanced flexibility
- Upgradability

III. STIMULATED SCATTERING

When the optical power of the signal transmitted through the fiber cable is increased then nonlinear scattering or scattering takes place. Stimulated scattering transfers energy from one 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 .

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)

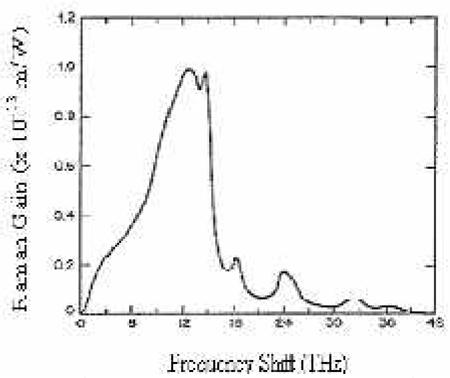

Fig. 2. Plot for Raman Gain Versus Frequency shift.

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:

$$\frac{dI_p}{dz} = -g_R I_P I_S - \alpha_P I_p$$

$$\frac{dI_p}{dz} = -g_R I_P I_S - \alpha_S I_S$$

(i). Advantages of SRS:

a. Raman amplifiers are a boon for WDM systems.

b. It 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.

A. 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.

(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 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.

IV. Origins of Nonlinearities

A number of nonlinearities arise in the optical fibers which are the causes of the various unwanted effects in the optical fiber.

(a) Nonlinear Phase Modulation

All materials behave nonlinearity at high intensities and their refractive index increases with intensity.To include nonlinear refraction we modify the core and cladding indices of a silica fiber as

$$n'_{j} = n_j + n_2(P/A_{eff})$$

where n_2 is nonlinear index coefficient ,P is optical power and A_{eff} is effective mode area.

(b) Optical Kerr Effect

The optical Kerr effect or AC Kerr effect is the case in which the electric field is due to the light itself. This causes a variation in index of refraction which is proportional to the local irradiance of the light. This refractive index variation is responsible for the nonlinear optical effects of self-focusing and self-phase modulation. This effect only becomes significant with very intense beams such as those from lasers. In fact, phase modulation due to intensity dependent refractive index induces various nonlinear effects ,namely ,self-phase modulation(SPM), cross-phase modulation (CPM), and four-wave mixing (FWM) [5].

(c)Self Phase Modulation (SPM)

Phase modulation of an optical signal by itself is known as self-phase modulation (SPM).SPM is primarily due to the self-modulation of the pulses. Generally, SPM occurs in single wavelength systems. At high bit rates however, SPM tends to cancel dispersion. However, consideration must be given to receiver saturation and to nonlinear effects such as SPM, which occurs with high signal levels. SPM results in phase shift and a nonlinear pulse spread. As the pulses spread, they tend to overlap and are no longer distinguishable by the receiver. The acceptable norm in system design to counter the SPM effect is to take into account a power penalty that can be assumed equal to the negative effect posed by XPM [4]. By the SPM-impact new spectral components are generated in the optical signal spectrum resulting in a spectral broadening.

(i). Advantages of SPM:

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

(ii). Disadvantages of SPM:

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

(d) Cross Phase Modulation (XPM)

Cross-phase modulation (XPM) is a nonlinear effect that limits system performance in wavelength Division Multiplexed (WDM) systems. XPM is the phase modulation of a signal caused by an adjacent signal within the same fiber. XPM is related to the combination (dispersion/effective area). XPM results from the different carrier frequencies of independent channels, including the associated phase shifts on one another. The induced phase shift is due to the walkover effect, whereby two pulses at different bit rates or with different group velocities walk across each other. As a result, the slower pulse sees the walkover and induces a phase shift. The total phase shift depends on the net power of all the channels and on the bit output of the channels. Maximum phase shift is produced when bits belonging to high powered adjacent channels walk across each other [6].

(i). Advantages of XPM:

   a. Nonlinear Pulse Compression.
   b. Passive mode locking
   c. Ultra fast optical switching.
   d. Demultiplexing of OTDM channels.
   e. Wavelength conversion of WDM channels.

(ii). Disadvantages of XPM:

   a. XPM leads to interchannel crosstalk in WDM systems.
   b. It can produce amplitude and timing jitter.

(e) Four Wave Mixing (FWM)

FWM can be compared to the inter modulation distortion in standard electrical systems. When three wavelengths (λ1, λ2, and λ3) interact in a nonlinear medium, they give rise to a fourth wavelength (λ4), which is formed by the scattering of the three incident photons, producing the fourth photon. This effect is known as four-wave mixing (FWM) and is a fiber-optic characteristic that affects WDM systems [7]. The effects of FWM are pronounced with decreased channel spacing of wavelengths and at high signal power levels. High chromatic dispersion also increases FWM effects. FWM also causes inter channel cross-talk effects for equally spaced WDM channels. The electric field of such signal can be written as

$$E= E_P\sum_{p=1}^{n} \cos(w_P t-k_p z) \qquad (8)$$

Then the nonlinear polarization is given by

$$P_{nl} =\varepsilon_0 \chi^{(3)} E^3$$

Figure 3 shows a simple example of mixing of two waves at frequency ω1 and ω2. When these waves mixed up, they generate sidebands at ω3 and ω4 such that (ω1+ ω2=ω3+ω4) . Similarly, three copropagating waves will create nine new optical sideband waves at frequencies given by Eq. (8).

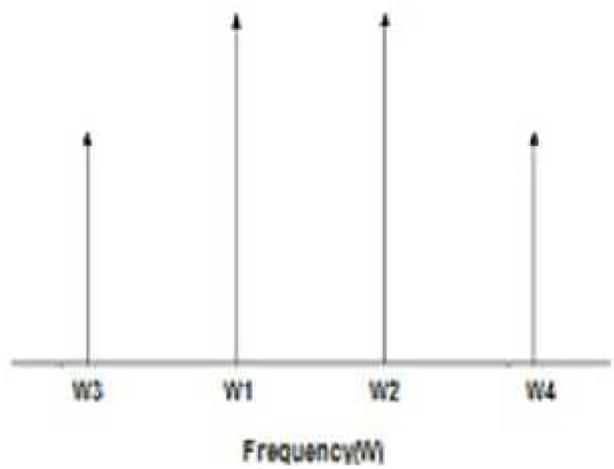

Fig.3. FWM of two wave ω1and ω2

These sidebands travel along with original waves and will grow at the expense of signal-strength depletion. In general for **N** wavelengths launched into fiber, the number of generated mixed products **M** is,

$$M =(N^2/2)(N-1)$$

(i). Advantages of FWM:
- a. Parametric amplification.
- b. Optical phase conjugation.
- c. Demultiplexing of OTDM channels.
- d. Wavelength conversion of WDM channels.
- e. Supercontinuum generation.

(ii). Disadvantages of FWM:
- a. FWM leads to interchannel crosstalk in WDM systems.
- b. It generates additional noise and degrades system performance.

V. CONCLUSION

Optical nonlinearities in fibers give rise to a wealth of new effects. This is primarily due to the fact that, because these nonlinearities operate in a distributed manner, the effects they produce vary widely with the chromatic dispersion and birefringence characteristics of the fiber and, by consequence, with the wavelength, chirp, and polarization of the propagating lightwaves. In addition, several nonlinearities may act simultaneously, as in the examples of self-phase modulation (SPM) and cross-phase modulation (XPM), XPM and four-wave mixing(FWM), or stimulated Raman scattering (SRS) and FWM resulting in an even greater variety of manifestations. Nonlinear effects can be detrimental for optical communications, especially in wavelength-division multiplexing (WDM) systems, where they can result in backscattering [stimulated Brillouin scattering (SBS)], noise (spontaneous Raman), pulse distortion (SPM, XPM, MI), and crosstalk between channels (XPM, FWM).

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