Non -Linearities of optical fiber affecting modern communication system: An Overview

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Abstract

In recent years, even after the installation of erbium doped fiber amplifier which has a higher bit rate transmission usually suited for transoceanic communication, but people's demand for higher data transmission capacity is unprecedented and growing continuously. The paper is presented in the form of overview addressing all the non-linear effects encountered in fiber, and what are the advantages and disadvantages it will have on the optical telecommunication. Topics covered are the types of non-linear effect occur under non-linear scattering and changes in refractive index whenever the beam interacts with various components inside the optical fiber.

Keywords: Optical fiber, kerr effect, four wave mixing (FWM), self-phase modulation (SPM), cross phase modulation (CPM)

INTRODUCTION:

Fiber nonlinearities are important in optical communications, both as useful attributes and as characteristics to be avoided. They must be considered when designing long-range high-data-rate systems that involve high optical power levels and in which signals at multiple wavelengths are transmitted

non-linear effects in optical fiber impose different limitations on the communication link and the knowledge of such effects is a prerequisite for lightwave system designers. It is a system design objective to achieve the improved bit error rate at the o/p of any communication system.

[o/p power = i/p power –system losses]……….(1)

From the above relation, it seems that if input power increases, then the resulting output power will be enhanced. This contradiction is valid as long as the graph between the input power and output power is linear and system losses are constant. But the practical system behavior is far away from an ideal one. As input power crosses a threshold value the system losses do not remain at a constant and vary with input given, and the relation between input and output power remains no longer linear.

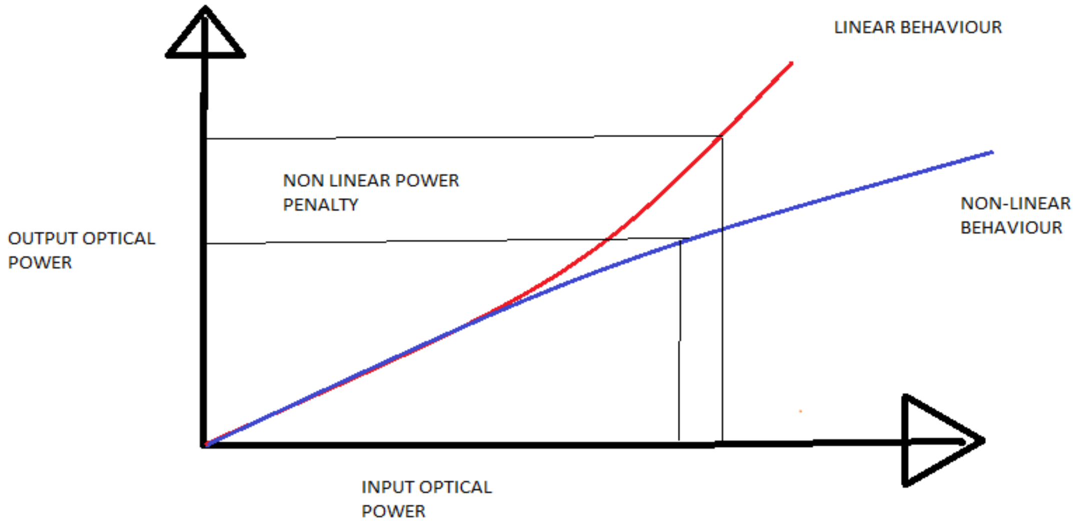

Fig.1 graph showing the linear and non-linear behavior of optical power at output

Because the waveguide channels cannot always behave as a linear channel several non-linear effects cause scattering while the light transmits through the fiber. The non-linear scattering is basically due to the transfer of the optical power from lower frequency mode to higher frequency mode. The non-linear effect is classified as

1.) **INELASTIC SCATTERING:**
a.) STIMULATED RAMAN SCATTERING(SRS)
b.) STIMULATED BRILLOUIN SCATTERING (SBS)

2.) **OPTICAL KERR EFFECT:**
a.)SELF PHASE MODULATION(SPM)
b.)CROSS PHASE MODULATION (CPM)
c.)FOUR WAVE MIXING(FWM)

These effects occur due to the interaction of propagating light with fiber, these are weak generally at low powers but can become stronger once threshold values are reached or power is increased.

These non-linear effects also tend to depend on the transmission length of the fiber, longer the length of fiber the more the interaction between the light ray and fiber hence the non; linear effect becomes stronger.

The non-linear refractive index is also called a Kerr effect, Kerr nonlinearity manifests itself into 3 effects such as SPM, CPM, FWM.

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SBS and SRS are nothing but inelastic scattering phenomenon generally occur at higher power levels.

Non-linear effects like FWM, SBS, and SRS provide gains to some channels at the cost of draining power from the other channels. Due to this crosstalks among certain WDM channels create a disturbance while communicating. These non- linear effects contribute to signal impairment to compensate for this additional amount of power is needed at the receiver side to maintain the BER ratio as before. This additional amount of power is called as "power penalty".

BACKGROUND:

How fiber parameters contribute to non-linearity:

Effective Length (Leff):

The nonlinear interactions in optical fibers depend on the effective transmission length and the effective cross-section area of the fiber. The longer the link length of the cable, the more interaction of signal with fiber components increases, and the signal gets attenuated. The power reduces over the axis of the cable exponentially, and this will become more prominent at the transmitter end because of the high power level. It can be said that the time the signal spends inside the fiber span can be its crucial period to decide whether the signal will be diminished or remain intact.

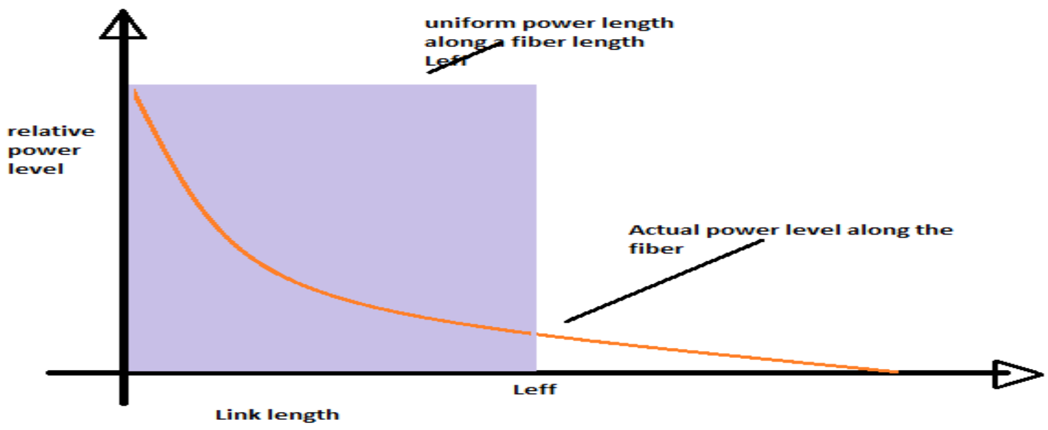

Fig.2 showing the effective length for optimum power to be transferred

The effective length of 20km is required for power attenuation of 0.22db/km at 1550 nm.

Effective cross-section area(Aeff):

Non-linear effects increase with the light intensity, for a given optical power, the intensity is inversely proportional to the area of the fiber core cross-section. Since the power is not distributed uniformly in the cross-sectional area of the fiber.

One can make use of Aeff effective cross-sectional area which predicts uniform intensity distribution across most of the core.

The effective area of standard single-mode fiber (SMF) is around 85 µm2 and that of Dispersion-Shifted Fiber is around 50 µm2.

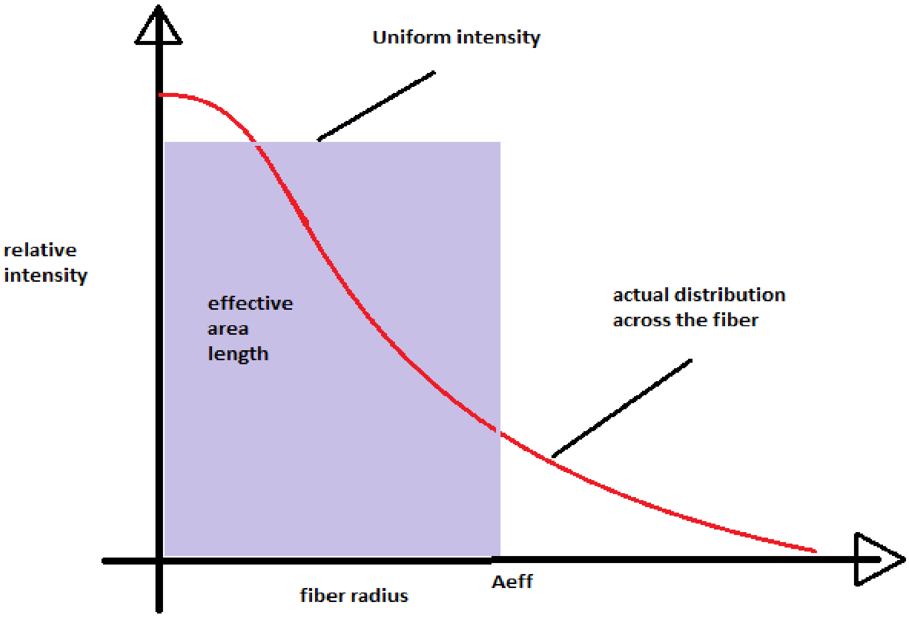

Fig. 3 The above diagram can be stated as a common graph for both the effective length and effective area.

DESCRIPTION OF NON-LINEARITIES:

Optical Kerr effect: variation of refractive index with optical intensity

(SPM) (CPM) (FWM)

1.) Self-phase modulation:

When an optical pulse is injected into the fiber the higher refractive index will be encountered by higher intensity portions of the pulse in comparison to lower intensity portion.

Time-varying signal intensity will produce a time-varying refractive index in a medium, this varying refractive index results in varying phase change, phase of the optical signal changes with varying time, since this non-linear phenomenon is self- induced and that's why it is called self-phase modulation. (FERRIERA, 2008) (Nonlinear Effects in Optical Fibers Part 1)

The primary effect of the SPM is that when additional frequency components get added to the trailing or leading edge of the pulse contributes to the increase in spectral width. The effects of SPM are more pronounced in the system with high transmitted power, because the chirping effect is proportional to transmitted signal power.

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Management:

The change in the phase induces an additional chirp of the pulse leading to the dispersion penalty. This penalty would be small if the input power is less than the threshold value. Also to cut down on the amount of chirping a suitable input pulse shape should be applied at the input to reduce the chirp and the SPM induced broadening.

Advantages:

Solitons: they refer to some optical field that does not change during their propagation through fiber they will propagate undistorted with the mutual compensation of dispersion and SPM. Such a pulse's spectral width will be increased nor in frequency domain neither in the time domain. Since it doesn't get broaden during its propagation this has got tremendous applications in high bandwidth optical communications. (E.-H. Lee, 2002)

FOUR WAVE MIXING:

Four-wave mixing or four-photon mixing describes a non-linear optical effect at which four waves or four photons will interact with each other.

The phenomenon originates from a third-order non-linear effect, caused by the dependence of refractive index on the intensity of the optical power. The effects of FWM generates one or more new channels (or harmonics) when three waves are traversing in optical fiber at frequencies f1,f2, and f3 these frequencies generate another signal such that,

[f123 = f1+-f2+-f3]…….2)

Forex. Two input signals at ω1 and ω2 are injected in optical fiber after traversing optical fiber length L the output at the receiver end is four signals located at ω1, ω2, 2ω1-ω2 and 2ω2-ω1.(mixing of two waves). (Muriel, 2015)

Whenever the new frequencies are generated in optical fiber this causes cross-talks and power depletion of signal if they are at the same wavelength as incident channels. (Singh, 2007)

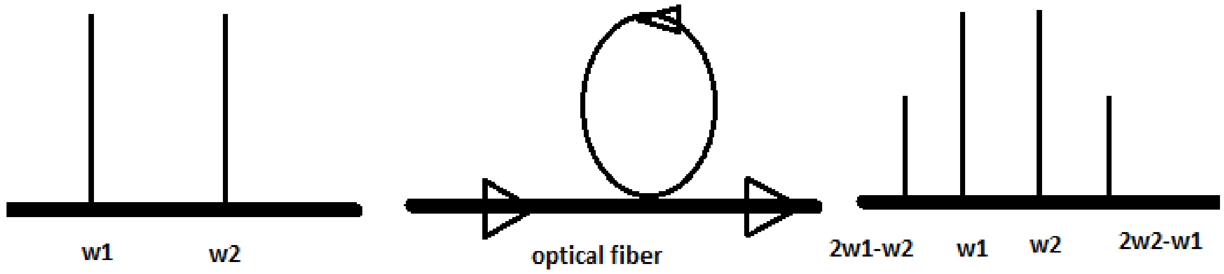

Fig.4 showing how additional frequencies are generated within the fiber

Management:

Four-wave mixing of signals results in power drained at one channel which in turn degrades the system performance. To achieve the original BER at the transmitter end some additional power is used which is called a power penalty. Since FWM is itself interchannel cross talk. This interference again will damage the system's performance. To reduce this interchannel spacing must be increased which increases the group velocity mismatching and in turn, reduces the power penalty. (optics1)

Advantages:

1.) FWM processes are very effective in reducing the quantum noise by a phenomenon called Squeezing. The process generates some special states in an electromagnetic field under which noise fluctuations and chirping are lowered than the quantum noise level in some frequency ranges. (Agrawal, 2006)

2.)Wavelength conversion:

Wavelength conversion is an important tool in optical network. Sometimes the wavelength of the incoming signal may already be in use with another information channel in that case we convert the incoming signal to a new wavelength which will give access to both information channels to traverse simultaneously in one optical fiber. (Davis)

3.) Cross phase modulation:

Until the SPM was the major non- linear drawback imposed on a single channel system. CPM originates when two or more optical pulses are propagating simultaneously and causes spectral broadening (WHAT IS EFFECTIVE LENGTH AND EFFECTIVE AREA ? (CONCEPTS FOR UNDERSTANDING NONLINEAR EFFECT IN OPTICAL FIBERS), 2011)

This type of modulation is always occupied by SPM and occurs when non-linear refractive index changes concerning the high and low-intensity optical beams copropagating in the fiber.

CPM is a fundamental effect as it determines the capacity of the optical transmission system.

Management:

The phase shifts induced by the CPM can occur only when the two pulses overlap in time. Due to this modal noise and frequency chirping gets enhanced. Hence we see the pulse broadening which affects the optical communication system to a greater extent. This can be controlled by increasing the spacing between individual WDM channels. (Slideshare, 2015)

These types of effects depend on the long interaction length of the fiber. To make these effects less pronounce we must keep the interaction length small.

Applications:

1. Phase shift-induced phenomenon by cross-phase modulation is effective in optical switching.

2. CPM induced frequency chirps are helpful in pulse compression. With the use of CPM, we can compress even weak input pulse s by using the co-propagating intense pump pulses.

NON-LINEAR SCATTERING:

2 phenomenon are caused due to non-linear scattering and are related to excited and vibrational modes of silica. These are called SBS and SRS the only fundamental difference is that the optical phonons are generated in SRS and acoustic phonons are generated in SBS .that;s why SBS can occur only in one direction which is backward while SRS can occur in both directions. (sp Singh, 2007)

1.) stimulated Brillouin scattering (SBS):

Interaction between the optical wave and the propagation density fluctuations in fiber causes Brillouin scattering. These are called SBS and SRS the only fundamental difference is that the optical phonons are generated in SRS and acoustic phonons are generated in SBS.

Under this case, a high-frequency acoustic phonon is generated which travels at a speed of sound. Due to the thermal molecular vibrations within the fiber, there is a modulation of light in stimulated Brillouin scattering.

The scattered light which is separated from the incident light by the modulation frequency appears as a lower and upper sideband. A common method to suppress SBS is to make sure that the injected light has a large optical wavelength.

APPLICATION:

Normally SBS is a drawback to optical communication but with some definite arrangements, they can be manipulated to use optical devices. (A.D ELLIS, 2017)

Fiber sensors are used to sense the temperature and strain changes over longer distances, Brillouin fiber amplifiers are employed to strengthen the optical signal and the beam combiner also exploits the property of SBS to combine one and more optical beams.

2.) stimulated Raman scattering (SRS):

Under this case a high-frequency optical photon is generated, the process is initiated by thermally induced fluctuations in the optical field.

An incident optical pump field interacts with the thermal fluctuations losing a photon that is downshifted in vibrational frequency to produce a stoke wave and optical phonon.

The channels with a higher carrier frequency deliver a part of their power The channels with a higher carrier frequency deliver a part of their power to the channels with a lower carrier frequency.

In terms of wavelength, the channel with a higher wavelength is amplified at the expense of the channel with the lower carrier wavelength

Raman gain introduces crosstalks between different WDM channels. This can be reduced by lowering the power per channel which reduces the no. of a channel used.

CONCLUSION:

After discussing various types of non-linear effects in an optical fiber, we concluded that though the non-linear characteristics must be avoided but they must be definitely considered while designing long-range high data rate systems that involve high optical power to be transmitted. And also these non-linear effects can play an important role by manifesting themselves into a fiber laser, amplifier, switches, logic devices, demultiplexers.

These optoelectronic devices are mainly used to enhance the optical signal strength of attenuated signals. But on the other hand, they can have their degenerative effect on limiting the performance of optical fiber communication. One should carefully examine the trade-off between the advantages and disadvantages of the non-linear effect to utilize their maximum effort.

Reference:

1. **WHAT** IS EFFECTIVE LENGTH AND EFFECTIVE AREA? (CONCEPTS FOR UNDERSTANDING NONLINEAR EFFECT IN OPTICAL FIBERS). (2011, 12 12). Retrieved 09 22, 2020, from FOSCO.: https://www.fiberoptics4sale.com/blogs/archive-posts/95044934-what-is-effective-length-and-effective-area-concepts-for-understanding-nonlinear-effect-in-optical-fibers#:~:text=The%20nonlinear%20interactions%20in%20optical,decreases%20because%20of%20fiber%
2. SlideShare. (2015, sept 08). Retrieved 09 22, 2020, from https://www.slideshare.net/eksingh1/optical-fiber-52519883
3. A.D ELLIS, M. M. (2017). PERFORMANCE LIMITS IN OPTICAL COMMUNICATIONS DUE TO FIBER NON LINEARITY. ADVANCES IN OPTICS AND PHOTONICS.
4. Agrawal, G. P. (2006). Retrieved 09 22, 2020, from Nonlinear Effects in Optical Fibers: http://www.ifsc.usp.br/~dispoptic/Aulas2013/Agrawal-internet/Photonics%20West%20Tutorial%20-SPIE.pdf
5. Davis, C. C. (n.d.). FIBER OPTIC TECHNOLOGY AND ITS ROLE IN THE INFORMATION REVOLUTION. Retrieved 09 22, 2020, from https://user.eng.umd.edu/~davis/optfib.html
6. E.-H. Lee, K. K. (2002). Nonlinear effects in optical fiber: Advantages and disadvantages for high capacity all-optical communication application. optical and quantum electronics.
7. FERRIERA, M. F. (2008). NONLINEAR EFFECTS IN OPTICAL FIBERS: LIMITATIONS AND POSSIBILITIES. non-linear optical physics and materials, 35.

8. Muriel, M. A. (2015). Nonlinear effects in optical fibers. UPM-ETSIT-MUIT-CFOP.
9. Nonlinear Effects in Optical Fibers Part 1. (n.d.). Retrieved 09 22, 2020, from http://what-when-how.com/fiber-optics/nonlinear-effects-in-optical-fibers-part-1/
10. optics1, p. f. (n.d.). Rp photonics encyclopedia. Retrieved September 22, 2020, from https://www.rp-photonics.com/passive_fiber_optics11.html:https://www.rp-photonics.com/passive_fiber_optics11.html
11. Singh, S. P. (2007). NONLINEAR EFFECTS IN OPTICAL FIBERS: ORIGIN. PIER, 73.
12. sp Singh, n. s. (2007). soliton based on optical communication. pier, 74.