Characterization Non-Deterministic of Optical Channels

V. A. C. Vale, E. T. L. Cöuras Ford

Abstract—The use of optical technologies in the telecommunications has been increasing due to its ability to transmit large amounts of data over long distances. However, as in all systems of data transmission, optical communication channels suffer from undesirable and non-deterministic effects, being essential to know the same. Thus, this research allows the assessment of these effects, as well as their characterization and beneficial uses of these effects.

Keywords—Optical communication, optical fiber, non-deterministic effects.

I. Introduction

AN optical channel is defined by a wavelength, this can be dedicated or shared, based on the number of users per wavelength.

In multipoint communication networks, there is the need of using multiplexing techniques to transmit data, such as Time Division (TDM) or Wavelength Division (WDM), as well as variations thereof, Adaptive Time Division Multiplexer (ATDM), Statistical Time Division Multiplexer (STDM), Coarse Wavelength Division Multiplexer (CWDM), Dense Wavelength Division Multiplexer (DWDM), Ultra Dense Wavelength Division Multiplexing (UDWDM), Wide Wavelength Division Multiplexing (WWDM), Wave Division Multiple Access (WDMA).

The WDM is a variant of FDM (frequency division multiplexing) for optical fibers, this occurs because it's used the term "wavelength" in optics, rather "frequency", in which each Wavelength refers to a color.

It is common to compare the TDM and WDM systems, with the purpose of finding the best solution. TDM systems tend to have a relatively lower cost, while WDM systems have a greater capacity regarding to number of users to a higher cost. A current solution is to use HDM (TDM/WDM) hybrid architectures that can achieve similar results with relatively lower costs, as suggested in [1] and [2]. Thus, the optical communication allows through a single fiber to simultaneous transmission of multiple channels, each with its own wavelength, however, like any transmission system, optical systems suffer from limitations, such as attenuation, dispersion

V. A. C. Vale is Ph.D Student in Electrical Engineering; M.Sc. in Mechanical Engineering; Engineer of Safety; Electrical Engineer. Universidade Federal do Pernambuco – UFPE / PPGEE, Recife – PE, Brazil. (e-mail: ale.vale.ssandra@gmail.com).

E. T. L. Cöuras Ford is Ph.D in Mechanical Engineering; M.Sc. in Administration; M.Sc. in Mechanical Engineering; Engineer of Safety; Mechanical Engineer; Automotive Engineer. Universidade Federal do Rio Grande do Norte – UFRN / PPGCEM, Av. Senador Salgado Filho, S/N, 59072-970, Natal - RN, Brazil. (e-mail: elmocouras@hotmail.com).

and noise effects not linear in their channels.

II. Nonlinear Effects

There are two categories of nonlinear effects in optical communication systems, the first is due to the interaction of light waves with phonons (quantum molecular vibrations), and the other is due to the dependence of the refractive index with the intensity of the applied electric field [3].

Two main non-linear effects related to the interaction of light with phonons (quantum molecular vibrations) are: Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS). For non-linear effects related to the refractive index, the main examples are: Self-Phase Modulation (SPM) and Four Wave Mixing (FWM).

III. Nonlinear Refractive Index

Similarly any dielectric, optical fibers have a nonlinear response to intense electromagnetic fields. This behavior is due to the no harmonic motion of electrons of the links of the material under the influence of an applied electric field. As result, the polarization of electric dipoles (P_d) induced by electric field (E) is not linear, satisfying the relation given below, where ε_o is the vacuum permittivity and $\chi^{(j)}$ is the j-th order of the electrical susceptibility [4].

$$P_d = \varepsilon_0 \cdot \left[\chi^{(1)} \cdot E^1 + \chi^{(2)} \cdot E^2 + \chi^{(3)} \cdot E^3 + ... \right] \qquad (1)$$

Due to the silica symmetry, terms pairs of the power series expansion of Pd are zero. Moreover, the terms of order higher than three are not significant. Therefore, only the term of grade first and the term of grade third are retained in the expansion. Knowing that the term of grade first corresponds to linear dependence, the susceptibility corresponds to term of order third, that induces non-linear effects in optical fiber [5], thus (1) results in (2):

$$P_d = \varepsilon_0 \cdot \left[\chi^{(1)} \cdot E^1 + \chi^{(3)} \cdot E^3 \right] = \varepsilon_0 \cdot \chi^{(1)} \cdot E^1 \left[1 + \chi^{(2)} \cdot E^2 \right] \qquad (2)$$

The third-order susceptibility is responsible for phenomena such as third harmonic generation, four-wave mixing and nonlinear refraction index. However, the effects involving the generation of new frequencies in the fibers are of low efficiency due to the difficulty in obtaining the phase weddings (FWM effect). Thus, the dependence of the refractive index with the intensity of the optical signal that propagates in the fiber the non-linear effect (SPM and XPM) with the highest probability. So, the refractive index of the

propagation medium is defined by (3), where I is the intensity of the light propagating in the fiber, n_0 is the linear part of the refractive index, and n_2 is the nonlinear part known as coefficient Kerr, because Kerr was who first studied this effect. Note that, n_2 for the silica fibers is approximately $2,6\times10^{-20}$ m^2/W, varying slightly if the core is doped, however, this small change considerably affects modern optical systems, in particular, leads to the phenomenon of phase self-modulation and cross-modulation [6] and [7].

$$n(t) = n_0 + n_2 \cdot I(t) = n_0 + n_2 \cdot |E|^2 \qquad (3)$$

As the light intensity can be determined by the power (P) divided by the effective area of the fiber core (A_{eff}), (4) is obtained:

$$n(t) = n_0 + n_2 \cdot \frac{P}{A_{eff}} \qquad (4)$$

The effective area refers to the area of the fiber where optical power is effectively transmitted. In single-mode fibers, this area is proportional to the diameter of the modal field, which is typically higher than the physical diameter of the optical core. Increasing the effective area increases the optical power that the fiber can carry without the effects of nonlinearities, because lower will be the power density guided. However, increasing the effective area produces an increase in chromatic dispersion and greater sensitivity to the effects of curvature of the fiber.

Equation (5) can be given in terms of propagation constant (β), being the equation multiplied by $2\pi/\lambda$, wherein λ is the wavelength and γ is the normalized nonlinear constant, which is an important parameter nonlinear with values around of 1 to 5W^{-1}/km, depending on the values of the effective area and the wavelength.

$$n\frac{2\pi}{\lambda} = n_0 \frac{2\pi}{\lambda} + n_2 \frac{2\pi}{\lambda} \cdot \frac{P}{A_{eff}} \quad \rightarrow \quad \beta' = \beta + \gamma P \qquad (5)$$

IV. Chirp Effect

The variation of carrier frequency during transmission is called chirp or chirp effect, which may be adiabatic type (depends of the absolute amplitude of the signal) and dynamic or transient type (depends of the variation of the power).

According to [8], the relationship between the frequency deviation of the carrier and the signal power is given by (6), where $\Delta f(t)$ is the variation of the frequency, P is the power, α is the chirp parameter, K_1 and K_2 are parameters of adiabatic chirp.

$$\Delta f(t) = \frac{\alpha}{4\pi} \cdot \left[\frac{1}{P(t)} \cdot \frac{\partial P(t)}{\partial t} + K_1 P(t) - \frac{K_2}{P(t)} \right] \qquad (6)$$

When the chirp effect in a channel is due to change of the intensity of a power in a transmission channel, resulting in only the effect of the dynamic chirp, the (6) can be reduced to

(9), where ω is radian frequency and ϕ is the carrier phase.

$$\Delta\omega = 2\pi\Delta f = \frac{\partial\phi}{\partial t} \qquad (7)$$

$$\Delta f(t) = \frac{\alpha}{4\pi} \cdot \frac{1}{P(t)} \cdot \frac{\partial P(t)}{\partial t} \qquad (8)$$

$$\alpha = \frac{\Delta\omega(t)}{\frac{1}{2P(t)}\frac{\partial P(t)}{\partial t}} = \frac{\frac{\partial\phi}{\partial t}}{\frac{1}{2P(t)}\frac{\partial P(t)}{\partial t}} \qquad (9)$$

V. SPM AND XPM

The dependence of the refractive index with the light intensity into intense fields leads to two nonlinear effects, which are SPM and XPM.

The SPM effect is the chirp effect on a channel due to the variation of the refractive index by the intensity of power into a transmission channel [3].

As expressed in Snell's law, the phase of a wave is related to the refractive index of the propagation medium, (10). Therefore, the phase variations are obtained with a variable refractive index depending on the intensity with which the light propagates. This effect of self-induced phase change by an optical signal during its propagation through a fiber is known as SPM, which results in the generation of new frequencies.

$$sen\theta_{core} = \frac{n_{cover}}{n_{core}} sen\theta_{cover} \qquad (10)$$

Another way to understand the phase change is through the propagation speed of light, how this is related with the refractive index by (11), where c is the speed of light in vacuum, and v is the velocity of propagation of light, it's possible to notice that the last alters.

$$n = \frac{c}{v} \qquad (11)$$

This change in propagation speed results in a shift in carrier phase with respect to the phase of the original pulse, as well as generating a change in frequency over time, (12), which will contribute to widen the spectrum of the optical signal, that interacting with the fiber dispersion results in additional signal distortion.

$$\omega = \omega_0 + \Delta\omega \qquad (12)$$

For the XPM, the same effect is observed, caused not only by its pulse, but by neighboring pulses. Thus, the change of the refractive index not only depends on the intensity of a light beam (such as SPM), but also of the others intensities of the light beams that propagate in the fiber simultaneously. Equation (2) is added the influence of the others fields of lights beams, resulting in (13), where q is the amount of light beams propagating at high outputs.

$$P_d = \varepsilon_0 \cdot \left[\chi^{(1)} \cdot E^1 + \chi^{(3)} \cdot \left(E_1 + E_2 + ... + E_q \right)^3 \right] \qquad (13)$$

Assuming a fiber along the z-axis, permits to note that the optical phase (ϕ) increases with z, for a fiber length L, however, this increase is non-linear (NL) due to γ term from (5). This relationship is represented in the following equations, where L_{eff} is the effective length of interaction.

SPM:
$$\phi_{NL} = \int_0^L (\beta' - \beta) dz = \int_0^L \gamma P(z) dz = \int_0^L \gamma P_o e^{-\alpha z} dz = \gamma P_o \left(\frac{1 - e^{-\alpha L}}{\alpha} \right)$$

$$\phi_{NL} = \gamma P_o \cdot L_{eff} \qquad (14)$$

XPM:
$$\phi_{NL}^r = \gamma \left(P_r + 2 \cdot \sum_{s \neq r} P_s \right) \cdot L_{eff} \qquad (15)$$

Equation (15) took into account the influence of other signals, however with a multiplicative factor of "2", because the XPM is twice as effective as SPM for the same amount of energy [9].

The cross phase modulation occurs only during the walk-off length. This length shows the duration of interact of a pulse with other due to speed difference of the pulses. That is, the length of the optical fiber that a pulse with higher speed achieves another pulse with lower speed, Fig. 1, there being an interaction between these optical pulses.
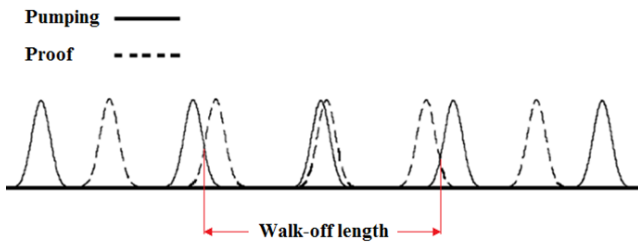

Fig. 1 Length of interaction between pulses

The walk-off length (L_w) is given by (16), where T_0 is the period of the pulse test, and v_{gi} is the speed of the energy with "i" mode traveling in the fiber.

$$L_W = \frac{T_0}{\left| v_{g1}^{-1} - v_{g2}^{-1} \right|} = \frac{T_0}{\left| d_{12} \right|} \qquad (16)$$

As v = λ.f, the XPM effect decreases with increasing difference between the wavelengths of the test pulse (probe) and of the pumping pulse (pump), because this increase causes a decrease into L_W.

A. Schrödinger equation

Until the early 20s, there was a great belief that the universe was strictly deterministic, and that, therefore, one could always to know the precise position of a body. For quantum mechanics, however, the universe is inherently non-deterministic.

In the mid-20s appeared important contributions of Max

Born, Paul Dirac, Werner Heisenberg, Wolfgang Pauli and Erwin Schrödinger. These resulted in a new vision of the quantum mechanics.

One of the most important theories of quantum mechanics in principle was the explanation of wave-particle duality in subatomic levels, that is, what was called subatomic particles had properties of waves, and what was considered wave had corpuscular property. Thus, for the analysis of nonlinear effects in optical fibers is necessary to consider the quantum theory of light propagation in nonlinear and dispersive medium, considering the electrical polarization induced in a medium with its linear and non-linear parts, beyond the dielectric constant that depends of the frequency.

The Schrödinger equation, proposed by Erwin Schrödinger (Austrian physicist) in 1925, describes the time evolution of a quantum state in a physical system. This equation has great importance in the theory of quantum mechanics, and its role is similar to Newton's second law in classical mechanics.

Starting from Maxwell's equations, it is possible to arrive at the Nonlinear Schrödinger Equation (NLSE), (17), which describes the propagation of optical pulse in a single mode fiber [8]. Where "A" is the normalized electric field as a function of time, "α" is the attenuation, "β_2" is associated with the group velocity dispersion (GVD), "z" is associated with the position of propagation, "t" is the time of propagation, "γ" is the normalized nonlinear constant and j is defined $j^2 = -1$

$$j \frac{\partial}{\partial z} A = -\frac{j}{2} \alpha A - \frac{\beta_2}{2} \frac{\partial^2}{\partial t^2} A + \gamma |A|^2 A \qquad (17)$$

Note that the terms relating to the Raman gain and the chromatic dispersions of high orders were disregarded, being this equation used with good accuracy for pulses of duration greater than 1ps. Obtaining this equation start of the Maxwell equations for electromagnetic wave, which considers the boundary conditions mentioned above, its development can be seen in [10], with the idea of slow variation of the wave phase. The XPM effect can be included in this equation making the following changes: A = A_s e $|A|^2 = |A_s|^2 + 2|A_r|^2$, where the XPM effect is added in term $2|A_r|^2$.

B. SPM Effect in a Sequence of Pulses NRZ (Non Return to Zero)

For analysis of the phase of a signal, it will be considered a sequence of NRZ pulses, which has the initial condition given in (18), where T_o is the duration of the pulse sequence, and m is the order of the sequence of pulses that determines the rise time and falling time in the edges of the sequence.

$$U(0, t) = \exp \left[\frac{-\ln(2)}{2} \cdot \left| \frac{2t}{T_0} \right|^{2m} \right] \qquad (18)$$

The expression of the normalized electric field is given by (19), where P_o is the peak power of the signal, and U(z, t) is the envelope of the normalized pulse in time and amplitude [11]. Substituting (19) in (17), (20) is obtained.

$$A(z,t) = \sqrt{P(z)} \cdot U(z,t) = \sqrt{P_o \cdot e^{-\alpha \cdot z}} \cdot U(z,t) \qquad (19)$$

$$j\frac{\partial}{\partial z}U = -\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}U + \gamma \cdot P(z) \cdot |U|^2 U \qquad (20)$$

To determine the chirp imposed by the self-modulation phase, (20) excludes the effect of chromatic dispersion of the fiber, preventing deformation of the pulse along the propagation, thus, making $\beta_2 = 0$.

$$j\frac{\partial}{\partial z}U = \gamma P(z) \cdot |U|^2 U = \gamma P_o \cdot \left(e^{-\alpha z} \cdot |U|^2 U\right) \qquad (21)$$

Solving the Ordinary Differential Equation (21), with the initial condition given in (18), the equation of the envelope of the pulse is obtained, (22):

$$U(z,t) = U(0,t) \cdot \exp\left[j\phi_{NL}(z,t)\right] \qquad (22)$$

The same analysis can be made with Gaussian pulses, with initial field as defined in (23), where C relates with the chirping in the form of (24).

$$U(0,t) = \exp\left[\frac{-(1+jC)}{2} \cdot \left|\frac{t}{T_0}\right|^{2m}\right] \qquad (23)$$

$$C = \frac{-T_o^2}{t}\frac{\partial \phi}{\partial t} \qquad (24)$$

VI. APPLICATIONS OF SPM AND XPM EFFECTS INDUCED

Noting that, the SPM and XPM effects produced spontaneously by system were analyzed from the point of view of damaging the system. However, these effects may be induced of controlled mode for applications and/or improvement of the system.
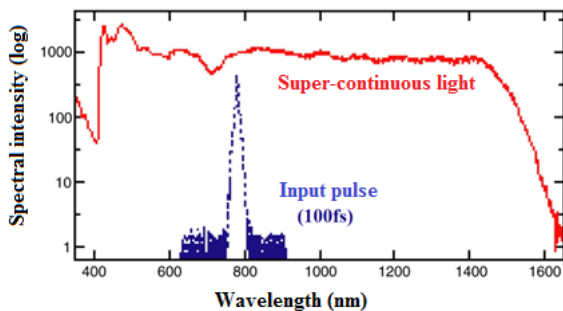

Fig. 2 SPM induced for generation of super-continuous light

Induced SPM can be used to generate light in Photonic Crystal Fibers (PCF). The principle behind this application is related to the fact that fiber type has strong nonlinear characteristics, causing a high widening from the higher phase modulation effect occurs, that is a high capacity to generate a continuous frequency from lasers short pulses. The spectral broadening obtained with a laser with pulses of 100fs (100

femto seconds = 100×10^{-15} seconds) is showed in the Fig. 2, which had a bandwidth of around 20nm and generated a super continuous signal with bandwidth around 1000nm (~400nm - 1400nm).

The induced SPM can also to cancel the effect of group velocity dispersion (GVD). As already said, the pulses propagating within an optical fiber can be described by the Schrödinger equation (NLSE), as the pulse propagates through the optical fiber, it will be subject to the effects of self-phase modulation (SPM), the which introduce the chirp effect in the pulse due to generation of optical frequencies news, causing a widening of the frequency spectrum which represents a narrowing of the pulse in the time domain. Moreover, effects due to dispersion result in a time pulse widening. Therefore, these two effects may balance, canceling one another. This solution is known for "Solitons".

The principle that an expansion in the frequency results in a narrowing of the range of time (or widening in time implies narrowing the frequency), both the SPM effect as XPM effect can be used to narrowing of pulses, noting that the energy used to narrow a pulse using SPM must be greater than using XPM.

With the XPM effect is possible to obtain wavelength conversion, which is achieved by placing in the channel a signal with the desired wavelength propagating simultaneously with the data signal which is desired to change the wavelength. Then by the effect of frequency spreading, after filtering, it is possible to receive the same data signal with a new wavelength.

VII. CONCLUSION

Despite all developments in optical systems, like any other transmission system, their channels have limited attenuation, dispersion, noise, and nonlinear effects.

Nonlinear effects are due to the interaction of light waves with phonons (quantum molecular vibrations) or due to the dependence of the refractive index with the intensity of the applied electric field. In this way they are impossible to be overcome, because there is not a structure molecular that behaves linearly for all situations that is submitted.

The change of nonlinear mode of the refractive index modifies phase, speed, and frequency of the signal, as well as other features that are directly linked to these.

Even in dedicated fibers may be present SPM effect, beyond the insertion of noise. While in shared fibers with multi-channel, beyond these effects can be added XPM effect.

The SPM and XPM effects can be analyzed starting from the quantum equation for propagation of electromagnetic waves, Schrodinger equation, being essentially a non-deterministic model, as well as noise. Thus, an optical communication channel can be characterized as non-deterministic, because they are subject to changes due to stochastic events, such as noise and change the behavior of the medium.

The XPM effect is more energetic than the SPM, because besides involving all signals in a channel, yours interference is

stronger. However, XPM effect only occurs in the length of walk-off, while the SPM occurs throughout the propagation time of the wave.

Although the SPM and XPM effects are not desirable in communication systems; they can be used in order to refine the system when used for creating super continuous light, dispersion compensation due to GVD (group velocity dispersion), creation and control of short pulses in laser, generation tunable semiconductor lasers, among others effects. Moreover, the SPM and XPM effects are important in systems that employ Wavelength Division Multiplexing (WDM) because how these effects widen the frequency spectrum should be alert to the choice of the spacing in frequency between different channels in order to make the most of the bandwidth.

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