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Analysis of linear and non-linear effects in the frequency domain for a three-channel optical transmission system

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Abstract. This paper presents the analysis of a wavelength division multiplexer communication system in the frequency domain, with the objective of visualizing the incidence of the linear phenomena of attenuation and chromatic dispersion, together with the phenomenon of phase self-modulation, the Kerr electro-optical effect and fourth wave mixing. The analyzed system consists of a laser transmitter with a Mach-Zender modulator and a standard G.625b single-mode fiber link transmitting three optical signals of 10 mW, 25 mW and 50 mW at a fundamental wavelength of 1550 nm at a rate of 10 Gbps. This system is analyzed through a graphical user interface programmed by the authors in the Python environment, which calculates the parameters corresponding to each phenomenon and graphically represents the transmission results at distances of 50 km and 100 km. The analysis methodology consists of varying the spectral separation of the transmitted channels, initially considering a spectral separation of 2 nm and subsequently a spectral separation of 0.2 nm, observing as a result that the harmonics generated by the fourth wave mixing phenomenon considerably alter the spectral density of the transmitted signals, since the energy of the harmonics is equal to the power of the transmitted signals. On the other hand, with the spectral spacing of 0.2 nm, it is obtained that, although the harmonics alter the spectral density waveform, the bandwidth is not compromised by these additional signals.

1. Introduction

One of the main advantages of this technology is the wavelength division multiplexing (WDM) capability, which, being the optical equivalent of frequency division multiplexing (FDM), greatly increases the capacity to transmit multiple data over a fiber optic link in different regions of the light spectrum [1]. This makes it possible to meet data traffic and information volume requirements, which increase as users consume more information [2]. However, the aforementioned advantages are limited by the intrinsic physical phenomena of fiber optic construction and material, which are exacerbated when multi-channel transmissions are carried out at a rate greater than 10 Gbps, especially when the spectral separation of each channel is minimal [3].

It is important to consider the phenomenon of fourth wave mixing (FWM) in optical communications systems based on fiber optic links under nonlinearity operating conditions, as exemplified by Alifdal H, Abdi F, and Abbou F, who analyze the bit error rate (BER) and optical signal-to-noise ratio (OSNR) in an eight-channel WDM system under operating conditions where crosstalk and FWM are present [4]. Therefore, the OSNR evaluation parameter is considered for the analysis of optical communication systems [4].



On the other hand, the use of software tools for the analysis of parameters in WDM systems allows the analysis of different scenarios based on predefined mathematical equations, as performed by Velandia, Puerto, and Ortíz with a WDM system in the time domain for linear phenomena and the linear phenomenon of self-phase modulation (SPM) [5], or as performed by Villamizar with the implementation of an algorithm for the numerical solution of the non-linear Schrödinger equation in specialized software [6]. Therefore, for the frequency domain analysis of FWM, which also includes linear phenomena, the Python programming environment is used to program a graphic user interface (GUI) to perform the analysis.

2. Methods

The mathematical definition of the WDM communication system analyzed is based on the contributions of Velandia [5], Agrawal [7], De Prado [8], Binh [9], Gómez [10] and García [11]; for the first stage, the solution of the non-linear Schrödinger equation for a complex Gaussian pulse in the time domain in a WDM system is proposed, as show in Equation (1), obtaining the different equations that allow the calculation of the characteristic values of the signal transmitted by the fiber link; where α is the attenuation coefficient of the fiber, β_2 corresponds to the group velocity dispersion (GVD), β_3 to the third order dispersion (TOD), γ to the non-linear coefficient of the optical fiber and \mathcal{K} to the complex Gaussian pulse transmitted in the time domain. This stage of the project builds on the previous development of [5], where attenuation, chromatic dispersion and SPM phenomena are considered for a single channel.

$$j \frac{\partial \mathcal{K}}{\partial z} = -j \frac{\alpha}{2} \mathcal{K} + \frac{\beta_2}{2} \frac{\partial^2 \mathcal{K}}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 \mathcal{K}}{\partial T^3} - \gamma |\mathcal{K}| \mathcal{K}. \quad (1)$$

Considering the solution for a Gaussian pulse in the time domain of the nonlinear Schrödinger equation (NLSE) in Equation (2) with an input power P_{in} , where C is the chirp factor and T_0 is the time width of the Gaussian pulse, we proceed to calculate the Fourier transform, thus obtaining Equation (3), observing that its behavior at the transmitting end also corresponds to a Gaussian pulse.

$$\mathcal{K}(0, t) = P_{in} \exp \left[-\frac{1+jC}{2} \left(\frac{t}{T_0} \right)^2 \right], \quad (2)$$

$$\mathcal{K}(0, \omega) = \frac{P_{in} T_0}{\sqrt{1+jC}} \exp \left[-\frac{(\omega T_0)^2}{2(1+jC)} \right]. \quad (3)$$

Now, considering the transfer function of the optical fiber, and expanding by means of Taylor's series the dispersion factor $\beta(\omega)$, we obtain Equation (4) that represents the transfer function of the optical fiber $H(z, \omega)$, where ω_0 is the spectral width of the pulse to be transmitted:

$$H(z, \omega) \approx \exp \left[\frac{\alpha z}{2} + \frac{jz\beta_2}{2} (\omega - \omega_0)^2 + \frac{jz\beta_3}{6} (\omega - \omega_0)^3 \right]. \quad (4)$$

If the fiber optic link is considered as a linear time invariant (LTI) system, it is possible to calculate the function $\mathcal{K}(z, \omega)$ in Equation (5) by applying the convolution theorem:

$$\mathcal{K}(z, \omega) = \mathcal{K}(0, \omega) H(z, \omega). \quad (5)$$

For three frequency components in an optical channel, these signals will mix and form a fourth wave produced by intermodulation, which, if it has a fundamental frequency in the range of the transmission bandwidth, produces severe crosstalk effects [4]. Assuming three communication channels in a WDM system, it is possible to calculate the new wavelengths for each of the harmonics from the set of ordered in Equation (6).

$$\begin{aligned}
\lambda_{112} &= 2\lambda_1 - \lambda_2, \\
\lambda_{113} &= 2\lambda_1 - \lambda_3, \\
\lambda_{123} &= \lambda_1 + \lambda_2 - \lambda_3, \\
\lambda_{132} &= \lambda_1 + \lambda_3 - \lambda_2, \\
\lambda_{221} &= 2\lambda_2 - \lambda_1, \\
\lambda_{223} &= 2\lambda_2 - \lambda_3, \\
\lambda_{231} &= \lambda_2 + \lambda_3 - \lambda_1, \\
\lambda_{331} &= 2\lambda_3 - \lambda_1, \\
\lambda_{332} &= 2\lambda_3 - \lambda_2.
\end{aligned} \tag{6}$$

The optical power of each of the generated harmonics is given in Equation (7), where d_{ijk} is the fibre degeneration factor, and η is the FWM efficiency of the communication system. Also, the non-linearity coefficient γ , being wavelength dependent, becomes a variable that must be recalculated for each of the harmonic wavelengths.

$$P_{ijk} = \eta(P_1 P_2 P_3) \exp \left[-\frac{\alpha z}{2} \right] \left[\frac{d_{ijk}}{3} \frac{2\pi n_0}{\lambda_{ijk} A_{eff}} L_{eff} \right]^2. \tag{7}$$

Optical signal to noise is a unit of measurement, defined as the ratio of the average power of the optical signal to the average power of the system noise, which evaluates the quality of the received signals that are corrupted by the noise generated by the FWM phenomenon (NFWM) [5]. To evaluate the OSNR_{ijk} parameter, Equation (8) is used, where P_{ijk} corresponds to the power of the harmonics generated at the same central operating wavelength of the WDM system, NFWM_{ijk} corresponds to the optical power of the noise generated by the harmonics, and b corresponds to the spectral efficiency of the system, represented in Equation (9).

$$\text{OSNR}_{123} = 10 \log \left[\frac{P_{123}}{\text{NFWM}_{123}} \right], \tag{8}$$

$$\text{NFWM}_{123} = 2b^2 P_{ijk} \left[\frac{\text{PFWM}}{8} \right]. \tag{9}$$

For the analysis of the linear and nonlinear phenomena in the frequency domain present in the WDM system, the QtDesigner programming environment is used, which is programmed with the equations modelled in [5] and in this article. This graphical interface allows to analyze the FWM phenomenon, which implicitly considers linear phenomena and phase self-modulation, calculating the OSNR in dB, the NFWM in μW at the receiving end of the system, and the bandwidth in nm for each channel, Among other variables implicit in the analysis. Moreover, the graphical user interface plots the new harmonics generated by the FWM effect at discrete wavelengths, together with the spectral density of each channel at each end of the links. The proposed GUI is visualized in Figure 1 and the programming algorithm, which consists of sequential and matrix logic, is arranged in Algorithm 1.

The transmission of the Gaussian pulse over the fiber optic link is performed by configuring the GUI with the required values for two communication scenarios, where the spectral spacing ($\Delta\lambda$) is varied. For the first scenario, three channels are considered with P_{in} optical input power of 10 mW, 25 mW and 50 mW respectively in a transmitter without C, and a centre wavelength of 1550 nm, which have a spectral spacing ($\Delta\lambda$) of 2 nm among each channel. As for the fiber link, the values defined in [11] and [12] are considered, adding the consideration of the attenuation by the connectors and splices implemented in the link (a total of two connectors and 30 splices with 0.1 dB each). Moreover, in the FWM parameters, a η of 95%, a d_{ijk} of 6 and a b of 0.7 are considered. By modifying the spectral spacing of the previous scenario to 0.2 nm and retaining the other characteristics, the transmission is repeated for the same distances.

The data analysis obtained in the analyzed communication scenarios focuses on the value of OSNR, NFWM, the bandwidth consumed by the three communication channels, and the ratio between the maximum power of the generated harmonics and the power of each channel. On the other hand, the waveform corresponding to the spectral power density of each channel as a function of wavelength is analyzed.

Figure 1. Graphical interface corresponding to the WDM digital optical communication system for the analysis of linear and FWM effects in transmission.

Algorithm 1. WDM system model.

Inputs: channel and fiber optic characteristics

Outputs: scalar values and 2D plots of each channel in the frequency domain

1. Definition of power, wavelength, and time-width vectors
2. Calculation of optical powers and wavelengths of harmonics with Equation (6) and Equation (7)
3. Calculation of chromatic dispersion, GVD and TOD with the harmonics of each channel
4. Calculation of γ with new wavelengths of each channel
5. For i as a function of the harmonics coinciding with the wavelength of each channel
6. Calculation of $NFWM_{123}$ with Equation (9) for each P_{ijk} satisfying the condition and each channel
7. Calculation of $OSNR_{123}$ with Equation (8) for each optical channel and each $NFWM_{123}$
8. Calculation of the function $|\mathcal{K}(z, \omega)|$ with Equation (3) and Equation (5) as a vector
9. Print output float data on screen

3. Results

The results of the transmission of the $|\mathcal{K}(z, \omega)|$ signal at 50 km and 100 km are displayed for each channel in the Figure 2 to Figure 7, and the scalar values are ordered in Table 1 to Table 6 for each channel. The numerical results for $\Delta\lambda$ of 2 nm are ordered in Table 1, Table 3, and Table 5, respectively; likewise, the numerical results for $\Delta\lambda$ of 0.2 nm are ordered in Table 2, Table 4, and Table 6, respectively. In the waveforms, it is observed that the spectral density suffers alterations with respect to the expected Gaussian wave due to the effect of the harmonics generated at wavelengths close to the central wavelength of each channel. As for the OSNR value, the value obtained in each scenario exceeds 37 dB, which is considered an optimum value in the evaluation of an optical system.

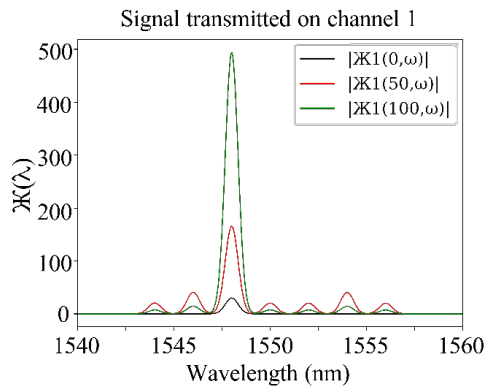


Figure 2. Channel 1 with $\Delta\lambda$ of 2 nm.

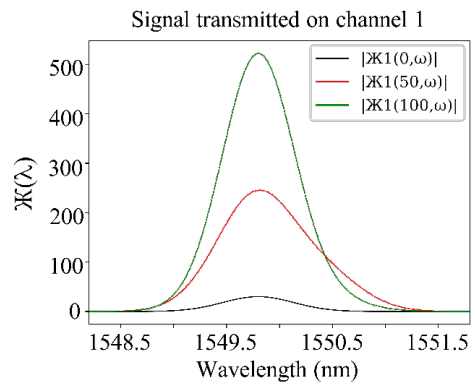


Figure 3. Channel 1 with $\Delta\lambda$ of 0.2 nm.

Table 1. Results for channel 1 with $\Delta\lambda$ of 2 nm.

Parameter	Value 50 km	Value 100 km
OSNR	37.646 dB	47.405 dB
NFWM	0.35511 μW	0.01121 μW
Bandwidth	14.3 nm	14.3 nm

Table 2. Results for channel 1 with $\Delta\lambda$ of 0.2 nm.

Parameter	Value 50 km	Value 100 km
OSNR	37.646 dB	47.405 dB
NFWM	0.35511 μW	0.01121 μW
Bandwidth	3.2 nm	3.2 nm

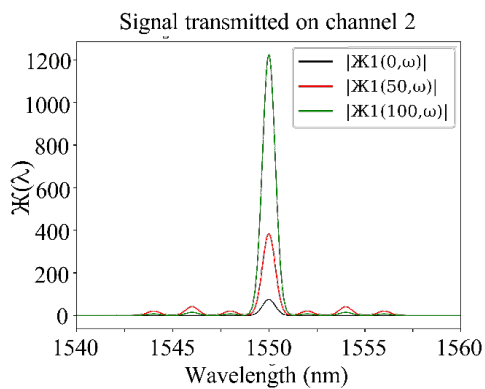


Figure 4. Channel 2 with $\Delta\lambda$ of 2 nm

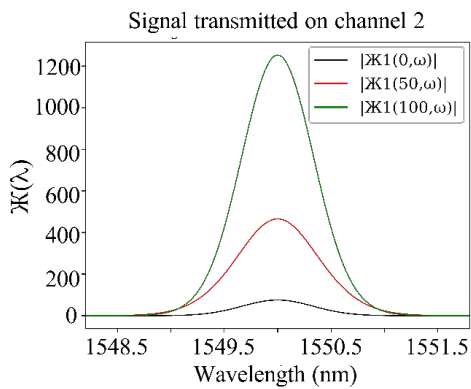


Figure 5. Channel 2 with $\Delta\lambda$ of 0.2 nm

Table 3. Results for channel 2 with $\Delta\lambda$ of 2 nm.

Parameter	Value 50 km	Value 100 km
OSNR	37.646 dB	47.405 dB
NFWM	0.36525 μW	0.01121 μW
Bandwidth	14.3 nm	14.3 nm

Table 4. Results for channel 2 with $\Delta\lambda$ of 0.2 nm.

Parameter	Value 50 km	Value 100 km
OSNR	37.666 dB	47.422 dB
NFWM	0.35356 μW	0.01126 μW
Bandwidth	3.2 nm	3.2 nm

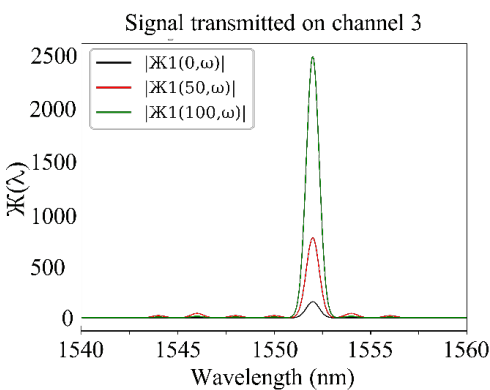


Figure 6. Channel 3 with $\Delta\lambda$ of 2 nm.

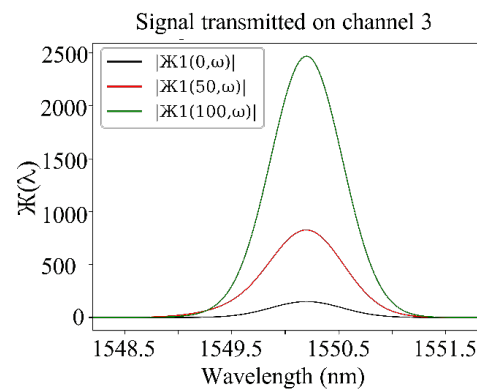


Figure 7. Channel 3 with $\Delta\lambda$ of 0.2 nm.

Table 5. Results for channel 3 with $\Delta\lambda$ of 2 nm.

Parameter	Value 50 km	Value 100 km
OSNR	37.698 dB	47.419 dB
NFWM	0.88778 μ W	0.05604 μ W
Bandwidth	14.3 nm	14.3 nm

Table 6. Results for channel 3 with $\Delta\lambda$ of 0.2 nm.

Parameter	Value 50 km	Value 100 km
OSNR	37.685 dB	47.452 dB
NFWM	0.88366 μ W	0.05578 μ W
Bandwidth	3.2 nm	3.2 nm

On the other hand, Table 7 and Table 8 show the relationship between the maximum optical power ($P_{ijk,max}$) of the harmonics generated by the FWM phenomenon and the optical power of each channel at the distances analyzed in each communication scenario. Quantitatively, high optical power ratio percentages cause significant transmission errors, because the waveform received at the far end of the fiber link contains different spectral components from the transmitting side.

Table 7. Power ratio between the $P_{ijk,max}$ and the power of each channel with $\Delta\lambda$ of 2 nm.

Parameter	Value 50 km	Value 100 km
Power ratio 1	24.653%	2.9254%
Power ratio 2	10.634%	1.1802%
Power ratio 3	5.4628%	0.5919%

Table 8. Power ratio between the $P_{ijk,max}$ and the power of each channel with $\Delta\lambda$ of 0.2 nm.

Parameter	Value 50 km	Value 100 km
Power ratio 1	8.2713%	1.3774%
Power ratio 2	4.3656%	0.5738%
Power ratio 3	2.4569%	0.2913%

4. Conclusions

It is possible to conclude that linear and non-linear phenomena generated by a fiber optic link in WDM systems alter the spectral density of the signals transmitted by this medium. Although no significant variations are observed between the scenarios, neither in OSNR nor in NFWM, it is possible to observe that the bandwidth of the first scenario is more than four times greater, due to the fact that there is a proportional relationship between the spectral spacing of each channel and the wavelengths of the harmonics generated. However, these time-domain variables can generate other drawbacks in signal recovery at the receiving end of the WDM system, so physical phenomena in the time domain must be considered when making transmissions.

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