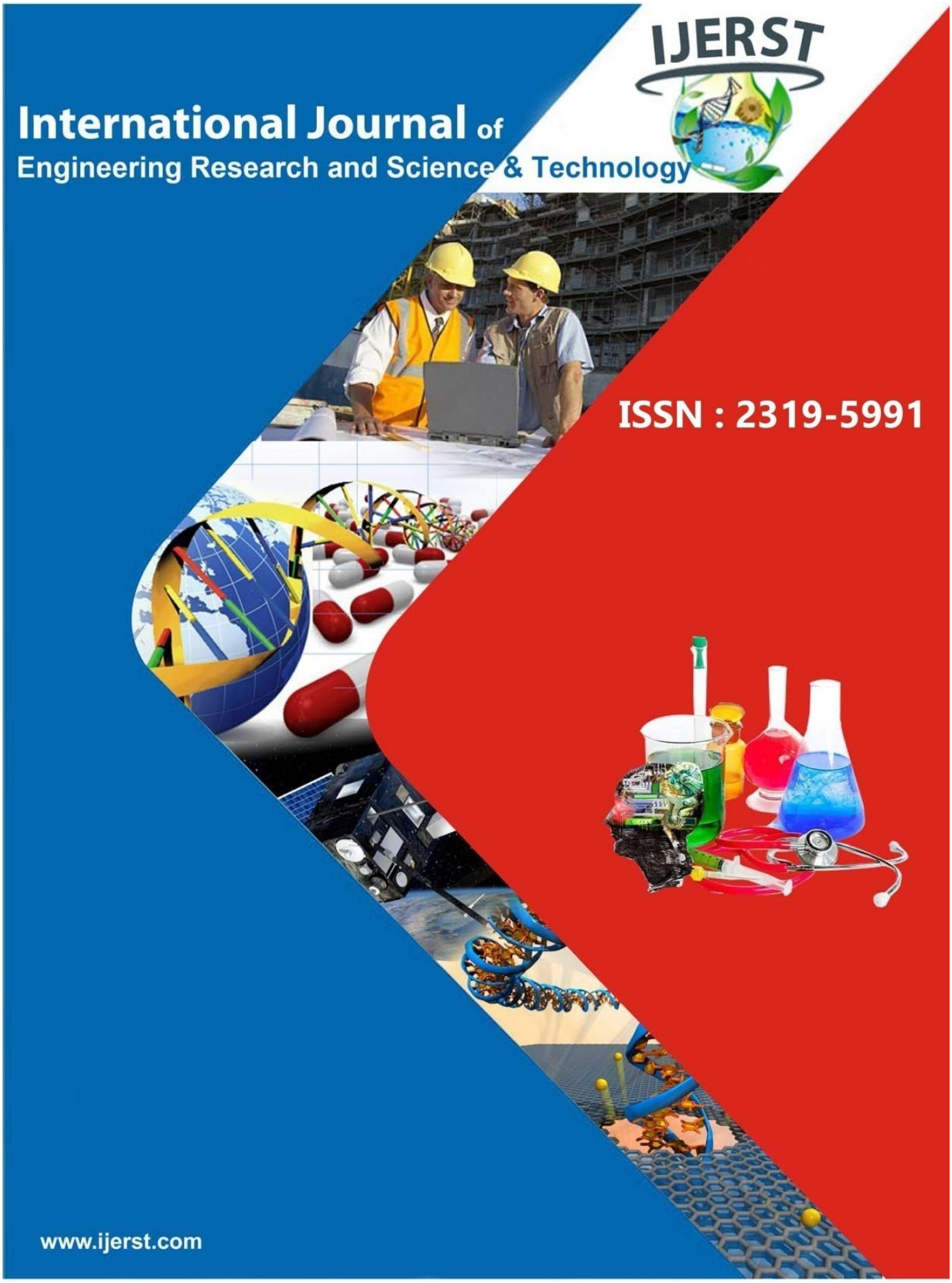

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Impact of input power on cross-phase modulation phenomenon in dense wavelength division multiplexed system

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Abstract

This paper investigates the influence of nonlinear phenomena, in particular the Cross-Phase Modulation, taking into account the input power. The simulated system models a 110 km optical fiber link, consisting of 32 Dense Wavelength Division Multiplexed system, each signal is transmitted with a rate of 200 Gbps. Different input powers per channel: 1 mW, 2 mW, 3 mW, 4 mW, 5 mW and 6 mW are considered. The simulations is carried out with the Optisystem, which is an environment essentially designed for the modeling and simulation of systems optical transmission. For the considered power range, the simulation results show that the system performance increases when the input power increases, in case where the nonlinear effects are removed. If the Cross-Phase Modulation is taken into account in the system, the distortion it created increases when the input power increases; therefore a decrease of system performance. Also, the Maximum of the Q-factor increases with the input power for the values of 1 mW, 2 mW, 3 mW and 4 mW, while it decreases with the values of 5 mW and 6 mW for which the distortion induced by Cross-Phase Modulation becomes very high.

Keywords: *DWDM transmission system, XPM phenomenon, Input power, nonlinear distortion.*

1. Introduction

Information traffic is growing exponentially every year, due to the rapid emergence of new communication services such as social networks, videos, data traffic from smartphones or tablets, and virtual computer services [1–3]. To deal with this explosion of information traffic, optical fiber remains the backbone of transmission systems, because of its enormous advantages, including: its low cost, enormous bandwidth and its compatibility with new multiplexing techniques. Thus fiber optic transmissions, with Dense Wavelength Division Multiplexing (DWDM) technology, would be a promising solution to meet the growing demand for bandwidth [3–6]. The DWDM system allows the transmission of several signals in the same optical fiber, with a small spacing (less than 50 GHz sometimes) [7]; this makes it possible to take advantage of the enormous bandwidth of the optical fiber.

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Simultaneously transmitting several signals in the core of a single optical fiber (about 10µm in diameter) is not only a difficult operation, but also a technique vulnerable to nonlinear effects. Indeed, during the transmission of light signals in an optical fiber, there may be interactions between the signals themselves, or interactions between the signals and the transmission medium (optical fiber). When the signal intensity becomes high, it can change the refractive index of the optical fiber; this effect, known as the optical "Kerr effect", is the source of several non-linear phenomena such as Self-Phase Modulation (SPM), Cross Phase Modulation (XPM) and Four-Wave Mixing (FWM) [4, 8–11]. Moreover, when the intensity of the signal is very high, there may be an exchange of energy between the signal and the optical fiber; this can lead to nonlinear phenomena such as stimulated Raman Scarttering (SRS), Stimulated Brouillon Scarttering (SBS) and Self-Steepening (SS) [12–14]. Several previous works have shown that these nonlinear effects limit the performance of transmission systems; even if they (under certain conditions) could offer a variety of possibilities for ultra-fast all-optical switching, amplification and regeneration [4, 8, 15]. Therefore, the study of nonlinear effects is becoming a major concern for researchers and engineers in the field of nonlinear optics and optical fiber transmission.

In this work, we have modeled and simulated a DWDM system of 32x200 Gbps using the Optisystem which is an environment essentially designed for the modelling and simulation of optical transmission systems. The analysis of nonlinear effects was made, exploring the impact of input power of signals; particular emphasis is placed on the XPM as the most predominant nonlinear phenomenon in optical transmission systems [16–18]. Performance parameters such as quality factor (Q-factor) and eye diagrams are used to evaluate the impact of distortions introduced by nonlinearities. The manuscript is organized as follows: In section 2, a theoretical analysis of nonlinear effects is presented, in section 3 the system setup is presented, and finally the results and discussion are presented in section 4.

2. Theoretical analysis of nonlinear effects

Theoretical modelling and analysis of nonlinear phenomena in optical fiber transmissions is often carried out through the study of nonlinear propagation equations, and the best known is the

Nonlinear Schrödinger Equation (NLSE). Indeed, the propagation of a signal in an optical fiber is perfectly described by the generalized NLSE given by [10, 13, 19]:

$$\frac{\partial A}{\partial z} + \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial T^2} - \frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial T^3} + \frac{\alpha}{2}A = i\gamma|A|^2 A + i\gamma\left[\frac{i}{\omega_0}\frac{\partial(|A|^2 A)}{\partial T}\right] + i\gamma\left[-T_R A \frac{\partial(|A|^2)}{\partial T}\right] \quad (1)$$

where variable $A = A(z,t)$ designates the envelope of the signal. The parameters α, β_2 and β_3 designate respectively the attenuation coefficient, the dispersion coefficients of order 2 and 3. These three parameters characterize linear phenomena such as dispersion and attenuation, while the parameter γ designates the nonlinearity coefficient and characterizes nonlinear phenomena. Specifically, the parameter $\tau_0 = \frac{1}{\omega_0 T_0}$ is SS effect coefficient; where T_0 is the duration of the pulse. The coefficient of the SRS effect is defined by $\tau_R = \frac{T_R}{T_0}$. In the Eq. (1), the term $i\gamma|A|^2 A$ alone can model three nonlinear effects (SPM, XPM, FWM), depending on the number of signals and the power of the signals.

In a recent work, it is demonstrated that the XPM effect is predominant over other nonlinear phenomena during optical fiber transmissions [16–18]. Indeed, XPM results from the intensity dependence of the refractive index of the propagation medium; it can appear when two or several pulses propagate simultaneously in an optical fiber. The XPM induces fluctuations in the wavelength intensity of a particular signal to phase fluctuations in the other co-propagating signals. For an N-channel transmission system, the nonlinear phase induced by the phenomenon of XPM on the i^{em} channel can be written [8, 12].

$$\phi_{NL}^{i} = \gamma L_{eff}\left(P_i + 2\sum_{n\neq i}^{N} P_n\right) \quad (2)$$

where P_i is the input power of the i^{em} signal and the P_n designate the input powers of the other signals; L_{eff} designates the effective length. The expression of ϕ_{NL}^{i} clearly shows that the nonlinear phase induced on a given signal depends not only on its own power (P_i), but also on those of other signals (P_n). The XPM is always accompanied by the SPM: The nonlinear refractive index seen by an optical signal not only depends on its own intensity, but also depends on the optical intensity of other co-propagating signals [8, 12]. In practice, XPM creates crosstalk in transmissions [17, 20].

Analytical or numerical resolution of NLSE contributes to the interpretation of nonlinear phenomena. However, it is very judicious to model and simulate nonlinear transmission system through software designed for this purpose. This would have phenomena in a the advantage the flexibility to manage the components as on a real transmission link.

3. System and setup

The designed system consists of 32 wavelengths at a nominal rate of 200 Gbps per channel with the DP-QPSK format. Figure 1 presents the schematic diagram of the modeled system. The 32 signals are multiplexed by a 32:1 multiplexer, which is directly connected to a signal processor implemented in MATLAB; the data is further injected into the transmission link, which consists of an SMF and a DCF in order to compensate for dispersion.

For this purpose, the parameters are set such that $L_{SMF} D_{SMF} = -L_{DCF} D_{DCF}$ where L_{SMF} and D_{SMF} are respectively the length and the dispersion coefficient of the SMF fiber; L_{DCF} and D_{DCF} respectively the length and the dispersion coefficient of the DCF fiber [21–23].

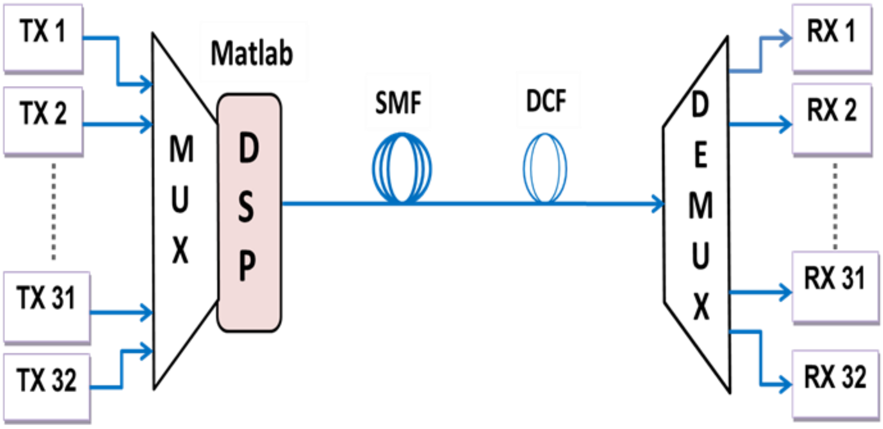


Fig. 1. Schematic diagram of a 32×200 Gbps optical transmission system

The table 1 presents the essential parameters of SMF and DCF.

Optical Fibers	SMF	DCF
Dispersion (ps/nm/km)	16.75	-167.5
Dispersion slot (ps/nm2/km)	0.07	-0.7
Effective area A_eff (µm2)	80	22
Attenuation (dB/Km)	0.2	0.6
Length (km)	100	10

Table 1. Essential parameters of SMF and DCF.

The frequency band is chosen such the central wavelength of the system is closer 1550 nm, since the optical fiber has low attenuation and dispersion around this wavelength. Thus, the frequency band of the designed system extend from 1543.73 nm to 1556.15 nm, with a spacing of 50 GHz or 0, 4nm (according to ITU-G652 standard). Also this model can be applied to real transmission systems, since 32-channel WDM is one of the most commercialized systems. An interface between Optisystem and matlab is created for digital signal processing, if possible. The system environment offers a wide possibility to simulate all the nonlinear effects likely to appear on an optical transmission link. The simulation of the system is carried out by considering a total propagation distance of 110 km.

4. Theorem Style

The evaluation of the system performance as well as the impact of the XPM phenomena was carried out by considering the parameters such as the Q-factor and the eye diagram. In order to evaluate the influence of the input power on the system, the simulation is performed with 6 different input powers per channel: 1 mW, 2 mW, 3 mW, 4 mW, 5 mW and 6 mW. The analysis is essentially focused on the central wavelength (1550.12 nm). Figure 2 presents graphs of Q-factor and eye diagrams, without considering nonlinear phenomena. Figure 2(a) shows six Q-factor curves plotted simultaneously in a single graph; the Fig. 2(b) shows the corresponding eye diagrams. Each eye diagram and the corresponding Q-factor curve are obtained for one of the six input powers; the legend associated with Fig. 2(a) is useful for all the graphs, and makes it possible to identify, through the colour, the curves and the eye diagram corresponding to a given input power. Fig. 2(d) represents the eye closure curves corresponding to the six input powers. The Fig. 2(c) shows the evolution of the maximum of Q-factor curves (Max Q-factor) as a function of the input power.

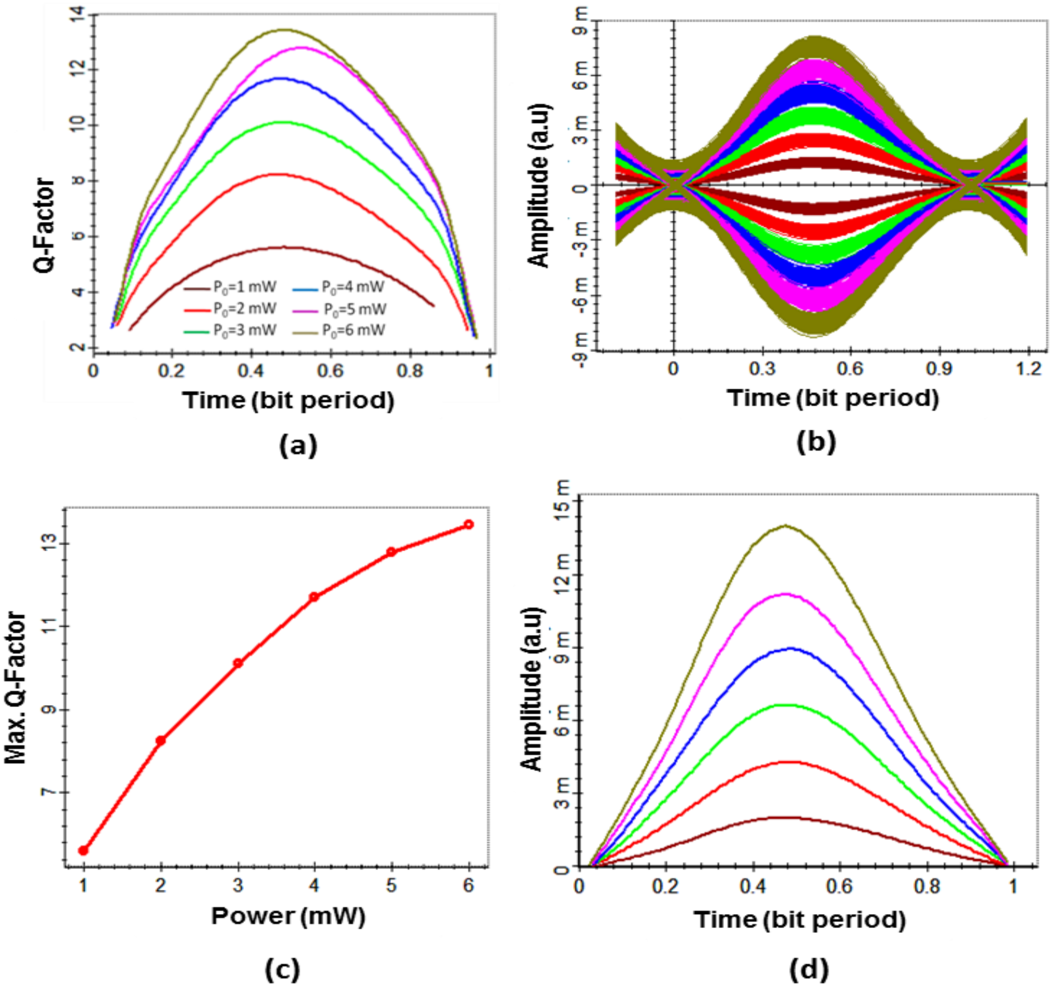


Fig. 2. Evaluation of performance, system without nonlinear effects: (a) Q-factor curves; (b) Eye Diagrams; (c) Max Q-factor with input power and (d) Eye Closure curves.

From the curves and diagrams of Fig. 2, it is clearly observed that the performance of the system depend on the input power: the Max Q-factor curve increases with the input power, over all the powers considered and varies between Q = 5.6 and Q = 13.7 (Fig. 2(c)); the Q-factor curves are arranged in increasing order of power (Fig. 2(a)). Similarly, on Fig. 2(b) and Fig. 2 (d), we can observe that the amplitude (a.u) of the eye opening varies between 2 m and 14.2 m. From these results, it can be noted that the transmission quality of the system increases with the power, over all of input powers considered. Under these conditions, it would be possible to increase the power or the propagation distance to obtain a very high performance. For this end, the Fig. 3 shows the evolution of Max Q-factor for a propagation distance of 1100 km for input power range of 5 mW to 30 mW; we can note higher values of Q than those obtained in Fig. 2 (c).

Therefore the performance of a WDM system strongly depends on the input power per channel [24–26].

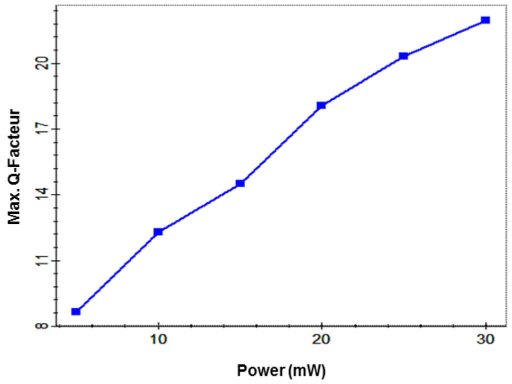
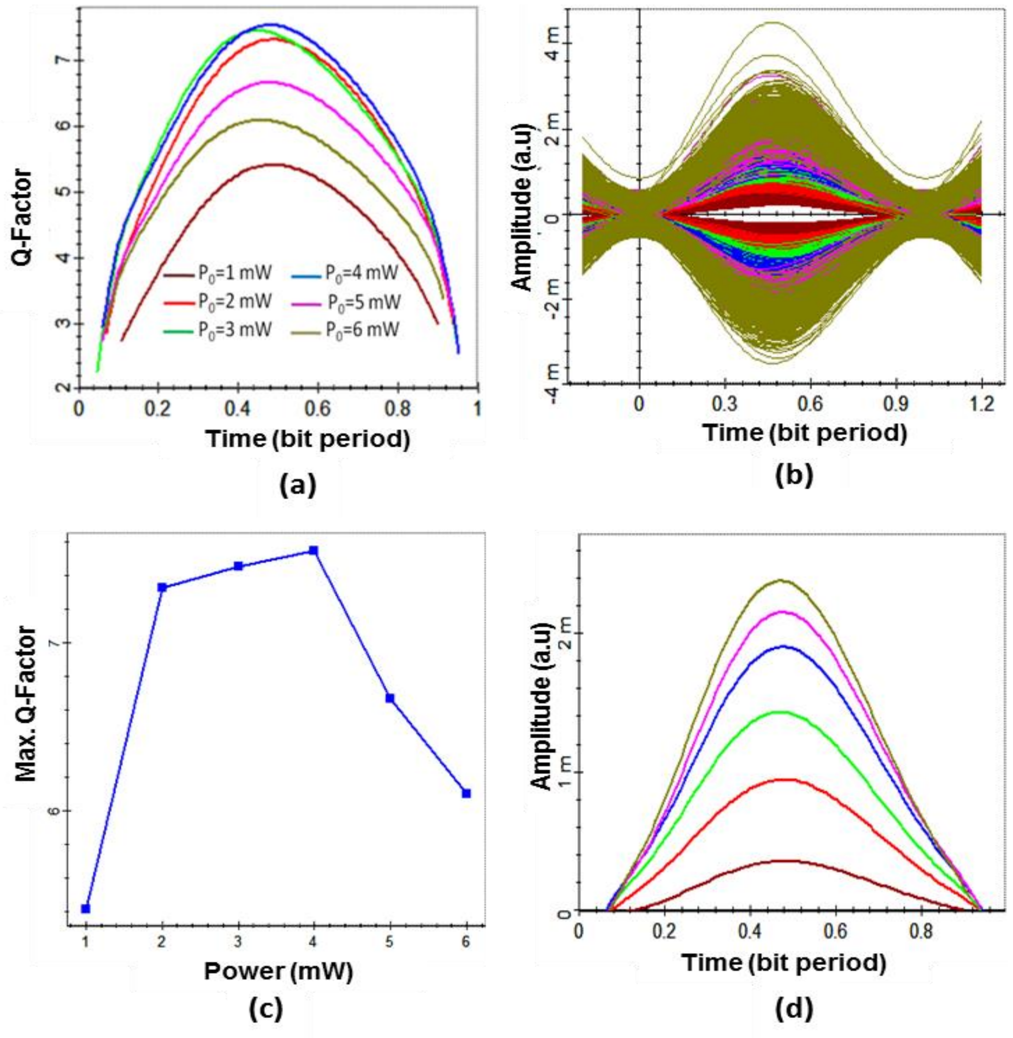


Fig. 3: Variation of the Q-factor with the input power, without the nonlinear effects

Now, the XPM phenomenon has been taken into account, as the most dominant nonlinear effect of the system [16, 17, 20, 27]. The Fig. 4 presents: six eye diagrams represented simultaneously in a single graph Fig. 4(b); the six eye closure curves, Fig. 4(d); and the six Q-factor curves corresponding, Fig. 4(a). The Fig. 4(c) represents the evolution of the maximum of the Q-factor curves with the input power per channel. Similarly, the legend associated with Fig. 4 (a) is useful for the four graphs.



(a) (b)

(c) (d)

Fig.4. Evaluation of performance, system with XPM phenomenon: (a) Q-factor curves; (b) eye diagrams; (c) Max Q-factor with the power and (d) eye closure curves.

In Fig. 4(b), we can clearly observe the eye diagrams more closed than those of Fig. 2(b). We can observe in Fig. 4(a) that the values of the Q-factors for each of the six curves are smaller than those of Fig. 2(a). Also, it appears that the Q-factor curves of Fig. 4(a) are not arranged in increasing order of power, as in the case of Fig. 2(a). This is precisely what Fig. 4(c) illustrates where the Max Q-factor increases with the input power for the values of 1 mW, 2 mW, 3 mW and 4 mW; while it decreases for the values of 5 mW and 6 mW.

It is very important to note that the performance depends on the input power of each signal of the DWDM system; similarly, the impact of the XPM phenomenon depends on the input power. Especially, for the input powers used in this work, the distortion created by the XPM increases when the input power increases. Indeed, the change in variation of the Max Q-factor curve (after the input power of 4 mW in Fig. 4(c) reflects the degradation of the quality of the system. This degradation would be due to the XPM effect which would introduce very significant distortions. This could be predicted by the theoretical analysis which showed that the nonlinear phase ϕ_{NL}^{i}introduced by XPM depends on the input power of co-propagating signals in the DWDM system. Thus, when the input power exceeds a threshold, the interference between the signals themselves, and the interference between the signals and the optical fiber will increase; which would imply a degradation of the quality of the system. So it would be important to optimize the input power, in order to minimize the nonlinear effects and to have a good transmission performance in DWDM systems.

5. Conclusion

Nonlinear phenomena distort information in fiber optic transmissions. Specifically, XPM induces the fluctuations in intensity from the wavelength of a particular signal to the phase fluctuations in the other co-propagating signals in a DWDM system. The analysis of the results shows that the nonlinear phase introduced by XPM depends on the peak power of the Co-propagating signals. For the power range used in this work, the distortion created by the XPM increases when the peak powers increase. In particular the change in the direction of variation of the curve of Max. Q-factor (after the input power of 4 mW) reflects a greater degradation of the quality of the system. The input power has an influence on the XPM effect; therefore the impact of nonlinear phenomena in the transmission system is strongly related to the input power. Then it would be very important to optimize the input power, in order to minimize the nonlinear effects and to have a good transmission performance in DWDM systems. However, this optimization could be more effective by considering simultaneously other important parameters such as the channel spacing, the frequency band, the number of signals in DWDM system.

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