ANALYSIS OF THE EFFECT OF FIBER LENGTH ON FOUR-WAVE MIXING POWER IN WDM OPTICAL COMMUNICATION SYSTEM

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Abstract
This study has revealed that the dominant nonlinear of four-wave mixing (FWM), shown a significant impact of performance limitation of the wavelength division multiplexing systems (WDM). The interaction and accumulation of the chromatic dispersion and the effect of the fiber nonlinear along the optical link length, are shown a limited performance of the long distance of optical communication system. Also, we investigated the relationships of FWM power with the fiber length of several values of the inter channel spacing, input power, the effective core area, number of channels in the system. The results are shown that the dominant influence of FWM at the dispersion of zero-wavelength in comparison to the end wavelength, where ultimately, it reaches the maximum value of fiber length ≈ 22 km. Furthermore, it is also shown that the FWM noise power is, consequently, increased, after assembly of other factors, including, (1) the increase of the input power, (2) the number of channels in the system, (3) the decrease of the frequency spacing, effective core area.

Keywords: Four-Wave Mixing, WDM system, Chromatic Dispersion, Attenuation.

1. Introduction

Crosstalk due to four-wave mixing (FWM) is the dominant nonlinear effect on multichannel optical communication systems which can severely limit system performance [1]. The negative impact of (FWM) products in the performance of the multichannel optical communication systems is still a controversial. Moreover, the simultaneous propagate of three of the frequencies \( f_i, f_j \) and \( f_k \) (optical field signals) inside the fiber, however, as a result of the fiber nonlinear effect, there are new weak signals of frequencies generated, which are explained by the following relation [2],

\[
N_f = \frac{1}{2} (N^3 - N^2)
\]

Two factors strongly influence the magnitude of the FWM products. The first factor is the channel spacing, where the mixing efficiency increases dramatically as the channel spacing become closer, while the second factor, is the fiber dispersion [3]. There are two ways of causing degradation as a result of generation of FWM products: Firstly, by depleting the power of transmitting signal lights. Secondly, by the interference of the original signals, which have the same frequencies as the FWM products. The frequencies are either found within the N original channels and/or within different
locations. Moreover, Those FWM signals which overlap with the original ones, are considered as
crosstalk and will interfere with the normal WDM channe ls [4]. The main objective of this study is to
evaluate the effect of the optical fiber length on the FWM power production in dispersion-shifted
optical fiber and the study evaluation are achieved by the design a simulated model in MATLAB.

2. Mathematical Model

Equation (1) explains the consequence state of the assumption that if the three optical signals
participating in the FWM process are nearly not depleted, however, the evolution of the FWM
amplitude (at the angular frequency \( W_F \) along the length of a fiber), will be dominated [5]:

\[
\frac{d}{dz} A_F(z) + \frac{\alpha}{2} A_F(z) = \frac{n_2 W_F}{c A_{\text{eff}}} A_p(z) A_q(z) A_r(z) \exp(i\Delta \beta z)) \quad (1)
\]

Where \( A_F(z) \) is the amplitude of the FWM signal generated at the frequency \( f_F = f_p + f_q - f_r = \frac{W_F}{2\pi} \), (p, q, r= 1, ….. N) from interaction of original signals of amplitude \( A_s(z) = A_s(0) \exp(-\frac{\alpha z}{2}) \) injected into the fiber
with frequencies \( f_s (s=p, q \text{ and } r) \), \( \alpha \) - fiber attenuation coefficient, \( n_2 \) - nonlinear refractive index coefficient
of the fiber, \( c \) - velocity of light in vacuum, \( A_{\text{eff}} \)- Effective area of the fiber core, \( i = \sqrt{-1} \) \( \) and (*) indicates
the complex conjugate and \( \Delta \beta \) represents the phase mismatch. The fiber dispersion characteristics are
included indirectly through the variation of the phase constant with frequency. FWM induced power located
in one channel in WDM systems for one product generated from the interaction of p, q and r signals that are
necessary for generating of one FWM product is described by [6]:

\[
P_F(L) = |A_F(L)|^2 = \frac{4\pi n_2^2}{\lambda F} \frac{P_0(0) P_r(0) e^{-\alpha L} e^{(-\alpha + i\Delta \beta) L} - 1}{i\Delta \beta - \alpha} \quad (2)
\]

The calculation of the FWM power, needs to identify all the FWM products that fall within the
passband of the optical fiber in WDM systems responsible for channel separation. FWM powers
induced in WDM systems for all products from the interaction of the original signals in a channel
system (2, 3,… channels) are then added together and described by the following equation [6]:

\[
P_{\text{FWM}}(L) = \sum_{i_p} \sum_{i_q} \sum_{i_r} P_{pqr}(L) = \sum_{i_p} \sum_{i_q} \sum_{i_r} \frac{4\pi n_2^2}{\lambda F} \frac{P_0(0) P_r(0) e^{-\alpha L} e^{(-\alpha + i\Delta \beta) L} - 1}{i\Delta \beta - \alpha} \quad (3)
\]

Where \( \lambda_F \) is the wavelength of generated FWM products and \( d \) is the degeneracy factor which is equal 1
if \( p= q\neq r \), and =2 if \( p\neq q \neq r \). The phase mismatch \( \Delta \beta \) is described in the following equation [7]:

\[
\Delta \beta = \beta(f_p) + \beta(f_q) - \beta(f_r) \quad (4)
\]

The problem of phase mismatch is well known, which describes the travel of different signals at
different group velocities within the fiber. The phase mismatch \( \Delta \beta \) described in equation (4), represents
the difference of propagation constants \( \beta_p \), \( \beta_q \) and \( \beta_r \) of original signals \( p, q \text{ and } r \) and the propagation
constant of the FWM-generated signal. The fiber dispersion effect precisely, can be explained, when
the constant \( \beta \) of mode propagation in a Taylor series, is expanded about the frequency \( \omega_0 \) at which the
pulse spectrum is centered [5].

\[
\beta(w) = \beta(w_0) + \beta_1 (w-w_0) + \frac{\beta_2}{2!} (w-w_0)^2 + \frac{\beta_3}{3!} (w-w_0)^3 \quad (5)
\]

Where: \( \beta_m = \left( \frac{d^m \beta}{dw^m} \right)_{w=w_0} \) \( \) (m = 1, 2,…)

Consequently, an analytical expression for the parameter \( \beta_i \) (i= p, q or r) can be obtained in the
neighborhood of a certain angular frequency \( \omega_0=2\pi f_0 \) by the following equation:

\[
\beta_i = \beta_0 + 2\pi f_0 \tau + \frac{4\pi^2}{2!} (f_1-f_0)^2 \frac{d\tau}{dw} + \frac{9\pi^3}{3!} (f_1-f_0)^3 \frac{d^2\tau}{dw^2} \quad (6)
\]

Where: \( \tau = \frac{d\beta}{dw} \) is the propagation delay per optical length. Moreover, the equation (7) was coming
out as a result of a combination of a set of equations. Initially, the equation was used to individually,
calculating the \( \Delta \beta \), and subsequently, substitute these equations in equation 4. These processes were described in the following equation:

\[
\Delta \beta = \beta (t_p) + \beta (t_q) - \beta (t_0) = \frac{(2\pi)^2}{2} \left[ \left( (t_p + t_q - t_0) - (t_p - t_0) \right)^2 + \left( (t_r - t_0) - (t_p - t_0) \right)^3 \right] \frac{d^2 \tau}{d\omega^2} \quad \cdots (7)
\]

By simplifying equation (7), we get:

\[
\Delta \beta = \frac{\lambda_0^2 \pi D}{c} - \frac{\lambda_0^2 \pi}{c^2} \left[ \frac{2D}{\lambda} + \frac{dD}{d\lambda} \right] \quad \cdots (8)
\]

Where \( D \) is the dispersion parameter of the fiber and \( dD/d\lambda \) is the corresponding dispersion slope. The most common equation used is the equation (8). However, in this study, we have been using equation (7), because it is easier than equation (8) for programming. These equations are valid in the frequency range around \( f_0 \) where the dispersion slope is linear. According to the equation (7), the occurrence of the phase mismatch is depended on the type of fiber (through dispersion parameters) and the spacing between neighboring channels. Therefore, the satisfactory phase matching condition of \( \Delta \beta = 0 \), occurred, when the wavelength of the fiber value becomes approximately close to the zero-dispersion wavelength. The dispersion parameters \([8]\), are defined in the following three sets of equations:

First:

\[
\beta_p = \frac{d\tau}{d\omega} = -\frac{\lambda_0^2}{2\pi c} D
\]

Second:

\[
\beta_a = \frac{d^2 \tau}{d\omega^2} = \frac{\lambda_0^2}{(2\pi c)^2} \left[ 2D \lambda_0 + \lambda_0^2 D_1 \right]
\]

Third:

\[
D = \frac{d\tau}{d\lambda}, D_1 = \frac{d^2 \tau}{d\lambda^2} = \frac{dD}{d\lambda}
\]

Where \( D_1 \) is the dispersion slope.

3. FWM Efficiency

The definition of the FWM efficiency \( \eta \) was reported in \([7]\), which is described in the following equation:

\[
\eta = \frac{P_{\text{FWM}}(L, \Delta \beta)}{P_{\text{FWM}}(L, 0)} \quad \cdots (9)
\]

However, by substituting equation (2) in the equation (9), the following equation is produced \([7]\):

\[
\eta = \frac{\alpha^2}{\alpha^2 + \Delta \beta^2} \left( 1 + \frac{4e^{-\alpha L} \sin^2 \left( \frac{\Delta \beta L}{2} \right)}{1 - e^{-\alpha L}} \right) \quad \cdots (10)
\]

The differential group of velocities of the signal and generated waves related to the differ of the wavelength dispersion, consequently, this differential manner, will be responsible for destroying the phase matching of interacting waves and also, lower the efficiency of transferring the power to the newly generated frequencies. Furthermore, show the reflective relationships between the high rate of the group velocity mismatch, the width of the channel spacing and the low rate mix of the four waves.

4. Results and discussion

Equations (1-10) are represented all the mathematical methods that are needed to investigate the effect of the fiber length on the FWM power of the WDM systems. These equations were implemented in the numerical model used in the simulation process that was programmed using MATLAB. Before
the discussing of the results, it is worthy of mention, we suggest that, the grids have equally spaced channels. The frequency of the wavelength center $\lambda_0$ was chosen for the channel system as $\lambda_0$. We also assumed that the calculation of the equal input power of the channels is stated as follows: $P_i = P_s = P_r = P_0$. The simulation results of the program are presented in the graphical form and the following data were applied [6]:

**Case (1):** is the state of using the system of three channels and changing the values of input powers three times (0.1, 0.5 and 1 mw) at selected central wavelengths with fiber core area is $= 50 \mu m^2$ and the frequency spacing is $\Omega$ = 50 GHz for different fiber lengths as in the (Figure 1: a, b, c, d, e) respectively. Moreover, the selected central wavelength is at $\lambda_0$= 1550 nm. for (Figure 1. a), and ($\lambda_0$=1530, 1500,1570, and 1600 nm for Figure 1: b, c, d, e) respectively. It can be seen the similarities between (Figure 1: b and d) and (Figure 1: c and e), and from this similarity we can see that, the behavior and values of FWM power depend on the absolute value of wavelength difference from zero dispersion wavelength $\lambda_0$= 1550 nm, so depending on this conclusion we shall focus only on the three central wavelengths $\lambda_0$= 1550nm,1530nm,1500 nm. From Figure 1, both of the input and FWM powers are increased proportionally. It is also revealed that, although, it has been applied at different input powers, however, the FWM curves profiles kept constant. Figure (1.a), illustrates, the curve performance in the state of applying the value of the central frequency $\lambda_0$=1550 nm.

The values of FWM of each line in the graph begin from small values when the fiber lengths are small (< 20 km) and increased in ascending manner when the value of fiber length is increased until it reaches the value which is near to 24km ($\Delta\beta$=0 for all products located at $\lambda_0$=1550 nm of this curve but $P_{FWM}$ reaches maximum value in $L= \ln(3)/\alpha$ which is $= 24$ km. When the values of fiber length become >24km, the values of FWM decrease slowly and that is because the values of attenuation become larger than the values of nonlinearity. This happens to the lines for different input power. Figure (1. b), illustrates, the diversion of the curve performance in the state of changing the value of the central frequency to $\lambda_0$= 1530 nm, in comparison, that shown in Figure (1. a), yet, the FWM power values less while lengths remain similar. These curves are characterized by having some resonances which are increasing in numbers and decreased in their sizes when using $\lambda_0$=1500 nm, as shown in Figure (1. c), these resonances take place because the change of phase mismatch $\Delta\beta$ with fiber length periodically, especially in the first 100 Km of the fiber.

**Case (2):** is explained, the state of using the system of three channels and changing the values of the fiber effective area of the fiber three times (25, 50, 100 $\mu m^2$) at selected central wavelengths with input power of 1mwatt, and the frequency of spacing is $\Delta f$ = 50 GHz for different fiber lengths as illustrated in the (Figure 2: a, b and c), respectively. However, the three Figures shown the reverse relationship between the fiber effective area and the FWM power, taking into consideration that the profiles of FWM curves kept constant, when three wavelengths are applied in the different effective areas. Moreover, each line of the three curves also shown the proportional increases of the values of FWM power at the first 20 Km. However, this proportion relationship is started as small values of the FWM

![Figure 1: Variations of FWM power as a function of the fiber length for three values of signal input powers.](image-url)
power and as smallest as (< 20 km) of the fiber lengths values, which increases proportionally in ascending manner, until the fiber length in which the FWM reach its maximum values at (~ 24 km). For values of fiber length greater than this value, the FWM value is starting slowly, decreasing, and that has happened because the attenuation becomes larger than the value of nonlinearity of FWM. In the state of Figure 2.b, which illustrates, the diversion of the curve performance in the state of reducing the value of the central frequency to \(\lambda_0=1530\) nm, in comparison with the curve, that shown in Figure (2. a), yet, the values become less while lengths remain similar. These curves are characterized by having resonances which increase in the numbers and decrease in their sizes at \(\lambda_0=1500\) nm, as it is shown in Figure (2. c).

![Figure 2: Variations of FWM power as a function of the fiber length for three values of fiber effective area.](image)

**Case (3):** explained, the state of using many channel systems (3, 5, 7, 9 and 11 channels), and using the value of the fiber effective area= 50 \(\mu\)m\(^2\) at selected central wavelengths (\(\lambda_0=1550\) nm) with input power of 1 mwatt, and the frequency of spacing is \(\Omega= 50\) GHz for different fiber lengths as illustrated in the Figure (2.a). The selected central wavelengths are changed to (\(\lambda_0= 1530\) nm and \(\lambda_0= 1500\) nm) for Figure 2 (b and c), respectively. These three Figures are shown the proportional increasing on both the number of channels and the FWM power, taking into consideration that the profiles of FWM curves kept constant, when different numbers of channels are applied. Moreover, the three curves are also, shown the proportional increases of the values of FWM power and the numbers of channels. However, this proportion relationship is started as small values of the FWM power and as smallest as (< 20 km) of the fiber lengths values, which are increasing proportionally, in quickly ascending manner until the FWM power reaches its maximum values of fiber length near (~ 24 km) at \(\lambda_0= 1550\) nm. The FWM value is starting slowly, decreasing because the values of attenuation ultimately become larger than the value of nonlinearity of FWM. In the state of Figure (3.b), which illustrates, the diversion of the curve performance in the state of using the value of the central frequency \(\lambda_0=1530\) nm, in comparison with the curve, that is shown in (Figure 3.a), yet, the values of FWM powers become less while lengths remain similar. These curves are characterized by having some resonances, and these resonances increases in the numbers and decrease in their sizes at \(\lambda_0=1500\) nm, as it is shown in Figure (3.c). There is a proportional association between the determination of the locations of the FWM maximum numbers and other parameters including the channel numbers and the central wavelength signals. It is shown, that the locations of the maximums FWM values at \(\lambda_0= 1550\) nm is 24 km, in comparison with the < 10 km when the FWM values at \(\lambda_0= 1530\) nm. Moreover, it is also, when using \(\lambda_0= 1530\) nm as in Figure (3.b) it is shown, that the FWM maximum power of line of eleven channels is taking place approximately at 5 km, in comparison of 10 km when using only three channels of FWM maximum power are applied.
Case (4): is explained, the state of using the system of three channels and changing the values of frequency channel spacing three times (Ω= 25 GHz, Ω= 50 GHz and Ω= 100 GHz) and using the value of the fiber effective area= 50 μm² with input power of 1 mwatt, for different fiber lengths at selected central wavelengths which equal to λ₀= 1550 nm as illustrated in Figure (4.a), the selected central wavelengths are changed to (λ₀= 1530 nm and λ₀= 1500 nm) for Figure 4(b and c), respectively. From the curves of the three figures, both the channel spacing and FWM powers are increased inversely. It is also revealed that, although, it has been applied a different channel spacing, however, the FWM curves profiles kept constant. The Figure (4.a), illustrates, that the curve values of the FWM power at λ₀= 1550 nm is extremely at a maximum ratio, when the channel spacing of Ω= 25 GHz is applied. Although, the curve values of the FWM powers of Ω= 25 GHz and Ω= 50 GHz show a similarity in comparison to each other (the difference between them is very little), however, they are shown a higher values in comparison to the curve values of Ω= 100 GHz. Moreover, it is also shown of the coincidence of both Ω= 25 GHz and Ω= 50 GHz of the FWM curves and the central wavelength of λ₀= 1550 nm. This means that at the value of λ₀=1550 nm, the FWM curves do not alter whether the value of the channel spacing is Ω= 25 GHz or Ω= 50 GHz, the FWM efficiency is shown a very small different in the first 100 km of fiber length as illustrated in figure (5.a). It is also revealed that at Ω=100 GHz, the three of the FWM curves values are shown a matching in their lengths, particularly in the range of first 12 km, these length values become distinguished when their ranges are further extended. The Figure (4.b), illustrates, the behavior of the FWM curve in the presence of another parameter of central wavelength λ₀= 1530 nm and Ω =25GHz. It is increased gradually from as small as a length value of < 10 km, until it reaches the maximum values at the location of (=18 km), before it starts decreasing soon after. The second curve, is shown that the FWM value at the Ω= 50 GHz is lesser in comparison to the first curve, it is also shown a two distinguished resonances. The third curve, is shown that the FWM value at Ω= 100 GHz is further lesser in comparison to the previous curves, it is also shown a many less significant resonances. The Figure (4.c), illustrates, the behavior of the FWM value curve, in the present of other parameters including the central wavelength λ₀= 1500 nm and Ω= 25 GHz, it is lesser in comparison to the curves of λ₀= 1550 nm or 1530 nm of Ω= 25 GHz. The second curve, is shown that the FWM value at Ω= 50 GHz is lesser in comparison to the second curves of the Figure 4. (a, b), yet, it is shown extra resonances, but smaller sizes. The third curve, is shown that the FWM value at Ω= 100 GHz is further lesser in comparison to the other curves of this figure and to the curves of the Figure 4 (a and b), furthermore, these curves are showing more slightly small resonances and yet, oscillatory performance. Therefore, the Figure 4 (a, b and c), are showing that the maximum value of the FWM curves occurred at λ₀= 1550 nm and at the fiber length L≈ 24 km.
Case (5): is explained, the state of the variations of the FWM efficiency as a function of fiber length when using a system of three channels and changing the values of frequency channel spacing three times ($\Omega=25$ GHz, $\Omega= 50$ GHz and $\Omega=100$ GHz), and the value of the fiber effective area= 50 $\mu$m$^2$ with input power of 1mwatt at selected central wavelengths which equal to $\lambda_0= 1550$ nm as illustrated in Figure (5.a). The selected central wavelengths are changed to ($\lambda_0= 1530$ nm and $\lambda_0= 1500$ nm) for Figure 5 (b and c ), respectively. The Figure (5.a), illustrates, that the values of the FWM efficiency at $\lambda_0= 1550$ nm is extremely at a maximum ratio, when the channel spacing of $\Omega=25$ GHz is applied and it seems equal to 1 for all values of fiber length and that is because $\Delta\beta$ is equal to zero or approximately equal to zero for all values of fiber length. FWM efficiencies of the value of $\Omega= 100$ GHz decrease until $L= 100$ km, for $L>150$ km the values of FWM efficiency become constant and=0.69. The FWM efficiency is shown a very small difference between the case of $\Omega= 25$ GHz and $\Omega=50$ GHz and the value of the difference becomes constant after $L> 120$ km. The Figure (5.b), illustrates, the behavior of the FWM efficiency curve, which, in the presence of other value of $\lambda_0= 1530$ nm and in the case of $\Omega= 25$ GHz, where it is decreased gradually from as small as a length value of < 10 km, until it reaches the minimum values near the location of (≈ 100 km), before it starts having a constant value equal to (0.27). The second curve is shown that the FWM efficiency value at $\Omega= 50$ GHz is lesser in comparison to the first curve and a sharp decrease of the values of FWM efficiency in the first 20 km until it reach its constant value at 50 km. Moreover, the third curve, is shown that the FWM value at the $\Omega= 100$ GHz is further lesser in comparison to the previous curves and shown a very sharp decrease of the values of FWM efficiency in the first 10 km until it reaches its constant value at 20 km. The Figure (5.c), illustrates, the behavior of the FWM efficiency curve, which, in the presence of another value of $\lambda_0= 1530$ nm and in case $\Omega= 25$ GHz, where it is decreased gradually from as small as a length value of < 10 km, until it reaches the minimum values at the location of (≈ 50 km), before it starts having a constant value equal to (0.08). The second curve, is shown that the FWM efficiency value at $\Omega= 50$ GHz is lesser in comparison to the first curve and a sharp decrease of the values of FWM efficiency in the first 10 km until it reaches its constant value at 20 km. The third curve, is shown that the FWM value at the $\Omega= 100$ GHz is further lesser in comparison to the previous curves and shown a very sharp decrease of the values of FWM efficiency in the first 5 km until it reach its constant value at 5 km.
5. Conclusion

The study is investigated of the consequences of the impact of the FWM phenomenon on the WDM systems (showing the effect of the fiber length on the FWM power and efficiency), by using the G.653 of specific ITU-T context. The use of specific uniform channels spacing of (25 GHz, 50 GHz and 100 GHz) are recommended. The development of the numerical model that based on the non-depleted pump hypothesis is shown of enhancing the phase mismatch progress and the FWM power generation. Furthermore, the FWM power generation is also shown to be affected by the chromatic dispersion of the fiber, however, since the requirements of the phase matching for FWM generations are encountered, once the transmitted channels are positioned around the zero-dispersion wavelength of the fiber. Therefore, the difficulties that encountered the FWM can be sorted out by utilizing a highly chromatic dispersive optical fiber, which causes a phase delay amongst a different propagating channels through, the use of the wavelength window (1500-1540 nm) or (1460-1600 nm). Several results are achieved in this study, which essentially, are indicating, of the possibility of FWM phenomenon lessening. Firstly, this is achieved by allocating the WDM channels away of the zero-dispersion wavelength of the DSF fiber, and secondly, by avoiding using fiber length < 24 km especially in the case of $\lambda_0 = 1550$ nm. It is important to avoid using fiber length < 12 km in the case $\lambda_0 >$ or < 1550 nm because of the oscillatory behavior in this region of the fiber. Moreover, it is also shown that the use of large effective area of (>100 $\mu$m$^2$) may possibly alleviate the nonlinear crosstalk between channels, yet, using the minimum input signal's powers, once added extra channels in the system.

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