

## Research Article

### Four Wave Mixing Suppression in Optical Systems Through System Parameters Optimization

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**Abstract:** Four-Wave Mixing (FWM) is defined as an undesirable nonlinear effect that gives significantly degraded system performance and is expected to become the major drawback for optical communication systems. This study presents a method to suppress the FWM through system parameters optimization. The study was conducted on four different types of optical fiber, i.e., Single-Mode Fiber (SMF), Dispersion Shifted Fiber (DSF), Non-Zero Dispersion Fiber (NZDF) and Non-Zero Dispersion Shifted Fiber (NZDSF). The results proved that the optimization of the parameters can reduce the effect of FWM in optical fiber link. It showed that a maximum FWM power level was observed with DSF and a minimum FWM power level with SMF with little effect on the optical link channel. Moreover, the results demonstrated that the SMF type with reduced the input power and increased channel spacing decreases the effect of FWM power materialization to a minimum value with reduction rate of 22 dB in compared to varying other parameters. In the case of system performance with the optimization of (decreasing the input power and increasing channel spacing), the BER was  $1.90 \times 10^{-25}$  at received power of 7 dBm. However, in the presence of optimization (increasing both effective area and channel spacing) the BER was found to be less than  $2.84 \times 10^{-20}$  at same received power.

**Keywords:** BER, four-wave mixing, FWM suppression methods, nonlinear effect, Single Mode Fibre (SMF),

## INTRODUCTION

The performance of optical transmission systems under ultra-high data rate and long-haul transmission distance face some of the undesirable phenomena that may degrade the optical system efficiency and causes probable distortion of the optical signal (Wehmann *et al.*, 2005; Feng *et al.*, 2010; Jintae *et al.*, 2001). This phenomenon is called nonlinear effects (Kaura *et al.*, 2010). FWM is one of these effects, which represent the strongest detrimental behavior. It occurs when two or more waves propagate in the same direction in the same fibre. Some of the signals become mixed to produce new signals as the same interval spacing (Kaler and Kaler, 2012). Normally, when multiple optical channels are launched into the same optical fiber, it will interact with each other very weakly. However, for a long fibre transmission distance, these interactions can become more significant (Jamshidifar *et al.*, 2009). In Wavelength Division Multiplexing (WDM) systems, the occurrence of FWM generally depends on a number

of factors such as power per channel, wavelength spacing between channels, transmission distance, effective area and dispersion characteristics of the optical fibre (Kaler and Kaler, 2012).

In the past few years, several approaches and methods have been developed to overcome the effect of FWM. Jamshidifar *et al.* (2009) suggested a technique to reduce the effect of FWM crosstalk by using short fiber Optical Parametric Amplifiers (OPAs) which decreases the fiber length from 340 to 50 m and raises the pump power to keep the gain to 20 dB. It reduces the effect of FWM by 16 dB, but the disadvantage of this technique is that the crosstalk level reduction predicted by Standard Single Mode Fibre (SSMF) simulation was less than what was experimentally observed.

Kaler *et al.* (2004) made a comparison through computer simulation the effect dispersion on FWM. It was suggested that the FWM could be reduced by dispersion techniques and it was shown that the FWM power was reduced when the dispersion is increased. However, the main drawback of this approach is that the dispersion compensation is not taken into account.

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Singh *et al.* (2008) proposed a theoretical analysis of both single and combined effects of second, third, fourth and fifth-order dispersion parameters on FWM at different input channels powers and core effective areas. It was proved that the FWM power can be reduced by mixing the effects of second to fifth dispersion terms, but the main defect of this technique there is no calculation of the effect of increasing the dispersion on bit-error-rate.

Emdadul (2010) compared the performance of Non-Return-to-Zero Differential Phase Shift Keying (NRZ-DPSK) with normal NRZ Intensity Modulation-Direct modulation (IMDD) in the presence of FWM under effect of channel spacing, input optical power and chromatic dispersion. DPSK modulation showed high tolerance to nonlinear effect (FWM) than IMDD. However, the main lack of this approach that under the effect of dispersion with the values of (0 and 17 ps/nm.km), the optical spectra and eye diagrams is the same for these two values.

In this study, we suggested using optimized system parameters to reduce the FWM effect in the WDM system. A theoretical analysis has been done to describe the behavior of FWM power under the effects of both single and mixed parameter such as effective area, input power and channel spacing with different type of optical fibre. Subsequently, the impact of FWM on system performance was performed. The objective of this study is to find an optimized method to reduce the FWM effect and enhance the system performance in term of bit error rate.

**Evaluation of system parameter optimization for FWM suppression:** The FWM effect is the phenomenon that occurs when two or more light waves propagate inside the fibre. The generated FWM terms may fall into the spectrum of transmitted channels. The FWM effect appears when the phases of the light wave channels are matching. The power transferred due to FWM signal to new frequencies after light has propagated for a distance L in the fibre can be estimated by the following equation (Sabapathi and Sundaravadivelu, 2011):

$$P_{FWM} = \frac{1024 \pi^6}{n^4 \lambda^2 C^2} \left( \frac{Dx_{111} L_{eff}}{A_{eff}} \right)^2 (P_i P_j P_k)^N e^{-\alpha L} \frac{\alpha^2}{c \alpha^2 + 2\pi D_c (\Delta f_{ik})(\Delta f_{jk})} \quad (1)$$

where,  $P_i$ ,  $P_j$  and  $P_k$  are the input powers at central frequency  $f_i$ ,  $f_j$  and  $f_k$ , respectively. D is the degeneracy factor and is equal to 3 for two-tone and 6 for three-tone systems,  $X_{111}$  is the third order susceptibility, equal to  $6 \times 10^{-15}$  ( $m^3/w.s$ ),  $A_{eff}$  is the effective area, C is the speed of light,  $\lambda$  is the laser wavelength,  $\alpha$  is the fiber loss coefficient, L is the total fiber length, n is the refractive index of the fiber,  $L_{eff}$  is the nonlinear

effective length,  $D_c$  is the fiber chromatic dispersion,  $dD/d\lambda$  is a derivative dispersion coefficient of optical fiber, N is the number of channels and  $(\Delta f_{ik}, \Delta f_{jk})$  is the channel spacing. Table 1 shows the system simulation parameters that are used in this study.

The FWM noise power  $N_{FWM}$  is obtained from (Chin *et al.*, 2008) as follows:

$$N_{FWM} = 2b^2 P_s \left( \frac{P_{FWM}}{8} \right) \quad (2)$$

where, b is the responsivity of the detector,  $b = (\eta e/hf)$ , h is the Planck's constant,  $\eta$  is the quantum efficiency of the detector, e is the elementary electric charge and  $P_s$  is the signal light power at the receiver that it may be assumed. The system performance can be evaluated using Q factor as Chin *et al.* (2008):

$$Q = \frac{bP_s}{\sqrt{N_{th} + N_{sh} + N_{FWM}} + \sqrt{N_{th}}} \quad (3)$$

where,

- Q = The maximum Q factor
- $N_{FWM}$  = The FWM noise
- $N_{sh}$  = The shut noise
- $N_{th}$  = The thermal noise

The FWM noise is the dominate noise in this system and all noise is can be neglected:

$$Q^2 = \frac{b^2 P_s^2}{2b^2 P_s \frac{P_{FWM}}{8}} \quad (4)$$

and the BER can be calculated from the Q factor:

$$BER = 0.5 \times \text{erfc} \left[ \frac{Q}{\sqrt{2}} \right] \quad (5)$$

Table 1: System parameters for FWM suppression study

Parameter	Unit	Values
Fiber length, L	km	5-60
Input power, $P_i$	W	0.08-0.01
Channel spacing, $\Delta f$	GHz	100
Dispersion	ps/nm.km	0-18 (depend on fiber type)
Cross effective area, $A_{eff}$	$\mu m^2$	15-64
Degeneracy factor, D	-	6
Third order susceptibility, $X_{111}$	$m^3/w.s$	$6 \times 10^{-15}$
Speed of light, c	(m/s)	$3 \times 10^8$
Operating wavelength, $\lambda$	(nm)	1550
Attenuation factor,	(dB/km)	0.2
Nonlinear effective length, $l_{eff}$	km	10
Responsivity, b	$AW^{-1}$	0.8
Number of channel	-	3

Table 2: Main parameters of the four fiber samples under test

Fiber type	Dc (ps/nm/km)	$\alpha$ (dB/km)	$\gamma$ (wkm) <sup>-1</sup>
SMF	17	0.20	2.50
DSF	0	0.24	4.00
NZDF	3	0.23	3.90
NZDSF	4.5	0.25	3.84

The first parameter that was varied is the cross effective area. Figure 1 shows the relationship between FWM power and cross effective of 50 km fiber length and 0.08 W input power. The calculation was done for different types of optical fibers, i.e., SMF, DSF, NZDF and NZDSF respectively after applied Eq. (1). The results illustrate that when the cross effective area increases, the FWM power decreases where the behavior varies between the fiber types. It is observed that the FWM power is highest with DSF where it reaches to a value of 3 dBm at the cross effective area of  $15 \mu\text{m}^2$ . This is due to the zero dispersion case in the DSF fiber at 1550 nm. The opposite case is with the SMF that has dispersion value of 17 ps/nm.km, where the FWM power dropped to the lowest value of -6 dBm for the effective area of  $15 \mu\text{m}^2$ . Table 2 shows the system Parameters of four optical fiber samples.

The FWM power suppression performance was found to be suppressed under the combined effect of increasing both the effective area with channel spacing for the same condition. Figure 2 depicts the effect of the cross effective area on the FWM power when the channel spacing is increased (from 100 to 150 GHz). It can be seen in Fig. 2 that the FWM power has a maximum with the DSF fibre, which reached -8 dBm while it has a minimum value with SMF fiber at -17 dBm. The difference in these results of FWM power reduction of Fig. 1 and 2 confirmed that the combined effect of increasing the cross effective area and increasing the channel spacing reduced the FWM further with 11 dB suppression.

Based on the above finding, further investigation was conducted using SMF as chosen fibre. The second parameter investigated is the input power. Figure 3 illustrates the FWM power as a function of input power with variable length of SMF under input parameters such as channel spacing of 100 GHz and effective area of  $64 \mu\text{m}^2$ . As shown in the Fig. 3, decreasing the input power reduces the FWM effect. Interestingly also, the FWM power is lowest (-30 dBm) when the fibre length is equal to 25 km at 0.08 W. While it the highest value reaches 0 dBm when fibre length is equal to 10 km at similar input power.

Figure 4 shows the effect when the input power is reduced and the channel spacing are increased (increase  $\Delta f$  from 100 to 150 GHz). The FWM power is highest

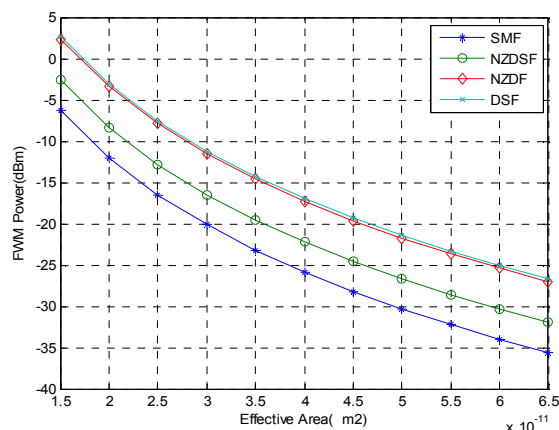


Fig. 1: FWM power with varying effective areas for 4 types of optical fiber

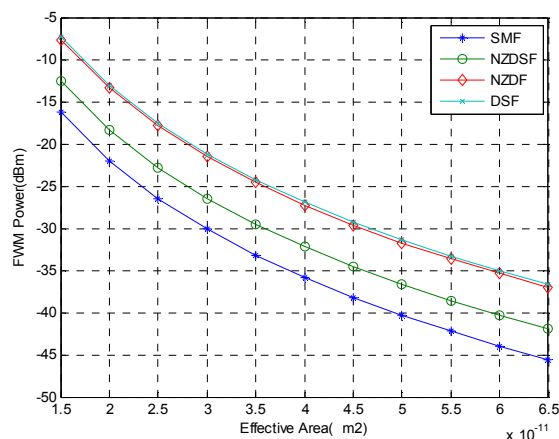


Fig. 2: FWM power vs. effective areas for an increased in channel spacing

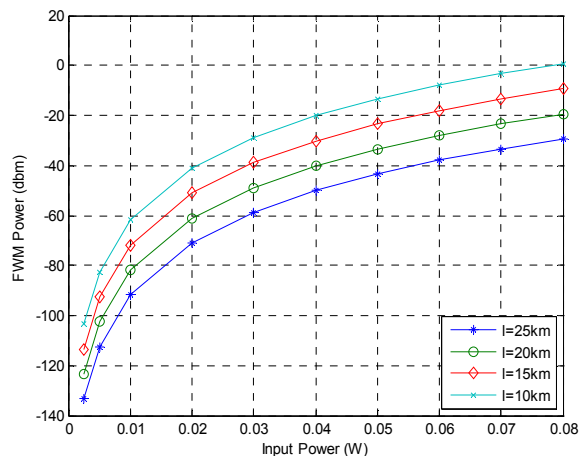


Fig. 3: Relation between FWM powers with input power for different fiber length

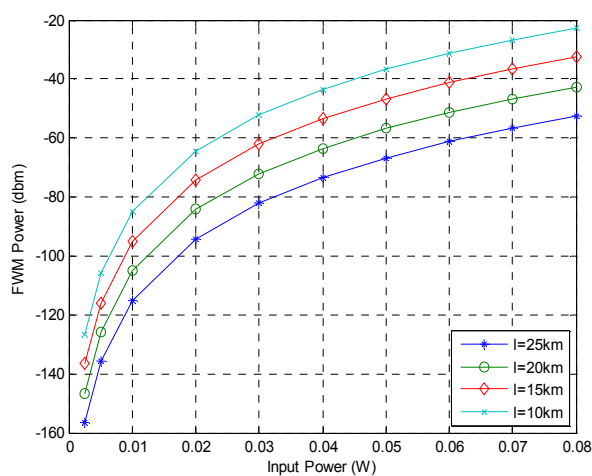


Fig. 4: Relation between FWM powers with input power for different fiber length with an increase in channel spacing

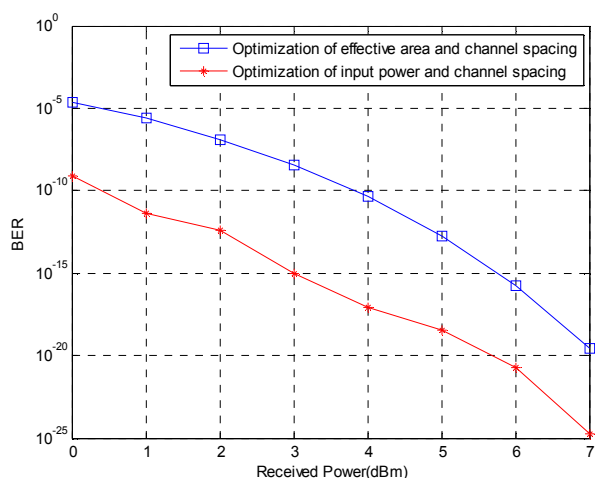


Fig. 5: Relation between received power and BER under optimization effect of different parameter

Table 3: Summary of system optimization results

Optimization name	Min. FWM power (dBm)	FWM reduction ratio (%)	Min. BER
Effect of (increase effective area + increase channel spacing)	-17	11	$2.84 \times 10^{-20}$
Effect of (reduce the input power + increase channel spacing)	-54	22	$1.90 \times 10^{-25}$

Min.: Minimum

at 10 km length with a value of -22 dBm, while at 25 km the value is -54 dBm for a same input power. When both figures are compared, the FWM power has been reduced by more than 22 dB. This leads to a conclusion that the combined effect of decreasing the input power

and increase the spacing between channels would suppress the FWM power to optimum values.

Figure 5 shows the relationship between the received power and BER under the effect of optimization (effective area and channel spacing) and optimization of (input power and channel spacing). The results are obtained after applied Eq. (2) to (5) and the system performance has been calculated in the case of single mode fiber that introduced minimum FWM power. Observation of the results show that increased received power will reduce the BER for both types optimization effect. The behavior of BER differed from one optimization to other to the FWM noise. In the case of optimization of (input power and channel spacing) the system performance gives the minimum value for BER and it is  $1.90 \times 10^{-25}$  at received power of 7 dBm. Inversely, in optimization of (effective area and channel spacing), it gives the maximum value of BER in the range of  $(2.84 \times 10^{-20})$  at the same received power. Table 3 explains the summary of system optimization results.

## CONCLUSION

In this study, the effect of single and combined system parameters towards the reduction of FWM power was studied and presented. The FWM power behaviour was studied using four different fiber optic; SMF, DSF, NZDF and NZDSF. The results proved that the FWM power is highest in DSF and lowest in SMF. It also showed that optimizing two parameters, which were reducing the input power and increasing the channel spacing together, are a good combination to reduce FWM power. The value is lowest where up to 22 dB reduction was achieved if compared to optimizing only one parameter at a time. In addition, In the case of system performance under optimization of (input power and channel spacing), the BER reaches to  $1.90 \times 10^{-25}$  at received power of 7 dBm, while in available of optimization (effective area and channel spacing) the BER was found to be less than  $2.84 \times 10^{-20}$  at same received power. Overall, it can predicted that FWM suppression through combined system parameters optimization should be considered for ridding the optical transmission system of impairments caused by the FWM effect.

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