Comparative Analysis of DCF and OPC as Means to Minimize FWM in WDM System

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Abstract

Wavelength Division Multiplexing (WDM) has made possible bidirectional communication while simultaneously multiplying the capacity of Optical Communication System. Apart from dispersion, WDM system is prone to non-linear effects like Four-Wave Mixing (FWM). In this paper, FWM effects have been discussed in detail with important techniques to mitigate FWM effects. Dispersion Compensating components like, Dispersion Compensating Fiber (DCF) and Optical Phase Conjugator (OPC), used for FWM reduction, have been compared on the basis of certain parameters. The comparison is carried out in the OptiSystem simulator, varying different parameters and analyzing the results. Based on these results and observations, the best component at various values of important parameters can be determined. This comparison will help determine the feasibility of using any one component in practical applications. Also, this research opens the door to check the possibility of utilizing hybrid configurations of dispersion compensating components for FWM reduction.

Keywords: Channel Spacing, Dispersion Compensating Fiber, Four Wave Mixing, Input Power, Number of Channels, Optical Phase Conjugator

1. Introduction

Multiplexing is a technique used to send various digital data streams or analog message signals over a shared medium i.e. more than one signal is sent over the same line. It is used in telecommunications and computer networks. An expensive resource can be shared by multiplexing technique. Multiplexing is of two types: Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM). TDM is a method in which independent signals can be transmitted and received over a single path by synchronizing each end of the line of transmission such that each signal appears on the line in an alternating pattern for a fraction of the time. It is the least efficient form of multiplexing. This method is not economical for digital information transfers[1]. TDM technique is illustrated in Figure 1.
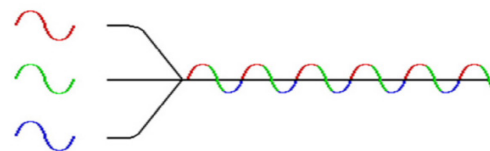

Figure 1. Time division multiplexing.

On a communication line when the number of users remains same or is very high, a method of multiplexing called WDM can be used. WDM is a technology in which whole information is transmitted through multiple channels over a single fiber. It enables bidirectional communications and multiplication of capacity. The advantage of WDM is high rate of transmitted signal all the time. The transfer rates proportional to the number of users on the line are not affected by WDM system. Another added advantage is the transfer of information without much of

the signal integrity loss. Efficiency of optical fiber communication system has been improved significantly by WDM. This technique has provided optical fiber communication system with large channel capacity. WDM fully utilizes the large bandwidth provided by optical fiber[2,3] by permitting huge amounts of data in different channels to be transferred at different wavelengths. The process of WDM is shown in Figure 2.
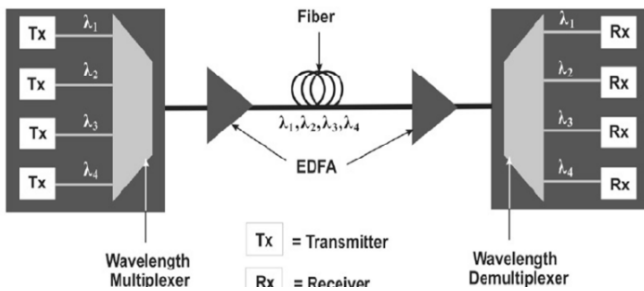

Figure 2.   Wavelength division multiplexing.

In WDM system, optical fiber suffers from some form of undesirable effects, known as nonlinear effects. The nonlinear effects occur either due to inelastic – scattering phenomenon or due to the intensity dependency of refractive index of medium. Nonlinear effects cause the energy of the channel to be wasted[2,3] by creating distortion of the output signal. The nonlinear impairment affecting the efficiency and performance of the system should be minimized[2,4] in order to meet the high speed and long –haul transmission distance in WDM systems**.**

2 Non-Linear Effects

Non-linear effects degrade performance of WDM system. Linear effects like dispersion and attenuation can be compensated, but it is very difficult to overcome non-linear effects. They put limitation to the quantity of transmittable data in optical fiber. The nonlinear effects occur either due to the inelastic scattering phenomenon or the intensity dependence of refractive index of the medium. As shown in Figure 3, non-linearity can be classified into three different types based upon the type of input signal: Self Phase Modulation (SPM), Cross Phase Modulation (CPM) and Four Wave Mixing (FWM). Stimulated effects like Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS) can be induced by the inelastic scattering phenomenon at high power levels. Four-wave mixing has the strongest detrimental effects[2,4] among all

nonlinear effects. The performance of the system can be limited by FWM when a high power signal entered into a fiber, where the linearity of the optical response is lost.
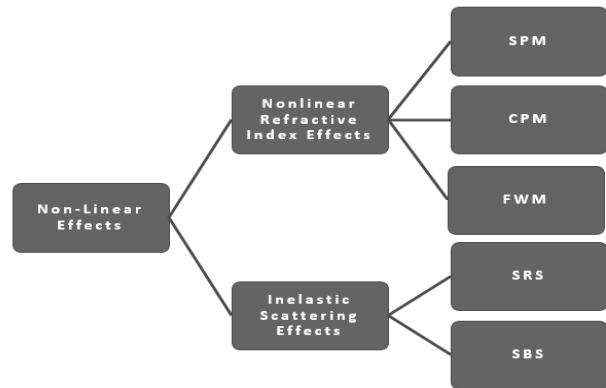

Figure 3.   Nonlinear effects in optical fibers.

2.1 Self-Phase Modulation

In SPM, the phase of an optical signal is modulated by itself, well depicted in Figure 4. It occurs in single-wavelength systems. SPM tends to cancel dispersion at high bit rates. SPM depends on signal power levels. SPM occurs at high levels of signal. It results in phase shift and a nonlinear pulse spread. Pulses are overlapping and no longer be distinguished by the receiver in SPM. SPM is used for fast optical switching, for the formation of standard and dispersion-managed optical solitons[5]. It is useful for all optical regeneration of WDM channels. It has many other applications like chirped-pulse amplification, pulse compression and spectral broadening.

Figure 4.   Self phase modulation.

2.2 Cross-Phase Modulation

The most dominating phenomenon in WDM system is Cross-Phase Modulation (CPM/XPM). CPM is a nonlinear effect in which the wavelength of one light, through the optical Kerr effect, can affect the phase of another wavelength of light. Kerr effect is a limiting factor for optical network. The change in phase due to variation in power of adjacent channels strongly affects the system

performance[5]. It results in interaction of laser pulses in a medium. It is used for passive mode locking, ultrafast optical switching, non-linear pulse compression and wavelength compression of WDM channels. This phenomenon is shown in Figure 5.
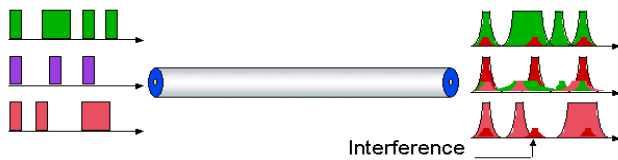
Figure 5. Cross-phase modulation.

2.3 Four-Wave Mixing

Another dominating effect in WDM systems is Four Wave Mixing (FWM), which is having a low chromatic dispersion and dense channel spacing. When the channels in WDM system are equally spaced, crosstalk is produced due to FWM as the FWM generated waves are present at channel frequency. FWM is a process in which interaction of various frequencies with each other and generation of new spectral components takes place[4,6]. It is an example of nonlinear effect which occurs when light of distinct wavelengths enter the fiber. When light of three distinct wavelengths enters into the fiber and results in new wave (known as anidler) whose wavelength does not match with parent light (Figure 6). FWM is used in squeezing and wavelength conversion[7].
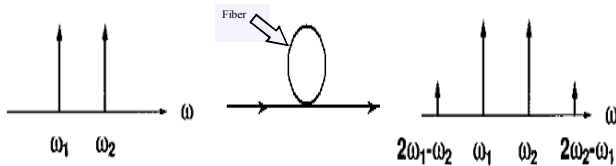
Figure 6. Four-wave mixing.

2.4 Stimulated Raman Scattering (SRS)

In SRS, propagation of light is through a medium. During the propagation, the interaction of photons with silica molecules takes place. They also interact with themselves and produce scattering effects like Stimulated Raman Scattering in the reverse and forward propagation directions along the fiber resulting in energy distribution in a random direction[4,6]. In SRS, scattering of energy creates a low-wavelength wave called **Stoke's wave** which amplifies higher wavelengths (Figure 7). The basis of Raman amplification is the gain obtained by using such a wave.

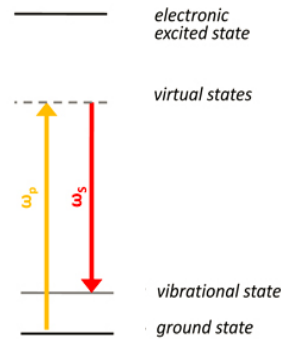By lowering the input power the effect of SRS can be reduced.

Figure 7. Stimulated raman scattering.

2.5 Stimulated Brillouin Scattering (SBS)

In SBS also, propagation of light is through the medium. Interaction of photons with silica molecules takes place during propagation of light. Interaction among themselves produces scattering effects such as SBS in a reverse direction, i.e. direction reverse to the direction of propagation. In SBS, scattering of energy creates a low-wavelength wave called **Stoke's wave** which amplifies higher wavelengths (Figure 8). The basis of Brillouin amplification is formed by this gain obtained from such waveforms[1].
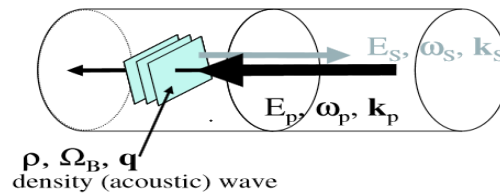
Figure 8. Stimulated brillouin scattering.

3. Parametric Analysis of Four-Wave Mixing in WDM Optical Fiber Systems

3.1 Effect of Input Power

Input power is one of the most important and experimented parameters for decreasing the effect of FWM in WDM systems. Input power is directly proportional to FWM. By keeping all the parameters constant and decreasing the input power of transmitter FWM decreases. It is noticed that by decreasing the input power minimum Bit Error Rate (BER), eye height, quality factor, threshold and Optical Signal-To-Noise Ratio (OSNR) decreases[2,8].

3.2 Effect of Channel Spacing

Channel spacing is the difference of adjacent frequencies allocated in a WDM system. It is also a widely studied parameter for mitigating FWM effect. Work has been reported in the literature in which various methods have been investigated for reducing FWM by using different channel spacing[13]. Channel spacing is inversely proportional to FWM effect. Keeping all the parameters constant, an increase in the channel spacing decreases FWM. It also reduces the quality factor, OSNR and signal power. Minimum BER remains constant while other parameters are influenced to a minimum extent. In a study it has been observed that for 6.25 GHz spacing BER, FWM is quite large while for 80 GHz spacing BER, FWM is minimum[8–11].

3.3 Effect of Number of Channels

Number of channels in an optical system also determine FWM effect. As reported in numerous researches, by keeping the entire parameters constant and decreasing the number of channels decreases the FWM while increases the OSNR, quality factor and signal power[2,8,9].

3.4 Effect of Optical Gain

Optical Gain describes optical amplification of a semiconductor laser. Simulated emission created by recombination of electrons and holes causes optical gain. FWM increases with increase in optical gain. It has observed that increasing the optical gain FWM also increases. Height of the eye diagram and quality factor decreases while the rest of the parameters remains same. It also improved the OSNR[8].

3.5 Effect of Core Size of Optical-Fiber

Core size is the diameter of plastic or glass that runs along the length of an optical fiber. The core size affects FWM in a manner that if core size is increased proportionally effective core area reduces and consequently FWM also reduces[2,8].

3.6 Effect of RZ Modulation instead of NRZ

Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ) are modulations that are generally used in WDM systems for transmission of signals. RZ modulation is preferred over NRZ as it decreases FWM. It slightly reduces the eye height and quality factor while min BER remains same[8].

3.7 Effect of Duty Cycle

Percentage of a period in which a signal is active is called the duty cycle. Time taken by a signal to complete an on-and-off cycle is called a period. When the duty cycle decreases FWM also decreases and vice versa. It also decreases the min BER, quality factor, and OSNR and signal power[8].

3.8 Effect of Bit Rate

The number of bits that can be transmitted per unit time through an optical fiber is known as bit rate. Bit rate is an important parameter while studying techniques to reduce FWM. Keeping all the parameters constant and increasing bit rate increases OSNR and quality factor. It also increases dispersion thereby increasing FWM[2,8].

3.9 Effect of Placing OA in Place of DCF

A device for amplifying an input optical signal without the need of converting it into an electrical signal is known as an Optical Amplifier (OA). It is like laser with feedback from cavity suppressed or simply excluding an optical cavity. By replacing DCF by OA results in a slight reduction in FWM. Other factors show no significant change. It reduces the OSNR and signal power[8].

3.10 Effect of Optical Coupler and Equal Channel Spacing

For analyzing this parameter, optical couplers, four in number, were used. They coupled input channels and forwarded to optical combiner. The combination was of fifth and first channel, sixth and second, seventh and third; and eighth and fourth. The observation, with equal channel spacing and optical coupler, was exponential decay of FWM power[12].

3.11 Effect of Channel Delay and Equal Channel Spacing

In this alternating channel was delayed by 10ps using deterministic differential group delay. It was noticed that as compared to equal and unequal channel spacing, FWM power is less in equal channel spacing with alternate delay[12].

3.12 Effect of Alternate Variable Power and Equal Channel Spacing

Alternating variable laser power was used in this method. By keeping laser power of alternating channel between

10dBm and -5dBm it was observed that FWM power was significantly less as compared to conventional methods[12].

3.13 Effect of Inter-Amplifier and Interchannel Separation

The analysis based on parameters such as interchannel separation and interamplifier separation has been done to assay the SNR in the presence of spontaneous amplifier emission. The main finding was decreasing the interchannel separation will decrease the SRS effect, decreasing the interamplifier separation will decrease the amount of ASE noise introduced. There is no effect of number of channels on inter amplifier separation[2,12–14].

4. Different Components to Mitigate FWM Effects

4.1 Dispersion Compensation Fiber (DCF)

It is a specially designed fiber that has a very high negative value of dispersion. It is used to reverse the effects of chromatic dispersion that occur when the signals traverse in standard single mode fiber at 1550 nm. It can be used for post-compensation, pre-compensation and symmetrical compensation (combination of pre and post compensation)[15,16]. Various techniques can be employed to reduce dispersion in WDM systems. But a fiber with zero-dispersion experiences additional problems like the FWM effect. FWM effect occurs in non-linear WDM systems where dispersion is negligible. For overcoming this we use components that deliberately introduce dispersion in WDM systems. Now to compensate this deliberately added dispersion, components like DCF are employed. DCF introduces negative dispersion in optical fiber cables. This functionality is used in non-zero dispersion fibers. DCF compensates deliberately added dispersion in optical fiber which in turn reduces FWM effects[17]. The disadvantage of this is that the negative dispersion deliberately introduced is difficult to overcome, the reason being, dispersion varies with length, and in fibers with multiple wavelengths this can prove to be more detrimental rather than advantageous.

4.2 Optical Phase Conjugator (OPC)

New techniques and components are being deployed to counter FWM effects in WDM Optical system, one of them is Optical Phase Conjugation. The device that causes

optical phase conjugation is called Optical Phase Conjugator (OPC). OPC is used to reverse the phase propagation direction and phase of beam of light, the reversed beam is called conjugated beam.

Mathematically, it is the complex conjugate of the input power signal. In order to suppress FWM effects the optical phase conjugation is the best alternative[18,19]. OPC is placed in the middle of the fiber link which finds the optical phase conjugation of the signal. After conjugation, impairments occurring in the second part of the link cancel impairments that occurred before conjugation in the first part of the transmission link.

This paper will compare these components on the basis of the parameters which have an effect on FWM power. Experimental results and observations will help in finding out the best alternative for FWM compensation.
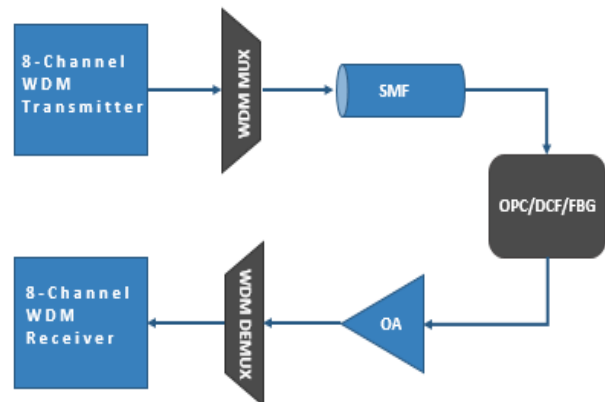
5. Simulation Setup

Figure 9.   Schematic diagram of optical system.

Figure 9 shows the schematic diagram of basic optical WDM system consisting of WDM transmitter having 8-channel with channel spacing of 100GHz, input power of 0 dBm and NRZ modulation technique followed by WDM multiplexer, optical fiber of length 100km is used. Further signal passed through DCF/OPC and optical fiber of optical gain 20dB. The output obtained from optical amplifier is fed to optical receiver via WDM demultiplexing.

In case of OPC, the optical fiber is equally divided into two fiber span and OPC is placed in the middle of the two fiber span[6].

In this paper, all the simulations have been carried out using Optisystem simulator on a 2.5Gbps WDM

System with the following specification: 2.5Gbps bit rate, sequence length of 128Bits, sample per bit 64 and sample rate of 160GHz working at normal mode. The input power was kept at 0 dBm with an 8-channel WDM transmitter.

The following equations (1, 2) have been used for calculating dispersion (D_{DCF}) and dispersion slope (S_{DCF}) of DCF in relation with SMF.

$$D_{DCF} = (D_{SMF} * L_{SMF})/L_{DCF} \qquad (1)$$

$$S_{DCF} = (S_{SMF} * L_{SMF})/ L_{DCF} \qquad (2)$$

where D_{DCF} = Dispersion in DCF
D_{SMF} = Dispersion in SMF
S_{SMF} = Dispersion Slope of SMF
S_{DCF} = Dispersion Slope of DCF

For OPC, the power obtained has been added from both the analyzers. The reason being that OPC divides the circuit into two parts and power of both parts is to be taken into account[6]. For analyzing the graphs, different visual analyzers are used, like BER analyzer, Optical Spectrum analyzer and WDM analyzer.
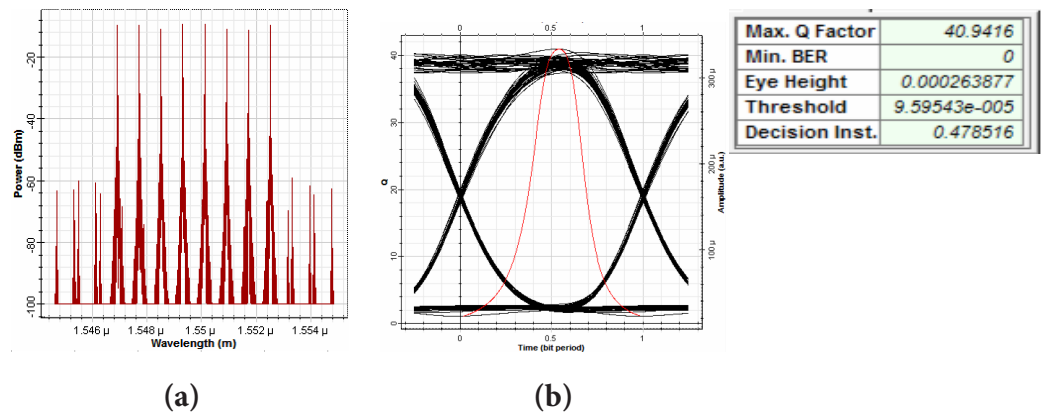

Max. Q Factor	40.9416
Min. BER	0
Eye Height	0.000263877
Threshold	9.59543e-005
Decision Inst.	0.478516

Figure. 10. **(a)** Spectrum before demux using DCF. **(b)** Eye diagram of output using DCF.
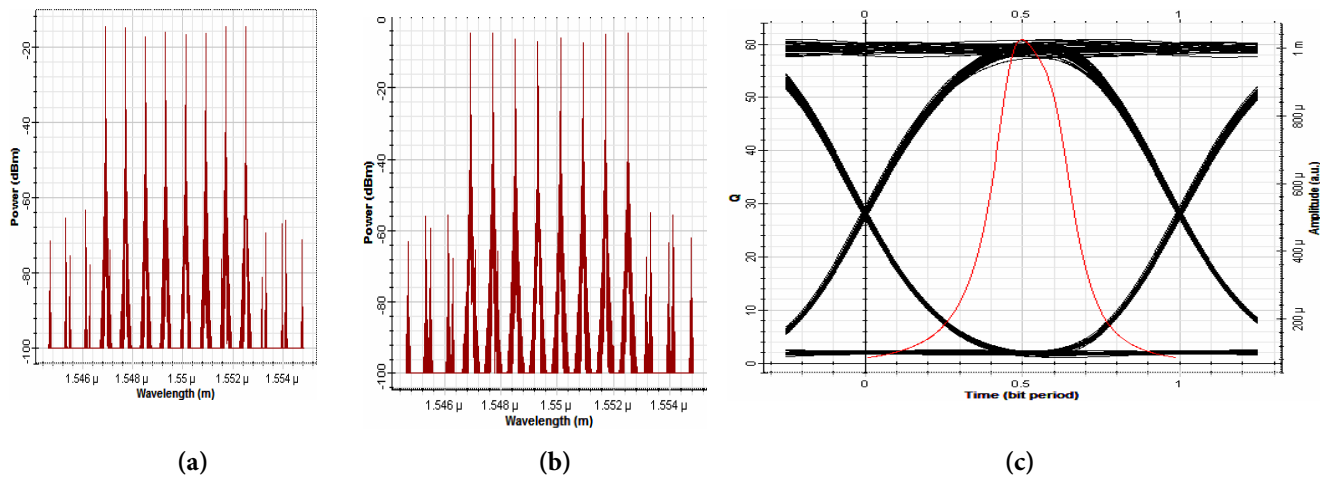

Figure 11. **(a)** Spectrum before OPC. **(b)** Output spectrum after OPC. **(c)** Eye diagram of output using OPC.

By using above parameters and simulating, Figure 10(a) shows the output of spectrum analyzer using DCF module and Figure10(b) and Table 1 shows output obtained at BER analyzer and WDM analyzer respectively. It can be observed that the original input pulses have power of -10dBm and FWM power are -60 dBm. While with OPC Figure 11(a) and 11(b) shows that the power of original input pulses are above -20 dBm and FWM power is -120 dBm. Figure11(c) and Table 2 shows the eye diagram and output obtained at WDM analyzer respectively.

Table 1. Opticle signal to noise ratio (OPC)

| Frequency (THz) | Output Values | | |
	Signal Power (dBm)	Noise Power (dBm)	OSNR (Db)
193.1	-7.73058	-35.8044	28.07387
193.2	-55.542	-82.4097	26.86769
193.3	-67.6153	-92.7574	25.14212
193.4	-74.668	-100	25.332
193.5	-79.5884	-100	20.41161
193.6	-83.4733	-100	16.52675
193.7	-86.6998	-100	13.30023
193.8	-89.3752	-100	10.62479

Table 2. Opticle signal to noise ratio (OPC)

| Frequency (THz) | Output Values | | |
	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
193.1	-84.3783	-100	15.62165
193.2	-81.7012	-100	18.29879
193.3	-78.4681	-100	21.53187
193.4	-74.5883	-100	25.41174
193.5	-69.6734	-100	30.32661
193.6	-62.6158	-93.3298	30.71393
193.7	-50.5316	-80.7234	30.19184
193.8	-2.73738	-34.4039	31.66649

6. Comparative Analysis of OPC and DCF based on Various Parameters

DCF and OPC are components that are employed in WDM systems for compensation of dispersion as well as FWM effects reduction[17,19]. There are various other factors on the basis of which these two components can be compared. Some of these parameters are input power, data rate, and number of channels on the basis of which the performance analysis of the proposed system is carried out.

6.1 Input Power

Input power is one of the most studied and experimented parameter for decreasing the effect of FWM in WDM

systems[4]. It is directly proportional to FWM. By keeping all other parameters constant and varying input power it can be observed from readings (Table 3 and Table 4) that, reducing input power to -10 dBm in DCF it can be seen that average decrease in OSNR is 50%. From Figure 12(b) the considerable decrease in eye height and Quality factor can be observed. Power of FWM products also reduces by more than 20 dBm (Figure 12(a)).

In OPC, on decreasing input power to -10 dBm the average decrease in OSNR is 35%. From Figure 13(c) it can be seen that eye height and Quality factor also decreases. The advantage of decreasing input power is that FWM products power decreases by more than 30 dBm (Figure 13(a) and Figure 13(b)).

Thus, on the basis of input power, it can be concluded input power causes OSNR to decrease to a larger extent in DCF as compared to OPC. Also, reduction in FWM is

Table 3. Effect of input power (DCF)

| Frequency (THz) | Output Values | | |
	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
193.1	-17.7373	-35.8044	18.06713
193.2	-65.5329	-82.4097	16.87675
193.3	-77.62	-92.7574	15.13739
193.4	-84.659	-100	15.34101
193.5	-89.5939	-100	10.4061
193.6	-93.4757	-100	6.524305
193.7	-96.6957	-100	3.304259
193.8	-99.3772	-100	0.622781

Table 4. Effect of input power (OPC)

| Frequency (THz) | Output Values | | |
	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
193.1	-94.374	-100	5.626007
193.2	-91.6985	-100	8.301456
193.3	-88.4766	-100	11.5234
193.4	-84.5977	-100	15.40227
193.5	-79.6588	-100	20.34122
193.6	-72.6183	-93.3298	20.71146
193.7	-60.5333	-80.7234	20.19012
193.8	-12.7361	-34.4039	21.66774

Max. Q Factor	11.2831
Min. BER	7.21411e-030
Eye Height	2.0751e-005
Threshold	1.18046e-005
Decision Inst.	0.548828

(a)   **(b)**
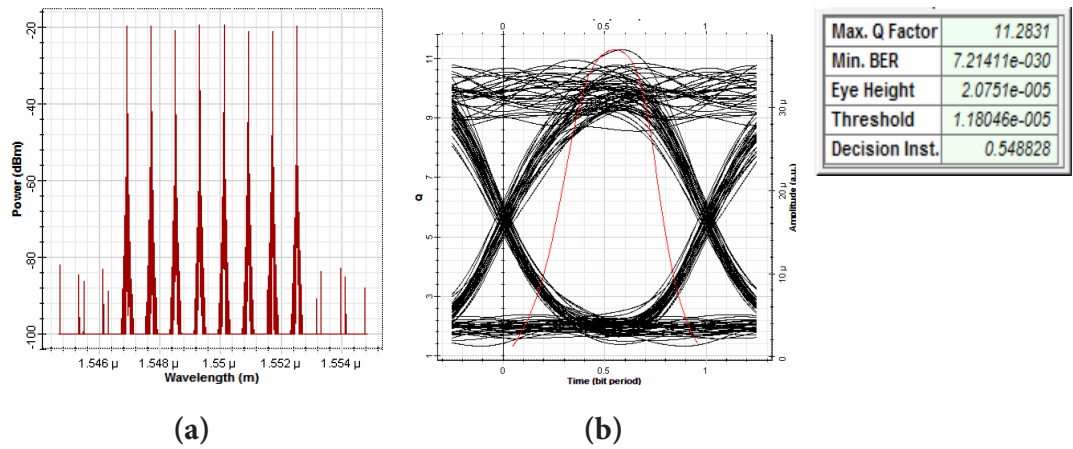
Figure 12. **(a)** Spectrum before demux when input power = -10 dBm using DCF. **(b)** Eye diagram of output using DCF.

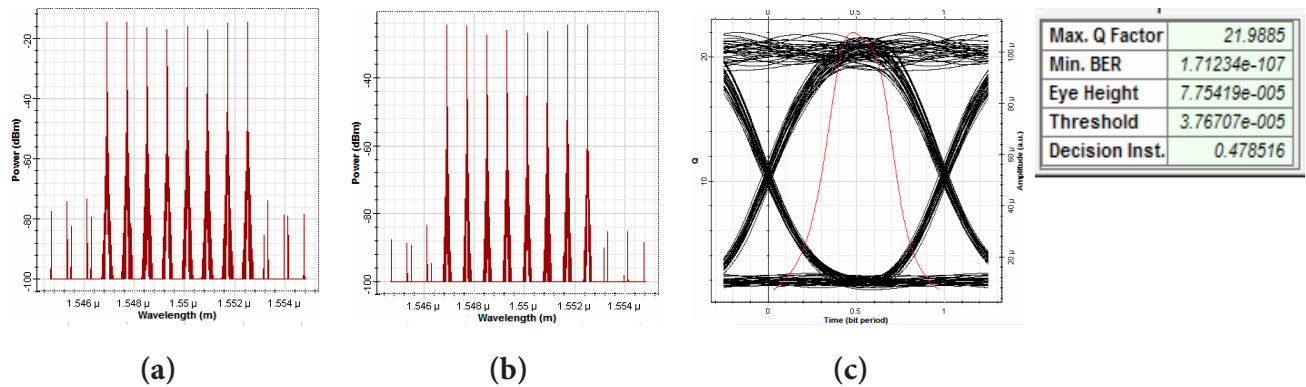| Max. Q Factor | 21.9885 |
Min. BER	1.71234e-107
Eye Height	7.75419e-005
Threshold	3.76707e-005
Decision Inst.	0.478516

(a)   **(b)**   **(c)**

Figure 13. **(a)** Spectrum before OPC when input power = -10 dBm. **(b)** Output spectrum after OPC when input power = -10dBm. **(c)** Eye diagram of output using OPC.

more in OPC. As a result, at low input power values OPC would be more efficient.

6.2 Number of channels

Number of channels in an optical system plays an important role in determining FWM effect[4]. Changing the number of channels while keeping other parameters constant, it can be observed from Table 5 and Table 6 that, reducing the number of channels from 8 to 3 in DCF, the OSNR remains almost same, but FWM power decrease by approximately 4 dBm (Figure14(a)). Eye Height remains constant (Figure 14(b)).

In OPC, on reducing number of channels, OSNR increase by more than 70%. This indicates vast signal output improvement. FWM power also reduces by more than 8 dBm (Figure 15(a), (b)), but eye height remains almost same (Figure15(c)).

Table 5. Effect of number of channels (DCF)

Frequency (THz)	Output Values		
	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
193.1	-7.73931	-35.8044	28.06513
193.2	-55.5276	-82.4097	26.88211
193.3	-67.6225	-92.7574	25.13489

Table 6. Effect of number of channels (OPC)

Frequency (THz)	Output Values		
	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
193.1	-2.73816	-35.8044	33.06628
193.2	-50.5352	-82.4097	31.87446
193.3	-62.6156	-92.7574	30.14184

(a)

(b)
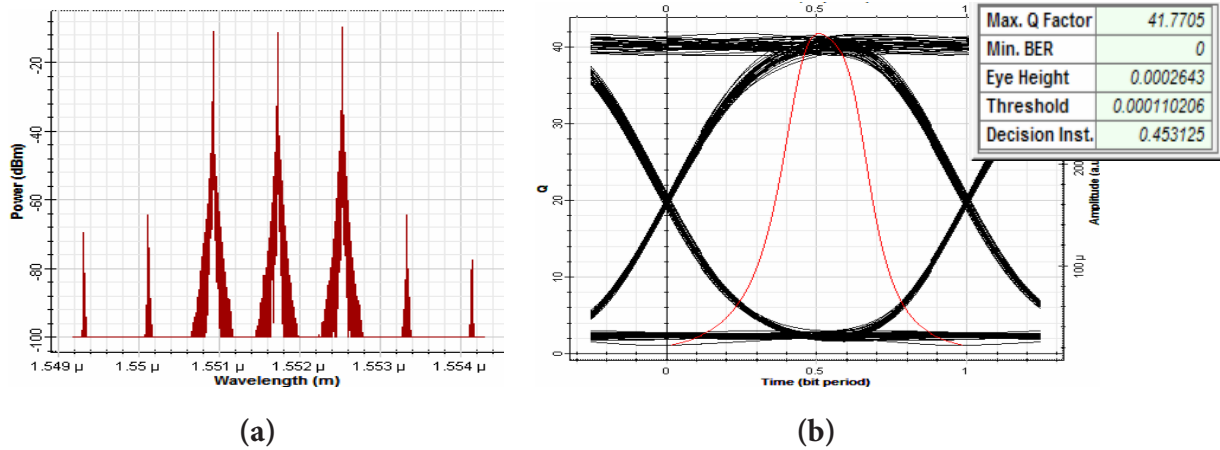
Figure 14. **(a)** Spectrum before demux when number of channels = 3 using DCF. **(b)** Eye diagram of output using DCF.
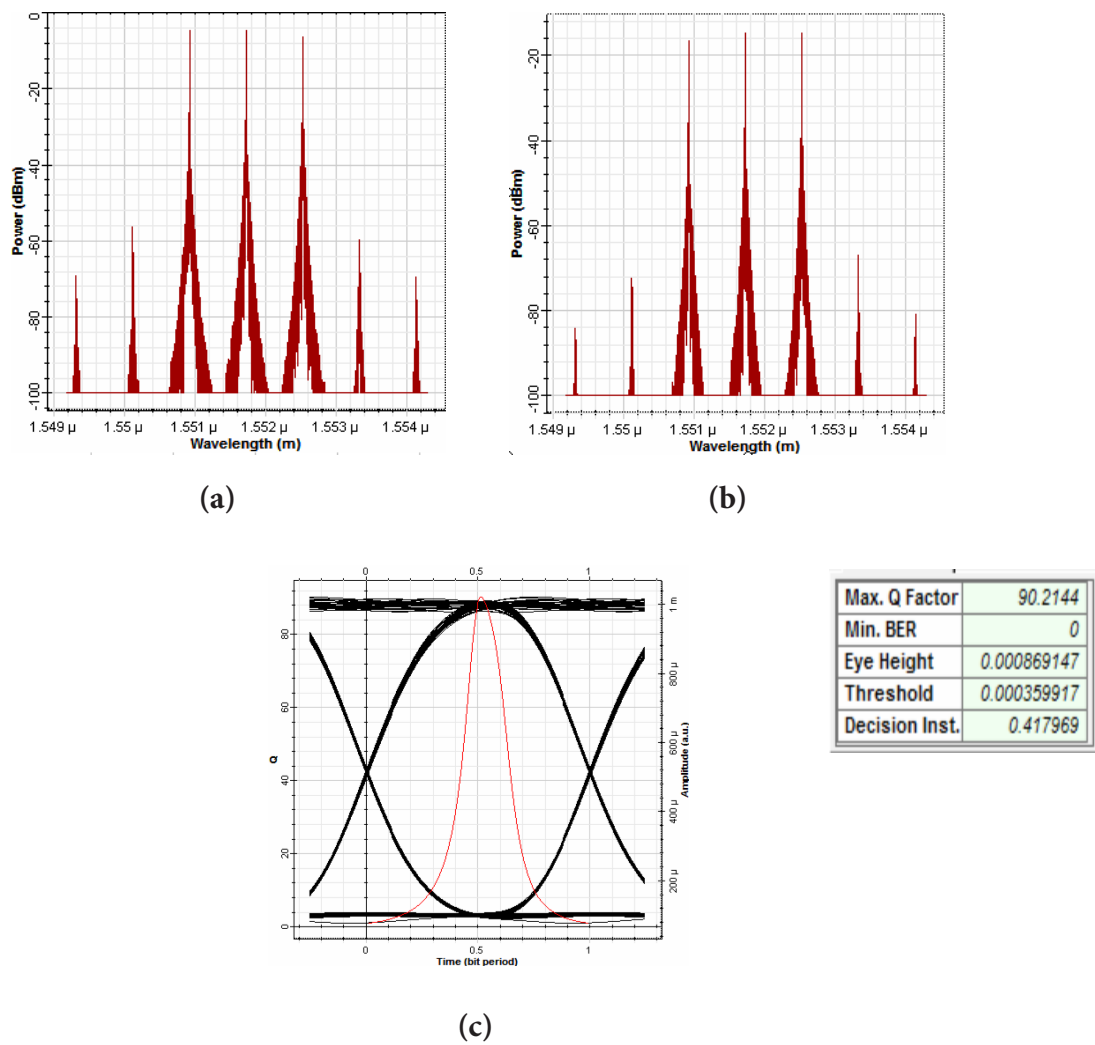

(a)

(b)

(c)

Figure 15. **(a)** Spectrum before OPC when number of channel = 3. **(b)** Output spectrum after OPC when number of channels = 3. **(c)** Eye diagram of output using OPC.

Thus, it can be concluded from these observations that OPC is best utilized when numbers of channels are less, causing better FWM power reduction at high OSNR values.

6.3 Channel spacing

Channel spacing is difference of adjacent frequencies allocated in a WDM system. It is also a widely studied parameter for mitigating FWM effect[4]. In OPC, effect of channel spacing change is very drastic. The apt value of channel spacing for OPC operation is 100 GHz. By a slight change in the value the signal almost vanishes, therefor we have done the analysis in OPC at 102 GHz and at 105 GHz in DCF. By keeping all the parameters constant and changing the channel spacing between the channels from 100 GHz to 105 GHz in DCF and to 102 GHz in OPC, results in average increase of 75% in OSNR in DCF (Table 7), whereas in OPC, OSNR decreases by 45% (Table 8).

Table 7. Effect of channel spacing (DCF)

Frequency (THz)	Output Values		
	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
193.1	-89.3757	-100	10.62431
193.2	-89.4628	-100	10.53719
193.3	-92.8932	-100	7.106768
193.4	-94.6335	-100	5.36648
193.5	-93.7289	-100	6.2711
193.6	-89.2425	-91.3122	2.069687
193.7	-76.5073	-75.0147	-1.49257
193.8	-67.1555	-63.8702	-3.28537

Table 8. Effect of channel spacing (OPC)

| Frequency (THz)	Output Values		
	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
193.1	-98.9582	-100	1.041837
193.2	-93.8526	-100	6.147353
193.3	-88.0523	-100	11.94772
193.4	-81.3012	-100	18.69879
193.5	-73.3975	-100	26.60247
193.6	-63.6052	-93.3298	29.72452
193.7	-48.7415	-80.7234	31.98185
193.8	-17.3546	-47.4361	30.08145

On comparing FWM it can be seen that in DCF, FWM power decreases by about 20 dBm (Figure 16(a)) and in OPC by 10 dBm (Figure 17(a), (b)). Eye height in DCF remains almost same (Figure16(b)) whereas in OPC it decreases (Figure17(c)). Based on this, it can be concluded that when Channel Spacing is increased, DCF is better utilized than OPC.

7. Conclusion

WDM systems, which consist of zero dispersion shifted fibers, suffer from FWM effects. This is the reason that non-zero dispersion-shifted fibers are preferred. Components like DCF and OPC are used to mitigate FWM effects. We have compared OPC and DCF based on parameters like Input Power, Channel spacing, Number of Channels and Bit Rate. Based upon our readings
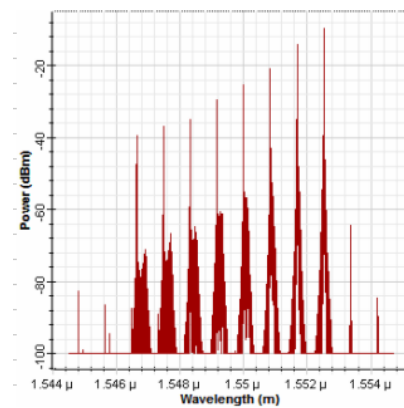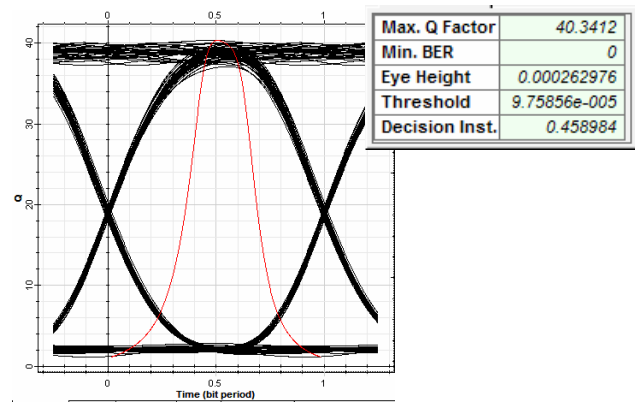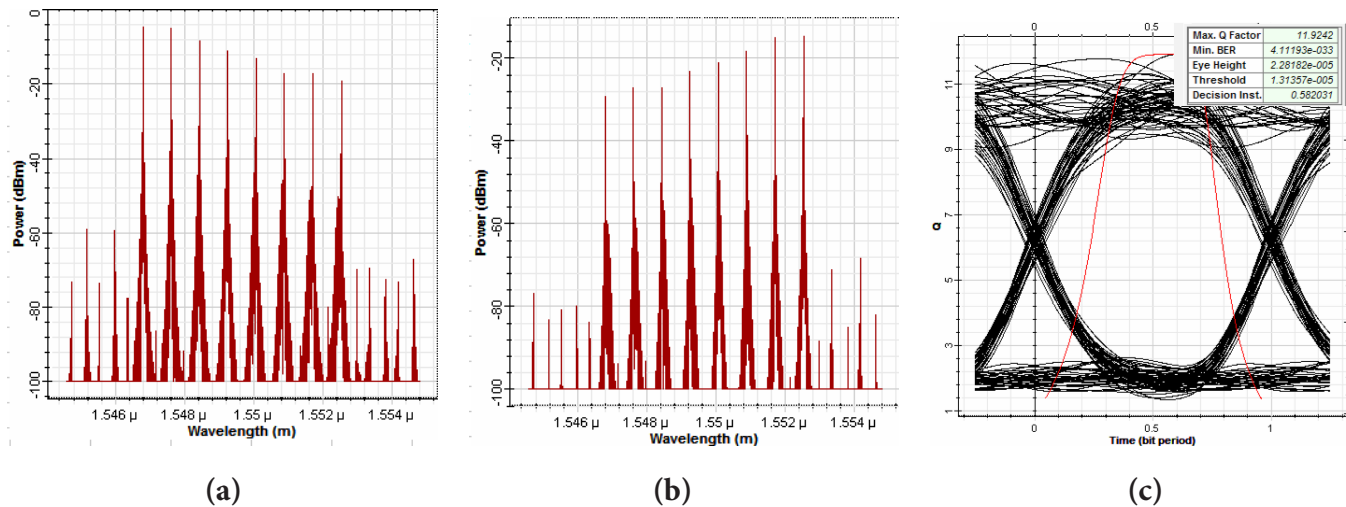

Figure 16. **(a)** Spectrum before demux when channel spacing = 105 GHz using DCF. **(b)** Eye diagram of output using DCF.

Figure 17. **(a)** Spectrum before OPC when channel spacing = 102 GHz. **(b)** Output spectrum after OPC when channel spacing= 102 GHz. **(c)** Eye diagram of output using OPC.

we are able to conclude that out of OPC and DCF, OPC is better utilized at lower input power as OSNR reduction is less. On decreasing number of channels, in OPC, OSNR increases much more than in DCF, where OSNR is almost constant. So, at less number of channels OPC gives better performance. Channel Spacing is the parameter that helps in differentiating OPC and DCF to a large extent. On increasing channel spacing, in case of OPC, OSNR is increased, whereas in DCF, it decreases. So, it can be concluded that at higher channel spacing OPC is again better. On the basis of bit rate, also OPC gives better performance. Further, it can be proposed to extend the analysis of parameters for four-wave mixing in a WDM optical fiber system using Hybrid modules consisting of OPC, DCF or FBG in conjugation. They are liable to give better performance than single components and may prove to be a better choice for FWM reduction in WDM systems.

8. References

1. Agrawal GP. Nonlinear fiber optics. Second Edition. San Diego, USA: Academic Press; 1995 Jan.
2. Abed HJ, Al-Mansoori MH, Din NM, Abdullah F, Fadhil HA. Priority-based parameter optimization strategy for reducing the effects of four-wave mixing on WDM system. Optik. 2014 Jan; 125(1):25–30.
3. Abed HJ, Din NM, AL-Mansoori MH, Fadhil HA, Abdullah F. Recent four-wave mixing suppression methods. optik. 2013 Aug; 124(15):2214–18.
4. Ajmani M, Singh P. FWM in WDM system, effects and techniques to minimize. IEEE Fifth International Conference on Advanced Computing and Communication Technology; 2015. p. 385–9.
5. Singh SP, Singh N. Nonlinear effects in optical fibers: Origin, management and application rogress in electromagnetics research. PIER. 2007; 73:249–75.
6. Kaur G, Singh ML, Patterh MS. Effect of fiber nonlinearities in a WDM transmission system. Optik. 2010 Jun; 121(10):889 –96.
7. Betti S, Giaconi M, Nardini M. Effect of four-wave mixing on WDM optical systems: A statistical analysis. IEEE Photonics Technology Letters. 2003 Aug; 15(8):1079–81.
8. Kaler R, Kaler RS. Investigation of four wave mixing effect at different channel spacing. Optik. 2012 Feb; 123(4):352–6.
9. Ahmed J, Hussain A, Siyal MY, Manzoor H, Massod A. Parametric analysis of four-wave mixing in DWDM system. Optik. 2014; 125:1853–9.
10. Wason A, Kaler RS. Investigation of four wave mixing effect with different number of input channels at various channel spacing. Optik. 2013 Oct; 124(20):4227–30.
11. Sharma V, Kaur R. Implementation of DWDM system in the presence of Four Wave Mixing (FWM) under the impact of channel spacing. Optik. 2013 Sep; 124(17):3112 –4.
12. Singh A, Sharma AK, Kamal TS. Investigation on modified FWM suppression methods in DWDM optical communication systems. Optics Communications. 2009 Feb; 282(3):392–5.
13. Kaur G, Singh ML. Effect of four wave mixing in a WDM optical fiber system. Optik. 2009 Mar; 120(6):268 –73.

14. Kaur G, Singh ML. Optimization of interchannel separation in WDM transmission systems in the presence of fibre nonlinearities. IEEE Photonics Technology Letters; 2007 Jul 2–4. p. 1–6.

15. Noshada M, Rostamia A. FWM minimization in WDM optical communication systems using the asymmetrical dispersion-managed fibers. Optik. 2012 May; 123(9):758–60.

16. Singha A, Sharma AK, Kamal TS. Four-wave mixing analysis in WDM optical communication systems with higher-order dispersion. Optik. 2008 Dec; 119(16):788–92.

17. Betti S, Giaconi M, Nardini M. Effect of four-wave mixing on WDM optical systems: A statistical analysis. IEEE Photonics Technology Letters. 2003 Aug; 15(8): 1079 –81.

18. Kaur G, Patterh MS. Suppression of four wave mixing effect in WDM systems with hybrid modules. Optik. 2014; 125(15):3894 –6.

19. He GS. Optical phase conjugation: Principles, techniques, and applications. Progress in Quantum Electronics. 2002 May; 26(3):131–91.