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## Research Article

**Keywords:** FWM, DWDM system, channel spacing, Optical spectrum, XPM, SRS, effect of dispersion.

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# Performance evaluation and analysis of four waves mixing in DWDM optical communications

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## i. Abstract

Optical nonlinearities give rise to many ubiquitous effects in optical fibres'. These effects are interesting in themselves and can be detrimental in optical communication. In the Dense Wave length division multiplexing system (DWDM) the nonlinear effects plays important role .DWDM system offers component reliability, system availability and system margin. DWDM system carries different channels. Hence power level carried by fiber increases which generates nonlinear effect such as SPM ,XPM, SRS, SBS and FWM. Four wave mixing (FWM) is one of the most troubling issues. The FWM gives crosstalk in DWDM system whose channel spacing is narrow. Wavelength exchanging enables data swapping between two different wavelengths simultaneously. These phenomena have been used in many applications in Wavelength Division Multiplexing (WDM) optical networks such as, wavelength conversion, wavelength sampling, optical 3R, optical interconnects and optical add-drop multiplexing.

KEYWORDS: FWM, DWDM system, channel spacing, Optical spectrum, XPM, SRS, effect of dispersion.

## ii. INTRODUCTION

FWM (Four Wave Mixing) or Four Photon Mixing (FPM) is the process whereby optical power from one channel in a multi-channel system is spilled over into adjacent channels. Three waves mix together to produce the fourth wave which may coincide with the original channel or may not be coinciding [1-8].

$$f_{ijk} = f_i \pm f_j \pm f_k \quad \text{Equ.1 [16]}$$

$$\text{Total FWM products} = \frac{N^2(N-1)}{2}. \quad \text{Equ.2 [16]}$$

Where N is the no. of wavelengths.

Equation (1) shows the formula for the generation of FWM interfering term.

Equation (2) shows the total no. of interfering terms.

- **Newly formed FWM products**
  - ✚ May fall on the original signal (cannot be filtered out).
  - ✚ May not fall on the original signal (can be filtered out).
- **Spurious components are created, causing**
  - ✚ • Interference
  - ✚ • Degradation of signals
  - ✚ • Cross talk

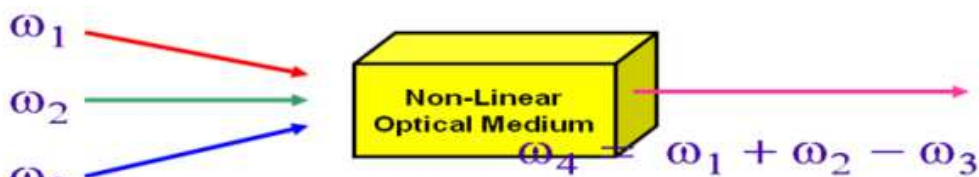


Figure 1 Formation of Fourth Spurious Component

Four-wave mixing transfers' energy from a strong pump wave to two waves up shifted and downshifted in frequency from the pump frequency  $\omega_1$  [8-14]. If only the pump wave is incident at the fibre, and the phase matching condition is satisfied, the Stokes and anti-Stokes waves at the frequencies  $\omega_3$  and  $\omega_4$  can be generated from noise. On the other hand, if a weak signal at  $\omega_3$  is also launched into the fibre together with the pump, the signal is amplified while a new wave at  $\omega_4$  is generated simultaneously. The gain responsible for such amplification is called the parametric gain [4, 12-16].

### iii. Effects of FWM

Four wave mixing (FWM) is one of the most troubling issues. Three signals combine to form a fourth spurious or mixing component, hence the name four waves mixing. Spurious components cause following problems [16-20]:

- ✚ Interference between wanted signal(cross)
- ✚ It generates additional noise and degrades system performance
- ✚ Power is lost from wanted signals into unwanted spurious signals

FWM can be substantially reduced or perhaps completely eliminated through the following steps [18-20].

- Individual channel power reduction
- Increased dispersion (Phase Mismatch)
- Increased channel spacing.

In a multi wavelength system like DWDM, three waves mix together and produces the fourth wave given by Equation (3).

$$P = \frac{(DXl_{eff})^2}{A_{eff}^2} \frac{1024\pi^6}{n^4 c^2 \lambda^2} P_i P_j P_K e^{-\alpha L} \eta \quad \text{Equ.3 [16]}$$

Where

$n$  is the refractive index

$\lambda$  &  $c$  are the wavelength and speed of the light respectively.

$P_i P_j P_K$  are the input powers of the three channels.

$X$  is the electric susceptibility.

$D$  is the degeneracy factor which is 3 for Two tone and 6 for Three tone mixing.

$\eta$  is the Four wave mixing efficiency (inversely proportional to Dispersion).

#### iv. FWM FOR EQUAL AND UNEQUAL CHANNEL SPACING

From Figure 2, it is inferred that when the inter channel spacing is equal means then the FWM power falls on the original signals such that it will induce crosstalk. To avoid this, unequally spaced channels are used. Fabrizio (1995) has analysed the FWM for different bandwidth expansion factors and demonstrated the reduction in overlapping of interfering FWM terms with the original channels for the unequal channel spacing [16-20].

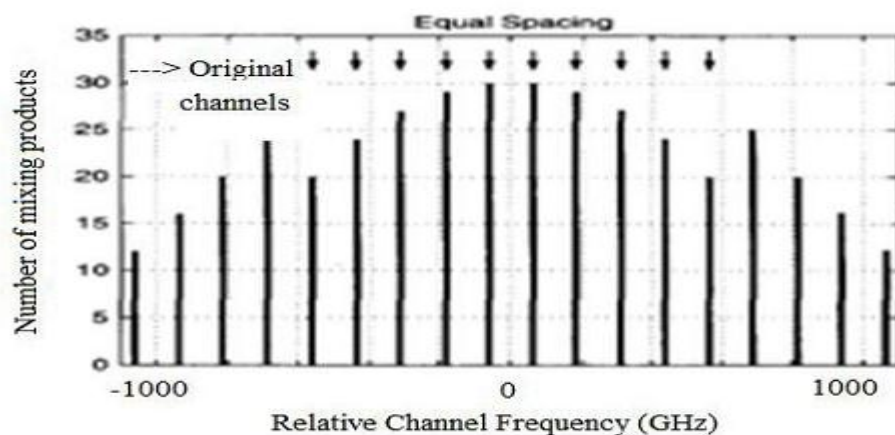


Figure .2: Spectrum for Equally spaced channels.

[Courtesy : FabrizioForghieri,JLWT,Vol.13,No.5, Page:891,1995]

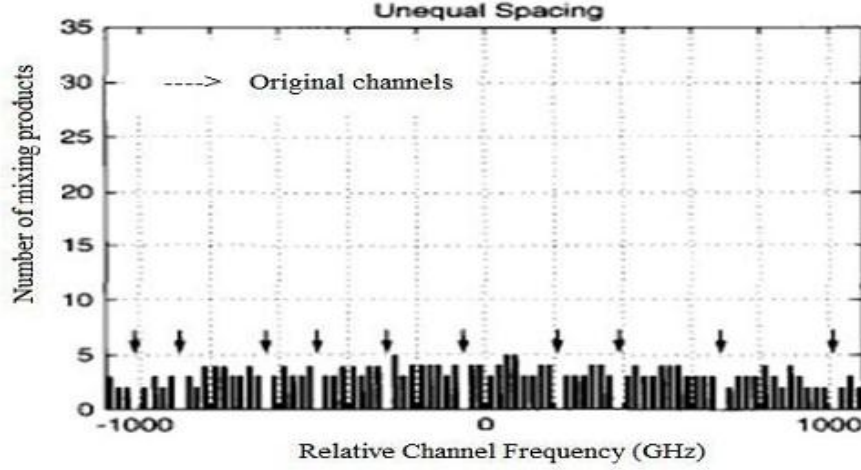


Figure.3: Spectrum for unequally spaced channels

[Courtesy: Fabrizio Forghieri , JLWT, Vol.13, No.5, Page: 891, 1995].

The FWM effect is described as [12] :

$$(\nabla^2 + k_q^2) E_q = -S_q \quad q=1,2,3,4 \quad \text{Equ.4}$$

In order to fulfill the coupling conditions, the four frequencies

must be commensurate in a manner of  $\omega_1, \omega_2, \omega_3,$  and  $\omega_4$  .

Combining three waves, a fourth wave can be generated and the four wave signals are written as [12]:

$$\frac{\partial A_1}{\partial z} = -\frac{\alpha}{2} A_1 + j\gamma(|A_1|^2 + C|A_2|^2 + 2|A_3|^2 + C|A_4|^2)A_1 + jC\gamma A_2 A_3 A_4^* \exp(j\Delta\beta Z). \text{Equ.5}$$

$$\frac{\partial A_2}{\partial z} = -\frac{\alpha}{2} A_2 + j\gamma(C|A_1|^2 + |A_2|^2 + C|A_3|^2 + 2|A_4|^2)A_2 + jC\gamma A_1 A_3^* A_4 \exp(j\Delta\beta Z). \text{Equ.6}$$

$$\frac{\partial A_3}{\partial z} = -\frac{\alpha}{2} A_3 + j\gamma(2|A_1|^2 + C|A_2|^2 + |A_3|^2 + C|A_4|^2)A_3 + jC\gamma A_1 A_2^* A_4 \exp(j\Delta\beta Z). \text{Equ.7}$$

$$\frac{\partial A_4}{\partial z} = -\frac{\alpha}{2} A_4 + j\gamma(C|A_1|^2 + 2|A_2|^2 + C|A_3|^2 + |A_4|^2)A_4 + jC\gamma A_1^* A_2 A_3 \exp(j\Delta\beta Z). \text{Equ.8}$$

Where  $A_j$  is the slowly varying envelope amplitude of the optical field with frequency  $\omega_j$ ,  $\alpha$  is the fiber loss coefficient and  $\gamma$  is the nonlinear coefficient. Depending on the state of polarization of the waves, the parameter  $C=2$  for parallel polarization and  $C= 2/3$  for orthogonal polarization. The propagation mismatch constant  $\Delta\beta = (\beta_1 + \beta_4) - (\beta_2 + \beta_3)$ , where  $\beta_j = \beta(\omega_j)$  ( $j = 1,2,3$  and  $4$ ) are the propagation constants in the fiber.

v. EFFECT OF DISPERSION ON FWM

The dispersion in the fiber produces the phase mismatch and hence the interfering terms may get reduced. The simulation of the layout in the optsim software gives the power of the FWM terms for various no. of channels [20-22]. The dispersion in the fiber could be set from 0 ps/nm/km to any value [15, 16, 20 ].

Table 4.1 FWM Vs No. of Channels for the Dispersion of 0 ps/nm/km

No of channels	Input frequency (THZ)	Input power (Mw)	FWM power (Mw)	OSNR (dBm)	Frequency at which Max. FWM occurs ((THz
1	192	1	0.0000	$\infty$	No
2	192&192.2	1	0.0400	13.98	192.2
8	[192:0.2:193.4]	1	0.0510	12.92	193.0
16	[192 : 0.2 :195]	1	0.0511	12.91	195.0
32	[188:0.2:194.2]	1	0.0520	12.84	196.0
64	185:0.2:198.6	1	0.0560	12.51	203.4

vi. Minimization of FWM Effects

Traditional non-multiplexed systems have used dispersion shifted fiber at 1550nm to reduce chromatic dispersion. Unfortunately operating at the dispersion minimum increases the level of FWM. Conventional fiber (dispersion minimum at 1330 nm) suffers less from FWM but chromatic dispersion rises .Solution is to use "Non-Zero Dispersion Shifted Fiber" (NZ DSF), a compromise between DSF and conventional fiber (NDSF, Non-DSF). ITU-T standard is G.655 for non-zero dispersion shifted single mode fibers. By using unequal spacing between DWDM channels effect of FWM decreases [14-16, 22-25].

vii. PROGRAMS FOR FINDING OUT THE EXACT NUMBER OF FWM INTERFERING TERMS

```

%%Program for Equal channel spacing with 16 channels
L = [1550 1551 1552 1553 1554 1555 1556 1557 1558 1559 1560 1561
1562 1563 1564 1565];
LFWM = zeros(16);
for i = 1:16
    for j = 1:16
        for k = 1:16
            LFWM(i,j,k) = L(i)+L(j)-L(k);
        end
    end
end
end

```

```

%%Program for Unequal channel spacing with 16 channels
L = [ 1501 1505 1508 1510 1515 1516 1518 1523 1526 1530 1531 1534
1536 1541 1545 1548 ]
LFWM = zeros(16);
for i = 1:16
    for j = 1:16
        for k = 1:16
            LFWM(i,j,k) = L(i)+L(j)-L(k);
        end
    end
end
LFWM

%%Program for Equal channel spacing with 32 channels
clc;
clear all;
close all;
L=[1547 1548 1549 1550 1551 1552 1553 1554 1555 1556 1557 1558 1559
1560 1561 1562 1563 1564 1565 1566 1567 1568 1569 1570 1571 1572 1573
1574 1575 1576 1577 1578 1579 ];
LFWM=zeros(32,32);
for i=1:32
    for j=1:32
        for k = 1:32
            LFWM(i,j,k) = L(i)+L(j)-L(k);
        end
    end
end
LFWM

%%Program for Unequal channel spacing with 32 channels
clc; clear all; close all;
L=[1547 1548.6 1549.8 1550.6 1551 1551.6 1553 1554 1555.6 1556.2 1557
1557.4 1558 1559.4 1560.4 1562 1563.2 1564 1564.4 1565 1566.4 1567.4
1569 1570.2 1571 1571.4 1572 1573.4 1574.4 1576 1577.2 1578 1578.4];
LFWM=zeros(32,32);
for i=1:32
    for j=1:32
        for k = 1:32
            LFWM(i,j,k) = L(i)+L(j)-L(k);
        end
    end
end
LFWM

%% Program for Equal channel spacing with 64 channels
clc; clear all; close all;
L=[1547 1548 1549 1550 1551 1552 1553 1554 1555 1556 1557 1558 1559
1560 1561 1562 1563 1564 1565 1566 1567 1568 1569 1570 1571 1572 1573
1574 1575 1576 1577 1578 1579 1580 1581 1582 1583 1584 1585 1586 1587
1588 1589 1590 1591 1592 1593 1594 1595 1596 1597 1598 1599 1600 1601
1602 1603 1604 1605 1606 1607 1608 1609 1610 1611 ];
LFWM=zeros(64,64);
for i=1:64
    for j=1:64
        for k = 1:64
            LFWM(i,j,k) = L(i)+L(j)-L(k);
        end
    end
end

```

```

%%Program for Unequal channel spacing with 64 channels
clc;
clear all;
close all;
L=[1547 1548.6 1549.8 1550.6 1551 1553 1554 1555.6 1556.2 1557 1557.4
1558 1559.4 1560.4 1562 1563.2 1564 1564.4 1565 1566.4 1567.4 1569
1570.2 1571 1571.4 1572 1573.4 1574.4 1576 1577.2 1578 1578.4 1579
1580.4 1581.4 1583 1584.2 1585 1585.4 1586 1587.4 1588.4 1590 1591.2
1592 1592.4 1593 1594.4 1595.4 1597 1598.2 1599 1599.4 1599.8 1600.4
1601.8 1602.8 1604.4 1605.6 1606.4 1606.8 1607.4 1608.8 1609.8]
LFWM = zeros(64,64);
for i=1:64
    for j=1:64
        for k = 1:64
LFWM(i,j,k) = L(i)+L(j)-L(k);
        end
    end
end
LFWM

```

The Matlab programs are executed and the interfering terms are Table 2.

Number of Channels	Equal Channel Spacing	Unequal Channel Spacing [Bandwidth Expansion Factor = 1]	Unequal Channel Spacing [Bandwidth Expansion Factor = 1.5]	Unequal Channel Spacing[Bandwidth Expansion Factor = 2
4	104	92	78	56
8	344	296	245	203
16	11762	7984	5678	4548
32	21844	13009	11232	9459
64	39720	22815	20345	18367

Table 2. Comparison of Interfering Terms.

The numbers inside the cells of the table are obtained by counting the coinciding terms for each channel from the results of execution of Matlab program.

#### viii. RESULTS AND DISCUSSION

By varying the dispersion from 0 to 4 ps/nm/km we observed effect of dispersion on FWM by Optisystem 7. And also effect equal and unequal spacing on FWM is observed. These effects are shown in following figs [15] .





### Optical Spectrum Analyzer

Db1 Click On Objects to open properties. Move Objects with Mouse Drag

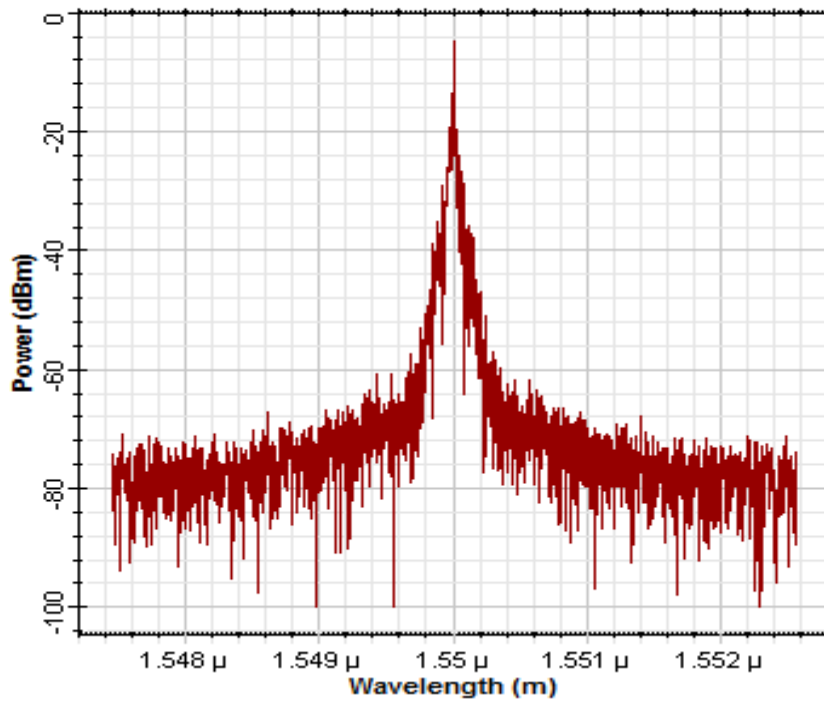


Fig.4: The spectrum at the fiber end



### BER Analyzer

Db1 Click On Objects to open properties. Move Objects with Mouse Drag  
Time (bit period)

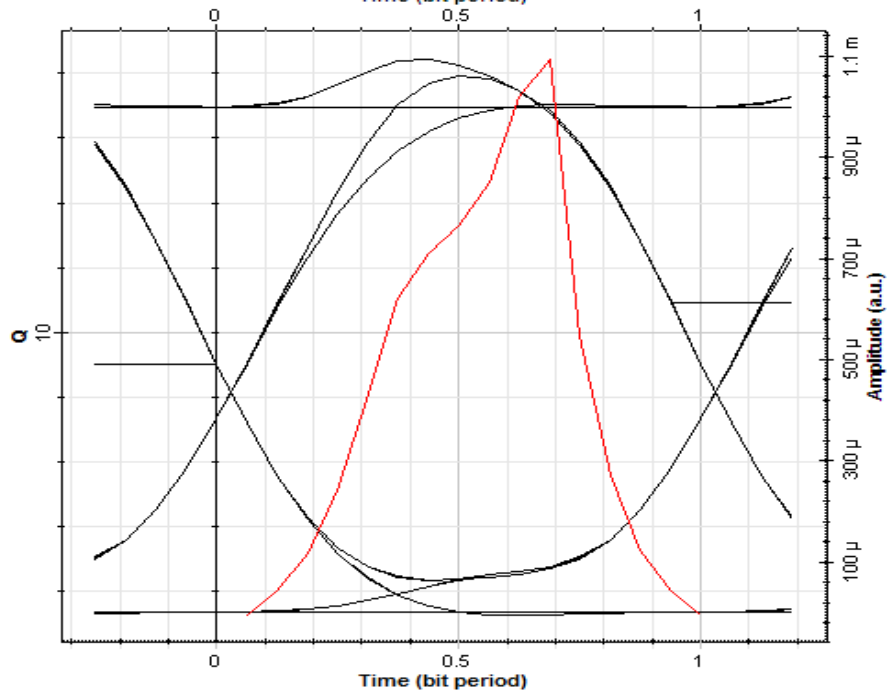


Fig.6: Eye Spectrum.

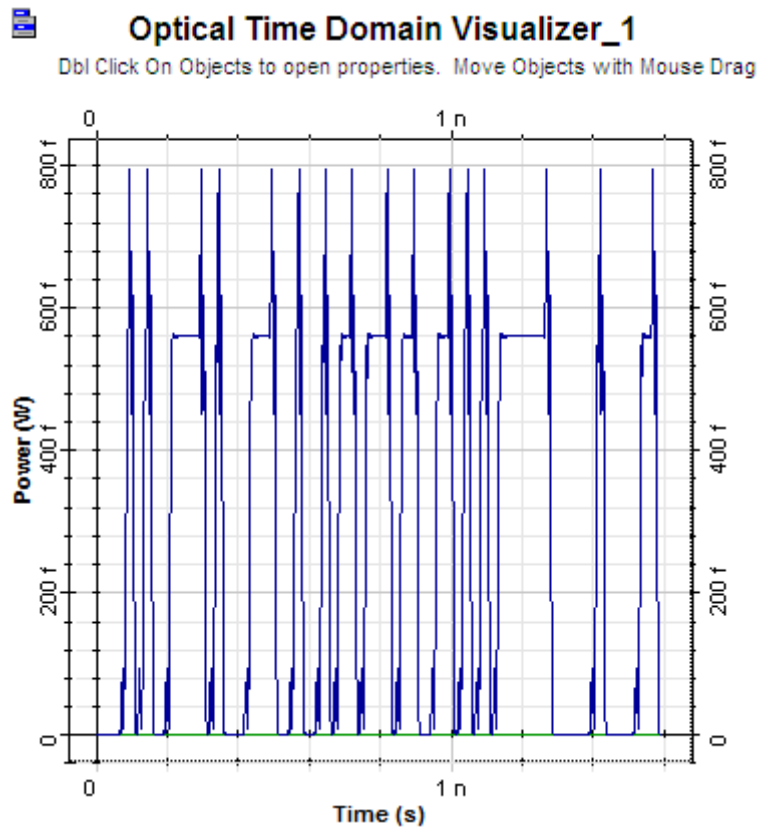


Fig.7(a)Optical Time Domain Visualizer, Time(s) vs Power (W) .

#### ix. CONCLUSION

FWM leads to interchannel crosstalk in DWDM systems. It generates additional noise and degrades system performance. By using non zero dispersion shifted fiber i.e. fiber having 4 ps/nm/km and using unequal spacing among channels FWM effect can be reduced. As Unequal channel spacing could simultaneously reduce non linearities [FWM & SRS], it may result in better performance reduced BER arising out of more OSNR.

#### x. REFERENCES

- [1] Moncef B.Tayahi\*, Sivakumar Lanka, Banmali Rawat, Four Wave Mixing in Closely Spaced DWDM OpticalChannels, International Journal of Microwave and Optical Technology,vol.1, No.2.August 2006.
- [2] J. Toulouse, Optical Nonlinearities in Fibers: Review, Recent Examples, and Systems Applications, Journal of Light Wave Technology, Vol. 23, No. 11,November 2005.

- [3] L. G. L. Wegener, M. L. Povinelli, A. G. Green, P. P. Mitra, J. B. Stark, P. B. Littlewood, The effect of propagating nonlinearities on the information capacity of WDM optical fiber systems: Cross-phase modulation and four-wave mixing, *Physica, D*, vol. 189, no. 1–2, pp. 81–99, Feb. 15, 2004.
- [4]. N. Bloembergen, editor, *Proceedings of the International School of Physics Enrico Fermi Course LXIV: Nonlinear Spectroscopy*, (North Holland, Amsterdam, 1977) .
- [5]. N. Bloembergen, *Nonlinear Optics*, (World Scientific Publishing, Singapore, 1996)
- [6]. N. Bloembergen, “Nonlinear Optics and Spectroscopy,” *Science* 216, 1057-1064 (1982).
- [7] M.C.Gupta and J. Ballato, “The hand book of photonics,” 2<sup>nd</sup> Edition, CRC Press, 2006.
- [8] G.P. Agrawal, “Fiber-optic communication systems,” 4th Edition, Wiley, 2010.
- [9] A. Chowdhury, C. Staus, B. F. Boland, T. F. Kuech, and L. Mc Caughan, “Experimental demonstration of 1535:1555 nm simultaneous optical wavelength interchange with a nonlinear photonic crystal,” *Opt. Lett.*, vol. 26, no. 17, pp. 1353-1355, Sep. 2001.
- [11] K. Uesaka, K. K.-Y. Wong, M. E. Marhic, and L. G. Kazovsky, “WaveLength exchange in a highly non linear dispersion- shifted fiber : Theory and experiments,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 8, no. 3, pp. 560-568, May/June 2002.
- [12]. Performance Evaluation of Wavelength Exchanging in Optical Interconnect  
Tawfik Ismail, Hassan Mostafa, and Yehia Ismail, 978-1-5090-0246-7/15/\$31.00  
©2015 IEEE.
- [13] G. P. Agrawal, *Applications of Nonlinear Fiber Optics*, (San Diego, CA : Academic, 2001).
- [14] Introducing DWDM  
[http://www.cisco.com/univercd/cc/td/doc/product/mels/dwdm/dwdm\\_fns.htm](http://www.cisco.com/univercd/cc/td/doc/product/mels/dwdm/dwdm_fns.htm)
- [15] Four Wave Mixing In DWDM Optical System, Gouri Deshmukh, Prof. Santosh Jagtap, *International Journal of Computational Engineering Research* | Vol, 03 | Issue, 6 | .
- [16]. Analysis of Four Wave Mixing in Fiber Optic Communication and to devise a mechanism for combating the FWM', has been published in an International Conference on Emerging Trends in Engineering Technologies-2010, organized by Noorul Islam University, March 25-26, 2010.

- [17] Hien T. T. Pham., Ngoc T. Dang: Performance improvement of spatial modulation-assisted FSO systems over Gamma–Gamma fading channels with geometric spreading, *Photon Netw Commun*, 34, pp.213–220, 2017
- [18] E. E. Elsayed and B. B. Yousif, "Performance evaluation and enhancement of the modified OOK based IM/DD techniques for hybrid fiber/FSO communication over WDM-PON systems," *Opt. Quantum Electron.*, vol. 52, no. 9, 2020, doi: 10.1007/s11082-020-02497-0.
- [19] B. B. Yousif, E. E. Elsayed, and M. M. Alzalabani, "Atmospheric turbulence mitigation using spatial mode multiplexing and modified pulse position modulation in hybrid RF/FSO orbital-angular-momentum multiplexed based on MIMO wireless communications system," *Opt. Commun.*, vol. 436, pp. 197–208, 2019, doi: 10.1016/j.optcom.2018.12.034.
- [20] A. M. Mbah, J. G. Walker, and A. J. Phillips, "Outage probability of WDM free-space optical systems affected by turbulence-accentuated interchannel crosstalk," *IET Optoelectron.*, vol. 11, no. 3, pp. 91–97, 2017, doi: 10.1049/iet-opt.2016.0057.
- [21] B. B. Yousif and E. E. Elsayed, "Performance Enhancement of an Orbital-Angular-Momentum-Multiplexed Free-Space Optical Link under Atmospheric Turbulence Effects Using Spatial-Mode Multiplexing and Hybrid Diversity Based on Adaptive MIMO Equalization," *IEEE Access*, vol. 7, pp. 84401–84412, 2019, doi: 10.1109/ACCESS.2019.2924531.
- [22] E. E. Elsayed and B. B. Yousif, "Performance enhancement of hybrid diversity for M-ary modified pulse-position modulation and spatial modulation of MIMO-FSO systems under the atmospheric turbulence effects with geometric spreading," *Opt. Quantum Electron.*, vol. 52, no. 12, 2020, doi: 10.1007/s11082-020-02612-1.
- [23] Ebrahim E. Elsayed, Bedir B. Yousif, and Mahmoud M. Alzalabani, "Performance enhancement of the power penalty in DWDM FSO communication using DPPM and OOK modulation", *Optical and Quantum Electronics*, vol. 50 (7), pp. 282, (26 June 2018).
- [24] Ansari, N., Zhang, J.: 'Media access control and resource allocation for next generation passive optical networks' (Springer, 2013)
- [25] Ebrahim E. Elsayed and Bedir B. Yousif, "Performance enhancement of the average spectral efficiency using an aperture averaging and spatial-coherence diversity based on the modified-PPM modulation for MISO FSO links", *Optics Communications*, vol. 463, pp. 125463, (15 May 2020).

### **Compliance with ethical standards**

Conflict of interest: The author declares that there is no conflict of interest regarding the manuscript. The author is responsible for the content and writing of this article. The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.