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FWM Crosstalk Reduction in 32-Channel DWDM Optical Network using Unequal Channel Allocation and Chirped FBG

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Abstract— **In this paper, Chirped Fiber Bragg Grating (FBG) and unequal channel allocation have been implemented to reduce the Four Wave Mixing (FWM) crosstalk in Dense Wavelength Division Multiplexing (DWDM) optical system, which is considered as a mainstream solution for 5G transmission systems in smart cities due to the intense bandwidth demand. The proposed technique has been examined using several design parameters that affect FWM nonlinear crosstalk, such as total transmission distance, channel frequency spacing, the number of WDM channels and the input power per channel. The suggested technique has further been compared with a previous model proposed by other author to prove the effectiveness of this work. The simulation results have been investigated and validated by analyzing the optical spectrum analyzer and the power of the highest FWM spectral products. Simulation results demonstrate the reliability and the efficiency of the developed method.**

Keywords—Four Wave Mixing (FWM), Dense Wavelength Division Multiplexing (DWDM), Fiber Bragg Grating (FBG), Nonlinear effects (NE).

I. Introduction

Due to its several advantages such as high transmission rate, large capacity, and low latency, 5G technology can meet the increasing bandwidth demand driven by video streaming and cloud services such as augmented reality, super-resolution 4K and 8K videos. In parallel, optical communications have known an accelerated expansion due to the introduction of Erbium Doped Fiber Amplifiers (EDFA), which eliminated the intermediate optoelectronic conversions necessary during the signal regeneration [1]. Very high-capacity optical systems can be obtained by employing Dense Wavelength Division Multiplexing (DWDM) to fully exploit the bandwidth allowed by the EDFA, which fulfills perfectly the need of high data rate in smart cities. However, as DWDM technology comes into picture to ensure the ever-growing demands of Internet traffic, chromatic dispersion and nonlinear effects start to impose new limits on the achievable performance [2]. The information capacity of a light wave is limited in the WDM systems by the phase mismatch and the nonlinear interactions between the information signals and the fiber medium, which leads to distortion, interference and attenuation of the signals. Four wave mixing (FWM) is one of the different types of nonlinear effects that happens in WDM systems when light of different wavelengths is launched into the optical fiber. It occurs when the different frequencies interact and by frequency mixing produce new fake spectral component [3]. The commonly used equal channel spacing (ECS) is more sensitive to FWM, as all FWM products pop up as in-band crosstalk disturbances. For this reason, several research papers reported unequal channel spacing (UCS) to reduce the FWM nonlinear effects [4-6]. Nevertheless, the previous methods require a large bandwidth expansion, which is not convenient in DWDM application with high number of channels. Another major problem associated with UCS in DWDM is due to the difficulty in computing the optimum channel allocation for high number of channels. It becomes extremely difficult to compute such an UCS allocation because of the exhaustive computer analysis [6-7]. In this paper, we introduce an improved technique to reduce FWM effects in WDM systems using an optimum method for UCS with chirped FBG in data receivers. The proposed channel allocation ensures that the frequency separation of any two channels is different from any other pair of channels in the operating bandwidth, so no FWM signals will be generated at any of the channel frequencies, without the need of extreme complexed algorithm computations. Chirped FBG would be used in data receivers as one of the many types of Fiber Bragg Grating (FBG) with some created changes in period of grating to ensure the suppression of adjacent FWM products. As the period of grating changes along the axis in Chirped FBG, different wavelengths are reflected by different parts of the grating, and therefore are delayed with different time intervals. Thus, the final effect is compression in incident pulse and can be appropriate to reduce FWM nonlinear effects [8]. The use of Chirped FBG requires optical amplification to overcome the signal attenuation that occurs inside the grating. Thereupon, the Chirped FBG would be used with EDFA after the demultiplexing process to ensure the correct reception of the transmitted signals [9]. To demonstrate the effectiveness of this work, the suggested technique has been compared with the previous models. The simulation results have been examined and validated by analyzing the optical spectrum analyzer and the power of the highest FWM spectral products. Simulation results demonstrate the reliability and the efficiency of the developed method. The paper is organized as follows: In Section II, we briefly describe the FWM phenomenon and how it affects the optical signal transmission. Afterwards, a detailed study will be devoted to the design and the simulation of the proposed model in order to prove the technical feasibility of the new technique implemented in this paper. In Section III, we analyze thoroughly the FWM nonlinear effects based on transmission distance, input power, channel number and channel allocation. The analysis is further quantified to demonstrate the efficiency of the suggested technique. The conclusions are given in Section IV.

II. THOERY AND MODELING

A. Four Wave Mixing

FWM is a is a nonlinear optical phenomenon that affects WDM systems, where the 4th wavelength is produced by the interaction of 3 different wavelengths [3]. The FWM phenomenon gets stronger when decreasing channel spacing and increasing signal power levels. In general, for N wavelengths input channel, M cross mixing products will be generated, according to the following equation:

$$M = \frac{N^2}{2}(N - 1) \tag{1}$$

These fake signals coincide with the original wavelength, which makes it difficult to filter the original wavelength out. Taken into account that there is no efficient solution to suppress the fake signals that fall on top of the original ones, the only way is to prevent them from being created in the first place. On the other hand, FWM effects decrease when chromatic dispersion increases, since the signal wavelengths lose coherence, and accordingly increases the phase mismatch. However, in long-haul optical networks, FWM occurs and generates high number of spurious signals eventhough with high values of chromatic dispersion.

B. Chirped FBG

FBG is a single mode fiber that exposes the core to the periodic pattern of intense ultraviolet light. The exposure increase the refractive index and the pattern will create a fixed index modulation that is called Grating with wavelength selective mirror as can be shown in Fig. 2. Various methods were employed in order to map grating in optical fiber with extensive types of pulsed and continuous lasers to be used in visible and ultraviolet region. Resulted gratings reflect the propagated light in fiber according to Bragg wavelength, which is given as follow:

$$\lambda_B = 2n\Lambda \tag{2}$$

Where n and Λ are the core refractive index and the grating period in fiber respectively [8].

Chirped FBG is one of the many types of FBG with some created changes in period of grating. As the period of grating changes along the axis, different wavelengths are reflected by different parts of the grating, and therefore are delayed with different time intervals. Thus, the final effect is compression in incident pulse and can be appropriate to reduce nonlinear effects in communication links. The working principle of Chirped FBG is presented in Fig. 1.

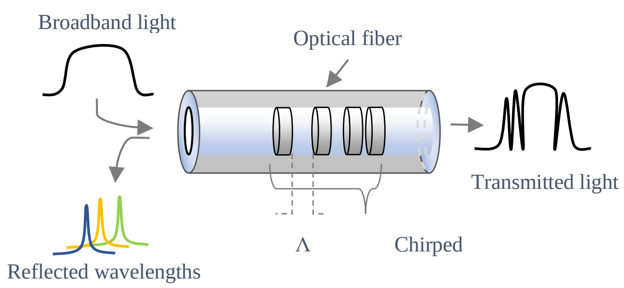


Figure 1. Chirped Fiber Bragg Grating

C. Unequal channel allocation

The commonly used equal channel spacing (ECS) is more sensitive to FWM, as all FWM products appear as in-band crosstalk disturbances. ECS frequency allocations have signal light with equal frequency separations between adjacent channels. A lot of FWM spectral products are generated due to the constant channel spacing with $f_{FWM} = f_i$, where f_i is the frequency of channel i. Unequal Channel Allocation (UCS) have signal light whose frequency separations are different in every two channels, so as not to have FWM light with $f_{FWM} = f_i$, in contrast to ECS. In UCS, the constant spacing Δf_s should be as small as possible with keeping $\Delta f_s \neq \Delta f_i$ making the total bandwidth as narrow as possible. The advantage of unequal channel spacing is that it requires no modification of transmitted data; Only selective component frequencies along the transmission link need to be matched with the channel allocation. Several methods have been proposed to allocate component frequencies with different channel spacing in literature [4-7]. However, the previous methods require a large bandwidth expansion, which is not very convenient in complexed transmission architectures with high number of channels. A good solution was proposed by Bogoni et al [6] using the three-channel island method for UCS. This simple and modular scheme requires a modest bandwidth expansion factor, which depends on the acceptable level of signal to noise ratio. The working principle of three channel allocation is illustrated in Fig. 2.

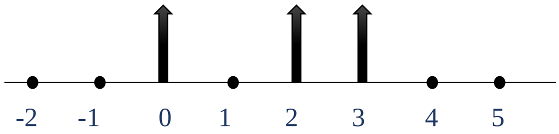


Figure 2. Three Channels Allocation

D. *Proposed method*

In this work, we propose an improved unequal channel allocation technique based on the three-channel island method with Chirped FBG in data receivers, with the aim to suppress almost all FWM nonlinear spectral products. The proposed channel allocation has signal light whose frequency allocations are different in every two channels, with only two empty frequencies after each three channels allocation in order to keep the total bandwidth as small as possible. In order to prove the technical feasibility of the new model implemented in this paper, firstly we design 8-channels WDM optical transmission system for the proposed technique with unequal channel allocation and chirped FBG in data receivers to reduce the FWM effects. The proposed WDM simulation model is operated with basic optical communication system, which consists of a transmitter, transmission link and a receiver. The input signal contains electrical data represented by zeros and ones that have been generated by Pseudo-Random Binary Sequence (PRBS) through a non-return to zero (NRZ). Then the input signal is modulated through Mach-Zender Modulator with semiconductor laser that is represented by Continuous Wave (CW) laser. A WDM Mux 8x1 is used as a multiplexer for 8 channels having unequal channel spacing: 0.8nm, 1.6nm and 2.4nm.

The system transmits information using optical carrier wave from transmitter to receiver via optical fiber. At the receiver part, WDM Demux 1x8 is required to demultiplex the signal. Afterwards, the Chirped FBG will be used to reduce the FWM effects. The use of Chirped FBG requires optical amplification to overcome the signal attenuation inside the grating, so the signal will pass through EDFA before being received by Photo detector PIN. Fig. 3 shows the proposed model for the 8-channel WDM optical transmission system.

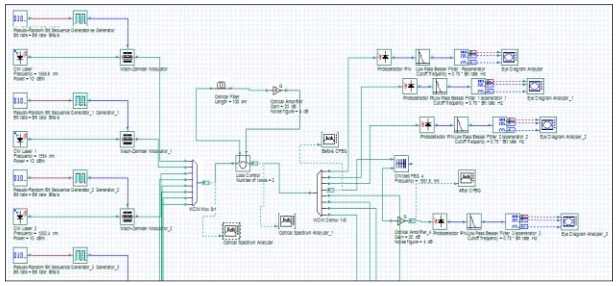


Figure 3. Proposed model for 8 channel DWDM transmission system

In the second stage, the same configuration has been extended to 32-channels to test the reliability of the proposed method in Dense WDM optical transmission systems. Both configurations have been modelled and simulated using the same initial setting: Bit rate 2.5GBits/s, dispersion 16.75 ps/nm/km, dispersion slope 0.075 $ps/nm^2/km$ and attenuation coefficient at cable section 0.2dB/km. TABLE 1 shows the channel frequency allocation implemented in the proposed method. Fig. 4 shows the proposed model for the 32-channels WDM optical transmission system.

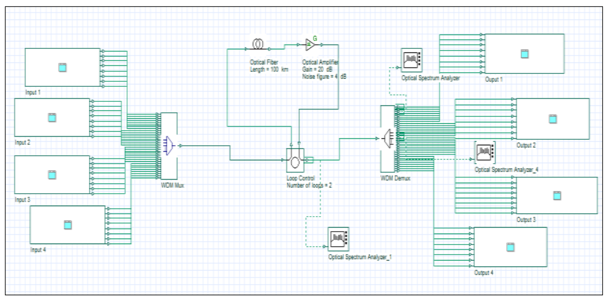


Figure 4. Proposed model for 32 channel DWDM transmission system

TABLE I. 32-CHANNELS DWDM FREQUENCY ALLOCATION

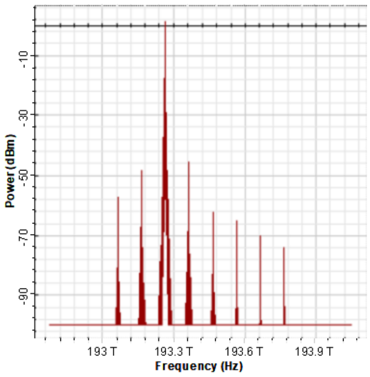
Channel number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Frequency (nm)	1525.2	1526	1527.6	1530	1530.8	1532.4	1534.8	1535.6	1537.2	1539.6	1540.4
Channel number	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Frequency (nm)	1542	1544.4	1545.2	1546.8	1549.2	1550	1551.6	1554	1554.8	1556.4	1558.8
Channel number	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	
Frequency (nm)	1559.6	1561.2	1563.6	1564.4	1566	1568.4	1569.2	1570.8	1573.2	1574	

III. RESULTS AND DISCUSSIONS

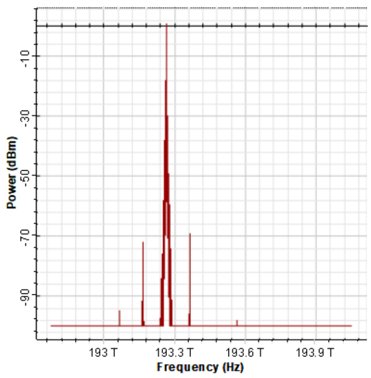
In this section, the performance of the proposed model for DWDM long-haul network is investigated and compared with previous models to evaluate its efficiency. The study has been focused on two optical communication scenarios, first with 8-channels WDM transmission system, then with 32-channels DWDM transmission system, so the effect of the proposed method on FWM minimization can be evaluated in a complexed transmission system. The simulations are performed by assuming that chromatic dispersion is 16.75 ps/nm²/km, chromatic dispersion slope is 0.075 ps/nm²/km and attenuation coefficient at cable section is 0.2dB/km.

A. 8-channels WDM Transmission system

Fig. 5 illustrates the effect of FWM nonlinear interactions between the information signals and the fiber medium using equal channel allocation in 8-channels WDM communication system over 300km transmission distance. FWM nonlinear effect is analyzed in this case before the use of Chirped FBG and after the use of chirped FBG to evaluate the impact of Chirped FBG on FWM minimization.



Before Chirped FBG

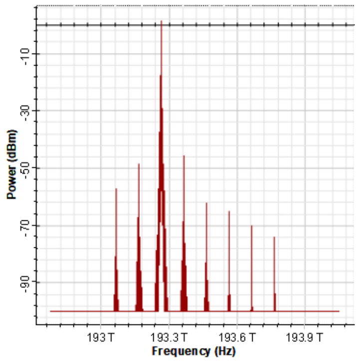


After Chirped FBG

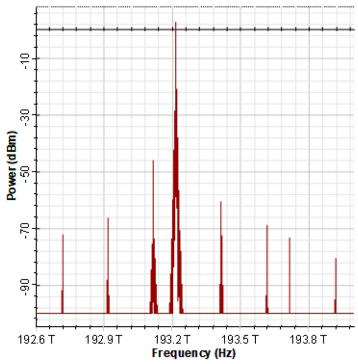
Figure 5. Optical spectrum analyzer for 8-ES WDM over 300km

By comparing the two optical spectrums related to the 8-channel WDM output *-After chirped FBG* and *Before chirped FBG-* in Fig. 5, it can clearly be seen that less fake pulses have remained around the main pulse after the use of Chirped FBG. Besides, the output power of the FWM products have also significantly decreased after the use of Chirped FBG, which proves the efficiency of using Chirped FBG in FWM nonlinear effects reduction.

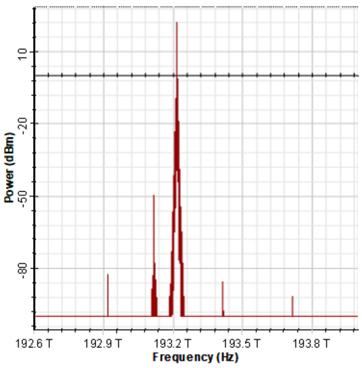
Fig. 6 depicts the performance comparison between the commonly used Equal Channel Spacing (ECS), Unequal Channel Spacing (UCS) and the proposed method using the same unequal channel allocation in the 8-channels WDM transmission system over 300 km.



ECS



UCS



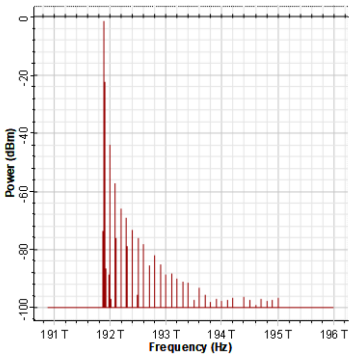
Proposed method

Figure 6. Performance comparison by Optical Spectrum Analyzer for 8-channels WDM over 300km

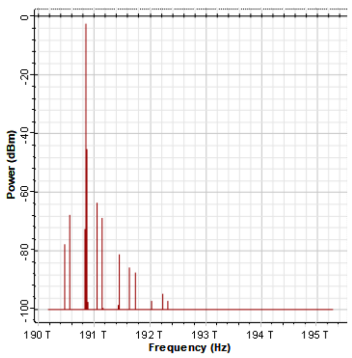
One can observe from this figure that UCS method have relatively reduced the FWM nonlinear effects compared to ECS, even though they are still in a considerable level. However, with the use of the proposed method, 50% of the FWM products have completely been suppressed, besides the output power of the remained fake pulses has dramatically decreased, which demonstrates the technical efficiency of the suggested technique.

B. 32 channels DWDM Transmission system

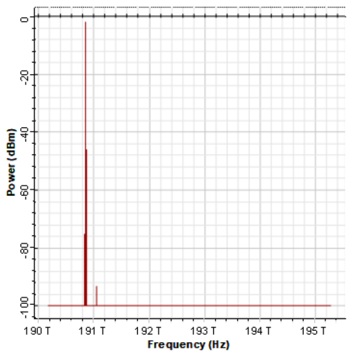
Using the same simulation setup, the proposed method has been applied in 32-channels DWDM transmission system to test its performance in such a complexed architecture. Fig. 7 illustrates the optical spectrum analyzer for ECS, UCS and the proposed method in 32-channels DWDM over 300km.



ECS



UCS

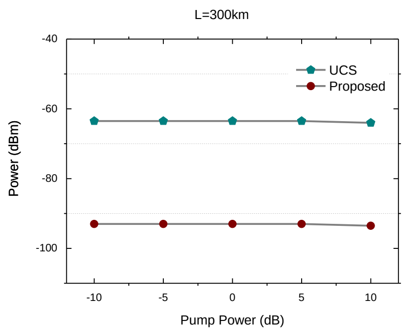


Proposed method

Figure 7. Optical spectrum analyzer for 32-channels DWDM over 300km

It can be observed from Fig. 7 that FWM spectral components have strongly been generated in ECS due to the same frequency spacing between all the 32 channels in DWDM transmission system. UCS resulted in better signal quality compared to ECS, less FWM products have been generated with a slight power decrease from -44 dBm to -63 dBm. However, it can clearly be observed that the proposed method provides the best results as almost all the fake spectral components have been eliminated, in addition to the significant power decrease of the highest FWM product from -44 dBm to -93 dBm. . It has also been shown that when the transmission distance of the optical network increases, the impact of the suggested technique on FWM nonlinear effects becomes better, which proves the reliability and the efficiency of the proposed method.

Fig. 8 highlights the comparison results between the proposed method and Unequal Channel Spacing (UCS) based on the power of the highest FWM spectral component in respects to transmission distance and input power.



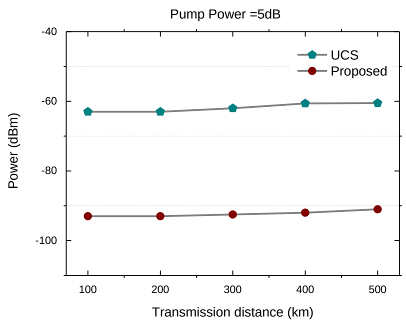


Figure 8. Power of the highest FWM product

It can be noticed from Fig. 8 that transmission distance has a slight impact on the highest FWM products as both methods keep nearly the same values for all transmission distances and all pump power values. It can also be observed from both graphs in Fig. 8 that the proposed method offers an evident reduction of the power of the highest FWM fake spectral component compared to UCS method regardless of design setting values. The power of the highest additional pulse has strongly been reduced using the proposed method as all its values remain under -90dB. One can conclude from the previous results that the use of chirped FBG with unequal channel allocation decreases dramatically the FWM nonlinear effects, and enables better reception of the transmitted signals.

IV. CONCLUSION

In this work, we introduced an improved technique to reduce the FWM nonlinear effects in DWDM long-haul optical network using unequal channel allocation and Chirped FBG in data receivers. The proposed technique has been investigated based on two optical communication scenarios, first with 8-channels WDM transmission system, then with 32-channels DWDM transmission system over 300km in order to test the reliability of the proposed technique in a complexed optical network architecture. The effect of the proposed method on FWM have been examined and validated by analyzing the optical spectrum analyzer and the output power of the highest FWM spectral product. Results demonstrate that the proposed method provides a very satisfactory performance as it results in less FWM products with reduced output power compared with the state-of-art alternative. It has also been shown the impact of the suggested technique on FWM nonlinear effects remain valid regardless of transmission distances and input power, which proves the reliability and the efficiency of the proposed method.

REFERENCES

[1] B.H. Choi, H.H. Park, and M. J. Chu "New Pump Wavelength of 1540-nm Band for Long-Wavelength-Band Erbium-Doped Fiber Amplifier (L-Band EDFA)", *IEEE Journal Of Quantum Electronics,* Vol. 39, No. 10, 2003

[2] Y. Ito, J. Onishi, S. Kojima, T. Numai "Influence of modulation formats on FWM noises in FDM optical fiber transmission systems", *Optics Communications,* 281, 2008

[3] Y.Song and P.Yu " Simulation and experimental investigation of nonlinear effects in 5G fronthaul transmission system based on WDM-PON architecture ", *Optical Fiber Technology* 65, 2021

[4] A. Singh, A. K. Sharma, T.S. Kamal, "Investigation on modified FWM suppression methods in DWDM optical communication system" *Optics Communications,* 282, 2009

[5] Monika, A. Wason, R.S. Kaler "Investigation of four wave mixing effect with different number of input channels at various channel spacing" *Optik,* 124, 2013

[6] A. Bogoni and L. Potì,, "Effective Channel Allocation to Reduce Inband FWM Crosstalk in DWDM Transmission Systems," *IEEE Journal Of Selected Topics In Quantum Electronics*, Vol. 10, No. 2, 2004

[7] K. Singh, S. Bansal "Suppression of FWM Crosstalk on WDM Systems Using Unequally Spaced Channel Algorithms – A Survey" *International Journal of Advanced Research in Computer Science and Software Engineering,* Volume 3, Issue 12, 2013

[8] F. Chaoui A. Hajaji and O. Aghzout, "Chirped Bragg Grating Dispersion Compensation in Dense Wavelength Division Multiplexing Optical Long-Haul Networks", *International Journal Of Microwave And Optical Technology,* Vol.10, No.5, 2015

[9] H. Venghaus, "Venghaus H.Wavelength filters in fibre optics,wavelength filters in fibre optics," *Springer (Chapter 5) 3-540-31769-4.*