Four-wave Mixing in Multi-channel Optical Systems

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Abstract. As the signal propagates through the network the fiber nonlinearities like four-wave mixing degrades the signal quality. In this paper, the effect of four-wave mixing in multi-channel optical system with using equal and unequal channel spacing was simulated. The results were evaluated by using of Bit Error Rate, eye diagram and output spectrum. As simulation tool was used VPIphotic. Results show that the effect of four-wave mixing has less impact at the transmitted signal for unequal channel spacing than equal channel spacing. The simulation results show that four wave mixing effect is minimum at 100 GHz channel spacing between input channels.

Keywords
FWM, WDM, nonlinear effects, channel spacing, BER, eye diagram.

1. Introduction

Current situation in the world, where single-channel communication systems are almost replaced by multichannel systems. Wavelength division multiplexing (WDM) is common method of multiplexing to create high-speed full-optical networks. WDM can both significantly enhance transmission capacity and provide more flexibility in optical network design. This technique allows data transmission via multiple wavelengths transmitting in single optical fiber. The advantage of WDM is the ability to transmitting the data with different transmission speed, modulation and format in every single wavelength [1-12].

There are a number of optical nonlinear effects in optical fibers, such as stimulated Raman scattering, stimulated Brillouin scattering, carrier-induced phase modulation and four wave mixing (FWM). FWM is one of the dominant effects. It can cause crosstalk between different wavelength channels in WDM, especially in dense-WDM optical networks, and limit the performance of such systems [1, 2, 6, 11, 13].

FWM in fibers is related to self-phase modulation and cross-phase modulation: all these effects originate from the same (Kerr) nonlinearity and differ only in terms of degeneracy of the waves involved. In this paper, we have simulated the effect of FWM products in WDM by varying channel spacing. There are two types of channel spacing in WDM system, equidistant channel spacing (current ITU grid specifies \(\Delta f = 100, 50, 25 \text{ and } 12.5 \text{ GHz}\)) and non-equidistant channel spacing (\(\Delta f \neq \text{const.}\), respectively [1, 3, 6-9, 12, 17]).

2. Nonlinear effects

Fiber nonlinearity is the main destructive phenomena in high data rate optical communication systems. The geometrical structure of fiber opens the opportunity for raising the nonlinear effects, because the light is launched to the optical fiber, which lead to high levels of power density. The power dependence of refractive index has its origin in the third-order nonlinear susceptibility. The nonlinear phenomenon, known as four-wave mixing, also originate from it [1, 2, 12, 14, 15].

2.1 Origin of FWM

The four-wave mixing is one of the dominating degradation phenomenon in non-linear optics that characterize multi-channel communication systems. It arises from a third-order optical nonlinearity, as is described with a \(\chi^{(3)}\) coefficient. It occurs when two or more different frequency components propagate together in optical fiber. Interactions between two co-propagating wavelengths produce two new group of optical spectral components at different frequencies. The newly produced FWM products can mix with channel signals or themselves to produce higher-order FWM products which can overlap with channels and result in crosstalk [5-7, 9, 12, 16, 17].

On a fundamental level, FWM process represents a scattering process in which two photons of energies \(\omega_{01}\) and \(\omega_{02}\) are destroyed, and their energy appears in the form of two new photons of energies \(\omega_{2}\) and \(\omega_{3}\) (the law of conservation of energy applies) [1].

Mixing of two different frequencies \(\omega_{1}\) and \(\omega_{2}\) in the pulse creates new frequencies which can be marked as \(\omega_{12}\) and \(\omega_{21}\) [2, 5, 7, 12-14]:

\[\omega_{12} = 2\omega_{1} - \omega_{2}\]  \hspace{1cm} (1)
\[\omega_{21} = 2\omega_{2} - \omega_{1}\]  \hspace{1cm} (2)
The Figure 1 shows newly created frequencies (green color) in multi-channel communication systems caused by FWM.

Figure 1. Schematic diagram that shows four-wave mixing in the frequency domain.

For FWM are important two conditions which have to be fulfilled for generating new optical waves; it is a frequency condition and a phase matching condition. The second one is a requirement of momentum conservation. The phase mismatch is the main reason behind FWM. The frequency condition for degenerative and non-degenerative combinations is given by [6-9, 11, 13]

\[
\sigma_{FWM} = \begin{cases} 
\sigma_i + \sigma_j - \sigma_k, & \text{if } i \neq j \neq k \\
\rightarrow \text{non-degenerative FWM} \\
\sigma_i + \sigma_j - \sigma_k, & \text{if } i = j \neq k \\
\rightarrow \text{degenerative FWM}
\end{cases}
\]

(3)

The degenerative FWM is often the dominant process and highly impacts the system performance.

The number of FWM components generated increases with the increase in number of users. In theoretical way, the total number of new FWM components FWM \( N \) for given number of channels \( M \) can be calculated by [6, 8, 9]

\[
N = \frac{M^2(M-1)}{2}.
\]

(4)

The Figure 2 shows the FWM products due to the channels increases according to (4) where can be easily seen the exponential growth of number of FWM components with increasing number of optical channel [8].

Figure 2. FWM products.

FWM represents serious limits in WDM transmission systems. Its impact can be suppress and eliminate by increasing the spacing between the channels, increasing the chromatic dispersion of the transmission fiber, decreasing the average input power per channel. For the future optical multi-channel systems with high-order modulation formats, stochastic nature of FWM will be also the crucial limiting factor and therefore we assume its further investigation will be necessary. Otherwise, FWM can provide beneficial properties and the opportunity for wavelength conversion or signal amplification [1, 3, 5, 6, 12].

3. Eliminating FWM by Channel spacing

One way how to suppress and eliminate FWM impact in transmission system is to increase the spacing between the channels or use unequal channel spacing. In this new scheme of channel arrangement, the new optical waves fall outside of useful optical channels and thus decrease the possibility of intra-channel interference [1, 3].

3.1 Simulation setup and description

Optical communication systems are limited by chromatic dispersion and nonlinear effects of fiber, which interact and accumulate along the length of the optical link. Chromatic dispersion, which broadens the pulses, can be reduced by using dispersion-shifted fibers at the 1550 nm wavelength range, but low chromatic dispersion enhances some nonlinear effects of fiber, especially four-wave mixing [2, 9, 12, 18].

In this paper, we use the VPItransmissionMaker, powerful simulation software provided by VPIsystems, Inc. We observe the effect of FWM in 4 x 10 Gbit/s WDM transmission system configuration (schematic illustration on Fig. 3.). This fiber model takes into account the impact of linear and nonlinear effect. We can set the fiber type, length and core area of the fiber, attenuation, dispersion and nonlinear parameters. We used DSF fiber with nonlinear refraction index \( n_2 = 2.2 \times 10^{-20} \text{ m}^2/\text{W} \) and attenuation \( \alpha = 0.2 \text{ dB/km} \). Input power bounded into optical fiber was \( P_{in} = 20 \text{ mW} \) and length of optical fiber was \( L = 10 \text{ km} \). At the output VPItransmissionMaker provides a visualization tool. We investigated BER, eye diagram and optical spectrum by using VPIPhotonicAnalyzer tool. Eye diagrams can be used to effectively analyze the performance of an optical system so that it can be easily visualized. Bit Error Rate (BER) is a more accurate metric to evaluate the performance of an optical transmission system.
3.2 Equidistant Channel Spacing

We have investigated the effect of FWM in WDM optical transmission system in terms of BER and eye diagram. The four input signals were launched at 193.025 THz, 193.075 THz, 193.125 THz and 193.175 THz respectively, so that they have uniform spacing (100, 50, 25 and 12.5 GHz) and we have observed the plot of BER versus equal channel spacing. The results of this model are presented in Fig. 4.

Fig. 4. Dependence of BER on channel spacing.

From Fig. 4, it is seen that the BER improves with increasing channel spacing, because lesser the spacing between input channels, more the interference between input frequencies. Figure below depict the eye diagram of the received signal for each of the four channel with channel spacing 50 GHz. In Fig. 6, we can see the output optical spectrum of this model.

Fig. 5. Eye diagram of 4-channel WDM transmission system.

Fig. 6. Optical spectrum of 4-channel WDM transmission system with channel spacing 50 GHz.
3.3 Non-equidistant Channel Spacing

We simulated the same situation as before with the same parameters, but now we used unequal channel spacing (four signals at 193.010 THz, 193.075 THz, 193.125 THz and 193.190 THz). The results are presented in terms of BER (Fig. 7.), eye diagram (Fig. 8.) and output optical spectrum (Fig. 9.) It is seen that we can decrease FWM efficiency with non-equidistant channel spacing because more the spacing between input channels, less the interference between input frequencies.

![Fig. 7. Dependence of BER on channel spacing.](image)

![Fig. 8. Eye diagram of 4-channel WDM transmission system.](image)

![Fig. 9. Optical spectrum of 4-channel WDM transmission system with non-equidistant channel spacing.](image)

4. Conclusion

In this paper, we were focused on investigation of four-wave mixing in WDM system. Analysing the results obtained by model implemented in VPIphotonic software. Results show that the effect of FWM reduces more effective for unequal channel spacing than equal channel spacing. FWM effect is minimum at 100 GHz channel spacing between input channels. The results of our simulation have important consequences for understanding multi-channel WDM systems that suffer signal degradation by FWM.

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References


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