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Recent four-wave mixing suppression methods

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ABSTRACT

This paper reviews various techniques that have been proposed by many researchers to reduce the effect of four-wave mixing (FWM). A review was suggested to investigate the recent method of each technique and to compare their benefits and limitations in a wavelength division multiplexing (WDM) system. A 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. Among all the suppression techniques, there are six categories that are reviewed in this paper to suppress the effect of FWM and improve the overall system performance, which are: analysis of the individual and combined effects of high dispersion on FWM; using a hybrid WDM and time division multiplexing technique; using optic code division multiple access, using a short fiber optical parametric amplifier; using ultra-low unequal channel spacing, and finally, using a return-to-zero frequency shift-keying modulation format. The reduction techniques of FWM effect were compared according to the benefits and weaknesses of each technique in the application of WDM communication systems.

1. Introduction

One of the major limitations in optical fiber systems under high data rates and long-haul transmission distances is called nonlinear effects. Four-wave mixing (FWM) is one of these effects, which represents the inelastic scattering that occurs as a result of changes in the refractive index inside the fiber [1]. The FWM occurs when two or more waves propagate in the same direction in the same fiber. The signals are mixed to produce new signals of wavelengths spaced at the same intervals of the mixing signals [2]. The resulting signals of FWM co-propagate with the original signal and interfere with them. This leads to degradation of the performance of high-powered wavelength division multiplexing (WDM) optical networks and causes probable distortion of the optical signal and loss of energy of the channel, which induces crosstalk in dense WDM (DWDM) [3,4]. In general, the occurrence of FWM in WDM systems depends on a number of factors, such as the power per channel, the wavelength spacing between channels, the transmission interact distance, effective area, and the dispersion characteristics of the optical fiber.

Recently, many techniques have been proposed to reduce the deleterious effects of FWM in WDM communication systems [5–10]. These include analysis of the individual and combined effects of high dispersion on FWM [5], using a hybrid WDM/TDM technique [6], using optic code division multiple access [7], using a short fiber optical parametric amplifier (OPAS)[8], using ultra-low unequal channel spacing [9], using an RZ-FSK modulation format [10]. Due to the negative side of FWM limitations, which reflect on the performance of optical transmission, as well as the demand for increasing the channel capacity and bandwidth in telecommunication networks all over the world, due to the change in people's requirements, where most of them are dependent on ultra high speed in all aspects [11,12], it is important to have solutions to limit the defects of FWM. Hence, it is appropriate to review the techniques that have been carried out to reduce the effects of FWM in WDM communication systems. The importance of this paper is that it discusses the significant reduction methods of FWM and gives a clear picture to the reader that the reduction level for all techniques reaches specific values to help future researchers to enhance their systems.

This paper provides a review and comparison between the techniques used to overcome the FWM effect in WDM systems. The comparison includes description of the technique, benefits and weaknesses. This paper is organized as follows. In Section 2 we investigate the FWM suppression methods in detail, in Section 3 we make a summary of the review work, and in Section 4 we give our conclusions and possible future research directions.

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Table 1
Comparison of FWM power reduction due to due to different higher order of dispersion for fiber length of 5 km and input power of 5 and 40 mW, respectively (OD: order of dispersion).

Dispersion parameter	FWM power in dBm when channel power = 5 mW	FWM power in dBm when channel power = 40 mW
3OD + 5OD only	−22	22
2OD + 3OD only	−47	−19
3OD only	−22	22
4OD only	14	34
5OD only	14	37
2OD + 3OD + 4OD + 5OD only	−47	−20

2. Four-wave mixing suppression methods

Suppression methods of FWM are applied to overcome the limitations of the FWM effect in WDM systems. These methods introduced different approaches to reduce the impact of FWM [5–10]. Of course, many researchers would ask about our choice of only these techniques. In fact, these techniques, presented in the next section are considered the most recent and effective methods in suppressing the effects of FWM.

2.1. Effect of higher-order dispersion

Singh et al. [5] proposed a theoretical analysis of both the single and combined effect of second, third, fourth and fifth-order dispersion parameters on FWM at different input channels, powers and core effective areas. The propagation constant in terms of Taylor series can be expanded as [5]:

$$B = B_0 + (w - w_0)\frac{d\beta}{dw} + \frac{1}{2}(w - w_0)^2\frac{d^2\beta}{dw^2} + \frac{1}{6}(w - w_0)^3\frac{d^3\beta}{dw^3} + \frac{1}{24}(w - w_0)^4\frac{d^4\beta}{dw^4} + \frac{1}{120}(w - w_0)^5\frac{d^5\beta}{dw^5} \quad (1)$$

Where $d\beta/d\omega = \tau$, the propagation delay per optical length is the angular velocity. We can ignore τ, because it produces a phase delay of the carrier signal and has no influence on distortion of the signal [13]. Therefore, the phase matching factor can be described as [5]:

$$\Delta\beta = 2\pi^2\Delta f^2 \begin{bmatrix} \frac{\lambda^2}{2\pi c}D + \frac{2\pi\Delta f}{3}\frac{\lambda^2}{(2\pi c)^2}(\lambda^2 D_1 + 2\lambda D) \\ + \frac{\pi^2}{3}\frac{\Delta f^2\lambda^3}{(2\pi c)^3}(\lambda^3 D_2 + 6\lambda^2 D_1 + 6\lambda D) \\ + \frac{2\pi^3}{15}\frac{\Delta f^3\lambda^4}{(2\pi c)^4}(\lambda^4 D_3 + 12\lambda^3 D_2 + 36\lambda^2 D_1 + 24D) \end{bmatrix} \quad (2)$$

where $\Delta\beta$ is the phase matching, Δf is the channel spacing, D is the fiber chromatic dispersion, λ is the operating wavelength, $\partial D/\partial\lambda$ is the dispersion slope, α is the attenuation factor, and c is the velocity of light. FWM induced cross talk in WDM systems [14–19], which is given as [5]:

(3)$P_{FWM} = \frac{\eta}{9}d^2\gamma^2 P_i P_j P_k \exp^{-\alpha L}\left[\frac{1-\exp(-\alpha L)^2}{\alpha^2}\right]$And the four-wave mixing efficiency is expressed as [5]

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left[1 + \frac{4\exp(-\alpha L)\sin^2(\Delta\beta L/2)}{(1 - \exp(-\alpha L))^2}\right] \quad (4)$$

where γ is the nonlinear-coefficient, which is equal to ($\gamma = 2\pi n_2/\lambda A_{eff}$), L is the fiber length, n_2 is the fiber nonlinear refractive index, P_1, P_2, P_3, are the channel input power, A_{eff} is the effective area of the fiber core, L_{eff} is the effective fiber length, and d is the denegerate factor. The comparison of FWM power reduction due to different higher order of dispersion is given in Table 1 [5]. The simulated results show that the FWM power decreased by mixing the effect of 2OD + 3OD + 4OD + 5OD dispersion terms. Also the impact of 3OD, 4OD and 5OD is low in the comparison to 2OD. However, the drawback of this analysis is that it does not take into account the dispersion compensation, and did not explain the effect of this different order of dispersion on output system performance. Also, there is no calculation of the channel spacing effect on FWM, although it is seen in a model analysis.

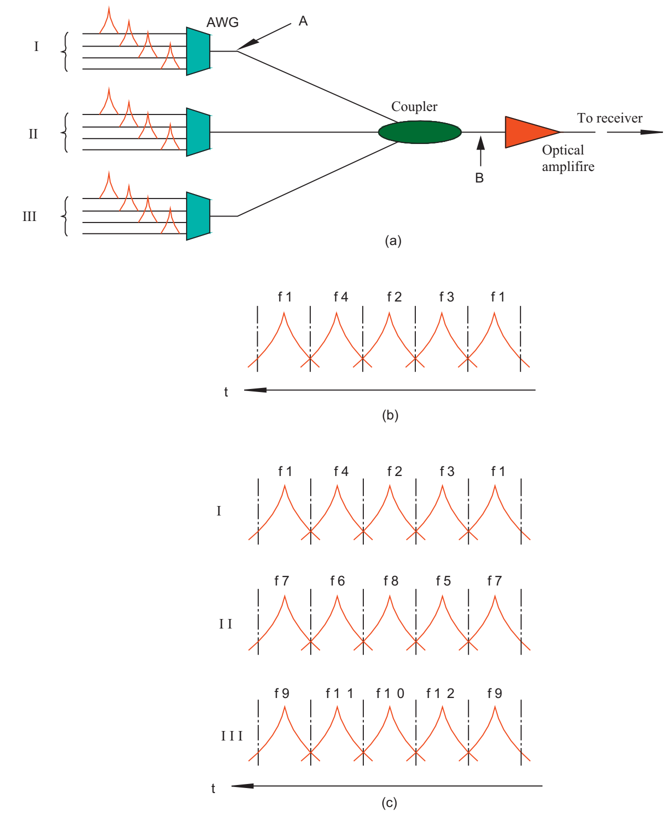

Fig. 1. Schematic diagrams for (a) hybrid WDM/TDM system, (b) channel arrangement at point A, and (c) channel arrangement at point B [6].

2.2. Hybrid WDM/TDM technique

In the zero-dispersion wavelength region, FWM has a potential effect, where a phase mismatch is very low. Therefore, several techniques have been achieved for trying to reduce the effect of FWM, such as optical multi-demultiplexers with the combination of delay lines, and bit-phase arranged IRZ (BARZ) signals [20–22]. Okada et al. [6] introduced a technique to overcome the FWM effect by using a hybrid WDM/TDM. The effectiveness of this approach was done by simulations. The main interest of using a hybrid WDM/TDM proposed is that all channels are of equal spacing in the frequency domain. The system configuration is shown in Fig. 1. Twelve channels with equal channel spacing are used ($(f_{i+1} - f_i) = \Delta f$, where f_i is the frequency of the ith channel and Δf is the channel spacing. It includes three groups, each group consists of 4 channels and it is modulated to generate an RZ pulse, and then is multiplexed into the time domain to reduce the FWM effects. The channel group of TDM is arranged as shown in Table 2.

However, in order to estimate the effectiveness of this technique in the FWM crosstalk reduction, Okada et al. [6] used a simple 4-channel system with a data rate equal to 2.5 Gb/s for each channel. System performance was analyzed in case of (system 1) where the hybrid WDM/TDM technique is applied and (system 2) in the case of not using this technique (hybrid WDM/TDM). For system 1, the channels are multiplexed in a series of $f1$, $f2$, $f3$, $f4$, where $f_i < f_{i+1}$ and all channels are spaced by 100 GHz. The zero-dispersion