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Suppression of inter and intra channel four wave mixing effects in optical CDMA over DWDM hybrid system

Naif Alsowaidi[1], Tawfig Eltaif[1 *], Mohd Ridzuan Mokhtar[2]
(1. *Faculty of Engineering & Technology*, *Multimedia University*, *Bukit Beruang*, *Melaka* 75450, *Malaysia*;
2. *Faculty of Engineering*, *Multimedia University*, *Cyberjaya*, *Selangor* 63100, *Malaysia*)
* *Corresponding author*, *E-mail*: *tefosat@ieee.org*

Abstract: In this study, a hybrid system of optical Code Division Multiple Access(optical CDMA) and Dense Wavelength Division Multiplexing(DWDM) is proposed with a comprehensive investigation into the effect of four-wave mixing(FWM). In such system, two major FWM problems exist, inter and intra-channel FWM, including multiple access interference(MAI) and inter-symbol interference(ISI). Results show that the optimum transmitted power is 18dBm in order to control the trade-off between inter and intra-channel FWM, where an increase in the BER of the hybrid system at transmitted power above 18 dBm is indicated. Hence, an electro-optic phase modulator(EOPM) module is proposed and placed after the WDM multiplexer to simultaneously modulate the phase of all wavelengths signals to increase the nonlinear tolerance in the hybrid system by suppressing the impact of intra-channel FWM, which is shown to greatly improve the performance of the optical CDMA-DWDM hybrid system based OOK transmission. In addition, the effect of MAI can be reduced by the use of multi-diagonal(MD) identification sequence code, due to the zero cross-correlation property of MD. The results also reveal that the CDMA technology in conjunction with chromatic dispersion helps to reduce the effect of inter-channel FWM. Moreover, the identification sequence code interval plays crucial role in the mitigating of ISI as the results expose that the best performance of the proposed hybrid system can be achieved when the identification sequence code interval squeezed into 25% of bit duration where the avoidance of ISI is guaranteed.

Key words: optical CDMA; DWDM; Inter and Intra-channel FWM; MAI; ISI; EOPM

DWDM 混合光学系统中帧间和信道内四波混频效应的抑制

Naif Alsowaidi[1], Tawfig Eltaif[1 *], Mohd Ridzuan Mokhtar[2]
(1. *Faculty of Engineering & Technology*, *Multimedia University*, *Bukit Beruang*, *Melaka* 75450, *Malaysia*;
2. *Faculty of Engineering*, *Multimedia University*, *Cyberjaya*, *Selangor* 63100, *Malaysia*)

摘要:本文提出了光码多分址(CDMA)和光密集波分复用(DWDM)的混合系统,全面研究了四波混频(FWM)的影响。在这个系统中,主要存在两个四波混频问题:包括多址干扰(MAI)和码间干扰(ISI)的帧间四波混频和信道内四波混频。结果表明,综合考虑信道间和信道内四波混频的影响,最佳发射功率可选为 18 dBm。当发射功率大于 18 dBm 时,混合

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系统的误码率(BER)将增加。基于此,本文提出了一种电光相位调制器(EOPM)模块,将其放置在波分复用器之后,通过抑制信道内四波混频的影响,同时调制所有波长信号的相位,从而增加混合系统的非线性容限,这极大地改善了基于OOK传输的光学CDMA-DWDM混合系统的性能。此外,由于多对角线(MD)结构具有零互相关特性,通过使用多对角线识别序列码可以减少多址干扰的影响。结果还表明,CDMA技术与色散相结合有助于降低信道间四波混频的影响。此外,识别序列码间隔在减轻码间干扰中起着至关重要的作用,如结果所示,当识别序列码间隔压缩至比特持续时间的25%时,可以避免码间干扰,此时所提出的混合系统的性能最佳。

关　键　词:光码多分址;光密集波分复用;帧间信道内四波混频;多址干扰;码间干扰;电光相位调制器

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1　Introduction

Wavelength Division Multiplexing (WDM) serves as a technique to increase the capacity of optical networks, due to its advantages of long distance, large sustainable bandwidth per customer, scalability and transparency[1-2]. However, nonlinearity effects have a huge impact on the performance of optical transmission systems[3-6], for instance, inter and intra-channel four-wave mixing (FWM) effects are the main obstacle for high data rate and high capacity transmission, they are considered as one of the foremost application issues in optical networks, such effects have been widely investigated and studied in WDM systems[7-14]. On the other hand, optical Code Division Multiple Access (optical CDMA) has been emerging as a promising technology. The CDMA has a unique capability in term of data confidentiality in which it assigns a single specific code for each user. Unfortunately, the Multiple Access Interference (MAI) in CDMA limits the performance of the system especially when a large number of users accesses the shared media simultaneously. The suppression of MAI has extensively studied/investigated using different techniques of MAI suppression based on the design of identification sequence code[15-16], and the receiver architectures with the implementation of interference cancellation[17-20]. Recently, few studies have been proposed to overcome the limitations that arise from the sole WDM and the sole optical CDMA system using a hybrid methods of WDM with optical CDMA grid to meet the high demand of high bit rate services[21-26]. These hybrid studies have resulted in increasing the capacity, security, and the bandwidth of the system. One of the studies for example, in Ref. [24] proposed a hybrid system of optical CDMA interconnected through a reconfigurable WDM ring, in which add/drop router was used to enable the optical network. The measurements result showed an acceptable power penalty. Another study in Ref. [25], proposed a hybrid WDM-optical CDMA with ring architecture. The study used the optical features of CDMA in which bandwidth was shared by the number of segments and the intersegment communication was performed using WDM. Such a novel technology limits the number of codes, thus reducing the MAI effect, and reusing the same codes in other segments could increase the number of users. However in Ref. [26], optical CDMA overlaid WDM-PON hybrid system was proposed where there are two WDM-PONs, each encoded by different encoder, with different optical codes. The first WDM PON consists of 8 ONUs carried on 192.1 – 193.5 THz with 200 GHz channel spacing, while the second supported 2 ONUs carried on center frequencies of 192.9 and 193.1 THz. It is shown that the Bit Error Rate (BER) of channels that operates at 192.9 THz and 193.1 THz are increased due to the cross-correlation caused by the second WDM PON. However, the effects of inter and intra-channel FWM has not been addressed in previous studies conducted on optical CDMA-WDM hybrid systems.

Therefore, in this paper, we for the first time propose a cost-effective optical CDMA-DWDM hybrid system with 25 GHz channel spacing at data rate of 40 Gbps per wavelength where each wavelength carried eight optical CDMA signals at data rate of 5 Gbps per user. Considering the effects of MAI, Inter-Symbol Interference (ISI) and inter and intra-channel FWM, Multi-diagonal (MD) code is used due to its features of reducing the MAI. On the other hand, CDMA, which based on spread spectrum technology, has the ability to reduce the FWM effects, as the optical energy of each bit is spread over an optical identification sequence code. In addition, an Electro-Optic Phase Modulator (EOPM) is used to suppress the intra-channel FWM effect by introducing a phase shift between pulses.

2 Hybrid System Description

In On-Off Keying (OOK) modulation format, the information is carried by the signal's intensity, where the signal's phase is an extra degree of freedom. Utilizing such features is our interested in suppression of the intra-channel FWM effect. Moreover, the use of Return to Zero (RZ) modulation format would provide a higher robustness against nonlinearity effects compared to Non-Return to Zero (NRZ) modulation format[27]. In addition, the shorter duty cycle of RZ pulses causes less degradation on the system performance caused by ISI as compared with NRZ pulses. Therefore, RZ-OOK modulation format is used in the proposed hybrid system. The operational block diagram for the optical CDMA-DWDM hybrid system is depicted in Fig. 1. Where there is M number of wavelengths with wavelength spacing of 25 GHz generated by continuous wave Distributed Feedback (DFB) lasers, an external modulator is placed after each DFB laser source to create a periodic train of RZ pulses. Each wavelength split into N outputs ports; each represents one user's data, where another external modulator is driven by an electrical NRZ data source used to impose the modulation by blocking the zero bits. Where then the modulated data of each user is encoded by optical identification sequence code, the coding operation is performed in a unipolar (0,1) manner. Then the N encoded users' data are combined together by an optical combiner, where the same optical identification sequence code can be reused for other wavelengths. Finally, all the M wavelengths multiplexed by WDM multiplexer followed by an EOPM to simultaneously modulate the phase of all wavelengths signal with a frequency equal to the data rate of a wavelength. The output of EOPM then sent over Single Mode Fiber (SMF). In addition, Dispersion Compensating Fiber (DCF) is used for dispersion compensation, and preamplifier is used to compensate the loss. The output of the preamplifier is then de-multiplexed by WDM de-multiplexer, where the received signal of a wavelength split into N outputs ports one encoded user's data is represented by one output port, the output of each then proceeds for the decoding operation. The photodetector is used to convert the optical signal of each user where thresholding scheme is then employed for bit detection. In the proposed hybrid system each wavelength/channel

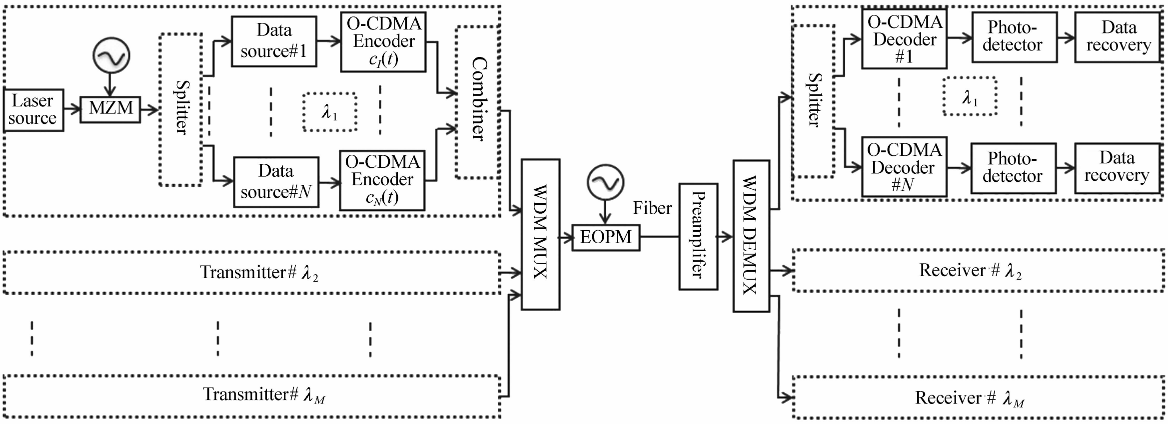

Fig. 1 Configuration of the hybrid system with the EOPM

can accommodate N users, so, $M \times N$ users can be accommodated.

3 Hybrid System Analysis

Nonlinear FWM effect occurs when signals of different wavelengths propagate and interact to generate new wavelengths that can interfere with the information signal and result in performance degradation; the FWM power due to the interaction of frequencies f_{p}, f_{q} and f_{r} is given as:

$$P^{\mathrm{pqr}}_{\mathrm{OCDMA\text{-}DWDM}} = \frac{\eta}{9}(\mathrm{d}\gamma)^2(\frac{P_{\mathrm{p}}}{N}(\frac{P_{\mathrm{q}}}{N})(\frac{P_{\mathrm{r}}}{N}) \cdot \exp[-\alpha L][\frac{(1-e^{-\alpha L})^2}{\alpha^2}], \quad (1)$$

where P_{p}, P_{q} and P_{r} represent the power of these frequencies (f_{p}, f_{q} and f_{r}). The FWM efficiency η depends on the phase mismatching and can be expressed as (2).

$$\eta = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2}[1 + \frac{4e^{-\alpha L}\sin^2(\frac{\Delta\beta \cdot L}{2})}{(1-e^{-\alpha L})^2}], \quad (2)$$

$\Delta\beta$ refers to the phase mismatch and it can be represented by

$$\Delta\beta = \frac{2\pi\lambda^2}{c}(\Delta f_{\mathrm{pr}})(\Delta f_{\mathrm{qr}}) \cdot [D_{\mathrm{c}} + (\frac{\lambda^2}{2c})(SD)(\Delta f_{\mathrm{pr}} + \Delta f_{\mathrm{qr}})], \quad (3)$$

where d is the degeneracy factor, and its value is 1 when $f_{\mathrm{p}} = f_{\mathrm{q}}$, and 2 when $f_{\mathrm{p}} \neq f_{\mathrm{q}}$; γ is the nonlinearity coefficient, L is the transmission length; P_{p}, P_{q}, P_{r} are the transmitted power per wavelength/channel, each wavelength is shared with N optical CDMA users where the transmitted power per chip is $\frac{P_{\mathrm{p}}}{FN}$; and α is the attenuation of the fiber, the chromatic and slope dispersion are represented by D_{c} and SD respectively.

The data corresponding to the mth wavelength of the nth user which is the input of the optical CDMA encoder is given as;

$$d_m^n(t) = \sqrt{P_t}\, b_m^n(t) \cdot \cos^2[\frac{\pi}{2}\cos^2(\pi B t)] \text{ where, } 0 < t \leqslant T, \quad (4)$$

where, $b_m^n(t)$ and B are the data of the nth user in mth WDM channel and the clock frequency respectively.

In this work, there are N MD sequences used to carry the users data; each sequence code has a weight (number of ones) w and a length (number of chips) F, where the length of the MD sequences is $F = N \times w$, the interested reader may refer to [15] for further details.

Hence, the identification sequence code of the nth user in mth wavelength is given as:

$$C^{mn}(t) = \sum_{f=1}^{F} C_f^{mn} P(t - fT_{\mathrm{c}}), \quad (5)$$

where; $C^{mn} \in \{0, 1\}$ and $P(t)$ refers to the unit rectangular pulse with T_{c} duration.

An optical combiner used to combine all N encoded users' data. Hence, the encoded optical CDMA signals corresponding to mth wavelength is mathematically expressed as;

$$S_m(t) = \sum_{n=1}^{N}\sum_{f=1}^{F}\sqrt{P_{\mathrm{t}}}\, b_m^n(t) C_{\mathrm{f}}^{mn} \cdot P(t - fT_{\mathrm{C}})\cos^2[\frac{\pi}{2}\cos^2(\pi B t)], \quad (6)$$

Finally, all the M channels were multiplexed by WDM multiplexer, where each wavelength consisting of N optical CDMA users is given as:

$$S(t) = \sum_{m=1}^{M} S_m(t). \quad (7)$$

Then an EOPM module is placed after the WDM multiplexer to simultaneously modulate the phase of all-optical CDMA signals of DWDM channels with a frequency equal to the data rate of a single wavelength, so the intra-channel FWM can be suppressed. It is noteworthy that the EOPM is driven by a sinusoidal clock signal; therefore the phase of each wavelength is modulated as;

$$\phi(t) = \phi_{\mathrm{EOPM}}\sin(2\pi f_{\mathrm{SCS}} t), \quad (8)$$

where ϕ_{EOPM} is the phase deviation of the EOPM and f_{SCS} is the frequency of the sinusoidal clock signal.

Therefore; the transmitted signal into the fiber is given as;

$$S(t) = [\sum_{m=1}^{M} S_m(t)] e^{\mathrm{j}\phi(t)}. \tag{9}$$

At the receiver side, the output of the WDM de-multiplexer for the i^{th} wavelength signal of the n^{th} user is expressed by:

$$r_i(t) = \sum_{n=1}^{N} \sum_{f}^{F} \sqrt{P_{\mathrm{s,in}}} b_i^n(t) C_f^{in}(t) \cos(\theta_i) + \sqrt{P_i^{\mathrm{FWM}}}(t) \cos(\theta_i - \theta_{\mathrm{FWM}}) , \tag{10}$$

where $P_{\mathrm{S}} = \frac{P_{\mathrm{r}}}{F}$, P_{r} is the received power, b_i^n is the data bit of the n^{th} user in i^{th} wavelength, which is either '1' or '0' and $P_i^{\mathrm{FWM}} = \sum_{pqr} P_{\mathrm{OCDMA\text{-}DWDM}}^{\mathrm{pqr}}$ is the total power of FWM products generated at frequency f_i.

Without the loss of generality, the first user in i^{th} wavelength is the desired user. So, after the decoding process, the received optical field at the photo-detector of the desired user in i^{th} wavelength is given as;

$$E(t) = E_{i1}(t) + E_{i,\mathrm{MAI}}(t) + E_{i,\mathrm{FWM}}(t) , \tag{11}$$

The first term is the electric field of the first user in i^{th} wavelength; the second term is the electric field of the MAI while the third term is the total electric field of FWM generated at frequency f_i.

The total signal current at the output of photo-detector can be derived as;

$$i_{\mathrm{b}}(t) = \frac{\Re w P_{\mathrm{r,ib}}}{F} + \frac{\Re}{F} \sum_{n=j+1}^{N} P_{\mathrm{r,in}} b_i^n I_{\mathrm{in},j}(t_{\mathrm{in},j}) + i_{\mathrm{FWM}}(t) + i_{\mathrm{sh}}(t) + i_{\mathrm{th}}(t) , \tag{12}$$

The first term is the desired signal, where $\Re$ is the responsivity of the photo-detector, the second term is due to the MAI, where $I_{\mathrm{in,j}}(t_{\mathrm{in,j}})$ is the cross-correlation between n^{th} user and j^{th} users in i^{th} wavelength, the third term is due to the FWM, fourth and fifth terms are due to the shot and thermal noises respectively.

The mean current of FWM, the signal-FWM and MAI-FWM are represented by the first, second and third terms respectively in Eq. (13).

$$i_{\mathrm{FWM}}(t) = 2\Re P_i^{\mathrm{FWM}}(t) \cos^2(\theta_i - \theta_{\mathrm{FWM}}) + 2\Re \sqrt{\frac{P_{r,il}}{F}(t) P_i^{\mathrm{FWM}}(t)} \cos(\theta_i) \cos(\theta_i - \theta_{\mathrm{FWM}}) + 2\Re \sum_{n=j+1}^{N} \sqrt{\frac{P_{r,\mathrm{in}}}{F} I_{\mathrm{in,j}}(t_{\mathrm{in,j}}) P_i^{\mathrm{FWM}}(t)} \cos(\theta_i) \cos(\theta_i - \theta_{\mathrm{FWM}}) , \tag{13}$$

The signal current for bit '1' can be written as:

$$i(1) = \frac{\Re w P_{r,i1}}{F} + \frac{\Re}{F} \sum_{n=j+1}^{N} P_{\mathrm{r,in}} I_{\mathrm{in},j}(t_{\mathrm{in},j}) + 2\Re P_i^{\mathrm{FWM}}(1) \cos^2(\theta_i - \theta_{\mathrm{FWM}}) + 2\Re \sqrt{\frac{P_{r,i1}}{F} P_i^{\mathrm{FWM}}(1)} \cos(\theta_i) \cdot \cos(\theta_i - \theta_{\mathrm{FWM}}) + 2\Re \sum_{n=j+1}^{N} \sqrt{\frac{P_{r,\mathrm{in}}}{F} I_{\mathrm{in,j}}(t_{\mathrm{in,j}}) P_i^{\mathrm{FWM}}(1)} \cos(\theta_i) \cos(\theta_i - \theta_{\mathrm{FWM}}) + i_{\mathrm{sh}}(1) + i_{\mathrm{th}}(t) , \tag{14}$$

Where the mean and variances for bit '1' can be expressed as;

$$\langle i(1) \rangle = \frac{\Re w P_{r,i1}}{F} + \Re \langle P_i^{\mathrm{FWM}}(1) \rangle , \tag{15}$$

$$\sigma^2(1) = \frac{\Re^2}{F^3} \sum_{n=j+1}^{N} P_{\mathrm{r,in}}^2 + \sigma_{\mathrm{signal\text{-}FWM}}^2(1) + \sigma_{\mathrm{MAI\text{-}FWM}}^2(1) + \sigma_{\mathrm{sh}}^2(1) + \sigma_{\mathrm{th}}^2(1) , \tag{16}$$

where;

$$\sigma_{\mathrm{signal\text{-}FWM}}^2(1) = \frac{2\Re^2 P_{\mathrm{r},i1}}{F} \{ \frac{1}{8} \sum_{p \neq q \neq r} P_i^{\mathrm{FWM}} + \frac{1}{4} \sum_{p = q \neq r} P_i^{\mathrm{FWM}} + \frac{1}{4} \sum_{p \neq q \neq r = i} P_i^{\mathrm{FWM}} \} , \tag{17}$$

and;

$$\sigma_{\mathrm{MAI\text{-}FWM}}^2(1) = \frac{2\Re^2}{F^2} \sum_{n=j+1}^{N} P_{\mathrm{r,in}} \{ \frac{1}{8} \sum_{p \neq q \neq r} P_i^{\mathrm{FWM}} + \frac{1}{4} \sum_{p = q \neq r} P_i^{\mathrm{FWM}} + \frac{1}{4} \sum_{p \neq q \neq r = i} P_i^{\mathrm{FWM}} \} , \tag{18}$$

The mean and variance values for bit "0" are given as:

$$\langle i(0)\rangle = \Re\langle P_i^{\text{FWM}}(0)\rangle , \tag{19}$$

$$\sigma^2(0) = \sigma^2_{\text{MAI-FWM}}(0) + \sigma^2_{\text{FWM-FWM}}(0) + \sigma^2_{\text{sh}}(0) + \sigma^2_{\text{th}}(1) , \tag{20}$$

where:

$$\sigma^2_{\text{MAI-FWM}}(0) = \frac{2\Re^2}{F^2}\sum_{n=j+1}^{N} P_{\text{r,in}}\left\{\frac{1}{8}\sum_{p\neq q\neq r} P_i^{\text{FWM}} + \frac{1}{4}\sum_{p=q\neq r} P_i^{\text{FWM}}\right\} , \tag{21}$$

$\sigma^2_{\text{MAI-FWM}}(1)$ has the term order of $(P_i^{\text{FWM}})^2$ and, it has very small value compared to the thermal noise, hence it can be neglected. Then the bit error rate (BER), following Ref. [28] is given as:

$$BER = Q\left(\frac{\langle i(1)\rangle - \langle i(0)\rangle}{\sigma(1) + \sigma(0)}\right) . \tag{22}$$

4 Results and Discussion

The proposed hybrid system accommodates 15 wavelengths/channels of DWDM with channel spacing of 25 GHz operating at 1 558.58 – 1 561.4 nm and the data rate of each is 40 Gbps, where each channel carries 8 optical CDMA users′ data. So, the total capacity of the hybrid system is 120 users at a data rate of 5Gbps per user. The performance of the hybrid system is evaluated utilizing SMF and Dispersion Compensating Fiber (DCF). In this work, the Amplified Spontaneous Emission (ASE) is neglected in order to have some insight on inter and intra-channel FWM effects. Other hybrid system properties are tabulated in Tab. 1.

Tab. 1 Hybrid system properties

Parameter	Value	Parameter	Value
Number of channels	$M = 15$	Attenuation of SMF	0.2 dB/km
Number of users in each channel	$N = 8$	Dispersion for SMF	16.75 ps/nm · km
Length and weight of the sequence code	$F = 24$, $w = 3$	Dispersion slope for SMF	0.075 ps/nm^2 · km
Input transmitted power to the fiber	22 dBm	Cross effective area for DCF	22 μm^2
Total channel length	105.075 km	Dispersion for DCF	–100 ps/nm · km
Preamplifier gain	15 dB	Dispersion slope for DCF	–0.45 ps/nm^2 · km
Channel spacing	25 GHz	Attenuation of DCF	0.5 dB/km
Cross effective area for SMF,	80 μm^2	Data rate per channel	40 Gbps
Nonlinear refractive index	2.6×10^{-20} m^2/W	Data rate per user	5 Gbps

The broadening of the pulses induces an unwanted ISI which leads to errors in the decision at the receiver. As a result, a limitation of the bit rate of the optical communication system is taken place. To guarantee the avoidance of ISI, the identification sequence code interval should be squeezed into less than a bit duration. Fig. 2 shows the relationship between the BER and the identification sequence code interval with respect to the bit duration, where the performance of the proposed hybrid system was tested at different identification sequence code intervals. The results reveal that the best performance can be achieved when the code sequence interval squeezed into 25% of a bit duration where the avoidance of

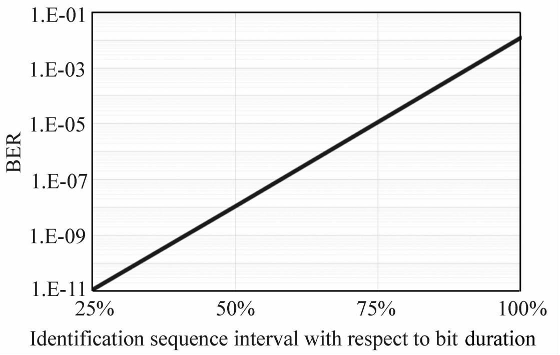

Fig. 2 Identification sequence code interval with respect to bit duration

ISI is guaranteed. Therefore, the optimum value of the interval of the identification sequence code is 25% of a bit duration. For instance for the system which has bit duration of 200 ps, the code sequence interval has to be squeezed to 50 ps.

The performance of the hybrid system is then tested in term of BER as a function of transmitted power without the implementation of EOPM at transmission length of 105.075 km (90 km of SMF and 15.075 km of DCF). The results show that the BER follows roughly V-shape when the effects of inter and intra-channel FWM are considered as shown in Fig. 3, where the average BERs of 6 random wavelengths out of 15 are presented. The transmitted power range can be divided into two regions, the first region is receiver noise and inter-channel FWM dominant and the second region is intra-channel FWM dominant. By increasing the transmitted power, the BER decreases in the first region due to the minimization of the influence of inter-channel FWM, and that is because of the CDMA technology being used, where its concept is to spread the energy of each bit over the identification sequence code. Therefore, the implementation of CDMA technology concept in conjunction with chromatic dispersion introduced by SMF helps in the reduction of inter-channel FWM effect. Moreover, according to Eq. (13) the generated FWM also produces an extra noise associated with MAI, therefore the suppression of MAI helps to reduce MAI-FWM noise. In this proposed hybrid system, the effect of MAI is reduced due to the zero cross-correlation property of MD code. On the other hand, the reverse scenario takes place in the second region (18 – 22 dBm) as the BER increases when the transmitted power is increased, and this is due to the influence of intra-channel FWM which becomes dominant compared to the inter-channel FWM, as it is known that intra-channel FWM is a major performance limiting factor in optical fiber systems operating at data rates of 40 Gb/s per channel or higher and becomes more severe when the transmitted power is high. In Fig. 3 the BER reaches the smallest value when the transmitted power is 18 dBm.

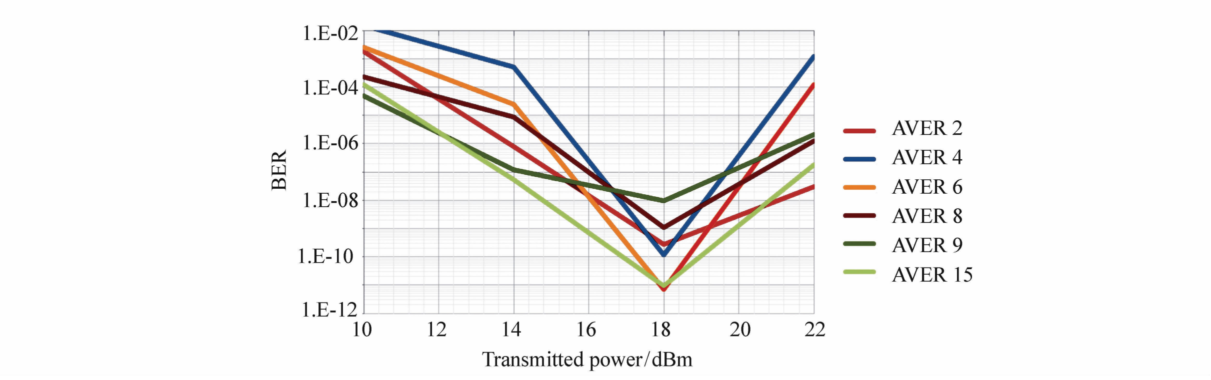

Fig. 3 BER versus transmitted power of random 6 wavelengths out of 15 wavelengths with 25 GHz spacing

Next, the performance of the proposed hybrid system is examined in term of BER versus the transmitted power with the implementation of EOPM. The EOPM module is placed after the WDM de-multiplexer as shown in Fig. 1 to simultaneously modulate the phase of all DWDM signals which generates a phase shift between pulses. It is noteworthy to mention that the Alternate-Phase Return-to-Zero (APRZ) modulation format has been used in literature to suppress the intra-channel FWM with optimum phase deviation above $\pi/2$[8]. However, APRZ is inherently specific to a single channel. Therefore the hybrid system performance is monitored with EOPM's phase deviation ϕ_{EOPM} above $\pi/2$. Based on the obtained results, it is found that the optimum value of ϕ_{EOPM} for optical CDMA-DWDM hybrid system is $2\pi/3$.

The phase shift expressed in Eq. (8), which has been introduced by the EOPM, is based on the phase deviation of the EOPM; therefore, choosing the right phase deviation will cause intra-channel FWM contributions, which come from different pulses to interfere destructively with each other. Fig. 4 shows the average BERs of 6 random wavelengths out of 15 for different values of the transmitted power. Each wavelength channel is carrying 8 optical CDMA user's data encoded by different MD optical codes, the rest of the properties of the hybrid system are summarized in Tab. 1. The results demonstrate significant improvements in the overall system performance as the BER decreases in the second region by increasing the transmitted power and this is due to the suppression of intra-channel FWM. By the implementation of EOPM at $\phi_{\mathrm{EOPM}} = 2\pi/3$, the reduction of intra-channel FWM takes place; and this is due to that different pulses involved in intra-channel FWM process gain a relative phase shift. Destructive interference can be obtained between different intra-channel FWM contributions by optimizing this phase shift. The obtained results are in line with that in Ref. [9]; the authors used Asynchronous Phase Modulator (APM) to suppress the intra-channel FWM for pure WDM system with only three channels spaced by 100 GHz. However our study used EOPM module with ϕ_{EOPM} equal to $2\pi/3$ and f_{SCS} is equal to the data rate of a single wavelength to suppress the intra-channel FWM effect in Optical CDMA-DWDM hybrid system, where the hybrid system contains 15 channels and each channel carries 8 optical CDMA users' data with channel spacing of only 25 GHz at data rate of 40 Gbps per channel. Optical CDMA-DWDM hybrid system becomes more nonlinear tolerant with the implementation of EOPM at the specifications mentioned above, and that can be clearly observed at transmitted power above 18 dBm. In addition, the proposed hybrid system has a spectral efficiency of 1.6 b/s/Hz as compared to 0.27 b/s/Hz reported in Ref. [22].

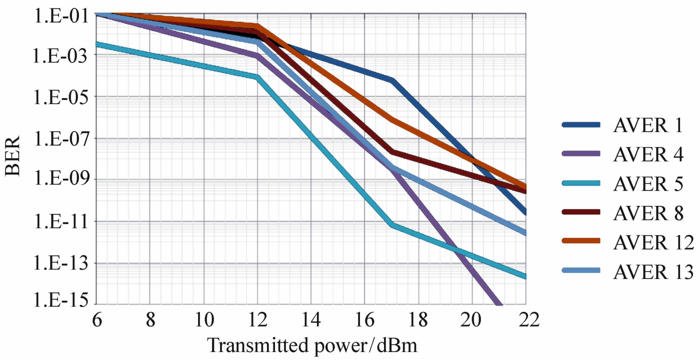

Fig. 4　BER versus transmitted power of random 6 wavelengths out of 15 wavelengths with 25 GHz spacing with the implementation of EOPM

To further validate the improvements in the performance of the proposed hybrid system as well as to ensure the effectiveness of EOPM in suppressing the intra-channel FWM effect. The performance of the hybrid system is tested in term of BER as a function of transmission distance at a transmitted power of 22 dBm. It is found that the optimum transmission distance for the proposed hybrid system with the use of EOPM is 105.075 km as shown in Fig. 5. The benchmark value of BER $\leqslant 10^{-9}$ has been achieved for the optical CDMA users in the 15 DWDM channels. It is worth noting that the obtained results prove the effectiveness of the EOPM implementation in increasing the nonlinear tolerance in the hybrid system, however, EOPM module, which is placed after the WDM multiplexer, is valid for OOK transmission since the signals' phase is an extra degree of freedom.

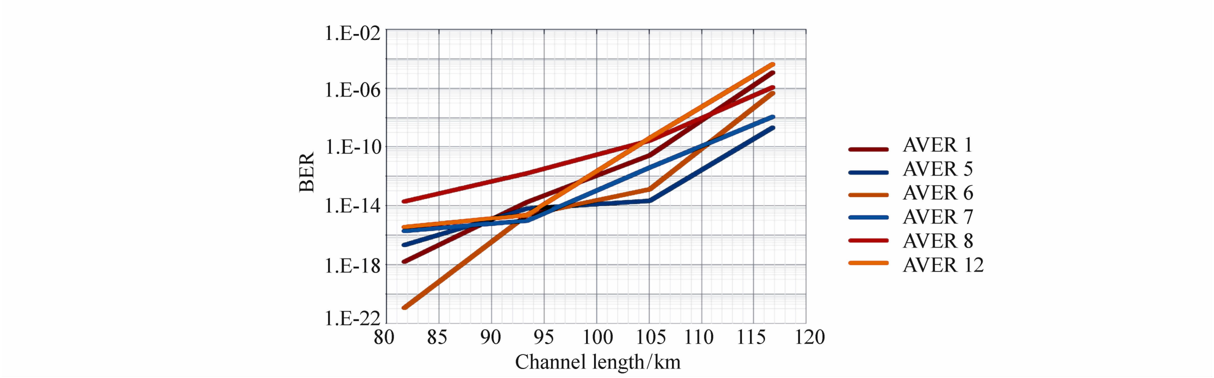

Fig. 5 BER versus transmission distance of random 6 channels out of 15 channels with the implementation of EOPM

5 Conclusion

In this article, optical CDMA-DWDM hybrid system has been proposed with 15 channels spaced by 25 GHz where each channel carries 8 optical CDMA users' data at a data rate of 5 Gbps per user. The effect of MAI, ISI and inter, intra-channel FWM have been taken into account. The use of MD sequence code helps to reduce the MAI effect on optical CDMA signals because of the zero cross-correlation property of MD identification code. The results reveal that the ISI can be mitigated when the interval of the identification sequence code is squeezed into 25% of a bit duration. The results also show that the CDMA technology in conjunction with chromatic dispersion helps to reduce the effect of inter-channel FWM. In addition, the results indicate an increase in the BER of the hybrid system when the transmitted power is above 18 dBm and this is due to the intra-channel FWM effect. As a result, an EOPM module is proposed and placed after the WDM multiplexer to simultaneously modulate the phase of all wavelengths signals. It is shown that the EOPM module implementation is indeed an effective method to greatly improve the performance of the optical CDMA-DWDM hybrid system based OOK transmission. By placing EOPM module after the WDM multiplexer, the suppression of intra-channel FWM effect takes place. It is noted that the optimum phase deviation of the EOPM module ϕ_{EOPM} is $2\pi/3$ and the frequency of the sinusoidal clock signal f_{SCS} is equal to the bit rate of a single channel.

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作者简介:

Naif Alsowaidi was born in Yemen on December 30, 1987. He received the B. Eng. degree(with honors) in communication engineering from International Islamic University Malaysia(IIUM), in 2012 and the M. Sc. degree. in engineering science from Multimedia University (MMU), Malaysia, in 2015, currently he is a Ph. D. candidate at the Multimedia University. His current research interests include wireless communication, Optical CDMA systems, and nonlinear optics. E-mail: nas_201013@ yahoo. com

Mohd Ridzuan Mokhtar received his PhD degree in optoelectronics from the University of Southampton, UK, in 2005. He is professor at the Faculty of Engineering, Multimedia University, Malaysia. He became a research fellow with City University London, UK, for a year in 2009, sponsored by the Technology Strategy Board in the UK. He has been the director of research and collaboration at Multimedia University since 2011. His main research interests include fiber optic sensors and optical communications

Tawfig Eltaif received his BSc degree in communication engineering from University of Tripoli, Libya, 2003, and MSc degree in microelectronics and PhD degree in micro-engineering & nanoelectronics from National University of Malaysia, Malaysia, 2005, 2009, respectively. He joined Photronix Technologies Company, 2008 – 2011, as a product and research engineer. Since 2012 he has been a senior lecturer at Multimedia University. His current research is focused on optical communication, optical frequency comb, FBG, and optical amplifiers.