Transmission Distortion Compensation Using Optical Phase Conjugation in Chalcogenide Waveguides

Binh T. Tran[1], Trang T. Ngo[2]

[1,2]Dept. of Signals and Systems, Posts and Telecommunications Institute of Technology, Vietnam

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Abstract - *Fiber dispersion, nonlinearities and the interactions between them are the main causes of transmission distortion in high bit rate optical systems. In this paper, we present the transmission distortion compensation scheme using optical phase conjugation (OPC) for dense wavelength division multiplexing (DWDM) 4x56 Gbits/s DQPSK system. The OPC is realized by four wave mixing process in chalcogenide waveguide. The simulation shows that, OPC placed at the middle of the transmission link can compensate simultaneously for both fiber dispersion and nonlinearities. The effectiveness in compensation of the symmetric Power – Accumulated Dispersion Diagram is also investigated.*

Key Words: **Optical phase conjugation; third-order nonlinearity; chalcogenide waveguide; distortion compensation; transmission system; DWDM.**

1. INTRODUCTION

Chromatic dispersion and Kerr nonlinearities are the main sources of impairment in high bit-rate optical transmission systems [1]. In order to mitigate these impairments, optical phase conjugation (OPC) has been shown as a promising and cost-effective method. Typically, the OPC is placed at the middle of the transmission link. Based on a spectral inversion process through OPC, the distortions caused by dispersion and nonlinearities in the first part of the link are reversed in the second part. Because of implementing totally in the optical domain, this solution takes many advantages such as fast response, wide dynamic ranges, modulation transparency and simultaneous multichannel compensation [2]-[9].

OPC can be realized through different nonlinear media including periodically poled lithium niobate (PPLN) waveguides, highly nonlinear fibers (HNLFs), semiconductor optical amplifiers (SOAs) and silicon waveguides. In the case of PPLN, this technique is based on the second order harmonic ($\chi^{(2)}$) process to produce the phase-conjugated wave (idler) [2][3]. However, the PPLN waveguides are limited in operation at high pump powers and by unchangeable pump wavelength. Alternately, broadband and wavelength flexible OPC can be implemented using four-wave mixing (FWM) process via third-order nonlinearity such as SOAs [8], HNLFs [4]-[7], planar silicon waveguides [9]. Although HNLFs have often been used in OPC due to their low propagation and coupling losses, they are not good candidates for integrated solutions. Compact OPC devices can be performed in SOA and silicon waveguide platforms. However, their performance can be degraded by the generation of free carriers via two-photon absorption which reduces the conversion efficiency in FWM process. Recently, As_2S_3 chalcogenide glass waveguides, a third-order nonlinear medium, have emerged as a promising device for ultra-high speed photonic processing [10]-[14]. Some works on dispersion [14][16] and nonlinear compensation [17] separately using OPC in chalcogenide have been reported. In this paper we demonstrate the using of the chalcogenide waveguide in OPC to compensate simultaneously both effects of the chromatic dispersion and Kerr nonlinearities in long-haul DWDM transmission system.

The paper is organized as follows: Section II gives a brief of chalcogenide waveguide and basic principles of OPC for dispersion and nonlinear compensations. Section III describes the simulation model based on Simulink platforms for investigations. The simulation results are given in section IV. Finally, the conclusions are given in section V.

2. USING CHALCOGENIDE OPC FOR DISPERSION AND NONLINEAR COMPENSATION

2.1 Chalcogenide waveguides

Chalcogenide glasses, recently, have become an attractive nonlinear material due to their desirable properties including ultra-high nonlinearity, fast response time and low nonlinear absorption [10]. Therefore, they can be used to fabricate the planar waveguides for variety of signal processing functions such as OTDM demultiplexing, ultra-broadband RF spectrum monitoring and 2R [12]-[14]. However, the large material dispersion of -364 ps/nm/km at 1550 nm limits the As_2S_3 waveguide to the OPC application. Therefore, the thickness of the As_2S_3 waveguide is reduced to increase the waveguide dispersion that offsets the material dispersion. The dispersion engineering of the As_2S_3 waveguide offers not only a small total dispersion of less than +30 ps/nm/km but also a very small effective mode area of 1.2 μm^2, corresponding to a nonlinearity coefficient γ of ~ 10000 $W^{-1}km^{-1}$ [12]. A typical structure of the dispersion engineered As_2S_3 waveguide is shown in Fig. 1.

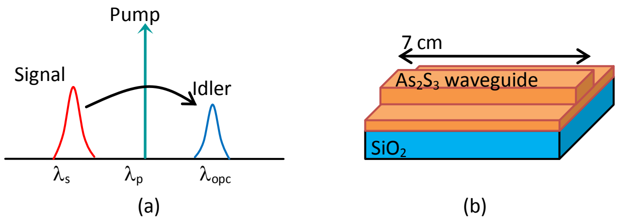

Figure -1: (a) Optical phase conjugation via the degenerate FWM process. (b) A typical structure of As_2S_3 nonlinear waveguide.

2.2 Optical Phase Conjugation

The schematic configuration of the OPC is shown in Fig. 2. Here, E_p is a pump wave at frequency ω_p and E_s is the signal wave at frequency ω_s. In the third-order nonlinear medium, optical phase conjugation is implemented by parametric mixing or four wave mixing (FWM) between the pump and signal waves, in which two photons of pump will interact with a signal photon. A fourth photon, the idler wave at frequency $\omega_i = 2\omega_p - \omega_s$ will be formed with a phase such that the phase difference between the pumps and the signal and the idler photons satisfies a phase matching condition.

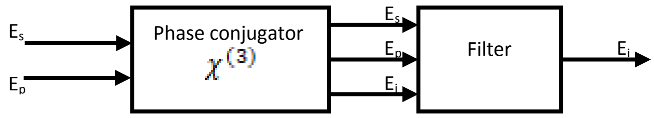

Fig -2: Schematic configuration of OPC

This process can be described by three coupled equations for complex field of three waves $A_{p,s,i}$ [15]:

$$\frac{\partial A_p}{\partial z} = -\frac{\alpha}{2}A_p + i\gamma A_p\left[\left|A_p\right|^2 + 2(|A_s|^2+|A_i|^2)\right] + i2\gamma A_s A_i A_p^* exp(-i\Delta kz)$$

$$\frac{\partial A_s}{\partial z} = -\frac{\alpha}{2}A_s + i\gamma A_s\left[|A_s|^2 + 2\left(\left|A_p\right|^2+|A_i|^2\right)\right] + i2\gamma A_p^2 A_i^* exp(-i\Delta kz) \quad (1)$$

$$\frac{\partial A_i}{\partial z} = -\frac{\alpha}{2}A_i + i\gamma A_i\left[|A_i|^2 + 2\left(|A_i|^2+\left|A_p\right|^2\right)\right] + i2\gamma A_p^2 A_s^* exp(-i\Delta kz)$$

where α, γ are the attenuation and nonlinearity coefficients of the nonlinear medium respectively. The gain experienced by the signal and the idler is determined by the parametric gain coefficient [15]:

$$g^2 = -\Delta k\left(\frac{\Delta k}{4} + \gamma P_p\right) \quad (2)$$

where P_p is the pump power, and the phase mismatch Δk can be approximated by expanding the propagation constant in a Taylor series around ω_0:

$$\Delta k = -\frac{2\pi c}{\lambda_0^2}\frac{dD}{d\lambda}(\lambda_p - \lambda_0)(\lambda_p - \lambda_s)^2 \quad (3)$$

Here, $dD/d\lambda$ is the slope of the dispersion at zero dispersion wavelength, $\lambda_k = 2\pi c/\omega_k$ is the optical wavelength.

The idler field can be obtained from equation (1) as: $E_i \propto A_p^2 A_s^* e^{-j\Delta kz}$ or $E_i \propto rA_s^* e^{[j(-kz-\omega\tau)]}$ with the signal wave $E_s \propto A_s e^{[j(kz-\omega\tau)]}$. Thus the idler field is a complex conjugate of the signal field. It means that the spectrum of the signal is inverted at the output of OPC.

2.3 Principle of transmission impairments compensation by OPC

To compensate transmission impairments caused by the chromatic dispersion and nonlinear effects, the OPC device is typically placed at the middle of the transmission link as shown in Fig 3 which also shows a schematic diagram of a typical DWDM transmission system. Hence this compensation technique is also called mid-span spectral inversion (MSSI).

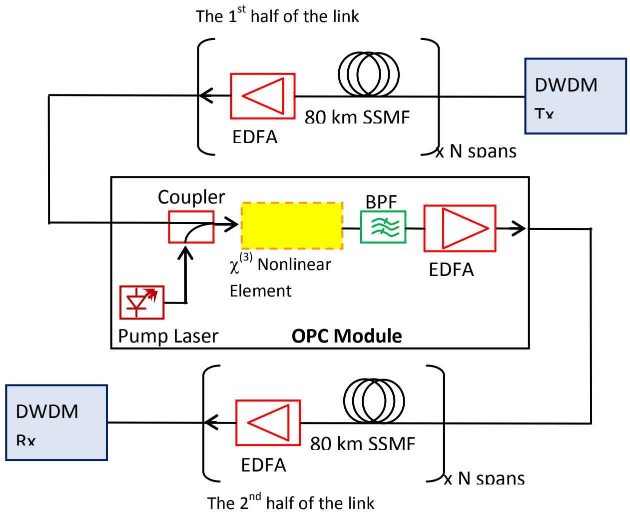

Fig -3: Block diagram of DWDM transmission system using OPC

The propagation of the signal in a lossy, dispersive and nonlinear medium can be described by nonlinear Schrödinger equation (NLSE) as [23]:

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A - \frac{j}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial T^3} + j\gamma|A|^2 A \quad (4)$$

Equation (4) describes the evolution of complex field A of the optical signal in the first part of the transmission link before the OPC. The propagation of the signal in the second half of the link can be obtained by taking the complex conjugate of the (4) as follow:

$$\frac{\partial A^*}{\partial z} = -\frac{\alpha}{2}A^* + \frac{j}{2}\beta_2\frac{\partial^2 A^*}{\partial T^2} + \frac{1}{6}\beta_3\frac{\partial^3 A^*}{\partial T^3} - j\gamma|A^*|^2 A^* \quad (5)$$

Because of the signs of the second-order dispersion and the nonlinearity are inverted after the OPC, it means that if the optical field of the signal is phase conjugated in the middle of the link, the OPC can be used to compensate the effects of the chromatic dispersion and the nonlinearities in the second part of the link.

2.4 The limitation of mid-span OPC to compensate nonlinearity

Using mid-link OPC can compensate totally the fiber dispersion and nonlinearities if these effects before and after OPC are symmetric. The symmetric condition can be easily achieved with the dispersion if the transmission link using the same type of fiber. The fiber is a lossy medium that is normally compensated by erbium-doped fiber amplifiers (EDFAs) along the link, therefore the nonlinearity distribution through OPC is asymmetric. Because of that, the effectiveness of MSSI in nonlinear compensation is very limited.

In the high bit rate transmission systems, it has been proved that the nonlinear distortion can be generally modeled as a perturbation to the dominant dispersive effect. So if the Power – Accumulated Dispersion Diagram (PADD) of the link is symmetric through the OPC position, the effectiveness of nonlinear compensation by the OPC can be improved [18]. By locating the OPC at the optimum position on the transmission link, the symmetric PADD can be achieved [19]. However this solution requires an extra access point on the transmission system. So with the deployed system the preferred solution is to add an appropriate span of fiber before the OPC in a nonlinear regime or after the OPC in a linear regime.

Fig. 4 shows PADD of a four-span transmission system with an adding fiber in the linear area after the OPC. The optimum length of the added-fiber (L_A) is calculated by the following equation [20]:

$$L_A = \pm \frac{D_0}{D_A}\left(L_{amp} - L_{eff}\right) \quad (6)$$

where D_0 and D_A are the dispersion coefficients of the transmission fiber and the added-fiber, respectively; L_{amp} is the amplifier spacing; L_{eff} is the effective length. The plus sign is used when dispersion of the added-fiber is the same sign as that of the transmission fiber. Otherwise, the minus sign is used.

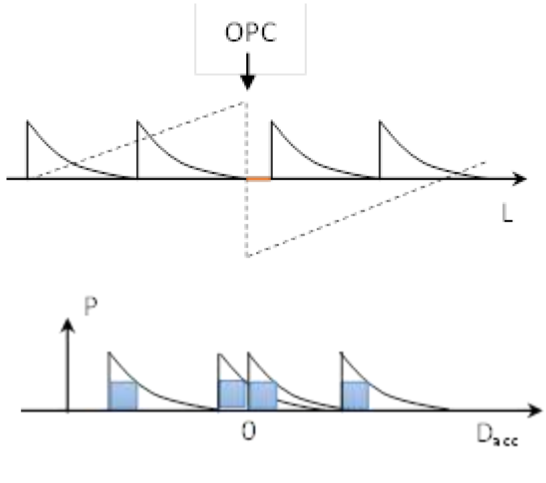

Fig -4: Adding fiber (yellow) in the linear area after the OPC. (a) Power (solid) and accumulated dispersion (dashed) distribution along the link, (b) With added-fiber, symmetry of nonlinear regions (filled rectangles) is achieved in PADD [20]

In case of having added fiber in the nonlinear area before the OPC, an amplifier is required to create a nonlinear area in the added-fiber. Fig. 5 shows the PADDs of three-span transmission system after adding fiber in the nonlinear area before the OPC.

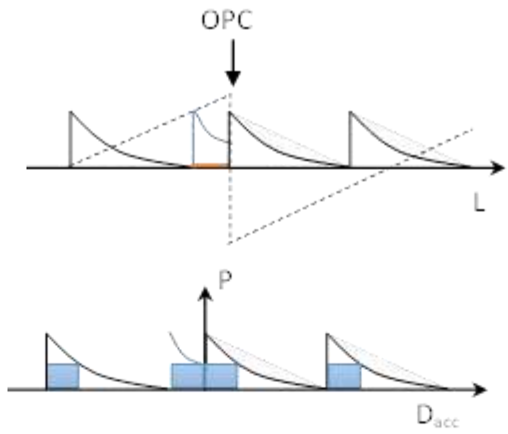

Fig -5: Adding fiber (yellow) in the nonlinear area before the OPC. (a) Power (solid) and accumulated dispersion (dashed) distribution along the link, (b) With added-fiber, symmetry of nonlinear regions (filled rectangles) is achieved in PADD [20]

The length of added-fiber and the launched power at its input must satisfy two following equations to obtain the symmetric PADD [20]:

$$L_A = L_{eff}\frac{D_0}{D_A} \quad (7)$$

$$P_A = P_0\frac{\gamma_0}{\gamma_A}\frac{1-exp\left(-\alpha_0 L_{eff}\right)}{1-exp\left(-\alpha_A L_{eff}\frac{D_0}{D_A}\right)} \quad (8)$$

where α, D, γ are the attenuation, dispersion and nonlinearity coefficients of the fiber, respectively. Subscript 0 designates for parameters of the transmission fiber and subscript A designates for those of the added-fiber.

To facilitate the implementation, if the number of spans is odd, it had better to locate the added-fiber in the nonlinear regime before the OPC. In case of even spans, the added-fiber should be placed in the linear regime after the OPC. The dispersion of added-fiber should be compensated by an appropriate way.

3. SIMULATION SETUP

In order to demonstrate the transmission distortion compensation scheme using optical phase conjugation in high nonlinear chalcogenide waveguide, a simulation model of long-haul DWDM transmission systems is set up. The RZ-DQPSK modulation format at 56 Gbits/s is used for this simulation. Fig. 6 shows the simulation model of the long-haul DWDM transmission systems that consists of 4 wavelength channels.

In the transmitter, the DQPSK signals are generated by an IQ modulator (a nested Mach-Zehnder Modulator (MZM) structure) with driving data signals that is differentially precoded. A MZM is used for 28 GHz pulse carving from a 14 GHz sinusoidal drive signal. This pulse carver can be placed before or after the IQ modulator. The RZ-DQPSK DWDM signals at the bit rate of 56 Gbit/s are multiplexed by a DWDM multiplexer (MUX). The signal wavelengths of WDM channel used in this investigation are 1550.92 nm, 1551.72 nm, 1552.52 nm, and 1553.32 nm (following ITU-T wavelength grid for DWDM systems).

The transmission link comprises 10 x 80 km spans of standard single mode fiber (SSMF). Erbium doped fiber amplifiers (EDFAs) are used to compensate the loss in each span. The OPC module is placed in the middle of the transmission link to compensate both dispersion and nonlinearities. Optical phase conjugation is realized via FWM process in the planar nonlinear chalcogenide waveguide. After propagation through the first half of the link the signal is phase conjugated in the OPC module, and then it propagates through the second half of the link.

At the output of the link, the DWDM-DQPSK signals are demultiplexed by an optical bandpass filter before the signal of each channel is fed into an incoherent receiver. An incoherent receiver consists of two sets of Mach-Zehnder delay interferometers (MZDIs) and balanced detectors to detect the in-phase and quadrature components of the received signal. MZDI converts the phase difference into amplitude modulation, hence any phase distortions from nonlinear effects can be easily observed. After the noise reduction by a low-pass filter in the receiver, the signal is recovered for the performance estimation.

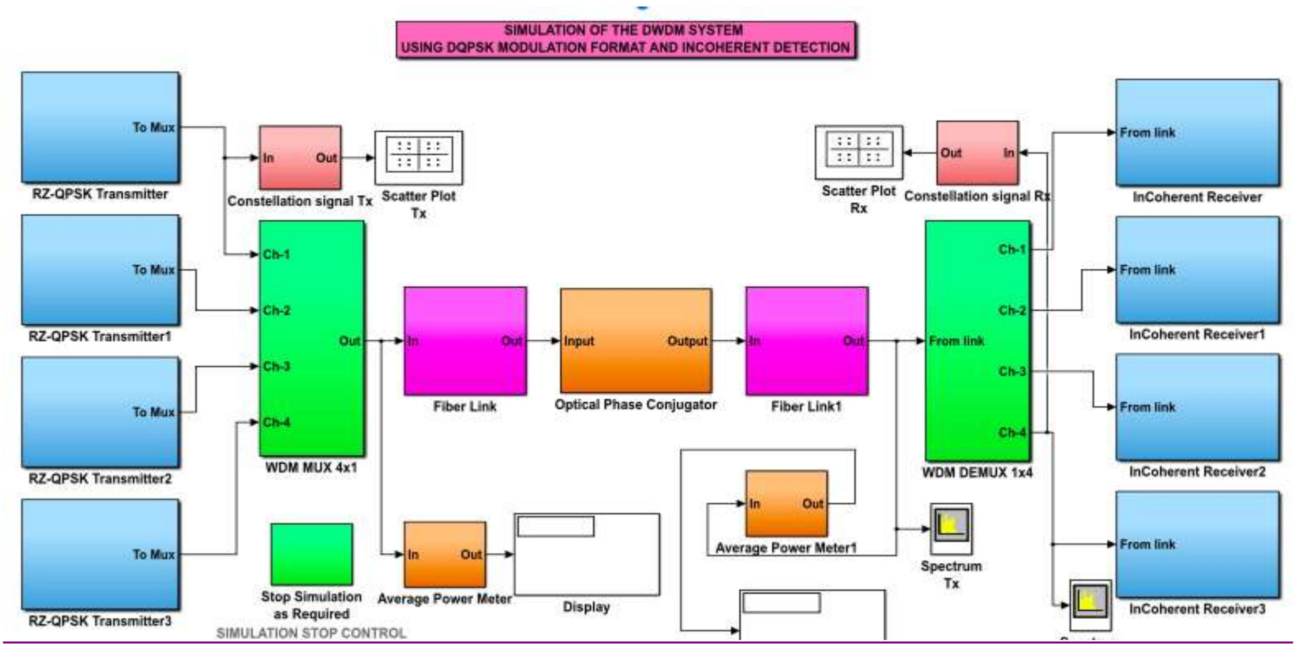

Fig -6: Simulation model of the long-haul transmission system with mid-link OPC.

Simulation models of the long-haul transmission system are developed from Simulink® modeling platform [21]. Simulink® blocks of basic components in the system such as EDFA, transmission fibers, optical modulators and balanced detectors are described in detail in [21]. Propagation of the optical signal in fiber is modeled by the nonlinear Schrodinger equation (NLSE)[23]. The EDFA block with ASE noise is modeled as a black box. Simulink model of the OPC module is similar to the one that was developed for dispersion compensation and OTDM demultiplexer [22].

The important parameters of whole systems including those of the OPC module in simulation are summarized in Table 1. In this setup, the parameters are set to consider all Kerr nonlinear impairments including intrachannel and interchannel nonlinear effects.

Table -1: Important parameters of simulation system

Transmitters
Ppeak = 2 to 16 mW, B = 56 Gbits/s, λ_s = {1553.32, 1552.52, 1551.72, 1550.92} nm Modulation format: RZ-DQPSK;
Fiber transmission link: each span
SSMF: Lspan = 80 km, A_{eff} = 70 μm^2, D = 17 ps/nm/km, S = 0.036 ps/nm^2/km, α = 0.2 dB/km, n_2 = 2.6x10^{-26} km^2/W, EDFA: Gain = 12-16 dB, NF = 6dB; Number of spans: 10
OPC module
Ppump = 100 to 600 mW, λ_p = 1556.55 nm, B_{BPF} = 500 GHz Waveguide: L_w = 7cm, D_w = 28 ps/km/nm, α = 0.5 dB/cm, γ = 10^4 1/W/km
Receivers
Balanced Rx: B_e = 28GHz, i_{eq} = 20 pA/Hz$^{1/2}$, i_d = 10 nA.

4. SIMULATION RESULTS AND DISCUSSIONS

4.1 Dependence on Pump Power

Operation of the OPC module depends considerably on a pump power because of its influence on the conversion efficiency. In principle, the conversion efficiency is proportional to the pump power. However at the high launched signal power, nonlinear interactions such as XPM that occur in the nonlinear waveguide can degrade the conversion efficiency. As a result, the nonlinearity compensation performance can be reduced at a high pump power.

Fig. 7 shows the performance of the transmission system versus the pump power at different peak launched levels. These results were obtained when the OPC module is located at the middle of the link. The performance is improved when the pump power increases. At the high pump power, however the system performance is degraded by reducing conversion efficiency from other nonlinear interactions. The system performance is generally optimized with the pump power of 300 to 400 mW at different launched powers as shown in Fig. 7. At lower signal peak power, the performance is improved and the optimum pump power is shifted toward to higher value. These pump levels is available in practice.

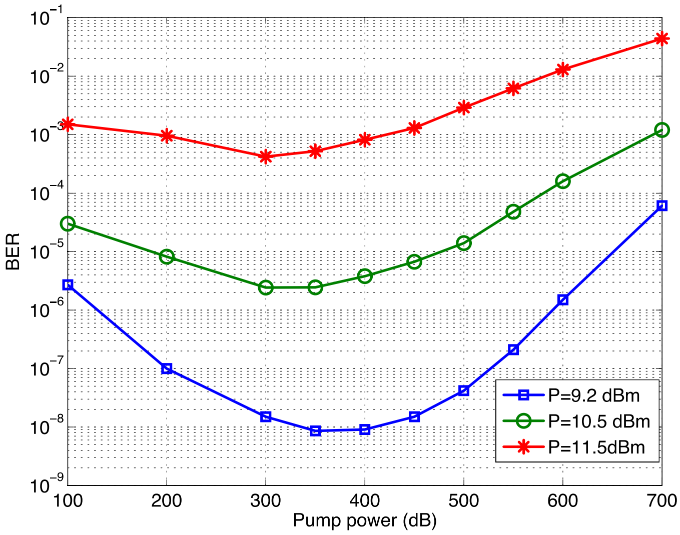

Fig -7: Dependence of the performance on pump power at different peak launched powers.

4.2 Back to Back Performance

In order to check the penalty caused by the phase conjugation in the chalcogenide waveguide, the back to back performance of the system has been investigated. Apart from the desirable conjugated signal, nonlinear mixing processes in the OPC also generate some unwanted products, which fall within the band of the conjugated signal, therefore can cause a performance penalty. The launched power in this investigation is set at high level to get the nonlinear propagation regime. Fig. 8 plots the back to back performance of the DQPSK transmission system with and without OPC. The OPC module is pumped at an optimum pump power level of 350 mW. The simulation results show that there is almost no sensitivity penalty for the DQPSK signals that the phase conjugation indicates no phase distortion occurring in the chalcogenide waveguide during OPC process.

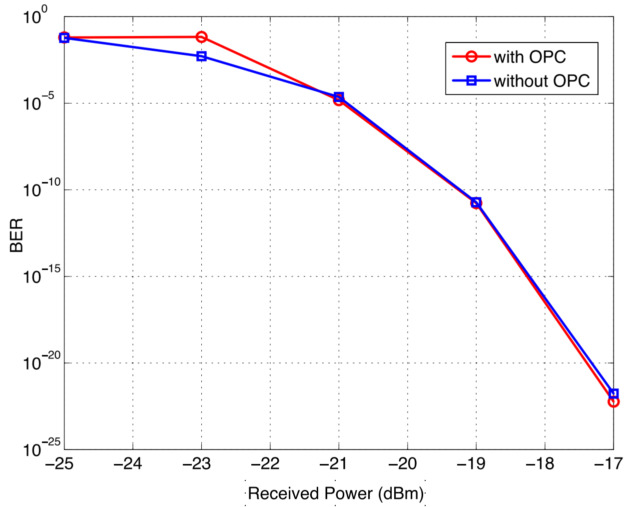

Fig -8: Back to back BER performance with and without OPC.

The negligible penalty of the OPC module can be demonstrated by the spectrum at the output of the chalcogenide waveguide as shown in Fig. 9. The power of the conjugated signal is much higher than that of the unwanted nonlinear products caused by XPM and FWM processes in the nonlinear waveguide. This advantage results from short length and moderate dispersion of the chalcogenide waveguide used in OPC.

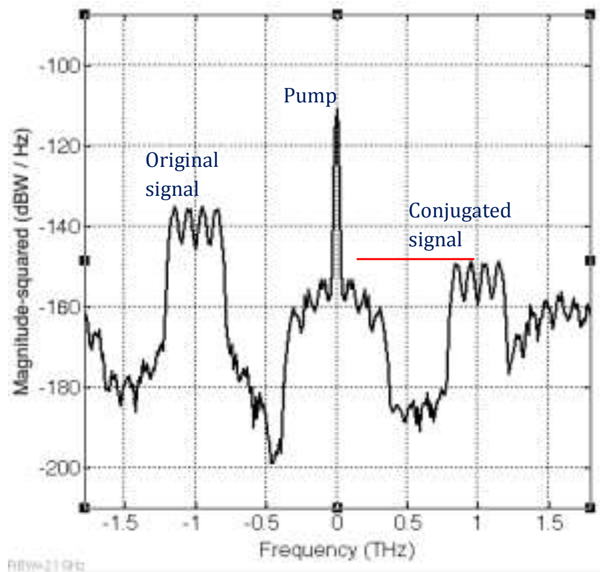

Fig -9: Spectrum at the output of the chalcogenide waveguide OPC device.

4.3 Influence of the dispersion mismatch

Using MSSI to compensate transmission distortion requires that the OPC module is located at the middle of the link. It means that the fiber length and the configuration of the second half of the link are the same as those of the first half. However it is difficult to achieve this in reality.

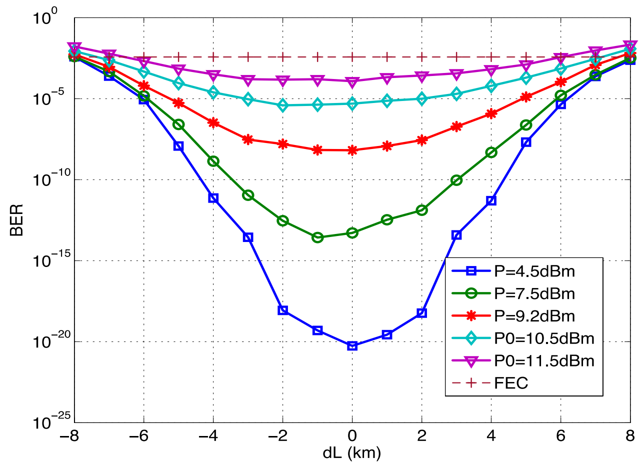

Fig -10: Performance of the transmission system as a function of the length mismatch (dL) between two halves of the link.

We have investigated the influence of the dispersion mismatch caused by the fiber length mismatch between two halves of the link on the system performance with different launched powers. By varying the length of transmission fiber in each span, the length of the second half of the link can be set shorter (dL < 0) or longer (dL > 0) than that of the first half. The results in Fig. 10 show that the mismatch tolerances in the FEC limit are the same that is about ± 8km, larger than the allowed tolerances of ± 3 km for the systems using the OPC to compensate the dispersion only [16]. This improvement can be originated by the interaction between dispersion and nonlinearities in the fiber.

4.4 Performance of nonlinear compensation

In this section, we have performed the simulation to evaluate nonlinear compensation through the dependence of the system performance on the launched power. It is noted that the signal of the system without OPC is totally collapsed because of dispersion and nonlinear impairments of 800 km standard single mode fiber.

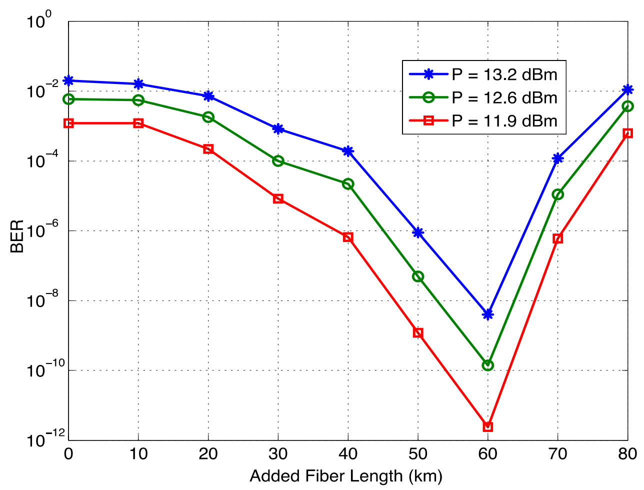

Fig -11: Performance improvement as a function of added fiber length

The effectiveness of symmetric PADD in nonlinear compensation has also been investigated. In this simulation, the symmetric PADD is created by adding a span of fiber, which is the same type as the transmission fiber, in the linear regime, after the OPC. The dispersion of added fiber is compensated by a dispersion compensated fiber (DCF). Fig. 11 shows the dependence of system performances on the length of added fiber. The investigations show that the optimum length of added fiber is 60 km which matches to the result calculated by Eq. (6). If the added fiber has a larger dispersion coefficient, then the shorter length can be used.

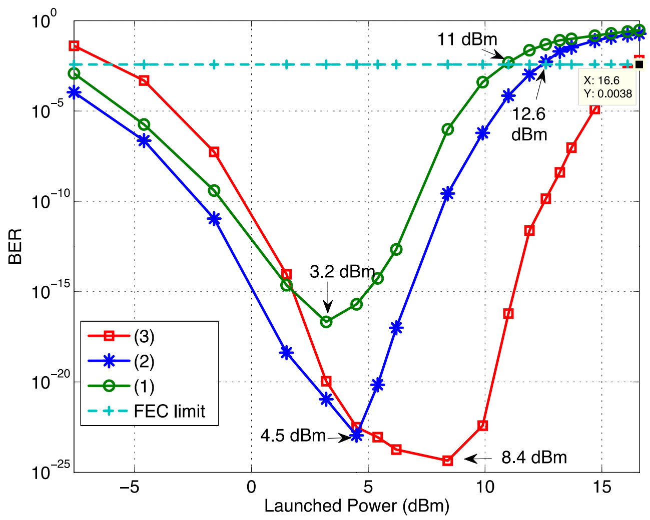

Fig -12: The dependence of the system performance on the launched power.

Fig. 12 plots the system performance as a function of launched power with different configurations: (1) mid-link OPC configuration to compensate nonlinearities, while dispersion is compensated by DCFs; (2) mid-link OPC configuration to compensate both the dispersion and nonlinearities; (3) symmetric PADD configuration with optimum length of added fiber to compensate both the dispersion and nonlinearities. The results show that the nonlinear threshold, the launched power at the FEC limit and the system performance are all improved with using the symmetric PADD configuration. Performance of the system using mid-link OPC to compensate both of the fiber dispersion and nonlinearities is also effectively improved much more than that to compensate nonlinearities only. In configuration (1) using the DCF with small A_{eff} to compensate dispersion can enhance the nonlinear processes along the link which lowers the nonlinear threshold and degrades the system performance.

5. CONCLUSION

We have, by simulation, investigated the performance of the 4x56 Gbits/s DQPSK DWDM long-haul transmission system using the chalcogenide OPC to compensate transmission distortion caused by the fiber dispersion and nonlinearities.

By using the As_2S_3 waveguide as a nonlinear medium, the function of OPC has been assessed by simulation model based on Simulink® platforms. The simulation results show that the mid-link chalcogenide OPC can compensate both of dispersion and nonlinearities simultaneously. Moreover, this configuration can operate effectively with large length mismatch tolerance. The investigation has also demonstrated that using the symmetric PADD can significantly improve the compensation efficiency of the chalcogenide OPC.

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BIOGRAPHIES

Tran T. Binh, Dept. of Signals and Systems, Posts and Telecommunications Institute of Technology in Vietnam.

Trang T. Ngo, Dept. of Signals and Systems, Posts and Telecommunications Institute of Technology in Vietnam.