한국해양정보통신학회지 제7권 2호

Compensation for the Distorted NRZ Signals in WDM System using Optical Phase Conjugator

Seong-Real Lee

Div. of Marine Electro. & Comm. Eng., Mokpo National Maritime University

목 차

Ⅰ. Introduction

In recent, the paradigm in communications is changing as the demand of communication capacity is drastically increased, and in future, the communication system with capacity more than Tb/s will be inevitable because of evolutionof personality and multimedia services. The WDM systems are currently developed and used in order to satisfy these requirements.

Since the 10 Gbps optical transmission systems were realized, dispersion shifted fiber (DSF) instead of conventional single mode fiber (SMF) is widely used in order to overcome signal distortion due to chromatic dispersion in optical fiber. But, the crosstalk owing to Kerr effects, especially four-wave mixing (FWM) is appeared in multi-channels transmission system with DSF, consequently serious problem should be generated in the case of expanding to WDM system [1]. In mostly recent, the fiber overcoming this problem of DSF is developed for realizing multi-channel WDM system. The zero dispersion wavelength of this new type fiber is appeared beyond transmission bandwidth and chromaticdispersion of this fiber is relatively large, because FWM effect is more decreased as chromatic dispersion is larger. This fiber is called to non zero - DSF (NZ-DSF) [2].

But the bit-rate distance product is limited by combining erbium doped fiber amplifier (EDFA) with NZ-DSF for expanding transmission distance because self phase modulation (SPM) and cross phase modulation (XPM) are generated owing to high power of optical signal, even if NZ-DSF is used to suppress FWM effect [3]. One of the techniques to overcome this limitation is mid-span spectral inversion (MSSI). Theoretically, this technique overcomes both SPM effect and dispersive effects by using optical phase conjugator (OPC) for compensating distorted signals in mid-way of total transmission length, when SMF is used as the transmission line [4],[5].

The serious problems have to be solved in order to apply this technique into the multi-channel transmission system. The first is that a perfectly symmetrical distribution of power and local dispersion with respect to OPC position is formed for nonlinearity cancellation in real transmission links [6]. The second is that the OPC must exhibit the similar characteristics over total WDM channels for transmitting further numbers of channels with similar reception performance. Fortunately, the second problem is solved by using highly-nonlinear dispersion shifted fiber (HNL-DSF) as a nonlinear medium of OPC because the effective bandwidth of HNL-DSF is wide and flattened

[7]. But, the first problem still remains in the perfectly compensating for distorted overall WDM channels. Furthermore it is more difficult to obtain the solution simultaneously applying the total transmitting channels, because these channels with different wavelength copropagate in an optical fiber, even if the symmetrical distribution problem was solved for a special wavelength. Thus it is require to researching the new method that alternate with method for solving the first problem in order to effectively compensate overall channels by using OPC.

This research focus on the numerical methods of finding the optimal OPC position and the optimal dispersion coefficients of NZ-DSF in order to alternate with the method of making the symmetrical distribution of power and local dispersion in real optical link for long-haul multi-channel transmission. That is, the optimal position of OPC and the optimal dispersion coefficient of fiber sections are numerically induced and applied to WDM system. And then, the compensation characteristics of overall WDM channels in the case of using those optimal parameters are investigated, comparing with that in the case of OPC placed at mid-way of total transmission length and the fixed fiber dispersion.

The considered WDM system has 8 channels of 40 Gbps. The intensity modulation format is assumed to be NRZ. The split-step Fourier method [8] is used for numerical simulation. The evaluation parameters of compensation degree are eye-opening penalty (EOP). The effects of XPM on WDM signals are more decreased as the fiber dispersion is larger [9]. XPM effect of inter-channels is neglected in order to simplify the analysis in this research. Because the dispersion coefficients of fiber in this research are assumed to be 6 ps/nm/km, which less affect the signal distortions due to XPM. We also neglect the effect of FWM on WDM channel distortion by using the unequal channel spacing scheme [10].

Ⅱ. Modeling of WDM System

Consider 8 optical waves with the same polarization copropagating in an optical fiber. Let $A_j(z, t)$ be the slowly varying complex field envelope of each wave normalized to make equal to the instantaneous optical power. $A_j(z, t)$ satisfies the following equation [8] :

$$\frac{\partial A_j}{\partial z} = -\frac{\alpha}{2}A_j - \frac{i}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial T^2} + \frac{1}{6}\beta_{3j}\frac{\partial^3 A_j}{\partial T^3} + i\gamma_j|A_j|^2 A_j + 2i\gamma_j|A_k|^2 A_j \tag{1}$$

where $j, k = 1,2,\cdots,8$ $(j \neq k)$, α is the attenuation coefficient of the fiber, λ_j is the j-th channel signal wavelength, β_{2j} is the fiber chromatic dispersion parameter, β_{3j} is the third-order chromatic dispersion parameter, γ_j is the nonlinear coefficient and $T=t-z/v_g$, respectively. The last two terms in equation (1) induce SPM and XPM, respectively.

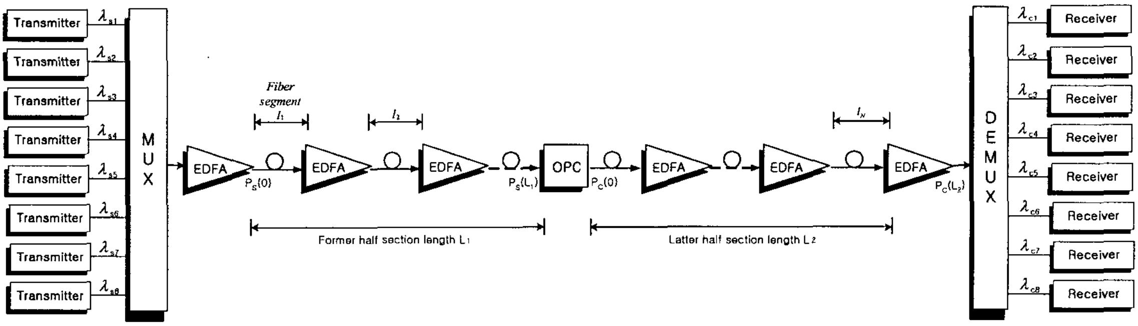


Fig. 1. Simulation model of 8-channels WDM system.

The last term, that is XPM term is neglected in order to simplify numerical analysis in this paper.

Fig. 1 shows a configuration of intensity modulation / direct detection (IM/DD) WDM system with OPC placed at mid-way of total transmission length. In Fig. 1, total transmission length (L) is divided two sections of respective length L_1(=L/2) and L_2, and each fiber section consist of 10 amplifier spans of length l=50 km. Fiber parameters assumed for analysis and numerical simulations throughout this paper are summarized in Table 1 [11].

Table. 1. Fiber parameter assumptions.

Parameter	Symbol & Value
Type	NZ-DSF
Chromatic dispersion	D_{1x} = 6 ps/nm/km
Nonlinear refractive index	$n_2 = 2.5\times10^{-20}$ m^2/W
Attenuation	α = 0.2 dB/km
Effective core area	A_{eff} = 72 μm^2

Watanabe and Shirasaki generalized the MSSI by considering that above fiber parameters can be functions of distance z [4]. The general condition for perfect distortion compensation is shown to be

$$\frac{\beta_{2j}(-z_1')}{P_j(-z_1')\gamma_j(-z_1')} = \frac{\beta_{2j}(z_2')}{P_j(z_2')\gamma_j(z_2')} \qquad (2)$$

where the third-order chromatic dispersion parameter is neglected.

This relation means that by providing the equal ratio of the dispersion and nonlinearity at the corresponding positions -z_1' and z_2', perfect distortion compensation can be obtained. That is, the OPC need not be placed at the mid-way of total transmission length and dispersion coefficient of latter half section need not equal with that of former half section which depend on the signal wavelength. However, the equation (2) also means that it is not easy to find the common OPC position and dispersion coefficient of fiber sections that is applicable to total allocated WDM wavelengths in real transmission link, because of the distribution of wavelengths in the relative broad. Thus, this research intended to find out the optimal OPC position and dispersion coefficient of fiber sections through the numerical approach. The optimal OPC position is found by evaluating the compensation characteristics as a function of the OPC position (z_{OPC}) varied within one span length (±25 km) from the mid-way. The difference between z_{OPC} and z_{mid} ($z_{OPC}-z_{mid}$) is called to the OPC position offset, Δz. And the optimal dispersion coefficient of each section (D_{1x}, x=1,2) is also found by evaluating the compensation characteristics as a function of dispersion offset, ΔD_{1x}. The dispersion offset is defined to difference of dispersion coefficient between two fiber sections, that is $\Delta D_{11}=D_{11}-D_{12}$ and $\Delta D_{12}=D_{12}-D_{11}$.

Each laser diode in transmitter of Fig. 1 is externally modulated by an independent 40 Gbps 128(=2^7) pseudo random bit sequence (PRBS). And output electric field of NRZ format signal from external optical modulator is assumed to be second-order super-Gaussian pulse. The direct detection receiver consist of the pre-amplifier of EDFA with 5 dB noise figure, the optical filter of 1 nm bandwidth, PIN diode, pulse shaping filter (Butterworth filter) and the decision circuit [12]. The receiver bandwidth is assumed to be 0.65×bit-rate.

The unequal channel spacing proposed by F. Forghieri *et al.* is used to completely suppress the crosstalk due to FWM effects [10]. The allocated wavelengths of each channel used in this research are 1550.0, 1550.7, 1551.7, 1552.5, 1553.4, 1553.9, 1555.0 and 1555.6 nm, respectively.

Ⅲ. Results and Discussion

Fig. 2 shows EOP of overall channels as a function of the launching power when OPC placed at mid-way of total transmission length and ΔD_{1x}=0 ps/nm/km (that is, MSSI). It is shown that EOPs are more degraded as the signal wavelengths are more deviated from the zero dispersion wavelength of OPC. The difference of compensation extents between the channels is resulted from the asymmetrical distribution of power and local dispersion. Thus, it is impossible to expand channel numbers in directly applying MSSI using OPC to WDM systems.

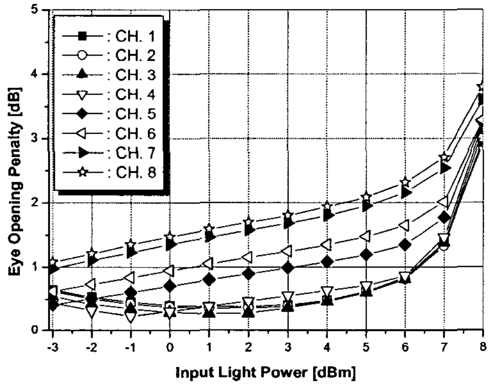


Fig. 2. EOP as a function of the launching power in WDM system with MSSI.

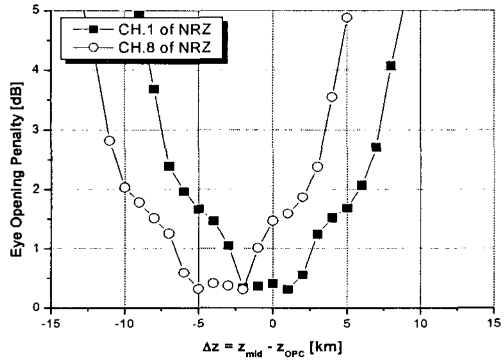


Fig. 3. EOP as a function of Δz for ΔD_{1x} = 0 ps/nm/km.

Fig. 3 shows EOP of channel 1 and 8 depending on the OPC position offset, Δz in order to find the best OPC position. If WDM channels had the relatively high launching power, the difference of EOP depending on the OPC position between channel 1 and 8 is so large that is impossible to compare each other. For this reason, the launching powers are assumed to 0 dBm. It is shown from Fig. 6 that the OPC positions resulting the smallest EOP difference between channel 1 and 8 are 498 km (Δz = -2 km) .

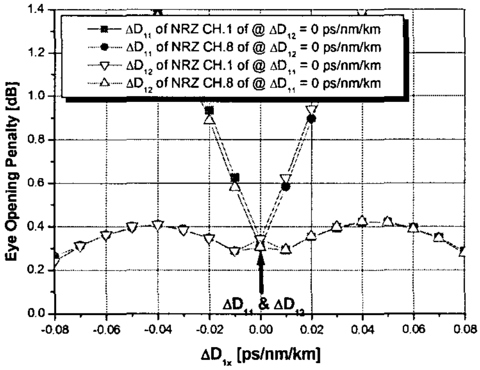


Fig. 4. EOP as a function of ΔD_{1x} when the OPC placed at Δz.

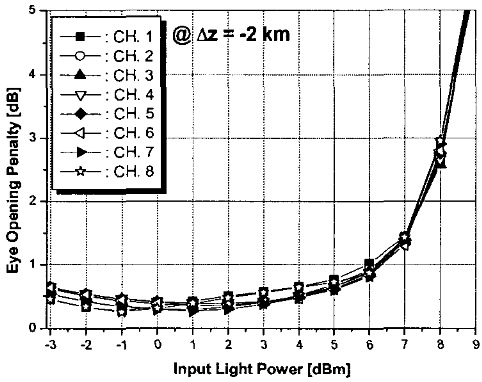


Fig. 5. EOP as a function of the launched light power in WDM system with the optimal parameters obtained from the results of Fig. 7

Fig. 4 shows EOP depending on the dispersion offset, ΔD_{1x} when the OPC placed at the position obtained from results of Fig. 3. It is shown from Fig. 4 that the characteristics of EOP depending on ΔD_{11} and ΔD_{12} are mutually symmetrical. That is, EOP depending on ΔD_{11} under the condition of ΔD_{12} = 0 ps/nm/km is reverse of EOP depending on ΔD_{12} at ΔD_{11} = 0 ps/nm/km. The best ΔD_{1x} that result in the smallest EOP are obtained to

0 ps/nm/km in all cases. The results of Fig. 3 and 4 mean that it is need not change the dispersion coefficients of fiber sections, if OPC was placed at the optimal position, at least for NRZ transmission.

Fig. 5 shows EOP of overall channels as a function of the launching light power in WDM system with the optimal OPC position and the optimal dispersion coefficients of fibers, which are obtained from the results of Fig. 4. The compensation extents of WDM system adopted the obtained optimal parameters are largely improved than the results of Fig. 2. That is, if 1 dB EOP is allowed for performance criterion, it is confirmed that power penalties are within 0.5 dB. This fact means that overall channels will be transmitted with similar performance each other, when only the optimal parameters were applied to conventional WDM system if not make the condition of the symmetrical distribution of optical power and local dispersion.

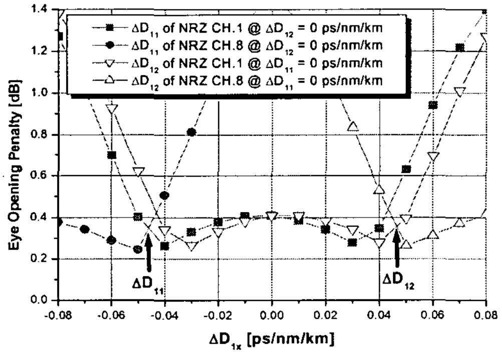
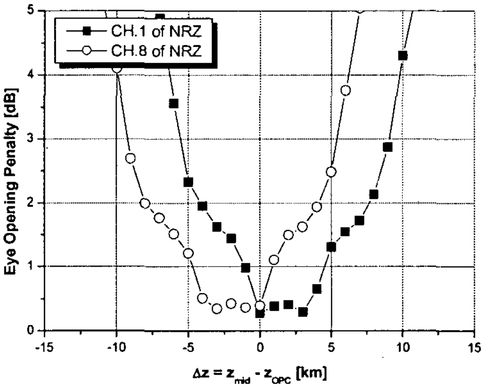
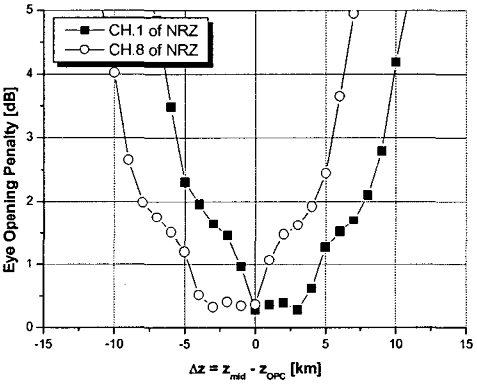


Fig. 6. EOP as a function of ΔD_{1x} in the case of assuming Δz = 0 km.

Fig. 6 and 7 show the results obtained through the same numerical methods with the previous, but the reverse procedure of finding the best parameter. In Fig. 6, the best ΔD_{11} that result in the smallest EOP difference between channel 1 and 8 is obtained to -0.045 ps/nm/km in the case of assuming ΔD_{12} = 0 ps/nm/km, on the other hand the best ΔD_{12} is +0.045 ps/nm/km in the case of assuming ΔD_{11} = 0 ps/nm/km. It is shown from Fig. 7 that the best Δz are obtained to 0 km in the cases of $D_{11} = D_{1x}$ and $D_{12} = D_{1x} + \Delta D_{12}$, independence on fiber dispersion coefficients. Here, ΔD_{12} is the optimal value obtained from Fig. 6 for every case. Also the best Δz are obtained to 0 km in the cases of $D_{12} = D_{1x}$ and $D_{11} = D_{1x} + \Delta D_{11}$.



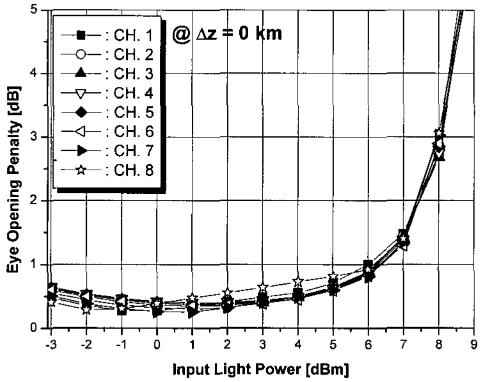
(a) for ΔD_{11} = 0 ps/nm/km



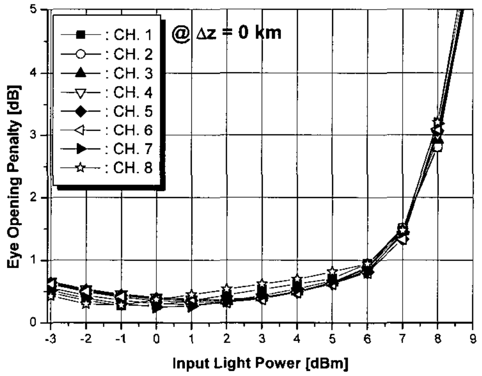
(b) for ΔD_{12} = 0 ps/nm/km

Fig. 7. EOP as a function of Δz for ΔD_{1x}.

Fig. 8 shows EOP of overall channels as a function of the launching light power in WDM system with the optimal OPC position and the optimal dispersion coefficients of fibers, which are obtained from the results of Fig. 7. Fig. 8(a) is EOP characteristics obtained in the case of optimizing dispersion coefficient of only the second fiber section to $D_{12} + \Delta D_{12}$, and Fig. 8(b) is EOP characteristics obtained in the case of optimizing dispersion coefficient of only the first fiber section to $D_{11} + \Delta D_{11}$. It is shown from Fig. 8 that EOP characteristics are similar with each other. And, EOP characteristics shown in Fig. 8 are also similar with EOP characteristics shown in Fig. 5.



(a) @ D_{11} = 6 ps/nm/km, D_{12} = 6.045 ps/nm/km



(b) @ D_{11} = 5.955 ps/nm/km, D_{12} = 6 ps/nm/km

Fig. 8. EOPas a function of the launched light power in WDM system with the optimal parameters obtained from the results of Fig. 10.

By comparing Fig. 5 and 8, it is confirmed that the optimal parameter values are changed with the procedure of finding the optimal parameters, but the compensation extents in Fig. 8 are almost coincide with those in Fig. 5. That is, values of the optimal parameters related with the finding procedure are not important, only if two optimal parameters depend on each other.

Ⅳ. Conclusion

Up to now the numerical method of finding the optimal position of OPC and the optimal dispersion coefficient of fiber sections was proposed, which is expected to replace with the method for making the symmetrical distribution of power and local dispersion. It was confirmed that the numerical method considered in this research will be available to multi-channel WDM system irrelevant with the finding procedure of these two optimal parameters only if two optimal parameters depend on each other. The results induced in this research will provide the improvement of the received signal and the flexibility of WDM transmission system design. That is, the performance of the compensated signal is improved by applying the optimal parameters into WDM system with OPC.

References

[1] N. Shibata, K. Nosu, K. Iwashita and Y. Azuma, "Transmission limitations due to fiber nonlinearities in optical FDM systems", *IEEE J Select. Areas in Comm.*, Vol. 8, No. 6, pp. 1068~1077, 1990.

[2] ITU Recommendation "Characteristics of a non-zero dispersion shifted single-mode optical fibre cable" *G.655*, 2003.

[3] A. R. Chraplyvy, "Limitations on lightwave communications imposed by optical-fiber nonlinearities", *J. Lightwave Technol.*, Vol. 8, No. 10, pp. 1548 ~1557, 1990

[4] S. Watanabe and M. Shirasaki, "Exact compensation for both chromatic dispersion and Kerr effect in a transmission fiber using optical phase conjugation", *J. Lightwave Technol.*, vol. LT-14, no. 3, pp. 243~248, 1996.

[5] P. Kaewplung, T. Angkaew and K. Kikuchi, "Simultaneous suppression of third-order dispersion and sideband instability in single-channel optical fiber transmission by midway optical phase conjugation employing higher order dispersion management", *J. Lightwave Technol.*, vol. LT-21, no. 6, pp. 1465~1473, 2003.

[6] C. Lorattanasane and K. Kikuchi, "Design of long-distance optical transmission systems using midway optical phase conjugation", *IEEE Photon. Technol. Lett.*, vol. 7, no. 11, pp 1375~1377, 1995.

[7] S. Watanabe, S. Takeda, G. Ishikawa, H. Ooi, J. G. Nielsen and C. Sonne, "Simultaneous wavelength conversion and optical phase conjugation of 200 Gb/s (5×40 Gb/s) WDM Signal using a highly nonlinear fiber four-wave mixing", *ECOC 97 Conf.*, pp. 1 ~ 4, 1997.

[8] G. P. Agrawal, *Nonlinear Fiber Optics*, Academic Press, 2001.

[9] Seong-Real Lee, S. N. Kwoen and Y. H. Lee, "Cross phase modulation effects on 120 Gbps WDM transmission systems with MSSI for compensation of distorted optical pulse", *The J. of Korea Electromagnetic Eng. Soc.* (Korean), vol. 14, no. 7, pp. 741~749, 2003.

[10] F. Forghieri, R. W. Tkach and A. R. Chraplyvy, "WDM systems with unequally spaced channels", *J. Lightwave Technol.*, vol. LT-13, no. 5, pp. 889~897, 1995.

[11] M. Wu and W. I. way, "Fiber nonlinearity limitations in ultra-dense WDM systems", *J. Lightwave Technol.*, Vol. 22, No. 6, pp. 1483~1498, 2004

[12] G. P. Agrawal, *Fiber-optic communication systems*, John Wiley & Sons, Inc., 2002.

저자소개

Seong-Real Lee

1990년 한국항공대학교 통신정보공학과 (공학사)
1992년 한국항공대학교 대학원 통신정보공학과 (공학석사)
2002년 한국항공대학교 대학원 통신정보공학과 (공학박사)
1996년 1월~2002년 5월 (주)세영통신 전파기술연구소 책임연구원
2002년 6월~2004년 2월 (주)에이티엔 기술연구소장
2004년 3월~현재 국립목포해양대학교 해양전자통신공학부 조교수
※관심분야 : WDM 시스템, 광의 비선형 현상 분석, 광솔리톤 전송