Effective Compensation of the Distorted 1.12 Tbps WDM Signals Using Optimization of Total Dispersion

Seong-Real Lee, *Member, KIMICS*

Abstract**—**Nonlinear effects and chromatic dispersion are the main causes of pulse degradation in high bit-rate WDM transmission systems and several architectures have been proposed to compensate them by means of optical phase conjugation. In this paper, a new method to exploit an optical phase conjugator (OPC) for nonlinearity and dispersion cancellation is disclosed. The proposed method is using optimal total dispersion of each fiber sections and it is simpler than those previously described in literature. Power penalty between WDM channels and the maximum launch power in 28×40 Gbps WDM transmission system designed by optimal total dispersion are more decreased and more increased than those in the conventional WDM transmission system with OPC, respectively. Furthermore, optimal total dispersion proposed in this research should provide the flexible design of WDM system, which less depends on OPC position.

Index Terms**—**Optimal total dispersion, WDM transmission system, Chromatic dispersion, Kerr nonlinearity, Optical phase conjugator, Eye opening penalty.

I. INTRODUCTION

It is well known that spectral inversion (or phase conjugation) within a fiber-optical communication link can in principle eliminate both linear (dispersive) and nonlinear (Kerr-nonlinearity-induced) impairments [1]. Generally, this technique is called to mid-span spectral inversion (MSSI) because optical phase conjugator (OPC) has to be placed at mid-way of total transmission link for compensating the distorted optical signals. MSSI does not require accurate knowledge of the dispersion of each fiber section, as long as one has access to the middle point of the total fiber span and the two resulting halves produce similar accumulated dispersion.

But, theoretically, nonlinearity cancellation by MSSI requires a perfectly symmetrical distribution of power and local dispersion with respect to OPC position. Due to the presence of fiber attenuation, this condition cannot be satisfied in real links. Thus, the effectiveness of this technique has only been demonstrated in specifically designed links such as those based on the use of short amplifier spacing [2], or special fibers [3], or high-power Raman distributed amplification [4]. But, in WDM transmission systems, it is more difficult to obtain the perfectly symmetrical distribution in MSSI link, because WDM transmission requires wide bandwidth, even if the perfectly symmetrical distribution was obtained for a special WDM channel.

In this paper, a new scheme for the compensation of nonlinear effects and chromatic dispersion, without the need for symmetrizing the signal power and local dispersion in WDM transmission system with OPC, is numerically investigated. The proposed scheme in this paper is using total dispersion of both fiber sections, which are discussed in Section Ⅲ. OPC must exhibit the similar conversion efficiency, which is defined as a ratio of the conjugated power to the signal power [5], over total WDM channels for compensating overall WDM channels to similar reception performance. Fortunately, this requirement is satisfied 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 [6]. The configuration of 1.12 Tbps (i.e., 28 channels × 40 Gbps) WDM transmission system with OPC using HNL-DSF is discussed in Section Ⅱ. The results of simulations are presented and the analysis of these results is discussed in Section Ⅳ. And, the conclusion of this research is described in Section Ⅴ.

II. CONFIGURATION OF WDM TRANSMISSION SYSTEM

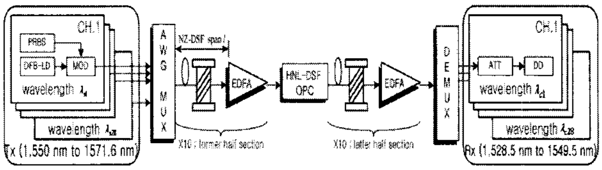


Fig. 1 The configuration of 28×40 Gbps WDM transmission system with OPC.

The configuration of intensity modulation / direct detection (IM/DD) WDM transmission system with OPC is illustrated in Fig. 1. Transmitter (Tx) of WDM transmission system consist of 28 distributed feedback laser diode (DFB-LD). The center wavelengths of DFB-LD of channel 1 and 28 are assumed to be 1,550 nm and

---

Manuscript received November 23, 2007.

Seong-Real Lee is with the Division of Marine Electronic and Communication Eng., Mokpo National Maritime University, Joennam, 530-729, Korea (Tel: +82-61-7315, Fax: +82-61-7283, Email: reallee@mmu.ac.kr)

1,571.6 nm, respectively. The wavelength spacing between each channels is assumed to be 100 GHz (0.8 nm) based on ITU-T recommendation [7]. Each DFB-LD are externally modulated by an independent 40 Gbps 128(=2^7) pseudo random bit sequence (PRBS). The modulation format from external optical modulator is assumed to be NRZ. And output electric field of NRZ format is assumed to be second-order super-Gaussian pulse with 10 dB extinction ratio (ER) and chirp-free.

28·WDM channels are multiplexed in the arrayed-waveguide grating multiplexer (AWG MUX) and then transmitted into optical link. Total transmission length of link is assumed to be 1,000 km in this paper. It is divided into two sections (former and latter half section) of respective length L_1 and L_2 (with $L = L_1+L_2$) and each fiber section consist of 10 fiber spans of length $l = 50$ km. The L_1 is equal to L_2 in the case of MSSI technique. The transmission fiber span made of nonzero dispersion-shifted fiber (NZ-DSF) was characterized by the attenuation coefficient α=0.2 dB/km, dispersion coefficient D_{1x}=2 ps/nm/km (x=1,2; where 1, 2 present former and latter fiber section, respectively), the effective core area of fiber A_{eff}=72 μm^2, nonlinear refractive index n_2= 2.5×10^{-20} m^2/W and the nonlinear coefficient γ_1=1.41 $W^{-1}km^{-1}$ at 1,550 nm.

The nonlinear medium of OPC in Fig. 1 is HNL-DSF. The parameters of OPC using HNL-DSF are as follows; loss of HNL-DSF α_0=0.61 dB/km, nonlinear coefficient of HNL-DSF γ_0=20.4 $W^{-1}km^{-1}$, length of HNL-DSF z_0=0.75 km, zero dispersion wavelength of HNL-DSF λ_0=1,550 nm, dispersion slope $dD_0/d\lambda$=0.032 ps/nm^2/km, pump light power P_p =18.5 dBm, and pump light wavelength λ_p=1549.75 nm. The 3-dB bandwidth of conversion efficiency η of the OPC is obtained to be 48 nm (1526~ 1574 nm). The signal wavelengths are converted to 1,549.5 ~ 1,528.5 nm (these are called to the conjugated wavelength). Thus, the allocated 28 signal wavelengths and these conjugated wavelengths are belong within 3-dB bandwidth of η.

The multiplexed 28 conjugated channels propagated through latter half section are demultiplexed and then sent into each receiver (Rx) of direct detection. Each Rx 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[8]. The receiver bandwidth is assumed to be 0.65×bit-rate.

III. NONLINEAR SCHRÖDINGER EQUATION AND EVOLUTION METHOD

The propagation of signal in a lossy, dispersive and nonlinear medium can be expressed by the nonlinear Schrödinger equation assuming a slowly varying envelope approximation [1]

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

where j,k =1,2,⋯,28 ($j\neq k$), A_j represents the complex amplitude of signal of j-th channel, z is the propagation distance, β_{2j} is the group velocity dispersion (GVD), β_{3j} is third-order dispersion (TOD), and $T=t-z/v_j$ is the time measured in a retarded frame. The last two terms of (1) induce self phase modulation (SPM) and cross phase modulation (XPM), respectively. The effects of XPM on WDM signals are more decreased as the fiber dispersion is larger [9]. The XPM effect of inter-channels is neglected in this paper, because the dispersion coefficient of fiber in this research is assumed to be 2 ps/nm/km, which less affect the signal distortions due to XPM. The numerical approach of (1) is completed by using split-step Fourier (SSF) method [1].

The purpose of this research is proposing a new method for the improvements of WDM transmission system performance without the need for symmetrizing the signal power and local dispersion. The key solution of the proposed method is optimal total dispersion (fiber section length × dispersion coefficient of fiber section) minimizing eye opening penalty (EOP) of overall WDM channels. That is, optimal total dispersion must to be found out and system performances in 40 Gbps × 28 channel WDM transmission system with optimal total dispersion will be assessed in this research.

The inducing of optimal total dispersion is based on two kinds of approaches. First kind of approach is only related with OPC position, but is not related with dispersion coefficients of both fiber sections. That is, if OPC position was changed from mid-way of total transmission length (500 km), total dispersion is also changed by $D_{11}L_1$ and $D_{12}L_2$ (=$D_{12}(L- L_1)$). L_1 is the length of former half section from Tx to the varied OPC position, and L_2 is the length of latter half section from the varied OPC position to Rx. But, in this case, dispersion coefficients of both fiber sections, D_{11} and D_{12}, are fixed to be 2 ps/nm/km. Optimal value of total dispersion is found out by evaluating EOP characteristics for the channel 1 and 28 as a function of $D_{11}L_1$ and $D_{12}L_2$.

The second approach is vice versa. That is, the second approach is only related with dispersion coefficients of both fiber sections. That is, if dispersion coefficient of one fiber section among both fiber sections was changed from 2 ps/nm/km, total dispersion is also changed by $D_{11}L_1$ or $D_{12}L_2$, in this case L_1 and L_2 are fixed to be 500 km. And, D_{12} is assumed to be 2 ps/nm/km when $D_{11}L_1$ is considered, and D_{11} is assumed to be 2 ps/nm/km when $D_{12}L_2$ is considered, respectively. Optimal value of total dispersion is also found out by evaluating EOP characteristics for the channel 1 and 28 as a function of $D_{11}L_1$ and $D_{12}L_2$. And then, optimal total dispersions induced by different approach are compared each other.

IV. SIMULATION RESULTS AND DISCUSSION

Fig. 2 illustrates EOP of overall channels as a function of the launch power when $D_{11}L_1$= $D_{12}L_2$=1,000 ps/nm, i.e., OPC placed at mid-way of total transmission length and D_{1x}=2 ps/nm/km (that is, conventional MSSI). The

EOP of each channel is defined as 10*log*(*a*/*b*) where *a* is the eye opening in back-to-back and *b* is the eye opening calculated after transmission. It is shown that EOPs are more degraded as the signal wavelengths are more deviated from the zero dispersion wavelength of OPC. That is, the conventional MSSI has the limitation to transmit overall WDM channels with the similar performance.

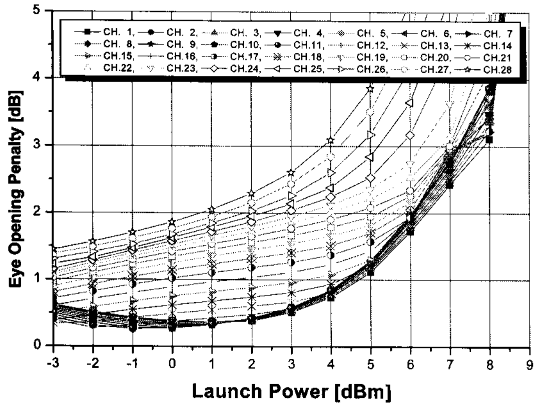


Fig. 2 EOP as a function of the launching power in WDM transmission system with MSSI.

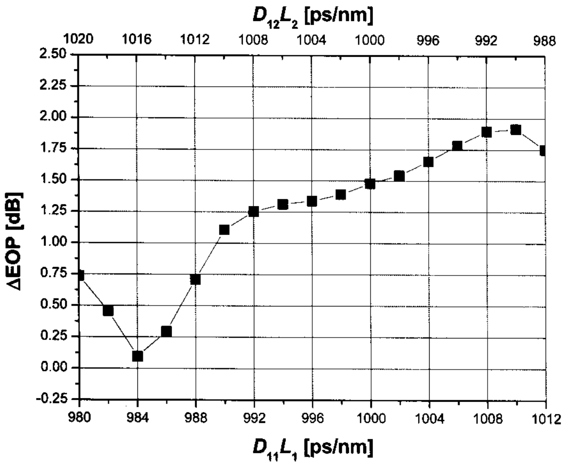


Fig. 3 ΔEOP as a function of total dispersion in the case of $D_{11} = D_{12} = 2$ ps/nm/km.

Fig. 3 illustrates ΔEOP, a difference of EOP between channel 1 and 28, i.e., $| EOP_{ch1} - EOP_{ch28} |$, depending on total dispersion, $D_{11}L_1$ and $D_{12}L_2$ in order to find out the best total dispersion in assuming both D_{11} and D_2 to be 2 ps/nm/km, when OPC position is changed from 500 km. It is shown from Fig. 3 that the best values of total dispersion resulting in the smallest ΔEOP are 984 ps/nm for $D_{11}L_1$ and 1,016 ps/nm for $D_{12}L_2$, respectively. These results mean that EOP of overall WDM channels are improved by positioning OPC at 492 km from Tx ($L_1 = 984/2 = 492$ km, $L_2 = 1{,}016/2 = 508$ km) in the case of no changing dispersion coefficient of both fiber sections for total dispersion variation.

Fig. 4 illustrates ΔEOP depending on total dispersion, in assuming both L_1 and L_2 to be 500 km, when dispersion coefficient of one fiber section is changed from 2 ps/nm/km but that of the other is fixed to be 2 ps/nm/km.

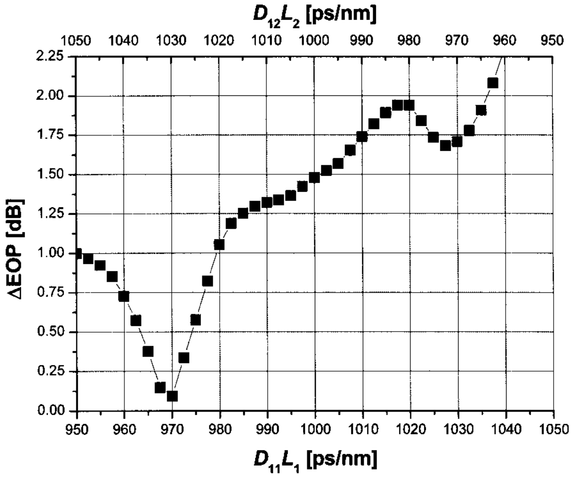


Fig. 4 ΔEOP as a function of total dispersion in the case of $L_1 = L_2 = 500$ km.

That is, $D_{11}L_1$ shown in the bottom of Fig. 4 is the product of 500 km (=L_1) and the varying D_{11} under $D_{12} = 2$ ps/nm/km, while $D_{12}L_2$ shown in the top of Fig. 4 is the product of 500 km (=L_2) and the varying D_{12} under $D_{11} = 2$ ps/nm/km. It is shown from Fig. 4 that the best values of total dispersion resulting in the smallest ΔEOP are 970 ps/nm for $D_{11}L_1$ and 1,030 ps/nm for $D_{12}L_2$, respectively. These results mean that EOP of overall WDM channels are improved by setting dispersion coefficient of former half section to 1.94(=970/500) ps/nm/km when OPC placed at 500 km and dispersion coefficient of latter half section is fixed to be 2 ps/nm/km, or by setting dispersion coefficient of latter half section to 2.06(= 1,030/500) ps/nm/km when OPC placed at 500 km and dispersion coefficient of former half section is fixed to be 2 ps/nm/km.

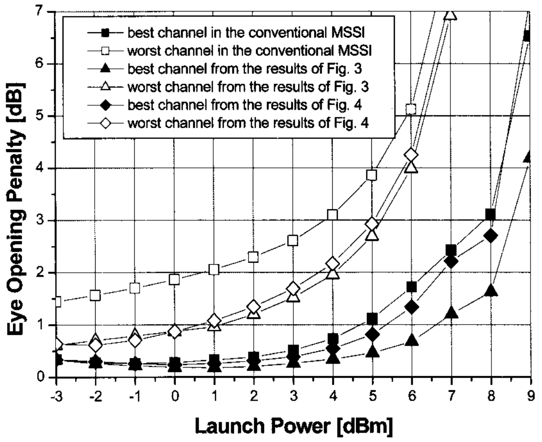


Fig. 5 EOP of the best channel and worst channel as a function of the launch power in WDM transmission system.

Fig. 5 shows EOP of the best and worst channel among 28 channels as a function of the launch power in WDM transmission system with optimal total dispersion obtained from Fig. 3 and 4, compared with those in the conventional MSSI system, i.e., the result of Fig. 2. If 1 dB EOP is allowed for performance criterion, it is confirmed that power penalty is reduced to almost 5 dB in WDM transmission system with optimal total dispersion from infinite value in the conventional MSSI system. And, in the case of transmitting the worst channel, the maximum launch power resulting 1 dB EOP is increased to almost 0.5 dBm in WDM transmission system with optimal total dispersion, while that is smaller than -3 dBm in the conventional MSSI system. These facts mean that compensation extents of overall channels are improved by applying the only optimal total dispersion proposed in this research into WDM transmission system with OPC, even if the "perfect symmetry" was not made.

The important point to be confirmed is that optimal total dispersion values induced in Fig. 3 and 4 will be used to design the flexible WDM transmission system. That is, the criterion values necessary to design the flexible WDM transmission system will be obtained by comparing optimal total dispersion values from the different procedures. From the comparing Fig. 3 with 4, it is confirmed that dispersion coefficient of latter half section is decreased by 0.0075 ps/nm/km in the case of fixing only D_{11} to 2 ps/nm/km as the OPC position is closer to Tx by 1 km. This value is resulted from the below facts; optimal total dispersion is obtained to be 1,016 ps/nm when OPC placed at 508 km as illustrated in Fig. 3 and optimal total dispersion is obtained to be 1,030 ps/nm when OPC placed at 500 km as illustrated in Fig. 4, thus 0.0075 ps/nm/km is induced from (1016 /508 - 1030/500) / (508-500). Also, dispersion coefficient of former half section is increased by 0.0075 ps/nm/km in the case of fixing only D_{12} to 2 ps/nm/km as the OPC position is closer to Tx by 1 km, because of (970/500 - 984/492) / (500-492).

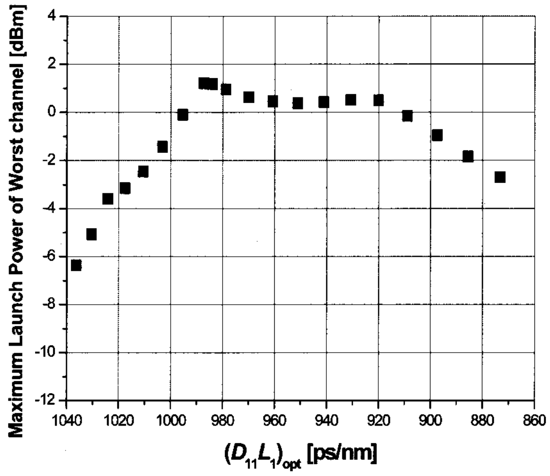
Consequently, these values and the results of Fig. 3 and 4 should be used in the flexible design of WDM transmission system with the improved performance better than that in the conventional MSSI system. That is, the flexible decision of optimal total dispersion of one fiber section is possible when dispersion coefficient of the other half section is fixed to be 2 ps/nm/km, depending on the below equations;

$$(D_{11}L_1)_{opt} = \left(D_{11,mid} + 0.0075(z_{mid} - z_{OPC})\right)L_1 \qquad (2)$$

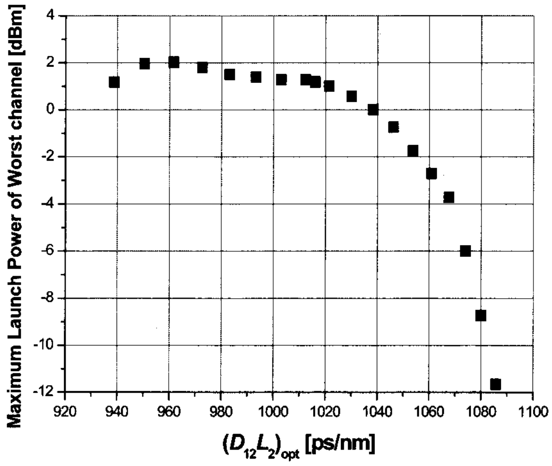
$$(D_{12}L_2)_{opt} = \left(D_{12,mid} - 0.0075(z_{mid} - z_{OPC})\right)L_2 \qquad (3)$$

where, $(D_{11}L_1)_{\rm opt}$ and $(D_{12}L_2)_{\rm opt}$ are optimal total dispersions of former half section and latter half section, respectively. $D_{11,\rm mid}$ and $D_{12,\rm mid}$ are dispersion coefficients of former half section and latter half section, respectively, when OPC is placed at 500 km, which correspond to 1.94 ps/nm/km and 2.06 ps/nm/km, respectively. $z_{\rm mid}$ is the position of mid-span of total transmission length, i.e., 500 km, and $z_{\rm OPC}$ is the desired position of OPC from Tx. And, L_1 is the length from Tx to OPC, and L_2 is the length from OPC to Rx.

For example, if one designed WDM transmission system with OPC placed at 470 km from Tx when only D_{12} is fixed to 2 ps/nm/km, $(D_{11}L_1)_{\rm opt}$ is decided to be 1017.55 ps/nm as the result of (1.94+0.0075(500-470))×470. While, $(D_{12}L_2)_{\rm opt}$ is decided to be 972.55 ps/nm as the result of (2.06-0.0075(500-470))×530 when only D_{11} is fixed to 2 ps/nm/km.



(a) in the case of only D_{12} = 2 ps/nm/km



(b) in the case of only D_{11} = 2 ps/nm/km

Fig. 6 The maximum launch power of worst channel in the various cases of optimal total dispersion.

Fig. 6(a) and (b) show the maximum launch power of the worst channel in WDM transmission system in the various cases of $(D_{11}L_1)_{\rm opt}$ and $(D_{12}L_2)_{\rm opt}$ calculated by (2) and (3), when D_{12} and D_{11} fixed to be 2 ps/nm/km, respectively. If the allowed launch power was determined to 0.5 dBm alike the result in Fig. 5, in the case of the fixed D_{12}=2 ps/nm/km, the allowable range of $(D_{11}L_1)_{\rm opt}$ is 920 to 987 ps/nm, which means that OPC can located from 490 km to 530 km from Tx. While, in the case of the fixed D_{11} = 2 ps/nm/km, the allowable range of $(D_{12}L_2)_{\rm opt}$ is 940 to 1,030 ps/nm, i.e., the allowable position of OPC is 455~500 km from Tx. Therefore, it is confirmed from the results of Fig. 6 that the flexible design of WDM transmission system less depending on OPC position is possible by using optimal total dispersion proposed in this paper. And, it is confirmed that the optimization of total dispersion of latter half section is more effective to enlarge the flexible OPC position than that of former half section.

V. CONCLUSION

Up to now, a new scheme using the optimization of total dispersion, without the need for symmetrizing the signal power and local dispersion in 1.12 Tbps WDM transmission system with OPC, was investigated. It was confirmed that power penalty between WDM channels is more decreased and the maximum launch power of worst channel is more increased in system designed by optimal total dispersion of each fiber section than those in the conventional MSSI system. Furthermore, it is also confirmed that optimal total dispersion proposed in this research should provide the flexible design of WDM transmission system, which less depends on OPC position. Thus, it is expected to realize a exact wideband WDM transmission system with OPC by using the proposed method of total dispersion optimization, without the formation of the symmetrical distribution of signal power and local dispersion.

REFERENCES

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

[2] W. Pieper *et al.,* "Nonlinearity-insensitive standard-fiber transmission based on optical-phase conjugation in a semiconductor-laser amplifier," *Electron. Lett.,* vol. 30, pp. 724–726, Apr. 1994.

[3] S. Watanabe and M. Shirasak, "Exact compensation for both chromatic dispersion and Kerr effect in a transmission fiber using optical phase conjugation," *IEEE J. Lightwave Technol.,* vol. 14, pp. 243–238, Mar. 1996.

[4] I. Brener *et al.,* "Cancellation of all Kerr nonlinearities in long fiber spans using a LiNbO3 phase conjugator and Raman amplification," in *Optical Fiber Communications (OFC) Conf. 2000, vol. 4, 2000,* pp. 266–268.

[5] K. Inoue, "Four-wave mixing in an optical fiber in the zero-dispersion wavelength region", *J. Lightwave Technol.,* vol. LT-10, no. 11, pp. 1553–1561, 1992.

[6] 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.

[7] ITU Recommendation "Spectral grids for WDM applications: DWDM frequency grid" *G.694.1,* 2006.

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

[9] S. R. Lee, J. W. Kim, and S. C. Son, "Effect of cross phase modulation on channel compensation in 320 Gbps Intensity / Direct Detection WDM transmission systems", *J. of The Korean Ins. Of Maritime Inform. & Comm. Science,* vol. 8, no. 5, pp. 1134~1140, 2004.

Seong-Real Lee (M'04) became a Member (M) of KIMICS in 2004. He received the B.S., M.S. and Ph. D. degree in telecom-munication and information eng. from Hankuk Aviation University, Korea in 1990, 1992 and 2002, respectively. He is currently an assistant professor at the Division of Marine Electronic and Communication Eng., Mokpo National Maritime University. His research interests include optical WDM systems, optical soliton systems and the optical nonlinear effects.