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MSSI 기법을 채택한 WDM 시스템에서 HNL-DSF를 이용한 광대역 광 위상 공액기의 펌프 광 전력

정회원 이 성 렬*, 조 성 언**

Pump Light Power of Wideband Optical Phase Conjugator using HNL-DSF in WDM Systems with MSSI

Seong real Lee*, Sung eun Cho** ***Regular Member***

요 약

장거리 3×40 Gbps 파장 분할 다중 시스템에서 색 분산과 자기 위상 변조에 의해 왜곡된 광 펄스를 최상으로 보상할 수 있는 최적의 펌프 광 전력을 수치적 방법으로 살펴보았다. 광 펄스 왜곡 보상 기법으로 경로 평균 강도 근사를 채택한 MSSI (Mid-Span Spectral Inversion) 기법을 사용하였고, 전체 전송로 중간에서 MSSI를 수행하는 광 위상 공액기(OPC)의 비선형 매질로는 HNL-DSF(Highly-Nonlinear Dispersion Shifted Fiber)를 이용하였다. 광 대역 WDM 전송을 위한 OPC의 비선형 매질로는 HNL-DSF가 매우 유용하다는 것을 확인하였고, 최상의 보상을 위한 OPC의 펌프 광 전력은 OPC를 통해 두 번째 광섬유로 입사하는 공액파 광 전력이 WDM 채널의 입력 광 전력과 같아지도록 전체 전송 거리와 관련하여 선택되어야 한다는 것을 확인하였다. 또한 적은 변환 효율을 갖는 WDM 채널의 개선된 보상은 전력 변환비를 1 이상으로 증가시킬 수 있는 전력의 펌프 광을 이용해야 얻을 수 있다는 것을 확인하였다.

Key Words : Optical Phase Conjugator (OPC), Highly Nonlinear Dispersion Shifted Fiber(HNL-DSF), Mid-Span Spectral Inversion (MSSI), Pump light power, WDM system

ABSTRACT

In this paper, we numerically investigated the optimum pump light power resulting best compensation of pulse distortion due to both chromatic dispersion and self phase modulation (SPM) in long-haul 3×40 Gbps wavelength division multiplexing (WDM) systems. We used mid-span spectral inversion (MSSI) method with path-averaged intensity approximation (PAIA) as compensation approach, which have highly nonlinear dispersion shifted fiber (HNL-DSF) as nonlinear medium of optical phase conjugator (OPC) in the mid-way of total transmission line. We confirmed that HNL-DSF is an useful nonlinear medium in OPC for wideband WDM transmission, and in order to achieve the excellent compensation the pump light power is selected to equal the conjugated light power into the latter half fiber section with the input light power of WDM channel depending on total transmission length. Also we confirmed that compensation degree of WDM channel with small conversion efficiency is improved by using pump light power increasing power conversion ratio upper than 1.

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* Div. of Marine Electro. and Comm. Eng., Mokpo National Maritime University (reallee@mmu.ac.kr)
** School of Inform. and Telecomm. Eng., Sunchon National University

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Ⅰ. Introduction

Long distance and high bit-rate optical fiber communication systems have been realized by using of erbium-doped fiber amplifier (EDFA)[1]. But in these systems optical pulse distortion due to the wavelength dispersion and Kerr effects in fibers limit the optical transmission capacities. Various approaches like as prechirping[2] and fiberoptic dispersion management[3], have been proposed to compensate these pulse distortions due to the fiber dispersion and so on, and systems using an optical phase conjugator (OPC) are also one of the approaches[4],[5]. The OPC converts the signal lights propagating in the former half section into the phase conjugated lights. In systems using OPC, the distortion generated in the former half section can be compensated by the latter half section propagation of the phase conjugated lights.

Furthermore, a wavelength convertor is one of the key components for enhancing the capacities and flexibility of future wavelength division multiplexing (WDM) systems. Recent developments in ultra broadband EDFA shows the possibility of WDM systems in a variety of wavelength ranges[6]. In WDM systems with OPC as wavelength convertor and pulse distortion compensator, channel signals have to be converted into the phase conjugated lights as a whole. Therefore OPC in the mid-span transmission line has to have the same bandwidth as that of the EDFA used.

It is difficult to use conventional dispersion shifted fiber (DSF) as a nonlinear medium for four wave mixing (FWM) generation in OPC. Because the generation efficiency of FWM is drastically changed depending on the wavelength separation between the signal and pump lights nearby the zero dispersion wavelength (ZDW) of DSF. In order to solve this problem, OPC using highly nonlinear dispersion shifted fiber (HNL-DSF) is proposed by Watanabe *et al*[7].

Also self phase modulation (SPM) compensation by using of OPC is limited by the asymmetry of the strength of the Kerr effects along the fiber with respect to the OPC position. This is caused by the asymmetric light intensity change along the fiber due to fiber loss and amplifier gain. To reduce the influence of such an intensity change, a method using path-averaged intensity approximation (PAIA) mid-span spectral inversion (MSSI) was proposed[8],[9]. It is predicted that the compensation extent varies with pump light power fluctuation in OPC. But this effect on the MSSI is not evaluated numerically or experimentally up to now.

We investigate a pump light power of wideband OPC using HNL-DSF as the nonlinear medium in PAIA MSSI. We induce a optimum pump power resulting best compensation for WDM channel distortion. We use the split-step Fourier numerical simulation in 3×40 Gbps WDM systems. And we use eye-opening penalty (EOP) parameter in order to evaluate the compensation degree of WDM channel distortion. In order to simplify the analysis we neglect the cross phase modulation (XPM) of inter-channels. Consequently, we take account of the chromatic dispersion and SPM as origins of distorted WDM channel, since FWM can be suppressed by using of unequal channel spacing scheme[10].

Ⅱ. Wideband OPC using HNL-DSF

The flattened FWM efficiency generated in OPC is the key point to realized the wideband OPC because of using FWM to obtain optical phase conjugated lights.

By using HNL-DSF with a small dispersion slope instead of conventional DSF as the third order nonlinear medium, the flattened FWM generation efficiency will is expected. If it is possible to convert different wavelength signals over wide bandwidth in a lump by using such fibers, it can be expected to apply the OPC for WDM systems.

Fig. 1 shows the configuration of the OPC using HNL-DSF. The signal light A_s with the wavelength λ_s propagated in the first half fiber section is amplified by the first EDFA, and the signal light will be coupled with the pump light

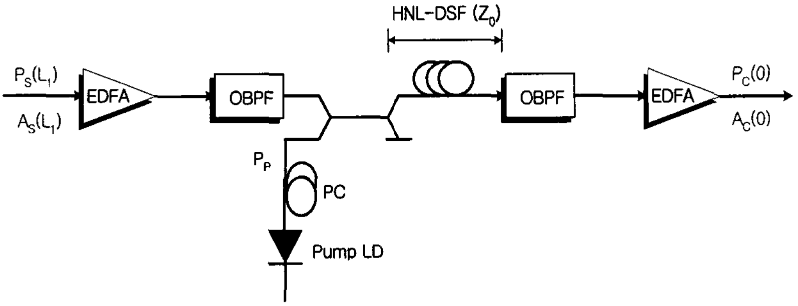


Fig 1. Optical phase conjugator using highly-nonlinear dispersion shift fiber

of the wavelength λ_p.

The coupled light is injected into HNL-DSF with the ZDW λ_0, and consequently the FWM lights are generated. The wavelength of the obtained phase conjugated light is $\lambda_c = 1/(2/\lambda_p \; 1/\lambda_s)$. The light is filtered by an optical band pass filter (OBPF), and the output light is amplified by the EDFA and launched into the latter half of the transmission line.

The conversion efficiency η is defined as a ratio of the FWM product power to the input probe (signal) power. The output power of the FWM product is calculated by the following equations[11].

$$P_{FWM} = \gamma_o^2 P_p^2 P_s(L_1) \exp(-\alpha_o z_o) L_{eff}^2 \eta \tag{1}$$

$$L_{eff} = [1 - \exp(-\alpha_o z_o)] / \alpha_o \tag{2}$$

$$\eta = \frac{\alpha_o^2}{\alpha_o^2 + \Delta\beta^2}\left[1 + \frac{4e^{-\alpha_o z_o}\sin^2(\Delta\beta z_o/2)}{(1 - \exp(-\alpha_o z_o))^2}\right] \tag{3}$$

$$\Delta\beta = -\frac{2\pi c \lambda_0^3}{\lambda_p^3 \lambda_S^2}\frac{dD_o}{d\lambda} \cdot (\lambda_s - \lambda_p)^2 (\lambda_0 - \lambda_p) \tag{4}$$

L_{eff} and $\Delta\beta$ are effective interacting length and phase mismatch parameter, respectively. Table 1 summarizes HNL-DSF OPC parameters in our calculation.

Table 1. Parameters of HNL-DSF OPC

Parameters	Value
Loss (α_o)	0.61 dB/km
Nonlinear coefficient (γ_o)	20.4 W^{-1} km^{-1}
Pump light power (P_p)	18.7 dBm
Length (z_o)	0.75 km
ZDW (λ_0)	1550 nm
Pump light wavelength (λ_p)	1549.5, 1548.3 1547.0 nm
Dispersion slope ($dD_o/d\lambda$)	0.032 ps/nm^2/km

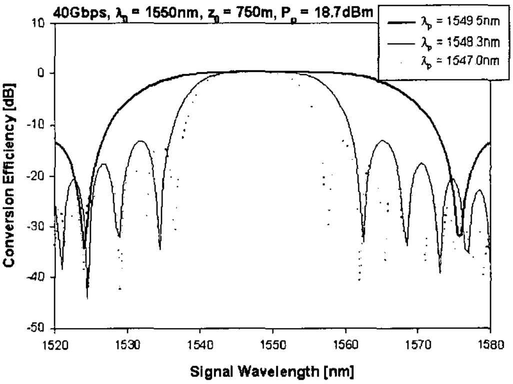


Fig 2. The calculated values of conversion efficiency

The calculated value of η using table 1 parameters is plotted in Fig. 2. The obtained highest η is 0.18 dB. The 3-dB bandwidth is 34 nm (1532.5~1566.5 nm), 18 nm (1539.5 ~1557.5 nm) and 14 nm (1540~1554 nm) in HNL-DSF OPC with 1549.5, 1548.3 and 1547.0 nm pump light wavelength, respectively. The 34 nm bandwidth is corresponding to cover almost entire gain band of EDFA.

Ⅲ. Simulation and Evaluation Methods

The numerical analysis begins with the nonlinear wave propagation equation[12]. The evolution of the j-th signal wave of WDM A_j is described by

$$\begin{aligned} \frac{\partial A_j}{\partial z} &= -\frac{\alpha}{2}A_j - \frac{i}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial T^2} \\ &\quad + \frac{1}{6}\beta_{3j}\frac{\partial^3 A_j}{\partial T^3} + i\gamma_j |A_j|^2 A_j \\ \beta_{2j} &= -\frac{D\lambda_j^2}{2\pi c}, \\ \beta_{3j} &= \frac{\left(\lambda_j \frac{dD}{d\lambda} + D\right)\lambda_j^2}{(2\pi c)^2}, \\ \gamma_j &= \frac{n_2\omega_0}{cA_{eff}},\ T = t - \frac{z}{v_{gj}} \end{aligned} \qquad (5)$$

where 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, D is the fiber dispersion coefficient, c is the light velocity, n_2 is the nonlinear refractive index, A_{eff} is the fiber effective cross section, v_{gj} is the group velocity, and $dD/d\lambda$ is the dispersion slope, respectively.

We use the unequal WDM channel spacing proposed by F. Forghieri *et al.*[10] in order to suppress the crosstalk due to FWM effects. The WDM channel signal wavelengths and conjugated light wavelengths used for the various pump light wavelength are listed in Table 2. The simulation model in this paper is presented in Fig. 3 and simulation parameters is summarized in Table 3, respectively.

The compensation of pulse distortion due to the chromatic dispersion is achieved by equalizing the total dispersion of both fiber section, that is $D_1L_1 = D_2L_2$, in PAIA MSSI method. Since the basic parameters such as fiber section length, attenuation coefficient, EDFA spacing length, and the nonlinear coefficient of each fiber section are selected to be equal each other in this approaches, compensation of pulse distortion due to SPM is also achieved by equalizing the input signal averaged-power into former half section to the phase conjugated light averaged-power into the latter half section as following

$$P_s(0) = P_c(0) \qquad (6)$$

But it is difficult to analytically verify the satisfaction of (6) in PAIA MSSI because the conjugated light power into L_2 is not expressed by initial signal light power into L_1 simply. Initial conjugated light power magnitude depend on the pump light power in OPC. Therefore (6) is satisfied only in special pump light power, and it is

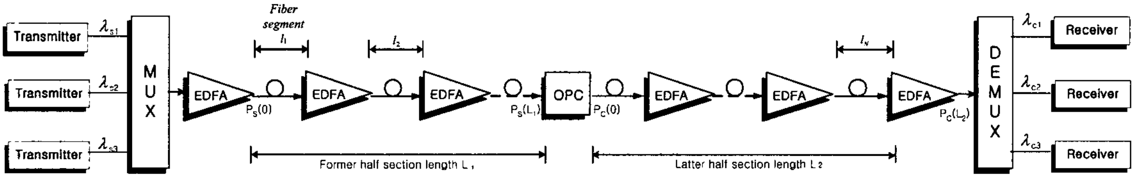


Fig 3. Model of simulation]

Table 2. Unequal spacing of WDM signal channel wavelengths and conjugated signal wavelengths

Channel Number	Signal light wavelengths	Conjugated light wavelengths		
		λ_p = 1549.5 nm	λ_p = 1548.3 nm	λ_p = 1547.0 nm
CH. 1	1550.0 nm	1549.0 nm	1546.6 nm	1544.0 nm
CH. 2	1553.0 nm	1546.0 nm	1543.6 nm	1541.0 nm
CH. 3	1555.8 nm	1543.3 nm	1540.9 nm	1538.3 nm

Table 3. Parameters of simulation

Parameters		Symbol & value
Transmitter	Bit rate	R_b = 120 Gbps (=3×40 Gbps)
	Waveform	NRZ super-Gaussian (m=2)
	Pattern	PRBS 2^7 (128 bits)
	Chirp	0
Fiber	Type	conventional DSF
	Loss	$\alpha_1 = \alpha_2 =$ 0.2 dB/km
	Total length	variable (L_1 = L_2)
	Dispersion coefficient	D_{11} = D_{12} = 0.1 ps/nm/km
	Nonlinear refractive coefficient	n_2 = 2.36×10^{-26} km^2/W
	Effective core section	A_{eff} = 60 μm^2
	Number of EDFA	variable
	EDFA spacing (Fiber section)	l = 50 km
Receiver	Type	PIN-PD with EDFA pre-amp
	EDFA noise figure	5 dB
	Optical bandwidth	1 nm
	Receiver bandwidth	0.65×R_b

predicted that the best compensation will be achieved at this pump light power.

In order to verify the compensation extent depending on the variation of pump light power, we define the power conversion ratio R_p as following

$$R_p = P_c(0) \;/\; P_s(0) \qquad (7)$$

The evaluation criterion of this approaches is the 1 dB EOP. And evaluation procedures are following. First, we evaluate the power conversion ratio and EOP dependence on the fluctuation of pump light power in OPC in various transmission length. And then we analyzed the relation of EOP with power conversion ratio. Second, we evaluate EOP dependence on the variation of input signal light power of 3×40 Gbps WDM systems with the fixed pump light power in particular transmission length.

Ⅳ. Results and Discussion

Fig. 4 shows EOP as a function of the pump light power for several transmission length when the fiber dispersion coefficient is 0.1 ps/nm/km, input signal light power is 3 dBm and signal light wavelength is 1550 nm (CH. 1 wavelength), respectively. As shown in Fig. 4, the ranges of pump light power for an excellent compensation with performance less than 1 dB EOP must become narrower as the transmission length becomes longer. In other words, it is necessary to determine a exact pump light power in the long-haul transmission systems for optimal compen sation. And it is found that pump light power ob-

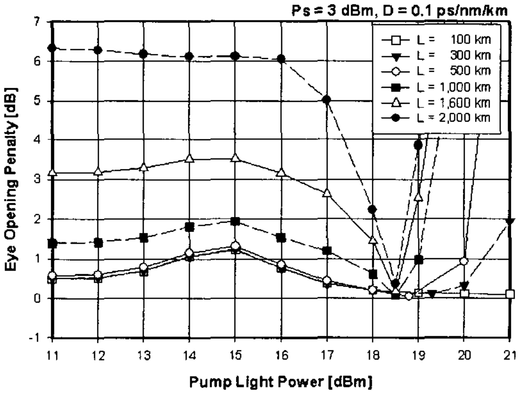


Fig 4. Eye opening penalty dependence on the pump light power fluctuation in OPC

taining the minimum EOP is 18.5 dBm when the transmission length becomes increased more than 1,000 km. This value is smaller than that of transmission length shorter than 500 km.

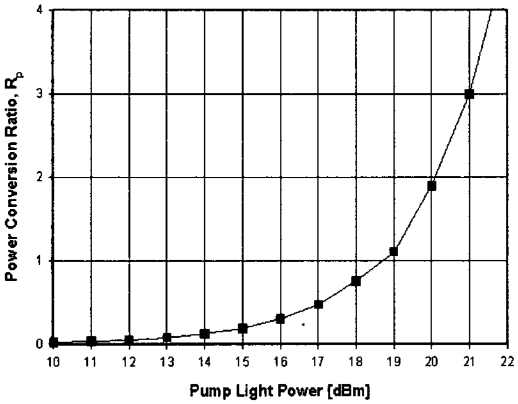


Fig 5. Power conversion ratio dependence on the pump light power fluctuation in OPC

Fig. 5 shows the power conversion ratio as a function of the pump light power. The same power conversion ratio is resulted regardless of the transmission length variation. The pump light power resulting unity power conversion ratio ($R_p = 1$) is 18.7 dBm. And power conversion ratio is 0.95 when pump light power is 18.5 dBm. As comparing between Fig. 4 and Fig. 5, the minimum EOP is achieved at 0.95 power conversion ratio in the transmission length longer than 1,000 km, whereas the minimum EOP is achieved at the higher than unity power conversion ratio in the shorter than 500 km.

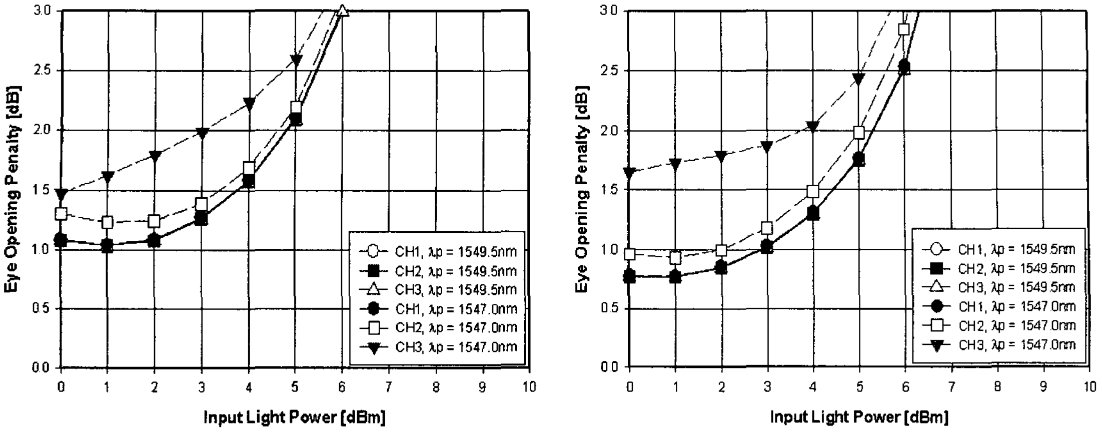
We think that this result is presented through following phenomena. A cancellation extent of total phase modulation (PM), which consist of PM caused by a chromatic dispersion and PM caused by SPM, is gradually reduced as the transmission length becomes gradually increased. And, consequently, the conversion of residual PM into amplitude is gradually increased in proportion to total transmission length.

Fig. 6 shows EOP as a function of the input signal light power for several pump light power when pump light wavelengths are 1549.5 and 1547.0 nm in 1,000 km 3×40 Gbps WDM system, respectively. We define in-band channel and out-band channel as whether WDM channel wavelength is included in 3-dB bandwidth of OPC or not, respectively. Thus overall WDM channels become in-band channel for 1549.5 nm pump light wavelength. On the other hand, when pump light power is 1547.0 nm, CH. 3 becomes out-band channel and CH. 2 has lower conversion efficiency in spite of in-band channel.

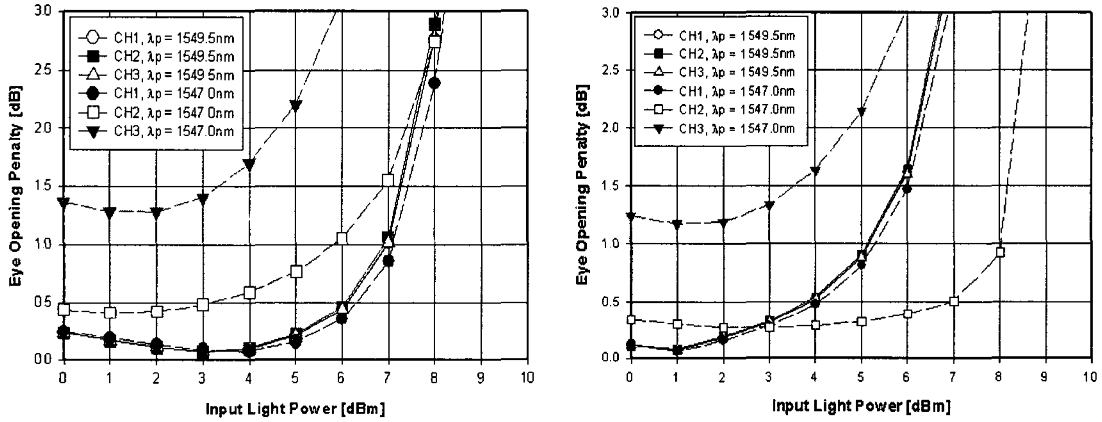
The power penalty of in-band channels are smaller than 1 dB at 18.5 dBm pump light power when pump light wavelengths are 1547.0 nm and 1549.5 nm. This fact imply that the optimal pump light power is 18.5 dBm for the best compensation of in-band channels in both 1547.0 nm and 1549.5 nm pump light wavelengths. And as pump light power becomes gradually increased, the compensation of out-band channel at 1547.0 nm pump light wavelength is improved.

Fig. 7 shows EOP as a function of the input signal light power for several pump light power when pump light wavelengths are 1549.5 nm and 1548.3 nm in 1,000 km 3×40 Gbps WDM system, respectively. And power conversion ratio of several in-band channels at 1547.0 nm and 1548.3 nm pump light wavelengths are plotted in Fig. 8. The overall channels represented in Fig. 7 are in-band channels. Like the preceding results, the optimal pump light power is 18.5 dBm for the best compensation of in-band channels. From the above results, the important point to be confirmed is that HNL-DSF is very useful nonlinear medium for wideband OPC in order to compensate for the distorted in-band channels in PAIA MSSI method, if pump light power of HNL-DSF OPC was selected to make power conversion ratio into nearby 1.

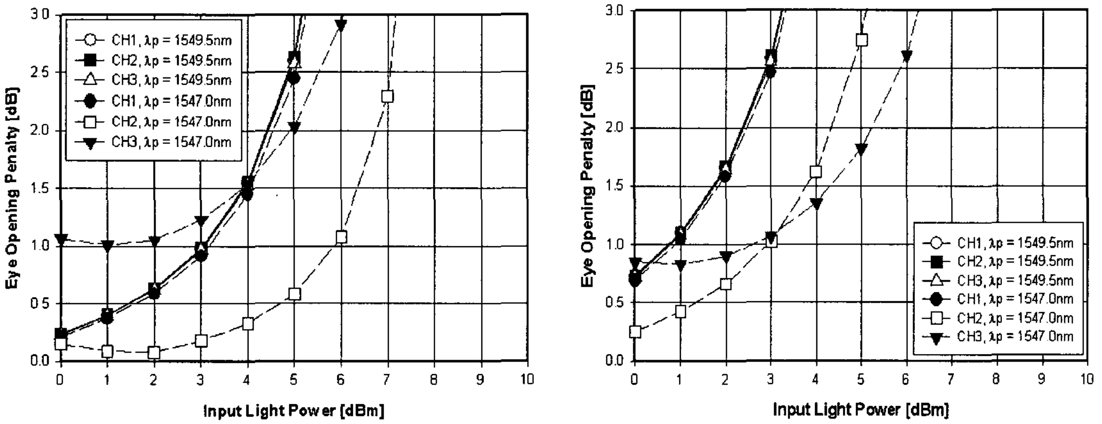
In Fig. 7, when pump light power becomes higher than 18.7 dBm (Fig 7(d)~(e)), the compensation extents of overall channels except channel 3 at 1548.3 nm pump light wavelength are similar to each other and are reduced than that of 18.5 dBm pump light power (Fig 7 (c)). Whereas the compensation extent of channel 3, when pump light has 1548.3 nm wavelength and 18.7 dBm power, is improved than that of uuder the con-



(a) Pp = 16.8 dBm (b) Pp = 17.4 dBm

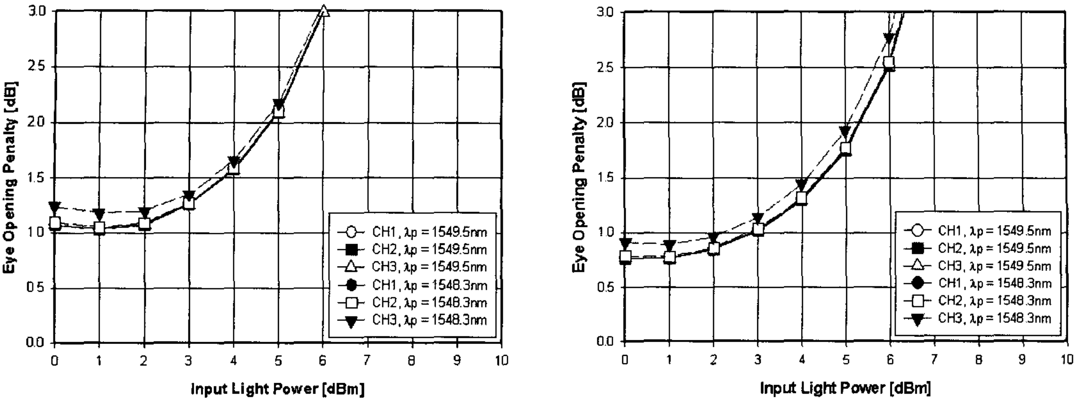


(c) Pp = 18.5 dBm (d) Pp = 18.7 dBm



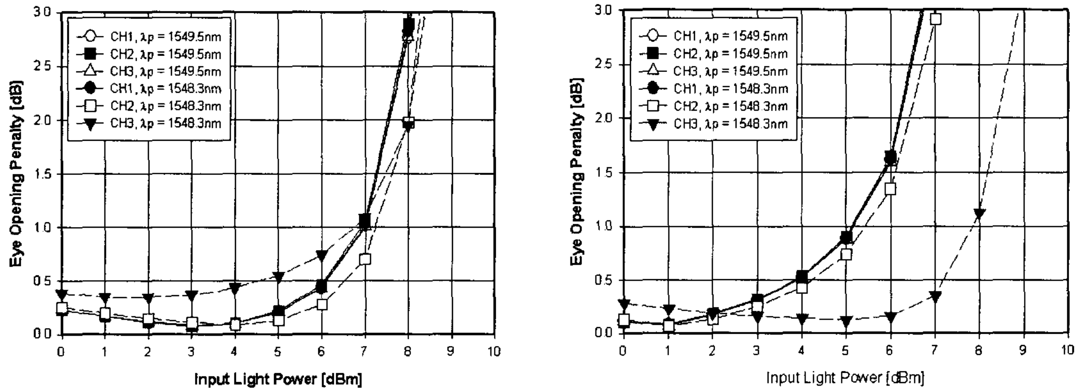
(e) Pp = 19.0 dBm (f) Pp = 19.4 dBm

Fig 6. Eye opening penalty as a function of the input signal light power for the various pump light power in OPC (Comparison of 1547.0 nm and 1549.5 nm pump light wavelengths)



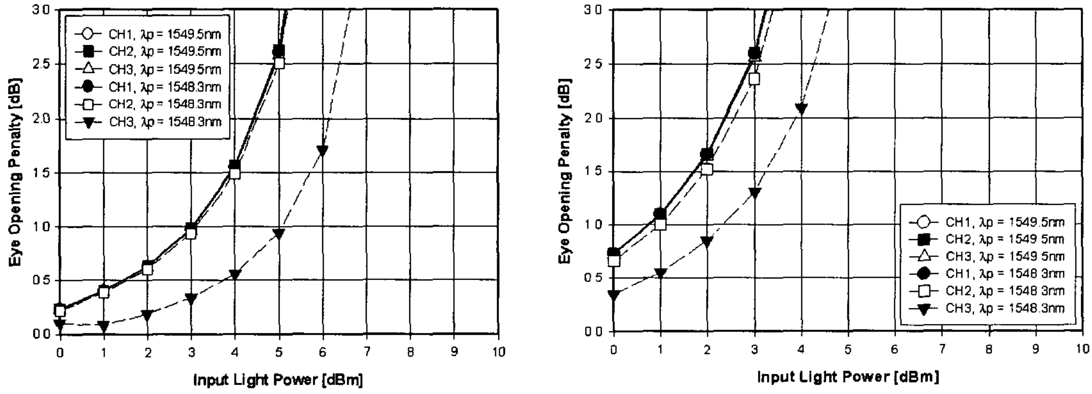
(a) Pp = 16.8 dBm

(b) Pp = 17.4 dBm



(c) Pp = 18.5 dBm

(d) Pp = 18.7 dBm



(e) Pp = 19.0 dBm

(f) Pp = 19.4 dBm

Fig 7. Eye opening penalty as a function of the input signal light power for the various pump light power in OPC (Comparison of 1548.3 nm and 1549.5 nm pump light wavelengths) dition of 18.5 dBm pump light power. This result is induced by lower conversion efficiency than that of the other channels as shown in Table 4. That is, though this channel has low conversion efficiency at 18.5 dBm pump light power, the conjugated wave of this channel is amplified to nearby unity power conversion ratio at 18.7 dBm pump light power, and then launches into DSF2. This result is used to explain the compensation improvement of out-band channel at 1547.0 nm pump light wavelength with low conversion efficiency as pump light power increasing plotted in Fig. 6.

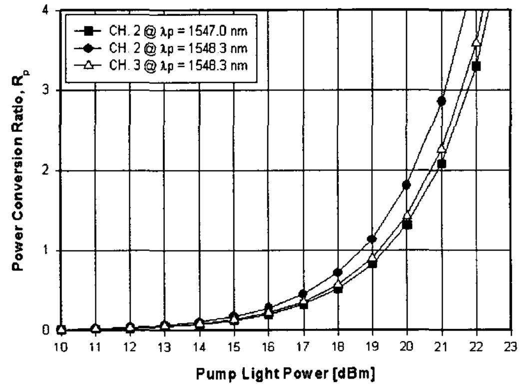


Fig 8. Power conversion ratio of several in-band channels at λ_p = 1547.0 nm and 1548.3 nm

Table 4. Conversion efficiency of each channel in HNL-DSF OPC with Pp = 18.5 dBm

λ_p	CH.1	CH. 2	CH. 3
1549.5 nm	0.18 dB	0.18 dB	0.08 dB
1548.3 nm	0.18 dB	-0.02 dB	-1.12 dB

V. Conclusion

We discussed optimal pump light power of OPC using HNL-DSF for WDM transmission systems with PAIA MSSI as compensation method.

We confirmed that HNL-DSF is very useful nonlinear medium for wideband OPC in order to compensate for the distorted in-band channels in PAIA MSSI method, if pump light power of HNL-DSF OPC was selected to make power conversion ratio of each channel into nearby 1. Futhermore, we confirmed that compensation extent of WDM channel with small conversion efficiency is improved by using pump light power increasing power conversion ratio upper than 1.

We also confirmed that the compensation extent of overall WDM channels are similar to each other in PAIA MSSI method when pump light wavelength in OPC get closer to zero dispersion wavelength of HNL-DSF. But, in this case, it is predicted that signal distortion due to cross phase modulaton (XPM) is gradually increased. Therefore we will investigate the effects of XPM in fiber and accumulated spontaneous emission (ASE) noise in EDFA on performance of WDM transmission system and exam the compensation for distorted WDM signal due to overall effects.

REFERENCES

〔1〕 D. Marcuse, "Single-channel operation in very long nonlinear fibers with optical amplifiers at zero dispersion", *J. Lightwave Technol.*, vol. LT-8, no. 10, pp. 1548~1557, 1990.

〔2〕 T. L. Koch and R. C. Alferness, "Dispersion compensation by active predistorted signal synthesis", *J. Lightwave Technol.*, vol. LT-3, pp. 800~805, 1985.

〔3〕 F. Quellete, "Dispersion cancellation using linearly chirped Bragg grating filters in optical waveguides", *Opt. Lett.*, vol. 12, pp. 847~849, 1987.

〔4〕 A. Yariv, D. Fekete, and D. M. Pepper, "Compensation for channel dispersion by nonlinear optical phase conjugation", *Opt. Lett.*, vol. 4, pp. 52~54, 1979.

〔5〕 S. Watanabe, T. Naito, and T. Chikama, "Compensation of chromatic dispersion in a single mode fiber by optical phase conjugation", *IEEE Photon. Technol. Lett.*, vol. 5, no. 1, pp. 92~95, 1993.

〔6〕 K. Song and M. Premaratne, "Effects of SPM, XPM, and four-wave-mixing in L-band EDFAs on fiber-optic signal transmission", *IEEE Photon. Technol. Lett.*, vol.

12, no. 12, pp. 1630~1632, 2000.

〔7〕 S. Watanabe, S. Takada, G. Ishikawa, H. Ooi, J. G. Nielson, 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 mixer", *IOOC/ECOC '98, PD Paper TA3A*, pp. 1~4, 1997.

〔8〕 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.

〔9〕 K. Kikuchi and C. Lorattanasene, "Compensation for pulse waveform distortion in ultralong distance optical communication systems by using midway optical phase conjugator", *IEEE Photon. Techno. Lett.*, vol. 6, pp. 1499~1501, 1994.

〔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〕 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.

〔12〕 G. P. Agrawal, *Nonlinear Fiber Optics*, Academic Press, pp. 34~44, 1989.

Seong real Lee ***Regular member***

He received the B.S., M.S. and Ph. D. degree in telecommunication and information engineering from Hankuk Aviation University, Korea in 1990, 1992 and 2002, respectively. He was a senior engineer at R&D center of Seyoung Co., Ltd. from January 1996 to June 2002, and CTO at R&D center of ATN Co., Ltd. from June 2002 to February 2004. He is currently an assistant professor at the Division of Marine Electronic and Communication Eng., Mokpo National Maritime University. His research interest include optical WDM systems, optical soliton systems and the optical nonlinear effects.

Sung eun Cho ***Regular member***

He received the B.S., M.S. and Ph. D. degree in telecommunication & information engineering from Hankuk Aviation University, Korea in 1989, 1991 and 1997, respectively. He is currently an associate professor at the School of Information and Telecommunication Eng., Sunchon National University. His research interest include optical communication systems, UWB and the wireless communication system.