Compensation Characteristics of Distorted WDM Channel dependence on Variation of Fiber Dispersion

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광섬유 분산 변동에 따른 왜곡된 WDM 채널의 보상 특성

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ABSTRACT

In this paper, compensation characteristics of distorted WDM channel due to both chromatic dispersion and self phase modulation (SPM) is numerically investigated under the assumptions of non-uniformly distributed fiber dispersion, in order to inspect the application of mid-span spectral inversion (MSSI) to any exact transmission links. The MSSI is compensation method used in this approach. This method has an optical phase conjugator (OPC) placed in mid-way of total transmission length to compensate distorted WDM channels. It is confirmed that MSSI will become applicable to long-haul WDM systems by controlling input light power of transmission channels, when the averaged dispersion of both fiber sections with respect OPC was varied and distributed unequally each other. Applying MSSI to long-haul WDM system, it is possible to remove all in-line compensator, consequently it will be expected to reducing system cost.

Key Words : Dispersion variation, MSSI, OPC, WDM channel distortion, SPM, Chromatic dispersion

요 약

광섬유의 분산이 균일하지 않다는 가정 하에 색 분산과 자기 위상 변조 (SPM : Self Phase Modulation) 현상에 의해 왜곡된 WDM 채널의 보상 특성을 수치적으로 살펴보았다. 본 연구에서 사용한 보상 기법은 전체 전송 링크 중간에 광 위상 공액기 (OPC : Optical Phase Conjugator)를 두어 보상하는 MSSI (Mid-Span Spectral Inversion)이다. OPC를 중심으로 두 광섬유 구간의 분산 계수 분포가 변동하면서 서로 일치하지 않은 경우에도 전송 채널의 입력 전력을 적절히 조절함으로써 MSSI를 통해 장거리 전송이 가능하다는 것을 알 수 있었다. 즉 장거리 WDM 시스템에 MSSI를 적용하게 되면 전송 선로 곳곳에 필요한 보상기(compensator) 등을 없앨 수 있고, 결과적으로 시스템 비용을 절감할 수 있을 것으로 기대된다.

I. Introduction

Recently, effective transmission length is gradually increased by using erbium-doped fiber amplifier (EDFA) as a in-line amplifiers. Therefore, signal distortion due to chromatic dispersion and Kerr effect is newly rising as a solving problem in multi-channel transmission techniques such as WDM systems[1],[2]. The compensation method for signal distortion due to chromatic dispersion, such as prechirping[3], the use of dispersion compensating fiber (DCF) as transmission line[4], and so on are researching up to now.

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And, special fibers with zero dispersion coefficient over broad wavelength range is developed in most recent[5],[6]. However, the distortion caused by Kerr effect such as self-phase modulation (SPM) cannot be compensated by these techniques.

A method using optical phase conjugator (OPC) in mid-way of total transmission length was theoretically and experimentally verified to be an attractive approach for Kerr effect and chromatic dispersion compensation [7]~[9]. And, it was confirmed that wideband WDM signals with excellent performance could be transmitted by using highly nonlinear dispersion shifted fiber (HNL-DSF) as a nonlinear medium of OPC[10]. The OPC converts incoming signal wave from former half section into conjugated wave, and then transmits the conjugated wave to latter half section. Another advantage of method using OPC is the use of installed fibers without other technical addition except equalizing total dispersion and path-averaged power of both fiber sections.

But dispersion coefficient of exact fiber is not uniform in everywhere due to variation of dopant distribution, etc. In this paper, therefore, compensation characteristics are numerically investigated in two assumption of nonuniform dispersion distribution of former half section and latter half section in WDM systems with HNL-DSF OPC.

The considered system has 8 WDM channels of 40 Gbps. The intensity modulation format is assumed to be NRZ. The split-step Fourier method[11] is used for numerical simulation and eye-opening penalty (EOP) is used to evaluate the degree of distortion compensation. In order to simplify the analysis, cross phase modulation (XPM) of inter-channels is neglected and four-wave mixing (FWM) can be suppressed by using unequal channel spacing scheme[12].

Ⅱ. Simulation Model

Fig. 1 shows a configuration of intensity modulation / direct detection (IM/DD) WDM system considered in this research. The evolution of the j-th signal wave of WDM A_j is described by[11]

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

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

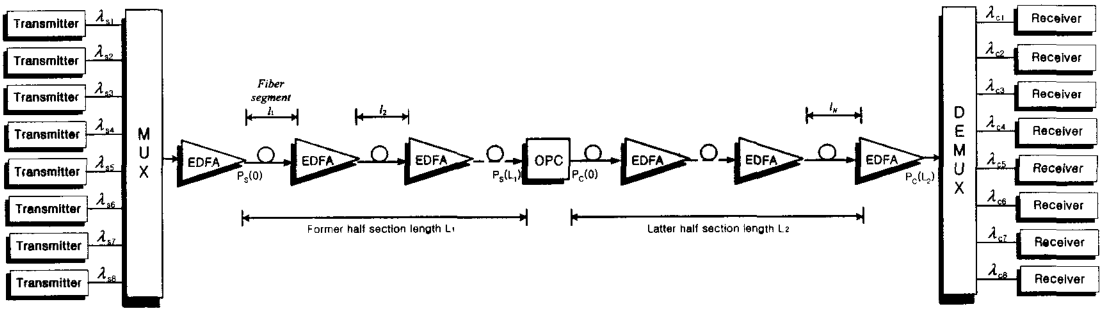


Fig. 1. 8-channel WDM system model

Table 1. Simulation parameters

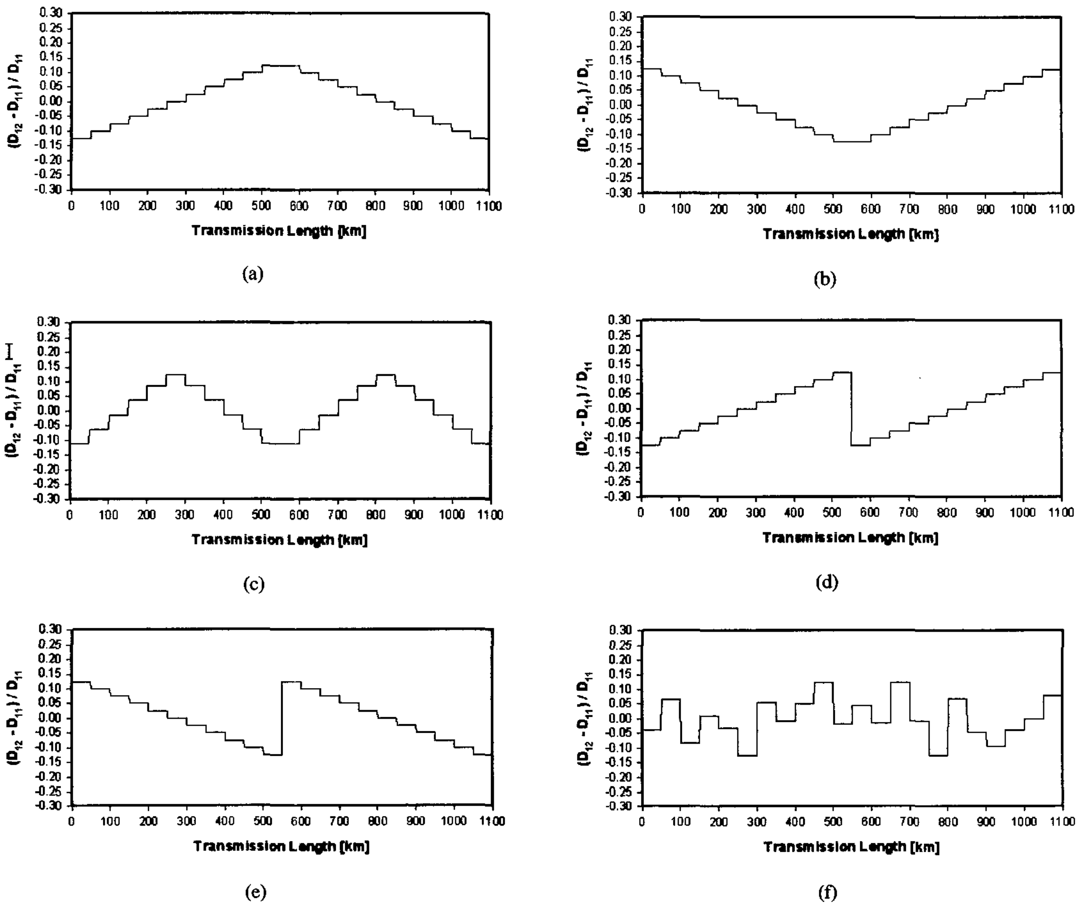
Parameters		Symbol & values
Transmitter	Bit Rate	$R_b = 320$ Gbps (=8×40 Gbps)
	Waveform	NRZ super-Gaussian (m = 2)
	Pattern	PRBS 2^7 (=128 bits)
	Chirp	0
Fiber	Type	Conventional DSF
	Loss	$\alpha_1 = \alpha_2 = 0.2$ dB/km
	Total length	1,100 km ($L_1 = L_2 = 550$ km)
	Averaged dispersion coefficient	$D_{av} = 0.4, 0.8, 1.6$ ps/nm/km
	Nonlinear refractive coefficient	$n_2 = 2.36 \times 10\text{-}26$ km^2/W
	Effective core section area	$A_{eff} = 50$ μm^2
	Number of EDFA	22
	EDFA spacing	$l = 50$ km
Receiver	Type	PIN-PD with EDFA pre-amp
	EDFA noise figure	5 dB
	Optical bandwidth	1 nm
	Receiver bandwidth	$0.65 \times R_b$
OPC	Loss of HNL-DSF	$\alpha_0 = 0.61$ dB/km
	Nonlinear coefficient of HNL-DSF	$\gamma_0 = 20.4$ W^{-1}km^{-1}
	Length of HNL-DSF	$z_0 = 0.75$ km
	Zero dispersion wavelength of HNL-DSF	$\lambda_0 = 1550.0$ nm
	Dispersion slope of HNL-DSF	$dD_0/d\lambda = 0.032$ ps/nm^2/km
	Pump light wavelength	$\lambda_p = 1549.5$ nm
	Pump light power	$P_p = 18.5$ dBm

neglected in order to simplify numerical analysis in this approach. Table 1 summarizes parameters of transmitter, receiver, fiber and OPC using HNL-DSF, respectively.

HNL-DSF is used as a nonlinear medium of OPC for compensation of wideband signal in WDM system of Fig. 1. The maximum conversion coefficient is 0.18 dB and 3-dB bandwidth of OPC using HNL-DSF is 34 nm (1532.5 ~ 1566.5 nm) from calculation of OPC parameters in Table 1[13].

The unequal WDM channel spacing proposed by F. Forghieri *et al.* is used in this research in order to suppress the crosstalk due to FWM effects. The signal wavelengths of WDM channel used in this research are 1550.2 nm, 1551.2 nm, 1553.2 nm, 1554.4 nm, 1556.0 nm, 1557.8 nm, 1560.0 nm and 1561.4 nm. Therefore, WDM channel signal wavelengths and conjugated light wavelengths belong to 3-dB bandwidth of OPC using HNL-DSF.

Optical fiber is constructed to be based on two assumptions in order to analyze compensation characteristics dependence on dispersion coefficient variation. The first assumption as follows : dispersion coefficient of fiber segments (fiber between two in-line amplifier) in former half section and latter half section regularly or irregularly changes such as Fig. 3, but averaged dispersion coefficient of both sections are equal each



(a)

(b)

(c)

(d)

(e)

(f)

Fig. 3. Distribution of dispersion coefficient in total transmission link for analysis of first assumption

other. Fig. 3 (a)~(c) show that dispersion coefficient distribution of former half section and latter half section is symmetry with respect to OPC position. Fig. 3 (d) and (e) present that dispersion coefficient distribution of latter half section follows as that of former half section. Fig. 3 (f) shows that dispersion coefficient of overall fiber segment is irregularly varied.

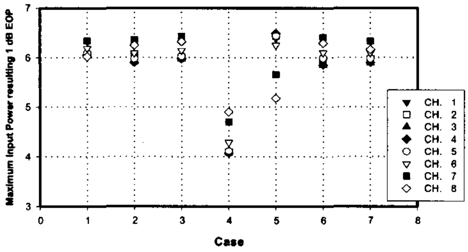
Table 2. Dispersion coefficient of each fiber section in order to analyze the second assumption. [unit : ps/nm/km]

D_{11}	ΔD_{12}	$D_{12} = D_{11} + \Delta D_{12}$
0.4	-0.1 ~ +0.1	0.3 ~ 0.5
0.8	-0.2 ~ +0.2	0.6 ~ 1.0
1.6	-0.4 ~ +0.4	1.2 ~ 2.0

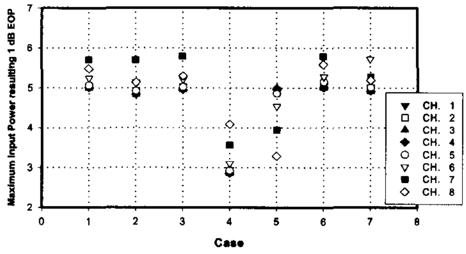
The second assumption is that dispersion coefficient of former half section (D_{11}) is uniform, but dispersion coefficient of latter half section (D_{12}) varies within ±12.5 % of D_{11} such as Table 2.

Ⅲ. Simulation results and discussion

Fig. 4 shows maximum input power resulting 1 dB eye opening penalty (EOP) at receiver of WDM systems. The D_{av} in Fig. 4 is averaged dispersion coefficient of each fiber section. The values in x-axis of Fig. 4 present six cases of Fig. 3, respectively. The case 7 in x-axis presents uniform and same dispersion distribution of each fiber segments in former half section and latter



(a) D_{av} = 0.4 ps/nm/km



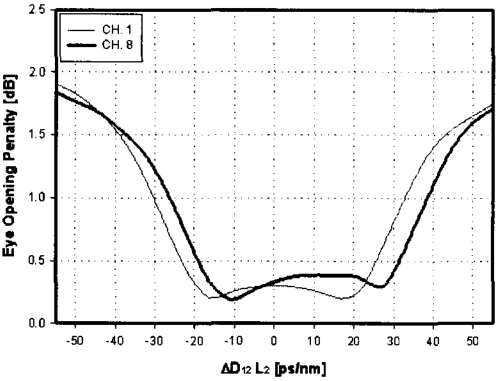
(b) D_{av} = 0.8 ps/nm/km

Fig. 4. Maximum input power of each channel resulting 1 dB EOP in the first assumption

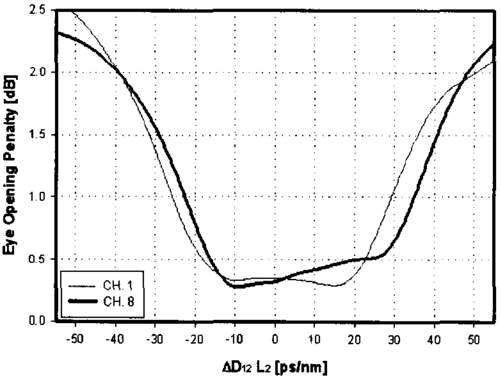
The results of Fig. 4 mean that dispersion variation of each fiber segment is not affect to compensation quality, if dispersion distribution of both fiber sections is symmetry with respect to OPC and averaged half section. This case is called to ideal case.

The maximum input power range of case 4 or 5 is generating a particular result in comparison with other cases of Fig. 4. That is, when dispersion distribution of latter half section follows dispersion distribution of former half section and first fiber segment of each section has lowest dispersion (case 4), maximum input power of each channel is reduced to almost 2 dB as compared with other cases. And, when first fiber segment of each section has highest dispersion (case 5), deviation of maximum input powers is increased.

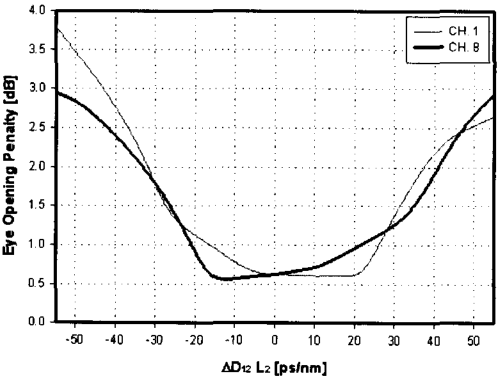
The important point to be confirmed is that, if averaged dispersion of both fiber sections was equal each other, compensation characteristics of WDM channels transmitted through fiber segments with irregularly distributed dispersion is similar to that of ideal case.



(a) Ps = 0 dBm



(b) Ps = 3 dBm



(c) Ps = 5 dBm

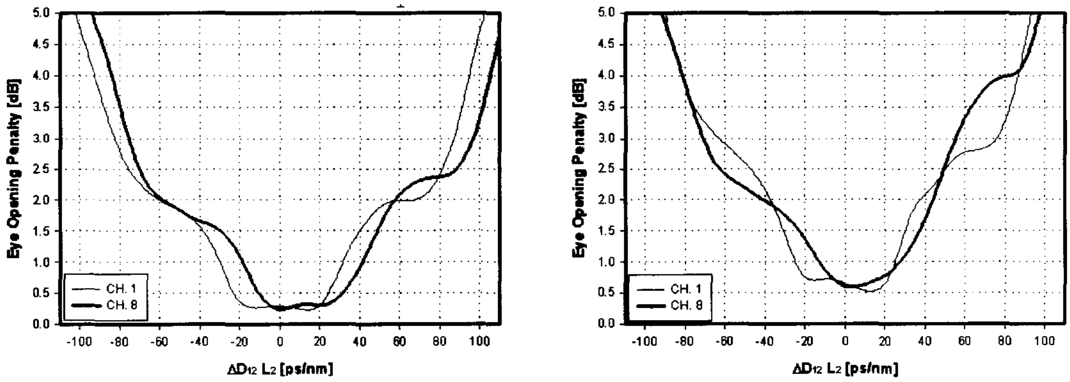
Fig. 5. EOP as a function of total dispersion deviation $\Delta D_{12}L_2$ for D_{11} = 0.4 ps/nm/km

dispersion of both fiber sections is equal each other, moreover even if fiber segment dispersion of both fiber sections was irregularly varied.

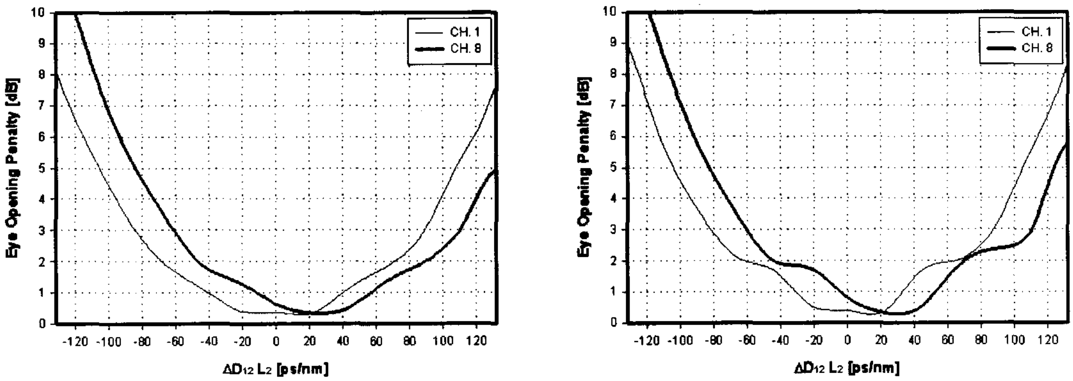
Fig. 5 shows EOP of channel 1 and 8 dependence on total dispersion deviation of latter half section ($\Delta D_{12}L_2$) when dispersion coefficient of former half section (D_{11}) is fixed on 0.4 ps/nm/km. It is shown that, if 1 dB EOP is allowed, the tolerable error in total dispersion of latter half section is between approximately -30.0 ps/nm and +33.0 ps/nm for satisfactory transmitting channel 1 with 0 dBm input power. And, allowable total dispersion of latter half section is between -26.3 ~ +38.5 ps/nm for transmitting channel 8 with 0 dBm input power. Therefore, allowable total dispersion of latter half section for transmitting total channels with 0 dBm input power is between -26.3 ~ +33.0 ps/nm. But, it is confirmed that allowable total dispersion of latter half section is reduced to -16.2 ~ +21.6 ps/nm when input power of overall channels was increasing to 5 dBm.

Fig. 6 shows EOP of channel 1 and 8 with particular input power dependence on particular input power as a function of total deviation ($\Delta D_{12}L_2$) when D_{11} is fixed on 0.8 ps/nm/km, or 1.6 ps/nm/km, respectively. The allowable total dispersions of latter half section presented in Fig. 5 and 6 are summarized in Table 3.

It is shown that from Table 3, in WDM system with D_{11} = 0.4 ps/nm/km, the allowable total dispersion of latter half section for transmitting overall channels with 3 dBm input



(a) D_{11} = 0.8 ps/nm/km ; Ps = 1 dBm (b) D_{11} = 0.8 ps/nm/km ; Ps = 4 dBm



(c) D_{11} = 1.6 ps/nm/km ; Ps = 0 dBm (d) D_{11} = 1.6 ps/nm/km ; Ps = 2 dBm

Fig. 6. EOP as a function of total dispersion deviation $\Delta D_{12}L_2$ for D_{11} = 0.8 ps/nm/km and D_{11} = 1.6 ps/nm/km

Table 3. The allowable total dispersion of L_2 for various D_{11} and P_s

D_{11}	P_s	Allowable total dispersion range of L_2	Allowable total dispersion of L_2
0.4 ps/nm/km	3 dBm	-22.6 ~ +29.2 ps/nm	51.8 ps/nm
	5 dBm	-16.2 ~ +21.6 ps/nm	37.8 ps/nm
0.8 ps/nm/km	1 dBm	-18.6 ~ +31.6 ps/nm	50.2 ps/nm
	4 dBm	-12.7 ~ +25.5 ps/nm	37.7 ps/nm
1.6 ps/nm/km	0 dBm	-10.0 ~ +40.0 ps/nm	50.0 ps/nm
	2 dBm	- 4.3 ~ +32.9 ps/nm	37.2 ps/nm

power is similar to that for transmitting overall channels with 1 dBm input power in WDM system with D_{11} = 0.8 ps/nm/km and overall channels with 0 dBm input power in WDM system with D_{11} = 1.6 ps/nm/km. And, the allowable total dispersion of latter half section for transmitting overall channels with 5 dBm input power in WDM system with D_{11} = 0.4 ps/nm/km is similar to that for transmitting overall channels with 4 dBm input power in WDM system with D_{11} = 0.8 ps/nm/km and overall channels with 2 dBm input power in WDM system with D_{11} = 1.6 ps/nm/km.

Above result means that it is necessary to decrease input light power of WDM channels to almost 1~2 dBm in order to uniformly maintain allowable total dispersion of latter half section, which is unequal with that of former half section, each time the averaged dispersion coefficient of WDM system is increased to 2 times.

Ⅳ. Conclusion

The characteristics of compensation are numerically investigated in two assumption of nonuniform dispersion distribution of former half section and latter half section in 8-channel WDM systems.

It is confirmed that the variation of fiber segment dispersion is not affect to compensation extents, if dispersion coefficient distribution of both fiber sections is symmetry with respect to OPC, and average dispersion of both fiber sections is equal each other although fiber segment dispersion of both fiber sections is random.

And, it is confirmed that maintenance of the allowable total dispersion is possible by controlling input light power of WDM, even if the averaged dispersion coefficient of both fiber sections is varied.

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