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Optimal Position of Optical Phase Conjugator for Compensation of Distorted WDM Signals with Initial Frequency Chirp

Seong-Real Lee · Byung-Ha Choi · Myung-Rae Chung

Abstract

In this paper, the optimal position of optical phase conjugator(OPC) excellently compensating distorted WDM channels with initial frequency chirp due to both chromatic dispersion and self phase modulation(SPM) is numerically investigated. Highly-nonlinear dispersion shifted fiber(HNL-DSF) is used as a nonlinear medium of OPC in order to widely compensate WDM signal band. It is confirmed that if the OPC position was shifted from mid-way of total transmission length dependence on the initial frequency chirp as well as modulation format and fiber dispersion coefficient, it is possible to cancel the performance degradation owing to the initial frequency chirp. Using proposed configuration, it is possible to remove all in-line dispersion compensator, reducing span losses and system costs in the long-haul broadband WDM systems.

Key words : Optical Phase Conjugator(OPC), Initial Frequency Chirp, Highly-Nonlinear Dispersion Shifted Fiber (HNL-DSF), Mid-Span Spectral Inversion(MSSI).

Ⅰ. Introduction

In high bit-rate transmission systems, an important origins of transmission penalty are fiber chromatic dispersion and nonlinear effects such as four-wave mixing (FWM), self-phase modulation(SPM) and cross- phase modulation(XPM)[1]. In order to overcome both nonlinear and dispersive effects, mid-span spectral inversion (MSSI) has been identified as a very promising technique[2],[3]. This technique uses optical phase conjugator(OPC) for compensating distorted signals in midway of total transmission length. Theoretically, nonlinearity cancellation by MSSI requires a perfectly symmetrical distribution of power and local dispersion with respect to OPC position. Owing to the presence of fiber attenuation, this condition cannot be satisfied in real transmission 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[4], or special fibers[5], or high-power Raman distributed amplification[6].

A semiconductor laser directly modulated by signal generates the optical pulse with initial frequency chirp in IM/DD system. It is necessary to analyze the system performance considering optical pulses initial frequency chirp in IM/DD WDM system with the compensation method such as MSSI, because frequency chirp effect became another origin of performance deterioration[7].

The optical pulse with initial frequency chirp is compensated by applying MSSI to WDM system, and it was confirmed that RZ format is more suited for long-haul transmission in WDM system with small fiber dispersion coefficient, on the other hand NRZ format is more suited for that system with large fiber dispersion coefficient. But, there is a remarkable difference of each channels compensation extents, depending on the initial frequency chirp[8].

Therefore, the optimal position of OPC for excellently compensating overall distorted WDM signals with initial frequency chirp is numerically investigated in this paper, for allowing nonlinearity cancellation with no other required equipment than an OPC. The considered system has 8 WDM channels of 40 Gbps. The intensity modulation format is assumed to be NRZ, or RZ. The initial frequency chirp is assumed to be -1.0 or $+1.0$, respectively. The split-step Fourier method[9] 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, XPM of inter-channels is neglected and FWM can be suppressed by using unequal channel spacing scheme[10].

Ⅱ. Modeling of 8×40 Gbps WDM System

Consider eight 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

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power. $A_j(z, t)$ satisfies the following equation[9] .

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

where j, k, l = 1, 2, ⋯, 8($j \neq k \neq l$), 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 $T=t-z/v_j$, respectively. The last two terms in equation (1) induce SPM and XPM, respectively. The last term, that is XPM term is neglected in order to simplify numerical analysis in this paper.

Fig. 1(a) shows a configuration of IM/DD WDM system with OPC placed at mid-way of total transmission length. And, Fig. 1(b) shows a transmission line configuration searching for optimal OPC position. In Fig. 1(b), OPC placed at a distance z_{OPC} from the transmitter. Total transmission length (L) is assumed to be 1,000 km and this will be divided two sections of respective length L_1 and L_2(with $L=L_1+L_2$). If position offset of OPC from mid-span position(z_{mid}) is presented as $\Delta z=z_{OPC}-z_{mid}$, L_1 will be $L/2+\Delta z$ and L_2 will be $L/2-\Delta z$, respectively. EOP of each channel will be investigated as a function of Δz, in following section Ⅲ.

Each laser diode in transmitter is externally modulated by an independent 40 Gbps 128(=2^7) pseudo random bit sequence(PRBS). And output electric field of NRZ orRZ format signal from external optical modulator is assumed to be second-order super-Gaussian pulse as following equation,

$$A(0,t) = \sqrt{P_0}\,\exp\left[-\frac{(1+iC)}{2}\left(\frac{t}{t_0}\right)^{2m}\right] \tag{2}$$

where P_0 is the input light power, m is the order of optical pulse, t_0 is the half-width[9]. And, C is a chirp parameter, which presents a frequency variation of external optical modulator or laser diode directly modulated by data, as following equation (3)[11]. In this paper, chirp parameter is assumed to be down-chirp of −1.0, up-chirp of +1.0, respectively. Table 1 summarizes simulation parameters of fiber and receiver[12], respectively.

$$C = \frac{\frac{dArg(A_0)}{dt}}{\frac{1}{|A_0|}\frac{d|A_0|}{dt}} \tag{3}$$

Fig. 2 shows the configuration of the OPC using highly-nonlinear dispersion shifted fiber(HNL-DSF), and Table 2 summarizes OPC parameters in this approach.

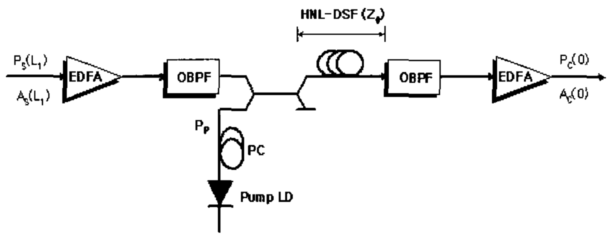
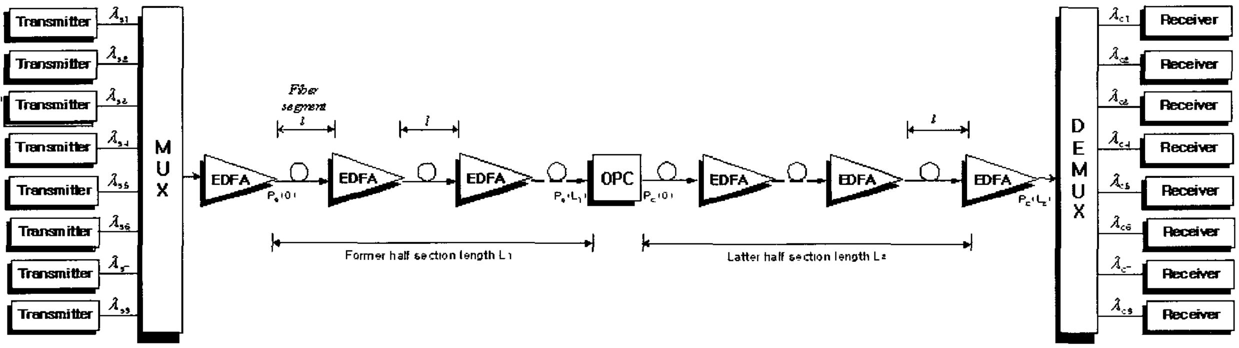
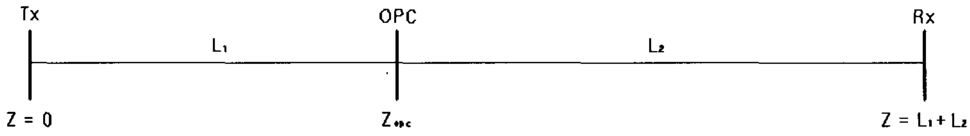


Fig. 2. Optical phase conjugator using highly-nonlinear dispersion shifted fiber.



(a) MSSI systems



(b) Transmission line configuration for optimal OPC position

Fig. 1. Simulation model.

Table 1. Simulation parameters of transmitter, fiber and receiver.

Parameters		Symbol & value
Fiber	Type	conventional DSF
	Loss	$\alpha_1=\alpha_2=0.2$ dB/km
	Total transmission length	1,000 km
	Averaged dispersion coefficient	$D_{11}=D_{12}=$ 0.4, 1.6 ps/nm/km
	Nonlinear refractive coefficient	$n_2=2.36\times10^{-26}$ $\mathrm{km^2/W}$
	Effective core section	$A_{eff}=50$ $\mu\mathrm{m}^2$
	Number of EDFA	20
	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	$0.65\times R_b$

Table 2. Simulation parameters of OPC using HNL-DSF.

Parameters	Symbol & value
Loss	$\alpha_0=0.61$ dB/km
Nonlinear coefficient	$\gamma_0=20.4$ $\mathrm{W^{-1}\ km^{-1}}$
Length	$z_o=0.75$ km
Zero dispersion wavelength	$\lambda_0=1550.0$ nm
Dispersion slope	$dD_o/d\lambda=0.032$ $\mathrm{ps/nm^2/km}$
Pump light wavelength	$\lambda_p=1549.5$ nm
Pump light power	$P_p=18.5$ dBm

The conversion efficiency η is defined as a ratio of the four-wave mixing(FWM) product power to the input probe(signal) power[13]. The calculated highest value of η using table 2 parameters is 0.18 dB, and 3-dB bandwidth is 34 nm(1532.5～1566.5 nm)[14].

The unequal channel spacing proposed by F. Forghieri *et al.* is used 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.

The evaluation of optimal OPC position for NRZ format and RZ format transmission will be accomplished in WDM system with large dispersion coefficient(D=1.6 ps/nm/km) and small dispersion coefficient (D=0.4 ps/nm/km), respectively. Because, in case of MSSI, RZ format is more suited for long-haul transmission in WDM system with small fiber dispersion coefficient, on the other hand NRZ format is more suited to the reverse case[8].

Ⅲ. Simulation Results and Discussion

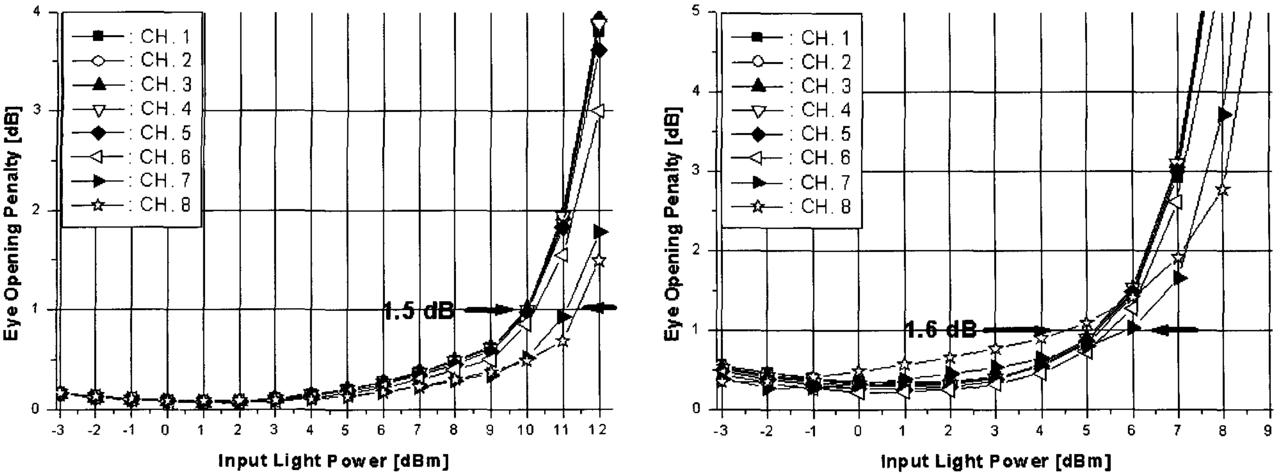
Fig. 3 shows EOP as a function of the input signal light power when each channels with C=0 or −1 or +1 is propagated in MSSI system with 0.4 ps/nm/km or 1.6 ps/nm/km dispersion coefficient, respectively. If 1 dB EOP is allowed, in both case of transmitting NRZ and RZ format with initial frequency chirp, the maximum tolerable input power of overall channels are reduced than that of the chirp-free cases(C=0). Moreover, the power penalty of inter-channel is largely increased, except for the case of transmitting RZ format with C=−1.0 in D=0.4 ps/nm/km.

Fig. 4 shows EOP of channel 1 and channel 8(or 7) as a function of OPC position offset(Δz) at input signal light power resulting 1 dB EOP in case of Fig. 3(c)~(f). It is shown that the compensation extents dependence on Δz are obviously distinguished as input light power and wavelength of transmission channel are changed. This fact means that the OPC position best compensating overall WDM channels with initial frequency chirp is shifted from the mid-way of total transmission length.

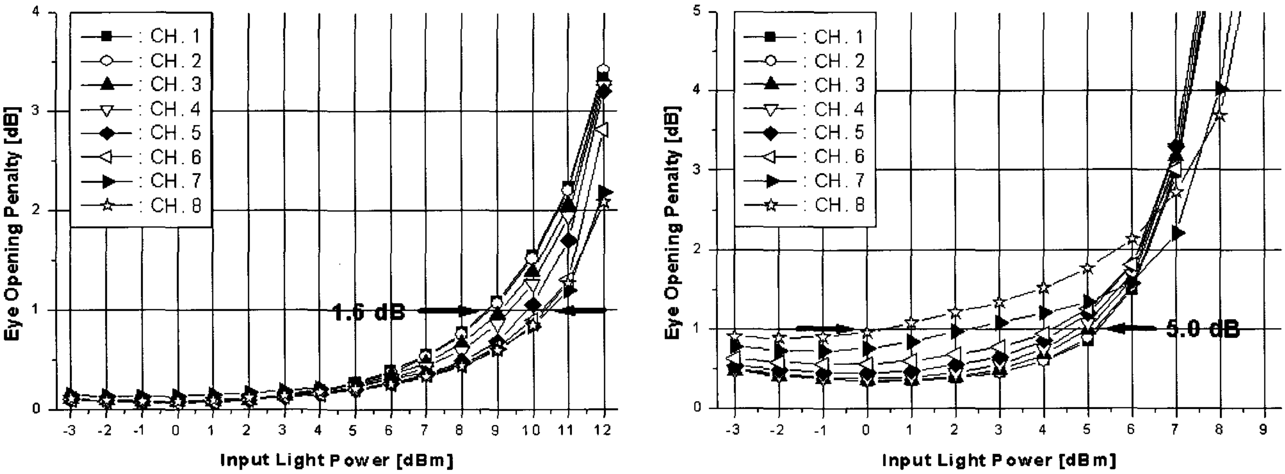
The optimal position of OPC in all case is marked in Fig. 4 as the arrow symbol. It is shown that the optimal OPC positions are 482 km(Δz=−18 km) and 489 km (Δz=−11 km) in D=0.4 ps/nm/km for transmission of RZ format signals with C=−1.0 and C=+1.0, respectively. And the optimal OPC positions are 495 km(Δz=−5 km) in D=1.6 ps/nm/km for all transmission of NRZ format signals with C=−1.0 and C=+1.0.

Fig. 5 shows EOP of overall channels propagated in WDM system with OPC placed at optimal position resulted from Fig. 4. Comparing Fig. 5 with Fig. 3(c) ~(e), the input light power will increase by maximum 7 dB and power penalty of inter-channel will decrease almost 1 dB as following Table 3, if the OPC position was shifted from mid-way of total transmission length dependence on the initial frequency chirp as well as modulation format and fiber dispersion coefficient.

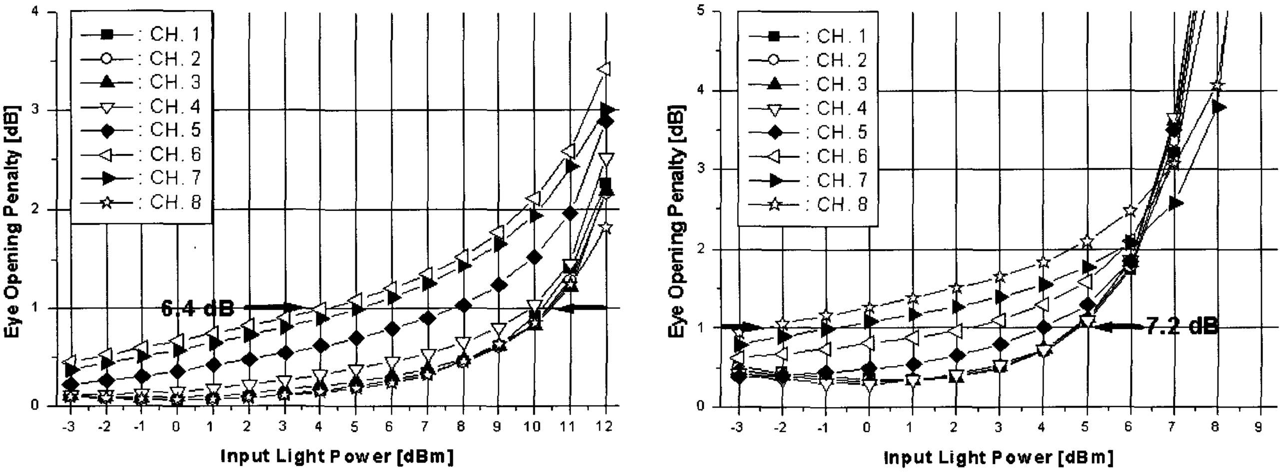
The results obtained from OPC position shift are similar to that of the chirp-free cases(Fig. 3(a) and (b)). This means that it is possible to cancel the performance degradation owing to the initial frequency chirp by



(a) C=0 ; RZ ; D=0.4 ps/nm/km (b) C=0 ; NRZ ; D=1.6 ps/nm/km



(c) C= − 1.0 ; RZ ; D=0.4 ps/nm/km (d) C= − 1.0 ; NRZ ; D=1.6 ps/nm/km

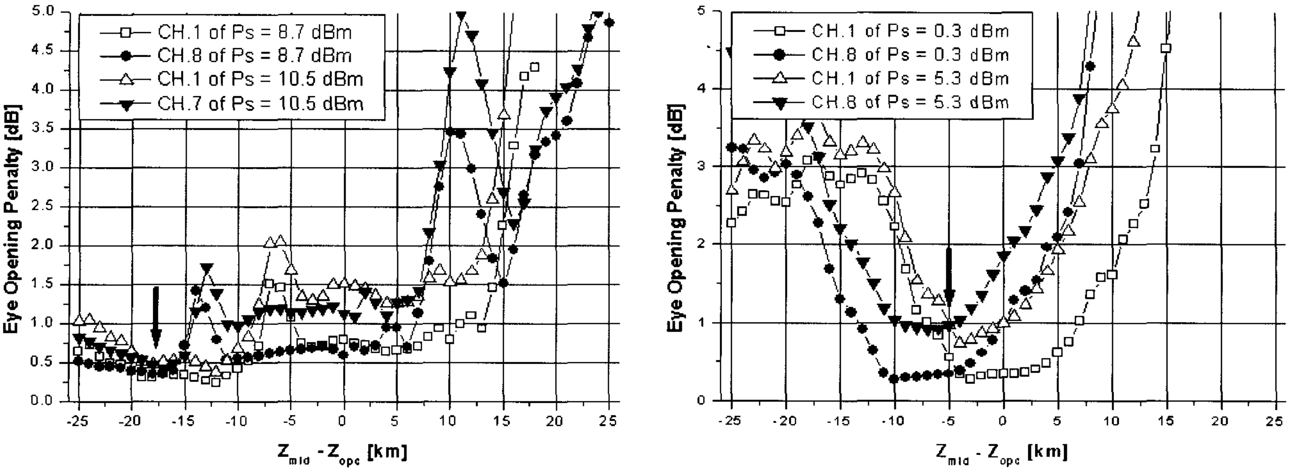


(e) C=+1.0 ; RZ ; D=0.4 ps/nm/km (f) C=+1.0 ; NRZ ; D=1.6 ps/nm/km

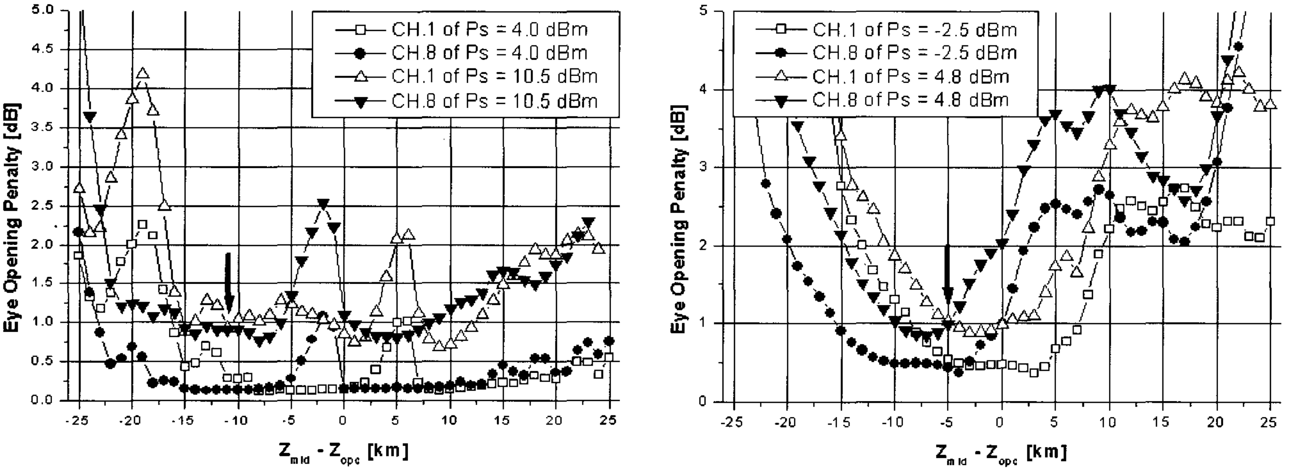
Fig. 3. EOP as a function of input light power for WDM system with MSSI method.

shifting OPC position from mid-way of total transmission length in WDM channel transmission with initial frequency chirp.

From Fig. 5(b) and (d), the optimal OPC positions are 495 km in all cases of transmitting NRZ format independent of chirp value. Furthermore, this optimal OPC



(a) $C=-1.0$; RZ ; D=0.4 ps/nm/km (b) $C=-1.0$; NRZ ; D=1.6 ps/nm/km



(c) $C=+1.0$; RZ ; D=0.4 ps/nm/km (d) $C=+1.0$; NRZ ; D=1.6 ps/nm/km

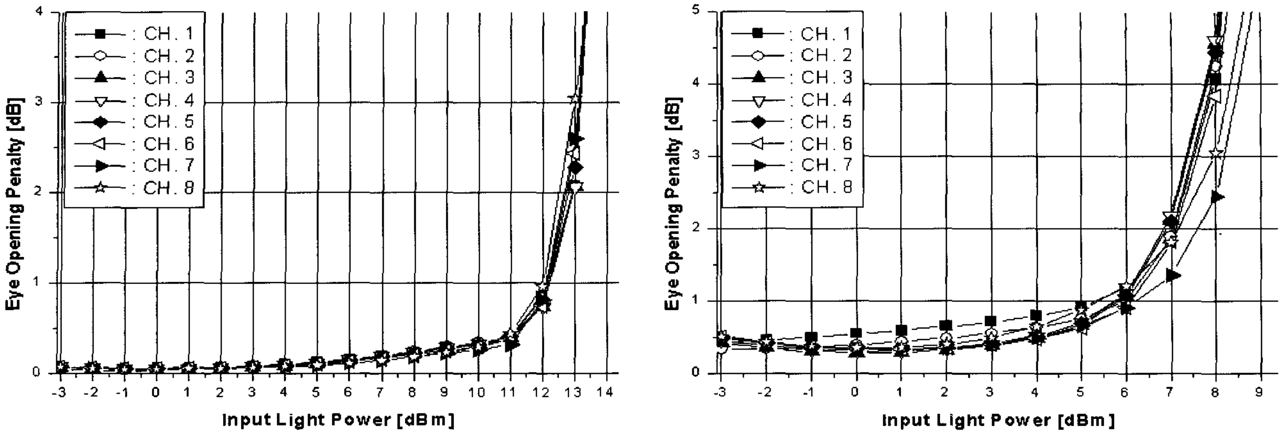
Fig. 4. EOP of channel 1 and 8(or 7) as a function of OPC position offset.

position is equal to that in case of $C=0$[15]. This is resulted by a fact that NRZ format is less affected by initial frequency chirp even when the large dispersion fiber used in WDM system[8].

Consequently, it is necessary to shift the OPC position from mid-way of total transmission length in order to cancel the compensation degradation due to the slight difference of dispersion parameter of second half section(β_{22}) from that of first half section(β_{21}), owing to the wavelength shift of phase-conjugated signal in MSSI system. And, the initial frequency chirp as well as sideband modulation instability[16] is added to the above effect. Particularly, the OPC position is largely shifted from the mid-way of total transmission length, when RZ format is used as modulation format.

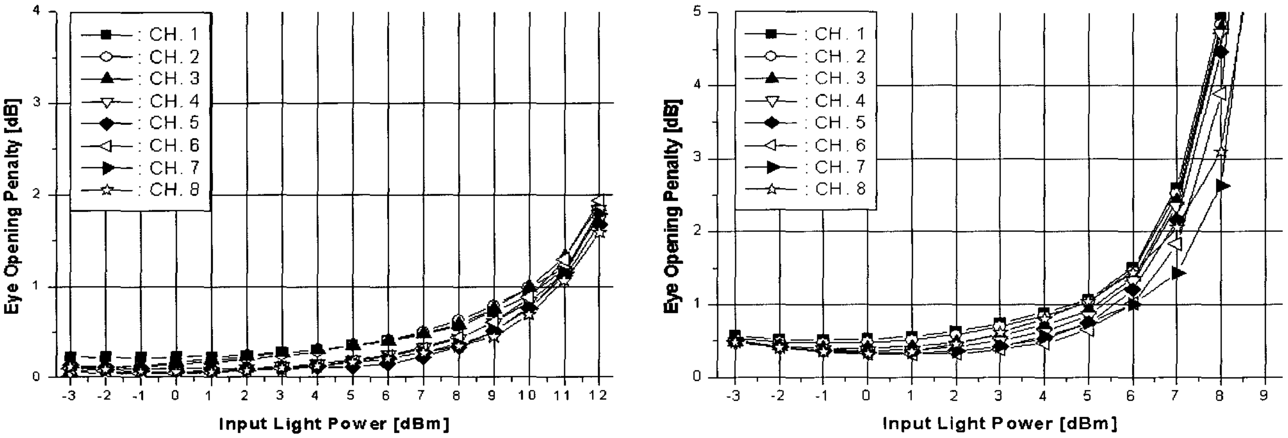
Table 3. The comparison of performance in cases of OPC placed at the mid-span and the optimal position.

Performance	Case	C = −1.0		C = +1.0	
		RZ ; D=0.4 ps/nm/km	NRZ ; D=1.6 ps/nm/km	RZ ; D=0.4 ps/nm/km	NRZ ; D=1.6 ps/nm/km
Maximum input light power [dBm]	MSSI	8.8	0.4	4.2	- 2.5
	Optimal position	12.0	5.4	10.1	4.6
Power penalty [dB]	MSSI	1.6	5.0	6.4	7.2
	Optimal position	0.3	1.0	1.0	1.2



(a) $C=-1.0$; RZ ; $D=0.4$ ps/nm/km

(b) $C=-1.0$; NRZ ; $D=1.6$ ps/nm/km



(c) $C=+1.0$; RZ ; $D=0.4$ ps/nm/km

(d) $C=+1.0$; NRZ ; $D=1.6$ ps/nm/km

Fig. 5. EOP as a function of input light power when OPC is placed at non-midway((a) at $\Delta z=-18$ km, (b) at $\Delta z=-5$ km, (c) at $\Delta z=-11$ km, and (d) at $\Delta z=-5$ km, respectively).

Ⅳ. Conclusion

Up to now, the optimal position of OPC excellently compensating distorted WDM signals with initial frequency chirp is investigated in various 40 Gbps × 8 channel WDM systems.

It was confirmed that, in WDM transmission with initial frequency, the optimal position of OPC is shifted from mid-way of total transmission length, because of the dispersion difference between both fiber section, the effect of sideband modulation instability and initial frequency chirp. That is, using OPC position shift dependence on modulation format and fiber dispersion coefficient, it is possible to cancel the performance degradation owing to the initial frequency chirp. Particularly, the OPC position is largely shifted from the mid-way of total transmission length, when RZ format is used as modulation format.

Using proposed configuration, it is possible to remove all in-line dispersion compensator, reducing span losses and system costs in the long-haul broadband WDM systems.

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