Compensation for Distorted Signals by using Optimal Pump Light Power in WDM Systems with Non-midway Optical Phase Conjugator

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ABSTRACT

In this paper, the optimal pump light power of optical phase conjugator (OPC) and the compensation characteristics of distorted WDM channel signals are numerically investigated, when the OPC with highly-nonlinear dispersion shifted fiber (HNL-DSF) not be placed at the mid-way of total transmission length. The total dispersion of former half section and latter half section is assumed to be same each other in this approach. It is confirmed that, in WDM transmission systems with OPC deviated from the mid-way, the pump light power for best compensation must be flexible selected depending on the OPC position. This optimal pump light power is gradually increased as the OPC is gradually closer to the receiver. Consequently, it is possible to establish the compensation system independent on the OPC position by setting optimal pump light power connected with the OPC position.

Key Words : Optical phase conjugator (OPC), Highly-nonlinear dispersion shifted fiber (HNL-DSF), Optimal pump light power, Mid-span spectral inversion (MSSI)

Ⅰ. Introduction

In long-distance high bit-rate transmission systems, nonlinear waveform distortion owing to the interplay between group-velocity dispersion (GVD) and Kerr effect of transmission fibers limits the transmission capacity of the systems[1],[2]. To overcome such limitations, mid-span spectral inversion (MSSI) using mid-way optical phase conjugator (OPC) was proposed[3], and has now become one of the promising techniques as an alternative to the more-sophisticated soliton transmission system.

It was confirmed that wideband WDM signals with excellent performance could be transmitted by using highly-nonlinear dispersion shifted fiber (HNL-DSF) instead of conventional DSF as a nonlinear medium of OPC in previous researches[4],[5]. In those researches, it is possible to widely compensate the distorted WDM channels by properly selecting pump light power dependence on total transmission length and fiber dispersion coefficient.

In this paper, the optimal pump light power of OPC and the compensation characteristics of distorted WDM channel signals are numerically investigated, when the OPC with HNL-DSF not be placed at the mid-way of total transmission length (this system is referred to non-midway OPC system below) for verifying availability of OPC. The total dispersion of former half section (fiber section from transmitter to OPC) and latter half section (fiber section from OPC to receiver) is assumed to be same each other. The compensation quality of non-midway OPC system is evaluated by comparing with that of MSSI system (namely, mid-way OPC system).

The considered WDM system has 8 channels of 40 Gbps. The intensity modulation format is assumed to be NRZ, or RZ. The split-step Fourier method[6] is used for numerical simulation and eye-opening penalty (EOP) is used to evaluate the degree of distortion compensation. In order to

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simplify the analysis, cross phase modulation (XPM) of inter-channels is neglected and fourwave mixing (FWM) can be suppressed by using unequal channel spacing scheme[7].

Ⅱ. Modeling of 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 power. $A_j(z, t)$ satisfies the following equation[6] :

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

where $j, k, l = 1, 2, \cdots, 8 (j \neq k \neq l)$, 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.

Watanabe and Shirasaki generalized the MSSI by considering that above fiber parameters can be functions of distance z[8]. The general condition for perfect distortion compensation is shown to be

$$\frac{\beta_2(-z_1')}{\gamma(-z_1')P(-z_1')} = \frac{\beta_2(z_2')}{\gamma(z_2')P(z_2')} \tag{2}$$

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. This relation gives the following possible fact : The OPC need not be placed at the mid-way of total transmission length. Assume that the GVD value, the power, and the length of former half section are β_{21}, P_s and L_1, respectively, and those of latter half section are β_{22}, P_c and L_2. It is found that equation (2) holds provided that $\beta_{22} = k\beta_{21}$, $P_c = kP_s$ and $L_1 = kL_2$.

Fig. 1 shows a configuration of intensity modulation/ direct detection (IM/DD) WDM system with OPC placed at non-midway of total transmission length. In Fig. 1, 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 $L=L_1+L_2$). The k values are assumed to be 0.05, 0.11, 0.33, *etc.* such as Table 1, in order order to evaluate and compare compensation extents of non-midway OPC system and MSSI system (case 5 in table 1). And, Table 1 also includes the resultant parameters depending on k .

Table 2 summarizes simulation parameters of transmitter[6], receiver[9] and the other parameters of fiber except that of listed in Table 1, respectively.

Fig. 2 shows the configuration of the OPC using highly-nonlinear dispersion shifted fiber

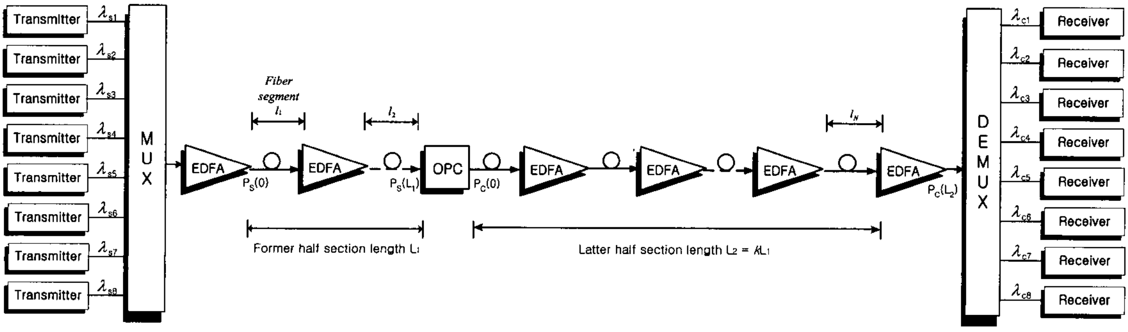


Fig. 1 Simulation model of 8×40 Gbps WDM system

Table 1. Parameters of transmission line

Case	The k value	L_1 [km]	L_2 [km]	Total dispersion of each section [ps/nm]	Dispersion coefficient of former half section [ps/nm/km]	Dispersion coefficient of latter half section [ps/nm/km]
1	0.05	50	950	80	1.600	0.084
				160	3.200	0.168
2	0.11	100	900	80	0.800	0.089
				160	1.600	0.178
3	0.25	200	800	80	0.400	0.100
				160	0.800	0.200
4	0.33	250	750	80	0.320	0.107
				160	0.640	0.213
5	0.67	400	600	80	0.200	0.134
				160	0.400	0.267
6	1.00	500	500	80	0.160	0.160
				160	0.320	0.320
7	1.50	600	400	80	0.134	0.200
				160	0.267	0.400
8	3.00	750	250	80	0.107	0.320
				160	0.213	0.640
9	4.00	800	200	80	0.100	0.400
				160	0.200	0.800
10	9.00	900	100	80	0.089	0.800
				160	0.178	1.600
11	19.0	950	50	80	0.084	1.600
				160	0.168	3.200

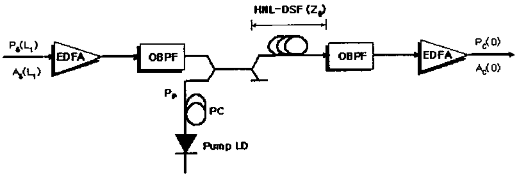


Fig. 2 Configuration of OPC using HNL-DSF

(HNL-DSF), and Table 3 summarizes OPC parameters in this approach. The conversion efficiency η is defined as a ratio of the four-wave mixing (FWM) product power to the input probe (signal) power[10]. 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)[4].

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.

Table 2. Simulation parameters of transmitter, fiber and receiver.

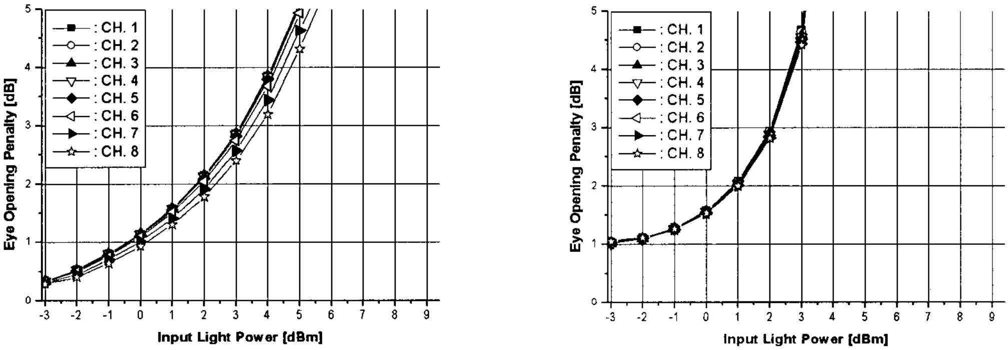
Parameters		Symbol & value
Trans-mitter	Bit rate	R_b=320 Gbps (=8×40 Gbps)
	Waveform	NRZ super-Gaussian(m=2) RZ super-Gaussian(m=2)
	Pattern	PRBS 2^7 (128 bits)
	Chirp	0
Fiber	Type	conventional DSF
	Loss	α_1=α_2=0.2 dB/km
	Dispersion coefficient	D_{l1}=D_{l2}=0.4, 1.6 ps/nm/km
	Nonlinear refractive coefficient	n_2=2.36×10^{-26} km^2/W
	Effective core section	A_{eff}=50 μm^2
	Number of EDFA	20
	EDFA spacing (Fiber section)	l=50 km
Recei-ver	Type	PIN-PD with EDFA pre-amp
	EDFA noise figure	5 dB
	Optical bandwidth	1 nm
	Receiver bandwidth	0.65×R$_b$

Table 3. Simulation parameters of OPC using HNL-DSF.

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

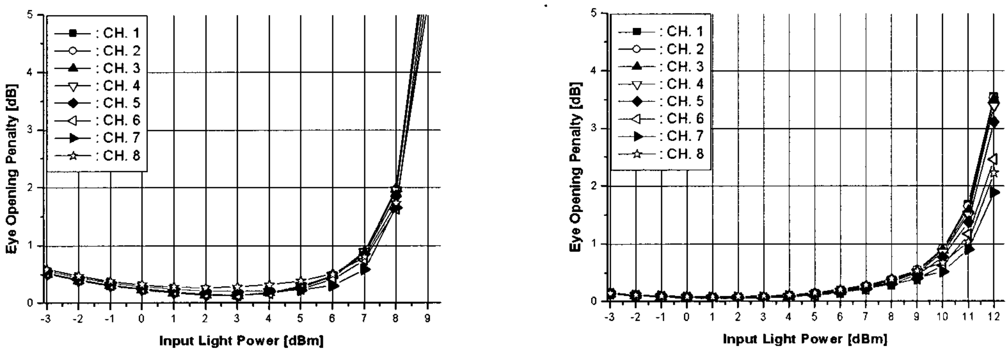
Ⅲ. Simulation results and discussion

From the previous research[4], it was confirmed that the optimal pump light power of OPC using HNL-DSF is 18.5 dBm for transmitting NRZ format or RZ format in 1,000 km WDM system with MSSI method, which make the power conversion ratio R_p (the conjugated light power to the input light power ratio) almost 0.95. The reason why the pump light power is selected to be



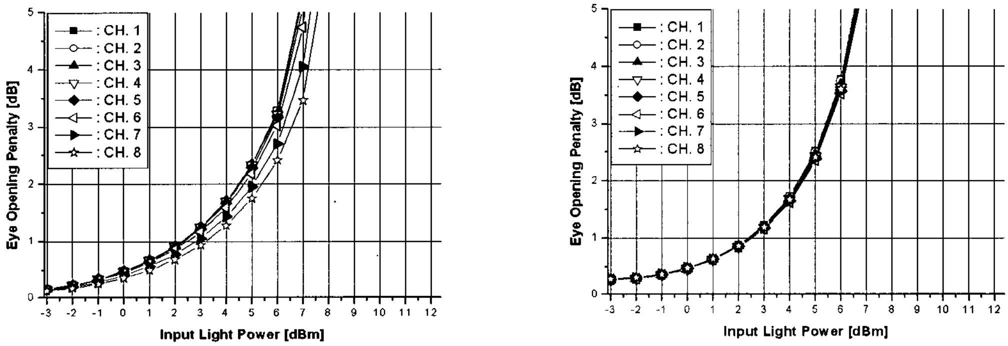
(a) NRZ ; case 1 ; Total dispersion = 80 ps/nm

(b) NRZ ; case 11 ; Total dispersion = 80 ps/nm



(c) NRZ ; case 6 ; Total dispersion = 80 ps/nm

(d) RZ ; case 6 ; Total dispersion = 160 ps/nm



(e) RZ ; case 1 ; Total dispersion = 160 ps/nm

(f) RZ ; case 11 ; Total dispersion = 160 ps/nm

Fig. 3 EOP as a function of input light power in several cases of table 1 when the pump light power of OPC is 18.5 dBm

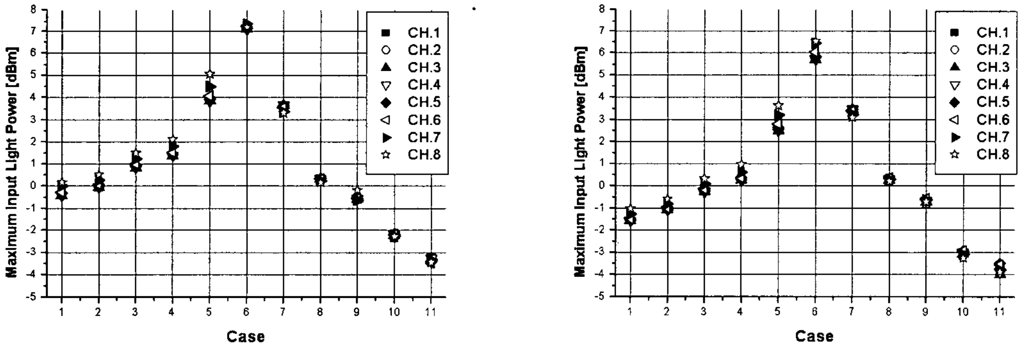
$R_p \approx 0.95$ is that the dispersion coefficient of latter half section (β_{22}) is slightly different to that of first half section (β_{21}).

Fig. 3 shows EOP as a function of the input signal light power in case 1, 6(MSSI), and 11 of table 1, respectively, when the pump light power of OPC is selected to be 18.5 dBm. It is confirmed that, if 1 dB EOP is allowed for the reception performance criterion, the maximum input light power is decreased than that of MSSI, when OPC placed at non-midway.

Fig. 4 shows the maximum input light power resulting 1 dB EOP when the pump light power is 18.5 dBm in all cases of table 1. The values in x-axis of Fig. 4 present 11 cases of table 1, respectively. The data plotted in Fig. 4 are extracted from the graphs that input light power versus EOP like as Fig. 3. It is confirmed that the maximum input light power is gradually decreased as the position of OPC was gradually deviated from the mid-way. And, the power penalties of inter-channel in the pre-compensation cases (case 1~5) are larger than that of the post-compensation cases (case 7~11).

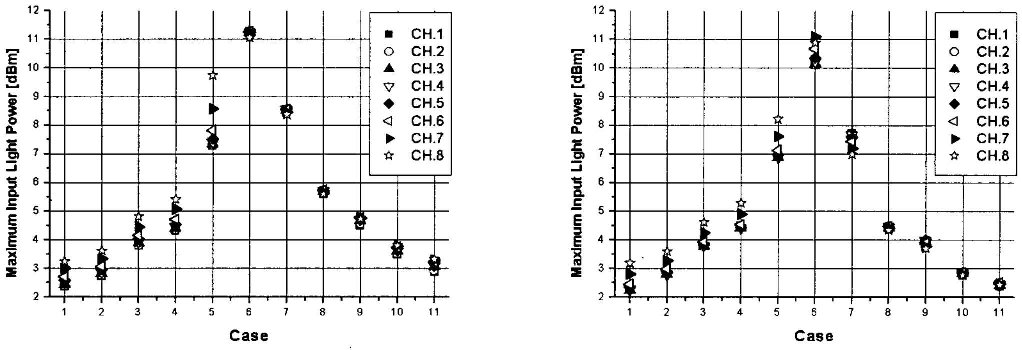
These results mean that, if the position of OPC was deviated from the mid-way, the optimal pump light power of OPC is altered from 18.5 dBm, which is the optimal pump light power in MSSI. That is, it will be expected to improve the allowed input light power and the power penalty of inter-channel only by selecting the optimal pump light power, because total dispersion of the latter half fiber section related to the k value in equation (2) was selected to equal with that of the former half fiber sections.

Fig. 5 shows EOP of channel 1 and 8 as a function of the pump light power of OPC in several cases of table 1. The selected input light power (P_s) is the power resulting 1 dB EOP in the corresponding case of Fig. 4. The pump light powers that resulting the minimum EOP and simultaneously the minimum EOP difference be-



(a) NRZ ; Total dispersion = 80 ps/nm

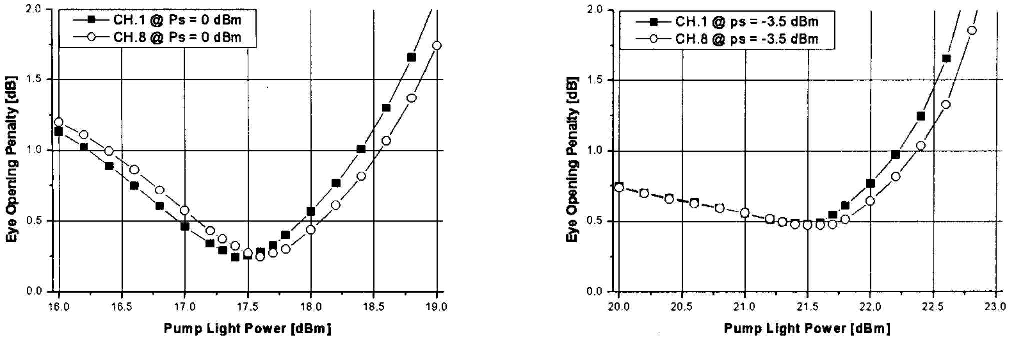
(b) NRZ ; Total dispersion = 160 ps/nm



(c) RZ ; Total dispersion = 80 ps/nm

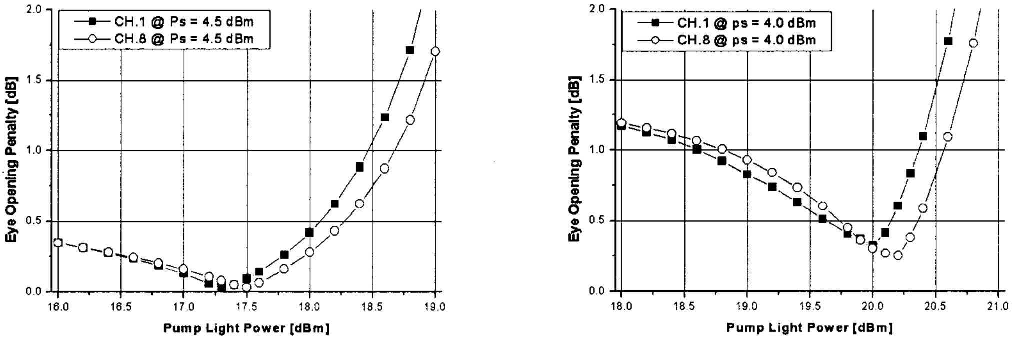
(d) RZ ; Total dispersion = 160 ps/nm

Fig. 4. The maximum input light power resulting 1 dB EOP of all cases presented in table 1



(a) NRZ ; case 1 ; Total dispersion = 80 ps/nm

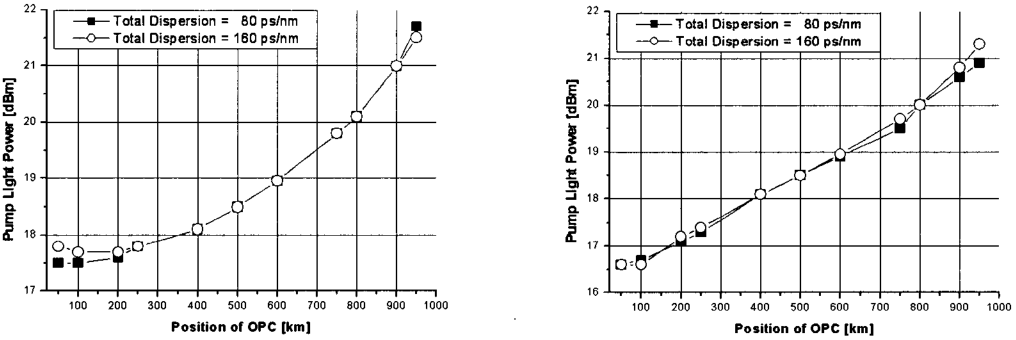
(b) NRZ ; case 11 ; Total dispersion = 160 ps/nm



(c) RZ ; case 4 ; Total dispersion = 80 ps/nm

(d) RZ ; case 9 ; Total dispersion = 160 ps/nm

Fig. 5. EOP as a function of pump light power of OPC in several cases of table 1



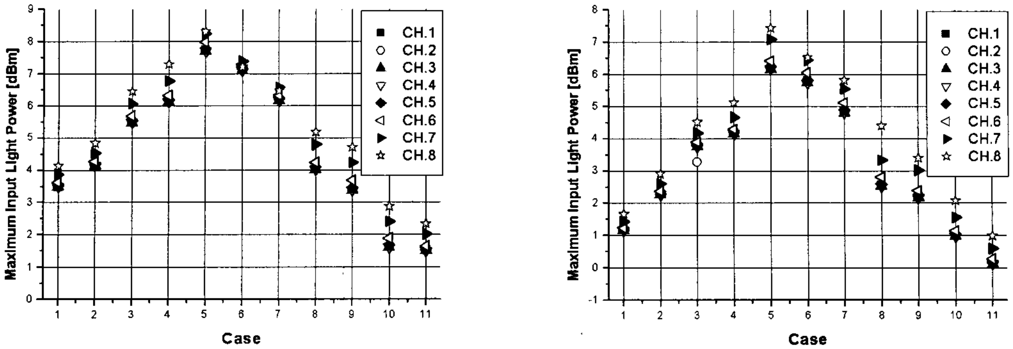
(a) The case of transmitting NRZ format

(b) The case of transmitting RZ format

Fig. 6. The optimal pump light power dependence on OPC position

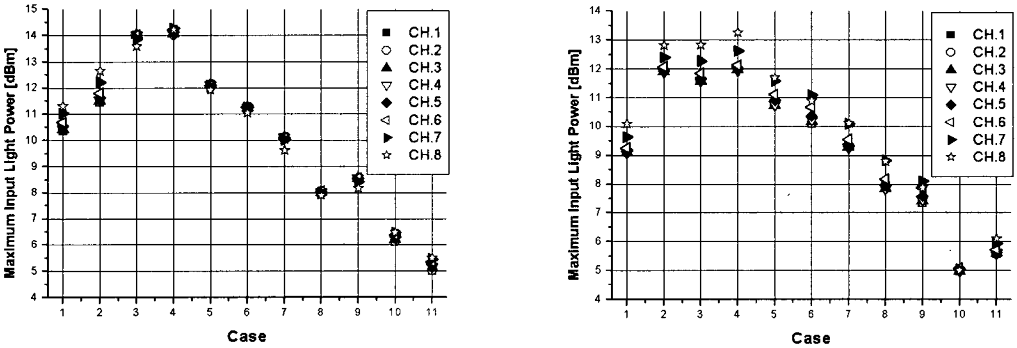
tween the two channels (this pump light power is referred to the optimal pump light power) are 17.5 dBm and 21.5 dBm when OPC are placed at 50 km of 80 ps/nm total dispersion and 950 km of 160 ps/nm total dispersion, respectively, in cases of transmitting NRZ format. And, the optimal pump light powers are 17.4 dBm and 20.0 dBm when OPC are placed at 250 km of 80 ps/nm total dispersion and 800 km of 160 ps/nm total dispersion, respectively, in cases of transmitting RZ format.

Fig. 7 shows the maximum input light power resulting 1 dB EOP, when the pump light powers are replaced to the values plotted in Fig. 6 from 18.5 dBm. It is confirmed that the maximum input light power for all cases are improved than that of Fig. 4 cases, namely, the uniform pump light power independence on the OPC position. Exactly, for transmitting NRZ format in 80 ps/nm total dispersion and 160 ps/nm WDM system, the



(a) NRZ ; Total dispersion = 80 ps/nm

(b) NRZ ; Total dispersion = 160 ps/nm



(c) RZ ; Total dispersion = 80 ps/nm

(d) RZ ; Total dispersion = 160 ps/nm

Fig. 7. The maximum input light power resulting 1 dB EOP, when the pump light powers are replaced to the values plotted in Fig. 6 from 18.5 dBm

maximum input light powers are increased to almost 3~5 dB and 3~4 dB by using the optimal pump light power suited to the OPC position, respectively. And, for transmitting RZ format in 80 ps/nm total dispersion and 160 ps/nm WDM system, the maximum input light powers are increased to almost 1~11 dB and 2~9 dB by using the optimal pump light power suited to the OPC position, respectively.

The important points to be confirmed are that ; first, the compensation extents in the pre-compensation systems with the optimal pump light power are better than that in the post-compensation systems in both cases of NRZ and RZ transmission. And, the best compensation is presented in case 5 (the OPC is placed at 400 km) and case 4 (the OPC is placed at 250 km) for transmitting NRZ format and RZ format, respectively. Furthermore, the compensation extents of these cases are superior to that of MSSI (case 5).

The first result means that the OPC with optimally-controlled pump light power is more available to compensate overall channels transmitted in the pre-compensation WDM system rather than in post-compensation WDM system. The second result is generated from the following reason : for excellently compensating the distorted WDM channels, the OPC position must to be shifted from mid-way, and simultaneously the OPC must have optimal pump light power dependence on the OPC position, because of the slight difference of dispersion parameter at 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.

Ⅳ. Conclusion

Up to now, the optimal pump light power of OPC and the compensation characteristics of distorted WDM channel signals are numerically investigated in condition of the optimal pump light power, when the OPC not be placed at the mid-way of total transmission length.

First, it is confirmed that, in WDM transmission systems with OPC deviated from the mid-way, the pump light power for best compensation must be flexible selected depending on the OPC position. This optimal pump light power is gradually increased as the OPC is gradually closer to the receiver in both cases of NRZ transmission and RZ transmission. And, it is confirmed that, by using the optimal pump light power in non-midway OPC system, the compensation extents is improved than that in WDM systems with the fixed pump light power. Consequently, it is not always apply the OPC to MSSI systems. In other word, the OPC is also applied to the non-midway systems under the optimal pump light power condition of OPC.

Therefore, it is possible to construct the compensation system independent on the OPC position by setting optimal pump light power to minimize the optical pulse distortion.

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