Compensation of the Distorted 640 Gbps WDM Signals using Optical Phase Conjugator

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Abstract—The numerical methods for finding the optimal parameters in 640 Gbps (16 channels × 40 Gbps) WDM system with optical phase conjugator (OPC) are proposed, which effectively compensate the distorted overall WDM channels. The considered optimal parameters are the OPC position and the dispersion coefficient of fibers. The numerical approaches are accomplished through two different procedures. One of these procedures is that the optimal OPC position is previously searched and then the optimal dispersion coefficient is searched at the obtained optimal OPC position. The other is the reverse of the above procedure. From the numerical results, it is confirmed that two optimal parameters depend on each other, but less related with the searching procedure. The methods proposed in this research will be expected to alternate with the method of making a symmetrical distribution of power and local dispersion in real optical link which is a serious problem of applying the OPC into multi-channels WDM system.

Index Terms—Optical Phase Conjugator, MSSI, WDM system, NZ-DSF, Optical Nonlinear Effect

I. INTRODUCTION

Long distance optical fiber communication systems have been realized by using of erbium-doped fiber amplifier (EDFA) [1]. But the bit-rate — distance product is limited by the combined effects of fiber dispersion and nonlinear effects (namely, Kerr effect) due to the high launched power into the fiber [2],[3]. It is required to decrease the limitation of the bit-rate – distance product in optical communication system for transmitting multi-channels with high bit-rate. One of the corresponding techniques to this requirement is mid-span spectral inversion (MSSI). Theoretically, this technique overcomes both self phase modulation (SPM) effect that is one of the nonlinear effects and dispersive effects by using optical phase conjugator (OPC) for compensating distorted signals in mid-way of total transmission length [4].

But, the serious problems have to be solved in order to apply this technique into the multi-channel transmission system with high bit-rate. The first is that a perfectly symmetrical distribution of power and local dispersion with respect to OPC position is formed for nonlinearity cancellation in real transmission links [5]. And, the second is that the OPC must exhibit the similar characteristics over total WDM channels thus the OPC must has the wide and flattened bandwidth for transmitting further numbers of channels with similar reception performance. In addition to these problems, the others of nonlinear effects such as four-wave mixing (FWM) and cross phase modulation (XPM) must also be cancelled.

FWM effect can be suppressed by using unequal channel spacing scheme [6]. But in the unequal channel spacing system the required bandwidth of OPC is more increased than in the equal channel spacing system. Fortunately, this problem is solved 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 [7]. That is, the several problems presented in previous will be expected to solve by using unequal channel spacing scheme within the bandwidth of HNL-DSF OPC.

Nevertheless the above fact, the problem generated from the symmetrical distributions still remains in the perfectly compensating for distorted overall WDM channels. Furthermore it is more difficult to solve this problem by using the common solution for overall channels because these channels with different wave-length copropagate in an optical fiber, even if the symmetrical distribution problem was solved for a special wavelength.

This research focus on the numerical methods of finding the optimal OPC position and the optimal dispersion coefficients of second fiber section which should alternate with the method of making the symmetrical distribution of power and local dispersion in real optical link. That is, the optimal position of OPC and the optimal dispersion coefficient of second fiber section are numerically induced and applied to WDM system with unequally spaced channels. And then, the compensation characteristics of overall WDM channels in the case of using those optimal parameters are investigated, comparing with that in the case of OPC placed at mid-way of total transmission length and the fixed fiber dispersion.

The considered WDM system has 16 channels of 40 Gbps. The intensity modulation format is assumed to be

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NRZ or RZ. The split-step Fourier method [8] is used for numerical simulation. The evaluation parameters of compensation degree are eye-opening penalty (EOP). XPM effect of inter-channels is neglected in order to simplify the analysis.

II. WAVE EVOLUTION AND WDM SYSTEM MODELING

Consider 16 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 [8] :

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

where j, k = 1, 2, ···, 16 ($j \neq k$), 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 effects of XPM on WDM signals are more decreased as the fiber dispersion is larger [9]. XPM effect of inter-channels is neglected in order to simplify the analysis in this research. Because the dispersion coefficients of fiber in this research are assumed to be 1.6 ps/nm/km, which less affect the signal distortions due to XPM.

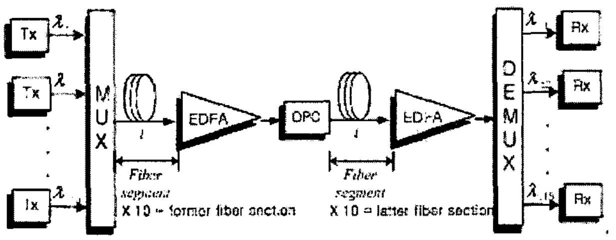


Fig. 1 The configuration of 16×40 Gbps WDM system with OPC.

The configuration of intensity modulation / direct detection (IM/DD) WDM system with OPC is illustrated in Fig. 1. Total transmission length (L = 1,000 km) is divided into two sections of respective length L_1 and L_2 (with $L=L_1+L_2$) and each fiber section consist of 10 fiber segment of length $l=50km$. The L_1 is equal to L_2 in the case of MSSI technique.

Fiber parameters assumed for analysis and numerical simulations throughout this paper are summarized in Table 1 [10].

Table 1 Fiber parameter assumptions.

Parameter	Symbol and values
Type	NZ-DSF
Chromatic Dispersion, D_{11} and D_{12}	1.6 ps/nm/km
Nonlinear refractive index, n_2	2.5×10^{-20} m^2/W
Attenuation, α	0.2 dB/km
Effective core area, A_{eff}	72 μm^2

Each laser diodes in transmitter of 16-channels WDM system depicted in Fig. 1 are assumed to be externally modulated by an independent 40 Gbps 128(=2^7) pseudo random bit sequence (PRBS). And output electric field of NRZ or RZ format signal from external optical modulator is assumed to be second-order super-Gaussian pulse. The direct detection receiver of 16-channels WDM system depicted in Fig. 1 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[11]. The receiver bandwidth is assumed to be 0.65×bit-rate.

Table 2 Simulation parameters of OPC using HNL-DSF.

Parameter	Symbol	Value
Loss	α_0	0.61 dB/km
Nonlinear coefficient	γ_0	20.4 W^{-1} km^{-1}
Length	z_0	0.75 km
Zero dispersion wavelength	λ_0	1550.0 nm
Dispersion slope	$dD_o/d\lambda$	0.032 ps/nm^2/km
Pump light power	P_p	18.5 dBm
Pump light wavelength	λ_p	1549.75 nm

The parameters of OPC using HNL-DSF depicted in Fig. 1 are summarized in Table. 2. The conversion efficiency η of OPC is defined as a ratio of the four-wave mixing (FWM) product power to the input probe (signal) power [12]. The 3-dB band-width of η is obtained to 48 nm (1526~ 1574 nm).

The unequal channel spacing proposed by F. Forghieri *et al.* [6] is used to suppress the crosstalk due to FWM effects in this research. Fig. 2(c) shows the channel allocations using unequal spacing scheme and which is compared with equal spacing scheme (Fig 2(b)). ITU-T recommends that the channel spacing for dense WDM includes 100 GHz (that is 0.8 nm). This channel spacing is divided to 8 frequency deviation df in order to effect-tively allocate wavelengths of 16 channels in unequal spacing scheme. And df is assumed to be 12.5 GHz (that is 0.1 nm) to expand the WDM channel number within 3-dB bandwidth of HNL-DSF OPC. If the channel spacing is to be $W\times df$, W becomes 8 in equal spacing scheme. But, W will be varied to cancel the FWM effect values in unequal spacing scheme. The decision of W value is accomplished under the condition that the selected frequencies of each channel are within each bandwidth of WDM filters. The bandwidth of WDM filters is designed to $\pm 2df$ from each center frequency in order to avoid

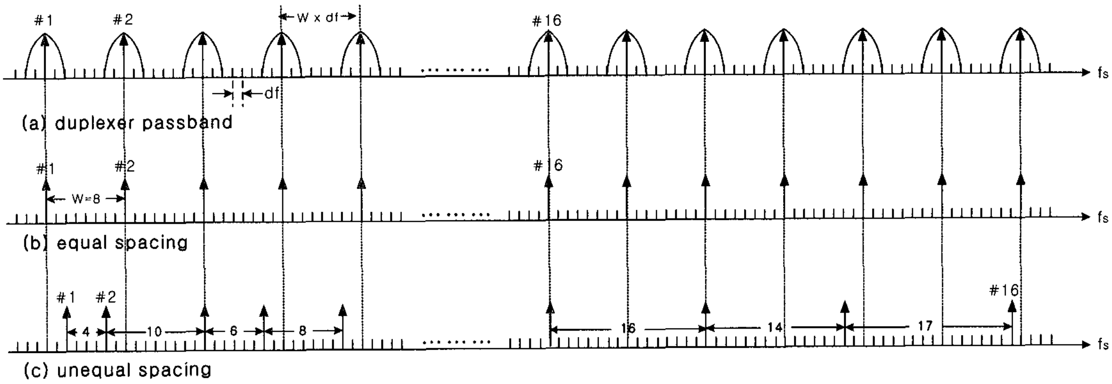


Fig. 2 The scheme of wavelength allocation.

Table 3 The wavelength allocation of 16 channels used in this research.

CH. No.	1	2	3	4	5	6	7	8
W	-	4	10	6	8	9	11	7
Wavelength	1550.2	1550.6	1551.6	1552.2	1553.0	1553.9	1555.0	1555.7
CH. No.	9	10	11	12	13	14	15	16
W	5	12	13	15	18	16	14	17
Wavelength	1556.2	1557.4	1558.7	1561.2	1563.0	1564.6	1566.0	1567.7

interference of channels. Hence setting the minimum permitted channel separation of the proposed unequally spaced allocation is $4df$. And the center wavelength of first WDM filer is assume to be 1550.0 nm. The allocated wavelength of each channel and W used in this research are presented in Table 2.

III. SCHEMES OF SEARCHING OPTIMAL PARAMETER VALUES

Watanabe and Shirasaki generalized the MSSI by considering that above fiber parameters can be functions of distance z[4]. The general condition for perfect distortion compensation is shown to be

$$\frac{\beta_{2j}(-z_1')}{\gamma_j(-z_1')P_j(-z_1')} = \frac{\beta_{2j}(z_2')}{\gamma_j(z_2')P_j(z_2')} \qquad (2)$$

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. That is, the OPC need not be placed at the mid-way of total transmission length and dispersion coefficient of latter half section need not equal with that of former half section which depend on the signal wavelength. However, the equation (2) also means that it is not easy to find the common OPC position and dispersion coefficient of latter half section that is applicable to total allocated WDM wavelengths in real transmission link, because of the distribution of wavelengths in the relative broad band. Thus, this research intended to find the optimal OPC position and dispersion coefficient of latter half section through the numerical approach. The optimal OPC position is found by evaluating the compensation characteristics for special WDM channels as a function of the OPC position (z_{OPC}) varied within one span length (50 km) from the mid-way. The difference between z_{OPC} and z_{mid} ($\Delta z = z_{OPC} - z_{mid}$) is called to the OPC position offset. And the optimal dispersion coefficient of latter half section, D_{12} is also found by evaluating the compensation characteristics for special WDM channels as a function of D_{12} varied within range of 10% of 1.6 ps/nm/km. Here, the dispersion difference between two fiber sections is defined to $\Delta D = D_{12} - D_{11}$ and this is call to the dispersion offset.

IV. RESULTS AND DISCUSSION

The numerical approaches are accomplished by classifying to four and by comparing the obtained results. The first section (section A) presents the simulation results in MSSI, that is the position of OPC is assumed to be placed at mid-way of total transmission length and the dispersion coefficients of both fiber sections are assumed to be equal. The section B shows the simulation results in the modified WDM system with the best OPC position and the best dispersion coefficient of latter half section, those will be minimize EOPs of overall WDM channels. Here, the best OPC position is previously obtained and then the best dispersion coefficient of latter half section is obtained under this OPC position. The section C shows the simulation results obtained from the reverse procedure of that in the section B. That is, the best dispersion coefficient of latter half section is previously obtained and then the best OPC position is obtained under this fiber dispersion. The last section (section D) presents the simulation results in the modified WDM system with the simply combined of the best OPC position obtained in section B and the best dispersion coefficient of latter half section obtained in section C.

A. Simulation results in MSSI

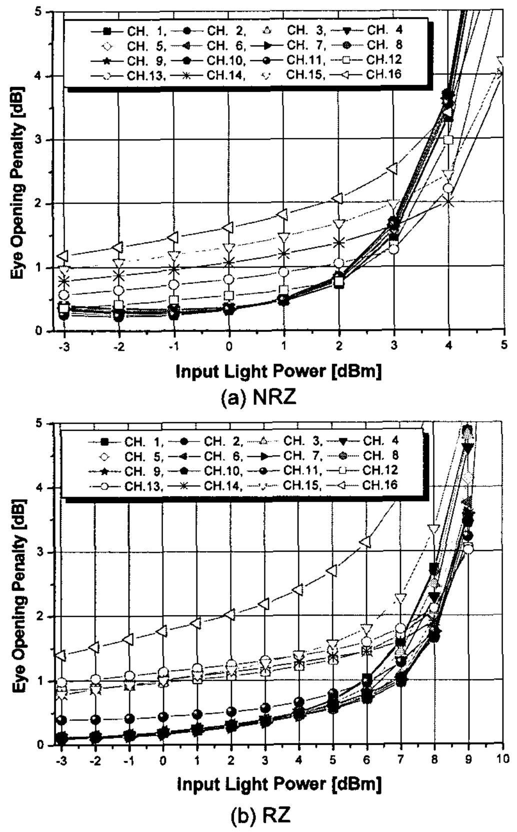


Fig. 3 EOP dependence on the launching power in 16 channels WDM system with MSSI.

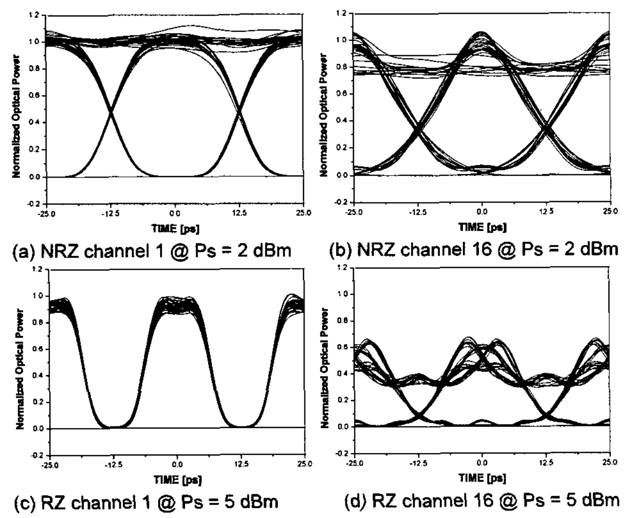


Fig. 4 Eye pattern of several WDM signals in 16 channels WDM system with MSSI.

Fig. 3 shows EOP of overall channels as a function of the launching (input) light power when OPC placed at mid-way of total transmission length and D_{11} and D_{12} are fixed to 1.6 ps/nm/km. And, Fig. 4 shows eye pattern of channel 1 and 16 with 2 dBm and 5 dBm launching power in the cases of NRZ and RZ format transmission, respectively. From Fig. 5 and Fig. 6, it is confirmed that EOPs are more degraded as the signal wavelengths are more deviated from the zero dispersion wavelength of HNL-DSF OPC in both cases of NRZ and RZ transmission. Thus, it is impossible to expand channel numbers in directly applying MSSI using HNL-DSF OPC to WDM systems.

B. Simulation results in the modified WDM system: Case 1

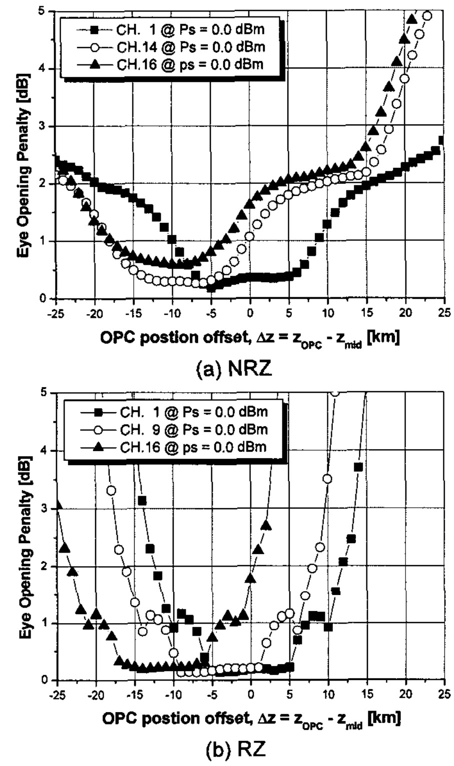
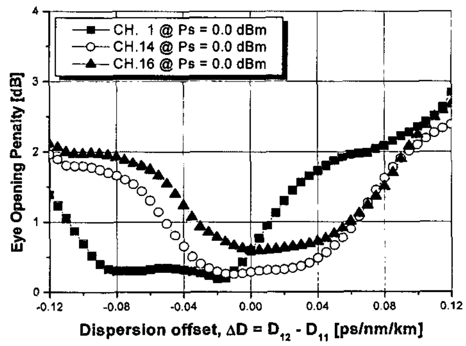
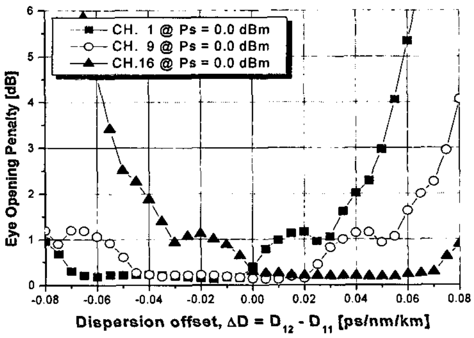


Fig. 5 EOP dependence on the OPC position offset.

Fig. 5 shows EOP of 3 channels dependence on the OPC position offset in order to find the best OPC position. Because channel 1, 14 and 16 in NRZ transmission and channel 1, 9 and 16 in RZ transmission show the different EOP characteristics as the launching light power are increased in Fig. 3, these channels are selected for the evaluation in Fig. 5. If WDM channels had the relatively high launching power, the difference of EOP between channel 1 and 16 depending on the OPC position is so large that is impossible to compare each other. For this reason, the launching power is selected to 0 dBm for both case of NRZ and RZ transmission. From Fig. 5, the OPC positions that result the smallest EOP difference between channels are 492 km for NRZ transmission and 494 km for RZ transmission, respectively. Fig. 6 shows EOP dependence on the dispersion offset when the OPC placed at the position obtained from results of Fig. 5. From Fig. 6, dispersion coefficients of latter half section that result the smallest EOP difference between channels are 1.6 ps/nm/km for NRZ and RZ format transmission.

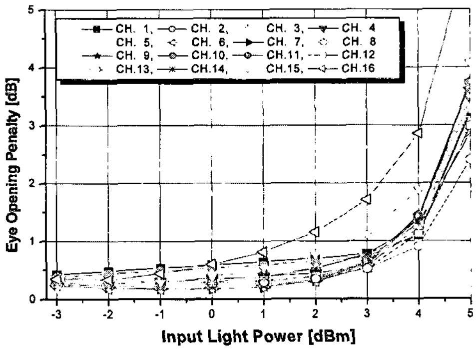


(a) NRZ @ Δz = -8 km

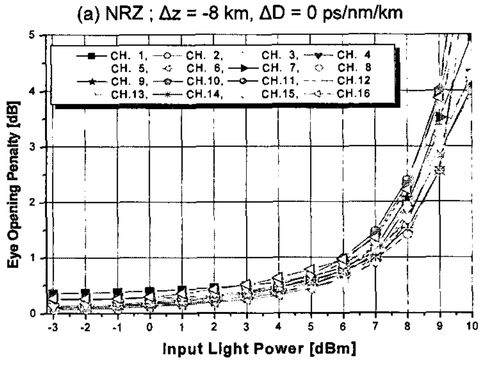


(b) RZ @ Δz = -6 km

Fig. 6 EOP dependence on the dispersion offset.

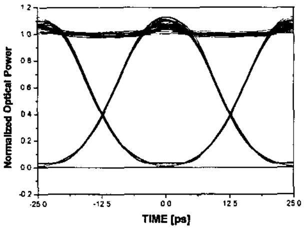


(a) NRZ ; Δz = -8 km, ΔD = 0 ps/nm/km

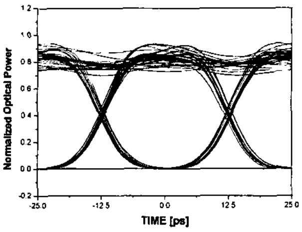


(b) RZ ; Δz = -6 km, ΔD = 0 ps/nm/km

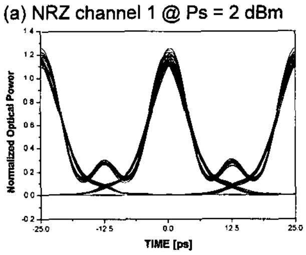
Fig. 7 EOP dependence on the launching power of each channel in WDM system with the best OPC position and the best D_{12}



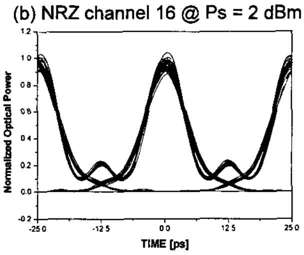
(a) NRZ channel 1 @ Ps = 2 dBm



(b) NRZ channel 16 @ Ps = 2 dBm



(c) RZ channel 1 @ Ps = 5 dBm



(d) RZ channel 16 @ Ps = 5 dBm

Fig. 8 Eye pattern of several WDM signals among the results in Fig. 7.

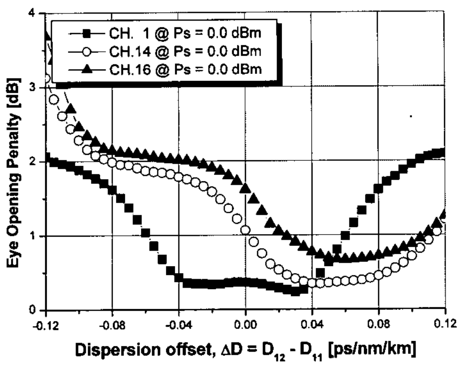
Fig. 7 shows EOP of overall NRZ and RZ channels as a function of the launching light power in WDM system with the OPC positions and dispersion coefficients of latter half section determined as the results of Fig. 5 and Fig. 6, respectively. And, Fig. 8 shows eye pattern of channel 1 and 16 under the same condition of Fig. 7. If 1 dB EOP is allowed for performance criterion, it is confirmed that the compensation performances of NRZ and RZ overall channels are largely improved than those of MSSI case. Especially, the compensation of each channel are obtained to similar performance over the all considered launching power in the case of transmitting RZ format than NRZ format.

From the above results, it is confirmed that if the OPC position was shifted from the mid-way depending on modulation format for the best compensating overall channels, dispersion coefficient of latter half section is not required to change.

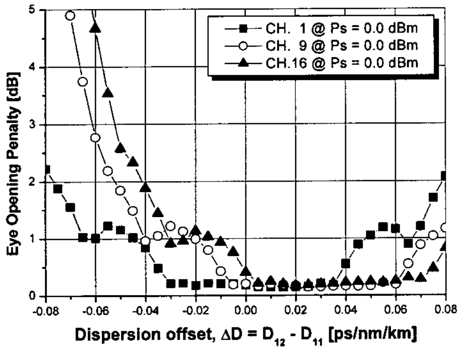
C. Simulation results in the modified WDM system: Case 2

Fig. 9 ~ 11 show the results obtained through the same numerical methods with the previous section B, but the reverse procedure of finding the best parameter. From Fig. 9, dispersion coefficients of latter half section that result the smallest EOP difference between channels are 1.65 ps/nm/km for NRZ and 1.605 ps/nm/km for RZ transmission, respectively. And, from Fig. 10, the OPC positions that result the smallest EOP difference between channels are 498 km for NRZ transmission and 495 km for RZ transmission at D_{12} value obtained from results of Fig. 9, respectively. It is shown from Fig. 11 that EOP characteristics of overall channels dependence on the launching light power and eye patterns are similar with the results in Fig. 7 in section B.

By comparing these results with the results obtained in section B, it is confirmed that the best OPC position must be shifted from the position obtained at ΔD = 0 ps/nm/km in both cases of NRZ and RZ transmission, if

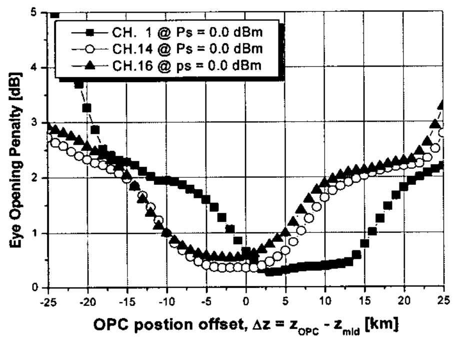


(a) NRZ

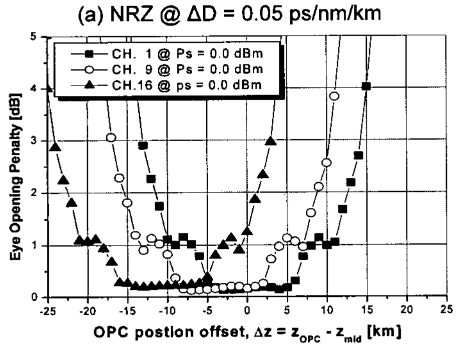


(b) RZ

Fig. 9 EOP dependence on the dispersion offset.



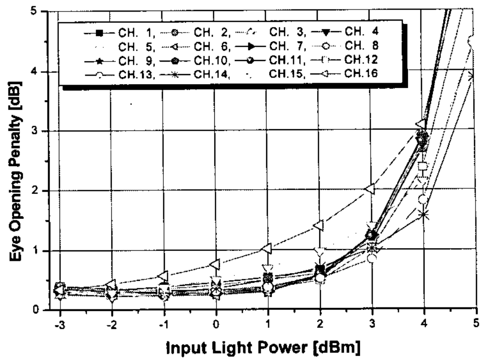
(a) NRZ @ ΔD = 0.05 ps/nm/km



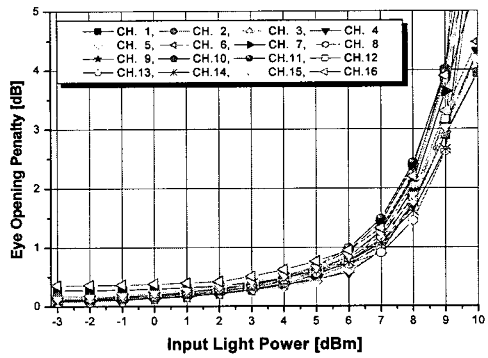
(b) RZ @ ΔD = 0.005 ps/nm/km

Fig. 10 EOP dependence on the OPC position offset.

the best dispersion coefficient of latter half section was deviated from 1.6 ps/nm/km. And, the offset degree of the OPC position must be determined with corresponding to the offset degree of dispersion. That is, the OPC position offset that efficiently compensate for overall WDM channels must be decreased as dispersion offset was increased

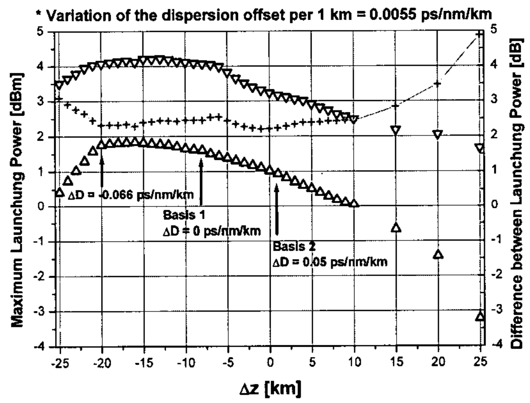


(a) NRZ ; ΔD = 0.05 ps/nm/km, Δz = +1 km

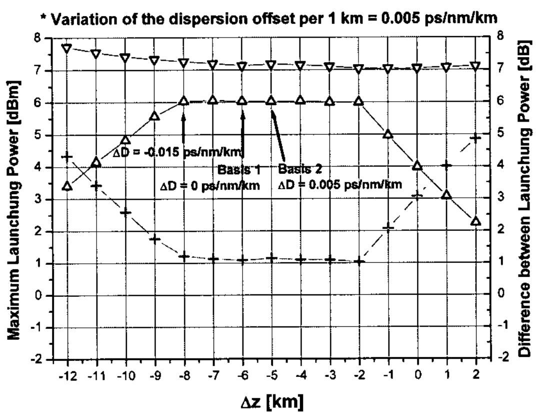


(b) RZ ; ΔD = 0.005 ps/nm/km, Δz = -5 km

Fig. 11 EOP dependence on the launching power of each channel in WDM system with the best OPC position and the best D_{12}.



(a) NRZ



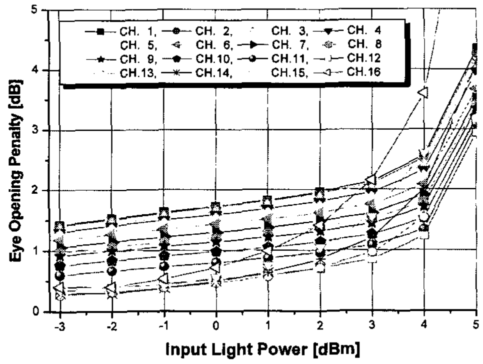
(b) RZ

Fig. 12 Allowable maximum launching power.

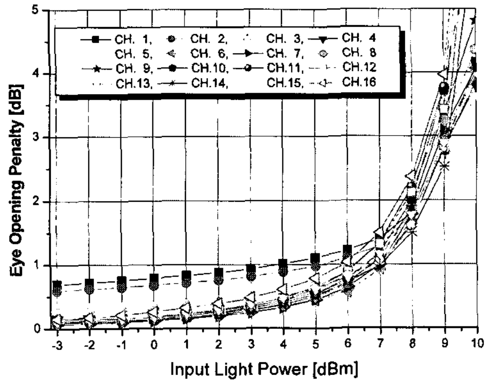
Fig. 12 shows the allowable maximum launching light power as a function of the OPC position offset and the dispersion offset, which is based on the above fact. In Fig. 12, ΔD of basis 1 and basis 2 are values obtained in section B and this section for NRZ and RZ transmission, respectively. Thus, in order to examine the allowable maximum launching light power, the variation of the dispersion offset is set up to ±0.0055 ps/nm/km per 1 km as the OPC position offset is increased or decreased for NRZ transmission because the difference of the dispersion offset is obtained to be 0.05 ps/nm/km as the result of 9 km increase of Δz. And, the variation of the dispersion offset is set up to ±0.005 ps/nm/km per 1 km as the OPC position offset is increased or decreased for RZ transmission. Here, the allowable maximum launching power means that the launching light power of channel results 1 dB EOP. In Fig. 12, the maximum launching power of channel among 16 WDM channels is represented by mark ∇ and the minimum launching power of channel among 16 WDM channels is represented by mark $\triangle$. And, the difference between two launching power is represented by mark +. It is shown from Fig. 12 that the difference of launching powers in RZ transmission system is almost uniformly 2.4 dB over the ranges from Δz = -20 km to Δz =+10 km, and 1.1 dB over the ranges from Δz = -8 km to Δz = -2 km in NRZ transmission system. Thus, the range of the optimal OPC position and the optimal dispersion coefficient of latter half section in NRZ transmission system are broader than that in RZ transmission system. On the other hand, the difference of launching powers in RZ transmission system less than that in NRZ transmission system, thus the effect of the optimal OPC position and the optimal dispersion coefficient of latter half section to RZ transmission system is larger than that in NRZ transmission system. It is confirmed from the results of Fig. 12 that the finding methods of the optimal OPC position and dispersion coefficient of latter half section considered in section B and this section are available to WDM system with OPC, and the optimal OPC position will be changed if dispersion coefficient of latter half section is changed to the corresponding value of OPC position variation.

D. Simulation results in the modified WDM system: Case 3

Fig. 13 shows EOP of overall channels as a function of the launching light power when OPC placed at the position obtained in section B and D_{12} is fixed to the values obtained in section C. And, Fig. 14 shows eye pattern of channel 1 and 16 under the same condition of Fig. 13. It is shown from the results of Fig. 14 that it is hard to achieve the effective compensation of overall WDM channels by individually inducing the best OPC position and the best dispersion coefficient of latter half section and then simply applying these two into WDM system.

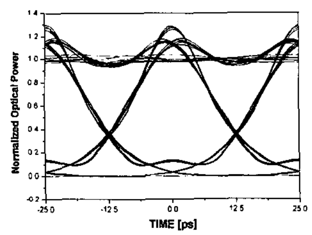


(a) NRZ ; Δz = -8 km, ΔD_{12} = 0.05 ps/nm/km

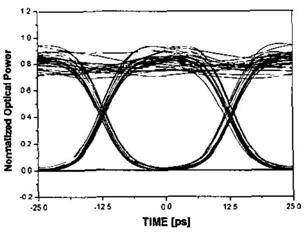


(b) RZ ; Δz = -6 km, ΔD_{12} = 0.005 ps/nm/km

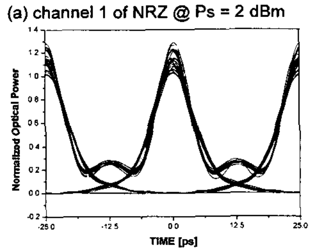
Fig. 13 EOP dependence on the launching power of each channel in WDM system with the optimal OPC position and optimal D_{12}.



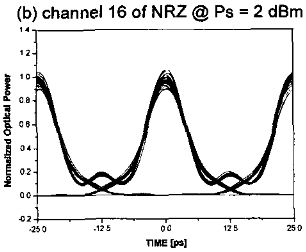
(a) channel 1 of NRZ @ Ps = 2 dBm



(b) channel 16 of NRZ @ Ps = 2 dBm



(c) channel 1 of RZ @ Ps = 5 dBm



(d) channel 16 of RZ @ Ps = 5 dBm

Fig. 14 Eye Pattern of several WDM signals in 16 channels WDM system with the optimal OPC position and optimal D_{12}.

V. CONCLUSION

Up to now the numerical method of finding the optimal position of OPC and the optimal dispersion coefficient of latter half section second was proposed, which effectively compensate overall channels in 16×40 Gbps WDM system with unequally spaced allocation. It was confirmed that the numerical method considered in this research will be available to multi-channel WDM system irrelevant with the search procedure of these two optimal parameters if two optimal parameters depend on each other. Of course, although the exact values of optimal parameter are different relating with the search procedure, these two values relate with each other and the useful ranges of the optimal parameters will be induced by expanding this relation over the considered offset extents. It was shown from this research that the useful range of the optimal parameters in the case of NRZ transmission is broader than in the case of RZ transmission under the same conditions, but the compensation quality by these optimal parameters in the case of RZ transmission is better than in the case of NRZ transmission.

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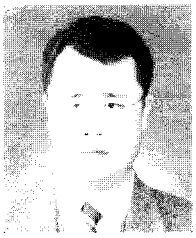

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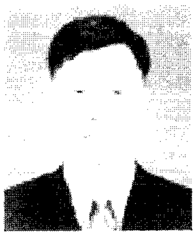

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