Performance Improvement of 24×40 Gbps NRZ Channels in WDM System with 1,000 km NZ-DSF using Optimal Parameters of Optical Phase Conjugator

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Abstract—In this paper, the new method alternating with the method for forming the symmetrical distribution of power and local dispersion in high bit-rate WDM system with optical phase conjugator (OPC) is proposed. The proposed method is carried by finding out the optimal values of OPC position offset and fiber dispersion offset. It is assumed to be that NRZ-formatted 24-channels of 40 Gbps are simultaneously propagated in WDM system with non zero - dispersion shifted fiber (NZ-DSF) of 1,000 km. It is confirmed that the compensation extents of overall WDM channels are more improved by applying the induced optimal values into WDM system than those in WDM system with the conventional mid-span spectral inversion (MSSI) technique, and the searching procedure of the optimal values makes little difference of performance if the optimal value of one parameter related with another parameter. And, it is confirmed that the flexible design of WDM system with OPC is possible by effectiviely using by these optimal values. Thus, it is expected that the proposed method alternate with the forming method of the symmetrical distributions of power and local dispersion.

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

I. INTRODUCTION

One of the main transmission impairments in optical communication systems based on high bit-rate (> 20 Gbps) amplitude modulation is the signal distortion caused by the interplay between fiber chromatic dispersion and nonlinearity [1], [2]. Many techniques overcoming these impairments have been proposed and demonstrated using either optical or electrical processes [3]-[6]. Several attentions among these techniques have been paid to compensation techniques based on the spectral inversion, which can be obtained through an optical phase conjugator (OPC). One of the most promising techniques is mid-span spectral inversion (MSSI), which allows for simultaneous compensation of the group velocity dispersion (GVD) [7] and the nonlinear effects [8]. Unfortunately, the MSSI technique is effective only in systems exhibiting a symmetrical distribution of GVD and optical power with respect to the center of the transmission link. Due to the presence of fiber losses, this "perfect symmetry" cannot be obtained in common transmission systems.

Currently, non zero – dispersion shifted fiber (NZ-DSF) is being interested for alternating with DSF as optical fiber in WDM systems, which can decrease the serious crosstalk owing to four-wave mixing (FWM) appeared in WDM systems with DSF [9]. But the bit-rate – distance product is still limited by combining erbium doped fiber amplifier (EDFA) with NZ-DSF for expanding transmission distance, because self phase modulation (SPM) and cross phase modulation (XPM) are generated owing to high power of optical signal, even if NZ-DSF is used to suppress FWM effect [10].

WDM signals in systems with the MSSI technique have to be converted into the phase conjugated waves as a whole by OPC, therefore the OPC used has to have the same bandwidth as those of total WDM channels. However, DSF has been mainly used as a nonlinear medium for FWM generation, which is the mechanism for converting signal wavelengths into conjugated wavelengths, in OPC. Then, the generation efficiency of FWM is drastically changed depending on the wavelength separation between the signal and the pump lights nearby the zero dispersion wavelength of the DSF. Because of this phenomenon, it is the difficult to apply OPC for WDM systems directly. In order to solve this problem, OPC using highly nonlinear dispersion-shifted fiber (HNL-DSF) is proposed by Watanabe et al [11].

But, the problem of "perfect symmetry" still remains in order to apply OPC into the long-haul and high-speed WDM systems. Furthermore, it is more difficult to solve this problem by using the common solution over the total channels because WDM channels with different wavelength are transmitted through the same optical fiber, even if 'perfect symmetry' was formed for a special wavelength. Thus, it is required to research other method alternating with the forming 'perfect symmetry' in WDM system with OPC

In this paper, the method alternating with the forming method of "perfect symmetry" is proposed. The proposed method is carried by numerically finding out the optimal OPC position and the optimal dispersion coefficients of fibers, which are compensating for the

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distortion of overall channels to similar performance. And in order to verify the effectiveness of these optimal parameters, the compensation characteristics of overall channels in WDM system with those optimal parameters are compared with that in WDM system without the optimal parameters (i.e. in WDM system with MSSI).

The considered WDM system has 24 channels of 40 Gbps. The intensity modulation format is assumed to be NRZ. The split-step Fourier method [12] is used for numerical simulation. The evaluation parameter for compensation degree is eye-opening penalty (EOP) of each channel. XPM effect of inter-channels is neglected in order to simplify the analysis.

II. WAVE EVOLUTION AND WDM SYSTEM MODELING

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

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

where $j,k = 1,2,\cdots,24(j \neq k)$, 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 [13]. 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 2 ps/nm/km, which less affect the signal distortions due to XPM.

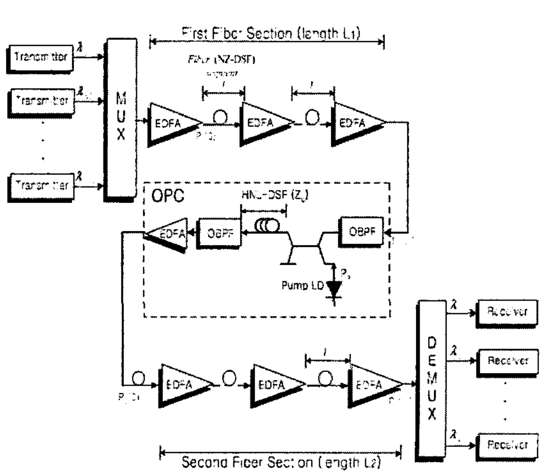


Fig. 1 The configuration of 16×40 Gbps WDM system with OPC.

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 spans 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 [14].

Table 1 Fiber parameter assumptions.

Parameter	Symbol and values
Type	NZ-DSF
Chromatic Dispersion, D_{11} and D_{12}	2 ps/nm/km
Nonlinear refractive index, n_2	2.5×10^{-20} m²/W
Attenuation, α	0.2 dB/km
Effective core area, A_{eff}	72 μm²

Each laser diodes in transmitter of 24-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 format signal from external optical modulator is assumed to be second-order super-Gaussian pulse. The direct detection receiver of 24-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[15]. 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/nm²/km
Pump light power	P_p	18.5 dBm
Pump light wavelength	λ_p	1549.75 nm

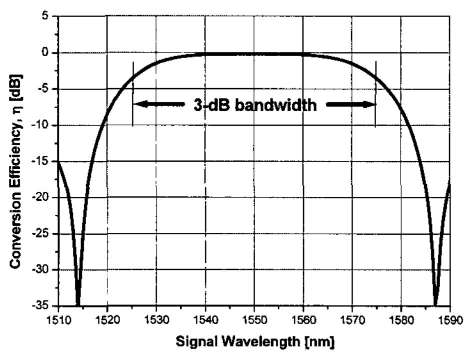


Fig. 2 The conversion efficiency value.

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 [16]. The 3-dB band-width of η is obtained to 48 nm (1526 ~ 1574 nm) as shown in Fig. 2.

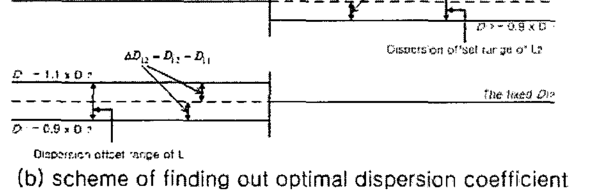
The center wavelengths of WDM channels are allocated by equally spacing scheme as ITU-T recommendation in this research. ITU-T recommends that the channel spacing for dense WDM includes 100 GHz (that is 0.8 nm). The center wavelength of first channel is assumed to be 1550.0 nm in this research. Thus the allocated 24 signal wavelengths (that is, from 1550.0 nm to 1568.4 nm) and these conjugated wavelengths (that is, from 1531.1 nm to 1549.5 nm) are belong within 3-dB bandwidth of Fig. 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 [17]. 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.



(a) scheme of finding out optimal OPC position

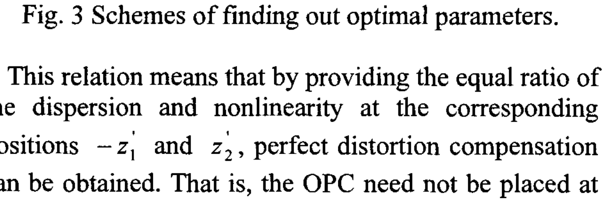

(b) scheme of finding out optimal dispersion coefficient

Fig. 3 Schemes of finding out optimal parameters.

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 out the common OPC position and dispersion coefficient of fiber sections which are applicable to total signal wavelengths allocated over the broad band in real transmission link. Thus, this research intended to find out the optimal OPC position and dispersion coefficient of fiber sections for overall WDM channels through the numerical approach.

The optimal OPC position is found by evaluating the compensation characteristics as a function of the OPC position (z_{OPC}) varied within one front and one rear span length (±50 km) from the mid-way (z_{mid}), as shown in Fig. 3(a). The difference between z_{OPC} and z_{mid} ($z_{OPC} - z_{mid}$) is called to the OPC position offset, Δz. And the optimal dispersion coefficient of each section ($D_{1x}, x = 1,2$) is also found by evaluating the compensation characteristics as a function of dispersion offset of one fiber section ΔD_{1x} in the case of fixing dispersion coefficient of another fiber section to 2 ps/nm/km, as shown in Fig. 3(b). The dispersion offset is defined to difference of dispersion coefficient between two fiber sections, that is $\Delta D_{11} = D_{11} - D_{12}$ and $\Delta D_{12} = D_{12} - D_{11}$.

IV. RESULTS AND DISCUSSION

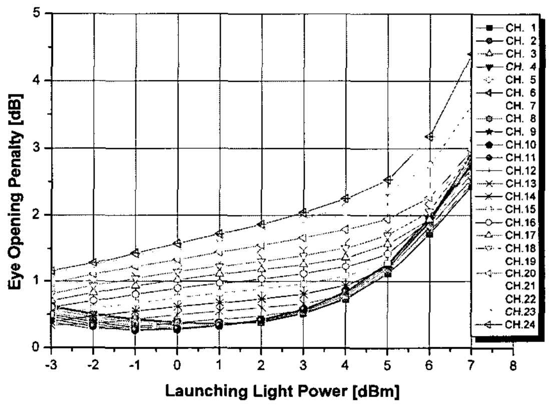


Fig. 4 EOP as a function of the launching power in WDM system with MSSI.

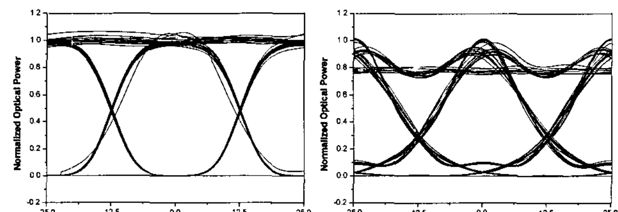
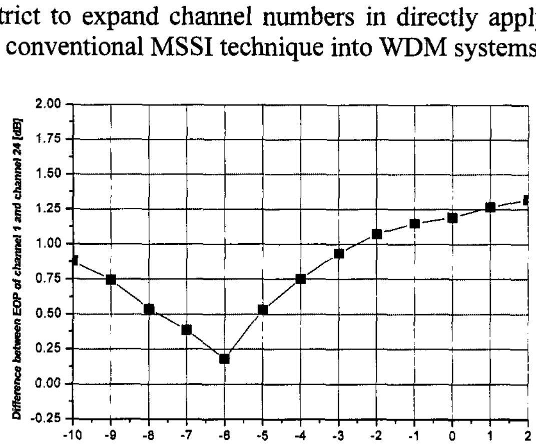
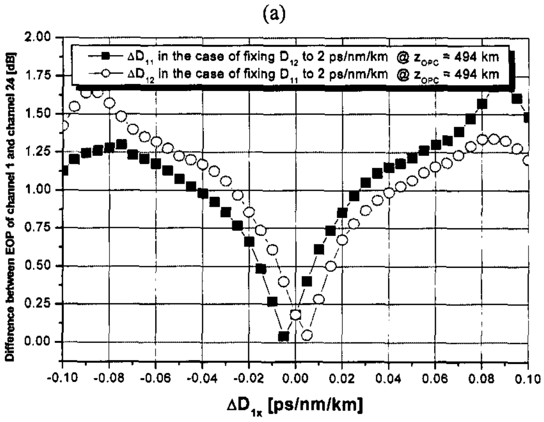

(a) CH. 1 @ Ps = 3 dBm (b) CH.24 @ Ps = 3 dBm

Fig. 5 Eye diagram of channel 1 and 24 in WDM system with MSSI.

Fig. 4 shows EOP of overall channels as a function of the launching power in the case of applying the conventional MSSI technique into 24 channels x 40 Gbps WDM system. It is shown that EOPs are more degraded as the signal wavelengths are more deviated from the zero dispersion wavelength of OPC. Thus, it is restrict to expand channel numbers in directly applying the conventional MSSI technique into WDM systems.



(a)

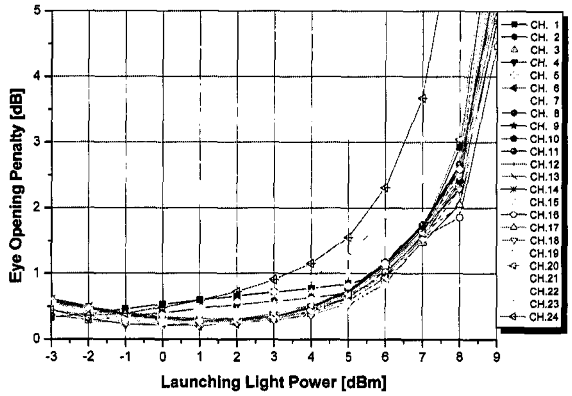


(b)

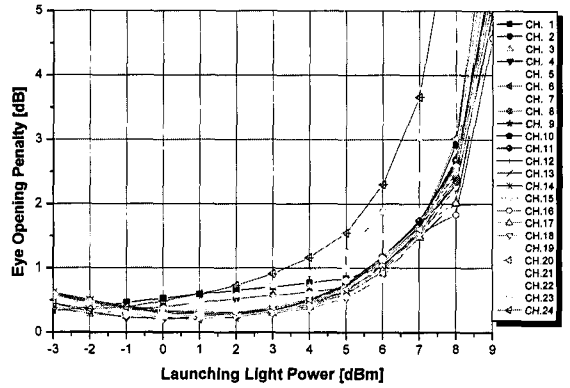
Fig. 6 EOP difference between channel 1 and 24. (a) depends on the Δz in the cases of $D_{11} = D_{12} = 2$ ps/nm/km, and (b) depends on ΔD_{1x} when the OPC placed at the optimal Δz, which is obtained from Fig. (a), respectively.

Fig. 6(a) shows EOP difference between channel 1 and 24 depending on the OPC position offset (Δz), when dispersion coefficients of both fiber sections are fixed to 2 ps/nm/km. In the case of assuming the launching power of channels to relatively high, EOP difference between channel 1 and 24 depending on the OPC position offset is so very large that is impossible to obtain the optimal parameter values. For this reason, the launching powers are assumed to be 0 dBm in all cases of finding out optimal parameters. It is shown from Fig. 6(a), the best OPC position, which result in the smallest EOP difference between channel 1 and 24, is 494 km (i.e., $\Delta z = -6$ km).

Fig. 6(b) shows EOP difference between channel 1 and 24 depending on the dispersion offset (ΔD_{1x}), when the OPC placed at 494 km as the result of Fig. 6(a). It is shown from Fig. 6(b) that EOP differences depending on ΔD_{11} (i.e., the dispersion offset of first half section) under the assuming of $D_{12} = 2$ ps/nm/km is symmetry with EOP differences in the reverse case. As shown in the results of Fig. 6(a), the best D_{11} that result in the smallest EOP difference is obtained to 1.995 ps/nm/km (i.e. $\Delta D_{11} = -0.005$ ps/nm/km) in the case of $D_{12} = 2$ ps/nm/km, while the best D_{12} is 2.005 ps/nm/km (i.e., $\Delta D_{12} = +0.005$ ps/nm/km) in the case of $D_{11} = 2$ ps/nm/km.

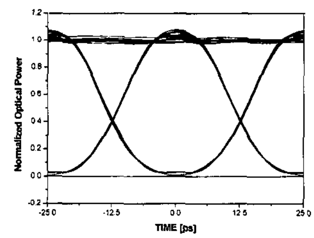


(a) $D_{11} = 2$, $D_{12} = 2.005$ ps/nm/km @ $z_{OPC} = 494$ km

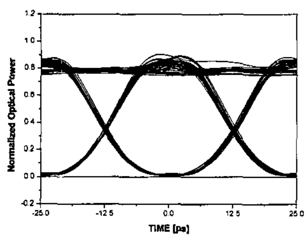


(b) $D_{11} = 1.995$, $D_{12} = 2$ ps/nm/km @ $z_{OPC} = 494$ km

Fig. 7 EOP as a function of the launched light power in WDM system with the optimal parameters obtained from the result of Fig. 6.



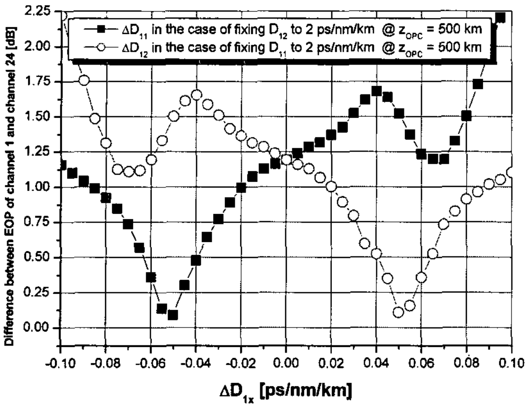
(a) CH. 1 @ $Ps = 3$ dBm



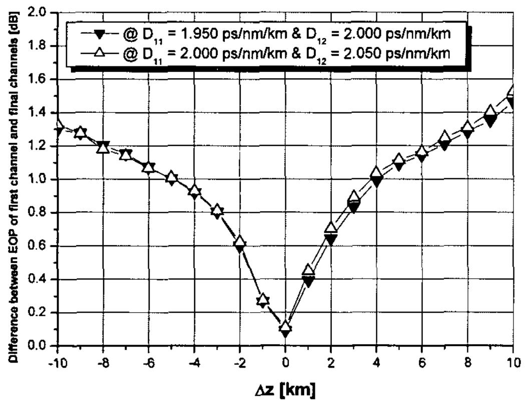
(b) CH.24 @ $Ps = 3$ dBm

Fig. 8 Eye diagram of channel 1 and 24 among the results of Fig. 7(a).

Fig. 7 shows EOP of overall channels as a function of the launching light power in WDM system with the optimal dispersion coefficients of fiber sections, which depend on the optimal OPC position, as the results of Fig. 6. The compensation extents shown in Fig. 7 are largely improved than the results of Fig. 4. If 1 dB EOP is allowed for performance criterion, it is confirmed that power penalty is reduced to almost 3 dB from 8 dB. This fact means that compensation extents of overall channels are improved by applying the only optimal parameters into WDM system with OPC, even if the "perfect symmetry" was not made.



(a)



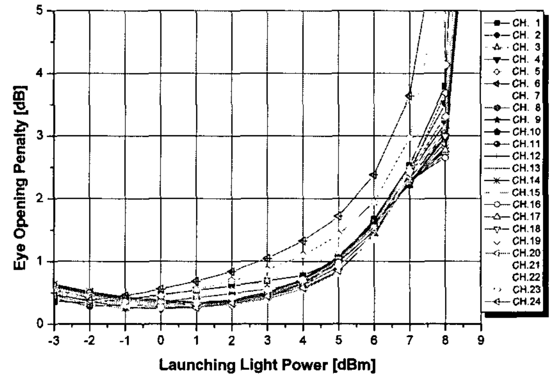
(b)

Fig. 9 EOP differences between channel 1 and 24. (a) depends on the ΔD_{1x} in the case of assuming z_{OPC} = 500 km, and (b) depends on the Δz when the D_{1x} of one fiber section is selected to the optimal values, which are obtained from Fig. (a), while that of the other fiber section is fixed to 2 ps/nm/km, respectively.

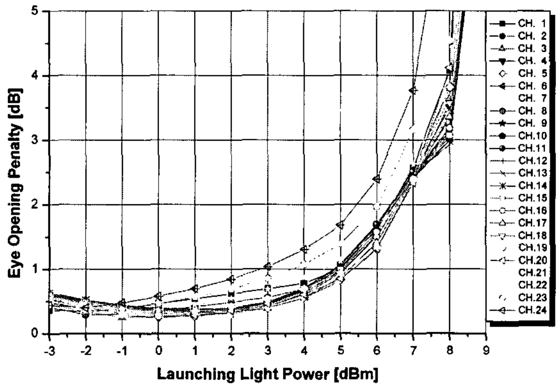
Up to now, the optimal OPC position is previously induced, and then the optimal dispersion coefficients of fiber sections, which depend on this optimal OPC position, are consequently induced. It is required to exchange the procedure of finding out the optimal parameters for investigating the correlation of two optimal parameters.

Fig. 9 shows the results obtained through the reverse procedure of finding out the optimal parameter values in Fig. 6. That is, the optimal dispersion coefficients are previously induced in the case of assuming z_{OPC} to be 500 km (the result is presented in Fig. 9(a)), and then the optimal Δz is consequently induced under the condition of fiber sections having the induced optimal dispersion coefficients (the result is presented in Fig. 9(b)). It is shown from Fig. 9(a) that the characteristics of EOP difference depending on ΔD_{11} are also symmetry with that depending on ΔD_{12} alike the aspects in Fig. 6(b). It is shown form Fig. 9(b), the optimal dispersion offset value between the two fiber sections is obtained to ±0.05 ps/nm/km.

It is shown from Fig. 9(b) that EOP differences between channel 1 and 24 in the case of optimizing dispersion coefficients of first fiber section to $D_{11} = D_{1x} + \Delta D_{11}$ under the assumption of $D_{12} = D_{1x}$ is nearly coincide with that in the case of optimizing dispersion coefficients of second fiber section to $D_{12} = D_{1x} + \Delta D_{12}$ under the assumption of $D_{11} = D_{1x}$. As the results of Fig. 9(b), the optimal Δz is obtained to be 0 km, i.e., z_{OPC} = 500 km, when the difference of the dispersion coefficients between both fiber sections was to be 0.05 ps/nm/km.

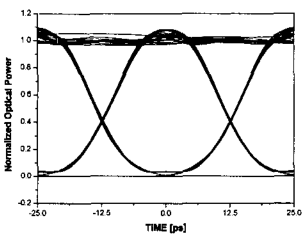


(a) Δz = 0 km @ D_{11} = 1.95 and D_{12} = 2.00 ps/nm/km

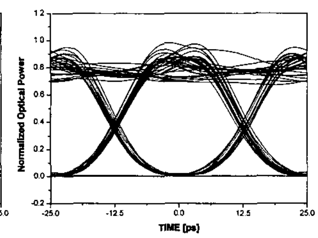


(b) Δz = 0 km @ D_{11} = 2.00 and D_{12} = 2.05 ps/nm/km

Fig. 10 EOP as a function of the launched light power in WDM system with the optimal parameters obtained from the results of Fig. 9.



(a) CH. 1 @ Ps = 3 dBm



(b) CH.24 @ Ps = 3 dBm

Fig. 11 Eye diagram of channel 1 and 24 among the results of Fig. 10(b).

Fig. 10 shows EOP of overall channels as a function of the launching light power in WDM system with the optimal OPC position, which depend on the optimal dispersion coefficients of fiber sections, as the results of Fig. 9. Fig. 10 compare EOP characteristics obtained in the case of optimizing D_{11} to $D_{11} = D_{1x} + \Delta D_{11}$, i.e., 1.95(=2-0.05) ps/nm/km under D_{12} =2 ps/nm/km (Fig.

10(a)) with EOP characteristics obtained in the case of optimizing D_{12} to $D_{12} = D_{1x} + \Delta D_{12}$, i.e., 2.05(2+0.05) ps/nm/km under D_{11}=2 ps/nm/km (Fig. 10(b)). It is shown that EOP characteristics of two cases are almost coincide with each other.

By comparing Fig. 7 and 10, it is confirmed that the values of the optimal parameters are varied with the procedure of finding the optimal parameters, but the compensation extents in Fig. 10 are almost coincide with those in Fig. 7. That is, it is confirmed that the values of the optimal parameters related with the searching procedure are not important, only if two optimal parameters depend on each other.

The important point to be confirmed is that the optimal parameters must be obtained by relating with each other, because this fact provides the effective factors for designing the flexible WDM system with OPC. That is, the criterion values necessary to design the flexible WDM system will be induced by comparing the optimal parameters obtained from the different procedures. From the comparing Fig. 7 with Fig. 10, it is confirmed that the optimal value of D_{12} is increased by 0.0075 ps/nm/km in the case of fixing only D_{11} to 2 ps/nm/km or the optimal value of D_{11} is decreased by same amount in the case of fixing only D_{12} to 2 ps/nm/km as the OPC position is closer to the receiver by 1 km, because the optimal ΔD_{12} is +0.005 ps/nm/km when the optimal OPC position is 494 km and the optimal ΔD_{12} is +0.05 ps/nm/km when the optimal OPC position is 500 km. Also, the optimal dispersion of the second fiber section is decreased by 0.0075 ps/nm/km in the case of fixing only D_{11} to 2 ps/nm/km as the OPC position is reversely closer to the transmitter by 1 km. That is, the OPC position or dispersion coefficient of fiber sections should be flexibly used in the design of WDM transmission system, for example, the optimal dispersion coefficient of second fiber section must be selected to 1.9 (= 2.05(this is the optimal D_{12} at 500 km) + 0.0075 x (-20 km)) ps/nm/km when OPC is placed at 480 km, if dispersion coefficient of first fiber section was fixed to 2 ps/nm/km.

By using Fig. 12, it is possible to investigate the availability of the optimal parameters for designing the flexible WDM systems with OPC. Fig. 12 shows the allowable launching light power as a function of the OPC position offset and the dispersion offset of second fiber section in the case of fixing D_{11} to 2 ps/nm/km. In Fig 12, the allowable launching power is defined to be the arbitrary WDM channel's launching power, which should result in 1 dB EOP. The allowable launching powers, which are represented by '▼' and '▲', are that of WDM channel having the best EOP characteristics (i.e., the maximum allowable launching power) and that of WDM channel having the worst EOP characteristics (i.e., the minimum allowable launching power), respectively. The power penalty of WDM channels, which is the difference between two allowable launching powers, is also shown by 'o' in Fig. 12.

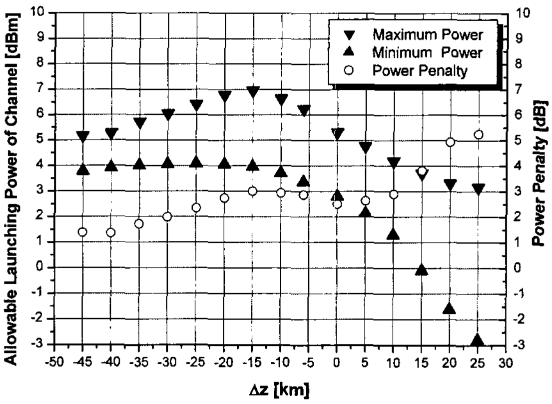


Fig. 12 The allowable launching power in 24 channels WDM systems.

In Fig. 12, the allowable launching powers and the power penalty at Δz=-6 km and Δz=0 km are obtained from Fig. 7 (a) and Fig. 9 (b), respectively. The values at the other Δz shown in Fig. 12 are obtained by increasing or decreasing ΔD_{12} by 0.0075 ps/nm/km as OPC position is closer to receiver or transmitter by 1 km, respectively. For example, the allowable launching powers and the power penalty at Δz =+10 km are obtained under the condition of D_{11}=2 ps/nm/km and D_{12} =2.125 ps/nm/km, in which the value of 2.125 ps/nm/km is obtained by adding 2.05 ps/nm/km (this is the optimal value of D_{12} at Δz =0 km) to 0.075 ps/nm/km (this is the optimal value of ΔD_{12} , i.e. 0.0075 x 10).

From Fig. 10 and Fig. 7, it is shown that the power penalty at Δz=-6 km and Δz=0 km in WDM system with the optimal parameters are obtained to almost 3 dB and 2.5 dB, respectively. If 3 dB power penalty is allowed for performance improvement criterion when the applying the optimal parameters obtained from the above approach into WDM system, it is confirmed that this 3 dB power penalty is resulted over the OPC position offset range from Δz=-45 km to +10 km. Within this range, the feature that the power penalty is more decreased as OPC position is closer to transmitter is appeared, and the minimum allowable launching powers are relatively uniform. Thus, the proposed method for searching the optimal parameters is more effective in the case of positioning OPC closer to transmitter.

V. CONCLUSION

Up to now, this paper deal with the method of finding out the optimal OPC position and the optimal dispersion coefficients of fiber sections that are efficiently compensating for the distortion of 24 WDM channels of 40 Gbps, without the forming of the 'perfect symmetry'.

It was confirmed that the performance of received signals should be improved by applying the optimal parameters induced in this research into WDM system. From a viewpoint of the performance improvement, the searching procedure of the optimal parameters makes little difference of performance. But the optimal value of one parameter has to be decided by relating with another parameter.

And, it is confirmed that the flexible design of WDM system with OPC is possible by applying the optimal values of OPC position offset and fiber dispersion coefficient offset, which are decided by comparing the optimal parameters obtained from two different procedures, into WDM system. But, this performance improvement using the optimal parameters is more effective in the case of positioning OPC closer to receiver. Consequently, it is expected to replace with the method for forming of 'perfect symmetry' in WDM system with OPC by applying the method proposed in this research.

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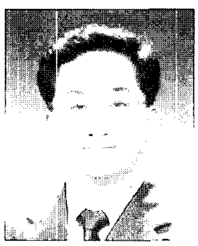

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