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1,000 km의 NZ-DSF를 전송하는 640 Gbps WDM 시스템에서 최적 파라미터를 갖는 Mid-Span Spectral Inversion 기법

Mid-Span Spectral Inversion Technique with Optimal Parameters in 640 Gbps WDM Transmission System over NZ-DSF of 1,000 km

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요 약

본 논문에서는 장거리 다채널 광 전송 시스템에서 MSSI(Mid-Span Spectral Inversion) 기술의 유용성을 확장하기 위하여 1,000 km의 비영 분산 천이 광섬유로 구성된 16×40 Gbps WDM 시스템에서 광 위상 공액기 (OPC ; Optical Phase Conjugator)의 최적 위치와 광섬유 구간의 최적 분산 계수를 도출한다. 유도된 이들 최적 파라미터들을 WDM 시스템에 적용하면 전통적인 MSSI 기술이 적용된 WDM 시스템에 비해 모든 채널의 보상 정도를 매우 크게 개선할 수 있는 것을 확인하였다. 따라서 제안된 최적 파라미터들은 OPC를 다채널 WDM에 적용하는데 있어 형성하지 못하면 심각한 문제를 발생시키는 OPC에 대해 광 전력과 국부 분산량을 대칭화시키는 방법을 대체할 것으로 기대된다. 본 논문에서 제안한 방법을 실제 WDM 시스템에 적용함으로써 유연한 시스템 설계가 가능할 것이다.

Abstract

In this paper, the optimum position of optical phase conjugator (OPC) and the optimal dispersion coefficients of fiber sections in 16×40 Gbps WDM system with non zero - dispersion shifted fiber (NZ-DSF) of 1,000 km are induced, in order to expand the availability of mid-span spectral inversion (MSSI) technique in long-haul multi-channel transmission systems. It is confirmed that the compensation degrees of overall WDM channels are more improved by applying the induced optimal parameters into WDM system than those in WDM system with the conventional MSSI. So it is expected that the proposed optimal parameters should alternate with the forming method of the symmetrical distributions of optical power and local dispersion with respect to OPC, which generate a serious problem in the applying OPC into multi-channels WDM system if it is not formed. It will be possible to realize the flexible system design by applying the methods proposed in this paper into the real WDM system with OPC.

Key words : MSSI, WDM system, Optical Phase Conjugator, Optimal parameters, NZ-DSF

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I. Introduction

Wavelength division multiplexing (WDM) techniques are realizing the broadband networks by offering ultra wide bandwidth. However, WDM systems also give rise to the signal distortion by chromatic dispersion and undesirable nonlinear Kerr effects such as self phase modulation (SPM), cross phase modulation (XPM) and four-wave mixing (FWM), when multi-channels are copropagated through the same fiber [1].

Since the 10 Gbps optical transmission systems were realized, dispersion shifted fiber (DSF) instead of conventional single mode fiber (SMF) is widely used in order to overcome the signal distortion due to chromatic dispersion in optical fiber. But, the crosstalk owing to Kerr effects, especially four-wave mixing (FWM) is appeared in multi-channels transmission system with DSF, consequently serious problem should be generated in the case of expanding to WDM system. In mostly recent, the fiber overcoming this limitation of DSF is developed for realizing multi-channel WDM system. The zero dispersion wavelength of this new type fiber is appeared beyond transmission bandwidth and the chromatic dispersion of this fiber is relatively large, because FWM effect is more decreased as the chromatic dispersion is larger [2]. This fiber is called to non zero - DSF (NZ-DSF).

But, even if NZ-DSF is used to suppress FWM effect, the bit-rate distance product in long-haul WDM system with erbium doped fiber amplifier (EDFA) is limited by self phase modulation (SPM) effect and cross phase modulation (XPM) effect, which are generated owing to high power of optical signal in EDFA [3]. One of the techniques to overcome this limitation is mid-span spectral inversion (MSSI). Theoretically, this technique overcomes both SPM effect and dispersive effects by using optical phase conjugator (OPC) for compensating distorted signals in mid-way of total transmission length [4].

The serious problems have to be solved in order to apply MSSI technique into WDM system. The first problem 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]. The second is that the OPC must exhibit the similar conversion efficiency over large bandwidth for increasing number of WDM channels. Fortunately, the second 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 [6]. The first problem 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 over the total channels because WDM channels with different wave- length are transmitted through the same optical fiber, even if the symmetrical distribution problem was solved for a special wavelength. Thus other method must be researched to effectively compensate overall channels by using OPC, which is able to alternate with the forming of the symmetrical distribution of power and local dispersion.

This research focus on the method that has the effect of alternating with the forming method of the symmetrical distributions mentioned in previous. This paper is first devoted to numerically find out the optimal OPC position and the optimal dispersion coefficients of fibers which are compensating for the distortion of overall channels to similar performance, without the making the symmetrical distribution of power and local dispersion. And, the effectiveness of these optimal parameters is numerically verified on the comparison of the compensation characteristics in WDM system with the induced optimal parameters and those in WDM system with conventional MSSI technique.

The considered WDM system has 16 channels of 40 Gbps. The intensity modulation format is assumed to be RZ. The split-step Fourier method [7] 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. Modeling of WDM system

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. satisfies the following equation [7].

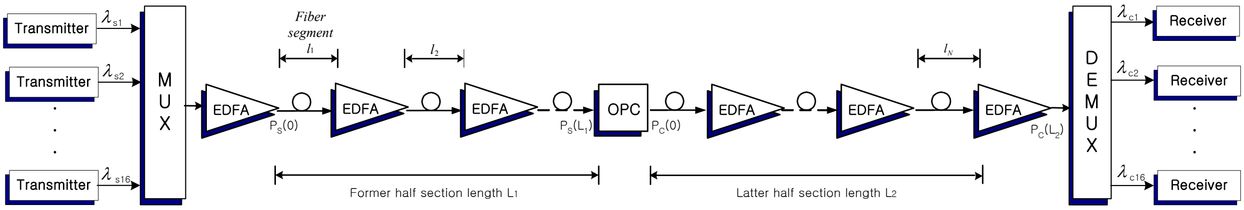


Fig. 1. Simulation model of 16×40 Gbps WDM system.

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

where j, k = 1,2,⋯,16 (j≠k), α is the attenuation coefficient of the fiber, λj is the j-th channel signal wavelength, β2j is the fiber chromatic dispersion parameter, β3j is the third-order chromatic dispersion parameter, γj is the nonlinear coefficient and T=t-z/vg, respectively. The last two terms in equation (1) induce SPM and XPM, respectively. The last term, i.e., XPM term is neglected in order to simplify numerical analysis in this paper.

Fig. 1 shows a configuration of intensity modulation/direct detection (IM/DD) WDM system with OPC placed at mid-way of total transmission length. In Fig. 1, total transmission length (L) is divided into two sections of respective length L1(=L/2) and L2, and each fiber section consist of 10 amplifier spans of length l=50 km. Fiber parameters assumed for numerical simulations throughout this paper are summarized in Table 1 [8].

Table. 1. Fiber parameter assumptions.

Parameter	Symbol & Value
Type	NZ-DSF
Chromatic dispersion	D_{1x} = 3, 4 ps/nm/km
Nonlinear refractive index	n_2 = 2.5×10^{-20} m^2/W
Attenuation	a = 0.2 dB/km
Effective core area	A_{eff} = 72 μm^2

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

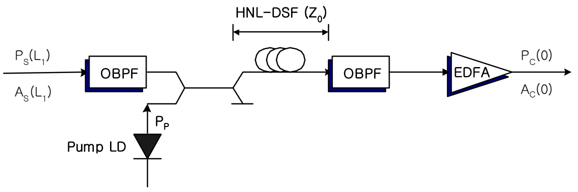
$$\frac{\beta_{2j}(-z_1')}{P_j(-z_1')\gamma_j(-z_1')} = \frac{\beta_{2j}(z_2')}{P_j(z_2')\gamma_j(z_2')} \quad (2)$$

where β_{3j} is neglected.

This relation means that perfect distortion compensation can be obtained by providing the equal ratio of the dispersion and nonlinearity at the corresponding positions $-z_1'$ and z_2'. 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. However, the equation (2) also means that it is not easy to find out the common OPC position and dispersion coefficient of each fiber sections available for total allocated WDM wavelengths in real transmission link, because equation (2) is dependent on the wavelength. Thus, this research is devoted to find out the optimal OPC position and dispersion coefficient of each fiber sections, which are available for 16 WDM channels. The optimal OPC position is found out by evaluating the compensation characteristics as a function of the OPC position (z_{OPC})

varied within one span length (±25 km) from the mid-way. The difference between z_{OPC} and z_{mid}, *i.e.*, $z_{OPC}-z_{mid}$ is called to the OPC position offset, Δz. And the optimal dispersion coefficient of each fiber section is also found out by evaluating the compensation characteristics as a function of dispersion offset, ΔD_{1x}(x=1,2). The dispersion offset is defined as difference of dispersion coefficient between two fiber sections, *i.e.*, $\Delta D_{11}=D_{11}-D_{12}$ and $\Delta D_{12}=D_{12}-D_{11}$.

Each laser diode in transmitter of Fig. 1 is externally modulated by an independent 40 Gbps 128(=2^7) pseudo random bit sequence (PRBS). And output electric field of RZ format signal from external optical modulator is assumed to be second-order super-Gaussian pulse. The direct detection receiver of 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 and the decision circuit [9]. The receiver bandwidth is assumed to be 0.65×bit-rate.



HNL-DSF loss : $\alpha_0 = 0.61 dB/km$

HNL-DSF nonlinear coefficient : $\gamma_0 = 20.4 W^{-1} km^{-1}$

HNL-DSF zero dispersion wavelength : $\lambda_0 = 1550.0 nm$

HNL-DSF length : $z_0 = 0.75 km$

HNL-DSF dispersion slope : $dD_0/d\lambda = 0.032 ps/nm^2/km$

Pump light power : $P_p = 18.5 dBm$

Pump light wavelength : $\lambda_p = 1549.75 nm$

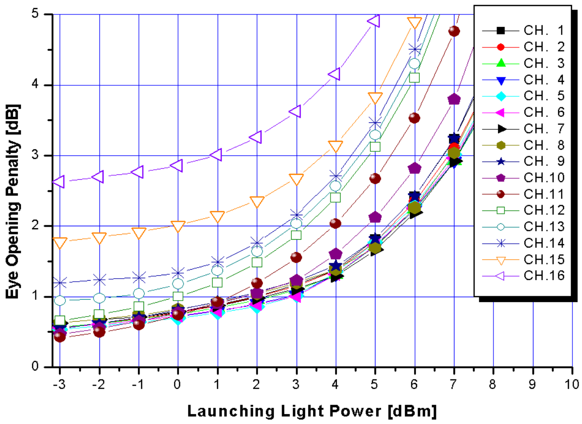
Fig. 2. OPC using HNL-DSF.

Fig. 2 shows the configuration of the OPC using HNL-DSF, and its parameters. The conversion efficiency η is defined as a ratio of the FWM product power to the input probe (signal) power[10]. The 3-dB bandwidth of η for the OPC in Fig. 2 is obtained to be 48 nm (1526~1574 nm).

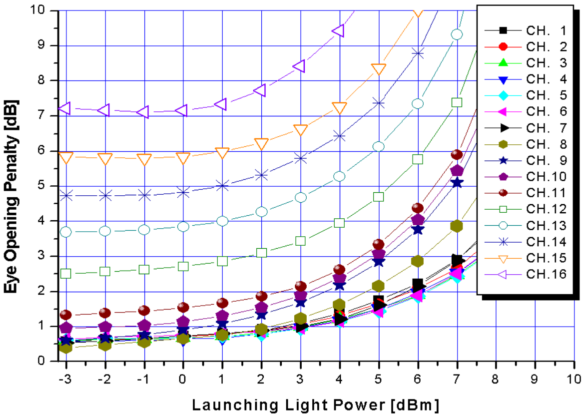
The center wavelength of first channel is assumed to be 1550.0 nm in this research. And the channel spacing is selected to be 100 GHz (that is 0.8 nm) by ITU-T recommendation G.694.1 [11]. Thus the allocated 16 signal wavelengths (that is, from 1550.0 nm to 1562.0 nm) and these conjugated wavelengths (that is, from 1537.5 nm to 1549.5 nm) are within 3-dB bandwidth of η.

III. Simulation results and discussion

Fig. 3 shows EOP of overall channels as a function of the launching light power when OPC placed at mid-way of total transmission length and ΔD_{1x}=0 ps/nm/km (that is, conventional MSSI). It is shown that EOPs of long wavelength channels are more degraded than those of the others. Furthermore, this degradation is more intensified as the dispersion coefficient of fiber is larger. Thus, it is impossible to simultaneously transmit multi-channels in WDM systems using the conventional MSSI.



(a) @ D_{1x} = 3 ps/nm/km



(b) @ D_{1x} =4 ps/nm/km

Fig. 3. EOP as a function of the launching power in WDM system with MSSI.

Fig. 4 shows EOP difference between channel 1 and 16 depending on the OPC position offset Δz, in order to find out the optimal OPC position. In the case of assuming the launching power of channels to relatively high, EOP difference between channel 1 and 16 depending on Δz is so large that is impossible to compare each other. For this reason, the launching powers are assumed to be 0 dBm in the case of finding out optimal parameters. From Fig. 4, the OPC positions that result in the smallest EOP difference are 497 km (Δz= -3 km) and 496 km (Δz= -4 km) in the cases of fixing D_{11}= D_{12} to 3 or 4 ps/nm/km, respectively.

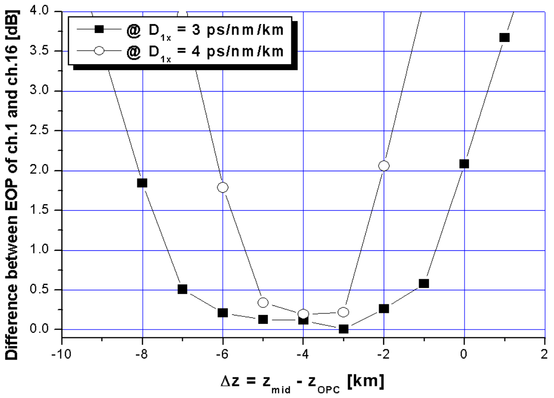


Fig. 4. EOP differences as a function of Δz for ΔD_{1x} = 0 ps/nm/km.

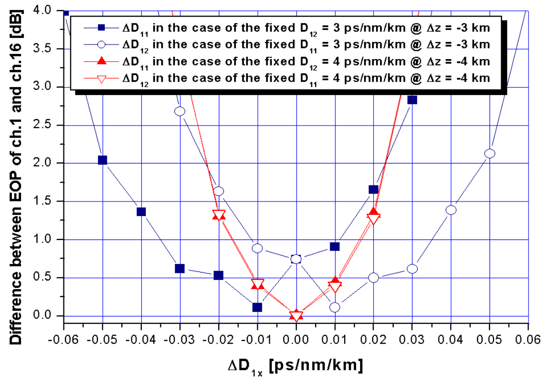
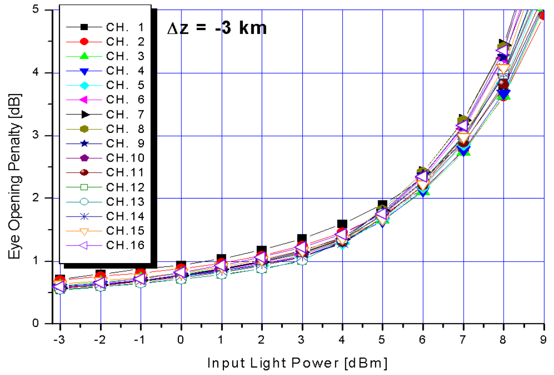
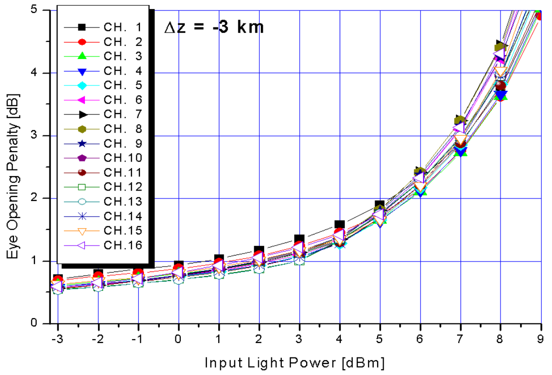


Fig. 5. EOP differences as a function of ΔD_{1x} when the OPC placed at Δz .

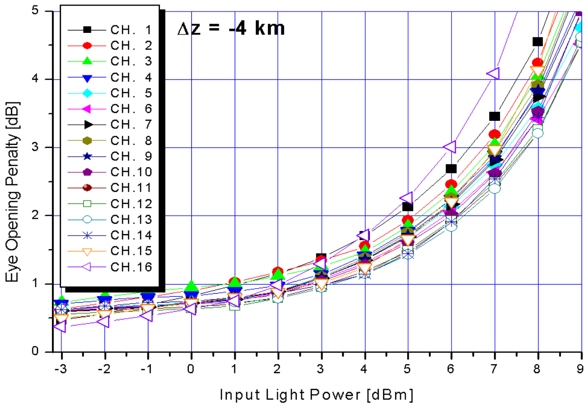
Fig. 5 shows EOP difference between channel 1 and 16 depending on the dispersion offset, ΔD_{1x} when the OPC placed at the position obtained from the results of Fig. 4. It is shown from Fig. 5 that EOP differences depending on ΔD_{11} under the condition of ΔD_{12} = 0 ps/nm/km is symmetry with EOP differences in the reverse case. For example, in WDM system with D_{1x} = 3 ps/nm/km, the optimal ΔD_{11} that result in the smallest EOP difference is obtained to -0.01 ps/nm/km in the case of assuming ΔD_{12} = 0 ps/nm/km (that is, D_{12}=3 ps/nm/km), while the optimal ΔD_{12} is +0.01 ps/nm/km in the case of assuming ΔD_{11} = 0 ps/nm/km (that is, D_{11}=3 ps/nm/km). This means that the optimal dispersion offset value between the two fiber sections must become to 0.01 ps/nm/km, i.e., the optimal D_{11} is decided to 2.99 ps/nm/km in the case of D_{12} =3 ps/nm/km and the optimal D_{12} is decided to 3.01 ps/nm/km in the case of D_{11}= 3 ps/nm/km. But, in WDM system with D_{1x} = 4 ps/nm/km, the optimal dispersion offset value between two fiber sections must become to 0 ps/nm/km, that is, it is no necessary to offset dispersion coefficients of both fiber section for efficiently compensating overall channels. In this case, the characteristics of EOP difference depending on one ΔD_{1x} is also symmetry with that depending on the other ΔD_{1x}, although these characteristics appear to be coincide with each other.



(a) @ D_{11} = 3 ps/nm/km & D_{12} = 3.010 ps/nm/km



(b) @ D_{11} = 2.990 ps/nm/km & D_{12} = 3 ps/nm/km



(c) @ $D_{11} = D_{12} = 4.0$ ps/nm/km

Fig. 6. EOP as a function of the launched light power in WDM system with the optimal parameters obtained from the result in Fig. 5.

Fig. 6 shows EOP of overall channels as a function of the launching light power in WDM system with the optimal OPC position and the optimal dispersion coefficients of fiber sections decided from the results of Fig. 4 and Fig. 5. If 1 dB EOP is allowed for performance criterion, it is confirmed that power penalty is reduced to 2 dB and 2.5 dB from the infinite values of Fig. 3 in the case of D_{1x} = 3 and 4 ps/nm/km, respectively. This fact means that compensation extents of overall channels are improved by only applying optimal parameters into WDM system with OPC, without the forming of the symmetrical distribution of optical power and local dispersion.

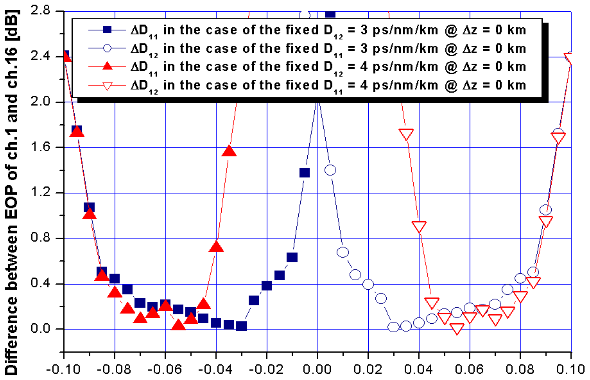


Fig. 7. EOP differences as a function of $\Delta D_{1}x$ in the case of assuming Δz = 0 km.

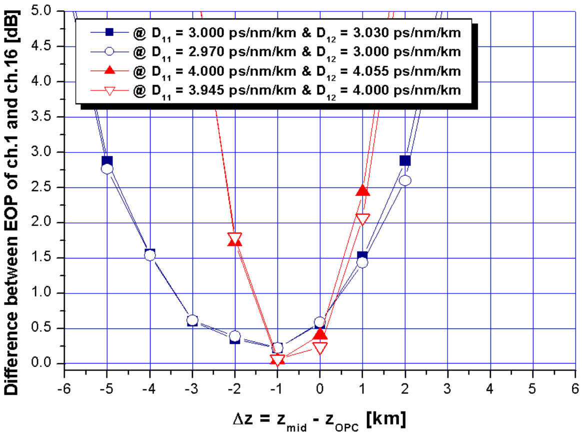


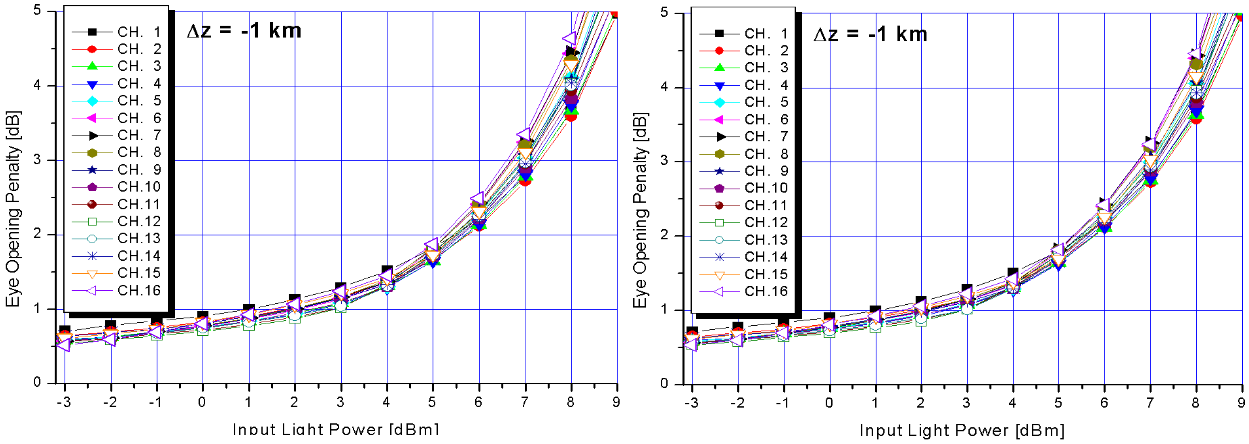
Fig. 8. EOP differences as a function of Δz for $\Delta D_{1}x$.

Up to now the optimal Δz is previously induced, and then the optimal ΔD_{1x} depending on this optimal Δz is consequently induced. It is required to exchange the procedure of finding out the optimal parameters for investigating the correlation of two optimal parameters.

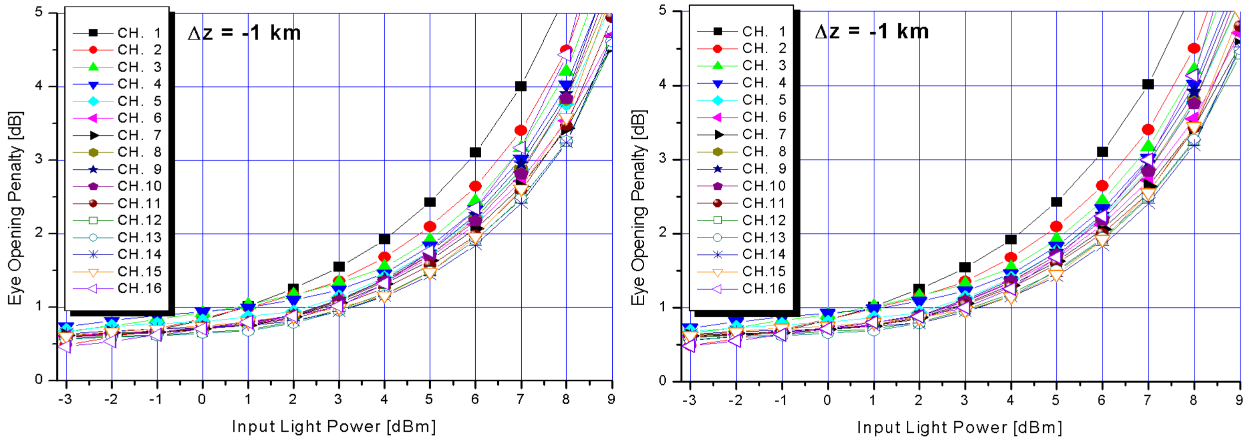
Fig. 7 and 8 show the results obtained through the reverse procedure of finding out the optimal parameters. That is, the optimal ΔD_{1x} is previously induced in the case of assuming Δz to be 0 km (the results were presented in Fig. 7), and then the optimal Δz is consequently induced under the optimal ΔD_{1x} decided thorough Fig. 7 (the results were presented in Fig. 8). It is shown from Fig. 7 that the characteristics of EOP difference depending on ΔD_{11} are also symmetry with that depending on ΔD_{12}, similar with Fig. 5. Thus, the optimal dispersion offset value between the two fiber sections must become to 0.03 and 0.045 ps/nm/km in WDM system with D_{1x}= 3 and 4 ps/nm/km, respectively

It is shown from Fig. 8 that EOP differences between channel 1 and 16 in all cases of optimizing dispersion coefficients of only first fiber section to $D_{1x} + \Delta D_{11}$ under the assumption of $D_{12} = D_{1x}$ are nearly coincide with those in all cases of optimizing dispersion coefficients of only second fiber section to $D_{1x} + \Delta D_{12}$ under the assumption of $D_{11} = D_{1x}$. It is confirmed that the optimal Δz are obtained to -1 km in both system with D_{1x} = 3 and 4 ps/nm/km.

Fig. 9 shows EOP of overall channels as a function of the launching light power in WDM system with the optimal OPC position and the optimal dispersion coefficients of



(a) @ D_{11} = 3 ps/nm/km, D_{12} = 3.030 ps/nm/km (b) @ D_{11} = 2.970 ps/nm/km, D_{12} = 3 ps/nm/km



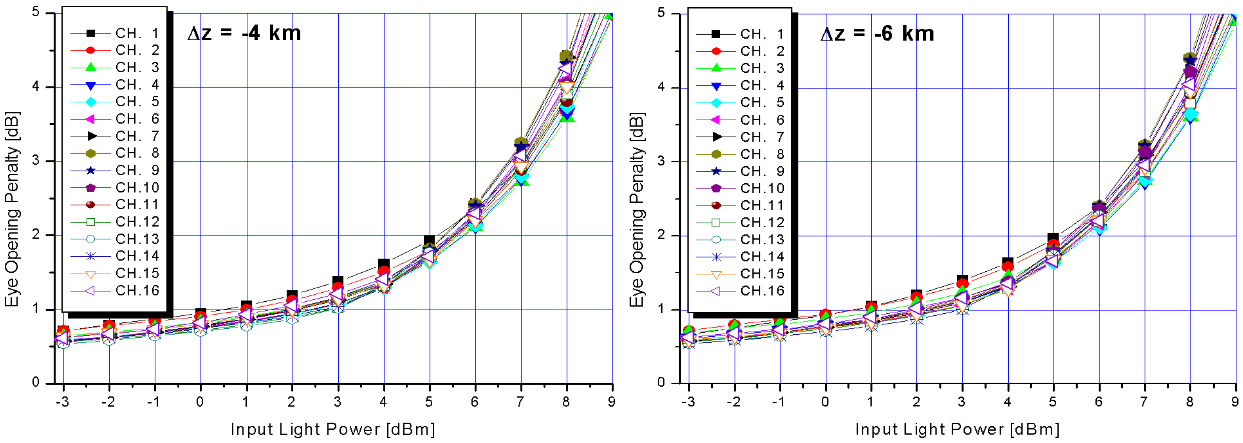
(c) @ D_{11} = 4 ps/nm/km, D_{12} 1= 4.055 ps/nm/km (d) @ D_{11} = 3.945 ps/nm/km, D_{12} = 4 ps/nm/km

Fig. 9. EOP as a function of the launched light power in WDM system with the optimal parameters obtained from the result in Fig. 8.

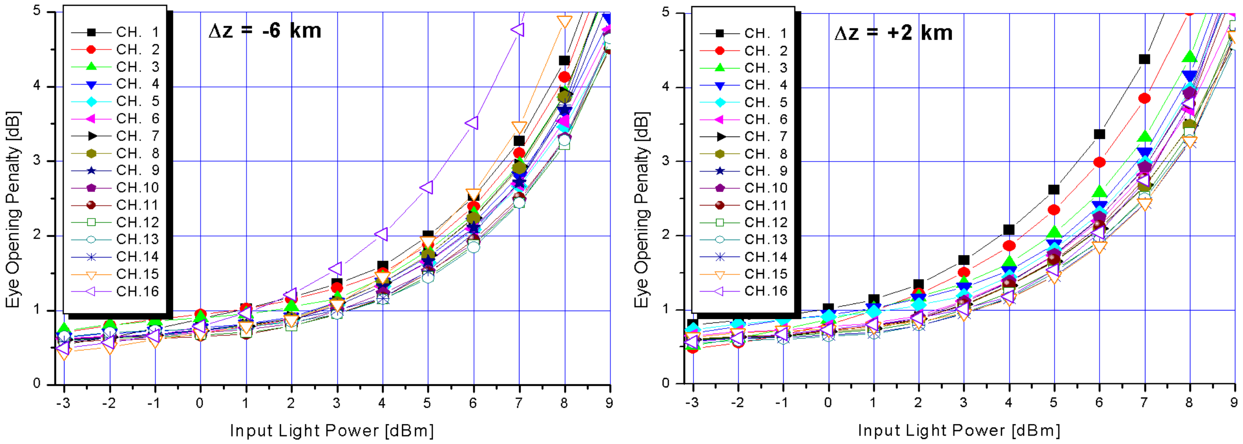
fibers decided from the results of Fig. 7 and Fig. 8. The left side figures of Fig. 9 are EOP characteristics obtained in the case of optimizing dispersion coefficients of second fiber section to $D_{1x} + \Delta D_{12}$ under the assumption of $D_{11} = D_{1x}$, while the right side figures of Fig. 9 are EOP characteristics obtained in the case of optimizing dispersion coefficients of first fiber section to $D_{1x} + \Delta D_{11}$ under the assumption of $D_{12} = D_{1x}$. It is shown that each EOP characteristics of the left side figures are similar with that of the right side figures.

By comparing Fig. 6 and 9, it is confirmed that the values of the optimal parameters are changed with the procedure of finding out the optimal parameters, but the compensation degrees of both cases are almost coincide with each other. This fact means that the optimal parameters induced in this research improve the system performance, but the procedure of finding out optimal parameters less affect on the performance improvements.

The important point to be confirmed is that the optimal parameter values induced in Fig. 4, 5, 7 and 8 will be used to design the flexible WDM system. 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. 4 and 5 with Fig. 7 and 8, it is confirmed that the optimal dispersion coefficient of the second fiber section is increased by 0.01 ps/nm/km in the case of fixing only D_{11} to 3 ps/nm/km or the optimal dispersion coefficient of the first fiber section is decreased by same amount in the case of fixing only D_{12} to 3 ps/nm/km as the OPC position is closer



(a) @ D_{11} = 3 ps/nm/km, D_{12} = 3.000 ps/nm/km (b) @ D_{11} = 3 ps/nm/km, D_{12} = 2.980 ps/nm/km



(c) @ D_{11} = 4 ps/nm/km, D_{12} = 3.9633 ps/nm/km (d) @ D_{11} = 4 ps/nm/km, D_{12} = 4.1099 ps/nm/km

Fig. 10. EOPas a function of the launched light power in WDM system with the flexibly selected parameters.

to the receiver by 1 km, because the optimal ΔD_{12} is +0.01 ps/nm/km when the optimal OPC position is 497km as illustrated in Fig. 4 and 5, while the optimal ΔD_{12} is +0.03 ps/nm/km when the optimal OPC position is 499 km as illustrated in Fig. 7 and 8. Also, the optimal dispersion of the second fiber section is decreased by 0.01 ps/nm/km in the case of fixing only D_{11} to 3 ps/nm/km as the OPC position is reversely closer to the transmitter by 1 km. These facts lead the OPC position equalizing D_{11} with D_{12}. This position is obtained to 496 km (that is Δz = -4 km). From the similar reason, that the optimal dispersion of the second fiber section is increased by 0.01833 ps/nm/km in the case of fixing only D_{11} to 4 ps/nm/km as the OPC position is closer to the receiver by 1 km.

That is, the OPC position or dispersion coefficient of fiber sections will be flexibly used in the design of WDM transmission system, for example, the optimal dispersion coefficient of second fiber section must be selected to be 2.98 (= 3(=D_{1x})+0.01×(-2 km)) ps/nm/km when OPC is placed at 494 km (this position is deviated by -2 km from 496 km, which makes $D_{11} = D_{12}$ to 3 ps/nm/km) of 1,000 km NZ-DSF, if dispersion coefficient of first fiber section was fixed to 3 ps/nm/km. Also, the optimal dispersion coefficient of second fiber section must be selected to be 3.9633(= 4(=D_{1x})+0.01833×(-2 km)) ps/nm/km or 4.1099 (= 4(=D_{1x})+0.01833×(6 km)) ps/nm/km when OPC is placed at 494 km or 502 km of 1,000 km NZ-DSF, respectively, when dispersion coefficient of first fiber section was fixed to 4 ps/nm/km.

Fig. 10 shows EOP of overall channels as a function of the launching light power in WDM system with the parameters previously mentioned. The results shown in Fig. 10 are nearly coincided with the results obtained from

Fig. 6 and 9. Thus the optimal parameters induced in this research are expected to contribute to realizing the flexible WDM system independent of OPC position.

Ⅳ. Conclusion

This paper deal with the searching method of the optimal OPC position and the optimal dispersion coefficients of fibers for efficiently compensating the distorted WDM signals in 16×40 Gbps WDM transmisson system.

It was confirmed that the numerical method considered in this research will be available to multi-channel WDM system, irrelevant with the searching procedure of these two optimal parameters only if two optimal parameters depend on each other. It was also confirmed that the optimal parameters induced in this research will provide the improvement of the received signal and the flexibility of WDM transmission system design. Thus the applying of the optimal parameters induced in the proposed method into multi-channels WDM system with OPC will be expected to replace with the method for making the symmetrical distribution of power and local dispersion.

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