Distortion Compensation of WDM Signals with initial frequency chirp in the Modified Mid-Span Spectral Inversion Technique

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Abstract—In this paper, the optimal value of optical phase conjugator (OPC) position and the optimal values of dispersion coefficients of fiber sections for the best compensation of the distorted WDM signals with frequency chirp of -1 are induced to alternate with the symmetrical distributions of power and local dispersion with respect to OPC, which is difficult to form in real optical link due to fiber attenuation in mid-span spectral inversion (MSSI) technique. It is confirmed that the Q-factors of total channels of -18.5 dBm launching light power exceed 16.9 dB, which value corresponds to 10-12 BER, by applying the induced optimal parameter values into 16 channels × 40 Gbps WDM system, on the other hand the Q-factors of only 9 channels exceed that value in WDM system with the conventional MSSI technique. Thus, it is expected to expand the availability of OPC in WDM system through the using of the optimal parameter values that are induced by the proposed method in this paper, without the symmetrical distributions of power and local dispersion.

Index Terms—Optical Phase Conjugator, MSSI, WDM system, Q-factor, Kerr nonlinearity, Chromatic Dispersion

I. INTRODUCTION

Optical phase conjugation is a promising technology to compensate for impairments in long-haul transmission system such as Kerr nonlinearities and chromatic dispersion. By optically conjugating the phase of signal in the mid-way of total transmission link, impairments that occurred in first fiber section of total transmission link (before conjugation) can be cancelled by impairments that occur in second fiber section of total transmission link (after conjugation)[1],[2].

One of the major limitations of optical phase conjugation for compensation of Kerr nonlinearities has been the requirement that power of signal and local dispersion are symmetric with respect to optical phase conjugator (OPC)[3]. But, it is difficult to obtain this requirement, because of the loss in real transmission link. Furthermore it is more difficult to obtain this requirement in WDM transmission systems, because WDM channels with different wavelength are transmitted through the same optical fiber, even if this requirement was obtained for a special WDM channel.

In this paper, a new scheme for the compensation of nonlinear effects and chromatic dispersion, without the need for symmetrizing the signal power and local dispersion in WDM, is numerically investigated. The proposed scheme in this paper is using the optimal OPC position and the optimal fiber dispersion coefficients, which are discussed in Section Ⅲ. OPC must exhibit the similar conversion efficiency, which is defined as a ratio of the conjugated power to the signal power [4], over total WDM channels for compensating these channels to similar system performance. Fortunately, this requirement is obtained 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 [5]. The total transmission capacity of WDM system is assumed to be 640 Gbps (i.e., 16 channels × 40 Gbps), and the intensity modulation formats of overall WDM channels are assumed to be NRZ.

II. MODELING OF WDM SYSTEM

The propagation of signal in a lossy, dispersive and nonlinear medium can be expressed by the nonlinear SchrÖdinger equation assuming a slowly varying envelope approximation [6]:

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

where $j,k = 1,2,\cdots,16(j \neq k)$, A_j represents the complex amplitude of signal of j-th channel, z is the propagation distance, α is the attenuation coefficient of the fiber, β_{2j} is the group velocity dispersion (GVD), β_{3j} is third-order dispersion (TOD), $\gamma_j (= 2\pi n_2 / A_{eff}\lambda_j)$ is the nonlinear coefficient, n_2 is nonlinear refractive index, A_{eff} is the effective core area of fiber, λ_j is the j-th channel signal wavelength and $T = t - z / v_j$ is the time measured in a retarded frame. The last two terms in

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Manuscript received January 22, 2007.

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equation (1) induce self phase modulation (SPM) and cross phase modulation (XPM), respectively. The last term, that is, XPM term is neglected in order to simplify numerical analysis in this paper.

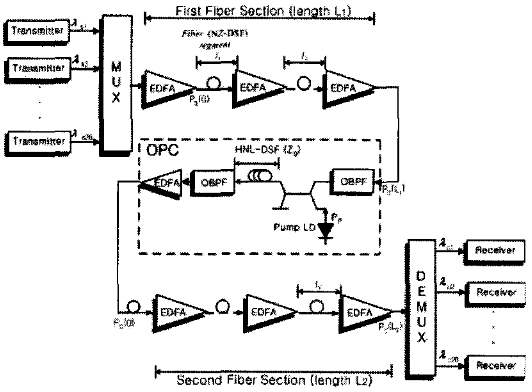


Fig. 1 The configuration of 16×40 Gbps WDM system with OPC.

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. The fiber span made of nonzero dispersion-shifted fiber (NZ-DSF) was characterized by α = 0.2 dB/km, dispersion coefficient D_{1x} = 3.5 ps/nm/km ($x = 1,2$, where 1, 2 present the first and second fiber section, respectively), A_{eff} = 72 μm^2, $n_2 = 2.5\times10^{-20}$ m^2/W and γ_1 = 1.41 W^{-1}km^{-1} at 1,550 nm.

Each laser diode in transmitter of Fig. 1 is externally modulated by an independent 40 Gbps 128(=2^7) pseudo random bit sequence (PRBS). The modulation format from external optical modulator is assumed to be NRZ. The output electric field of NRZ format is assumed to be second-order super-Gaussian pulse with 10 dB extinction ratio (ER). And, initial frequency chirp of Gaussian pulse is assumed to be -1.

The direct detection receiver 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[7]. The receiver bandwidth is assumed to be 0.65×bit-rate.

Table 1 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 illustrated in Fig. 1 are summarized in Table. 1. The 3-dB band-width of conversion efficiency η of the OPC is obtained to 48 nm (1526 ~ 1574 nm)[8].

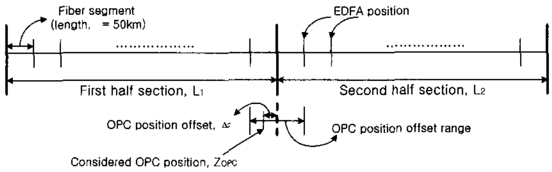
The center wavelength of first channel is assumed to be 1550.0 nm in this research. And, the center wavelengths of another WDM channels are assumed to be increased by 100 GHz (i.e., 0.8 nm) as ITU-T recommendation for dense WDM [9]. Thus the allocated 16 signal wavelengths (that is, from 1550.0 nm to 1562.0 nm) and these conjugated wavelengths (that is, from 1537.5 nm to 1549.5 nm) are belong within 3-dB bandwidth of η.

III. SCHEMES OF SEARCHING OPTIMAL PARAMETER VALUES

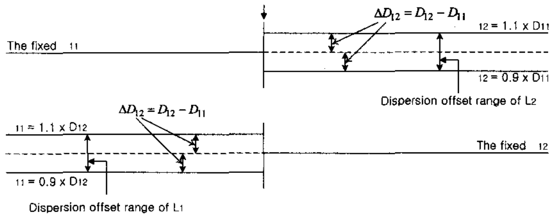
Watanabe and Shirasaki generalized the MSSI by considering that above fiber parameters can be functions of distance z [10]. The general condition for perfect distortion compensation is shown to be

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

where the TOD is neglected.



(a) scheme of finding out optimal OPC position



(b) scheme of finding out optimal dispersion coefficient

Fig. 2 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 both fiber sections need not equal with each other. 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 allocated WDM wavelengths in real transmission link, because overall WDM channels distributed over the relative broad band. Thus, this research aims to find out the optimal values of OPC position and dispersion coefficient of fiber sections, through the numerical approach, which are effective to compensate overall WDM channels.

The optimal value of OPC position is found out by evaluating the Q-factor for the channel 1 and 16 as a function of the OPC position offset Δz. The Δz is defined as the difference between OPC position z_{OPC} and mid-way z_{mid}, i.e. $\Delta z = z_{OPC} - z_{mid}$, where z_{mid} = 500 km and z_{OPC} varied within two span length (±50 km) from z_{mid}, as illustrated in Fig. 2(a). The reason of using channel 1 and 16 is that the wavelength difference between these two channels is greatly large. And the optimal values of dispersion coefficient of each fiber section is also found out by evaluating the Q-factor for the channel 1 and 16 as a function of dispersion offset, ΔD_{1x} ($x = 1,2$, where 1, 2 present first and second fiber section, respectively). The ΔD_{1x} is defined as the difference of dispersion coefficients between two fiber sections, that is $\Delta D_{11} = D_{11} - D_{12}$ and $\Delta D_{12} = D_{12} - D_{11}$. In ΔD_{11}, D_{12} is fixed to 3.5 ps/nm/km but D_{11} is varied within 90~110 % of D_{12}, and vice versa, as illustrated in Fig. 2(b).

IV. RESULTS AND DISCUSSION

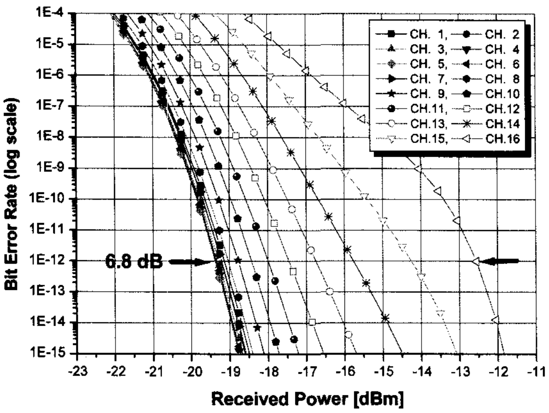


Fig. 3 BER characteristics in WDM system with the conventional MSSI technique.

Fig. 3 illustrates bit error rate (BER) characteristics of overall channels when OPC placed at mid-way of total transmission length and ΔD_{1x} = 0 ps/nm/km (that is, conventional MSSI). The BER characteristics can be calculated by the following equation [11]:

$$BER = \frac{1}{4}\left[erfc\sqrt{2}\left(\frac{(1-c_{ISI}^{+}-\tau)I_s}{\sigma_1}\right)\right] + \frac{1}{4}erfc\left[\sqrt{2}\left(\frac{(\tau-c_{ISI}^{-})I_s}{\sigma_0}\right)\right] \quad (3)$$

where the I_s is the time-averaged signal photo currents, c_{ISI}^{+} and c_{ISI}^{-} are the eye closures at mark('1') and space('0'), respectively, σ_1 and σ_0 are the standard deviation of the total noise including shot noise, signal-spontaneous beat noise, spontaneous-spontaneous beat noise, and thermal noise for mark and space, respectively.

It is shown that power penalty at 10^{-12} BER is obtained to 6.8 dB. Thus, it is difficult to maintain the similar performance for overall WDM channels in the conventional MSSI technique.

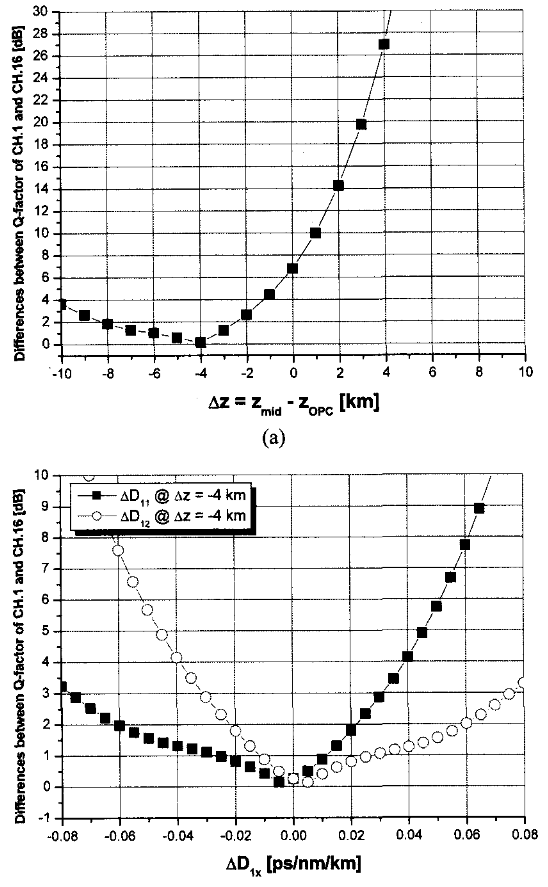


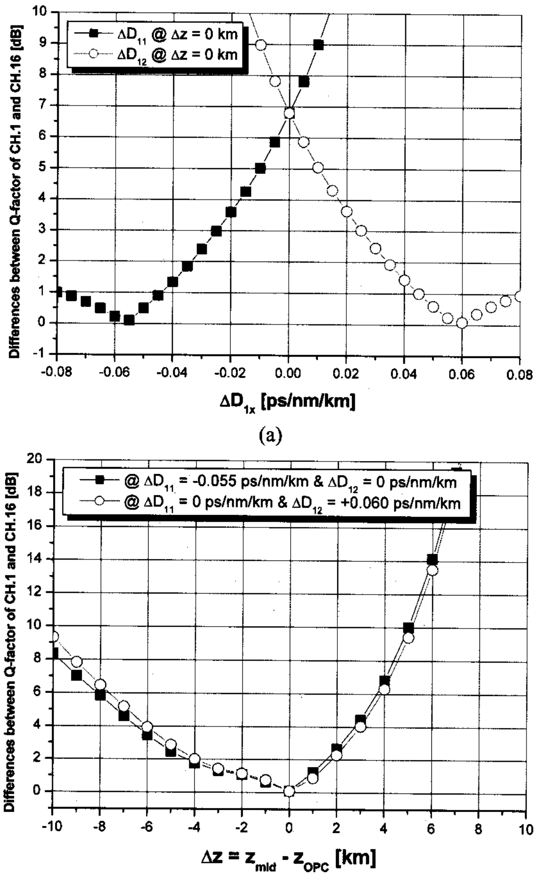
Fig. 4 Difference between Q-factor of channel 1 and 16. (a) depends on the Δz in the cases of ΔD_{11} = ΔD_{12} = 0 ps/nm/km, and (b) depends on ΔD_{1x} when the OPC placed at the optimal Δz, which is obtained from (a), respectively.

Fig. 4(a) shows the Q-factor difference between channel 1 and 16 of -17.5 dBm launching light power (after transmission) depending on the OPC position offset Δz, in order to find out the optimal OPC position. The Q-factor can be calculated by the following equation using the BER characteristics of (3) [12]:

$$Q - factor[dB] = 20\log\left(\sqrt{2}erfc^{-1}(2 \times BER)\right) \quad (4)$$

The Q-factor of 16.9 dB corresponds to the BER of 10^{-12}. And, these values correspond to error-free transmission after forward error correction (FEC) [13]. From Fig. 4(a), the optimal value of OPC position that results in the smallest Q-factor difference is 496 km (Δz = -4 km) in the cases of fixing D_{11} and D_{12} to 3.5 ps/nm/km.

Fig. 4(b) shows the Q-factor difference between channel 1 and 16 depending on the dispersion offset ΔD_{1x} in order to find out the optimal values of dispersion coefficients of each fiber section, when the OPC placed at 496 km as the result of Fig. 4(a). It is confirmed that the Q-factor differences depending on ΔD_{11} under the condition of ΔD_{12} = 0 ps/nm/km is symmetry with that of the reverse case. That is, the optimal value of ΔD_{11} is -0.005 ps/nm/km in the case of assuming ΔD_{12} = 0 ps/nm/km (that is, D_{12} = 3.5 ps/nm/km), while the optimal value of ΔD_{12} is +0.005 ps/nm/km in the case of assuming ΔD_{11} = 0 ps/nm/km (that is, D_{11} = 3.5 ps/nm/km). This means that the optimal value of dispersion offset between the two fiber sections must become to 0.005 ps/nm/km, i.e., the optimal value of D_{11} is decided to 3.495 ps/nm/km in the case of D_{12} = 3.5 ps/nm/km and the optimal value of D_{12} is decided to 3.505 ps/nm/km in the case of D_{11} = 3.5 ps/nm/km, when the OPC placed at 496 km.



(a)

(b)

Fig. 5 Differences of Q-factor between channel 1 and 16. (a) depends on the ΔD_{1x} in the case of assuming Δz = 0 km, and (b) depends on the Δz when dispersion offsets of each fiber sections D1x are selected to the optimal values, which are obtained from (a), respectively.

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

Fig. 5 shows the results obtained through the reverse procedure of Fig. 4. That is, the optimal values of ΔD_{1x} are previous-ly induced in the case of assuming Δz to be 0 km (the result was presented in Fig. 5(a)), and then the optimal value of Δz is consequently induced under the condition of fiber sections having ΔD_{1x} induced in Fig. 5(a) (the result was presented in Fig. 5(b)). It is shown from Fig. 5(a) that the characteristics of the Q-factor difference depending on ΔD_{11} are also symmetry with that depending on ΔD_{12}, but the optimal values of dispersion offset are slightly different with each other. That is, the optimal value of ΔD_{11} is obtained to -0.055 ps/nm/km in the case of assuming ΔD_{12} = 0 ps/nm/km, while the optimal value of ΔD_{12} +0.060 ps/nm/km in the case of assuming ΔD_{11} = 0 ps/nm/km. Also, it is shown from Fig. 5(b) that the optimal OPC position is 500 km (i.e., Δz =0 km), if the dispersion offsets of each fiber sections were decided to the above values.

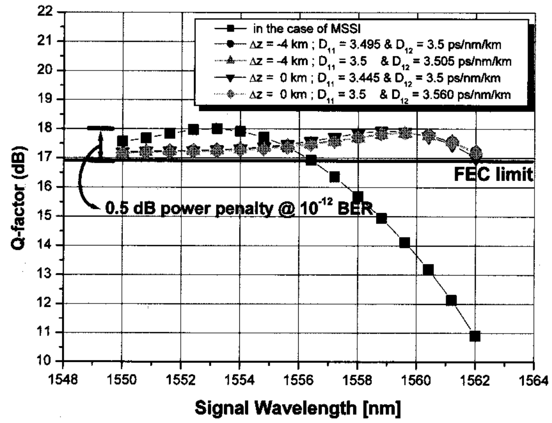


Fig. 6 The Q-factor of overall channels in the cases of applying the conventional MSSI technique or the best parameters obtained in Fig. 4 or 5.

It is necessary to confirm the effects of the optimal parameter values obtained in Fig. 4 and 5 on WDM system. Fig. 6 illustrates the Q-factor of overall channels of -18.5 dBm launching light power (after transmission) as a function of the signal wavelengths of 16 channels in WDM system with the conventional MSSI technique or with OPC of the optimal parameter values obtained in Fig. 4 or 5. In WDM system with the conventional MSSI technique, the Q-factors of upper than 16.9 dB are obtained only from channel 1 to 9 (i.e., only in signal wavelengths of 1550.0～1556.2 nm). But, the Q-factors of upper than 16.9 dB are obtained in overall channels, if the optimal parameter values of are applied into WDM system, independence on the procedure used in Fig. 4 or Fig. 5. Furthermore, these Q-factor characteristics of overall channels are almost coincided with one another, independent of the applied optimal parameter values. This means that the exact optimal values are largely dependent on the searching procedure, but the searching procedure is not seriously taken into account for the improvement of Q-factors.

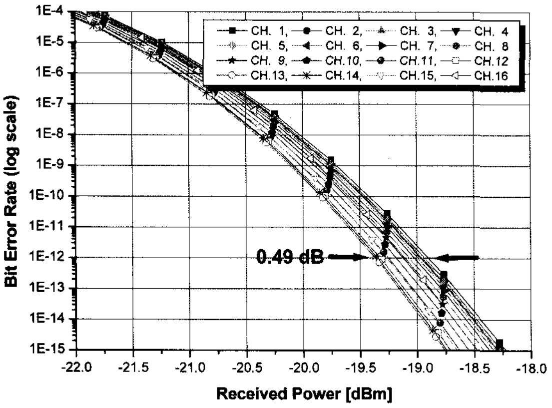


Fig. 7 BER characteristics in WDM system with Δz = -4 km, ΔD_{11} = -0.005 ps/nm/km and ΔD_{12} = 0 ps/nm/km.

And, it is known from the results of Fig. 6 that the minimum allowable launching light power of overall WDM channels will be -18.5 dBm, and power penalty is maintained within 0.5 dB if each channel's launching light powers of upper than -18.5 dBm was transmitted through NZ-DSF of 1,000 km. This fact is verified from Fig. 7, which shows the BER characteristics of overall channels in WDM system with OPC placed at 496 km, D_{11} = 3.495 ps/nm/km and D_{12} = 3.5 ps/nm/km. It is shown from Fig. 7 that the minimum sensitivity is almost -19.4 dBm, which is unequal with the minimum allowable launching light power of -18.5 dBm in Fig. 6, because the sensitivity is defined as the received light power resulting in the BER of 10^{-12} in this research.

V. CONCLUSION

The numerical method for searching the optimal position of OPC and the optimal dispersion coefficient of fiber sections was proposed, which is expected to replace with the method for forming the symmetrical distribution of power and local dispersion. 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 optimal parameter values only if two optimal parameters depend on each other.

The initial frequency chirp used in this research was the negative chirp of -1. The reason of the choosing of the negative chirp is that: optical pulse with the negative initial chirp is faster dispersed in fiber with an anomalous GVD than optical pulse with the positive initial chirp or chirp-free, thus the BER of optical pulse with the negative initial chirp is more degraded than the others, because of the relative small received peak power in longer signal wavelengths. Therefore, it will be expected that the optimal parameter values, which are different with the values induced in this research but are obtained from the same procedures with this research, should also contribute to the performance improvement in WDM signals with initial positive chirp and chirp-free, because power penalty was extremely improved even in the negative chirp more degrading the BER characteristics.

Thus, in future, the performance improvement through the optimal parameter values will be intended to analyze and compare, when the initial chirps of WDM channel signals are assumed to be the positive, negative and chirp-free.

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