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Compensation Characteristics Dependence on the Position of Optical Phase Conjugator in 320 Gbps WDM System

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Abstract

In this paper, optimal position of optical phase conjugator(OPC) for best compensating distorted WDM channels due to both chromatic dispersion and self phase modulation(SPM) is numerically investigated, and the compensation characteristics of overall WDM channels at this position is investigated, comparing with that in case of OPC placed at mid-way of total transmission length. It is confirmed that the compensation extents in WDM system with OPC is more improved by the shifting OPC position from the mid-way of total transmission length. And, we confirmed that the optimal position of OPC must be selected to the position decreasing not only eye opening penalty(EOP) of overall WDM channels but also EOP deviation between WDM channels, and this OPC position should be altered as various system parameters such as modulation format, and fiber dispersion, etc. Using proposed configuration, it is possible to remove all in-line dispersion compensator, reducing span losses and system costs.

Key words : Optical Phase Conjugator(OPC), Highly-Nonlinear Dispersion Shifted Fiber(HNL-DSF), Mid-Span Spectral Inversion(MSSI), WDM.

Ⅰ. Introduction

In high bit-rate transmission systems, an important origin of transmission penalty is the interaction between fiber chromatic dispersion and nonlinear effects[1]. So as to overcome both nonlinear and dispersive effects, mid-span spectral inversion(MSSI) has been identified as a very promising technique[2],[3]. This technique uses optical phase conjugator(OPC) for compensating distorted signals in mid-way of total transmission length. Theoretically, nonlinearity cancellation by MSSI requires a perfectly symmetrical distribution of power and local dispersion with respect to OPC position. Owing to the presence of fiber attenuation, this condition cannot be satisfied in real transmission links. Thus, the effectiveness of this technique has only been demonstrated in specifically designed links such as those based on the use of short amplifier spacing[4], or special fibers[5], or high-power Raman distributed amplification[6].

In this paper, optimal position of OPC is numerically investigated, for allowing nonlinearity cancellation with no other required equipment than an OPC. And then, we investigate the compensation characteristics of overall WDM channels at this position, comparing with that in case of OPC placed at mid-way of total transmission length.

The considered system has 8 WDM channels of 40 Gbps channel bit-rate. The intensity modulation format is assumed to be NRZ, or RZ. The split-step Fourier (SSF) method[7] is used for numerical simulation and eye-opening penalty(EOP) is used to evaluate the degree of distortion compensation. In order to simplify the analysis, cross phase modulation(XPM) of inter-channels is neglected and four-wave mixing(FWM) can be suppressed by using unequal channel spacing scheme[8].

Ⅱ. Modeling of 8×40 Gbps WDM System

Consider eight optical waves with the same polarization copropagating in an optical fiber. Let $A_j(z, t)$ be the slowly varying complex field envelope of each wave normalized to make equal to the instantaneous optical power. $A_j(z, t)$ satisfies the following equation[8] :

$$\frac{\partial A_j}{\partial z} = -\frac{\alpha}{2} A_j - \frac{i}{2} \beta_{2j} \frac{\partial^2 A_j}{\partial T^2}$$

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$$+\frac{1}{6}\beta_{3j}\frac{\partial^3 A_j}{\partial T^3}+i\gamma_j|A_j|^2 A_j$$
$$+2i\gamma_j|A_k|^2 A_j \qquad (1)$$

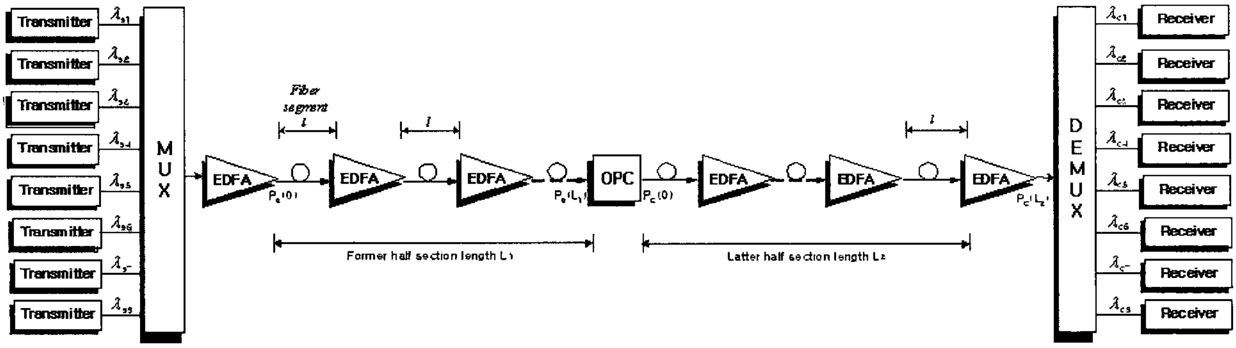
where j, k, l = 1, 2, ⋯, 8($j \neq k \neq l$), α is the attenuation coefficient of the fiber, λ_j is the j-th channel signal wavelength, β_{2j} is the fiber chromatic dispersion parameter, β_{3j} is the third-order chromatic dispersion parameter, γ_j is the nonlinear coefficient and $T=t-z/v_j$, respectively. The last two terms in equation (1) induce SPM and XPM, respectively. The last term, that is XPM term is neglected in order to simplify numerical analysis in this paper.

Fig. 1(a) shows a configuration of IM/DD WDM system with OPC placed at mid-way of total transmission length. And, Fig. 1(b) shows a transmission line configuration searching for optimal OPC position. In Fig. 1(b), OPC placed at a distance z_{OPC} from the transmitter. Total transmission length (L) is assumed to be 1,000 km and this will be divided two sections of respective length L_1 and L_2(with $L=L_1+L_2$). If position offset of OPC from mid-span position (z_{mid}) is presented as $\Delta z=z_{OPC}-z_{mid}$, L_1 will be $L/2+\Delta z$ and L_2 will be $L/2-\Delta z$, respectively. EOP of each channel will be investigated as a function of Δz, in following section Ⅲ.

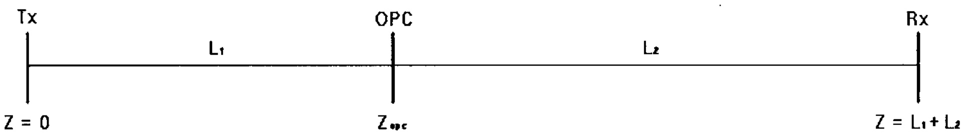
Table 1 summarizes simulation parameters of transmitter, receiver and fiber, respectively[7],[9]. We implement the program for the simulation based on the SSF method. The simulation step of this approach is selected

Table 1. Simulation parameters of transmitter, fiber and receiver.

Parameters		Symbol & value
Trans-mitter	Bit rate	R_b=320 Gbps (=8×40 Gbps)
	Waveform	NRZ super-Gaussian(m=2) RZ super-Gaussian(m=2)
	Pattern	PRBS 2^7 (128 bits)
	Chirp	0
Fiber	Type	conventional DSF
	Loss	$\alpha_1=\alpha_2$=0.2 dB/km
	Total transmission length	1,000 km
	Dispersion coefficient	$D_{11}=D_{12}$=0.4, 1.6 ps/nm/km
	Nonlinear refractive coefficient	$n_2=2.36\times10^{-26}$ km^2/W
	Effective core section	A_{eff}=50 μm^2
	Number of EDFA	20
	EDFA spacing (Fiber section)	l=50 km
Recei-ver	Type	PIN-PD with EDFA pre-amp
	EDFA noise figure	5 dB
	Optical bandwidth	1 nm
	Receiver bandwidth	0.65×R_b



(a) MSSI systems



(b) Transmission line configuration for optimal OPC position

Fig. 1. Simulation model.

to 1 km in order to decrease the calculation time. In order to overcome the accuracy degradation owing to relative large step, we carry out 10 times simulation of 2^7 PRBS, and then we obtain the averaged value. Also, we neglect the effect of accumulate spontaneous emission(ASE) noise of EDFA in order to evaluate only the effect of fiber dispersion and SPM on WDM signals, therefore the EDFA is modeled to exp(αl) in this research.

Fig. 2 shows the configuration of the OPC using highly-nonlinear dispersion shifted fiber(HNL-DSF), and Table 2 summarizes OPC parameters in this approach. The conversion efficiency η is defined as a ratio of the four-wave mixing(FWM) product power to the input probe(signal) power[10]. The calculated highest value of η using Table 2 parameters is 0.18 dB, and 3-dB bandwidth is 34 nm(1532.5~1566.5 nm)[11].

The unequal channel spacing proposed by F. Forghieri *et al.* is used to suppress the crosstalk due to FWM effects. The signal wavelengths of WDM channel used in this research are 1550.2 nm, 1551.2 nm, 1553.2 nm, 1554.4 nm, 1556.0 nm, 1557.8 nm, 1560.0 nm and 1561.4 nm. Therefore, WDM channel signal wavelengths and conjugated light wavelengths belong to 3-dB bandwidth of OPC using HNL-DSF.

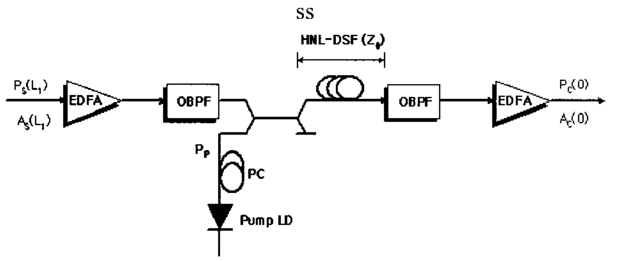


Fig. 2. Optical phase conjugator using highly-nonlinear dispersion shifted fiber.

Table 2. Simulation parameters of OPC using HNL-DSF.

Parameters	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	$dD_0/d\lambda$= 0.032 ps/nm^2/km
Pump light wavelength	λ_p=1549.5 nm
Pump light power	P_p=18.5 dBm

Ⅲ. Simulation Results and Discussion

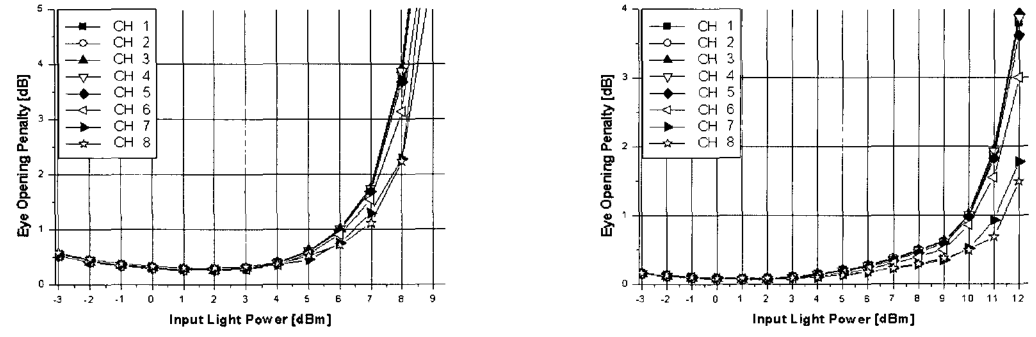
Fig. 3 shows EOP as a function of the input signal light power when NRZ, or RZ format channels is propagated in MSSI system with 0.4, or 1.6 ps/nm/km dispersion coefficient, respectively. If 1 dB EOP is allowed, in case of NRZ format transmission, maximum tolerable input power of overall channels are within almost 6~7 dBm at D=0.4 ps/nm/km and 4.5~6 dBm at D=1.6 ps/nm/km, respectively. And, in case of RZ format transmission, maximum tolerable input power of overall channels are within 10~11.3 dBm at D=0.4 ps/nm/km and 1.5~8 dBm at D=1.6 ps/nm/km, respectively. It is confirmed that the maximum difference between allowable input powers is generally appeared between channel 1 and channel 8.

Fig. 4 shows EOP of channel 1 and channel 8 as a function of OPC position offset (Δz) at input signal light power resulting 1 dB EOP in all cases of Fig. 3. From Fig. 4, it is shown that the compensation extents dependence on Δz are obviously distinguished as input light power and wavelength of transmission channel are changed. For example, the minimum EOP of channel 1 appeared at $\Delta z=-12$ km, on the other hand that of channel 8 appeared at $\Delta z=-5$ km or -3 km according to input light power, when NRZ signals are propagated in WDM system with D=0.4 ps/nm/km.

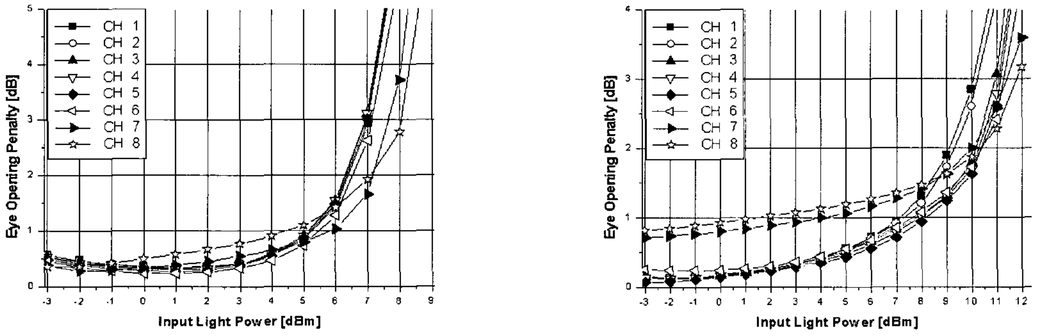
It should be confront a problem : where is an optimal OPC position from a viewpoint of excellently compensating overall channel in various cases. One method solving this problem is evaluating and comparing of overall channels EOP at several Δz resulting the minimum EOPs for various cases of Fig. 4. Table 3 presents the selected Δz in each case of Fig. 4 for evaluating overall channels EOP.

Fig. 5 shows EOP of overall NRZ channels propagated in D=0.4 ps/nm/km system as a function of input light power(case 1 and 2 in Table 3). Comparing Fig. 5 with Fig. 3(a), the desirable OPC position is 495 km ($\Delta z=-5$ km) rather than 488 km($\Delta z=-12$ km) for generally compensating overall channels, because difference of input light power resulting 1 dB EOP between channels at this position is reduced to 0.4 dB from almost 1 dB obtained in case of Δz=0.

In this case and the rest cases of Table 3, the maximum input light powers resulting 1 dB EOP for overall channels will be examined as following, in order to compare compensation extents in OPC placed at offset(Δz) and at mid-way of total transmission length.

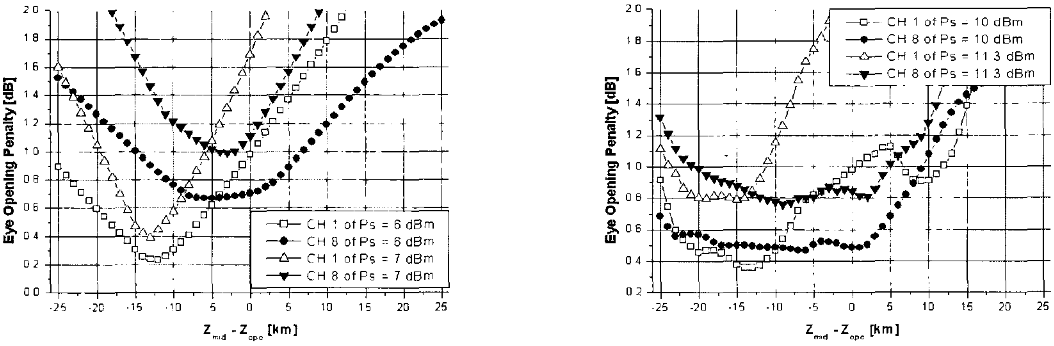


(a) D=0.4 ps/nm/km ; NRZ (b) D=0.4 ps/nm/km ; RZ

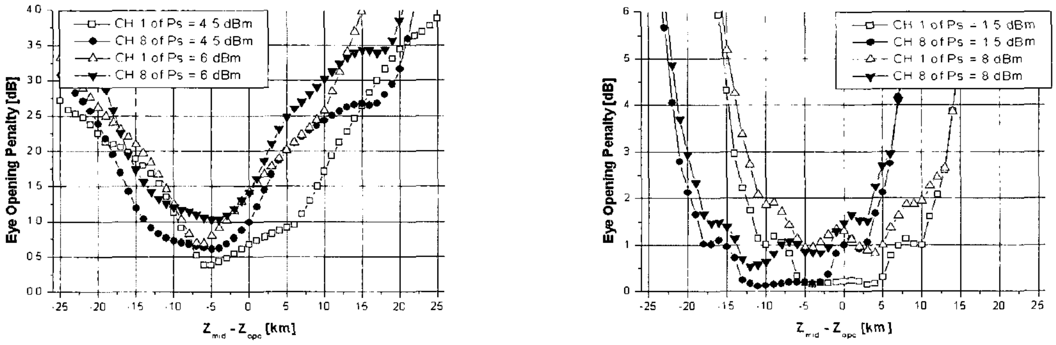


(c) D=1.6 ps/nm/km ; NRZ (d) D=1.6 ps/nm/km ; RZ

Fig. 3. EOP as a function of input light power for WDM system with MSSI method.



(a) D=0.4 ps/nm/km ; NRZ (b) D=0.4 ps/nm/km ; RZ



(c) D=1.6 ps/nm/km ; NRZ (d) D=1.6 ps/nm/km ; RZ

Fig. 4. EOP of channel 1 and channel 8 as a function of OPC position offset.

Table 3. Various cases for evaluating EOP of overall channels at Δz.

Case number	Modulation format	D [ps/nm/km]	Δz [km]	z_{OPC} [km]
1	NRZ	0.4	− 12	488
2	NRZ	0.4	− 5	495
3	NRZ	0.4	0	500
4	RZ	0.4	− 15	485
5	RZ	0.4	− 13	487
6	RZ	0.4	− 5	495
7	RZ	0.4	0	500
8	NRZ	1.6	− 8	492
9	NRZ	1.6	− 5	495
10	NRZ	1.6	0	500
11	RZ	1.6	− 5	495
12	RZ	1.6	0	500
13	RZ	1.6	+3	503

Fig. 6 shows each channels maximum input light powers resulting 1 dB EOP for various cases in Table 3. The values in x-axis present case number in first row of Table 3. It is shown from Fig. 5 that optimal OPC position excellently compensating for overall WDM channels is 495 km in case of NRZ signal transmission at D=0.4 ps/nm/km, or D=1.6 ps/nm/km. Also, in case of RZ transmission, optimal OPC positions are 487 km at D=0.4 ps/nm/km and 495 km at D=1.6 ps/nm/km, respectively.

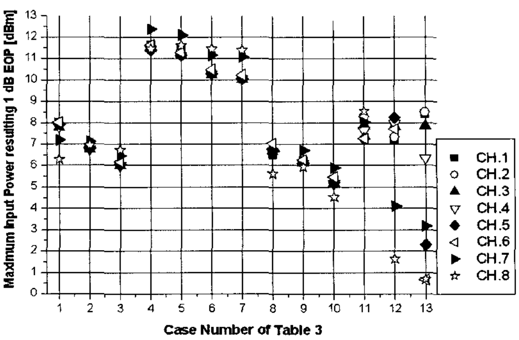


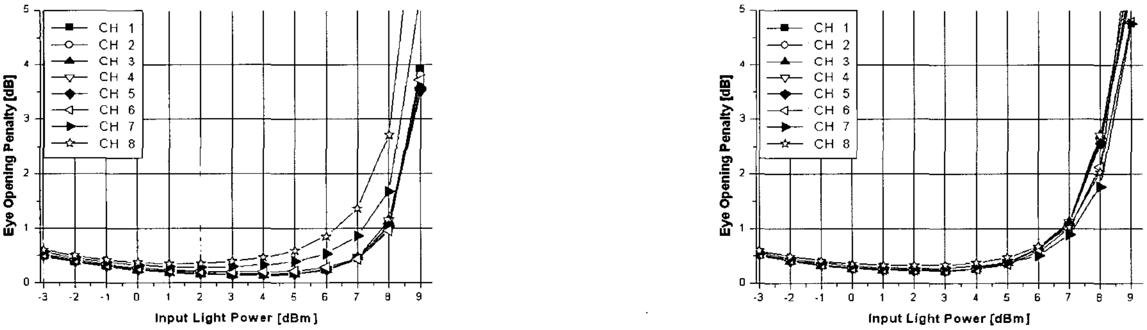
Fig. 6. Maximum input light power resulting 1 dB EOP for various cases.

We think that this result is generated by the slight difference of dispersion parameter of second half section (β_{22}) from that of first half section (β_{21}), owing to the wavelength shift of phase-conjugated signal in MSSI system. Furthermore, sideband modulation instability[12] is added to the above effect. That is, the compensation degradation due to both effects in MSSI system is improved by the shifting OPC position.

The important point to be confirmed is that, differences of maximum input light power resulting 1 dB EOP between channels are largely reduced at 495 km OPC position in case of RZ signal transmission at D = 1.6 ps/nm/km than those of another cases. This result means that, it is necessary to select accurately OPC position for compensating overall channels in the case of RZ transmission rather than NRZ transmission, and large dispersion coefficient fiber rather than small dispersion coefficient fiber.

Ⅳ. Conclusion

Up to now, the optimal OPC position excellently compensating overall channels was induced in various 40 Gbps × 8 channel WDM systems, and the compensation characteristics of overall WDM channels at this



(a) z_{OPC} = 488 km (Δz= − 12 km)

(b) z_{OPC} = 495 km (Δz= − 5 km)

Fig. 5. EOP as a function of input light power when OPC is placed at 488 km, or 495 km for NRZ transmission in WDM system with D=0.4 ps/nm/km.

position was investigated, comparing with that in case of OPC positioned at mid-way of total transmission length.

It was confirmed that, in WDM system with OPC for best compensating the distorted WDM signals, the optimal position of OPC is shifted from mid-way of total transmission length, because of the dispersion difference between both fiber section and the effect of sideband modulation instability. And optimal position of OPC must be selected to the position decreasing not only EOP of overall WDM channels but also EOP deviation between WDM channels, dependence on modulation format and fiber dispersion, etc.

In future researches, it will be evaluates optimal OPC position in WDM systems having not only SPM but also cross phase modulation(XPM) as origin of nonlinear distortion, and having initial frequency chirp in optical transmitter section.

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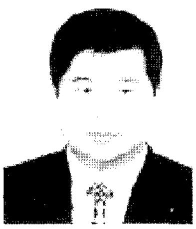

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