Characteristics of Compensation for Distorted Optical Pulse with Initial Frequency Chirp in 3×40 Gbps WDM Systems Adopted Mid-Span Spectral Inversion

Seong-Real Lee[1] · Yun-Hyun Lee[2]

Abstract

In this paper, we investigated the degree of compensation for distorted optical pulse of wavelength division multiplexed(WDM) channel with initial frequency chirp generated in optical transmitter. The WDM channel signal distortion is due to chromatic dispersion, self phase modulation(SPM) and cross phase modulation(XPM) in fiber. The considered system is 3×40 Gbps intensity modulation direct detection(IM/DD) WDM transmission systems, which adopted mid-span spectral inversion(MSSI) as compensation method. We confirmed that the effect of initial frequency chirp on compensation for signal distortion due to a SPM is gradually decreased as a dispersion coefficient of fiber becomes gradually small. But, in the aspect of a compensation for signal distortion due to both SPM and XPM, the effect of initial frequency chirp on compensation is gradually decreased as a dispersion coefficient of fiber becomes gradually large.

Key words : Mid-Span Spectral Inversion(MSSI), Highly Nonlinear Dispersion Shifted Fiber(HNL-DSF), Self Phase Modulation(SPM), Cross Phase Modulation(XPM), Frequency Chirp.

Ⅰ. Introduction

A mid-span spectral inversion(MSSI) is one of the compensation methods of optical pulse distortion due to the wavelength dispersion and Kerr effects in fiber[1],[2]. In MSSI, the compensation for optical pulse distortion due to self phase modulation(SPM) is limited by the asymmetry of the strength of the Kerr effects along the fiber with respect to the optical phase conjugator(OPC) position. But this is solved by applying a path-averaged intensity approximation(PAIA) method to MSSI[3],[4].

It is possible to realize a wideband wavelength division multiplexed(WDM) systems by using highly nonlinear dispersion shifted fiber(HNL-DSF) instead of conventional dispersion shifted fiber(DSF) as nonlinear medium of OPC, and by selecting pump light power of HNL-DSF OPC in concern with transmission length, fiber dispersion and modulation format[5].

The origin of distorted signal in intensity modulation /direct detection(IM/DD) WDM systems includes cross-phase modulation(XPM) in addition to chromatic dispersion and SPM. A XPM effect on WDM signal distortion is gradually increased as number of WDM channels are gradually increased. But it is confirmed that reception performance of IM/DD WDM influenced by chromatic dispersion, SPM and XPM is improved by applying MSSI using HNL-DSF OPC to IM/DD WDM systems in the previous research[6].

The semiconductor laser generates a optical pulse with frequency chirp in IM/DD systems. The frequency chirp effect on signal transmission must be considered for realization of wideband WDM systems, because this effect became another origin of performance deterioration[7].

In this paper, we investigated the initial frequency chirp effect on degree of compensation in IM/DD WDM systems based on PAIA MSSI. We assumed optical pulse distortion is to be generated by chromatic dispersion, SPM and XPM. The evaluation of frequency chirp effect on compensation is accomplished by calculating eye opening penalty(EOP) of optical pulse with up-chirp and down-chirp as compared with that of chirp-free optical pulse.

We used the split-step Fourier(SSF) numerical method in 3×40 Gbps WDM systems with 1,000 km transmission length. And system parameters were

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selected in accordance with [5]. The individual WDM signal is assumed to be probe channel directly modulated by information '0' and '1'. In order to simplify the analysis, we neglected the effect of four-wave mixing(FWM) on WDM channel, since FWM can be suppressed by using of unequal channel spacing scheme[8].

Ⅱ. Model of 3×40 Gbps WDM Systems with PAIA MSSI

Fig. 1 showed the model of 3-channel WDM system in this paper. The channel bit rate is 40 Gbps. The j-th slowly varying signal envelope of WDM system, A_j satisfy the following equation[9],

$$\frac{\partial A_j}{\partial z}+\frac{\alpha}{2}A_j+\frac{i}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial T^2} = i\gamma_j P_j A_j+2i\gamma_j[P_k(T-d_{jk}z,\ 0)+P_l(T-d_{jl}z,\ 0)]A_j \tag{1}$$

where $j,\ k,\ l=1,\ 2,\ 3(j\neq k\neq l)$, α is the attenuation coefficient, $\gamma_j=n_2\omega_j/cA_{eff}$ is the nonlinear coefficient, n_2 is the nonlinear refractive index, ω_j is the angle frequency, A_{eff} is the effective core area, $T=t-z/v_j$, v_j, is the group velocity. The first term of right hand side lead to SPM, and the second term result in XPM. The $d_{jk}(=1/v_j-1/v_k)$ and $d_{jl}(=1/v_j-1/v_l)$ are defined as a walk-off parameter. In a nonlinear dispersion region, walk-off parameters are approximated to $D\triangle\lambda_{jk}$ and $D\triangle\lambda_{jl}$, respectively, where D is the dispersion coefficient, $\triangle\lambda_{jk}$ and $\triangle\lambda_{jl}$ are the wavelength separation between the two channels.

Each laser diode in transmitter is 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 as following equation,

$$A(0,t) = \sqrt{P_0}\exp\left[-\frac{(1+iC)}{2}\left(\frac{t}{t_0}\right)^{2m}\right] \tag{2}$$

where P_0 is the input light power, m is the order of optical pulse, $t_0(=1/1.825\times R_b)$ is the half-width[10]. And C is a chirp parameter, which presents a frequency variation of external optical modulator or laser diode directly modulated by data, as following equation (3)[11]. In this paper, chirp parameter is assumed to be down-chirp of −1.0, −0.5, up-chirp of +1.0, +0.5 and zero-chirp.

$$C = \frac{dArg(A_0)}{dt}\Big/\left(\frac{1}{|A_0|}\frac{d|A_0|}{dt}\right) \tag{3}$$

The direct detection receiver consist of the pre-amplifier of erbium-doped fiber amplifier(EDFA) with 5 dB noise figure, the optical filter of 1 nm bandwidth, PIN diode, pulse shaping filter(Butterworth filter) and the decision circuit[12]. The receiver bandwidth is assumed to be $0.65\times R_b$.

The OPC used in the WDM systems of Fig. 1 must have a flattened conversion characteristics over the bandwidth of systems. It was confirmed in the [5] that overall WDM channels occupying wideband are converted to conjugated wave with equal or similar conversion efficient by using of HNL-DSF with a small dispersion slope instead of conventional DSF as nonlinear medium of OPC.

Fig. 2 and table 1 showed the configuration and parameters of OPC using HNL-DSF, respectively. The conversion efficiency η is defined as a ratio of the FWM product power to the input probe(signal) power. The calculated maximum conversion coefficient using of Table 1 parameter is 0.18 dB and 3-dB bandwidth of OPC is 18 nm(1539.5~1557.5 nm)[5].

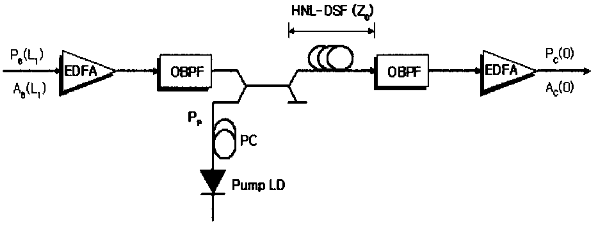


Fig. 2. Optical phase conjugator using highly-nonlinear dispersion shifted fiber.

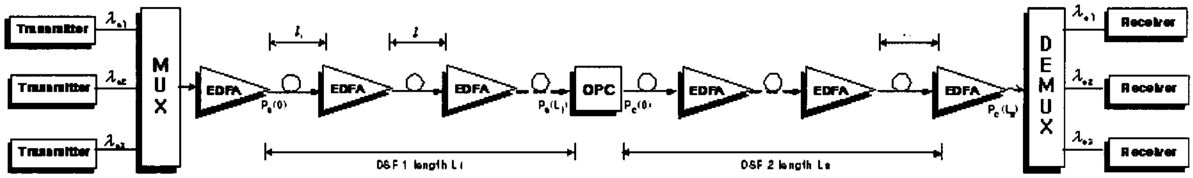


Fig. 1. Simulation model of 3×40 Gbps WDM system.

Table 1. Simulation parameters of fiber and OPC using HNL-DSF.

Parameters		Symbol & value
Fiber	Type	conventional DSF
	Loss	$\alpha_1 = \alpha_2$ = 0.2 dB/km
	Total length	variable ($L_1 = L_2$)
	Dispersion coefficient	$D_1 = D_2$ = 0.1 ps/nm/km
	Nonlinear refractive coefficient	$n_2 = 2.36 \times 10^{-26}$ km^2/W
	Effective core section	A_{eff} = 50 μm^2
	Number of EDFA	20
	EDFA spacing (Fiber section)	l = 50 km
OPC using HNL-DSF	HNL-DSF loss	α_o = 0.61 dB/km
	HNL-DSF nonlinear coefficient	γ_o = 20.4 W^{-1} km^{-1}
	HNL-DSF length	z_o = 0.75 km
	HNL-DSF ZDW	λ_o = 1550.0 nm
	HNL-DSF dispersion slope	$dD_o/d\lambda$ = 0.032 ps/nm^2/km
	Pump light wavelength	λ_p = 1548.3 nm
	Pump light power	P_p = 18.5 dBm

In this paper, channel signal wavelengths are assumed to be 1550.0 nm, 1551.6 nm and 1553.0 nm, respectively. The conjugated wavelengths resulted from HNL-DSF OPC are 1546.6 nm, 1545.0 nm and 1543.6 nm, respectively. Therefore overall channel signal wavelengths and conjugated wavelengths are within 3-dB bandwidth of HNL-DSF OPC. And the simulation parameter of fiber is also summarized in Table 1.

Ⅲ. Simulation Results and Discussion

In this paper, so as to evaluate the initial frequency chirp effect on compensation, we define EOP difference as following equation,

$$EOP\ Difference\ [dB] = EOP|_{chirp\ free} - EOP|_{chirp\ presented} \tag{4}$$

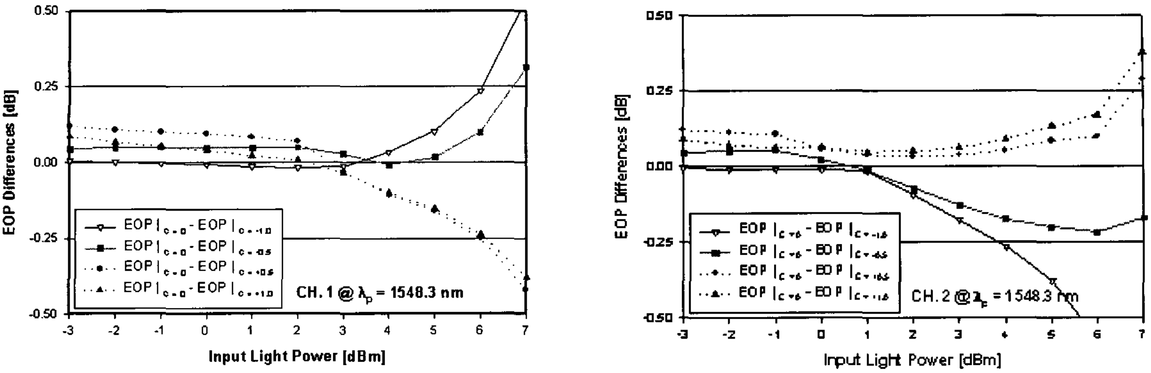
where $EOP|_{chirp\ free}$ is EOP of compensated signal with zero-chirp and $EOP|_{chirp\ presented.}$ is EOP of compensated signal with down-chirp(or up-chirp), respectively.

Fig. 3 shows EOP difference of each channel in IM/DD WDM system with 0.1 ps/nm/km fiber dispersion coefficient as a function of input signal light power in the both case of compensation for signal distortion due to chromatic dispersion and SPM, and due to chromatic dispersion, SPM and XPM, respectively. The effect of initial frequency chirp on compensation is similarly presented in overall WDM channels when signal distortion due to chromatic dispersion and SPM is compensated by MSSI. But the effect of initial frequency chirp on compensation is differently presented at each WDM channel when signal distortion due to chromatic dispersion SPM and XPM is compensated by MSSI. Particualarly, the compensation of channel 2 is quite different with that of channel 1 and channel 3.

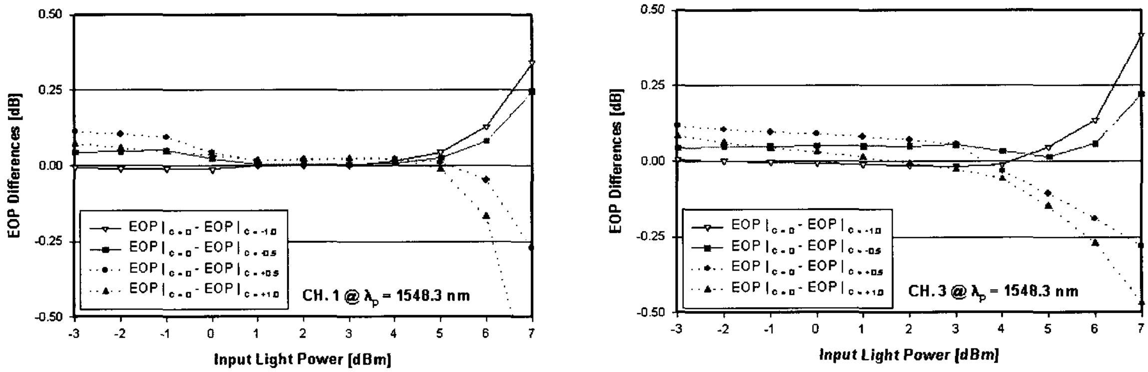
This result means that the initial chirp should complexly influence to compensation of signal distortion due to XPM in IM/DD WDM system with small dispersion coefficient regardless of input light power. This result is generated by following reasons : the addition of phase modulation(PM) owing to initial frequency chirp to PM owing to XPM is occured differently and complexly in each signal channel, furthermore this addition mechanism is more complicated by random bit sequence of each channel and increasement of group velocity difference between signal channel and neighbor channels in small fiber dispersion coefficient.

Fig. 4 shows EOP difference of each channel as a function of input signal light power in IM/DD WDM-system with 0.4 ps/nm/km fiber dispersion coefficient. It is confirmed that the initial frequency chirp effect on compensation is similarly presented in overall WDM channels at lower than 6 dBm input light power when signal distortion due to chromatic dispersion, SPM and XPM is compensated by MSSI. It is showed that EOP difference of optical pulse with − 0.5 initial chirp is to be equal in every channel in the both case of compensation for signal distortion due to chromatic dispersion and SPM, and due to chromatic dispersion, SPM and XPM.

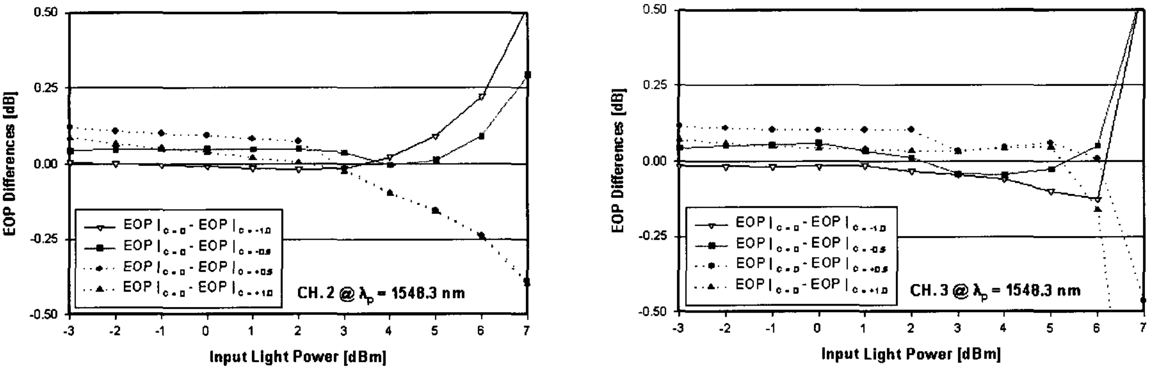
Fig. 5 presents EOP difference of each channel as a function of input signal light power in IM/DD WDM system with 1.6 ps/nm/km fiber dispersion coefficient. It is confirmed that the initial frequency chirp effect on compensation is more similarly presented in overall WDM channels than that of Fig. 4 at lower than



(a) channel 1: without XPM effect (d) channel 2: with XPM effect



(b) channel 2: with XPM effect (e) channel 3: without XPM effect



(c) channel 2: without XPM effect (f) channel 3: with XPM effect

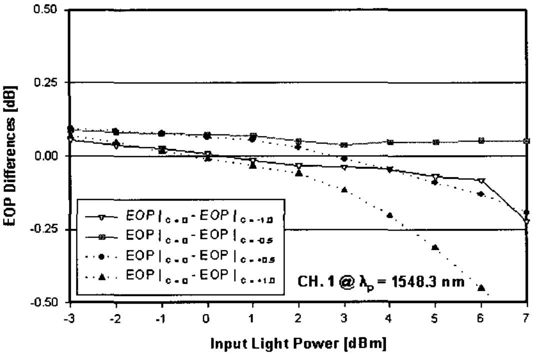
Fig. 3. EOP differences of each channel as a function of input signal light power in WDM transmission systems with D=0.1 ps/nm/km.

6 dBm input light power when signal distortion due to chromatic dispersion, SPM and XPM is compensated by MSSI. But the effect of initial frequency chirp on compensation is to be different in each WDM channels when signal distortion due to chromatic dispersion and SPM is compensated by MSSI.

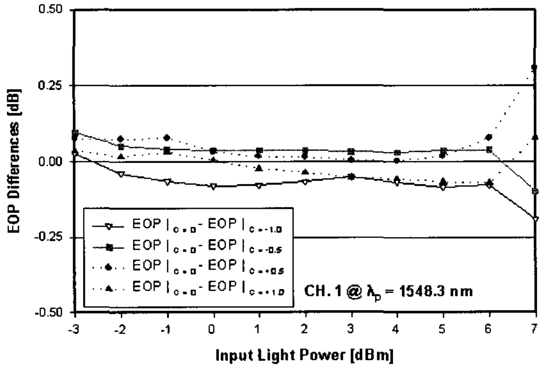
Ⅳ. Conclusion

We discussed the initial frequency chirp effect on compensation in IM/DD WDM systems based on PAIA MSSI compensation method for the optical pulse distortion due to chromatic dispersion, SPM and XPM.

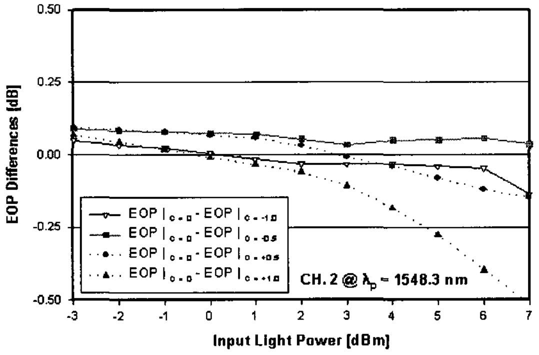
It is confirmed that the effect of initial frequency chirp on compensation for signal distortion due to a SPM is gradually decreased as a fiber dispersion coefficient becomes gradually small. But, in the aspect



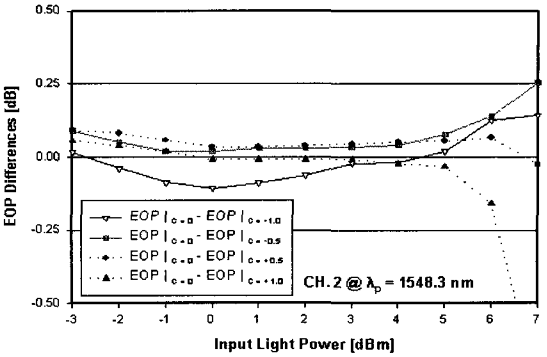
(a) channel 1: without XPM effect



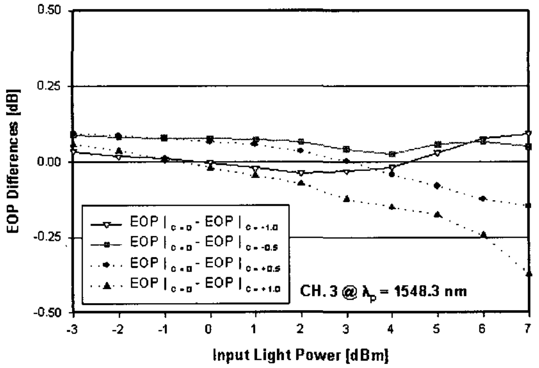
(b) channel 1: with XPM effect



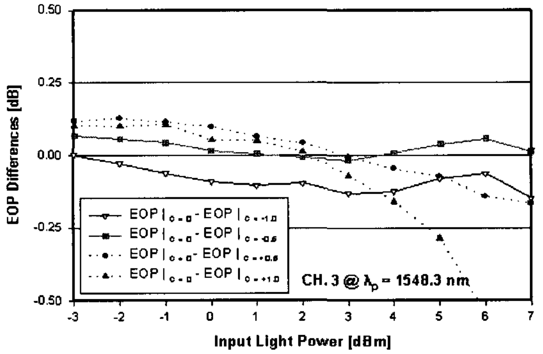
(c) channel 2: without XPM effect



(d) channel 2: with XPM effect



(e) channel 3: without XPM effect



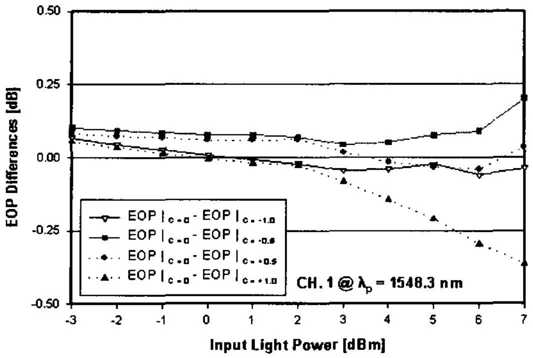
(f) channel 3: with XPM effect

Fig. 4. EOP differences of each channel as a function of input signal light power in WDM transmission systems with D=0.4 ps/nm/km.

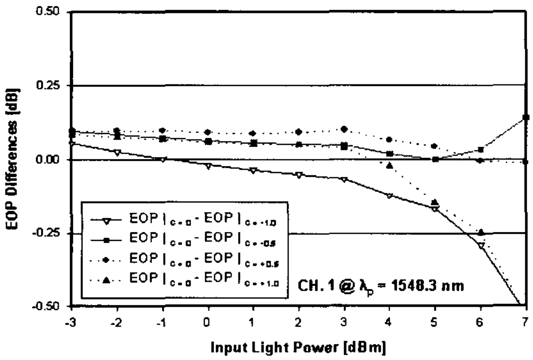
of a compensation for signal distortion due to both SPM and XPM, the effect of initial frequency chirp on compensation is gradually decreased as a fiber dispersion coefficient becomes gradually large.

This results should raise a trade-off of design and realization of long-haul wideband WDM systems. That is, it is needed that fiber dispersion coefficient becomes large in order to minimize the initial frequency chirp effect on fluctuation of compensation for optical pulse distortion due to chromatic dispersion, SPM and XPM. But, if large dispersion coefficient of fiber is selected in WDM systems, drop of bit rate due to high dispersion effect and reduction of maximum input light power due to relative increasement of phase modulation in WDM channel are inevitable.

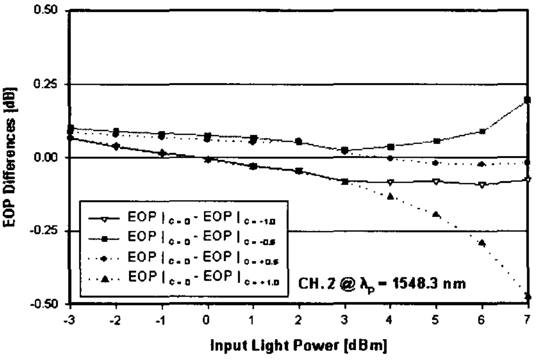
Therefore we will investigate the method of minimi-



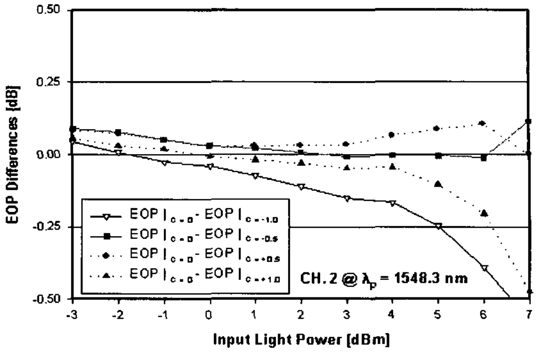
(a) channel 1: without XPM effect



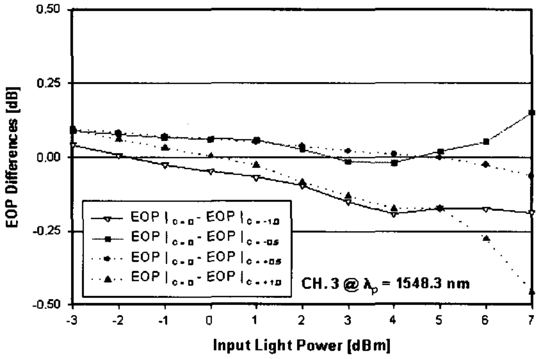
(b) channel 1: with XPM effect



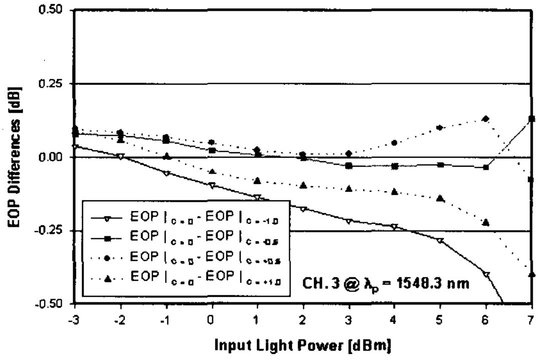
(c) channel 2: without XPM effect



(d) channel 2: with XPM effect



(e) channel 3: without XPM effect



(f) channel 3: with XPM effect

Fig. 5. EOP differences of each channel as a function of input signal light power in WDM transmission systems with D=1.6 ps/nm/km.

zing trade-off due to initial frequency chirp of optical pulse and XPM in inter-channels.

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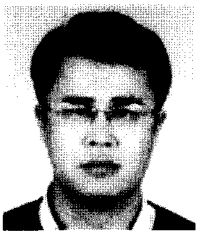

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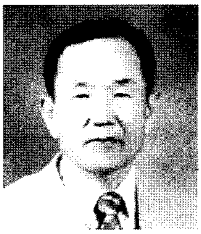

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