Journal of the Optical Society of Korea
Vol. 13, No. 3, September 2009, pp. 354-360

DOI: 10.3807/JOSK.2009.13.3.354

Transmission Performance of 40 Gb/s PM Duobinary Signals due to Fiber Nonlinearities in DWDM Systems Using VSB Filtering Techniques

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(Received July 2, 2009 : revised August 4, 2009 : accepted August 4, 2009)

We investigate theoretically the tolerance of 40 Gbps phase-modulated (PM) duobinary signals using a vestigial sideband (VSB) filter on impairments which occurred in dense wavelength-division multiplexing (DWDM) systems, compared to the conventional duobinary signals. Our simulation results show that PM duobinary signals can't have the gain on the spectral efficiency achieved by utilizing the VSB filtering technique. In order to increase the spectral efficiency, they indispensably require to be transmitted at the optimum bandwidth of multiplexer (MUX) and demultiplexer (DEMUX) since they are susceptible to inter-channel crosstalk. It is also shown that the PM duobinary modulation format has a large tolerance on self-phase modulation (SPM) and cross-phase modulation (XPM) under the condition which MUX and DEMUX have been tuned at an optimum bandwidth; it has 1.2 dB power penalty at the fiber launching power (FLP) of 15 dBm and the channel spacing of 50 GHz.

Keywords: Duobinary signals, Phase-modulated duobinary, Wavelength-division multiplexing, Vestigial sideband filtering

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2330) Fiber optics communications; (060.5060) Phase modulation

I. INTRODUCTION

Recently, dense wavelength division multiplexing (DWDM) transmission systems have been investigated to satisfy the demand on high capacity in optical transmission systems [1]. There are many factors which have to be considered in embodying DWDM transmission systems. Among them, data rate and channel spacing play an important role in framing the whole system in terms of spectral efficiency. In the framed DWDM transmission systems, the transmission performance is determined by the tolerance on the nonlinear effect of fiber and inter-channel crosstalk as well as the spectral width of modulation formats and the bandwidth of multiplexer (MUX) and demultiplexer (DEMUX).

In DWDM transmission systems, the spectral efficiency is an important factor and it can be increased by using the modulation formats with narrow spectral width such as duobinary and multilevel modulation formats [2-4]. Among duobinary modulation formats, the PM duobinary modulation format has been investigated with the focus on a large tolerance to the nonlinear effects of fiber such as SPM and XPM. The spectral width of optical signals can be further reduced by utilizing the vestigial sideband (VSB) filtering technique which requires an optical band-pass filter (OBPF) [5]. In VSB filtering, to reduce the bandwidth of OBPF is mandatory to improve the spectral efficiency but is harmful to the modulated signals since it causes the pulse distortion by narrow filtering. Therefore, the bandwidth of OBPF and its detuning frequency should be optimized to improve the spectral efficiency while maintaining the transmission performance adequately. Therefore, it is worthwhile to investigate the transmission performance of PM duobinary signals employing VSB filtering techniques and compare the result with that of the conventional duobinary signals.

In this paper, we investigated the transmission characteristics of 40 Gbps conventional duobinary signals using a low-pass filter (LPF) and phase-modulated (PM) duobinary signals in DWDM transmission systems

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employing a VSB filtering technique. First of all, for both modulation formats, we optimized the bandwidth and detuning frequency of an OBPF used in front of a receiver for VSB filtering. Secondly, to compare the tolerance on inter-channel crosstalk, we calculated the power penalties at 10^{-9} BER of conventional duobinary signals with/without a VSB filter and PM duobinary signals with/without a VSB filter according to channel spacing and the bandwidth of MUX and DEMUX. Finally, we compared the power penalties induced by self-phase modulation (SPM) and cross-phase modulation (XPM) in the optimum bandwidths of MUX and DEMUX.

The paper is organized as follows. In section II, we present our modeling method of optical fiber, optical receiver, and bit-error rate (BER) calculation. In section III, we describe the configuration of a DWDM transmission system used in the simulation and analyze the transmission characteristics of conventional duobinary signals with/without a VSB filter and PM duobinary signals with/without a VSB filter in a DWDM transmission system. Finally, in section IV we summarize our simulation results and discuss on the modulation formats having a strong tolerance for impairments occurring in the DWDM transmission system.

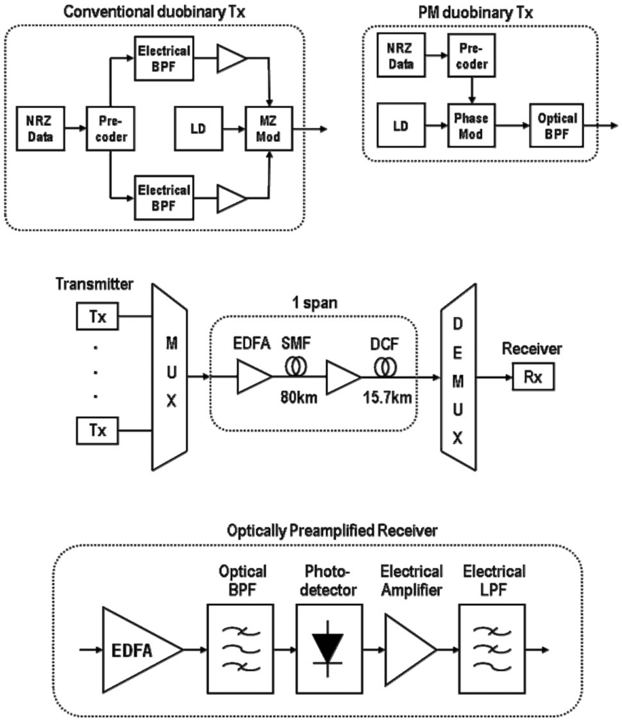


FIG. 1. Schematic diagram of a DWDM transmission system used in our simulation.

II. SIMULATION MODEL OF OPTICAL FIBER, RECEIVER, MUX/DEMUX, AND BER CALCULATION

Optical signals transmitted through the single mode optical fiber experience loss, dispersion, and nonlinear effects. Therefore, the evolution of a slowly varying pulse envelope can be obtained from the nonlinear Schrödinger equation [6]. Because the nonlinear Schrödinger equation is a nonlinear partial differential equation that does not have an analytic solution generally, it was numerically solved by the split-step Fourier method (SSFM) [6]. The SSFM obtains an approximate solution by assuming that the dispersive and nonlinear effects can be considereded to act independently in propagating the optical field over a small distance.

The optical filter characteristics of MUX and DEMUX used in our simulations were modeled as a super Gaussian-shaped optical filter. The super Gaussian function can be expressed as [6]

$$H(f) = \exp[-\frac{\ln 2}{2}\left(\frac{f}{f_{3dB}}\right)^{2m}] \tag{1}$$

where f is frequency, f_{3dB} is the 3 dB bandwidth of a filter, and m is the super Gaussian factor. The m can be calculated through the relation of $m \cong 0.2393/\log(f_{3dB}/f_{1dB})$. A super Gaussian filter has a constant group delay in passband. Therefore, the pulse distortion induced by group delay ripple can be ignored. The receiver used in our simulation was optically preamplified and consisted of an EDFA as a preamplifier, a Gaussian band-pass optical filter, a photodetector with square-law operation, an electrical amplifier and a fourth-order Bessel-Thomson electrical filter, shown as Fig. 1 [7].

The shot noise, beat noises generated by signal and amplified spontaneous emission (ASE) noise, and the receiver circuit noise were considered in the calculation of BER, which was optimized with both threshold level and sampling time [8]. BER was calculated from the Gaussian approximation. The BER for a single bit can be calculated by

$$BER = \frac{1}{4} erfc\left\{\sqrt{2}\left(\frac{(1-c_{isi}^{+}-\tau)I_s}{\sigma_1}\right)\right\} + \frac{1}{4} erfc\left\{\sqrt{2}\left(\frac{(\tau - c_{isi}^{-})I_s}{\sigma_0}\right)\right\} \tag{2}$$

where I_S is the time-averaged photocurrent signal, τ is the decision threshold level normalized by the rail-to-rail electrical pulse, and c_{isi}^{+} and c_{isi}^{-} are the eye closures determined at mark ("1") and space ("0"), respectively. σ_1 and σ_0 are the standard deviation of the total noises for mark and space, respectively. Overall BER characteristics were obtained by averaging BER calculated from each data bit. The receiver sensitivity at 10^{-9} BER was used to measure the power penalty induced by impairments.

III. TRANSMISSION CHARACTERISTICS OF DUOBINARY MODULATION FORMATS IN DWDM TRANSMISSION SYSTEMS USING VSB FILTERING TECHNIQUE

1. Configuration of a DWDM transmission system

Fig. 1 shows the diagram of a DWDM transmission system used in our simulation. The transmitter for 40 Gb/s conventional duobinary signals is composed of a duobinary precoder, LPF, and Mach-Zehnder modulator driven at the transmission null point. A LPF had a fourth-order Bessel-Thomson response and its 3 dB bandwidth was 10 GHz. The optimized bandwidths of the optical and electrical filters at the receiver were 60 GHz and 27 GHz, respectively. PM duobinary signals were generated by filtering nonreturn-to-zero differential phase shift keying (NRZ-DPSK) signals using an optical band-pass filter (OBPF) with narrow 3 dB bandwidth before receiver [9-10]. A phase modulator was used to generate NRZ-DPSK signals. The optimum 3 dB bandwidth of the OBPF used as a demodulator was 0.19 nm. The optimized bandwidths of the optical and electrical filters at the receiver were 62 GHz and 26 GHz, respectively. The transmission link consists of single-mode fiber (SMF), erbium-doped fiber amplifier (EDFA), and dispersion compensating fiber (DCF). The length of SMF was 80 km and its dispersion parameter (D) was 17 ps/nm·km. To compensate the chromatic dispersion occurred by SMF, the DCF with the dispersion parameter of -86.59 ps/nm·km and a length of 15.71 km was used. The channel spacing was varied from 50 GHz to 100 GHz.

2. Optimization of VSB filters

Fig. 2 shows the optimum condition of a VSB filter used in conventional duobinary and PM duobinary transmission systems. We used an OBPF in front of a receiver as a VSB filter, and power penalties were calculated with respect to the bandwidth and detuning frequency of the filter. Power penalties were used as a measure of receiver performance for each modulation format. The power penalty was obtained by calculating the difference in receiver sensitivities at 10^{-9} BER with and without using the VSB filter. The optimum condition has been searched around the OBPF bandwidth of 40 GHz considering the DWDM application of 40 Gb/s signal transmission. In the conventional duobinary transmission, the bandwidth of an OBPF used as a VSB filter can be decreased from 50 GHz to 40 GHz by detuning the center frequency of the OBPF as 10 GHz under 0.5 dB power penalty. However, in the PM duobinary transmission, detuning the center frequency of the OBPF has no effect on decreasing the bandwidth of the OBPF. In addition, it suffers 1.5 dB power penalty, larger than conventional duobinary, where the detuning frequency and bandwidth of the OBPF are 10 GHz and 40 GHz, respectively.

3. Tolerance on inter-channel crosstalk

Inter-channel crosstalk from adjacent channels can affect the transmission performance in DWDM transmission systems, depending on channel spacing and bandwidth of MUX/DEMUX as well as the spectral width of signals. Fig. 3 shows the power penalties of the conventional duobinary and PM duobinary modulation formats as a function of the bandwidth of MUX/DEMUX, which represent the tolerance on inter-channel crosstalk. As shown in Fig. 3 (a), the power penalties of the conventional duobinary modulation format can increase as increasing the bandwidth of MUX/DEMUX above an optimum value while decreasing the channel spacing. This is due to large inter-channel crosstalk. However, although there is a trade-off between the signal distortion induced by filtering and the suppression of inter-channel crosstalk, the conventional duobinary using a VSB filter whose detuning frequency is 10 GHz and bandwidth is 40 GHz has a significantly reduced inter-channel crosstalk-induced power penalty.

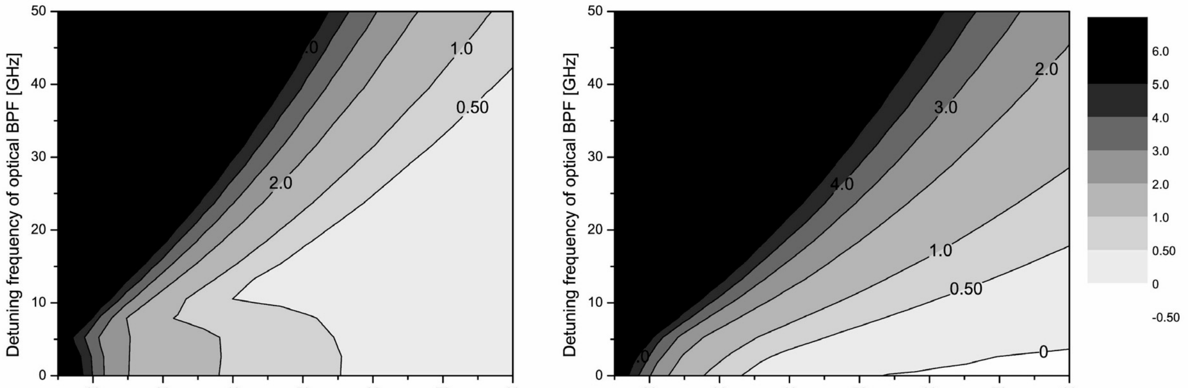
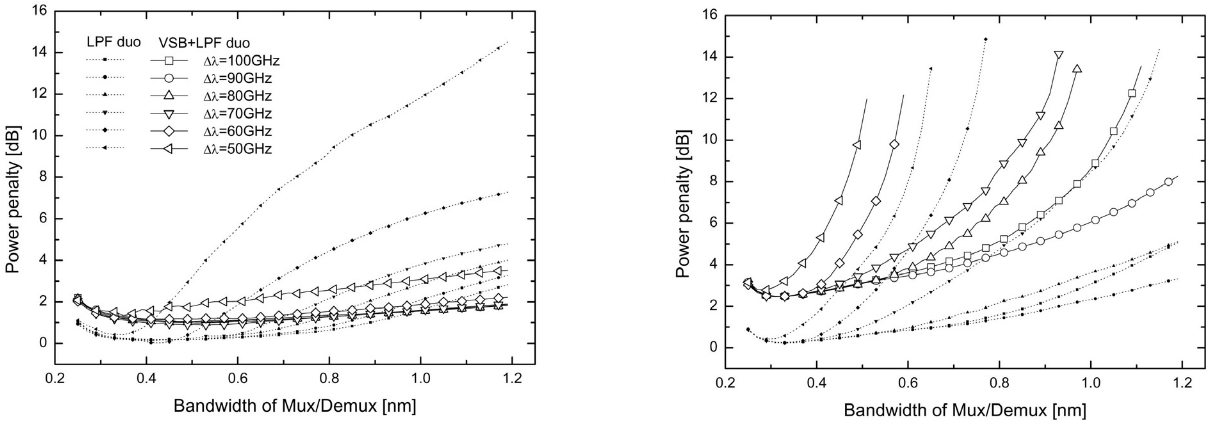


FIG. 2. Optimum condition of a VSB filter: (a) conventional duobinary and (b) PM duobinary.



(a) (b)

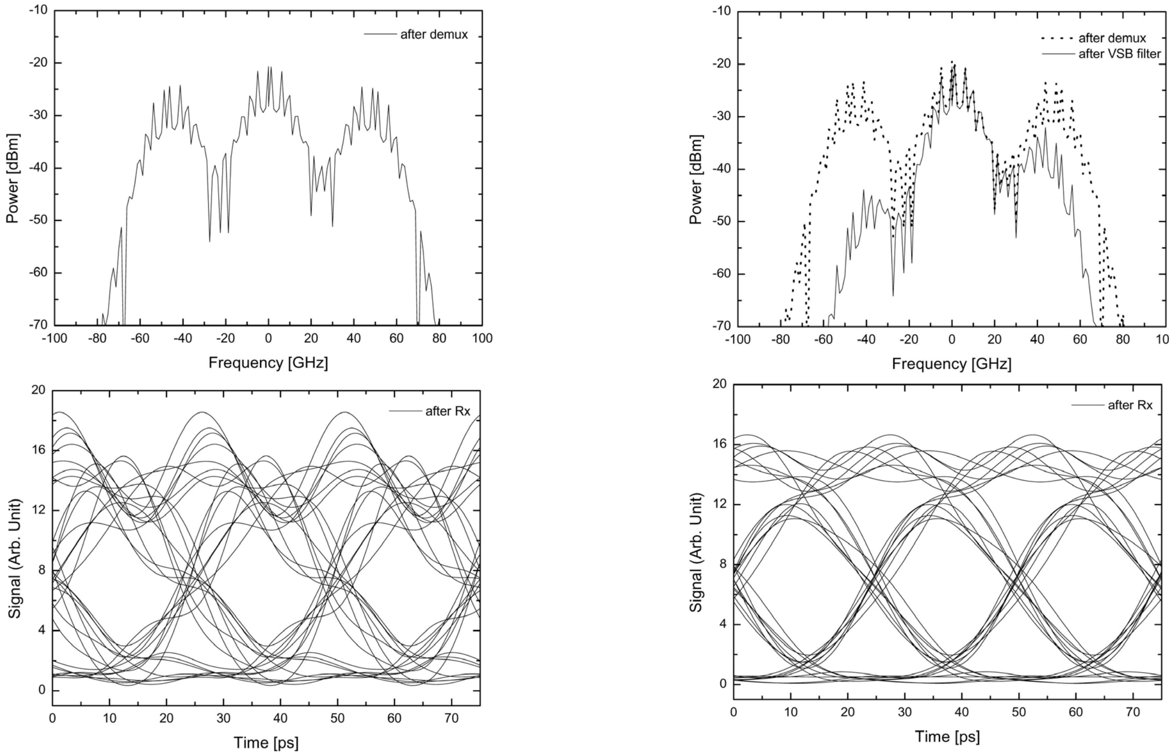
FIG. 3. Power penalties at 10^{-9} BER as a function of the bandwidth of MUX/DEMUX: (a) conventional duobinary with and without a VSB filter and (b) PM duobinary with and without a VSB filter.

At the bandwidth range smaller than an optimum value, the VSB filtering technique is not efficient since the inter-channel crosstalk is negligible, and instead the signal distortion is induced by filtering. On the other side, at the bandwidth range where the inter-channel crosstalk becomes a dominant impairment, it is sufficiently effective against the inter-channel crosstalk. When the channel spacing is 50 GHz and the bandwidth of MUX/DEMUX is 1.2 nm, the conventional duobinary modulation format has a large power penalty of 14.5 dB but the case using a VSB filter has at most 3.5 dB power penalty. Fig. 3 (b) shows the tolerance on the inter-channel crosstalk of the PM duobinary modulation format. The PM duobinary modulation format has a larger power penalty than the conventional duobinary modulation format with and without a VSB filter. When the channel spacing is 50 GHz and the bandwidth of MUX/DEMUX is 0.65 nm, it has a 14 dB power penalty but the conventional duobinary modulation format with and without a VSB filter have a relatively small power penalty of 7 dB and 2 dB, respectively. In addition, the PM duobinary modulation format using a VSB filter has larger power penalty than the case not using a VSB filter.

Fig. 4 and Fig. 5 show the spectra and eye diagrams of the conventional duobinary and PM duobinary modulation formats where the channel spacing is 50 GHz and the bandwidth of MUX/DEMUX is 0.65 nm. At 0.65 nm, the conventional duobinary modulation format has a large inter-channel crosstalk but the case using a VSB filter has a significantly suppressed inter-channel crosstalk. For the PM duobinary modulation format, although the inter-channel crosstalk is significantly reduced by OBPF used as a demodulator, it has more closed eye diagram than the conventional duobinary modulation format since the inter-channel crosstalk components placed within the spectrum of the signal are larger than the conventional duobinary modulation format due to its wide spectral width and additionally they are not suppressed perfectly by an OBPF used as a demodulator. Besides, to apply the VSB filtering technique has no effect on decreasing the inter-channel crosstalk and instead induces the additional signal distortion by filtering. Thus, for the PM duobinary modulation format, the VSB filtering technique is useless to improve spectral efficiency, and the bandwidth of MUX/DEMUX must be set to the optimum value for the given channel spacing in order to achieve the best performance. Fig. 6 shows the bandwidths of MUX/DEMUX where the 1 dB power penalty is induced by inter-channel crosstalk. As previously explained, the PM duobinary modulation format requires narrower bandwidth than conventional duobinary due to its wide spectral width and characteristics susceptible to inter-channel crosstalk placed within the spectrum of the signal. To achieve the spectral efficiency of 0.8 b/s/Hz, the conventional duobinary modulation format requires that the bandwidth of MUX/DEMUX is 0.41 nm, but the PM duobinary modulation format requires that the bandwidth of MUX/DEMUX is 0.36 nm.

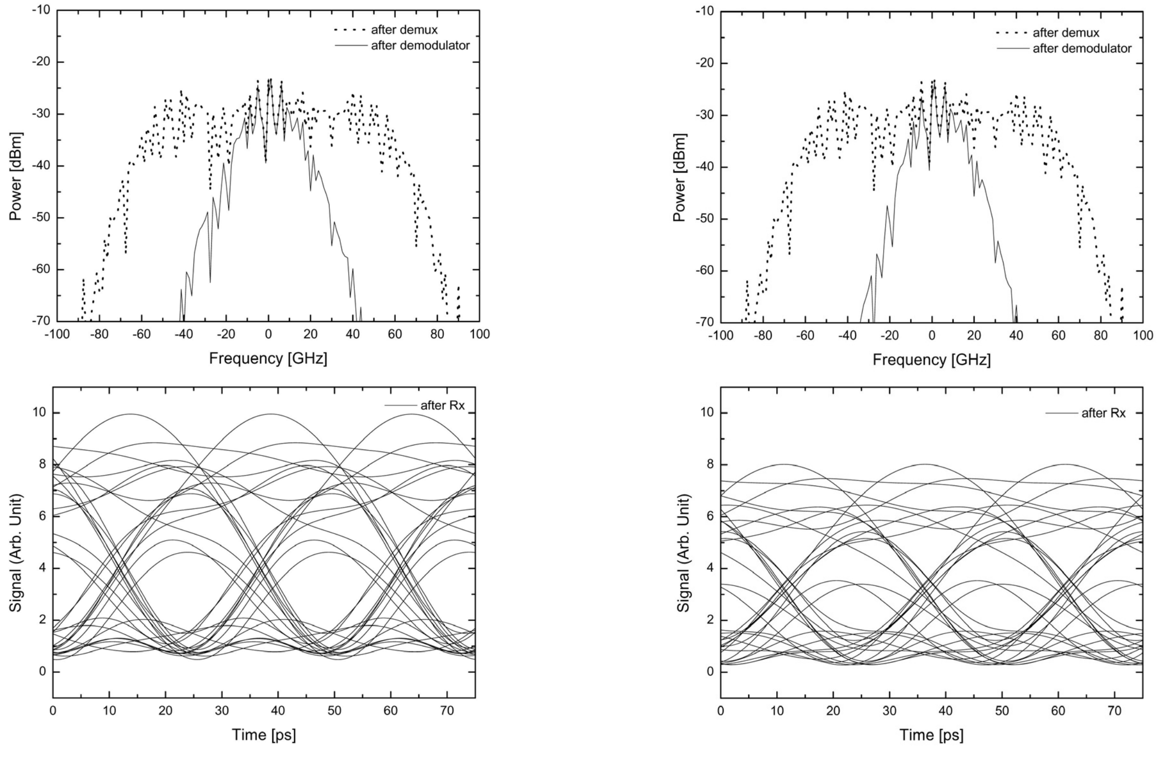
4. Tolerance on SPM and XPM

In DWDM transmission, the nonlinear effects of fiber such as SPM and XPM are one of the impairment factors degrading the transmission performance of systems. Fig. 7 shows the power penalties as a function of fiber launching power (FLP) according to channel spacing. Power penalties were calculated at the optimum bandwidth of MUX/DEMUX (0.31 nm) to consider the influence of SPM and XPM only. As shown in Fig. 3, both modulation formats obtain the best performance against inter-channel crosstalk regardless of using a VSB filter when the bandwidth of MUX/DEMUX is set to the optimum value. For the



(a) (b)

FIG. 4. Spectra and eye diagrams of conventional duobinary at the channel spacing of 50 GHz and the MUX/DEMUX bandwidth of 0.65 nm: (a) without a VSB filter and (b) with a VSB filter.



(a) (b)

FIG. 5. Spectra and eye diagrams of PM duobinary at the channel spacing of 50 GHz and the MUX/DEMUX bandwidth of 0.65 nm: (a) without a VSB filter and (b) with a VSB filter.

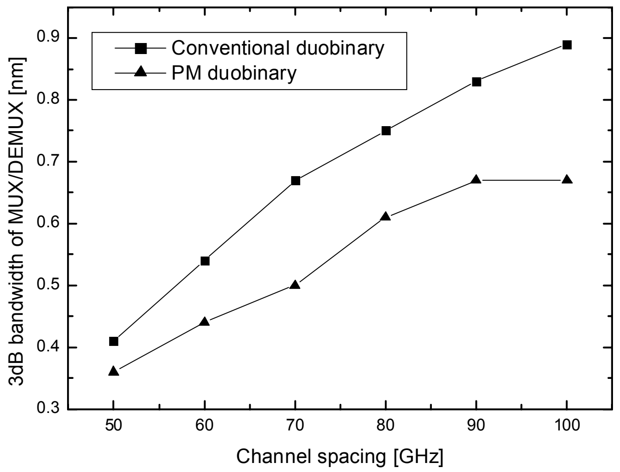


FIG. 6. 3 dB bandwidths of MUX/DEMUX where the 1 dB power penalty is induced by the inter-channel crosstalk.

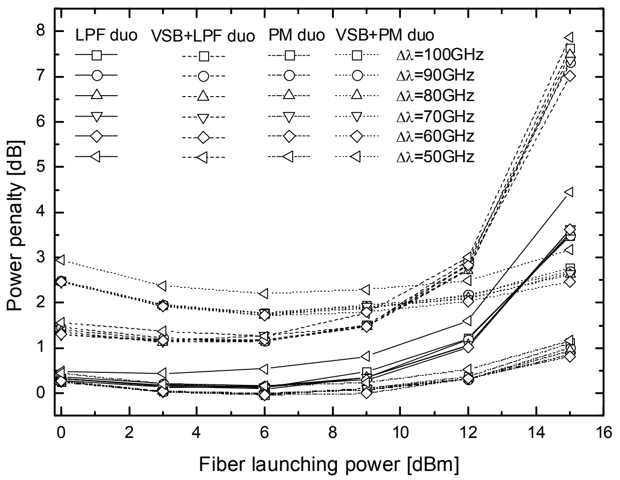


FIG. 7. Power penalties at 10^{-9} BER as a function of FLPs.

conventional duobinary modulation format, the power penalty induced by SPM and XPM increases little by little up to 1~1.25 dB when FLP is smaller than 12 dBm. However, at the FLP larger than 12 dBm, the power penalty abruptly increases to 3.5~4.5 dB. Also, it is shown that when the channel spacing is larger than 60 GHz, the XPM effect is not dominant. The influence of the XPM effect appears at the channel spacing of 50 GHz and the power penalty increases as 0~1 dB depending on FLP. For the conventional duobinary modulation format using a VSB filter, it has a larger power penalty than the case not using a VSB filter. This is attributed to the pulse distortion by filtering. The power penalty increases little by little up to 2.8~3 dB when FLP is smaller than 12 dBm. At the FLP larger than 12 dBm, the power penalty abruptly increases to 7~7.9 dB. Therefore, the tolerance of the conventional duobinary modulation format on the SPM effect is degraded by using a VSB filter; the case using a VSB filter has about 1.7 dB larger power penalty than the case not using a VSB filter at the FLP of 15 dBm. For the PM duobinary modulation format, it has very small power penalties regardless of channel spacing. At the FLP of 15 dBm, it has only 0.8~1.2 dB power penalties. This is attributed to the fact that PM duobinary has a large tolerance to SPM and XPM since DPSK signals with a constant power are transmitted through optical fiber. The property is maintained for the case using a VSB filter except for the additional power penalty induced by filtering.

IV. CONCLUSIONS

In this paper, we compared the tolerance on the inter-channel crosstalk and SPM and XPM of the conventional duobinary modulation format and the PM duobinary modulation format in a DWDM transmission system using the VSB filtering technique. The simulation results showed that using a VSB filter is an effective method to suppress the inter-channel crosstalk for the conventional duobinary modulation format only. For the PM duobinary modulation format, the inter-channel crosstalk with in the spectrum of the signal was not removed perfectly by a demodulator and a VSB filter and additionally made the signal distorted severely with a small amount. Also, it was shown that both modulation formats have the best performance at the optimum bandwidth of MUX/DEMUX regardless of using a VSB filter; both modulation formats can achieve the spectral efficiency of 0.8 b/s/Hz with a power penalty less than 1 dB at the optimum bandwidth of MUX/DEMUX (0.31 nm) where the influence of inter-channel crosstalk can be neglected. Meanwhile, when the bandwidth of MUX and DEMUX has an optimum value, the best and worst tolerance on SPM and XPM was obtained in the PM duobinary modulation format and the conventional duobinary modulation format using a VSB filtering technique, respectively. At the FLP larger than 12 dBm, the power penalties of the conventional duobinary modulation format using a VSB filter increase to 7~7.9 dB according to channel spacing. However, the PM duobinary modulation format has only 0.8~1.2 dB power penalties at the FLP of 15 dBm.

ACKNOWLEDGMENT

This research was supported in part by Brain Korea 21 project in 2009 and WCU (World Class University) program through the Korea Science and Engineering Foundation funded by the Ministry of Education, Science and Technology (R31-2008-000-10008-0).

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