Improvement of SPM Tolerance for Phase-Modulated Duobinary Transmissions Using Phase Modulator With Postfiltering Technique

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***Abstract*—We theoretically investigate self-phase modulation (SPM) tolerance of a new duobinary signals employed a phase modulator and optical filter, referred to as phase-modulated (PM) duobinary signals. For the conventional duobinary transmission (DBT) with electrical low-pass filters, fiber input power is strongly limited due to SPM. However, our results suggest that SPM tolerance can be improved while maintaining high dispersion tolerance using PM-DBT, since the signals with a constant power are transmitted over fibers. Adjusting the phase difference between mark and space levels of phase modulators, we can further improve SPM tolerance, compared with the conventional DBT.**

***Index Terms*—Duobinary, modulation format, optical communication, simulation.**

I. Introduction

OPTICAL duobinary transmission (DBT) is an attractive scheme for optical transmission systems since it provides a narrow spectral width, large tolerance on chromatic dispersion, and suppression of stimulated Brillouin scattering, compared with the standard nonreturn-to-zero (NRZ) transmission [1], [2]. Conventional duobinary transmitters consist of electrical low-pass filters with the bandwidth of a quarter of data rates, duobinary precoder, and Mach–Zehnder modulator (MZM). For the conventional DBT, system performance highly depends on word lengths due to the imperfection of electrical low-pass filters and asymmetric characteristics on both MZMs and their drivers [3]. For the conventional duobinary signals with high optical power, the spectral width broadens rapidly during transmission through fibers due to the self-phase modulation (SPM) effect. Dispersion tolerance of the conventional DBT was weakened rapidly with increasing optical input power [4], [5].

The phase-modulated DBT (PM-DBT) was suggested to overcome the degradation of the system performance depending on word lengths and asymmetry in MZMs and their divers [6], [7]. Chirped DBTs were proposed to improve SPM tolerance by the combined influence of prechirp, chromatic dispersion, and SPM [8]. A postfiltering PM-DBT can solve these problems simultaneously. This scheme also has a large tolerance to SPM since differential binary phase-shift keying (DBPSK) signals with a constant power are transmitted through optical fibers. The signals are converted into duobinary signals with time-variant power just in front of receivers. In addition to this, it overcomes the degradation of the system performance depending on word lengths since this scheme does not use electrical filters. This scheme can also eliminate symmetry requirements since it can use phase modulators instead of MZMs with double electrodes.

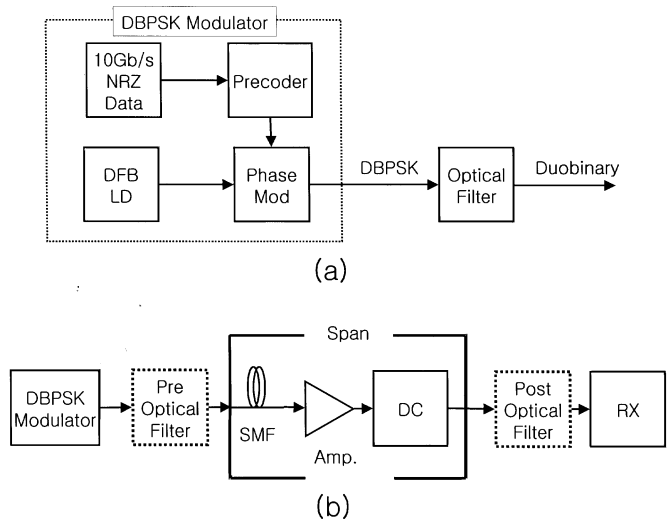

Fig. 1. Schematic diagrams: (a) PM duobinary transmitter and (b) PM-DBT system.

In this letter, we theoretically investigate the interaction between fiber dispersion and SPM on 10-Gb/s PM-DBT for single- and four-span dispersion-compensated systems. We compare the performance between the conventional DBT and PM-DBT for dispersion-managed fiber links. Furthermore, we optimize phase difference between mark and space levels of PM duobinary signals to improve SPM tolerance further.

II. Configuration and Modeling for PM-DBT

A. PM Duobinary Transmitters

Fig. 1(a) shows the schematic diagram for PM duobinary transmitters. To generate PM duobinary signals, DBPSK signals were generated first. We can use either an MZM or a phase modulator for the generation of DBPSK signals. Using MZMs, we cannot adjust the phase difference between mark and space levels, which used to be fixed at 180°. On the other hand, using

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phase modulators, we can adjust and optimize the phase difference between mark and space levels by changing driving voltages. Therefore, phase modulators were used for the generation of DBPSK signals. A precoder used in this scheme is exactly the same as the conventional duobinary precoder. DBPSK signals were converted into duobinary signals using a narrow-bandwidth optical filter.

B. Transmission Systems

Fig. 1(b) shows the schematic diagram for transmission systems. We have considered dispersion-compensated system with the span length of 100 km. To convert DBPSK signals into duobinary signals, an optical filter was located either at transmitters (prefiltering) or in front of receivers (postfiltering). The location of optical filters significantly affects the SPM tolerance. One span consists of the standard single-mode fiber (SSMF), erbium-doped fiber amplifier (EDFA), and dispersion compensator (DC). The fiber length of SSMF was 100 km followed by an EDFA. DC compensated the dispersion of SSMF and operated in the linear regime. Residual dispersion was adjusted at last DC.

C. Simulation Parameters

The lasing wavelength of the DFB lasers was set to 1.55 μm. Phase modulator was driven by precoded 10-Gb/s NRZ pseudorandom bit sequence signals. For an SSMF model, dispersion (D), nonlinear coefficient (n_2), and effective core area $(A_{\rm eff})$ were set to be 17 ps/nm/km, 3×10^{-20} m^2/W, and 78 $\mu\mathrm{m}^2$, respectively. The optical filter had the Gaussian-shaped passband with the bandwidth of 5.6 GHz, optimized for a maximum receiver sensitivity at back-to-back. For a receiver model, the frequency response from PIN photodiode to electrical amplifier was assumed to be the fourth-order Bessel–Thomson filter with the bandwidth of 7 GHz to achieve a maximum receiver sensitivity at back-to-back. The circuit noise was set to 17 $\mathrm{pA}/\sqrt{\mathrm{HZ}}$ with the Gaussian distribution. The noise figure of EDFAs was set to 4 dB.

III. Simulation Results and Discussions

A. Comparison of Dispersion Tolerance Among Different DBT Schemes

We compared dispersion tolerance among different DBT schemes. Focusing on transmission systems operating either in the linear or nonlinear regime, we chose the fiber peak input power of 0 and 15 dBm. After DBPSK signals passed through narrow-band optical filters for the conversion of PM duobinary signals, the average input power was changed but peak input power was not. Fiber peak input power is a suitable parameter to compare SPM tolerance.

Fig. 2 shows receiver sensitivities at 10^{-12} bit-error rate (BER) as a function of residual dispersion for the single-span system. The phase difference between mark and space levels of PM duobinary signals was set to 180°. With the fiber peak input power of 0 dBm, both the prefiltering and postfiltering PM-DBTs had worse dispersion tolerance than the conventional DBT. With the fiber peak input power of 15 dBm, however, the postfiltering PM-DBT had better dispersion tolerance than the

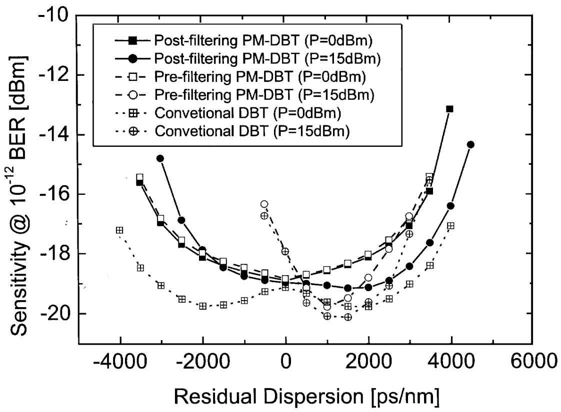

Fig. 2. Sensitivity as a function of residual dispersion for the conventional DBT, postfiltering and prefiltering PM-DBT with $\phi = \pi$.

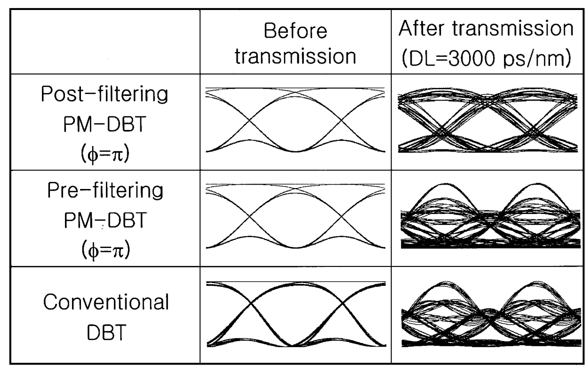

Fig. 3. Eye diagrams before and after transmission for the conventional DBT, postfiltering and prefiltering PM-DBT with $\phi = \pi$.

conventional DBT. The influence of SPM depends on power variation of optical signals through optical fibers. DBPSK signals using phase modulators have a constant optical power. For the postfiltering DBT, DBPSK signals are transmitted through optical fibers and converted into duobinary signals after transmission. Therefore, SPM did not affect transmission performance of the postfiltering PM-DBT. However, the prefiltering PM-DBT did not improve dispersion tolerance at high peak input power since DBPSK signals were converted into duobinary signals by optical filters before transmitting through optical fibers.

Fig. 3 shows eye diagrams before and after transmission with the fiber peak input power of 15 dBm for the single-span system. The combined influence of the strong SPM effect and chromatic dispersion deformed signals after transmission for both the conventional DBT and prefiltering PM-DBT. However, eye diagrams of the postfiltering PM-DBT were still open clearly for the dispersion $\times$ length of 3000 ps/nm.

B. Comparison of SPM Tolerance Between Conventional DBT and Postfiltering PM-DBT

To observe the effect of SPM on the transmission performance, we computed dispersion tolerance of the conventional DBT and postfiltering PM-DBT for various fiber peak input powers, depicted in Fig. 4. For the postfiltering PM-DBT, the phase difference between mark and space levels of PM duobinary signals was set to 180°. In this letter, dispersion tolerance

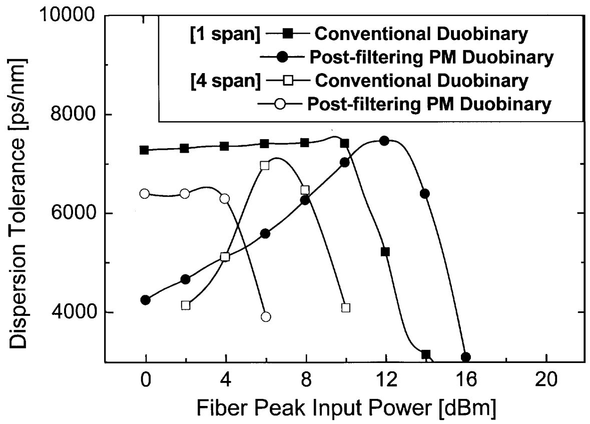

Fig. 4. Dispersion tolerance of the conventional DBT and postfiltering PM-DBT with $\phi = \pi$ as a function of fiber peak input power for single- and four-span dispersion-compensated systems.

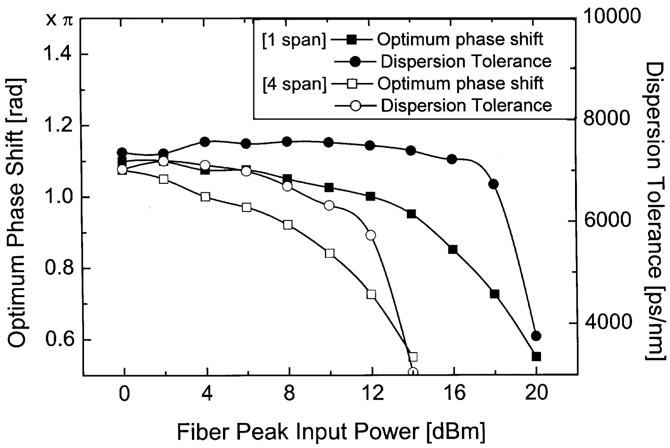

Fig. 5. Optimum phase difference of phase modulator and dispersion tolerance of the postfiltering PM-DBT as a function of fiber peak input power for single- and four-span dispersion-compensated systems.

is defined as the range of dispersion compensation where receiver sensitivities at 10^{-12} BER keep below -18 dBm. In the case of the single-span system, the conventional DBT had better dispersion tolerance than the postfiltering PM-DBT with fiber peak input powers less than 10 dBm. However, when the fiber peak input power was higher than 10 dBm, the postfiltering PM-DBT outperformed the conventional DBT. The fiber peak input power could be increased by 3 dB, compared with the conventional DBT. In the case of the four-span system, the postfiltering PM-DBT had a better performance than the conventional DBT with fiber peak input powers larger than 4 dBm.

C. Optimization of Phase Difference Between Mark and Space Levels for SPM Tolerance

We could further improve SPM tolerance of the postfiltering PM-DBT through optimizing the phase difference between mark and space levels of PM duobinary signals for each fiber peak input power. Fig. 5 shows the optimum phase difference and dispersion tolerance as a function of fiber peak input power for the single- and four-span systems. Although the power of the postfiltering PM duobinary signals was constant before fiber transmission, it would fluctuate due to fiber dispersion during transmission. Due to SPM, the phase variation was induced by power fluctuation and expanded the phase difference of PM duobinary signals during transmission. Therefore, the optimum phase difference of phase modulators was reduced with increasing fiber peak input power. Optimizing phase difference of phase modulators, we could improve not only SPM tolerance but also the dispersion tolerance at low fiber input power. When the phase difference was optimized, SPM tolerance of the PM-DBT could be improved by about 7 dB, compared with the conventional DBT for both the single- and four-span systems.

IV. Conclusion

We compared the transmission characteristics between the PM-DBT and conventional DBT for the single- and four-span dispersion-compensated systems. Because the PM-DBT did not use the electrical filters, it overcame the problems occurred from the word lengths. In addition of this, using the postfiltering PM-DBT, we could significantly improve SPM tolerance. Optimizing the phase difference of between mark and space levels of PM duobinary signals, we could improve SPM tolerance of PM-DBT by about 7 dB, compared with the conventional DBT.

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