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Effects of filter bandwidth and driving voltage on optical duobinary transmission systems

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Abstract

This work demonstrates how electrical driving voltage of a Mach–Zehnder modulator and the bandwidth of electrical low-pass filters (LPFs) affect optical duobinary signals. The fact that a 100% driving voltage does not necessarily yield optimal results in duobinary systems is established both numerically and experimentally. Various filter bandwidths correspond to respective optimum driving voltages. In a 10 Gbps duobinary system, compared with the conventional condition of using a 2.5 GHz electrical LPF, a 2.5 dB sensitivity improvement is obtained by employing a 3 GHz LPF with an 88% driving voltage of fully driving.

Keywords: Duobinary; Modulation format; Optical communication

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1. Introduction

Optical duobinary format has attracted much attention in recent years, since optical duobinary signals have a higher spectral efficiency and better tolerance of chromatic dispersion than the standard non-return-to-zero (NRZ) signals due to the narrower spectral bandwidth [1,2]. Moreover, optical duobinary modulation provides a higher threshold for the onset of stimulated Brillouin scattering (SBS) [3]. Various implementations of duobinary transmitters have been proposed [4–6]. However, the most cost-effective and simplest implementation involves the three-level electrical signals generated by electrical low-pass filters (LPFs) [6]. In this implementation, the bandwidth of the typical electrical Bessel LPF is about one quarter of the bit-rate [7,8], and the Mach–Zehnder modulator (MZM) is usually operated at 100% driving voltage, indicating that the full swing of the electrical signals is $2V_\pi$. Nonetheless, the bandwidth of an LPF influences the pulse shapes of the electrical signals, and the driving voltage of an MZM also alters the envelopes of the optical duobinary signals because the electrical-to-optical transfer curve of an MZM is nonlinear. Accordingly, filter bandwidths and driving voltages should be considered concurrently to optimize the duobinary signals.

This work studies how MZM driving voltages and LPF bandwidths affect the shapes of optical pulses and the transmission performance of optical duobinary signals. The finding that a 100% driving voltage does not necessarily yield the best results in duobinary modulation format is numerically and experimentally demonstrated. The trade-off among the amplitude jitters of marks, the ripples of spaces and the horizontal eye-opening is such that selecting wider LPFs increases the flexibility in optimizing the driving voltage to improve system performance. Optimizing the transmitter based on a 3 GHz LPF with 88% driving voltage offers a 2.5 dB sensitivity improvement over than provided by the traditional 2.5 GHz LPF after transmission through 240 km of standard single-mode fiber (SSMF).

2. Principle and simulation

In an optical duobinary transmitter, a dual-drive MZM is driven by two three-level electrical signals with inverse logic.

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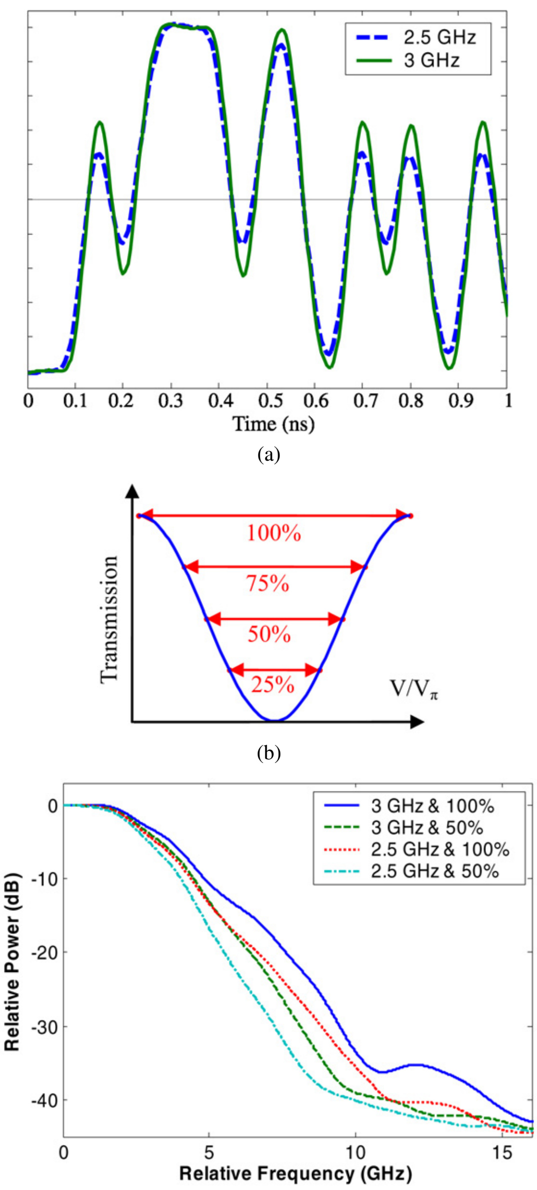


(c)

Fig. 1. (a) The electrical three-level signals generated by the LPFs with different bandwidths; (b) the transmission curve of an MZM as a function of the driving voltages; (c) spectra of optical duobinary signals.

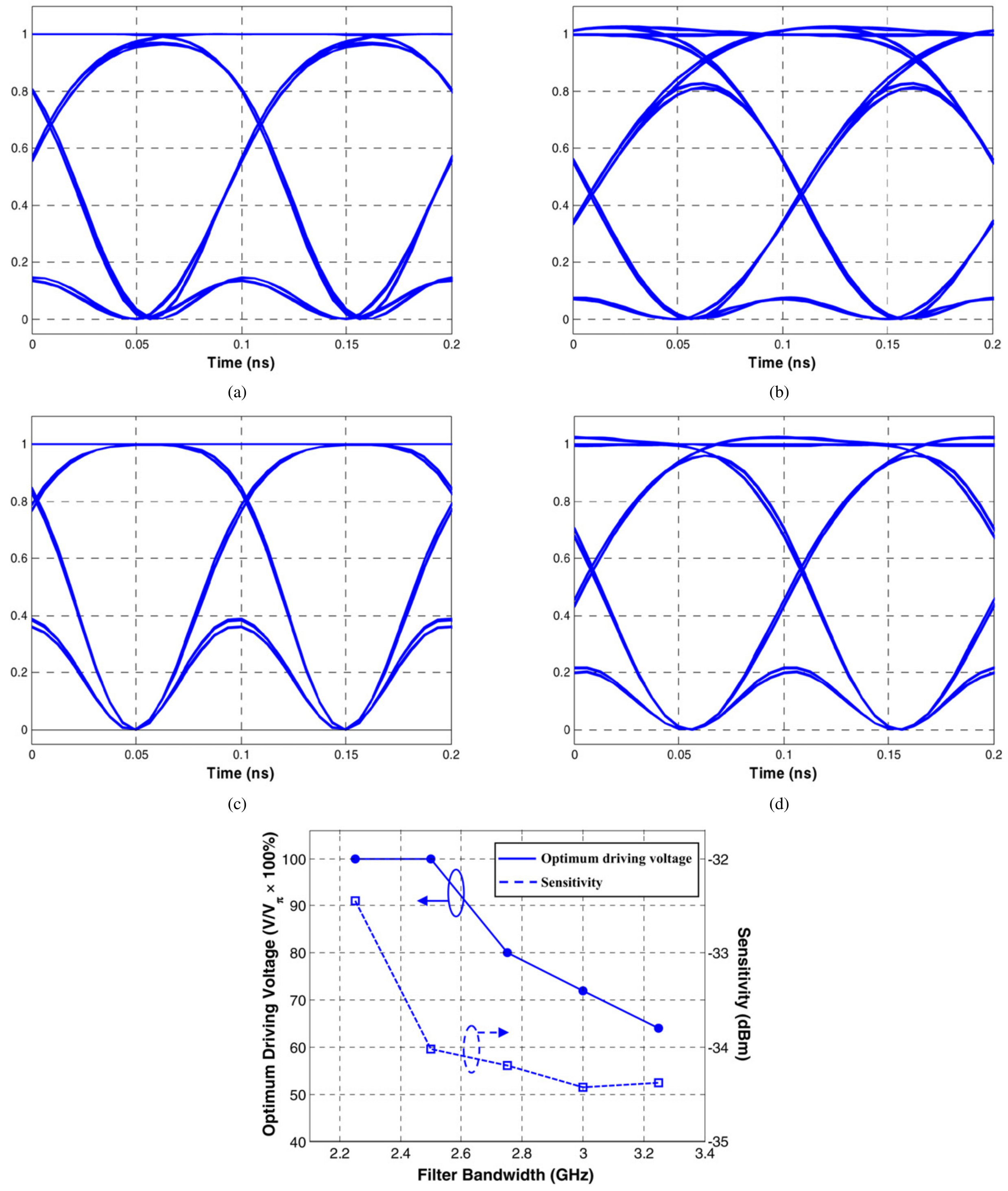
These three-level signals originate in the standard two-level signals that pass through LPFs. Figure 1a plots three-level signals after fifth-order Bessel LPFs with 3 dB bandwidths of 2.5 and 3 GHz to present the impact of the filter bandwidth on these signals. When the filter bandwidth is smaller (2.5 GHz), the amplitudes of oscillation at the middle level are smaller, but the fluctuations at the highest and the lowest levels are greater because fewer high-frequency components pass through the LPF. Figure 1b plots relationship between driving voltages and the transmission of the optical power of an MZM biased at the null point. The operating ranges of peak-to-peak driving voltages in each arm of an MZM are represented by the percentages of V_π. Because the transmission curve is inherently sinusoidal, as electrical signals biased at the null point, the optical powers that correspond to the highest and lowest levels of the electrical signals are the same. Consequently, the electrical three-level signals are converted into the optical two-level signals. Figure 1c compares the spectra of simulated duobinary signals obtained with different LPFs and at different driving voltages. Due to larger proportion of electrical signals operated in the linear region of the sinusoidal transmission of an MZM as shown in Fig. 1b, lowering the driving voltages reduces the spectral bandwidths, and reducing the bandwidths of LPFs shows the same effect.

Figures 2a and 2b exhibit the simulated duobinary eye-diagrams generated by 2.5 GHz LPFs with 100 and 50% driving voltages, respectively. Two differences are readily observed; firstly, the amplitude jitters of marks in Fig. 2a are smaller than those in Fig. 2b, because, at a 100% driving voltage, the fluctuations at the highest and the lowest levels of the electrical signals are suppressed at the top of the sinusoidal transmission of an MZM. Secondly, the ripples of spaces are reduced by lowering the driving voltages and the eye-opening is broadened horizontally. Similar effects are observed in 3 GHz LPFs case, as presented in Figs. 2c and 2d. However, with 3 GHz LPFs, lowering driving voltages reduces the increase in the amplitude jitters of marks, but increases the suppression in the ripples of spaces and the widening of the eye-opening. Hence, the system performance can be improved by properly selecting the driving voltage. Using pseudorandom binary sequence (PRBS) with length of $2^{12} - 1$, Fig. 2e plots the simulation results of optimum driving voltages that correspond to the best sensitivities (bit error ratio (BER) $= 10^{-9}$) following 150 km of SSMF. Evidently, the optimized driving voltage decreases as the filer bandwidths increased in order to balance their counter effects on pulse shapes. Namely, wider LPFs can be applied to adjust the ripples and the eye-opening without significantly increasing the amplitude jitters. Therefore, as shown in Fig. 2e, the signals based on 3 GHz LPFs at the optimum driving voltage outperform that based on conventional 2.5 GHz LPFs.

3. Experimental results

Filters with bandwidths of 2.5 and 3 GHz are adopted in the experiments herein to manifest the effects of the bandwidth of the LPFs. Figure 3 shows the experimental setup of an optical duobinary transmission system. A 10 Gbps PRBS with a length of $2^{15} - 1$ is sent into the duobinary pre-coder. The electrical signals then pass through a fifth-order LPF to generate the three-level signals. The amplitudes of the three-level signals are adjusted by electrical amplifiers and the signals are then sent into an MZM for which the V_π equals 5.8 V. The input optical power sent to the fiber is set to -2 dB m. Once the transmission distance longer than 100 km, an EDFA is put in mid-span to compensate the fiber loss. At the receiver, an optical pre-amplified receiver with an optical 3 dB bandwidth of 40 GHz is employed.

Figures 4a and 4b plot the measured sensitivities as a function of the transmission distance and the driving voltages based on 2.5 and 3 GHz LPFs, respectively. The insets display eye-diagrams at 0 km with 25, 100%, and optimum driving voltages. Figure 4a reveals that the optimum driving voltage is 100%, and



(a) (b) (c) (d) (e)

Fig. 2. Simulation of the optical duobinary signals. (a) Is eye-diagram based on 2.5 GHz LPFs and 100% driving voltage; (b) is eye-diagram based on 2.5 GHz LPFs and 50% driving voltage; (c) is eye-diagram based on 3 GHz LPFs and 100% driving voltage; (d) is eye-diagram based on 3 GHz LPFs and 50% driving voltage; and (e) shows the optimum sensitivities at 150 km and the corresponding driving voltages based on different LPF bandwidths.

reducing the driving voltage induces the sensitivities to deteriorate because the amplitude jitters of marks are significantly increased. However, as shown in Fig. 4b and as predicted by the simulation, the optimum driving voltage is reduced to 88% for signals that pass through a 3 GHz LPF. The main advantage of using a wider LPF bandwidth (3 GHz LPFs) is that the pulse shapes can be optimized by lowering the driving voltages without generating significant amplitude jitters. However, the system based on 2.5 GHz LPFs does not offer the flexibility to adjust the driving voltage, since the serious amplitude jitters of marks prevent the driving voltage from being reduced. Figure 5 plots the BER curves of the duobinary signals based

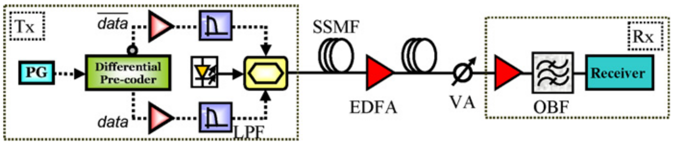
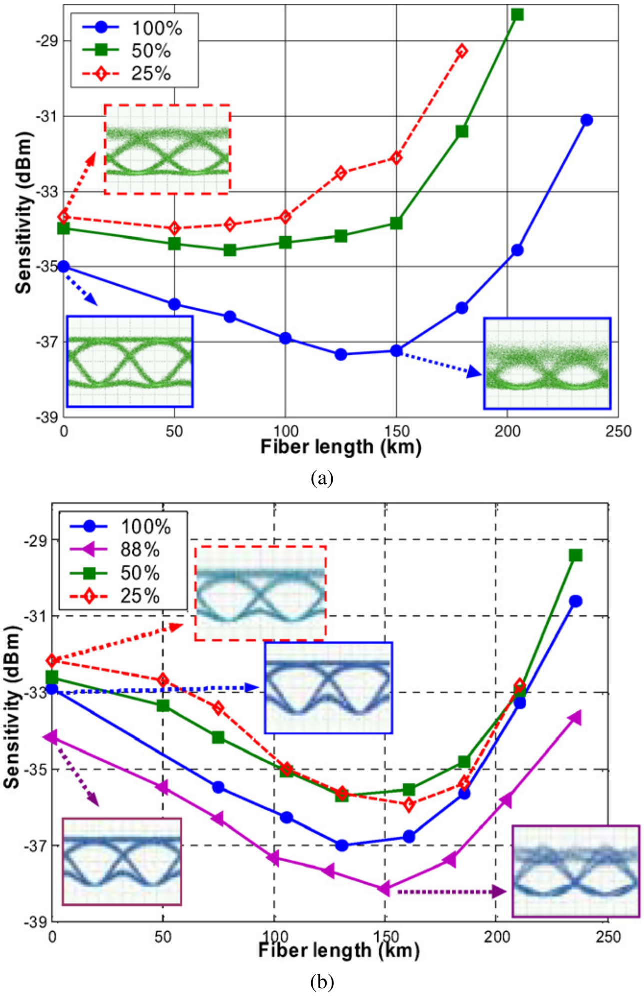


Fig. 3. Configuration of an optical duobinary transmission system (PG: pattern generator; VA: variable attenuator; OBF: optical bandpass filter).



(a)

(b)

Fig. 4. Measured sensitivities as a function of the transmission distance and the driving voltages based on (a) 2.5 GHz LPFs and (b) 3 GHz LPFs.

on 2.5 and 3 GHz LPFs with respective optimum driving voltages at back-to-back and after 240 km of SSMF transmission. At back-to-back, using a 2.5 GHz LPF has about 0.8 dB better receiving sensitivity than using the 3 GHz LPF. However, following 240 km of transmission, the transmission penalty of using a 2.5 GHz LPF is 3.8 dB while for the 3 GHz LPF is only 0.5 dB. As a result, there is about 2.5 dB sensitivity improvement using a 3 GHz LPF with 88% driving voltage compared with using a 2.5 GHz LPF with 100% driving voltage.

4. Conclusion

In this investigation, a 100% driving voltage was demonstrated not necessarily to yield the best results concerning the duobinary modulation format both numerically and experimentally. The trade-off among the amplitude jitters of marks, the ripples of spaces and the eye-opening enables the duobinary signals based on broader LPFs to be optimized with lower driving voltages. Accordingly, selecting wider LPFs offers the flexibility to adjust the driving voltage and improves system performance. Under optimum conditions, a duobinary transmitter based on 3 GHz LPFs exhibits better dispersion tolerance than conventional 2.5 GHz LPFs. Furthermore, the experiments indicate a 2.5 dB sensitivity improvement following 240 km of SSMF transmission.

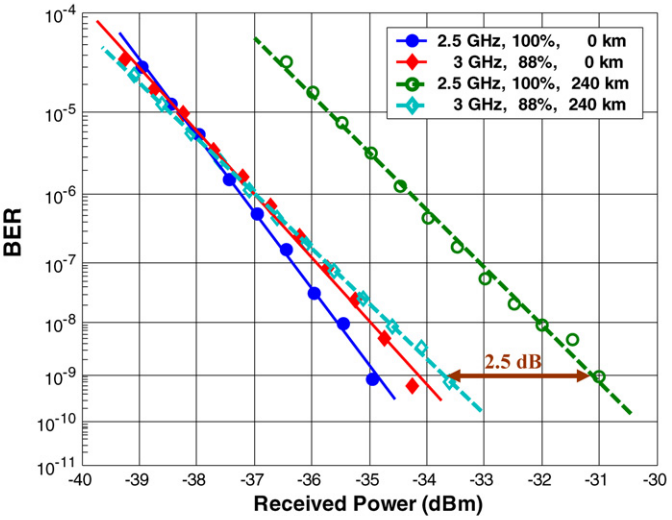


Fig. 5. BER curves of the duobinary signals based on 2.5 and 3 GHz LPFs with respective optimum driving voltages after 0 and 240 km of SSMF transmission.

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