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Receiver Optimization for 40-Gb/s Optical Duobinary Signal

Xueyan Zheng, Fenghai Liu, and Palle Jeppesen

***Abstract*—The optimized optical receiver for a 40-Gb/s optical duobinary signal is investigated by simulation. It is found, that by optimizing the optical filter and the electrical filter in the receiver, the sensitivity of the optical duobinary can be improved greatly; meanwhile, the high dispersion tolerance nature of the optical duobinary signal will not be degraded.**

***Index Terms*—Intersymbol interference, optical duobinary.**

I. Introduction

HIGH SPECTRAL efficiency modulation formats, such as optical duobinary or phase-shaped binary transmission [1] and carrier suppressed return-to-zero signal [2] are very effective ways to improve the capacity of a wavelength-division multiplexing (WDM) system, which is limited mainly by the bandwidth of optical amplifiers. Furthermore, an optical duobinary signal exhibits high tolerance of dispersion because of π-phase shifts occurring in the middle of each "space" bits, which can remain the energy in the "mark" bit longer due to the interference [1]. Up to now, the spectral efficiency of 0.6 bit/s/Hz on a single polarization state has been achieved using the optical duobinary format [3]. Though an ordinary binary receiver can still be used for an optical duobinary signal, the sensitivity of an optical duobinary signal will be degraded compared to the binary singal, because of the waveform distortion caused by the electrical filter with bandwidth of a quarter of a bit rate during the duobinary generation procession [4]. An extra external modulator working under a slight modulation index can be used to improve the sensitivity of the optical duobinary signal, meanwhile, the dispersion tolerance is still high [5]. However, this method will increase the cost of the transmitter. In this letter, in a 40-Gb/s duobinary system, it is shown by numerical simulation, the sensitivity of the optical duobinary signal can be improved greatly when the optimized optical receiver is used. A more narrow optical filter than in the binary system can be used before the optical/electrical (O/E) converter because of the narrowed spectrum. Consequently, more amplified spontaneous emission (ASE) can be filtered out, meanwhile, intersymbol-interference reduced ISI on "space" bits can be reduced by the more narrow optical filter due to the π-phase shifts in the middle of each "space" bits. Therefore, the sensitivity can be improved greatly. Furthermore, the dispersion tolerance of the optical duobinary signal is still kept high.

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II. Simulation Model

Fig. 1 shows the simulation model in our work. A 40-Gbit/s optical duobinary transmitter is constituted by a precoder, a fifth-order Bessel-electrical filter with a quart of bandwidth of bit rate, and Mach–Zehnder (M–Z) modulator, which works at the bottom of its transfer function [1]. In the receiver, it includes an optical preamplifier, a third-order Bessel optical filter, an O/E converter, and a fifth-order Bessel electronic filter. In our model, an ideal erbium-doped fiber amplifiers (EDFA) with noise figure (NF) of 4 dB and saturated output power of -4 dBm is used as the optical preamplifier. The fiber is only used to add dispersion to the signal. The length of the pseudo random bit sequence (PRBS) is 128 bit. Noise is treated as a Guassian distribution and the ISI effect is also taken into account [6]. We use a photodiode with a responsivity of $R = 1.0$ A/W at a wavelength of 1550 nm. The thermal noise is 10^{-11} A/Hz$^{1/2}$.

III. Results and Discussion

It should be pointed out in our model, since the receiver with an optical preamplifier is used, the thermal noise in the receiver has a much lower impact on the signal than the beat noise between signal and ASE, and between ASE and ASE.

Fig. 2(a) shows the back-to-back sensitivity of a 40-Gbit/s ordinary binary signal versus the bandwidth of the electrical filter in the optical receiver, when the optical filters with different bandwidth are used. We can see from Fig. 2(a), that the optimum bandwidth of the electrical filter is about 0.6$\times$ bit rate when different optical filters are used. This is because beat noise between ASE and ASE, and between ASE and signal are dominating factors in the receiver. A more narrow electrical filter can reduce more beat noise within the bandwidth of the signal, though the ISI effect is also increased, the sensitivity can still be improved. Even though an optical filter with a wider bandwidth is used, the beat noise can also reduced effectively by an electrical filter. The optimum receiver bandwidth is 0.6 $\times$ of bit rate.

Fig. 2(b) shows the back-to-back sensitivity of a 40-Gbit/s duobinary versus the bandwidth of the electrical filter after the photo detector, when optical filters with different bandwidths are used. We only consider the situation when the optical filter with a bandwidth more narrow than 100 GHz full-width at half

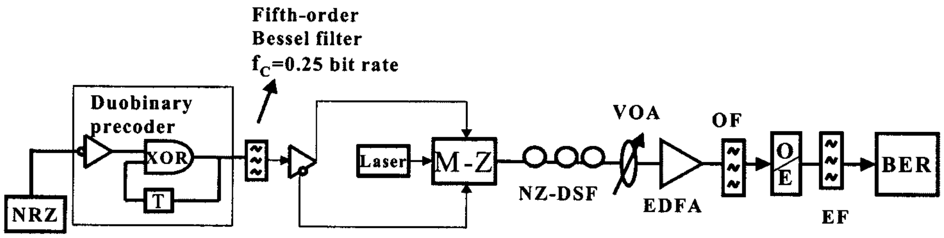

Fig. 1. Simulation model. M–Z modulator. Variable attenutor (VOA). Optical filter (OF). Electrical filter (EF).

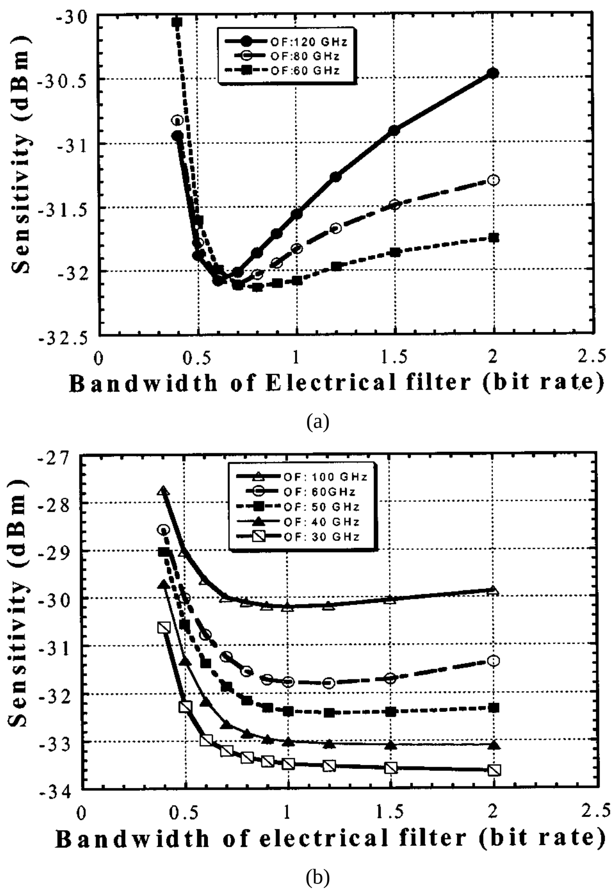

Fig. 2. Back-to-back sensitivity of 40 Gbit/s optical binary (a) and duobinary (b) signal versus the bandwidth of the electrical filter when optical filters with different bandwidth are used.

maximum (FWHM) is used before the PD. Under this case, ASE noise is reduced greatly.

As can be seen from Fig. 2(b), the optimum electrical bandwidth is around 1× bit rate and it is different from the results in Fig. 2(a), which has the optimum bandwidth of 0.6× bit rate. This is because the two electrical filters with the bandwidth of a quarter of a bit rate are used in the transmitter to generate an optical duobinary signal [1], which causes a small ripple (ISI) in the "space" bits of the optical duobinary signal. The small ripple is at a frequency of 40 GHz. If an electrical filter with narrow bandwidth is used, though it can reduce the in-band noise, the sensitivity will be degraded more by the increased ISI from both "space" and "mark" bits. The ISI in "space" is more serious due to the small ripple with high frequency components. So, the optimum bandwidth of an electrical filter in the receiver should be wider, considering the practical situation, an electrical filter

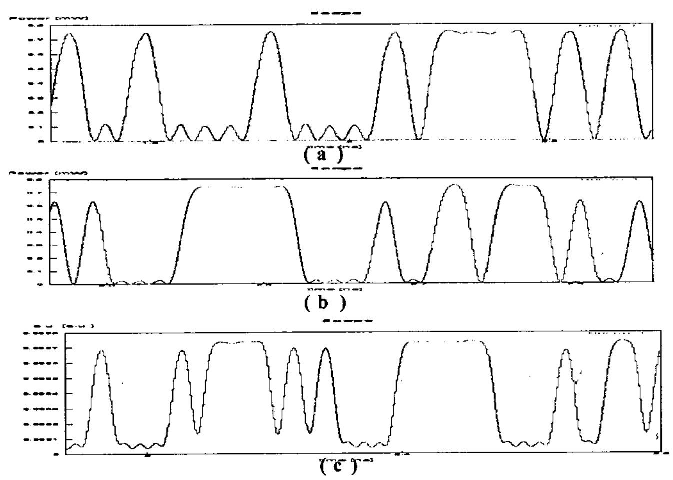

Fig. 3. (a) Waveform of the optical duobinary signals after Mach–Zehnder modulator. (b) Waveform after an optical filter with a 30-GHz bandwidth. (c) Waveform when an optical filter with a 100-GHz bandwidth and electrical filter with a bandwidth of 0.6× bit rate are used in the receiver.

with a bandwidth about 1× bit rate should be used in order not to increase the ISI further. Fig. 3(a) shows the waveform of duobinary signal after an optical filter with bandwidth of 100 GHz. From Fig. 3(a), we can see the small ripple with 40 GHz repeating frequency clearly.

We can also see from Fig. 2(b) that a narrow optical filter can improve sensitivity effectively. There are two reasons for the sensitivity enhancement. First, when a more narrow optical filter is used, the ISI effect will be less than that when a narrow electrical filter is used. As we know, there are π-phase shifts in the middle of each "space" bits, which helps to keep the power on "space" bit to be zero and improve the dispersion tolerance. In fact, the power level in the middle of "space" bits is also not changed after a more narrow optical filter because of the π-phase shifts. Consequently, no ISI is added to "space" bits after a narrow optical filter. Of course, it causes ISI on "mark" bits. However, when the optical signal is converted into an electrical signal, the π phase-shift in "space" bits disappears, and using a narrow electrical filter will increase ISI in "space" bits.

Fig. 3(a) and (b) shows the optical waveform of the duobinary signal output from optical filters with bandwidths of 100 and 40 GHz, respectively. Fig. 3(c) shows the waveform of an electrical signal when an optical filter with a bandwidth of 100 GHz and an electrical filter with bandwidth of 0.6× bit rate are used in the receiver.

Comparing Fig. 3(a) with Fig. 3(b), we can find that the optical filter can reduce the amplitude of the small ripple in "space" bits, but it does not change the power in the middle of each

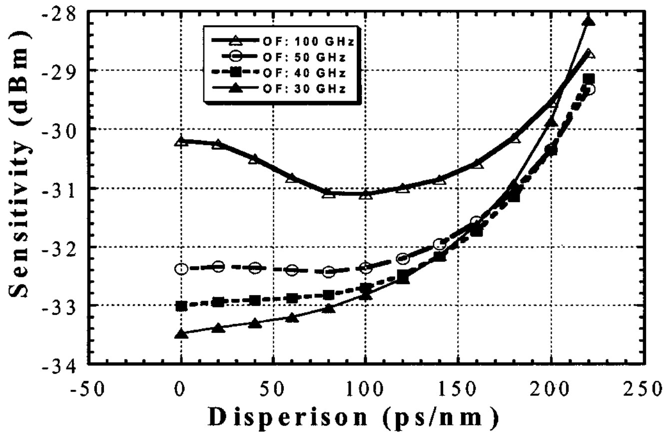

Fig. 4. The sensitivity of optical duobinary signal versus the dispersion under optical filter. The bandwidth of the electrical filter is 1× bit rate.

"space" bit, which can help to improve the sensitivity. It can be seen from Fig. 3(c), because there is no π-phase shifts in an electrical domain, the power in the middle of "space" bits will be increased and the sensitivity will be degraded.

The second reason for the sensitivity improvement is that the optical bandwidth of the optical duobinary signal is only half of the bandwidth of the optical binary signal, however, the electrical bandwidth of the received duobinary is the same to a binary signal. So, a more narrow optical filter can be used in an optical duobinary system than in an ordinary binary system. Consequently, more ASE noise can be filtered out and it is more effective to use an optical filter than an electrical filter. Compared to an ordinary binary signal, not only the beat noise between ASE and ASE will become smaller, but the beat noise between ASE and signal will also be smaller for the optical duobinary signal, if an optimized optical filter is used in the receiver. So, the sensitivity of duobinary signal enhancement is due to the reduced noise and ISI on "space" bits. As seen from Fig. 2(b), the optimized bandwidth of the optical filter is 30 GHz, and the corresponding highest sensitivity is about -33.5 dBm. The sensitivity is *about* 1 dB better than an ordinary 40-Gb/s binary signal using a normal receiver with a bandwidth of 0.6× bit rate, as shown in Fig. 2(a).

The dispersion tolerance is the most important factor for the optical duobinary signal. Fig. 4 shows that dispersion tolerance, when different optical filters are used before the O/E converter, the bandwidth of the electrical filter is 1× bit rate. It can be seen from Fig. 4 that the dispersion tolerance becomes worse when the bandwidth of optical filter with 30 GHz is used. This is because the signal will have a more serious ISI after dispersion is added to it and the more narrow optical filter can improve it further. So, considering dispersion, the optimum bandwidth of the optical filter is around 40 GHz.

IV. Conclusion

The optimized optical receiver for a 40-Gb/s optical duobinary signal is studied numerically. It is found that both the optimized bandwidth of the optical filter before the O/E and bandwidth of the electrical filter after the O/E is around 40 GHz. Under the optimum conditions, the sensitivity of optical duobinary signal can be improved greatly. Furthermore, the dispersion tolerance is still kept large enough. Our results are very useful for designing the optimum optical duobinary transmission system.

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