Performance Investigation of a Multiformat Transmitter With Pulsewidth Tunability

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***Abstract*—We propose and demonstrate a novel transmitter that enables versatile format generation with pulsewidth tunability. The transmitter is based on a single dual-parallel Mach–Zehnder modulator. By simply switching the driving and biasing conditions of the modulator, duobinary, return-to-zero alternate mark inversion and Manchester formats are obtained in a similar transmitter configuration. The back-to-back and transmission performances of the generated signals are investigated by experiments.**

***Index Terms*—Duobinary, Manchester code, modulation formats, return-to-zero alternate mark inversion (RZ-AMI).**

I. Introduction

THERE ARE various application scenarios where specific modulation formats would be best suited because of their advantageous features. For example, duobinary format provides narrow spectral bandwidth and large chromatic dispersion tolerance [1], [2], showing its effectiveness in dense wavelength-division-multiplexed systems and dispersion uncompensated transmissions. Return-to-zero alternate mark inversion (RZ-AMI) format is robust to fiber nonlinearity-induced transmission impairments [3], and thus is promising for long-haul applications. Furthermore, Manchester code shows equal power in each bit and enables simple clock recovery, manifesting its potential for burst-mode operation [4]. Usually, a transmitter is designed to generate a specific data format, and its application is, therefore, limited. To adapt to different applications, it is highly desirable to produce various formats via a single transmitter in a flexible manner.

Recently, we have demonstrated that duobinary, RZ-AMI, and Manchester formats can be generated by simply switching the driving and biasing conditions of a single dual-parallel Mach–Zehnder modulator (MZM) [5]. In this letter, the performances of the generated signals are evaluated in detail. Specifically, pulsewidth tunability is investigated for the duobinary and RZ-AMI signals and the optimal operation conditions are identified. Using a universal transmitter configuration, all three signal formats are encoded in the optical domain, thus alleviating the requirement on the complex, high-speed electrical processing stage. In addition, the optical encoding method has the potential to greatly reduce the pattern dependence that is commonly seen in low-pass-filter-based duobinary transmitters [6], [7]. Furthermore, our scheme also reduces the chirp effect associated with the previous technique for RZ-AMI signal generation [8].

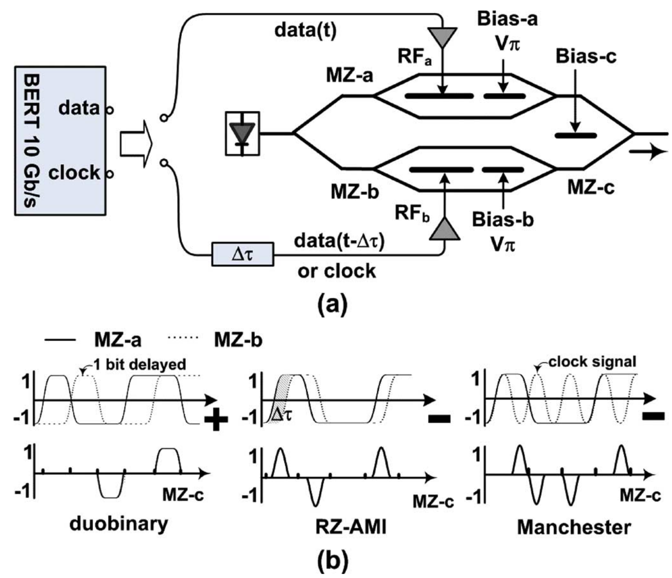

Fig. 1. (a) Configuration of the multiformat transmitter (b) modulated optical fields for duobinary, RZ-AMI, and Manchester format generations. Bias-c ensures add or subtract operations on the optical fields in MZ-a and MZ-b.

II. Proposed Transmitter

Fig. 1(a) shows the configuration of the proposed transmitter. The dual-parallel modulator consists of a pair of x-cut $LiNbO_3$ MZMs (MZ-a, MZ-b) embedded in the two arms of a primary MZ structure (MZ-c). It was designed for differential quadrature phase-shift keying [9] and frequency-shift keying [10] signal generations. Here we demonstrate that this modulator can be used for obtaining other formats. As shown in Fig. 1(a), for duobinary and RZ-AMI signal generations, MZ-a is driven by a nonreturn-to-zero (NRZ) signal and MZ-b is driven by a delayed replica, with the dc ports of MZ-a and MZ-b biased at V_π. This driving condition enables either 0 or π phase shift in each optical path depending on the binary values of the driving signals [5]. The phase difference between the two optical paths is adjusted by the bias port of MZ-c, which is set to be 0 or π to achieve add or subtract operation on the output optical fields of MZ-a and MZ-b. Fig. 1(b) shows the encoding processes for the three formats. When the differential delay time between the driving

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Color versions of Figs. 1–5 are available online at http://ieeexplore.ieee.org.

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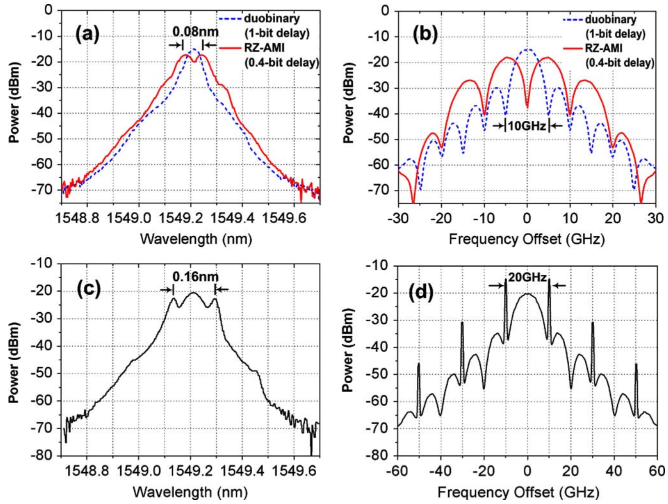

Fig. 2. (a) Measured (at 0.07-nm RB) and (b) simulated (at 1-GHz RB) optical spectra of duobinary (1-bit delay) and RZ-AMI signals (0.4-bit delay); (c) measured (at 0.07-nm RB) and (d) simulated (at 1-GHz RB) optical spectra of Manchester signal.

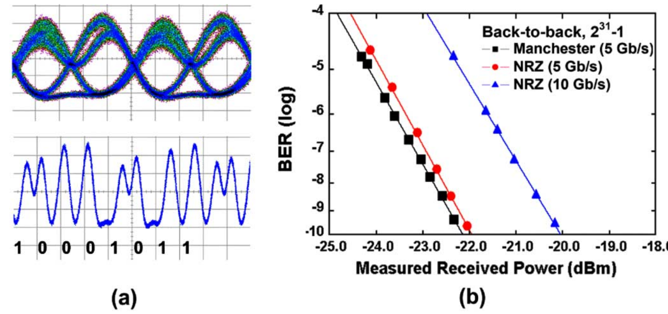

Fig. 3. (a) Eye diagram and bit pattern for the 10-Gb/s Manchester code. (b) BER performance along with an NRZ signal, without optical preamplifier.

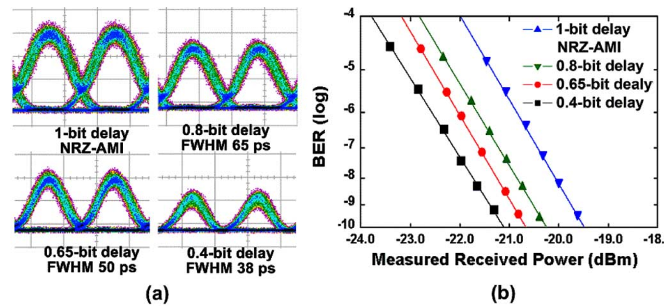

Fig. 4. (a) Measured eye diagrams of RZ-AMI signals with different pulsewidths. (b) BER performances of the generated RZ-AMI signals.

signals is 1 bit and bias-c ensures a 0 phase difference, the duobinary signal is produced. Note that the 1-bit-delay-and-add operation is achieved in the optical domain, and the encoded optical field shows three possible values $(-1, 0, +1)$, which is the requirement for duobinary coding. If the differential delay time is less than 1 bit and MZ-c results in a π phase difference, the RZ-AMI signal is generated. As shown in Fig. 1(b), the output pulses of MZ-c are formed at the rising and falling edges of the driving signal, with alternating phases of 0 and π. Because of the x-cut structure of the modulators, a chirp-free RZ-AMI signal is expected at the output of MZ-c. Our method is essentially equivalent to the scheme reported in [3], and the generated signal using either scheme can be chirp free. By varying the differential delay time, the pulsewidth of the generated RZ-AMI signal can be adjusted. Fig. 1(b) also shows the modulated optical fields for the Manchester code, where MZ-a is driven by an NRZ signal while MZ-b is driven by a clock signal with their dc ports biased at V_π. It can be seen that the output of MZ-c displays space-to-mark and mark-to-space transitions according to the binary values of the driving signals, and the conventional XOR operation can be achieved in the optical domain by this dual-parallel MZM.

In the experimental implementation, the peak-to-peak voltage value of the amplifier output is $\sim$7 V, which is about twice V_π. No precoding section was used in this experiment because of the nature of the pseudorandom bit sequence signal $(2^{31}-1)$.

III. Experimental Results

Fig. 2(a) and (c) shows the measured optical spectra of the generated duobinary, RZ-AMI, and Manchester signals at a resolution bandwidth (RB) of 0.07 nm. For the purpose of comparison, the simulated optical spectra at an RB of 1 GHz are also shown in Fig. 2(b) and (d). It is clearly seen that there is no carrier in the spectrum of the RZ-AMI signal, and the dips occur every 10 GHz because of the delay-induced filtering effect. The Manchester code shows much wider optical spectrum with strong spectral tones at the clock frequency, which is desired to ease clock recovery.

Fig. 3(a) shows the measured eye diagram of the generated Manchester signal at 10 Gb/s. The waveform of a bit pattern "1000 1011" is also provided, where a bit "1" is represented by the transition from space to mark. The dip in the eye diagram is caused by the phase change at the transition from "1" to "0". Fig. 3(b) depicts the bit-error-ratio (BER) performance of the generated Manchester code along with NRZ signals for comparison. Limited by the bandwidth of the 10-Gb/s PIN receiver, the BER measurement for the Manchester code is carried out at 5 Gb/s, as the Manchester signal possesses a bandwidth twice the bit rate considering the space-to-mark or mark-to-space transitions in each bit. At the receiver, simple threshold detection was performed and decisions were made on the second time slot of each data bit, which exhibited slightly better BER performance. The back-to-back receiver sensitivity for the Manchester signal is -22.4 dBm at BER $= 10^{-9}$ with direct detection, and is -22.2 and -20.3 dBm for a 5-Gb/s and a 10-Gb/s NRZ signal, respectively.

By switching the driving signal of MZ-b to the data signal and adjusting the differential delay time, the RZ-AMI signals are obtained. Fig. 4(a) provides the corresponding eye diagrams measured at different full-width at half-maximum by changing the differential delay time, with a constant power launched into the modulator. Note that for 1-bit delay, the generated waveform is an NRZ-AMI signal, although its eye diagram looks like an RZ format [11]. It can be seen that a pulsewidth of 38 ps can be achieved when the delay time is 0.4 bit at 10 Gb/s. Although it is possible to get even smaller pulsewidth, the signal performance is degraded because of the reduced extinction ratio and increased timing jitter of the pulses. Fig. 4(b) shows the measured BER performances of the RZ-AMI signals with different pulsewidths. At a BER of 10^{-9}, receiver sensitivities from -21.4 to -20.6 dBm could be obtained for the RZ-AMI

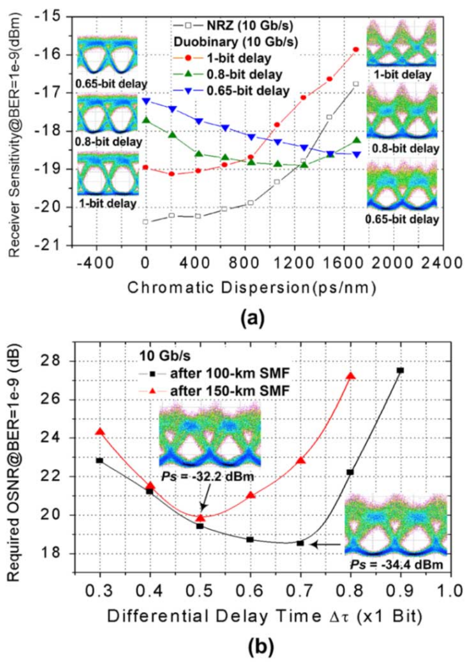

Fig. 5. (a) Measured receiver sensitivity versus chromatic dispersion, (b) measured required OSNR at BER $= 10^{-9}$ versus differential delay time after transmission over 100 and 150-km SMF. Insets show the measured eye diagrams at the optimal time delay points. Ps is the receiver sensitivity with preamplification.

signals with pulsewidths varying from 38 to 65 ps, showing sensitivity gains of 1.1–0.3 dB over a 10-Gb/s NRZ signal as previously characterized.

It should be noted that by simply changing the biasing condition of MZ-c, duobinary signals are generated in the same configuration. The differential delay time can be varied for better dispersion tolerance. Fig. 5(a) shows the measured receiver sensitivities for different chromatic dispersion values with a launch power of 5.3 dBm. The measured eye diagrams for back-to-back operation and after 100-km single-mode fiber (SMF) transmission are also presented as the insets. The back-to-back eye diagrams indicate that different pulsewidths can be obtained by changing the differential delay time. It can be seen that at a chromatic dispersion value of 1700 ps/nm, the receiver sensitivities are -18.3 and -18.6 dBm for the 0.8- and 0.65-bit-delayed duobinary signals, which are much better than the NRZ signal with a receiver sensitivity of -16.8 dBm. It is interesting to note that the 1-bit-delayed duobinary signal does not offer dispersion tolerance, although it is generated by the 1-bit-delay-and-add operation. The reason is that the 1-bit-delayed duobinary signal with 100% duty cycle has narrow spectral width [12] and lacks pulse spreading required to have large dispersion tolerance [13], [14].

To find the optimal differential delay time of the generated duobinary signal that can achieve the best dispersion tolerance, the required optical signal-to-noise ratios (OSNRs) at BER $= 10^{-9}$ are measured after 100- and 150-km SMF transmissions, respectively. The results are shown in Fig. 5(b), where the OSNR is measured at 0.1-nm noise bandwidth. After the 100-km SMF, it can be seen that the optimal delay time is in the range of 0.5–0.7 bit. While after the 150-km SMF, this range is shifted to 0.4–0.6 bit, which indicates that the dispersion tolerance of the generated duobinary signal is closely related to its pulsewidth. The measured eye diagrams at the optimal time delay points are also presented as the insets. Fig. 5(b) shows that, after the 150-km SMF, an OSNR of 19.8 dB is required to achieve BER $= 10^{-9}$ for the pulsewidth optimized duobinary signal, which corresponds to a receiver sensitivity of -32.2 dBm with preamplification.

IV. Summary

In conclusion, we have demonstrated that a dual-parallel MZM can be used for multiformat generation. A 10-Gb/s Manchester code is generated with signal encoding in the optical domain. RZ-AMI signals with tunable pulsewidths from 38 to 65 ps are obtained. Experimental results show that the pulsewidth optimized duobinary signals possess high dispersion tolerance.

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