Conversions among binary optical modulation formats

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Abstract: We study the intrinsic relations and conversions among different binary modulation formats such as non-return-to-zero (NRZ), return-to-zero (RZ), carrier-suppressed return-to-zero (CSRZ), differential-phase-shift-keying (DPSK), duobinary, and alternate-mark-inversion (AMI). In particular, we experimentally demonstrate the new conversion from CSRZ to duobinary using a Mach-Zehnder delay interferometer (MZDI).

OCIS codes: (060.4080) Modulation; (070.4560) Data processing by optical means; (060.4510) Optical communications; (230.1150) All-optical devices.

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1. Introduction

Advanced modulation formats with phase modulations have received much interest recently [1]. These formats are employed in various transmission systems due to their different dispersion and nonlinearity performances. For example, duobinary format provides narrow spectral bandwidth and large chromatic dispersion tolerance [2, 3], showing its effectiveness in dispersion uncompensated metro or local networks. Carrier-suppressed return-to-zero (CSRZ) shows good tolerance to some linear filtering and nonlinear impairments accumulated along a long-haul transmission line [4]. Alternate-mark-inversion (AMI) format is robust to fiber nonlinear impairments, thus also attractive for long-haul systems [5, 6]. For ultra-long-haul transmission, differential-phase-shift-keying (DPSK) and CSRZ-DPSK may become the chosen formats due to their superior receiver sensitivity, high tolerance to chromatic dispersion and polarization mode dispersion [7-10]. In future optical networks, different modulation formats may be selectively employed depending on the network size and the system settings. Thus, format conversion could become a necessary technology to interface different optical networks employing diverse formats. Conversions from non-return-to-zero (NRZ) to CSRZ [11], between CSRZ and return-to-zero (RZ) [11], and from CSRZ to NRZ have been demonstrated [12].

In this paper, we firstly reveal the intrinsic relations among various modulation formats in section 2. In section 3, we propose and experimentally demonstrate a simple format conversion scheme from CSRZ to duobinary, which was not investigated before, using a Mach-Zehnder delay interferometer (MZDI), suitable for multi-channel operation. To the best of our knowledge, this is the first report on all-optical format conversion from CSRZ to duobinary, which would be desirable at an intermediate node between a long-haul backbone and a metro network. The periodic frequency characteristic of an MZDI indicates that simultaneous multi-channel format conversions at the same data rate can potentially be implemented.

2. Principle of conversions among binary modulation formats

We reveal the intrinsic relations among commonly used binary formats in Fig. 1, including RZ, CSRZ, duobinary, AMI, and DPSK. Arrows indicate conversions among different modulation formats. It is well known that conversions between RZ and CSRZ and between duobinary and AMI can be realized by inversing the sign of the optical field at every bit transition [1], which is represented by arrows with $(-1)^n$ in Fig. 1. The constructive and destructive ports of an MZDI act as a delay-and-add filter and a delay-and-subtract filter, respectively. A delay-and-subtract filter can convert an NRZ or an RZ to an AMI format [1, 13]. Duobinary and AMI can be obtained from DPSK at the constructive and destructive ports of the MZDI, respectively [14]. However, conversion from CSRZ to duobinary was not studied prior to our work, which will be demonstrated in the following. In addition, CSRZ-DPSK, which is not shown in Fig. 1, is simply phase-inverted version of RZ-DPSK at every other bit. It can be converted into duobinary and AMI with an MZDI as the well-known conversions of DPSK.

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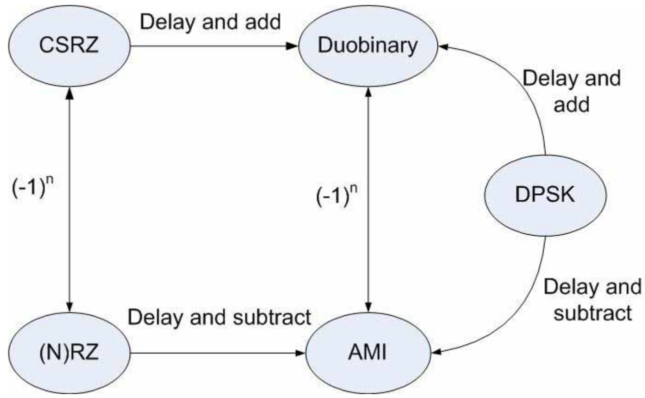

Fig. 1. Relations among (N)RZ, CSRZ, Duobinary, AMI, and DPSK.

One can express (N)RZ as *D(n)* and CSRZ as $(-1)^n D(n)$ correspondingly. *D(n)* represents the power {0, 1}. Passing CSRZ through a delay-and-add filter, we obtain:

$$(-1)^n D(n) + (-1)^{(n+1)} D(n+1) = (D(n) - D(n+1)) \times (-1)^n . \tag{1}$$

The first term on the right side of Eq. (1) describes the process of an (N)RZ passing through a delay-and-subtract filter, resulting in an AMI signal [1,13]. The subsequent bit-alternating phase inversions convert the AMI to a duobinary format. Therefore, CSRZ can be converted to RZ-duobinary at the constructive port of an MZDI. It is worth noting that (N)RZ to duobinary and CSRZ to AMI can be realized by cascading an MZDI with a phase-alternating process.

3. Experimental demonstration of CSRZ to duobinary format conversion

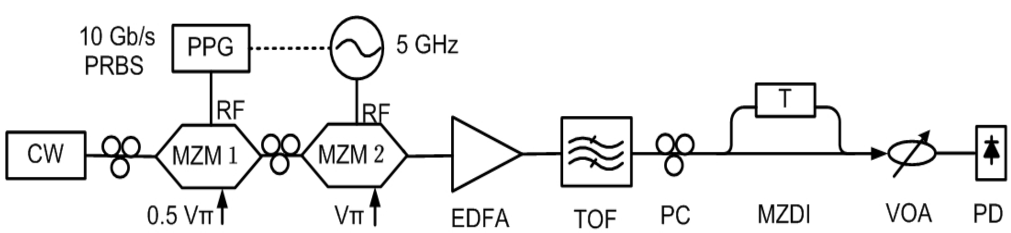

Fig. 2. Experimental setup of CSRZ to Duobinary conversion. CW: Continuous wave; PC: Polarization controller.

The experimental setup of the proposed all-optical CSRZ to duobinary conversion scheme is depicted in Fig. 2. The CSRZ transmitter at 1550.84 nm consists of two cascaded Mach-Zehnder Modulators (MZMs). The first MZM is biased at the quadrature point and modulated by a 10-Gb/s pseudorandom bit sequence (PRBS) of length 2^{31}-1 generated by a pulse pattern generator (PPG). The other MZM acting as a CSRZ pulse carver, is sinusoidally driven by a synchronized 5-GHz clock. The generated CSRZ is amplified by an erbium-doped fiber amplifier (EDFA) and then filtered by a tunable optical filter (TOF) with a bandwidth of 1.6 nm. The optical eye diagram and the spectrum of the CSRZ are provided in Figs. 3(a) and 3(e), and the detected eye diagram is shown in Fig. 3(c), respectively. After the MZDI, the RZ-duobinary format is obtained at the constructive port, and the corresponding optical eye diagram and spectrum are illustrated in Figs. 3(b) and 3(f), respectively. The optical eye diagrams of the CSRZ and the RZ-duobinary signals are measured with a sampling

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oscilloscope having a 20-GHz bandwidth. The mark levels of the duobinary signal present more amplitude fluctuations in Fig. 3(b), which can be attributed to the low extinction ratio of the MZDI (~6 dB), resulting from the imperfect optical splitters at the input and the output ports of the MZDI. Due to the limited electrical bandwidth (8.5 GHz) of the photodetector (PD), the electrical eye diagrams of the CSRZ [Fig. 3(c)] and the RZ-duobinary [Fig. 3(d)] signals show wider pulse widths than the optical ones in Figs. 3(a) and 3(b), and the noise has been suppressed in the photodetector by the filtering effect. In practice, a narrow-bandwidth optical filter should be used to convert RZ-duobinary to NRZ-duobinary, which would greatly increase the system tolerance to chromatic dispersion [15, 16].

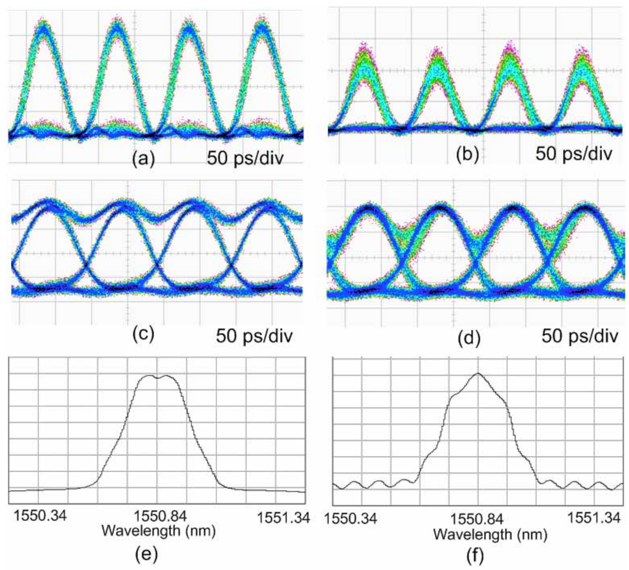

Fig. 3. Experimental results of CSRZ to Duobinary conversion. (a), (b) Optical eye diagrams of CSRZ and Duobinary, respectively; (c), (d) Electrical eye diagrams of detected CSRZ and Duobinary, respectively; (e), (f) Optical spectra of CSRZ and Duobinary, respectively. Spectrum resolution: 0.07 nm.

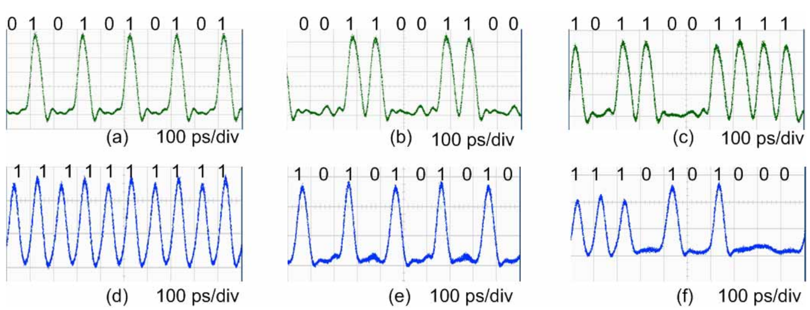

Fig. 4. Demonstration of some typical patterns. (a), (b), and (c): Input CSRZ data; (d), (e), and (f): Converted Duobinary signals.

To further prove the effectiveness of our proposed scheme, we use some typical data patterns as the input and observe the output at the constructive port of the MZDI. Figures 4(a), 4(b), and 4(c) show different input CSRZ data patterns, and Figs. 4(d), 4(e), and 4(f) provide the corresponding waveforms of the converted duobinary signal. Note that a pre-coding stage

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would be employed in the transmitter to ensure the correct reception of the data, which is similar to that of NRZ to AMI format conversion [13]. In our experiment, the pre-coding stage is not necessary due to the properties of PRBS.

We obtained error-free conversion from CSRZ to duobinary. The bit-error-rate (BER) curves are provided in Fig. 5. The power penalty of the conversion technique is 1.7 dB at BER = 10^{-9}. As shown in Fig. 6, when the relative delay between the two branches of the MZDI is less than a bit, part of a bit interferes with itself, which causes deterministic constructive interference for every bit [17], induces time jitter between adjacent bits, and produces residual power when the RZ-duobinary signal is a “0” bit obtained from two consecutive “1” bits of the CSRZ. In addition, the low extinction ratio (~6 dB) of the MZDI induces power difference between the two arms of the MZDI, which causes amplitude fluctuations of the RZ-duobinary signal, as shown in Fig. 3(b). The two imperfections create the eye closure of the converted RZ-duobinary signal and degrade the receiver sensitivity. Therefore, the conversion penalty of the scheme would be reduced if a better MZDI were used.

An attractive feature of this scheme is that one MZDI can simultaneously convert CSRZ signals at different wavelengths to duobinary signals due to its periodic frequency transmission characteristic. The scheme is feasible at 40 Gb/s or even higher data rates [13].

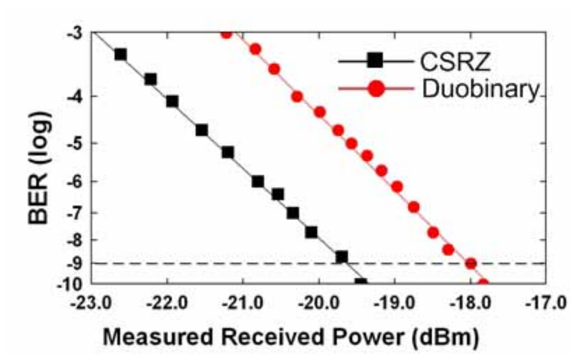

Fig. 5. BER curves of CSRZ and Duobinary.

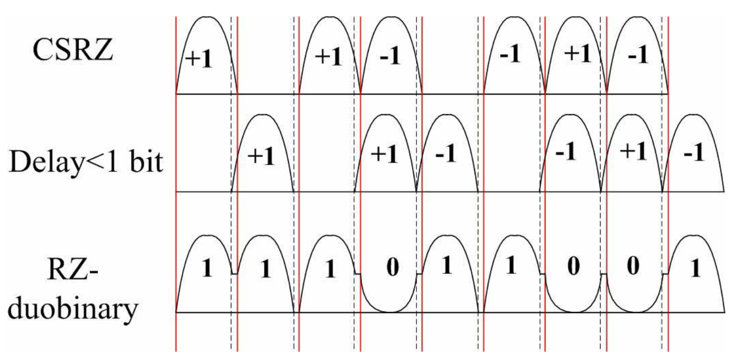

Fig. 6. Conceptual illustration of <1 bit delay

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4. Conclusion

We have investigated the relations among binary formats including RZ, CSRZ, duobinary, AMI, and DPSK. An experiment using an all-passive MZDI has been performed for the first time to convert a CSRZ to a duobinary format. Simultaneous multi-channel format conversions with a single MZDI can potentially be implemented.

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