Generation of modified duobinary return-to-zero format using polarization-maintaining fiber loop mirror

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Modified duobinary return-to-zero (MD-RZ) format is an improvement of optical duobinary (ODB) format. This paper proposes a novel, all-optical method to generate MD-RZ format by using a polarization maintaining fiber loop mirror (PMFLM). Operation principle for all-optical format conversion is theoretically analyzed and the output spectrum is simulated. 40-Gb/s MD-RZ data format generation is experimentally demonstrated.

OCIS codes: 060.4080, 060.5060, 060.2420, 060.4510.

Recently, various optical modulation formats have been proposed to improve the transmission capacity. Among them, optical duobinary (ODB) modulation format has been very attractive due to a narrow spectral width and high tolerance to chromatic dispersion[1−3].

Cheng *et al.*[4] found that modified duobinary return-to-zero (MD-RZ) format has much more advantage than non-return-to-zero (NRZ), return-to-zero (RZ), and traditional ODB because it has a phase-shifting of "π" in adjacent "1"s. As a result, nonlinear effects such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM) can be greatly alleviated. Yu[5] developed a method to generate MD-RZ by using only a single dual-arm $\mathrm{LiNbO_3}$ modulator. Differentiating of the precoded signal occurs in electrical domain. However, an electrical delay line is required and the signal processing in electrical domain is more complicated.

In this letter, we demonstrate a novel all-optical method to generate MD-RZ format using a single-arm $\mathrm{LiNbO_3}$ Mach-Zehnder modulator (MZM) and a polarization maintaining fiber loop mirror (PMFLM). The MZM is used to generate conventional NRZ differential-phase-shift-keying (NRZ-DPSK) signal. Differentiating of the NRZ-DPSK signal is achieved in optical domain by PMFLM which is composed of all fiber-based devices. Hence, the insertion loss is minimal and the PMFLM can be used as a passive device. Also, the MD-RZ signal can be detected by a common intensity receiver, which spares the expensive DPSK balanced-receiver.

The experimental setup is shown in Fig. 1. A MZM biased at intensity null is used for generating NRZ-DPSK signals. The MZM is driven by NRZ electrical signals, a pseudo random bit sequence (PRBS) with a length of $2^{15}-1$. This experiment bypasses the differential encoding step, because the pattern of PRBS does not change after encoding[5]. Differential encoding can be realized by using one bit delay feedback loop and an exclusive-OR gate[6]. The NRZ-DPSK signal is directed to the PMFLM, which consists of a 10-meter-long PMF and a polarization controller (PC).

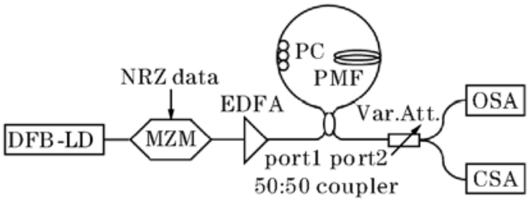

Fig. 1. Experiment setup for generation of MD-RZ format.

The principle to generate MD-RZ signal is described as follows. There are two orthogonal principal states of polarization in a PMF which propagate with no significant distortion, but with a fixed differential group delay (DGD) along the PMF[7]. Let us define the fast axis is x, the slow axis is y. We just analyze x-component of the input signal. For the y-component, the method is similar. All the transmission loss is ignored because it is inessential to the analysis, and the input is assumed an ideal NRZ-DPSK signal that can be written as

$$E_x(t) = E_{0,x} \cdot \mathrm{e}^{i\alpha(t)}\overrightarrow{x}, \tag{1}$$

where $\alpha(t)$ is the phase of the signal.

The x-polarized input signal is divided by the 3-dB coupler. The clockwise (cw) branch rotates 90° after the PC, and then travels through the slow axis of the PMF, while the counter clockwise (ccw) branch goes through the fast axis. A time delay (ΔT) emerges between the two branches, which is determined by the length of the PMF.

The two branches re-encounter at the 3-dB coupler, and the output at the destructive port is described as

$$\overrightarrow{E}_{\mathrm{des},y}(t) = \frac{1}{2}E_{0,x}(\mathrm{e}^{i\alpha(t-T)} - \mathrm{e}^{i\alpha(t-T-\Delta T)})\overrightarrow{y}. \tag{2}$$

Recall that the phase $\alpha(t)$ of the NRZ-DPSK signal has only two values: "0" and "π", thus all the four possible instances are

$$1)\quad \text{for}\quad \mathrm{e}^{i\alpha(t-T)} = \mathrm{e}^{i\alpha(t-T-\Delta T)} = 1,$$

$$\overrightarrow{E}_{\mathrm{out},y}(t) = 0, \tag{3a}$$

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2) for $\mathrm{e}^{i\alpha(t-T)} = \mathrm{e}^{i\alpha(t-T-\Delta T)} = -1$,

$$\overrightarrow{E}_{\mathrm{out},y}(t) = 0, \tag{3b}$$

3) for $\mathrm{e}^{i\alpha(t-T)} = 1$ and $\mathrm{e}^{i\alpha(t-T-\Delta T)} = -1$,

$$\overrightarrow{E}_{\mathrm{out},y}(t) = E_{0,x}\overrightarrow{y}, \tag{3c}$$

4) for $\mathrm{e}^{i\alpha(t-T)} = -1$ and $\mathrm{e}^{i\alpha(t-T-\Delta T)} = 1$,

$$\overrightarrow{E}_{\mathrm{out},y}(t) = -E_{0,x}\overrightarrow{y}. \tag{3d}$$

Together with Fig. 2, the result shows that if the phases of the two branches are identical, the output power will be null; if the phases of the two branches differ, an optical pulse is generated. The field values of "+" and "−" in Eqs. (3c) and (3d) lead to two different phases "0" and "π" in the optical pulses.

Optisystem 3.1 is used to simulate the spectrum in Fig. 3(a), while Fig. 3(b) is the experimental result. The original carrier frequency component is suppressed. The reason is that adjacent "1"s in MD-RZ have a phase difference of π. This feature relaxes the power input limitation due to stimulated Brillouin scattering (SBS)[1], and relieves the effect of FWM. MD-RZ is a sort of RZ format, which has a lower average power than NRZ and ODB. Therefore, the input peak power can be higher as to benefit in optical signal-to-noise ratio (OSNR) measurement. However, a narrow pulse in time domain means a wider spectrum in frequency domain. MD-RZ has a spectrum width as twice as ODB's, which may cause poor performance in dense wavelength division multiplexing (DWDM) systems and networks consisting of optical add-drop multiplexers (OADMs) and optical cross connectors (OXCs). A potential resolving method is using optical filters. According to the MD-RZ spectrum, two first order sidebands are symmetric relative to the carrier, and either has entire information of the signal. Therefore, filtering one of the first order sidebands elaborately will significantly narrow the spectrum while remain the integrity of signal information.

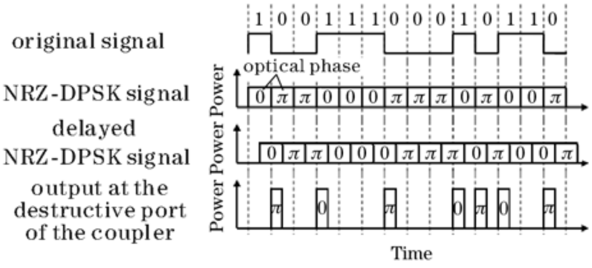

Fig. 2. Principle of MD-RZ format generation.

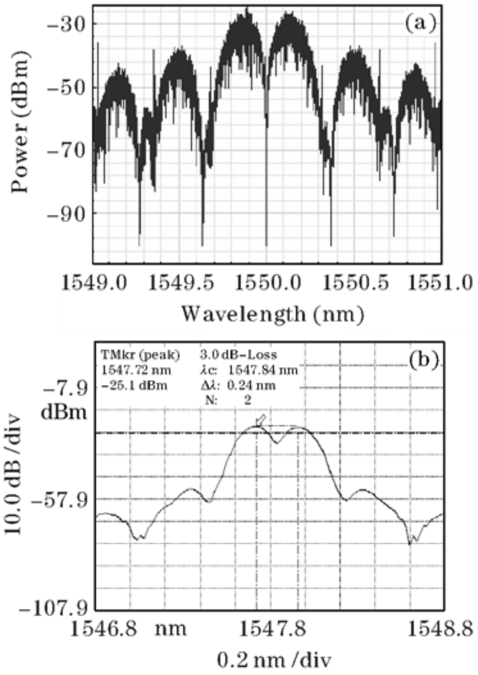

Fig. 3. (a) Stimulated and (b) experimental spectra of MD-RZ format at 40 Gb/s.

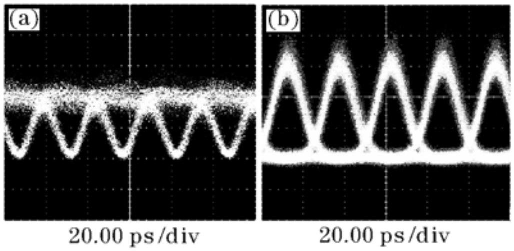

Fig. 4. (a) NRZ-DPSK and (b) MD-RZ (b) eye diagrams at 40 Gb/s.

Figure 4 shows the experiment result of the NRZ-DPSK eye diagram and the MD-RZ eye diagram. The data rate is 40 Gb/s. In order to minish the duty cycle of the output MD-RZ pulses, a shorter PMF should be exploited.

In this letter, a novel method is proposed to generate MD-RZ signal. We use a MZM to obtain NRZ-DPSK signal, and convert it to a MD-RZ signal by a PMFLM. The PMFLM can be also viewed as a passive DPSK to MD-RZ format convertor. The process is carefully proven in principle, and the availability of the scheme is demonstrated by simulation and experiment.

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