All-optical single-to-dual channel non-return-to-zero to return-to-zero format converter using a periodically poled LiNbO₃ and a reflective semiconductor optical amplifier

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Abstract. All-optical single-to-dual channel format converter from non-return-to-zero (NRZ) to return-to-zero (RZ) is proposed and demonstrated using cascaded sum- and difference-frequency generation (SFG+DFG) in a periodically poled LiNbO₃ (PPLN) waveguide. The pump optical clock is generated from the active mode locking in a reflective semiconductor optical amplifier (RSOA)-based fiber ring laser. We successfully observe 10- and 20-Gbit/s single-to-dual channel NRZ-to-RZ format conversions in the experiment. © *2007 Society of Photo-Optical Instrumentation Engineers.*
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1 Introduction

An all-optical format converter is an essential element in all-optical signal processing for future high-speed telecommunication. The basic format conversion from non-return-to-zero (NRZ) to return-to-zero (RZ) is very important and has been successfully implemented using devices based on a nonlinear optical loop mirror[1] (NOLM) or semiconductor optical amplifiers[2] (SOAs) with impressive operation performance. Recently, we proposed, theoretically analyzed, and experimentally investigated another scheme to perform NRZ-to-RZ format conversion using the cascaded second-order nonlinearity in a periodically poled LiNbO₃ (PPLN) waveguide.[3–6] PPLN is now considered to be a promising candidate in all-optical signal processing applications. Various experimental demonstrations were previously reported on PPLN-based all-optical signal processing, such as wavelength conversions[7–13] and logic gates.[14–16] In this paper, we further suggest and experimentally demonstrate a novel realization of single-to-dual channel format conversion from NRZ to RZ using a PPLN waveguide and a reflective semiconductor optical amplifier (RSOA). NRZ-to-RZ for-
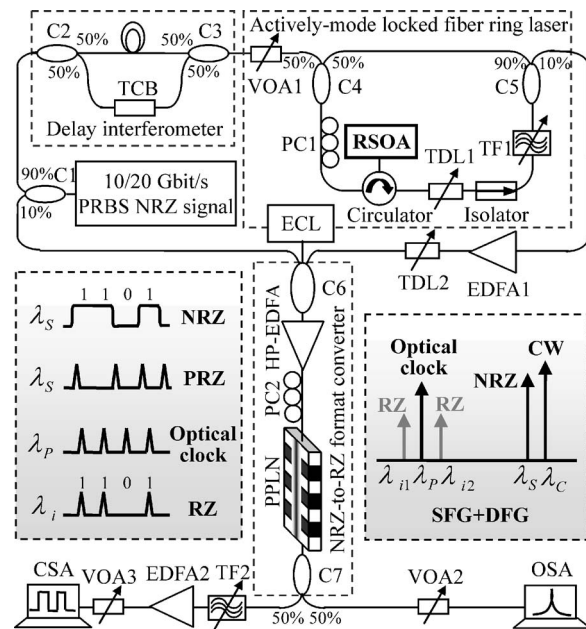
Fig. 1 Experimental setup for PPLN+RSOA-based all-optical single-to-dual channel NRZ-to-RZ format converter.

mat conversions with dual-channel outputs at 10 and 20 Gbit/s are successfully observed in the experiment.

2 Experimental Setup and Operation Principle

The experimental setup of the proposed PPLN+RSOA-based single-to-dual channel NRZ-to-RZ format converter is shown in Fig. 1. A pseudo-random binary sequence (PRBS) NRZ signal containing weak clock components at 10 or 20 Gbit/s is utilized. The PRBS NRZ signal is first converted to a pseudo-return-to-zero (PRZ) signal to enhance the clock components by passing it through an all-fiber delay interferometer (DI). The adopted DI has a 5.2-mm fiber length difference between two fiber arms, corresponding to a time delay of ∼25 ps. Note that such time delay enables the 10- or 20-Gbit/s NRZ signal to be converted to a PRZ signal. The phase difference of the two fiber arms can be adjusted by a temperature controlling block (TCB). The PRZ signal containing enhanced clock components is injected into an actively mode locked fiber ring laser (AMLFRL) to generate the synchronized pump optical clock. The AMLFRL consists of a variable optical attenuator (VOA1), two couplers (C4, C5), a polarization controller (PC1), a circulator, an RSOA, a tunable delay line (TDL1), an isolator, and a tunable filter (TF1). VOA1, PC1, TDL1, and isolator are, respectively, used to control the optical power coupled into the ring cavity, adjust the polarization state, change the cavity length, and keep the unidirectional oscillation inside the ring cavity. A 1000-μm-strained, multi-quantum-well (MQW) InGaAsP-InP material RSOA is employed to provide the gain of the ring cavity. The RSOA has a small signal gain of 18 dB with its peak gain wavelength at 1550 nm when biased at 200 mW. The pump optical clock with its wavelength determined by TF1 can be obtained by the proper adjustment of VOA1, PC1, and TDL1. The PRBS NRZ signal, gener-

ated pump optical clock, and a continuous wave (cw) control from an external cavity laser (ECL), are amplified through a high-power erbium-doped fiber amplifier (HP-EDFA) and launched into the PPLN waveguide, in which the cascaded sum- and difference-frequency generation (SFG+DFG) processes take place. The relative time delay between the NRZ signal and pump optical clock can be adjusted by TDL2. The commercial HP-EDFA offers a small signal gain of 40 dB and a saturation output power of 30 dBm. PC2 is placed before the PPLN to enhance the nonlinear interactions inside the PPLN waveguide. The optical spectra are monitored by an optical spectrum analyzer (OSA, Anritsu MS9710C) and the temporal waveforms are observed by a communications signal analyzer (CSA, Tektronix 8000B). The 50-mm-long PPLN waveguide used in the experiment was fabricated by the electric-field poling method and the annealing proton-exchanged (APE) technique. It has a microdomain period of 14.7 μm, a waveguide width of 12 μm, an initial proton exchange depth of 0.8 μm, and a quasi-phase-matching (QPM) wavelength of 1543.2 nm at room temperature.

The operation principle for the SFG+DFG-based single-to-dual channel NRZ-to-RZ format converter is illustrated in the right inset of Fig. 1, which can be briefly described as follows. The cw control is set close to the NRZ signal, because of which the SFG process between the cw control and pump optical clock is almost quasi-phase matched when the NRZ signal and pump optical clock meet the SFG QPM condition. As a result, two kinds of SFG+DFG processes exist. Both NRZ signal and cw control interact with the pump optical clock through SFG, generating two sum-frequency waves (SF1 and SF2). At the same time, the cw control and SF1 as well as the NRZ signal and SF2 participate in the subsequent DFG process to yield two channel idler waves. Note that the new idler wave is obtained only when all three optical waves (NRZ signal, pump optical clock, and cw control) are present. Thus, two channel RZ idler waves are actually achieved thanks to the two SFG+DFG processes, which indicates the implementation of single-to-dual channel NRZ-to-RZ format conversion.

3 Experimental Results

Figure 2 shows the typical optical spectra for SFG+DFG-based single-to-dual channel NRZ-to-RZ format conversion. The DI operates as a "notch" filter with a wavelength spacing of 0.32 nm. To perform the NRZ-to-PRZ format conversion at 10 and 20 Gbit/s, as illustrated in Figs. 2(a)–2(d) in the frequency domain, the "notch" is adjusted to aim at the center wavelength of the NRZ signal. We can see that two peaks with the wavelength spacing of 0.08 nm (10 GHz) for 10 Gbit/s in Fig. 2(b) and 0.16 nm (20 GHz) for 20 Gbit/s in Fig. 2(d) are present in the converted PRZ spectra, which implies the clock component enhancement due to NRZ-to-PRZ format conversion. Figure 2(e) depicts the optical spectrum at the output of the PPLN waveguide. The NRZ signal and pump optical clock are, respectively, set at 1546.8 and 1539.3 nm to satisfy the SFG QPM condition. The cw control is tuned at 1548.6 nm, which is close to the NRZ signal. It is found that dual-channel RZ idlers are obtained (RZ idler1,
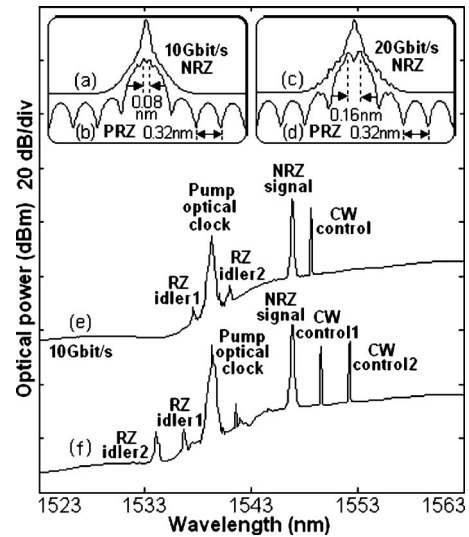

Fig. 2 Optical spectra of different optical waves: (a) input NRZ signal at 10 Gbit/s, (b) PRZ signal at 10 Gbit/s, (c) input NRZ signal at 20 Gbit/s, (d) PRZ signal at 20 Gbit/s, (e) SFG+DFG-based single-to-dual channel NRZ-to-RZ format conversion at 10 Gbit/s with cw control set close to NRZ signal, and (f) SFG+DFG-based single-to-dual channel NRZ-to-RZ format conversion by employing two cw control waves.

1537.6 nm; RZ idler2, 1541.0 nm), which is in good agreement with the description, as shown in the right inset of Fig. 1.

To further confirm the PPLN+RSOA-based single-to-dual channel NRZ-to-RZ format conversion, Fig. 3 presents the observed temporal waveforms of different optical waves. We used 10- and 20-Gbit/s 2^7-1 PRBS NRZ signals in the experiment based on the current lab conditions. The scale is 500.0 ps/div in Fig. 3(a) and 200.0 ps/div in Fig. 3(b). By clearly observing the waveforms of the input NRZ signal, PRZ signal, pump optical clock, and dual-channel RZ idlers, as shown in Figs. 3(a) and 3(b), it is obvious that the NRZ-to-PRZ format conversion, all-optical clock recovery, and single-to-dual channel NRZ-to-RZ format conversions at 10 and 20 Gbit/s are all successfully implemented.

Remarkably, another scheme, as shown in Fig. 2(f), can also be used to perform the SFG+DFG-based single-to-dual channel NRZ-to-RZ format conversion simply by arranging two cw control waves. In fact, with further improvement, it is possible to carry out the multicasting (single- to multiple-channel) NRZ-to-RZ format conversion by employing multiple cw control waves; i.e., n-channel cw control waves will produce n-channel RZ idler waves for a single-channel input NRZ signal.

4 Conclusion

We reported the experimental observation of single-to-dual channel NRZ-to-RZ format conversion based on SFG+DFG in a PPLN waveguide and active mode locking in an RSOA-based fiber ring laser. The cw control wavelength was set close to the NRZ signal wavelength. The NRZ-to-PRZ format conversion, all-optical clock recovery, and
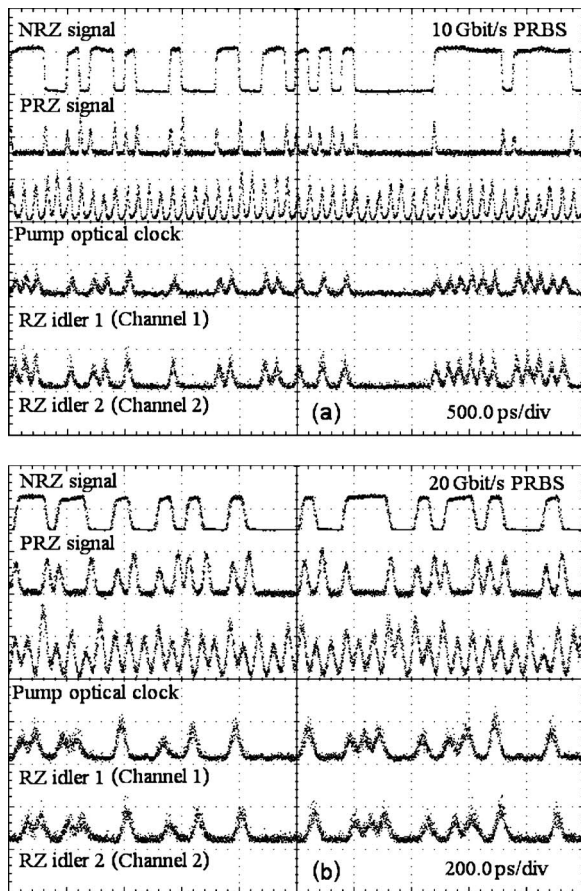
Fig. 3 Temporal waveforms of input NRZ signal, PRZ signal, pump optical clock, RZ idler1, and RZ idler2 for single-to-dual channel NRZ-to-RZ format conversion: (a) 10 Gbit/s (500.0 ps/div) and (b) 20 Gbit/s (200.0 ps/div).

single-to-dual channel NRZ-to-RZ format conversion at 10 and 20 Gbit/s were all successfully observed in the experiment.

Acknowledgments

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