Experimental observation of all-optical non-return-to-zero-to-return-to-zero format conversion based on cascaded second-order nonlinearity assisted by active mode-locking

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We report the experimental demonstration of all-optical format conversion by exploiting the cascaded second-harmonic generation and difference-frequency generation (cSHG/DFG) in a periodically poled lithium niobate (PPLN) waveguide assisted by the reflective semiconductor optical amplifier (RSOA)-based active mode-locking. 10 and 20 Gbit/s format conversions from non-return-to-zero (NRZ) to return-to-zero (RZ) are successfully observed. Two schemes with either the NRZ signal or the pump optical clock set at the quasi-phase matching (QPM) wavelength are both verified in the experiment. © 2007 Optical Society of America

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All-optical format conversion is likely to be widely used for future all-optical networks in order to enhance the network flexibility. For example, the basic format conversion from non-return-to-zero (NRZ) to return-to-zero (RZ) is an essential function to connect metro/access and core optical networks. So far, various kinds of all-optical NRZ-to-RZ format conversion have been proposed and demonstrated, including the use of semiconductor optical amplifier (SOA) loop mirror [1], SOA Mach–Zehnder interferometer (MZI) [2], etc. Recently, a promising candidate called a periodically poled lithium niobate (PPLN) waveguide has seen wide applications in all-optical signal processing for its advantages of ultrafast response and negligible spontaneous emission noise. PPLN-based wavelength conversions and logic gates have been investigated in the past few years [3,4], but to our knowledge the experimental demonstration on all-optical format conversion using a PPLN waveguide has not yet been reported. We have previously theoretically analyzed the PPLN-based NRZ-to-RZ format conversion [5]. In this Letter, we propose what we believe to be a novel scheme to experimentally demonstrate NRZ-to-RZ format conversion based on the cascaded second-harmonic generation and difference-frequency generation (cSHG/DFG) in a PPLN waveguide and the active mode-locking in a reflective semiconductor optical amplifier (RSOA)-based fiber ring laser.

The experimental setup is schematically shown in Fig. 1. The proposed device consists of four parts, i.e., the NRZ signal generator (I), the NRZ-to-pseudo-return-to-zero (PRZ) converter (II), the all-optical clock recovery module (III), and the NRZ-to-RZ converter (IV). The pseudo-random binary sequence (PRBS) NRZ signal, generated from part I including a tunable laser (TL), a Mach–Zehnder modulator (MZM), a bit pattern generator (BPG), a tunable frequency synthesizer (TFS), and an erbium-doped fiber amplifier (EDFA1), has weak clock components. Therefore, to effectively extract the optical clock, it is necessary to first enhance the clock components. Such function can be realized with the help of NRZ-to-PRZ conversion simply by using a fiber delay interferometer (FDI) in part II. The FDI has a simple configuration with two 3 dB couplers (C2, C3) and two fiber arms. Note that the two arms of FDI have a length difference of 5.2 mm, which results in a time delay of 25 ps (Δt). Also, the introduced phase shift ($\Delta\varphi$) of the lower arm can be adjusted by changing the operation temperature with a temperature controlling block (TCB) [6]. The converted PRZ signal with enhanced clock components is then injected into a RSOA-based actively mode-locked fiber ring laser (AMLFRL) in part III for the purpose of generating optical clock. A variable optical attenuator (VOA1), a 3-dB coupler (C5), a polarization controller (PC1), a RSOA, a circulator, a tunable delay line (TDL1), an isolator (ISO), a tunable filter (TF1), and a 10:90 coupler (C6) are utilized to form an AMLFRL. VOA1 is used to adjust the optical power coupled into the ring cavity. A 1000-μm-strained, multiquantum-well

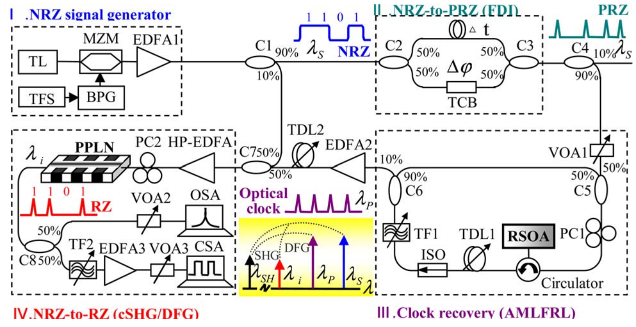

Fig. 1. (Color online) Experimental setup for PPLN +RSOA-based all-optical NRZ-to-RZ format conversion.

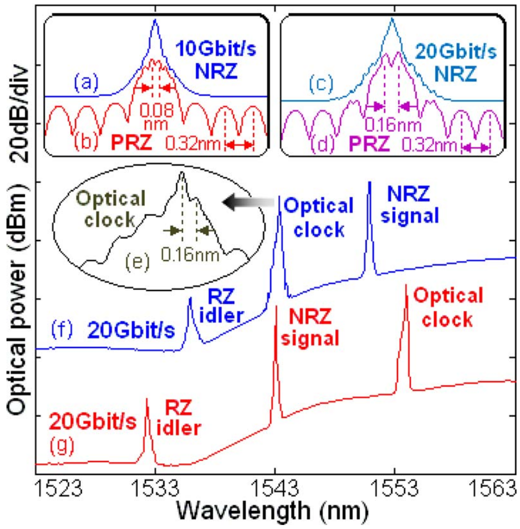

Fig. 2. (Color online) Measured optical spectra for NRZ-to-RZ format conversion. (a) Input NRZ signal at 10 Gbit/s. (b) PRZ signal at 10 Gbit/s. (c) Input NRZ signal at 20 Gbit/s. (d) PRZ signal at 20 Gbit/s. (e) Enlarged spectrum of pump optical clock at 20 GHz. (f), (g) Output spectra from PPLN for cSHG/DFG-based NRZ-to-RZ format conversion at 20 Gbit/s. (f) The pump optical clock is set at the SHG QPM wavelength. (g) The NRZ signal is set at the SHG QPM wavelength.

(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 the peak gain wavelength at 1550 nm when biased at 200 mW. The length of the ring cavity can be slightly changed by appropriately tuning TDL1. The isolator can keep unidirectional oscillation in the ring cavity, while PC1 can adjust the polarization state. The wavelength of the generated optical clock is decided by TF1 with a 3 dB bandwidth of 1 nm. It should be noted that the RSOA not only serves as a gain medium but also offers optical modulation based on the cross-gain modulation (XGM) effect. By carefully tuning TFS or TDL1 to satisfy the harmonic mode-locking condition, with the help of proper adjustment of VOA1 and PC1, optical clock synchronized with the input NRZ signal but at a changeable wavelength can be obtained. In part IV, the NRZ signal and extracted optical clock (pump) are amplified by a high power EDFA (HP-EDFA), polarization state controlled by PC2, and then launched into the PPLN waveguide to participate in the cSHG/DFG nonlinear interactions. The commercial HP-EDFA can offer a small signal gain of 40 dB and a saturation output power of 30 dBm. TDL2 is used to adjust the relative time delay between the input NRZ signal and pump optical clock. The PPLN waveguide adopted in the experiment with a length of 50 mm is fabricated by the electric-field poling method and annealing proton-exchanged (APE) technique. It has a micro-domain period of 14.7 μm and a quasi-phase matching (QPM) wavelength of 1543.2 nm at room temperature for the SHG process. The optical spectra and temporal waveforms are respectively monitored by an optical spectrum analyzer (OSA, Anritsu MS9710C) and a communications signal analyzer (CSA, Tektronix CSA 8000B). For the cSHG/DFG processes, either the pump (λ_P) or the signal (λ_S) can be set at the SHG QPM wavelength (λ_{QPM} =1543.2 nm), thus there exist two operation regimes, as follows.

- Scheme 1: the pump is set at the SHG QPM wavelength ($\lambda_P=\lambda_{QPM}$). As the pump travels along the PPLN waveguide, a second-harmonic (SH) wave is yielded through the SHG process. At the same time, the SH wave interacts with the signal to generate an idler wave (λ_i) thanks to the subsequent DFG process. It is obvious that the new idler wave is obtained only when both input signal and pump waves are present. As a result, the input PRBS NRZ signal and synchronized pump optical clock will produce an output PRBS RZ idler, which corresponds to the NRZ-to-RZ format conversion from the signal to the idler.
- Scheme 2: the signal is set at the SHG QPM wavelength ($\lambda_S=\lambda_{QPM}$). The signal produces a SH wave via the SHG process. Meanwhile, the pump optical clock mixes with the SH wave to generate an idler wave by DFG. It is expected that the NRZ-to-RZ format conversion can also be performed similarly to that of scheme 1.

The measured optical spectra for NRZ-to-RZ format conversion are clearly shown in Fig. 2. Figures 2(a)–2(d) depict NRZ-to-PRZ format conversion at 10 and 20 Gbit/s in the frequency domain. The FDI operates as a “notch” filter with a wavelength spacing of 0.32 nm, resulting in the spectrum tailoring from

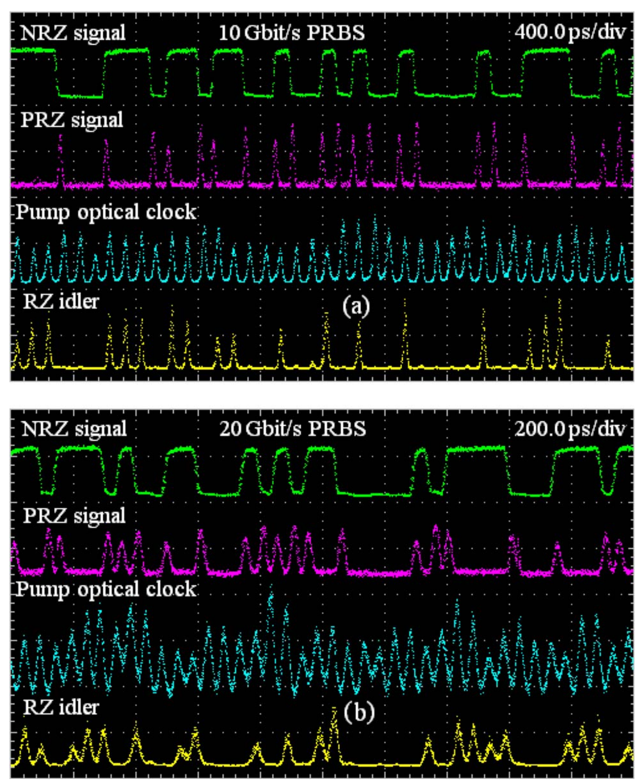

Fig. 3. (Color online) Temporal waveforms of input NRZ signal, PRZ signal, pump optical clock, and converted RZ idler for NRZ-to-RZ format conversion. (a) 10 Gbit/s. (b) 20 Gbit/s. The pump optical clock is set at the SHG QPM wavelength.

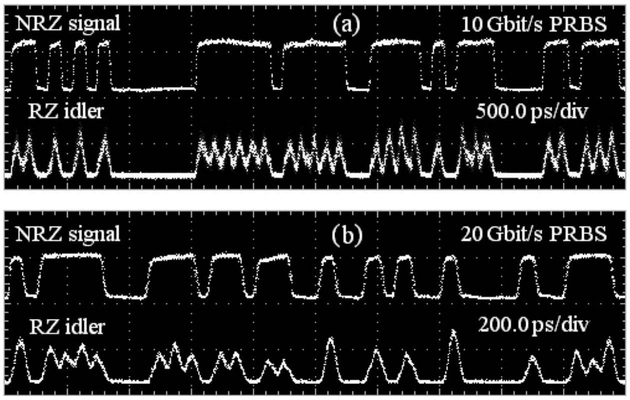

Fig. 4. Temporal waveforms of input NRZ signal and converted RZ idler for NRZ-to-RZ format conversion. (a) 10 Gbit/s. (b) 20 Gbit/s. The NRZ signal is set at the SHG QPM wavelength.

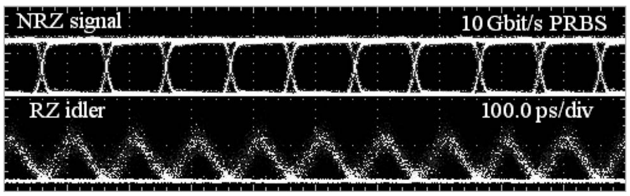

Fig. 5. Eye diagrams of input NRZ signal and converted RZ idler for NRZ-to-RZ format conversion at 10 Gbit/s. The NRZ signal is set at the SHG QPM wavelength.

NRZ to PRZ as the "notch" is adjusted to aim at the center wavelength of the input NRZ signal. It is noted 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 found in the converted PRZ spectra. Such a phenomenon implies that the clock components are enhanced by the aid of NRZ-to-PRZ format conversion. Figure 2(f) displays the output spectrum from PPLN for the cSHG/DFG-based NRZ-to-RZ format conversion at 20 Gbit/s. The pump optical clock is set at the SHG QPM wavelength (scheme 1:$\lambda_P=\lambda_{QPM}$). The RZ idler is obtained at 1536.0 nm as the NRZ signal is tuned at 1550.8 nm. Figure 2(e) presents the enlarged pump optical clock spectrum at 20 GHz. Note that the NRZ signal can also be set at the SHG QPM wavelength (scheme 2:$\lambda_S=\lambda_{QPM}$). As shown in Fig. 2(g), when the pump optical clock is tuned at 1554.0 nm, the NRZ-to-RZ format conversion at 20 Gbit/s is realized with the corresponding RZ idler generated at 1532.4 nm.

The temporal waveforms of different optical waves are observed as shown in Figs. 3–5. Figures 3(a) and 3(b) represent scheme 1 ($\lambda_P=\lambda_{QPM}$) at 10 and 20 Gbit/s, respectively. The input PRBS NRZ signal, PRZ signal, pump optical clock, and converted RZ idler are clearly displayed in Figs. 3(a) and 3(b), indicating the successful realization of NRZ-to-RZ format conversion. Figures 4(a) and 4(b), respectively, represent 10 and 20 Gbit/s NRZ-to-RZ format conversions for scheme 2 ($\lambda_S=\lambda_{QPM}$). Figure 5 plots the eye diagrams for the input NRZ signal and converted RZ idler corresponding to Fig. 4(a).

In our proposed schemes, PPLN and RSOA are combined to perform the NRZ-to-RZ format conversion at 10 and 20 Gbit/s for the first time to our best knowledge. As mentioned in [7], it could be possible to realize clock recovery from 40 Gbit/s NRZ signal in view of reported XGM speed up to 100 Gbit/s [8]. Thus it is also possible to perform 40 Gbit/s NRZ-to-RZ format conversion with the proposed schemes.

Remarkably, the proposed schemes can be further extended along two potential directions. First, simultaneous multichannel format conversion can be implemented by employing multiple NRZ signals with scheme 1 ($\lambda_P=\lambda_{QPM}$), i.e., n-channel NRZ signals will produce n-channel RZ idlers. Second, it is easy to carry out the tunable operation simply by changing the pump wavelength with scheme 2 ($\lambda_S=\lambda_{QPM}$). Moreover, it is possible to achieve tunable multicasting (single-to-multiple channel) format conversion by use of several RSOA-based AMLFRLs to yield multiple pump optical clocks, i.e., for single-channel NRZ signal, n-channel changeable pumps will generate n-channel variable RZ idlers. These are significant to enhance the flexibility for all-optical signal processing. In addition, the NRZ-to-RZ format conversion can also be realized based on the cSFG/DFG.

In conclusion, 10 and 20 Gbit/s NRZ-to-RZ format conversions have been experimentally observed using a PPLN and a RSOA. NRZ-to-PRZ format conversion, all-optical clock recovery, and NRZ-to-RZ format conversion are respectively implemented by an FDI, a RSOA-based AMLFRL, and cSHG/DFG in a PPLN waveguide. Two schemes with either the NRZ signal or the pump optical clock set at the SHG QPM wavelength are both verified in the experiment. The obtained results may stimulate further experimental research on PPLN-based all-optical format conversions.

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