Optical phase erasure and its application to format conversion through cascaded second-order processes in periodically poled lithium niobate

Jian Wang,[1] Junqiang Sun,[1,*] Xinliang Zhang,[1] Dexiu Huang,[1] and M. M. Fejer[2]

[1]*Wuhan National Laboratory for Optoelectronics, College of Optoelectronic Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China*

[2]*Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*

**Corresponding author: jqsun@mail.hust.edu.cn*

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We describe a new optical phase erasure characteristic of periodically poled lithium niobate (PPLN) by using cascaded second-harmonic generation and difference-frequency generation with the signal set at the quasi-phase-matching wavelength. A simple analytical expression is derived clearly explaining the operation principle. It is interesting that the optical phase erasure feature enables an all-optical format conversion from carrier-suppressed return to zero (CSRZ) to return to zero (RZ). We experimentally and theoretically demonstrate a PPLN-based 40 Gbits/s all-optical CSRZ-to-RZ format conversion. Moreover, tunable and multicasting CSRZ-to-RZ format conversions are also verified in the experiment. © 2008 Optical Society of America

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Recently, a promising candidate called the periodically poled lithium niobate (PPLN) waveguide has been widely used for nonlinear applications owing to its distinct advantages of a highly accessible nonlinear coefficient, ultrafast response, and negligible spontaneous emission noise [1]. During the past few years several attractive nonlinear applications, including wavelength conversions [2,3], logic gates [4], and format conversions [5,6], have been proposed and demonstrated by using various second-order nonlinearities and their cascading in PPLN waveguides. Previously, one kind of cascaded process known as cascaded second-harmonic generation and difference-frequency generation (cSHG–DFG) was extensively investigated. For the conventional cSHG–DFG processes a cw pump was set at the second-harmonic generation (SHG) quasi-phase-matching (QPM) wavelength of PPLN to take part in the SHG process. The generated second-harmonic (SH) wave by SHG simultaneously mixed with a signal to produce a new converted idler wave. Such processes could be applied to simultaneous multichannel wavelength conversion and were considered to be transparent to bit rate and modulation format [1].

In this Letter, we discuss a modified cascaded second-order process in which not the cw pump but the signal carrying the data information is set at the SHG QPM wavelength of PPLN [7]. We describe, for the first time to the best of our knowledge, a new unique characteristic of PPLN that can erase the optical phase information of the signal through the cSHG–DFG processes with the signal set at the SHG QPM wavelength. We demonstrate theoretically and experimentally that the optical phase erasure enables a potential application of PPLN-based all-optical format conversion from carrier-suppressed return to zero (CSRZ) to return to zero (RZ) at 40 Gbits/s. In addition, both tunable and multicasting operations are also verified in the experiment.

Figure 1 illustrates the schematic and operation principle. As shown in Fig. 1(a), one cw pump and one signal are launched into PPLN to participate in the cSHG–DFG processes, resulting in a new idler wave generated at the output of PPLN. In the cSHG–DFG processes as shown in Fig. 1(b), the signal is set at the SHG QPM wavelength. A SH wave is generated by the SHG process. At the same time, the SH wave interacts with the cw pump to yield a new converted idler wave via the subsequent DFG process. We can derive an analytical solution to the normalized complex amplitude of the idler (A_i) under the nondepletion approximation expressed as

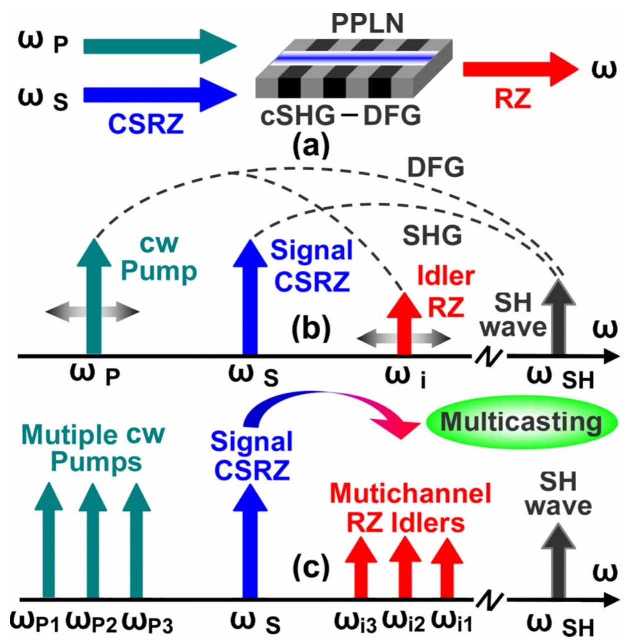

Fig. 1. (Color online) (a) Schematic and (b), (c) operation principle of PPLN-based optical phase erasure and CSRZ-to-RZ format conversion. (b) Tunable operation. (c) Multicasting operation.

$$A_i = -\frac{1}{2}\omega_i\omega_{\mathrm{SH}}\kappa_{\mathrm{SHG}}\kappa_{\mathrm{DFG}}A_S^2A_P^*\left\{\left[\frac{L}{\Delta}\sin(\Delta L) + \frac{\cos(\Delta L)-1}{\Delta^2}\right] + i\left[\frac{\sin(\Delta L)}{\Delta^2} - \frac{L}{\Delta}\cos(\Delta L)\right]\right\}, \quad (1)$$

where A_S and A_P are the normalized complex amplitudes of the input signal and pump, respectively. κ_{SHG} and κ_{DFG} are the coupling coefficients of the SHG and DFG processes, respectively. Δ is the phase mismatching for the DFG process. L is the length of PPLN. ω_i and ω_{SH} are the angular frequencies of the idler and SH wave, respectively. We can further obtain a simple expression from Eq. (1) written by

$$A_i \propto -A_S^2A_P^*. \quad (2)$$

Note that the normalized complex amplitudes (A_S,A_P,A_i) contain both amplitude and phase information. For the input signal with phase information the phase of the converted idler wave can be deduced as

$$\phi_i = \pi + 2\phi_S - \phi_P, \quad (3)$$

where ϕ_S, ϕ_P, and ϕ_i denote the optical phases of the input signal, pump, and converted idler, respectively. In general, the phase of the signal takes binary values of 0 or π. As a result, for a cw input pump without phase information and owing to the periodicity of 2π for optical phase, the phase information in the input signal is lost in the converted idler wave. Thus optical phase erasure can be achieved based on cSHG–DFG processes with the signal set at the SHG QPM wavelength. As shown in Figs. 1(a) and 1(b), when a CSRZ signal with optical phase alternating between 0 and π in adjacent bits is adopted, the converted idler is changed into the RZ format with a constant optical phase in all bits, which corresponds to the CSRZ-to-RZ format conversion. In addition, tunable operation can be easily performed simply by changing the wavelength of the cw pump. Moreover, as shown in Fig. 1(c), multicasting CSRZ-to-RZ format conversion can also be realized by use of multiple cw pumps.

In the experiment a 50 mm long PPLN waveguide fabricated by the electric-field poling method and annealing proton-exchange technique is employed [3,6]. It has a microdomain period of 14.7 μm and a QPM wavelength of 1543.2 nm at room temperature. A 40 Gbits/s 2^7-1 pseudorandom binary sequence (PRBS) CSRZ signal and a cw pump are used. Figure 2 shows typical optical spectra measured at the output of PPLN. The 40 Gbits/s PRBS CSRZ signal is set at 1543.2 nm to satisfy the SHG QPM condition. As can be seen in the right inset of Fig. 2(a), the phase alternating between adjacent bits of CSRZ results in the carrier suppression. A new idler wave is generated at 1535.2 nm as the cw pump is adjusted at 1551.3 nm. It is worth noting that the carrier of the idler is present again, as shown in the left inset of Fig. 2(a). Such an interesting phenomenon can be explained by the fact that the input CSRZ signal is converted into the output RZ idler through cascaded second-order processes, indicating successful implementation of the CSRZ-to-RZ format conversion. Figure 2(b) depicts the optical spectra for tunable operation. Variable RZ idlers at 1535.2, 1536.7, 1537.5, and 1539.6 nm can be obtained under different cw pump wavelengths of 1552.0, 1550.2, 1549.4, and 1547.2 nm. The insets of Fig. 2(b) clearly plot the enlarged optical spectra of converted RZ idlers with the notable appearance of the carrier. It is expected that the RZ idler can be tuned in a wide wavelength range larger than 70 nm [2].

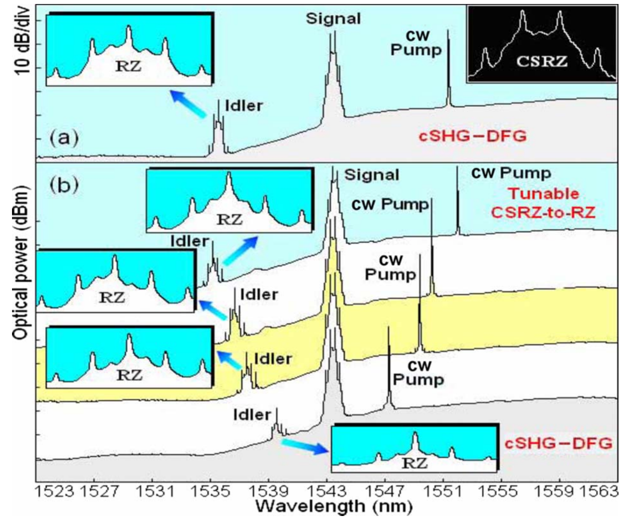

Fig. 2. (Color online) Measured optical spectra for PPLN-based 40 Gbits/s CSRZ-to-RZ format conversion. (a) The cw pump is set at 1551.3 nm. (b) Tunable operation under different cw pump wavelengths: 1550.2, 1549.4, and 1547.2 nm. Right inset of (a) is the enlarged optical spectrum of the input CSRZ signal. Left inset of (a) and insets of (b) are the enlarged optical spectra of RZ idlers.

Figure 3 displays the temporal waveforms corresponding to Fig. 2. It is apparent that the power information carried by the input CSRZ signal (1551.3 nm) is successfully copied onto the output RZ idler (1535.2 nm). It should be noted that the measured waveforms do not contain phase information. However, the observed optical spectra with or with-

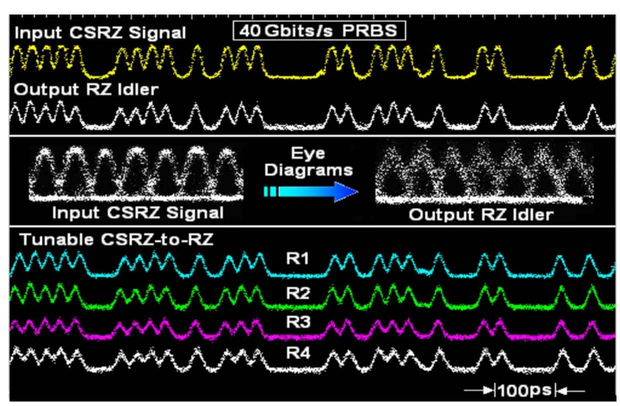

Fig. 3. (Color online) Measured temporal waveforms for the input CSRZ signal and output RZ idler corresponding to Fig. 2(a). R1–R3 denote tunable RZ idlers under different cw pump wavelengths of 1550.2, 1549.4, and 1547.2 nm corresponding to Fig. 2(b).

out the carrier shown in Fig. 2 reveal that the phase information of the input CSRZ signal is removed in the output idler. Therefore, the proposed cSHG–DFG processes with the signal set at the SHG QPM wavelength transfer the power information but remove the phase information. The eye diagrams of input CSRZ signal and output RZ idler with clear eye opening imply a good conversion performance. $R1$–$R4$ shown in Fig. 3 present the temporal waveforms for the tunable output RZ idlers under different cw pump wavelengths of 1552.0, 1550.2, 1549.4, and 1547.2 nm corresponding to Fig. 2(b). No obvious changes are found during the tunable operation.

A multicasting operation can also be performed by using multiple cw pumps as shown in Fig. 4. When two cw pumps are employed, single-to-dual channel CSRZ-to-RZ format conversion can be achieved as depicted in Fig. 4(a). Figure 4(b) shows a single-to-triple channel CSRZ-to-RZ format conversion by use of three cw pumps. The insets of Fig. 4 clearly illustrate the enlarged optical spectra of converted RZ idlers with the distinct existence of a carrier. Note that tunable operation and multicasting operation are attractive for effectively enhancing the flexibility of future all-optical networks.

Figure 5 further shows simulation results for optical phase erasure and a 40 Gbits/s CSRZ-to-RZ format conversion. The optical spectrum of the input CSRZ signal at 1543.2 nm with the carrier suppressed is depicted in Fig. 5(a). After cSHG–DFG the converted RZ idler at 1535.2 nm is produced with its carrier present again, as can be clearly seen in Fig. 5(b). Figures 5(c) and 5(d) plot the temporal waveforms for the input CSRZ signal and the output RZ idler. Figures 5(e) and 5(f) display the corresponding eye diagrams. It is noted that the simulated optical spectra and temporal waveforms are both in agreement with those observed in the experiment. Moreover, we also illustrate the constellation diagrams as shown in Figs. 5(g) and 5(h) to confirm the optical phase erasure characteristic. It is obvious that the input CSRZ signal has an alternating phase shift between 0 and π, as shown in Fig. 5(g), while the output RZ idler has a constant optical phase as shown in Fig. 5(h). Note that the slight phase shift in the idler shown in Fig. 5(h) is caused by the slight phase mismatching of the DFG process.

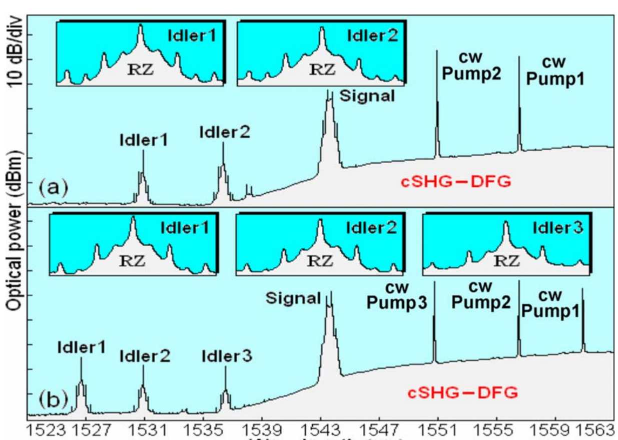

Fig. 4. (Color online) Measured optical spectra for PPLN-based 40 Gbits/s multicasting CSRZ-to-RZ format conversion. (a) Single-to-dual channel. (b) Single-to-triple channel. Insets are the enlarged optical spectra of RZ idlers.

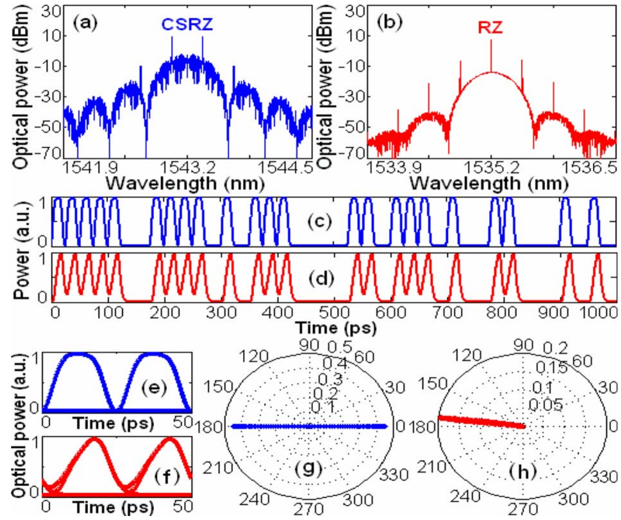

Fig. 5. (Color online) Simulation results for PPLN-based optical phase erasure and 40 Gbits/s CSRZ-to-RZ format conversion. (a), (b) Optical spectra. (c), (d) Temporal waveforms. (e), (f) Eye diagrams. (g), (h) Constellation diagrams. (a), (c), (e), (g) Input CSRZ signal. (b), (d), (f), (h) Output RZ idler.

In conclusion, we propose and demonstrate that PPLN can erase the optical phase information of the signal by using cSHG–DFG processes with the signal set at the SHG QPM wavelength. It is found that the optical phase erasure characteristic of PPLN enables a potential application of an all-optical CSRZ-to-RZ format conversion. A PPLN-based 40 Gbits/s all-optical CSRZ-to-RZ format conversion is experimentally and theoretically verified. Furthermore, tunable CSRZ-to-RZ and multicasting CSRZ-to-RZ format conversions are also successfully observed in the experiment.

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