

# 160-Gb/s all-optical phase-transparent wavelength conversion through cascaded SFG-DFG in a broadband linear-chirped PPLN waveguide

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**Abstract:** We experimentally demonstrated ultra-fast phase-transparent wavelength conversion using cascaded sum- and difference-frequency generation (cSFG-DFG) in linear-chirped periodically poled lithium niobate (PPLN). Error-free wavelength conversion of a 160-Gb/s return-to-zero differential phase-shift keying (RZ-DPSK) signal was successfully achieved. Thanks to the enhanced conversion bandwidth in the PPLN with linear-chirped periods, no optical equalizer was required to compensate the spectrum distortion after conversion, unlike a previous demonstration of 160-Gb/s RZ on-off keying (OOK) using fixed-period PPLN.

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## 1. Introduction

Advanced optical phase modulation formats, such as differential binary phase-shift keying (DPSK), differential quadrature phase-shift keying (DQPSK), and differential eight-ary phase-shift keying (D8PSK), have attracted considerable research attention as promising candidates for future optical communication systems. All-optical phase-transparent wavelength

conversion will play an important role in supporting the transparency of phase-modulated formats in future transparent optical networks. Periodically poled lithium-niobate (PPLN) waveguides are becoming attractive devices for optical signal processing thanks to their compactness, ultrafast dynamics, and high efficiency [1]. Ultra-fast wavelength conversion for intensity-modulated signals has been reported in [1–3]. For phase-modulated signals, wavelength conversion of 320-Gb/s return-to-zero DQPSK signals has been experimentally demonstrated through cascaded second-harmonic generation and difference-frequency generation (cSHG-DFG) in PPLN [4,5]. However, when using cSHG-DFG in PPLN, the wavelength of the converted signal cannot be flexibly changed. On the other hand, wavelength tunability of the converted signal can be easily achieved using cascaded sum- and difference-frequency generation (cSFG-DFG) [2,3] in PPLN. By simply changing the wavelength of one pump signal, the wavelength of the converted signal can be adjusted accordingly. In [2], with fixed-period PPLN, to overcome the spectrum distortion caused by the limited conversion bandwidth, an optical spectrum shaper was required to compensate the distortion to achieve error-free ultrafast (>100 Gbit/s) wavelength conversion.

In the study described here, we experimentally demonstrated all-optical phase-preserved wavelength conversion at 160 Gbit/s through the cSFG-DFG interaction in a linear-chirped PPLN waveguide. The LiNbO<sub>3</sub> in PPLN is linearly-chirped periodically poled crystal, which means that the crystal periods vary gradually. This could be an effective way to enhance the conversion bandwidth, and thus make it possible to achieve ultra-fast (>100 Gbit/s) wavelength conversion without deploying any optical equalizer. This is an advantage of linear-chirped PPLN over fixed-period PPLN when applying it to ultra-fast photonic processing for both phase- and intensity-modulated signals.

## 2. Operating principle

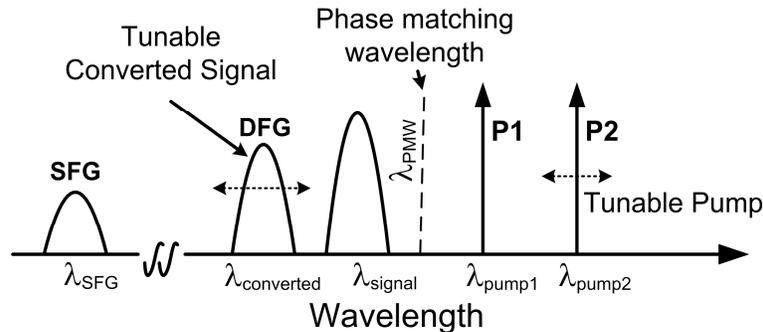


Fig. 1. Operating principle of cSFG-DFG process in PPLN for phase-transparent wavelength conversion.

The operating principle of the wavelength conversion based on cascaded SFG-DFG is shown in Fig. 1. An optical input signal at  $\lambda_{signal}$  and two amplified continuous wave (CW) pumps at  $\lambda_{pump1}$  and  $\lambda_{pump2}$  are combined and fed into a PPLN to participate in the cascaded SFG and DFG nonlinear interactions. To satisfy the quasi-phase matching (QPM) condition, the input signal ( $\lambda_{signal}$ ) and one of the pumps (P1 at  $\lambda_{pump1}$ ) are symmetrically placed with respect to the QPM wavelength of the PPLN. Under the QPM condition, the input signal interacts with P1 to generate a sum-frequency component at  $\lambda_{SFG}$  via SFG. Meanwhile, the generated SFG component mixes with the other pump (P2) to generate a converted signal at  $\lambda_{converted}$  through DFG. In the wavelength conversion based on the cSFG-DFG nonlinear interaction in PPLN, both intensity and phase information carried in the input signal and pumps is well-preserved and transferred to the converted signal [6]. Therefore, it could be applied to phase-preserved wavelength conversion.

To achieve ultra-fast wavelength conversion (>100 Gbit/s), it is important for PPLN to have a wide QPM-bandwidth with uniform efficiencies to enable wide-band wavelength

conversion. In [2], PPLN with a fixed period was employed to demonstrate the wavelength conversion for on-off keying (OOK) signals at 160 Gbit/s. In that study, however, due to the limited conversion bandwidth and the non-uniform conversion efficiency across the conversion bandwidth, an optical spectrum shaper was deployed for optical equalization to achieve error free operation at 160-Gbit/s. In the present study, to enhance the conversion bandwidth in PPLN, a linear-chirped MgO-doped PPLN was fabricated using the proton-exchange technique. The periods of the domains varied across the nonlinear crystal so as to provide chirped phase matching of the light propagating in the crystal. The resulting chirped QPM widened the conversion bandwidth of the PPLN.

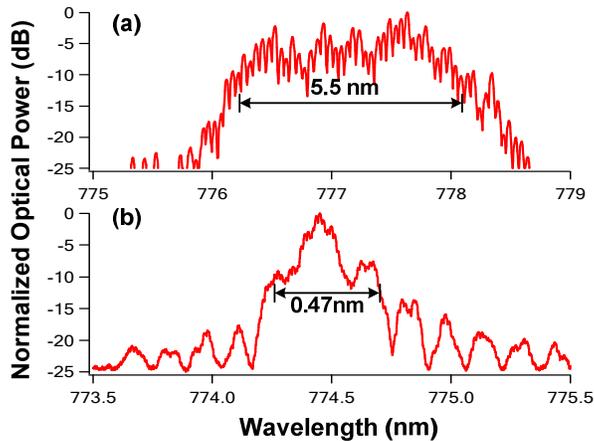


Fig. 2. Accumulated optical spectra of SFG component when tuning the wavelength of one pump from 1542 nm to 1560 nm for (a) the linear-chirped PPLN, and (b) the fixed-period PPLN used in [2].

The length of the fabricated linear-chirped PPLN was 45 mm. The measured QPM wavelength was around 1555 nm at room temperature. The maximum normalized SHG conversion efficiency was 80%/W for the packaged module. To evaluate and compare the conversion bandwidth of the SFG interaction, we measured the accumulated optical spectrum when tuning the wavelength of one of the pumps from 1542 nm to 1560 nm, while fixing the other pump's wavelength. The obtained accumulated spectra for the fabricated linear-chirped PPLN and the previous fixed-period PPLN, which was used in [2], are shown in Fig. 2(a) and Fig. 2(b), respectively. This figure shows that the 10-dB conversion bandwidth of the linear-chirped PPLN was effectively improved from around 0.47 nm to 5.5 nm, compared with the fixed-period one. Less variation in the converted SFG components was observed within the 5.5-nm bandwidth, which indicates that the QPM-bandwidth was improved in the linear-chirped PPLN compared with the previous fixed-period PPLN. Therefore, it is possible to deploy the linear-chirped PPLN to achieve ultra-fast wavelength conversion without using any additional optical equalization. Besides, doping of 5-mol% MgO in PPLN results in a remarkable increase in the photorefractive damage threshold, making it possible to operate it at room temperature (25 °C) with high input powers, which is helpful for improving the conversion efficiency.

As demonstrated in [2], by simply tuning the wavelength of one of the pumps (P2), wavelength tunability of the converted signal can be achieved. Moreover, the enhancement in conversion bandwidth in the linear-chirped PPLN could also give rise to a larger tunability.

### 3. Experiment and results

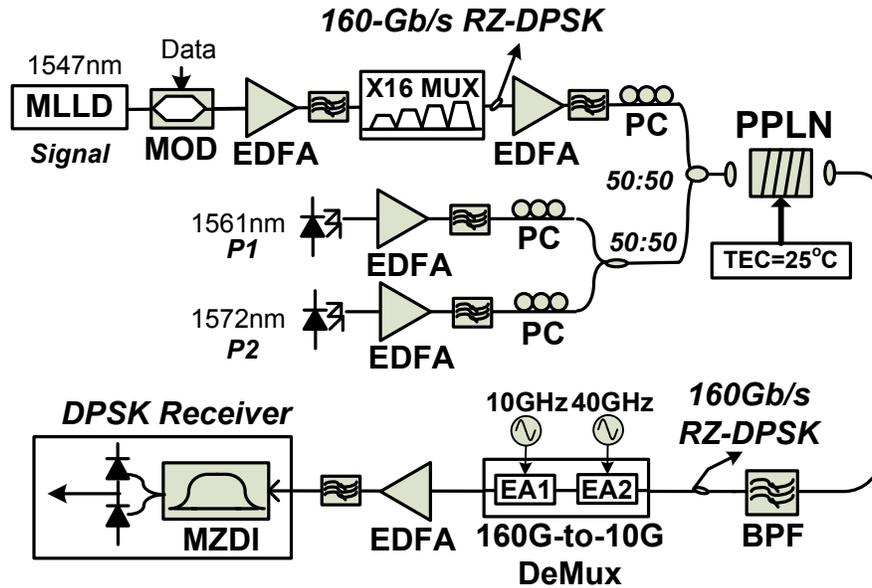


Fig. 3. Experimental setup.

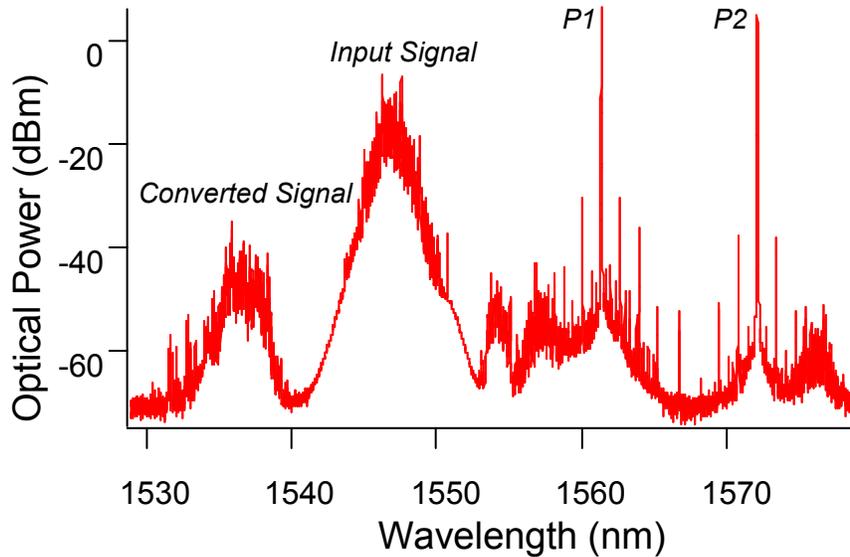


Fig. 4. Optical spectrum after PPLN (resolution: 0.01nm).

To demonstrate the phase transparency in the wavelength conversion based on the cSFG-DFG process in PPLN, phase-transparent wavelength conversion at 160-Gb/s bit rate was experimentally demonstrated. The experimental setup is illustrated in Fig. 3. To generate a 160-Gb/s RZ-DPSK signal, a pulse train with a repetition rate of 10 GHz and a pulse width of around 2 ps was generated from a semiconductor mode-locked laser diode (MLLD) at 1547 nm, and was then phase-modulated by an LN phase modulator to generate a 10-Gb/s RZ-DPSK signal. A 160-Gb/s RZ-DPSK signal was obtained after multiplexing through a four-stage PLC-based multiplexer. After individual power amplification, two CW beams at 1561

nm and 1572 nm, serving as pumps (P1 and P2), were combined with the 160-Gb/s RZ-DPSK signal and fed into the fabricated PPLN device through a fiber lens. The total fiber-to-fiber insertion loss was around 4 dB. The launched powers of P1, P2, and the input RZ-DPSK signal at the input of the PPLN were 22.2 dBm, 19.6 dBm, and 21.4 dBm, respectively. As shown in Fig. 4, the converted signal was obtained at 1537 nm with a conversion efficiency of around -25 dB. A 6-nm bandpass filter was used to filter out the converted 160-Gb/s RZ-DPSK signal after the PPLN. The waveforms of the input 160-Gb/s RZ-DPSK signal and the converted RZ-DPSK signal before phase de-modulation are shown in Fig. 5. The measured input pulsewidth was around 1.82 ps, while the converted pulse was slightly broadened with a pulsewidth of around 2.18 ps. A slight increase in amplitude jitter was observed after conversion. It was then de-multiplexed into a 10-Gb/s RZ-DPSK stream after a 160Gb/s-to-10Gb/s de-multiplexer, which was based on two cascaded electroabsorption modulators (EAMs). A Mach-Zehnder delay interferometer and balanced detector were employed for phase demodulation. Bit-error rates of the input and converted RZ-DPSK signals were measured at a bit rate of 10 Gb/s after de-multiplexing and phase demodulation.

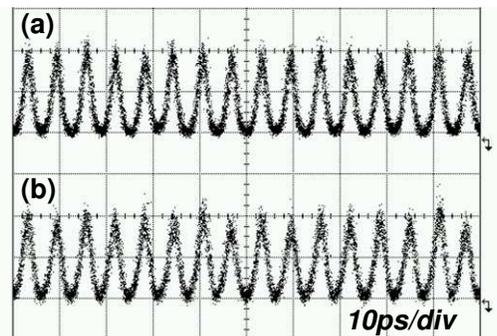


Fig. 5. Eye diagrams of the (a) input and (b) converted 160-Gb/s RZ-DPSK signals before phase de-modulation.

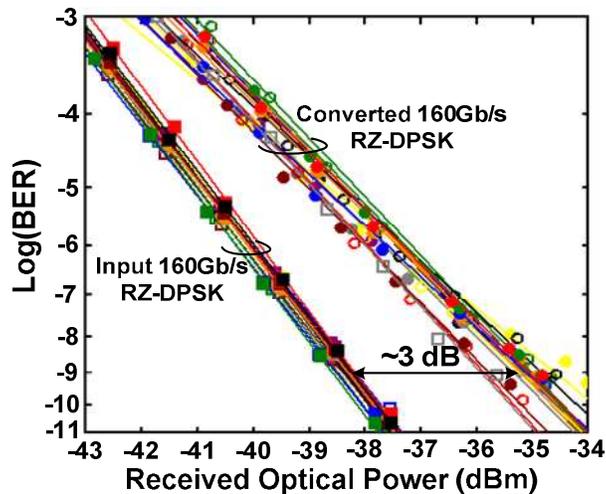


Fig. 6. The measured BER curves of the input and converted 160-Gb/s RZ-DPSK signals after de-multiplexing to 10-Gb/s data.

As shown in Fig. 6, for the input RZ-DPSK, a receiver sensitivity difference of less than 0.5 dB was obtained for 16 tributaries, whereas a sensitivity difference of around 1 dB was obtained among 16 tributaries for the converted RZ-DPSK signal. This indicates that uniform performance was observed for the de-multiplexed tributaries. Comparing with the input

tributaries, a power penalty of around 3 dB was obtained for the converted signals, which could be mainly attributed to the additional noise introduced in power amplification as the OSNR of the converted signal was relative low after conversion. Further improvement in overall performance could be achieved through the optimization in PPLN design to balance conversion bandwidth and efficiency. The measured eye diagrams of the input and converted 160-Gbit/s RZ-DPSK signals after being de-multiplexed to 16 tributaries are shown in Figs. 7 and 8, respectively. Note that, in this work, no optical equalizer, such as a spectrum shaper, was employed in the experiment. This implies that the conversion bandwidth in the linear-chirped PPLN is broad and uniform enough to support wavelength conversion at 160 Gb/s.

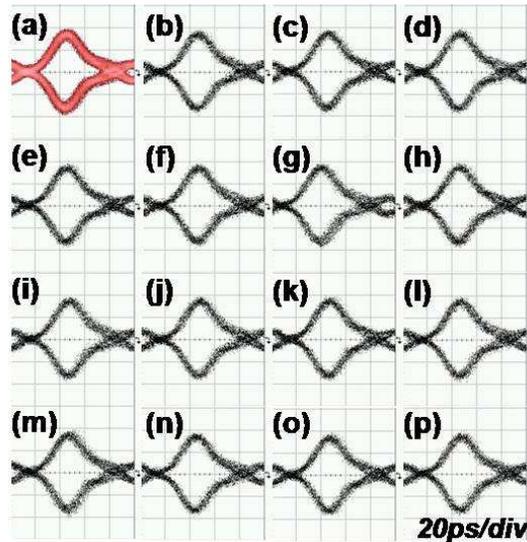


Fig. 7. The measured eye diagrams of the demodulated input 160-Gbit/s RZ-DPSK signal after de-multiplexing to 16 tributaries.

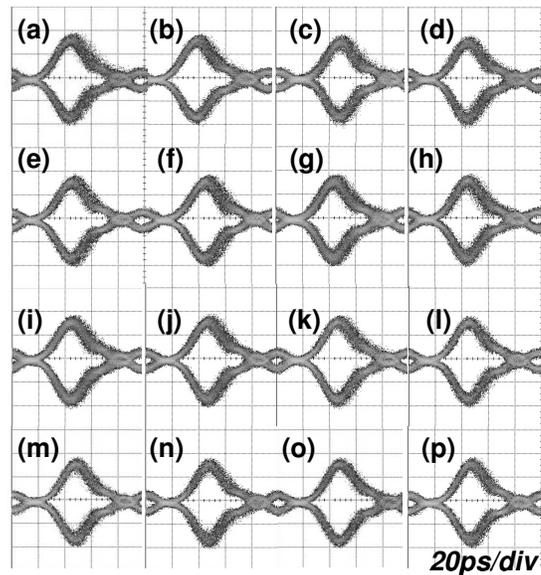


Fig. 8. The measured eye diagrams of the demodulated converted 160-Gbit/s RZ-DPSK signal after de-multiplexing to 16 tributaries.

#### **4. Conclusion**

To enhance the conversion bandwidth in wavelength conversion based on the cSFG-DFG process in PPLN, especially for applications at >100 Gb/s, linear-chirped PPLN was fabricated. Unlike the conventional fixed-period PPLN, no additional optical equalizer was required to achieve error-free operation at 160 Gb/s. Moreover, phase transparency was also successfully demonstrated by showing error-free operation of 160-Gb/s RZ-DPSK wavelength conversion with an average power penalty of around 3 dB.