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2*f*-3*f* Optical Wavelength Conversion Device with PPLN waveguides

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1. Introduction

A carrier-envelope-offset (CEO) -locked frequency comb at telecommunications wavelengths has become an indispensable tool in a variety of applications for precision spectroscopy [1], telecommunications, and coherent remote sensing. Furthermore, a CEO-locked frequency comb with a wide mode spacing (>10 GHz) could be applied to future photonic networks, astronomical spectroscopy [2], and line-by-line optical pulse shaping [3]. Laser sources with more than 10-GHz repetition rates typically have relatively long pulse durations and reduced pulse energy, which makes it difficult to generate octave-spanning supercontinuum (SC) spectra as required for detecting a CEO frequency in a conventional *f*-2*f* self-referencing interferometer.

In this paper, we propose a novel approach to achieving CEO frequency detection with high efficiency by a new 2*f*-3*f* interferometer that employs an integrated 2*f*-3*f* optical wavelength conversion device with periodically poled lithium niobate (PPLN) ridge waveguides [4].

2. Self-referencing interferometer with PPLN waveguides

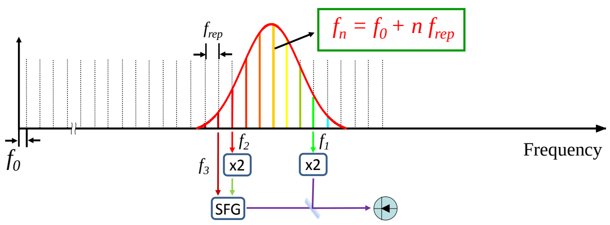

Fig. 1. Our scheme for detecting the CEO frequency with PPLN ridge waveguides.

Figure 1 shows the principle of our scheme with PPLN ridge waveguides. In the conventional 2*f*-3*f* self-referencing interferometer, second-harmonic (SH) and third-harmonic (TH) light are generated with nonlinear crystals (e.g., β-barium borate) [5]. With this way, we need two nonlinear crystals for making TH light, which results in decreasing the conversion efficiency, since Fresnel reflection loss at the end face of the lens is doubled. On the other hand, in our scheme, the SH and TH lights are generated with the PPLN ridge waveguides, which provides high conversion efficiency. The reasons for obtaining high efficiency are as follows: (1) The ridge waveguide structure exhibits strong resistance to photorefractive damage and no degradation of the nonlinear coefficient even at room temperature, since no ion-exchange/diffusion process is employed in the fabrication. (2) TH is generated with only a single double-pitch PPLN device [Fig. 2(b)], which is formed by direct bonding of two different pitched PPLN ridge waveguides.

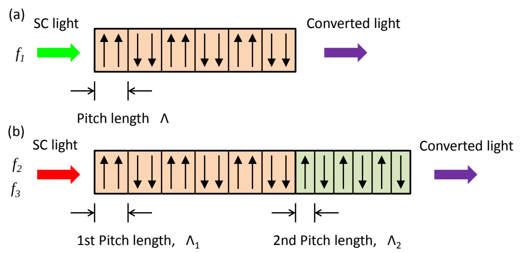

Fig. 2. PPLN ridge waveguides for the generation of the (a) SH and (b) TH.

3. SH and TH generation with PPLN waveguides

We use a passively mode-locked Er-doped fiber laser amplifier system (Menlo Systems GmbH). The amplifier laser delivers a 100-fs, 1.2-nJ laser pulse with a center wavelength of 1560 nm. The repetition rate is 250 MHz. Output power from the Er-doped fiber laser amplifier is launched into a highly nonlinear fiber. The SC spectra after the highly nonlinear fiber spans more than 2/3 of an octave (1200-2000 nm). We generated SH and TH with the PPLN waveguides using the short (~1200 nm)- and long (~1800 nm)-wavelength components of the SC spectra, respectively.

First, we explain a single-pitch PPLN waveguide [Fig. 2(a)] to generate the SH light. The pitch of quasi phase matching (QPM), Λ, is determined by the fundamental wavelength, λ, and refractive index of the fundamental (SH) light, n_{ω} ($n_{2\omega}$), which is given as $\Lambda = \lambda/[2(n_{2\omega} - n_{\omega})]$. Therefore, the conversion wavelength can be arbitrary selected by changing Λ.

In the first experiment, we injected the SC light (1200 - 2000 nm) to the PPLN waveguide and measured the SH spectrum. Figure 3(a) shows the SH spectrum obtained by using a spectrometer (Hamamatsu Photonics C10083CAH). We succeeded in generating the SH by using the short-wavelength component (~1200 nm) of the SC spectra.

In order to change the conversion wavelength, we prepared several QPM pitches for the PPLN ridge waveguide and measured the SH light. As Λ increases by 0.55 μm, the conversion wavelength changes from 588 to 603 nm [Fig. 3(b)].

Next, we discuss a double-pitch PPLN ridge waveguide [Fig. 2(b)] to generate the TH light. First, the long-wavelength component (~1800 nm) of the SC spectra is frequency-doubled (~ 900 nm) at the first QPM pitch, Λ_1. Then, the sum frequency (~ 600 nm) is generated by using the SH component (~ 900 nm) and the different long-wavelength component (~ 1800 nm) at the second QPM pitch, Λ_2. Note that the wavelength of the sum-frequency generation in our scheme is slightly different from that of the SF light.

In the second experiment, we injected the SC light (1500 - 2000 nm) to the double-pitch PPLN waveguide and measured the sum-frequency spectrum. Figure 3(c) shows the SH and TH spectrum obtained by the spectrometer. The SH light is generated at the first QPM pitch, Λ_1. As the pitch size increases by 0.40 μm, the conversion wavelength changes from 895 to 907 nm. The sum frequency is generated from the SH light (895 - 907 nm) and the fundamental light (~1800 nm), at the second QPM pitch, Λ_2. The TH wavelength as a function of the QPM pitch size is summarized in Fig. 3(d). The conversion wavelength is changed from 595 to 605 nm as Λ_2 varies by 0.6 μm. Therefore, from first and second experiments [Fig. 3(b) and (d)], we conclude that the converted wavelength is overlapped in the regime at around 600 nm, which is required for making a self-referencing interferometer.

For the detection of the CEO frequency in the *2f-3f* self-referencing interferometer, it is also necessary to choose the same wavelength for the SH- and the TH-light. We estimated the linewidth of the SH light by high-resolution spectrometer (Advantest Q8347), which is 0.1 nm. We also investigated the temperature dependence on the SH light. The peak wavelength increases 1 nm as temperature increases 20 degrees. Since it is easy to control the temperature of PPLN ridge waveguides on the order of 1 degree, which changes the center wavelength 0.05 nm, the CEO frequency signal can be detected by *2f-3f* optical wavelength conversion device with the PPLN ridge waveguides.

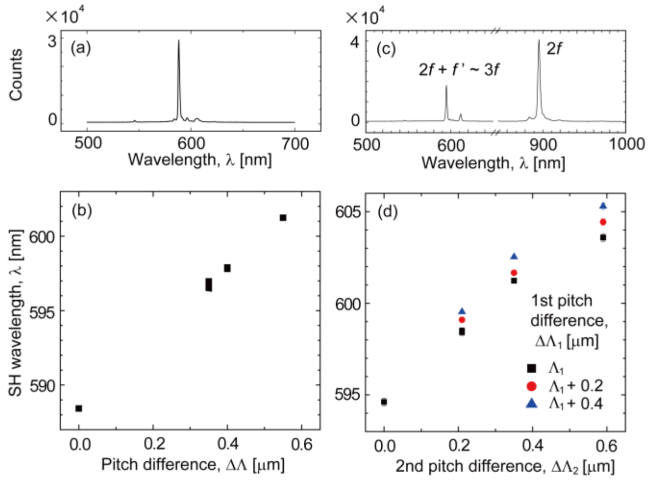

Fig. 3. (a) SH spectrum obtained by a spectrometer, (b) SH wavelength as a function of the QPM pitch, (c) SH and TH spectrum by a spectrometer, and (d) SF wavelength as a function of two kinds of the QPM pitch, Λ_1, Λ_2.

4. Conclusions

We propose a novel approach to detecting the CEO frequency signal and show how to implement a *2f-3f* self-referencing interferometer using both single-pitch and double-pitch PPLN ridge waveguides. We studied the QPM pitch dependence of the converted wavelength for both a SH device and TH device. We hope to achieve a CEO-locked frequency comb at telecommunications wavelengths using the *2f-3f* optical wavelength conversion device with our integrated PPLN ridge waveguide.

References

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