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# Temperature-insensitive frequency conversion by thermally-induced phase mismatch compensation using a non-phase-matched crystal

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ABSTRACT

A simple and versatile thermally-induced phase mismatch compensation method by three cascaded nonlinear crystals is proposed and experimentally demonstrated for temperature-insensitive frequency conversion. The middle crystal, which is not required to be phase matched, compensates the thermally-induced phase mismatch generated in the first crystal. Additionally, the dispersion of air, which causes a phase shift between fundamental and harmonic waves, is utilized to reduce the demand of length accuracy of the middle crystal. The temperature acceptance bandwidth of frequency conversion in the three cascaded crystals is about double that in a single long traditional crystal with the same interaction length.


## 1. Introduction

Frequency conversion is an efficient technology to extend laser wavelengths [1–3], and it has been widely used in many fields, such as industry, military, and biomedicine [4–6]. To obtain high conversion efficiency, the mixing waves should be phase matched. At present, birefringent crystals are commonly used for phase matching. For some applications, frequency conversion are required to operate in varying temperature environments [7,8]. However, the varying temperature would change the refraction index of the birefringent crystals and would cause thermally-induced phase mismatch, which can destroy phase matching condition and has severe impact on conversion efficiency [9–11]. Many techniques, such as beam shaping [12], electro-optics effect [13,14], and crystal cooling [15,16], are used for reducing the thermally-induced phase mismatch. However, these techniques require many extra components, complicating the system and consuming a great amount of energy.

Temperature-insensitive phase matching shows great potential for efficient and thermally stable frequency conversion and has attracted a great deal of interest [17–21]. Some unique crystals are characterized by temperature-insensitive phase matching, for example, yttrium calcium oxyborate (YCOB) [17]. The temperature acceptance bandwidth of second harmonic generation (SHG) of 1064 nm in YCOB can reach 150 °C·cm, which is significantly larger than that in conventional crystals. The temperature-insensitive phase matching scheme based on YCOB is simple and efficient, however, it is only valid for SHG at ~1 μm. Zhong et al. proposed a two-crystal temperature-insensitive phase matching scheme, based on two cascaded crystals with alternate signs in their first temperature derivatives of phase mismatch [18,19]. Both the two crystals are phase matched and take part in energy conversion. However, there are no commonly used nonlinear crystals with negative first temperature derivative of phase mismatch when employing Type I phase matching for SHG with the fundamental wavelength bluer than 0.7 μm. For Type II phase matching, this is the case across the spectrum. Therefore, the two-crystal scheme is valid for SHG of fundamental wavelength redder than 0.7 μm, but limited in type I phase matching, and not available for SHG of fundamental wavelength bluer than 0.7 μm.

Recently, we theoretically analyzed a simple and versatile temperature-insensitive phase matching method [20]. In the method, three nonlinear crystals are cascaded as a combination. The crystals located at the two ends of the combination perform the frequency conversion. The middle crystal, with opposite sign of the first temperature derivative of phase mismatch, compensates the thermally induced phase mismatch generated in the first crystal. The compensation crystal does not contribute to the nonlinear frequency conversion process, so it is not required to be phase matched. Thus, polarization orientations and propagation directions in compensation crystal can be arranged flexibly. So, it

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is very convenient to obtain desired value of the first temperature derivative of phase mismatch in the compensation crystal. Therefore, the proposed method may work effectively across a broad spectral range for various frequency conversion processes and is not limited by the material of the nonlinear crystal and the phase matching type as well. Since only a single additional crystal is needed, the system may be simple and reliable. In this paper, the proposed method is experimentally demonstrated and further studied. The feasibility of this method is verified by temperature-insensitive SHG of 1064 nm in two KTiOPO4 (KTP) crystals and a compensation crystal $LiB_3O_5$ (LBO). Besides, phase shift between fundamental and harmonic waves caused by the dispersion of air is analyzed and employed for reducing the demand of length accuracy of the compensation crystal.

## 2. Experimental set and results

The experimental configuration is shown in Fig. 1. A Nd:YAG laser operating at 1064 nm, with a pulse duration of 10 ns and a repetition frequency of 1 Hz, serves as the fundamental laser source. The two KTP crystals are both cut at ($\theta = 90°$, $\varphi = 23.3°$) and $LiB_3O_5$ (LBO) is cut at ($\theta = 90°$, $\varphi = 0°$), where $\theta$ is a spherical angle between beam propagation direction and the crystalline z-axis, and $\varphi$ is the azimuthal angle between the beam propagation direction and the x-y plane, where x, y and z are the principal axes of the crystal, and their refraction indices satisfy $n_x < n_y < n_z$. All the three crystals are anti-reflection (AR) coated at 1064 nm and 532 nm, and mounted in an oven where the temperature can be adjusted from −35 to 55 °C with a precision of ±0.1 °C. The beam splitter is a plane mirror which is high-reflection (HR) coated at 1064 nm and AR coated at 532 nm. The intensity of the fundamental and harmonic waves is detected by an energy meter (Model: J-50MB-YAG, Coherent). In the experiment, type II phase matching is employed, and polarization orientations of the mixing waves in each crystals are shown in Fig. 1. Before the laser propagating in the first KTP crystal, the angle between the polarization orientation of the fundamental wave (FW) and z axis of KTP is 45°, so that the fundamental energy of fast and slow light in KTP is equal. In LBO, fundamental waves polarize along y axis and z axis, and the harmonic wave (HW) polarizes along y axis.

In order to achieve temperature-insensitive phase matching, the phase mismatch value ($\Delta k \cdot L$) generated in LBO should be an integral multiple of $2\pi$ at the optimal temperature for phase matching in KTP, meanwhile, the signs of the first temperature derivatives of phase mismatch in KTP and LBO should be opposite and satisfy the specific ratio:

$$\Delta k_2(T_0) \cdot L_2 = N \cdot 2\pi \tag{1}$$

$$\frac{\partial \Delta k_1}{\partial T} \bigg/ \frac{\partial \Delta k_2}{\partial T} = -L_2/L_1 \tag{2}$$

where $T_0$ is the optimum temperature for phase matching in the KTP. $\Delta k_2(T_0)$ is the phase mismatch in LBO at $T_0$. $L_1$ and $L_2$ are lengths of KTP and LBO, respectively. $T$ denotes the temperature of KTP and LBO. $N$ is an integer. For KTP cut at ($\theta = 90°$, $\varphi = 23.3°$), the optimum temperature for phase matching of SHG of 1064 nm is 20 °C, and the first temperature derivative of phase mismatch ($\partial\Delta k_1/\partial\Delta T$) is 0.236 $cm^{-1}$ °$C^{-1}$ [20,22]. For LBO cut at ($\theta = 90°$, $\varphi = 0°$), the derivative ($\partial\Delta k_2/\partial\Delta T$) is −0.667 $cm^{-1}$ °$C^{-1}$ [20,23]. The lengths of the two KTP crystals are 6.0 mm, and then the length of LBO is designed as 2.1 mm according to Eq. (2). To guarantee the phase mismatch generated in LBO to be an integral multiple of $2\pi$, the LBO should be cut at 2.099 mm with an accuracy of 1 μm, which is difficult for current fabricating technology. Finally, the LBO crystal was cut at 2.14 mm with an accuracy of 50 μm. To make up the defect, we can slightly incline the LBO to tune the propagation direction angle ($\theta$) to bring the phase mismatch to an integer times of $2\pi$.

Initially, the experiment is operated at 20 °C. We slowly incline the LBO to change the propagation direction angle $\theta$ to tune the phase mismatch until maximum conversion efficiency is obtained. The propagation direction angle ($\theta$) in LBO is finally fixed at 89.31°, at which the phase mismatch ($\Delta k \cdot L$) generated in LBO is an integral multiple of $2\pi$. Then, we test the temperature characteristics of SHG in the three cascaded crystals. We change the temperature of the oven from −5 to 50 °C with an increment of 5 °C, and measure the HW energy after the reset temperature is stable within 20 min. Also, SHG in two cascaded KTP crystals without compensation crystal and only in the KTP crystal next to the Nd:YAG laser (KTP1) are experimentally studied for comparison.

The HW energy versus crystal temperature is shown in Fig. 2. We firstly analyze the experimental results obtained when the incident FW energy is 36.4 mJ. From Fig. 2(a), we can see that the temperature full width at half maximum (FWHM) of SHG based on the three-crystal scheme is 38 °C, and the HW energy takes its maximum of 21.2 mJ at 20 °C, corresponding conversion efficiency reaches 58.2%. From Fig. 2(b), we can see that the temperature FWHM of SHG in a single 6 mm-long KTP crystal is 39.3 °C, and the maximum HW energy is 13.4 mJ, corresponding conversion efficiency is 36.8%. From Fig. 2(c), we can see that the temperature FWHM of SHG in two cascaded 6 mm-long KTP crystals is 20.7 °C, and the maximum HW energy is 22.8 mJ, corresponding conversion efficiency reaches 62.6%. When the FW energy decreases to 15.6 mJ, the temperature FWHM of SHG in each crystal combination is approximately invariable. When the compensation crystal LBO is removed, the remained two cascaded 6 mm-long KTP crystals can be treated as a single 12 mm-long crystal. For the SHG without thermal-induced phase mismatch compensation, the temperature acceptance bandwidth is inversely proportional to the interaction length of the mixing waves. So, the temperature FWHM of SHG in the single 6 mm-long KTP crystal is about two times of that in the two cascaded KTP crystals. However, in the proposed scheme, the thermal-induced phase mismatch in the first KTP is well compensated by the following LBO, so the temperature insensitiveness is remarkably enhanced, and the temperature FWHM of SHG based on the three-crystal scheme is about double that in two KTP crystals without phase mismatch compensation, though they share the same interaction length. On the other hand, when the phase is perfectly matched at 20 °C, conversion efficiency of SHG is positively correlated with the interaction length of the mixing waves. So, the maximum conversion efficiency of SHG in the three cascaded crystals approximately equals that in the two KTP crystals, and is about 1.5 times that in a single 6 mm-long KTP crystal. From the experimental results shown in Fig. 2, we can conclude that the proposed method can effectively enhance the temperature insensitivity of SHG without decreasing the conversion efficiency.

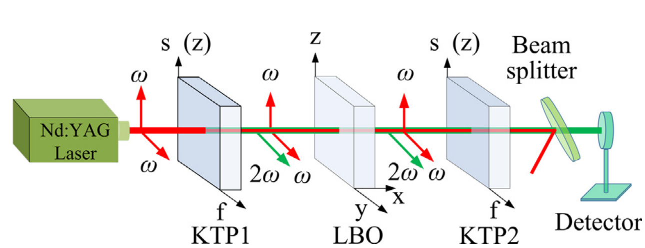


**Fig. 1.** Schematic diagram of the experimental setup, f and s denote the polarization orientations of fast light and slow light.