Versatile temperature-insensitive second-harmonic generation by compensating thermally induced phase-mismatch in a two-crystal design

To cite this article: H Z Zhong et al 2012 Laser Phys. Lett. 9 434

View the article online for updates and enhancements.

Related content

- Two-Crystal Design and Numerical Simulations for High-Average-Power Second-Harmonic Generation
  Zhong Hai-Zhe, Yuan Peng, Zhu He-Yuan et al.

- Green-to-red tunable SHG of a quantum-dot laser
  K A Fedorova, G S Sokolovskii, P R Battle et al.

- High-power single-frequency Nd:YVO4 green laser
  Y J Wang, Y H Zheng, Z Shi et al.

Recent citations

- Temperature-insensitive frequency conversion by thermally-induced phase mismatch compensation using a non-phase-matched crystal
  Xun Liu et al

- Temperature-insensitive quasi phase matching method for nonlinear frequency conversion
  Xun Liu et al

- Temperature-insensitive frequency tripling for generating high-average power UV lasers
  Haizhe Zhong et al
Abstract: We propose and experimentally demonstrate a novel second-harmonic-generation (SHG) scheme capable of supporting temperature-insensitive phase-matching (PM) at various laser wavelengths. This versatile temperature-insensitive PM is designed by using two cascaded crystals with opposite signs of temperature derivation of phase-mismatch, in which the temperature-induced phase-mismatch in the first crystal is well compensated in the second crystal. Two application examples are studied at the typical wavelengths of ~1.0 and 1.5 μm, respectively. The proof-of-principle experiment, using two crystals of LiB$_3$O$_5$ (LBO) and KH$_2$PO$_4$ (KDP), demonstrates that the temperature-acceptance of PM can be 2–3 times larger than that of using a traditional single crystal. The proposed two-crystal design may provide a promising route to high-average-power SHG at various laser wavelengths.

Versatile temperature-insensitive second-harmonic generation by compensating thermally induced phase-mismatch in a two-crystal design

H.Z. Zhong, P. Yuan, H.Y. Zhu, and L.J. Qian

1 Department of Optical Science and Engineering, Fudan University, Shanghai 200433, China
2 Key Laboratory for Laser Plasmas (Ministry of Education) and Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China

Received: 7 January 2012, Revised: 30 January 2012, Accepted: 7 February 2012
Published online: 24 March 2012

Key words: temperature-insensitive phase-matching; second-harmonic generation; thermal effects

1. Introduction

The second-harmonic generation (SHG) is a widely-used technique for extending the optical wavelength from a fixed laser source. The design and techniques of SHG are well developed for lasers with low average-power or single-shot long pulse. SHG in the high average-power regime, however, is still a challenge. Average powers over 10 kW may be generated directly from the diode-pumped solid-state lasers (DPSSL) [1], while SHG powers are less than 1 kW at maximum [2], which shows a great gap between the powers of DPSSL and their SHGs. Thermal effect is detrimental in high-power SHGs: Optical absorption of the nonlinear crystal will lead to a nonuniform distribution of temperature as well as refractive-index, thus perfect phase-matching (PM) condition of SHG could not be maintained across the beam transversely, resulting in a limited SHG efficiency.

Previous studies on high-average-power SHGs mainly focus on controlling the crystal temperature by using uni-
In this paper, we theoretically and experimentally demonstrate the temperature-insensitive PM at various specific wavelengths. There is lack of an approach to intentionally design the temperature-insensitive PM so far can be realized only occasionally in a single-crystal cases. More importantly, the PM wavelength acceptance bandwidth is defined as a measure for the sensitivity of PM condition to temperature deviation [7]. We note that yttrium calcium oxyborates (YCOB) is a unique crystal supporting temperature-insensitive PM at 1064 nm [8]. The green SHG power as much as ~350 W with conversion higher than 60% has recently been reported by using YCOB crystal [4]. However, the temperature-insensitive PM so far can be realized only occasionally in a specific wavelength. There is lack of an approach to intentionally design the temperature-insensitive PM at various wavelengths.

Here we propose a novel temperature-insensitive SHG scheme applicable to various laser wavelengths. The involved two crystals have opposite signs of the first derivation of phase-mismatch to temperature, and are arranged in a cascaded manner, resulting in a temperature-insensitive PM with larger temperature-acceptance bandwidth compared with the single-crystal cases. More importantly, the PM wavelength for this scheme can be designed intentionally within a broad wavelength range (from ~700 nm to over 2 µm).

In this paper, we theoretically and experimentally demonstrate our two-crystal design at a fundamental wavelength of 1064 nm. To illustrate our versatile temperature-insensitive PM, we also present a design example at 1550 nm corresponding to the wavelength of high-power Er-doped fiber lasers.

2. Basic principle

In this paper, we simply consider type-I SHG process. The phase-mismatch $\Delta k$ is defined as $\Delta k = k_{2SH} - 2k_{FH}$, where $2SH$ and $FH$ denote the fundamental-harmonic and the second-harmonic waves, respectively. To discuss the effect of thermal-induced phase-mismatch in the high-average-power regime, the sensitivity of PM condition to temperature deviation is an important parameter. The first temperature derivations of phase-mismatch at an initially set PM temperature of 20°C, against FH wavelength, are calculated for the five typical nonlinear crystals, i.e. $\text{KH}_{2}\text{PO}_{4}$ (KDP) [9], $\text{LiB}_{2}\text{O}_{3}$ (LBO) [10], $\text{BaB}_{2}\text{O}_{4}$ (BBO) [11], $\text{CsLiB}_{3}\text{O}_{10}$ (CLBO) [12], and YCOB [4]. As shown in Fig. 1, the first temperature derivation of phase-mismatch (i.e., $\partial \Delta k / \partial T$) may reach zero at a specific fundamental wavelength for some crystals, e.g. YCOB at ~1100 nm in the $xz$ plane, which supports a large temperature-acceptance bandwidth. Especially important to our proposed two-crystal scheme, we note that within a broad wavelength range (from ~700 nm to over 2 µm) it is always possible to find two crystals with opposite signs of the temperature deviation.

We propose a novel temperature-insensitive PM scheme using two or more crystals with alternatively changed signs of the temperature derivation of phase-mismatch (Fig. 2). For the SHG using one pair of crystal A and B, the thermal-induced phase-mismatch in the first crystal (crystal A) can be well compensated for in the second crystal (crystal B), resulting in a better global PM condition corresponding to a larger temperature-acceptance of PM. Basically, the number of crystals in our design can be two, three, four (as shown in Fig. 2), and more.
More plates alternatively using crystal A and B can support much larger acceptance of temperature variations for PM condition. For simplicity but without losing generality, we mainly discuss the two-crystal situation in this paper.

We assume preliminarily that both the two crystals satisfy their PM conditions at an initially set temperature. With the accumulation of thermal loading owing to the incident high average-power laser, the PM conditions will be degraded due to temperature deviation, and hence resulting in an accumulated phase difference among the interacting waves ($\Delta \phi = \Delta k L$). When this phase difference reaches to a value of $\pi$ or equivalently the crystal length equals to the coherent length ($L_c = \pi/\Delta k$), the back conversion process (i.e., SH wave is converted back to the FH wave) will occur and the conversion efficiency will be decreased with the crystal length. In our proposed SHG scheme using a pair of crystals, however, the phase difference accumulated in the first crystal ($\Delta \phi_1 = \Delta k_1 L_1$) will be compensated for by the second crystal ($\Delta \phi_2 = \Delta k_2 L_2$) owing to their opposite signs of phase-mismatch. In this situation, the SH wave can be kept increasing monotonically during the whole SHG process if both the phase differences in the first and second crystal are equal to or less than a value of $\pi$. As a result, the SHG conversion can be less sensitive to phase-mismatch and hence temperature-insensitive PM can be realized.

For type-I SHG of a high-average-power laser, the temporal effect is negligible (i.e., assuming the uniform temporal distribution with duration much longer than 1 ps). Employing the slowly varying envelope and plane-wave approximation (i.e. neglecting the diffraction), the equations that govern the envelopes $A_{FH}$ and $A_{SH}$ of the fundamental (FH) and the second harmonic (SH) lasers, respectively, are

$$\frac{\partial A_{FH}(z)}{\partial z} = -\frac{i\omega_{FH} d_{eff}}{n_{FH} c} A_{SH}(z) A_{FH}^*(z) \exp \left[-i\Delta k(T)z\right],$$

$$\frac{\partial A_{SH}(z)}{\partial z} = -\frac{i\omega_{FH} d_{eff}}{n_{SH} c} A_{FH}^2(z) \exp \left[i\Delta k(T)z\right],$$

where $d_{eff}$ denotes the effective nonlinear coefficient. $n_{FH}$ ($n_{SH}$) and $\omega_{FH}$ ($\omega_{SH}$) represent the refractive index and central frequency of the FH (SH) field, respectively. The thermal effect in SHG will be considered by taking a thermal-induced $\Delta k(T)$ into account [14].

The numerical prove of our proposed PM scheme is illustrated in Fig. 3, in which the SHG conversion efficiencies with a dependence of crystal length were calculated in the small-signal regime for several cases using a single crystal and the two-crystal design. In the case without thermal effect (i.e., perfect PM $\Delta k = 0$), a similar performance can be expected for both the designs using a single crystal and a pair of crystals, and the conversion efficiency increases monotonically with the propagation distance. When the thermal-induced phase-mismatch is present, for the single crystal situation, the generated SH wave will be smaller than that of the perfect PM case, and back conversion will occur when the crystal length is longer than the coherent length (Fig. 3a). In our two-crystal design, however, the conversion efficiency will be much less sensitive to the phase-mismatch (Fig. 3b), and always increases monotonically with the propagation distance if $|\Delta k_1 L_1| \leq \pi$ and $|\Delta k_2 L_2| \leq \pi$. This implies that the proposed two-crystal scheme may release the detrimental thermal problem to a large extent and greatly enhance the overall conversion efficiency. Taking $\Delta k_1 L_1 = -\Delta k_2 L_2 = \pi$ as an example, there will be no
generated harmonic-wave at the crystal exit in the case of using a single crystal due to the accumulated phase difference ($\Delta kL = 2\pi$), while the harmonic-wave in our two-crystal design can be as large as $\sim 40\%$ of that under the PM condition ($\Delta k = 0$).

3. Experimental results and discussions

We experimentally studied the proposed two-crystal design for temperature-insensitive PM. An Nd:YAG regenerative laser amplifier (High Q Pico-Regen) operating at 1064 nm, with a pulse duration of 480 ps and a maximum output power of up to 3.5 W at a repetition rate of 1 kHz, served as the fundamental laser. Two temperature-controlled crystal ovens were employed, which can quickly heat the crystal to a desired temperature and maintain the temperature uniformly. Over a range of approximately 40 to 180$^\circ$C, the temperature inside the ovens can be kept constant within $\pm 0.1^\circ$C. Since our laser power is relatively low and not enough for studying the SHG in high-average-power regime, we simulated the thermal-induced temperature variations within the nonlinear crystal by globally adjusting the oven temperature. According to Fig. 1, a combination of KDP and LBO can be an optional choice for the temperature-insensitive PM scheme at FH wavelength of 1064 nm, owing to their opposite signs of the thermal-induced phase-mismatches. In the proof-of-principle experiment, as shown in Fig. 4a, we adopted an 18-mm-long KDP combined with a 6-mm-long LBO in tandem. Each crystal was installed inside a temperature-controlled oven, and there is a distance of $\sim 25$ cm between the two crystals. In our experiment, the SHG setup operated in the small-signal SHG regime, with an incident FH power of $\sim 0.8$ W, resulting in an equivalent pump intensity of $\sim 130$ MW/cm$^2$. Conversion efficiency of $\sim 5\%$ was observed when the KDP and LBO crystals both operated at their initially set PM temperature of $\sim 60$ and $80^\circ$C, respectively. By adjusting the temperature deviation from the initially set PM temperature ($\Delta T$), for both of these two crystals, the temperature-dependent SHG conversion efficiency for this two-crystal design can be obtained, as shown in Fig. 5, showing a temperature-acceptance of $\sim 11.6^\circ$C defined by the full-width at half-maximum (FWHM). At each temperature, the generated SHG radiation power at 532 nm was measured by averaging over 30 seconds to eliminate the influence of the pulse fluctuation and divergence of the laser beam.

Since the crystal length affects both the SHG efficiency and temperature-acceptance for PM, in order to fairly compare the temperature-acceptance for our two-crystal design with that of a single-crystal case, all the SHGs should be designed with similar conversion efficiency at their initially set PM temperature under the same FH intensity. In our proof-of-principle experiment, the 18-mm-long KDP and 6-mm-long LBO were also adopted as the nonlinear materials for single-crystal cases. Whereas, in order to achieve similar SHG efficiency as the two-crystal de-

Figure 6 (online color at www.lasphys.com) Calculated temperature-dependent conversion efficiency for the proof-of-principle experiment. Solid line – 18-mm-long KDP and 6-mm-long LBO in tandem, dotted line – 36-mm-long KDP, and dashed line – 12-mm-long LBO. For each curve, all the efficiencies are normalized to the maximal value at the initially set PM temperature.

Figure 7 (online color at www.lasphys.com) Calculated small-signal SHG conversion efficiency at 1550 nm versus the crystal temperature, where the initially set PM temperature is fixed at 20°C. Solid line – 6-mm-long YCOB in the $xz$ plane and 10-mm-long BBO, dashed line – 13-mm-long BBO, and dotted line – 26-mm-long YCOB in the $xz$ plane. All the efficiencies are normalized to the maximal value at the initially set PM temperature in each curve.

sign does, for each case, the crystal was employed in a double-pass configuration (Fig. 4b), i.e., an equivalent 36-mm-long KDP and 12-mm-long LBO were adopted respectively. In both of the double-pass single-crystal cases, phase-matched efficiencies of $\sim 5\%$ were achieved under pump intensity of $\sim 130$ MW/cm$^2$, similar to the previous two-crystal design. By adjusting the oven temperature, we measured the temperature-dependent conversion efficiencies for these two double-passed single-crystal cases. As shown in Fig. 5, each single-crystal design using KDP or LBO is quite sensitive to temperature variation, while our two-crystal design may substantially improve the SHG conversion efficiency over a broad range of temperature variations, which clearly demonstrates our two-crystal design supporting temperature-insensitive PM. In our two-crystal design (square symbol in Fig. 5), the temperature-acceptance can be 2–3 times larger than those of using the traditional single crystals, which are only $\sim 5.4$ and $\sim 6.5^\circ$C for LBO and KDP, respectively.

For comparison, the numerical simulation results corresponding to our experimental condition are shown in Fig. 6. In the calculations, we adopted the Sellmeier equations and parameters available in SNLO version 21 [13]. The experimentally measured temperature-acceptance bandwidths for LBO and KDP are $\sim 6.1$ and $\sim 23.9^\circ$C-cm respectively; while the theoretical values are $\sim 6.2$ and $\sim 11.3^\circ$C-cm, respectively. Above comparisons show a good agreement between the experimental and numerical results for the case using LBO crystal. On the other hand, there is a discrepancy between the experimental and numerical results for the case using KDP crystal. This discrepancy may be due to the errors of the thermo-optic coefficients [15]. Similar experimental values of the temperature-acceptance bandwidth for KDP crystal were reported [9,15]. Nonetheless, above studies demonstrate that our proposed two-crystal design can support the temperature-insensitive PM. If a combination of YCOB and BBO would be adopted as shown in Fig. 1, the SHG efficiency will be much more insensitive to temperature, resulting in a temperature-acceptance larger than that of using a single YCOB crystal under the temperature-insensitive PM.

4. Numerical results for SHG at 1550 nm

In the last section, we have theoretically and experimentally studied the novel temperature-insensitive PM scheme at laser wavelength of 1064 nm. Actually, the proposed two-crystal design can also be valid for various wavelengths of interest. According to Fig. 1, taking the fundamental wavelength of 1550 nm as an example, a combination of YCOB and BBO ($d_{\text{eff}} = 1.95$ pm/V and $\delta k = \sim 0.08$ cm/$^\circ$C) can also be a good choice for temperature-insensitive PM. Compared with the $xy$ plane ($d_{\text{eff}} = 0.226$ pm/V and $\delta k = \sim -0.13$ cm/$^\circ$C), YCOB in the $xz$ plane ($d_{\text{eff}} = 1.08$ pm/V and $\delta k = \sim -0.11$ cm/$^\circ$C) has a larger effective nonlinear coefficient ($\sim 5$ times larger) for type-I SHG at 1550 nm. Thus we take YCOB...
in the $xz$ plane as the one for negative temperature-derivation of phase-mismatch. Under the small-signal situation, temperature-dependent SHG conversion efficiencies are numerically studied for a temperature range of 20 to 60°C (Fig. 7). For a fair comparison, all the SHGs are designed with the same efficiency at 20°C (i.e., the initially set PM temperature). Similar to the case for SHG at 1064 nm, the two-crystal design also exhibits a greatly promoted insensitivity to temperature variations.

It should be noted that there are no any single crystals available for temperature-insensitive PM at the wavelength of 1550 nm, our proposed two-crystal design in this paper is versatile for the temperature-insensitive PM. It is important to note, in order to achieve optimal temperature-insensitivity PM, that the lengths of these two different crystals should be designed properly in the proposed two-crystal scheme. The design procedure will be discussed elsewhere.

5. Conclusions

In conclusion, we have numerically and experimentally demonstrated a novel SHG scheme valid for temperature-insensitive PM at various wavelengths. This design of temperature-insensitive PM is based on employing two nonlinear crystals with opposite signs of the first temperature derivation of phase-mismatch. We have presented the two typical design examples for SHGs at the wavelengths of $\sim 1.0$ and $1.5\ \mu m$ in both theory and experiment. The proof-of-principle experiment using LBO and KDP crystals shows that the temperature-acceptance of PM can be 2–3 times larger than that of using a single crystal. The demonstrated two-crystal design may provide a promising route to achieve high-average-power SHG at various wavelengths.

Acknowledgements This work was partially supported by the Natural Science Foundation of China (grants No. 61008017 and No. 60890202).

References