Optik 139 (2017) 239–243

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Temperature-insensitive quasi phase matching method for nonlinear frequency conversion

Xun Liu*, Xueju Shen, Yudan Chen, Jianling Yin, Xiaoming Li

Mechanical Engineering College, Department of Electronic and Optical Engineering, Heping West Road No. 97, Shijiazhuang, Hebei, 050003, China

ARTICLE INFO

Article history:
Received 29 December 2016
Accepted 24 March 2017

Keywords:
Nonlinear frequency conversion
Quasi phase matching
Temperature-insensitive
Temperature acceptance bandwidth

ABSTRACT

A temperature-insensitive quasi phase matching method is proposed to increase the temperature acceptance bandwidth in nonlinear optical frequency conversion. In the method, the nonlinear crystal is cut at an angle that enables the first temperature derivation of phase mismatching to be zero, which makes the phase mismatching value to be insensitive to temperature variation. Then, the phase velocities of mixing waves are quasi phase matched by appropriate poled period of the nonlinear crystal. Simulations of second harmonic generation of 1064 nm in periodically poled $KTiOPO_4$ crystal and 5 mol% MgO-doped periodically poled $LiNbO_3$ are conducted. The temperature acceptance bandwidths in periodically poled $KTiOPO_4$ and 5 mol% MgO-doped periodically poled $LiNbO_3$ reach 943 °C cm and 393 °C cm, respectively.

1. Introduction

Optical frequency conversion in nonlinear crystal is an efficient technology to extend laser wavelengths [1–3]. However, the conversion efficiency is sensitive to the varying temperature of the nonlinear crystals, as the phase matching condition is satisfied under specific temperature in birefringence crystal. Usually, precise control of the crystal temperature is necessary for efficient frequency conversion [4,5]. But extra temperature control units make the system complicated, and lead to a great amount of energy consumption and inconvenience of operation. On the other hand, researchers are devoted to achieve broad temperature acceptance bandwidth in frequency conversion with simple and effective approaches. Temperature-insensitive phase matching schemes are proposed to meet the requirements. For instance, yttrium calcium oxyborate (YCOB) crystal is temperature-insensitive for second harmonic generation (SHG) of 1064 nm, and the temperature acceptance bandwidth can reach 150 °C Cm [6]. H. Zhong et al. [7,8] proposed a two-crystal temperature-insensitive scheme, which is based on thermal induced phase mismatching compensation, and the temperature acceptance bandwidth can be 2–3 times wider than that of using a single crystal. However, the application field of the two-crystal method is limited in the SHG of fundamental waves with wavelength redder than 0.7 μm. Grechin et al. [9] theoretically discovered and experimentally confirmed the existence of temperature-insensitive phase matching in SHG of 1064 nm with $KTiOPO_4$ (KTP) crystal cutting at $\theta = 71.1°$ and $\varphi = 67°$. However, The efficient nonlinear coefficient of KTP-SHG with phase matching angle (71.1°, 67°) is about a quarter of that with normal phase matching angle (90°, 23.5°) [10], which leading to low conversion efficiency. D. Zhang et al. [11] increased the temperature acceptance bandwidth of SHG in KTP through two short crystals cutting at slightly different phase matching

* Corresponding author.
E-mail address: liuxunddm@qq.com (X. Liu).

http://dx.doi.org/10.1016/j.ijleo.2017.03.107

angles. The harmonic waves generated from the two crystals should polarize orthogonally, which means that method is only available for type II phase matching.

On the other hand, through appropriately choosing the period for domain inversion, periodically poled crystal is capable for special phase matching which usually cannot be implemented by normal phase matching. Such as SHG with noncritical phase matching and largest nonlinear coefficient, d_{33}, in periodically poled KTP [12,13]. C. Cannalias and Pasiskevicius [14] achieved mirrorless optical parametric oscillator through quasi phase matching (QPM) in a nonlinear photonic structure with submicrometer periodicity. In addition, periodically poled crystal has been successfully used for broadband phase matching in nonlinear frequency conversion [15,16], in which matching of the group velocities of the second harmonic and the fundamental was achieved, and the phase velocities were quasi phase matched.

In this paper, to broaden the temperature acceptance bandwidth of SHG, we proposed a temperature-insensitive scheme which is based on QPM. In the scheme, the nonlinear crystal is cut at an angle that enables the first temperature derivation of phase mismatching to be zero ($\partial\Delta k/\partial T = 0$), which make the phase mismatching value to be insensitive to the variation of crystal temperature. The phase velocities are quasi phase matched by appropriate poled period. As the selection of cut angle and the poled period in nonlinear crystal is flexible, it is promising to achieve temperature-insensitive frequency conversion in a broad spectral range. SHG of 1064 nm in periodically poled $KTiOPO_4$ (PPKTP) and 5 mol% MgO-doped periodically poled $LiNbO_3$ (PPMgO:LN) with critical cutting angles are studied. The temperature acceptance bandwidths PPKTP and PPMgO:LN reach 943 °C cm and 393 °C cm, respectively, which are the largest bandwidths achieved, to the best of our knowledge.

2. Principle of temperature-insensitive QPM

In this section, we study the principle of temperature-insensitive QPM for SHG.

To obtain optimal conversion efficiency with QPM, the sign of the nonlinear susceptibility should be reversed for every coherence length l_c. The poling period is determined as

$$\Lambda = 2l_c = \frac{2\pi}{|k_2 - k'_1 - k''_1|} \tag{1}$$

where k_2 denotes the wave number of the second harmonic wave, k'_1 and k''_1 represent the wave numbers of the fundamental waves with different polarization orientations, $k'_1 = k''_1$ when there is only one polarization orientation of the fundament wave in the mixing. Then phase mismatch from the QPM condition is given by

$$\Delta k = \begin{cases} k_2 - k'_1 - k''_1 + 2\pi/\Lambda \ \ for\ k_2 \le k'_1 + k''_1 \\ k_2 - k'_1 - k''_1 - 2\pi/\Lambda \ \ for\ k_2 > k'_1 + k''_1 \end{cases} \tag{2}$$

Under the undepleted pump approximation, the conversion efficiency η can be obtained

$$\eta \propto d_{\mathrm{eff}}^2 L^2 \mathrm{sinc}^2\left(\frac{\Delta k L}{2}\right) \tag{3}$$

where L is the interaction length of the nonlinear crystal. η takes its maximum when $\Delta k = 0$, and it goes to half of its maximum when $\Delta k = \pm 0.886\pi/L$. For a specific interaction length, the conversion efficiency mainly depends on the value of Δk. In the case of $k_2 > k'_1 + k''_1$, the phase mismatching can be calculated by

$$\Delta k = 2\pi\left(\frac{n_2}{\lambda_2} - \frac{n'_1}{\lambda_1} - \frac{n''_1}{\lambda_1} - \frac{1}{\Lambda}\right) \tag{4}$$

where λ_1 and λ_2 represent the wavelengths of fundamental wave and harmonic wave, respectively. n_2 denotes the refraction index of harmonic wave in nonlinear crystal. n'_1 and n''_1 denote the refraction indexes of fundamental wave with different polarization orientations. The refraction index is a function of crystal temperature T, hence Δk will change with variational temperature, and we can expand $\Delta k(T)$ in a Taylor series

$$\Delta k(T) = \Delta k(T_0) + \frac{\partial \Delta k}{\partial T}\Big|_{T=T_0} \cdot \Delta T + \frac{1}{2}\frac{\partial^2 \Delta k}{\partial T^2}\Big|_{T=T_0} \cdot \Delta T^2 + \cdots \tag{5}$$

We define the temperature acceptance band by the full width at the half maximum (FWHM) point of the $\mathrm{sinc}^2\left(\Delta k L/2\right)$ function. Under the first-order approximation, the temperature acceptance bandwidth $\Delta k L$ at T_0 can be obtained

$$\Delta k \cdot L = 1.772\pi / \frac{\partial \Delta k}{\partial T}\Big|_{T_0} \tag{6}$$

From Eq. (6), we can learn that the temperature acceptance bandwidth takes its maximum when the first temperature derivation of phase mismatching to be zero ($\partial\Delta k/\partial T = 0$). As refraction index of mixing waves in crystal is dependent on the propagation direction (θ, φ), where θ and φ are respectively defined by the internal incident angles measured from the z axis (polar angle) and in the x–y plane from the x axis (azimuthal angle), we can appropriately design the propagation direction of mixing waves and poling period in poled crystal to satisfy temperature-insensitive QPM conditions.