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Multi-color laser generation in periodically poled KTP crystal with single period

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Frequency conversion based on three-wave mixing is a critical nonlinear optic application, extending the frequency range of existing lasers and realizing frequency-transduced detectors in a wavelength range that lacks an effective detector. Phase matching is vital for effective frequency conversion. The advantages of quasi-phase matching (QPM) over birefringent phase matching are a lack of walk-off effect, a maximum nonlinear coefficient, and phase matching in the entire transparency window. Herein, using different types and orders of QPM, four kinds of effective frequency doubling processes are realized in a periodically poled potassium titanyl phosphate (KTP) crystal with a single period, and three kinds of frequency doubling processes are experimentally verified. We also show a feasible way to construct an RGB color generator based on two different QPM processes. This study significantly expands the feasible frequency conversion of existing lasers to different wavelengths, providing an effective method for multi-color laser generation based on periodically poled KTP crystals.

Keywords: nonlinear optics; frequency doubling; multi-color laser; quasi-phase matching.
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1. Introduction

Nonlinear optics emerged with the first observation of second-harmonic waves in quartz crystals[1]. Three-wave mixing (TWM) based on second-order nonlinear processes such as second-harmonic generation (SHG), sum frequency generation (SFG), and the generation of different frequencies has been widely studied for decades. In TWM, phase matching is vital for efficient frequency conversion between the interacting waves. Typically, two kinds of phase matching exist in TWM: birefringent phase matching (BPM) and quasi-phase matching (QPM)[2]. The innovation of QPM in the 1960s led to significant progress in nonlinear optics[3], wherein efficient conversion was realized with relatively low pump laser power. Frequency conversion with QPM crystals possesses three obvious advantages over BPM crystals. The first is the absence of a walk-off effect in QPM because the interacting waves are propagating along the principal axes of the crystal. Second, in QPM, phase matching can be achieved in the entire transparency window of the crystal. Finally, using QPM, the highest element in the nonlinear tensor matrix can be reached.

Rapid development of the QPM technique has occurred in recent years. Domain structures have been specifically designed to realize novel functions in frequency conversion[4–11], such as achieving an all-optical Stern–Gerlach effect[5], high-order harmonics generation[6,7], and broad-bandwidth frequency conversion[4]. Researchers have also developed two-dimensional[8] and three-dimensional[9] structures to realize versatile functions in nonlinear optics.

For one-dimensional QPM, the poling period ranges from a uniform structure[12–15] to various structures such as a Fibonacci optical superlattice[16], aperiodic[17], linearly chirped[6,7,18], apodized[19], and multi-segmented[20]. Many studies on multi-color laser generation based on QPM crystals and waveguides have been reported[6,7,12–22]. One typical study reported white-light generation based on a segmented periodically poled potassium titanyl phosphate (PPKTP) crystal waveguide. The light generation was achieved with a single laser pump source, where the red, green, and blue (RGB) lasers were realized via first-order type-0 SHG, third-order type-0 SFG, and seventh-order type-0 fourth-harmonic generation[12]. A similar white-light source was reported based on a periodically poled lithium niobate (PPLN) waveguide and with a higher conversion efficiency[13]. A blue and orange laser was produced using first-order type-0 SFG and second-order SHG in a bulk PPLN crystal with a uniform domain structure[15]. A cascaded $LiTaO_3$ superlattice was used to achieve the generation of red light at 660 nm, green light at 532 nm, and blue light at 440 nm to obtain the output of red-green-blue laser light from a diode-side-pumped dual-wavelength Nd:YAG laser[14]. Other multi-color laser sources have been created based on non-uniform domain structures, as previously mentioned[6,7,16–22]. While developing new structures to realize novel functions in nonlinear optics is very promising, harnessing an existing simple uniform structure to realize new functions is also important for nonlinear optical applications. The PPKTP crystal is widely used in many nonlinear optical applications, though most current studies of frequency conversion in PPKTP crystals have focused on the broadband tuning abilities of a crystal possessing non-uniform domain structures[4,23]. Therefore, a systematic study of the various QPM processes with a single poling period is necessary. To our knowledge, generating a multi-color laser based on bulk PPKTP crystals with a single period has not yet been reported.

We demonstrate in this work that, using various kinds and orders of QPM in a PPKTP crystal with a single period, four effective QPM processes in frequency doubling can be obtained using a poling period of 8.95 μm. Specifically, the effective QPM processes exhibit frequency doubling of 1063.8 to 531.9 nm (type-0 first-order QPM, ZZZ), 783.9 to 391.95 nm (type-0 third-order QPM, ZZZ), 796.94 to 398.47 nm (type-II first-order QPM, YYZ), and 962 to 481 nm (type-I third-order QPM, ZYY). A detailed theoretical analysis was initially performed to reveal the possibility of realizing four QPM processes in a PPKTP crystal with a single period. Further, these multiple QPM processes could be realized in a wide wavelength range. The first three kinds of QPM processes were tested experimentally and were in good agreement with theoretical predictions. The fourth kind of QPM process was not tested because of the lack of a suitable laser. We also demonstrated that, by simultaneously pumping the crystal with 1063.8 and 783.9 nm lasers, a white light was generated whose color could be tuned by varying the pump power. This work can greatly expand the achievable frequency conversion wavelengths of a PPKTP crystal with a single period, which can be used for multi-color laser generation.

2. Experiments

First, we present a theoretical analysis for different QPM processes in a PPKTP crystal. The nonlinear polarizations of the interacting waves in a PPKTP crystal can be given in the form[2,24]

$$\begin{bmatrix} P_x(2\omega) \\ P_y(2\omega) \\ P_z(2\omega) \end{bmatrix} = 2\varepsilon_0 \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_x^2(\omega) \\ E_y^2(\omega) \\ E_z^2(\omega) \\ 2E_y(\omega)E_z(\omega) \\ 2E_x(\omega)E_z(\omega) \\ 2E_x(\omega)E_y(\omega) \end{bmatrix}, \quad (1)$$

where ε_0 is the permittivity of free space; $P_i(2\omega)$ $(i = x, y, z)$ is the polarization of the second-harmonic wave along the x, y, and z axes; d_{ij} $(i = 1, 2, 3; j = 1–6)$ is the nonlinear susceptibility tensor of the KTP crystal; and $E_i(\omega)$ $(i = 1, 2, 3)$ is the electrical field of the fundamental wave along the x, y, and z axes. For an x-cut PPKTP crystal, the possible phase matching types are type II (YYZ), type I (ZYY), and type 0 (ZZZ), whose nonlinear coefficients at 1064 nm are $d_{24} = 3.64\,\mathrm{pm/V}$, $d_{32} = 4.35\,\mathrm{pm/V}$, and $d_{33} = 16.9\,\mathrm{pm/V}$, respectively[25]. For a QPM crystal, the phase mismatch is given by $\Delta k = k_2 - 2k_1 + 2m\pi/\Lambda$, where $k_i = 2\pi n_i/\lambda_i\,(i = 2, 1)$ is the wave vector of the second harmonic and fundamental waves, and n_i and λ_i are the corresponding refractive index and wavelength; Λ is the poling period; and m is the order of phase matching. Under phase matching (i.e., $\Delta k = 0$), the poling period can be determined by $\Lambda = 2m\pi/(2k_1 - k_2)$. For different kinds of QPM processes, the poling periods can be obtained with the wavelengths and refractive indices of the interacting waves. For TWM in QPM crystals, the effective nonlinear coefficient is $d_{\mathrm{eff}} = 2d_{il}\sin(m\pi D)/m\pi$, where D is the duty cycle of the poling. For $D = 0.5$, $d_{\mathrm{eff}} \neq 0$ for $m = 1$ and 3. If the duty cycle deviates from the optimum value, the effective nonlinear coefficient will decrease[26].

Based on the above analysis, we calculated the poling period for different wavelengths under different kinds and orders of QPM. The results are shown in Fig. 1. The refractive indices of the potassium titanyl phosphate (KTP) crystal principal axes are taken from Refs. [27,28], and the temperature of the crystal was set as 22°C in the calculations. The poling periods for different types of phase matching processes are plotted against the second-harmonic wavelengths. We can see that multiple cross points exist for a constant poling period. The number of cross points depends on the value of poling period, and they are found to increase from 1 to 4 with increasing poling period value. The four phase matching processes are type-0 first-order QPM (ZZZ), type-0 third-order QPM (ZZZ), type-II first-order QPM (YYZ), and type-I third-order QPM (ZYY). There are two special cases when type-0 third-order QPM (ZZZ) and type-II first-order QPM (YYZ) or type-0 first-order QPM (ZZZ) and type-I third-order QPM (ZYY) are degenerated at a specific wavelength. The black horizontal solid line in Fig. 2 represents the poling period of the PPKTP crystal used in experimental testing.

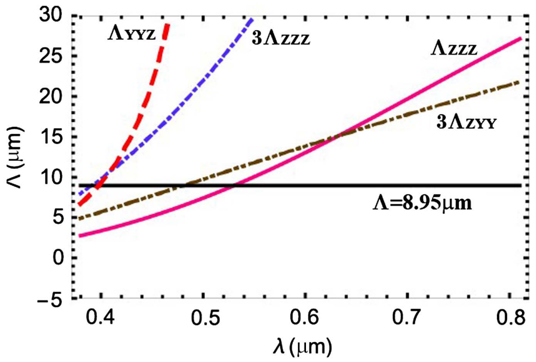

Fig. 1. Numerical simulations of poling period for different types and orders of QPM processes. The four named lines Λ_{ZZZ}, $3\Lambda_{ZZZ}$, Λ_{YYZ}, $3\Lambda_{ZYY}$ represent type-0 first-order QPM (ZZZ), type-0 third-order QPM (ZZZ), type-II first-order QPM (YYZ), and type-I third-order QPM (ZYY), respectively. Λ = 8.95 μm represents the poling period of the PPKTP crystal used for experimental testing.

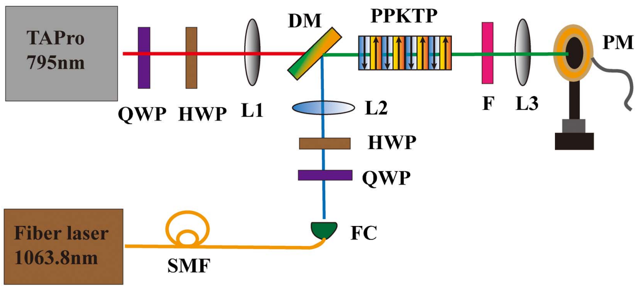

Fig. 2. Experimental setup for testing various QPM processes. QWP, quarter-wave plate; HWP, half-wave plate; SMF, single-mode fiber; FC, fiber collimator; DM, dichroic mirror; L1–L3, lenses; F, filters; PM, power meter; PPKTP, periodically poled potassium titanyl phosphate.

We experimentally tested various QPM processes and demonstrated a feasible method for white-light generation. The experimental setup for testing various QPM processes is shown in Fig. 2. Two continuous-wave narrow-bandwidth lasers were used: a Toptica TAPro laser, 780–800 nm wavelength, >2.5 W output power, <100 kHz line width; and a 1063.8 nm fiber laser, 5 W maximum output power, <100 kHz line width. These two lasers were used to test different QPM processes, and their polarizations were controlled with a group of wave plates comprising one quarter-wave plate (QWP) and one half-wave plate (HWP). The laser beams were focused separately by lenses L1 and L2 (both lenses had a 150 mm focal length) before the beams were combined with a dichroic mirror. The generated second-harmonic beams were filtered with low-pass filters and collimated with lens L3. The power of the generated second-harmonic beam was measured with a power meter (SC142C, Thorlabs). The temperature of the crystal was controlled with a high-precision homemade temperature controller (temperature fluctuations ±0.002°C). The PPKTP crystal had dimensions of 1 mm × 2 mm × 14.7 mm (Raicol Crystals) and a poling period of 8.95 μm. Further, both crystal end faces had broadband antireflection coatings for 780–1064 nm and 390–532 nm wavelengths.

3. Results

Different QPM processes were tested separately, with the type-0 first-order QPM (ZZZ) tested first. The pump power at 1063.800 nm was 0.49 W, and the phase matching temperature was 22.4°C. The 531.900 nm second-harmonic power was 2.42 mW, corresponding to a normalized conversion efficiency of 1% W^{-1}. The dependence of the second-harmonic power upon temperature is shown in Fig. 3(a). For SHG with plane-wave approximation, the SHG power can be expressed as $P_{\mathrm{SHG}} = 8\pi d_{\mathrm{eff}}^2 P_p^2 L^2 / \varepsilon_0 c n_p^2 n_{\mathrm{SHG}} \lambda_p^2 w_f^2$[29], where $d_{\mathrm{eff}} = 2d_{33}/\pi = 2 \times 16.9/\pi\ \mathrm{pm/V}$, ε_0 is the free space permittivity ($8.85 \times 10^{-12}\ \mathrm{F/m}$), c is the speed of light in vacuum ($3 \times 10^8\ \mathrm{m/s}$), ω_f is the confocal beam waist (∼45 μm), and n_p and n_{SHG} are the KTP refractive indices at the pump and SHG wavelengths, respectively. The theoretically calculated normalized conversion efficiency was 1.65% W^{-1}. The difference existing between this theoretically calculated value and the experimental value arose because a focused Gaussian beam was used in testing, and the value of the nonlinear coefficient d_{33} was varied between different samples. We note that, in Refs. [30–32], the reported effective values of d_{33} range from 11.8 to 17 pm/V owing to the imperfect domain inversion in the crystal fabrication. The measured value of the normalized conversion efficiency agrees with a previous reported value[32].

Next, we tested the type-0 third-order QPM (ZZZ) with the temperature of the crystal fixed at 21.80°C, the wavelength of the TAPro laser tuned to 783.9 nm, and a 0.58 W pump power, with the confocal beam waist of 35.65 μm. Figure 3(b) shows the results fitted to sinc^2 function. The optimal phase matching temperature and the temperature bandwidth (FWHM) are 21.8°C and 1.38°C, respectively. We obtained an output power of 0.62 mW at 391.95 nm, with a normalized conversion efficiency of 0.18% W^{-1}. The normalized conversion efficiency of type-0 third-order QPM should be about 1/9 that of the type-0 first-order QPM (for the third QPM, $d_{\mathrm{eff}} = 2d_{33}/3\pi$). The theoretically calculated normalized conversion efficiency was 0.94% W^{-1}, and the experimental data differ from the theoretical values. This is mainly caused by the absorption of crystal, the duty cycle of poling, and the confocal beam waist. Finally, the type-II first-order QPM (YYZ) was tested, where the polarization of the pump beam was tuned to 45° linear polarization, the temperature of the crystal was unchanged, the wavelength of the pump laser was tuned to 796.94 nm, and the pump power was 0.46 W, with the confocal beam waist of 36.24 μm. Figure 3(c) shows the measured doubling power as the temperature is tuning. It can be seen that the best phase matching temperature is at 21.8°C, and the FWHM is about 2.12°C. The output 398.47 nm second-harmonic power was 0.37 mW, with a normalized conversion efficiency of 0.17%/W (for type-II

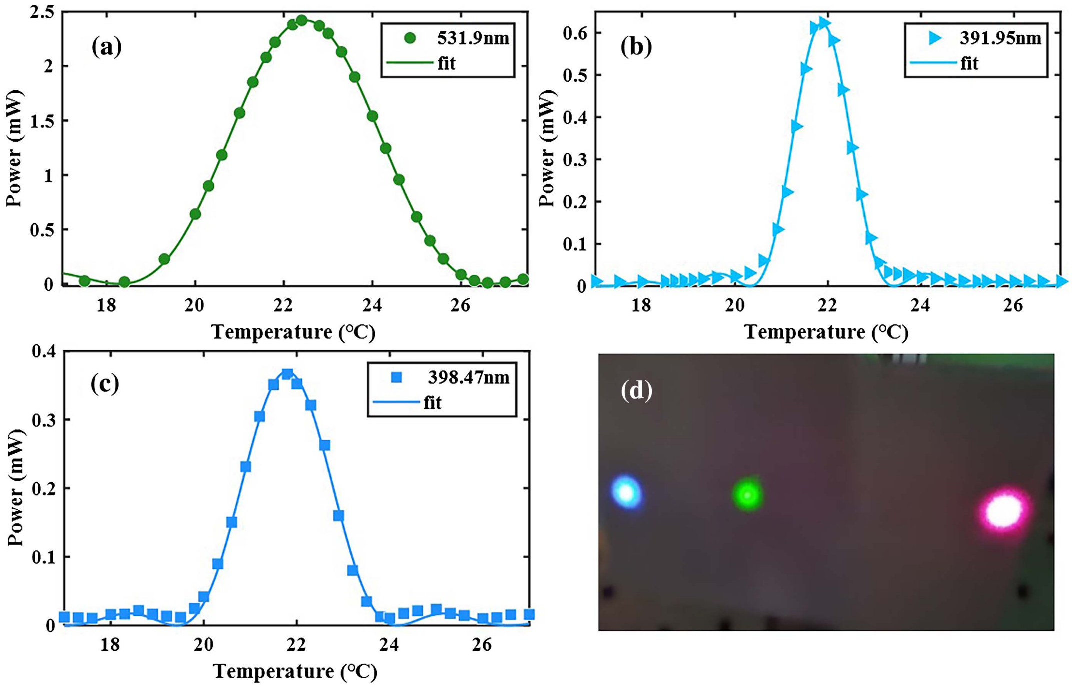

Fig. 3. Measurements of temperature phase matching and generated multi-color laser. (a)–(c) Temperature tuning curve of PPKTP crystal for different types and orders of QPM processes: (a) type-0 first-order QPM for SHG of 1063.8 to 531.9 nm; (b) type-0 third-order QPM for SHG of 783.9 to 391.95 nm; (c) type-II first-order QPM for SHG of 796.94 to 398.47 nm. (d) Photo of an RGB laser beam is obtained by splitting the multi-color laser beam with a visible grating.

first-order QPM, $d_{\mathrm{eff}} = 2d_{24}/\pi = 2 \times 3.64/\pi\ \mathrm{pm/V}$). The theoretically calculated normalized conversion efficiency was $0.39\%\ \mathrm{W}^{-1}$. The difference of normalized conversion efficiencies between the SHG of 783.9 and 796.94 nm arises from two factors. The first factor is the difference in effective nonlinear coefficients between these two QPM processes (i.e., type-0 third-order QPM and type-II first-order QPM). The second factor is the rapidly increasing UV absorption of the KTP crystal for the second-harmonic beam with decreasing UV beam wavelength. Theoretically, the present crystal can achieve type-I third-order (ZYY) phase matching for frequency doubling of a 962 nm laser to 481 nm, but this phase matching case is not tested for lack of a suitable laser.

To demonstrate a possible application of multi-phase matching in a PPKTP crystal with a single period, we combined type-0 first-order and type-0 third-order QPMs (first case), or type-0 first-order and type-II first-order QPMs (second case), to generate a white-light beam. The white-light beams comprised wavelengths of 783.9, 391.95, and 531.9 nm in the first case; or 796.94, 398.47, and 531.9 nm in the second case. The 1063.8 nm laser was filtered using a short-pass filter with a 950 nm cutoff wavelength. The grating had a visible light band to separate the white light. A photograph of an RGB laser generated using the first case (i.e., 783.9, 391.95, 531.9 nm) illuminated on white paper is shown in Fig. 3(d), where the photo was obtained using a cell-phone camera. The spectrum for each color was measured with an optical spectrum analyzer (AQ6373B, Yokogawa), with a 350–1120 nm wavelength measurement range. The measured spectrum is shown in Fig. 4. Further, narrow-bandwidth filters were inserted into the white-light beam. The color of the combined beam can be tuned using the wave plates placed in front of the dichroic mirror. Therefore, the setup in Fig. 2 can function as a feasible RGB color generator. Multi-color lasers can also be used for multi-color super-resolution microscopy[33,34].

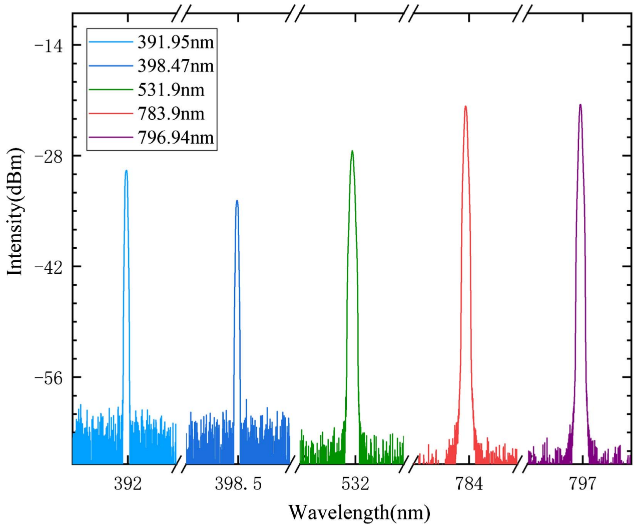

Fig. 4. Measured spectrum of the multi-color lasers that are composed of different QPM processes.

4. Discussions

In summary, this work reports possible effective phase matching processes for a PPKTP crystal with a single period, using both theoretical and experimental methods. We find that a PPKTP crystal with 8.95 µm poling period has four QPM processes with different types and orders, three of which are experimentally tested herein. We also show a feasible way to construct an RGB color generator based on two different QPM processes. In the future, we will show that high conversion efficiency can be achieved with an external cavity for type-0 third-order QPM. The present study is not limited to PPKTP crystals, but is also applicable to other kinds of periodically poled crystals such as PPLN and periodically poled stoichiometric lithium tantalite. The present work opens up new possibilities for using periodically poled crystals possessing a single period, which will lead to versatile applications in nonlinear optics.

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