Athermal design for Solc-type filter based on PPKTP

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An athermal design for Solc-type filter based on periodically poled KTP (PPKTP) is proposed. The athermal static phase retardation (ASPR) direction in KTP along which the quasi-phase-matched (QPM) condition is insensitive to the temperature is found. The optimal design for Solc-type filter along ASPR direction is obtained. The coupling theory of QPM linear electro-optic effect is employed to study the polarization coupling in PPKTP. The study results demonstrate that the central passing wavelength of Solc-type filter keep unchanged with an almost 100% output when the temperature varies from 268 to 328 K.

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A Solc-type filter based on periodically domain-inverted ferroelectric crystal was extensively studied for its compactness and fine tuning control. In such a Solc-type filter, the central passing wavelength is governed by the condition for quasi-phase-matching (QPM) in linear electro-optic effect, which is related to the poling period and the refractive indices of ordinary- and extraordinary-ray[1]. Generally, the central passing wavelength of the filter will shift with the changing of temperature, since the refractive indices of the crystals are sensitive to the temperature. Taking advantage of this property, researchers proposed a tunable Solc-type filter by adjusting the working temperature of the crystal[2−3]. However, in some special applications in which the passing wavelength of the filter is required to be unchanged, a thermostatic container is necessary for such a Solc-type filter.

Potassium titanyl phosphate (KTP) is extensively used in optical frequency converters due to a relatively high nonlinearity, excellent mechanical and optical properties, high damage threshold and thermally stable phase-matching properties. The KTP crystal is of great important application in second-harmonic generation (SHG) of Nd^{3+} based lasers emitting near 1 μm[4]. The available spectrum of KTP has dramatically broaden with the development of material growth and poling technologies, since a desired wavelength light over the whole transparency region of KTP can be achieved using noncritical phase matching in periodically poled KTP (PPKTP)[5−7]. In the mean time, its large linear electro-optic r-coefficients and low dielectric constants make KTP attractive for various electro-optic applications[8,9]. In addition, the higher damage threshold of KTP is advantageous for the output of high power laser. However, one of the primary limitations in the application of KTP as an electro-optical device is its natural-birefringence, which is sensitive to the temperature. In our previous work, we have found that the athermal static phase retardation (ASPR) direction in KTP, along which the Static Phase Retardation caused by natural-birefringence is insensitive to the temperature[10]. In periodically domain-inverted ferroelectric crystals, the nonlinear optical coefficients including the electro-optic (EO) coefficients, are also modulated periodically because of the periodically reversed ferroelectric domains. In this letter, we present a Solc-type filter based on PPKTP with the propagating light along the ASPR direction, and the theoretical study demonstrates that the central passing wavelength of Solc-type filter keep unchanged with an almost 100% output when the temperature varies from 298 to 328 K .

As well known, KTP is a birefringent crystal, and the static phase retardation between the two independent polarized waves is

$$\Gamma = \frac{2\pi}{\lambda}(n_2 - n_1)L, \tag{1}$$

where n_1 and n_2 are the refractive indices of the two independent polarized waves, L is the length of the crystal neglecting the influence of thermal expansion, and λ is the wavelength of the incident light wave. In order to find the ASPR direction in KTP, we let $\mathrm{d}\tau/\mathrm{d}T = 0$, i.e.,

$$\frac{\mathrm{d}n_2}{\mathrm{d}T} - \frac{\mathrm{d}n_1}{\mathrm{d}T} = 0. \tag{2}$$

In our previous work, we have found that the ASPR direction and z-axis form an angle of 32.5° in the $x - z$ plane[10]. It's noted that the ASPR direction changes when the wavelength of incident light is different. When the light propagates along ASPR direction, the two independent polarized directions are along $\mathrm{a} = (0, 1, 0)$ and $\mathrm{b} = (\cos 32.5°,\ 0,\ -\sin 32.5°)$, respectively.

In this study, the wave coupling theory of QPM linear electro-optic effect is employed[11,12]. Considering that the duty cycle of poling structure is 0.5 and only one single order of reciprocal vector is most close to phase matching, the resulting wave coupling equations for QPM linear electro-optic effect are[12]

$$\frac{\mathrm{d}A_1(r)}{\mathrm{d}r} \approx -\mathrm{i}\kappa_{\mathrm{q}} A_2(r) \exp(\mathrm{i}\Delta k r), \tag{3a}$$

$$\frac{\mathrm{d}A_2(r)}{\mathrm{d}r} \approx -\mathrm{i}\kappa_{\mathrm{q}}^* A_1(r) \exp(-\mathrm{i}\Delta k r), \tag{3b}$$

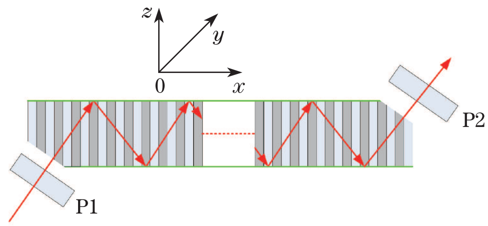

Fig. 1. Basic schematic diagram of an athermal Solc-type filter.

with

$$\Delta k = k_2 - k_1 + \alpha_m, \quad \alpha_m = \frac{2m\pi}{\Lambda},$$

$$\kappa_q = \frac{k_0}{2\sqrt{n_1 n_2}} r_{\text{eff1}} E_0 G_m, \quad \kappa_q^* = \frac{k_0}{2\sqrt{n_1 n_2}} r_{\text{eff1}} E_0 G_{-m},$$

$$G_m = \frac{1}{\mathrm{i}\pi m}[1 - \cos(2\pi m D) + \mathrm{i}\sin(2\pi m D)] \ (m \neq 0),$$

where $A_1(r)$ and $A_2(r)$ are the normalized amplitudes of two independent components of light field; n_1, n_2 and k_1, k_2 are the corresponding unperturbed refractive indices and wave numbers; k_0 is wave number of light in vacuum; α_m is the amplitude of the mth reciprocal vector, Λ is the poling period, D is duty cycle of the structure defined by $D = l/\Lambda$, and l is the length of one positive section; E_0 is the amplitude of external electric field; $r_{\text{eff}i}$ (i=1, 2, 3) are the effective electro-optic coefficients[11].

Figure 1 shows the basic schematic diagram of an athermal Solc-type filter. The filter consists of a 2.0-cm PPKTP with high reflection coating and two cross polarizers. A p-polarized (along b direction) incident light wave propagates along the ASPR direction, and the output from the filter is an s-polarized light (along a direction). In order to compensate the phase mismatch between the two independent polarized waves, the first order reciprocal vector α_1 is required to be $\alpha_1 = k_1 - k_2 = 2\pi(n_1 - n_2)/\lambda$. Correspondingly, the poling period is

$$\Lambda = \frac{\lambda}{[n_1(\lambda) - n_2(\lambda)]\cos 32.5^\circ}. \tag{4}$$

Assuming the central passing wavelength λ_0 is set to be 1 064 nm, the poling period Λ is equal to 72.1 μm.

The non-zero electro-optic coefficients (in pm/V) of KTP are $r_{13} = 9.5$, $r_{23} = 15.7$, $r_{33} = 36.3$, $r_{42} = 9.3$ and $r_{51} = -7.3$[10]. Assuming the direction of external electric field is $\vec{c} = (c_1, c_2, c_3)$, the effective electro-optic coefficient can be expressed as

$$r_{\text{eff1}} = n_y^2 \cdot n_z^2 \sin 32.5^\circ \cdot r_{42} \cdot c_2. \tag{5}$$

From Eq. (5), one can clearly see that the largest effective electro-optic coefficient happens when the external electric field is along the y axis, ie. $\vec{c} = (0, 1, 0)$. Note that the effective electro-optic coefficient here is less than that in the case of light propagating along the x axis. Fortunately, the effective length of the crystal has been increased by a factor of 1/sin 32.5° due to the multiple reflections. The amplitude of external electric field E_0 is set to be 0.77 kV/mm, so that the filter has largest output for the central passing wavelength. It should be mentioned that the spatial walk-off occurs in our design since the light does not propagate along the crystal axes of KTP. The s-polarized light does not experience walk-off because the Poynting vector and k vector are coincident. Follow the steps in Ref. [13], the walk-off length for p-polarized light is calculated to be 2.20 cm when a light beam with a radius of 0.5 mm propagates along the ASPR direction. In addition, the PPKTP is thin in height (1 mm), so that the two rays can exchange their energies efficiently employing multi-reflection.

Firstly, we study the transmission of the filter as a function of the wavelength of incident light at two different temperatures of 298 and 328 K, respectively. The study results are shown in Fig. 2. From Fig. 2, one can see that the central passing wavelength keeps almost unchanged, which means that the filter is of excellent thermal stability. Further, we study the temperature dependence of the output of central passing wavelength of 1 064 nm, as shown in Fig. 3. From Fig. 3, we can see that the transmission of the filter is above 99% when the temperature varies from 268 to 328 K.

In conclusion, the ASPR direction for 1 064 nm light is found in KTP crystal. An athermal design for Solc-type filter based on PPKTP is presented. An optimized design of athermal Solc-type filter is achieved by taking advantage of the wave-coupling theory of the linear electro-optic effect. The numerical study results show that the filter has excellent thermal stability. Our study is helpful for the design and fabrication of athermal electro-optical devices based on QPM biaxial crystals.

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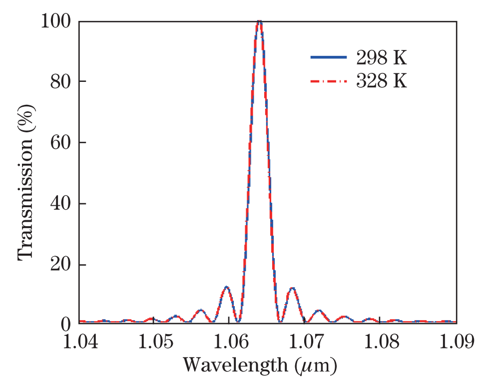

Fig. 2. Transmission of the filter as a function of wavelength.

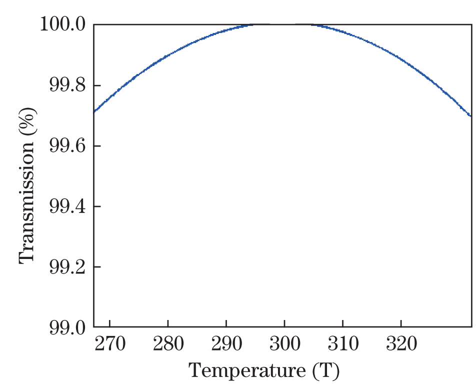

Fig. 3. Transmission of filter as a function of temperature, when the wavelength of incident light is 1 064 nm.

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