

Real-time monitoring in fabrication of PPKTP crystals utilizing electro-optical effect

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Abstract Compared with other nonlinear optical materials, KTP crystals have prominent advantages. However, they also have a high conductivity and become difficult to efficiently control domain-reverse with the conventional method, due to the existence of ionic current. To conquer the difficulty, it is necessary to monitor the polarization-reversal process of KTP crystals in real time. The real-time monitoring method in the fabrication of PPKTP, short for periodically-poled KTiOPO_4 , is carried out by utilizing electro-optical effect. The principle is analyzed theoretically and the result demonstrates the validity of the method experimentally. Compared with the result without using the monitoring method, the conversion efficiency of PPKTP crystal increases by many times. It is proved that this method can be used to enhance the quality and repeatability of PPKTP fabrication, and is also effective to examine the quality of PPKTP crystals.

Keywords nonlinear optics, quasi-phase matching (QPM), periodically poled KTP (PPKTP), electro-optical effect (EO effect), real-time monitoring

1 Introduction

In 1962–1963, Armstrong and Franken et al. published papers about quasi-phase matching (QPM) technology [1,2]. Because of the difficulty of material fabrication, this proposal was not popularly applied at that time. In recent decades, by utilizing high electrical field poling approach [3], QPM technology has developed very quickly. Using nonlinear effects in a QPM crystal to

realize the frequency conversion of laser is regarded as one of the most important developments in this field, and it is broadly known in the world. The most effective and practical approach to realize quasi-phase matching is to spatially modulate the nonlinear coefficient of the crystal, i.e., make them alternatively converted between $+d_{\text{eff}}$ and $-d_{\text{eff}}$.

There have been a lot of published papers about periodically poled LiNbO_3 (PPLN), LiTaO_3 (PPLT) and KTiOPO_4 (PPKTP) in recent years [4–15]. The most matured technology is the fabrication of PPLN, which has the advantages of larger nonlinear coefficient and higher conversion efficiency. However, it also has the disadvantages of lower optical damage threshold and obvious photorefractive effect. Moreover, the coercive voltage of LiNbO_3 is very high (about 21 kV/mm), which greatly restricts the applications of PPLN components. Compared with LiNbO_3 , KTP crystal has higher optical damage threshold and lower coercive voltage (2.1 kV/mm) without obvious photorefractive effect. It can be used to fabricate larger volume components, which could be used in higher frequency conversion applications.

The most popular method to realize QPM is to apply high voltage pulses to make the ferroelectric domains reverse periodically in the crystal, but it is very easy to create ionic current due to the high conductivity of KTP crystal (10 orders of amplitude higher than that of LiNbO_3), which makes it hard to control the process of poling. Therefore, it is necessary to monitor the domain reverse process during the poling.

In this paper, a real-time monitoring system is introduced by using the electro-optical effect of the KTP crystal. The feasibility of this method is theoretically analyzed and experimentally certified. The conversion efficiency of the second-harmonic-generation (SHG) of PPKTP, which is fabricated under this monitoring system, is obviously increased.

Translated from *Acta Optica Sinica*, 2006, 26(10): 1554–1558 [译自: 光学学报]

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2 Real-time monitoring system

2.1 Principle and setup

To control the poling process of lower conductive crystals like LiNbO_3 , the quantity of electrical charge that is lost during the domain reversing process should be controlled. Theoretically, the relation between the reversed domain size and cost charge can be described as $Q = \int Idt = 2P_s A$ [16]; here, P_s is spontaneous polarization, I is the reversing current while poling, and A is the area of the reversed domain. This formula can be used to calculate the area, which is the goal of the poling process.

Since the conductivity of KTP is 10 orders of amplitude higher than that of LiNbO_3 , a transmitting current exists besides the reversing current during the poling process. Meanwhile, since the conductivity of the KTP chip is random and inhomogeneous [17], it is impossible to assume the proportion of reversing current in the whole current. Figure 1 illustrates the change of conductivity of KTP crystal under the pulses lower than the coercive field. In this situation, no domain reversal occurs. The monitored current is purely transmitting current.

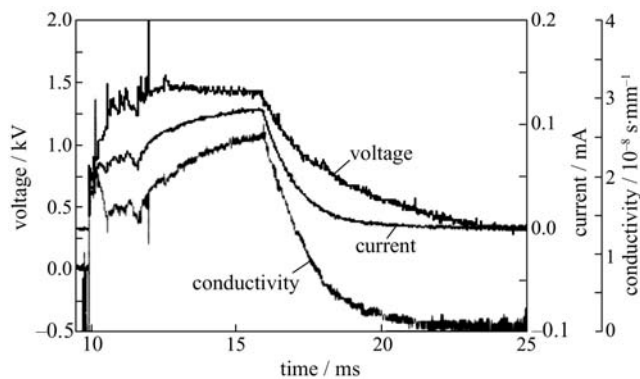


Fig. 1 Conductivity curve under application of electric field

Figure 1 also shows that the conductivity is not constant even if the electrical field is fixed.

To overcome this drawback of KTP crystals, electro-optical effect is used to monitor the process of poling during the pulses. This method is supposed to improve the quality and repeatability of the PPKTP fabrication. The experimental monitor setup using EO effect is shown in Fig. 2.

A trapezoid waveform is used as a poling pulse, which consists of an ascending edge, a flat top and a descending edge. When the crystal is operated under such a high voltage pulse along its z axis, its refractive index is changed, and this will induce the change of the polarization of the monitoring laser beam after its transporting through the whole crystal. A He-Ne laser

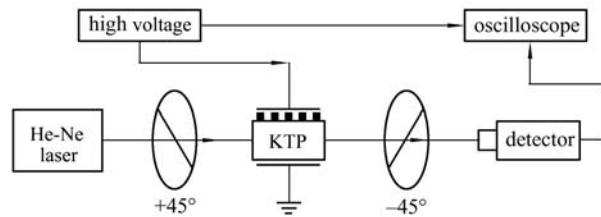


Fig. 2 Experimental setup of real-time monitoring system

is used as a monitoring laser, and its beam transports along the x axis of the crystal. The first polarization plate makes the laser beam polarized along $+45^\circ$ to the z axis of the crystal. After being modified by the electro-optical effect along the path in the crystal, the beam passes through the polarization plate -45° to the z axis. The detected intensity can reflect the changes of polarization of the monitoring beam.

When the voltage of the applied pulse is lower than the coercive field of the crystal, the detected intensity is just related to the change of the pulse, which means the detected intensity fluctuates only on the ascending and descending edges. However, the situation is different when the voltage is higher than the coercive field, because the ferroelectric domains are alternatively reversed. Correspondingly, the electro-optical factors also become negative in these domains. So the positive EO effect is gradually counteracted by the negative one. When the duty cycle is exactly 50%, the effective interacting length of EO effect is equivalent to zero. That means the poling process is a shortening process of the EO effective interacting length from the whole length of the crystal to zero. This method can be used to monitor the poling process of the crystal.

2.2 Theoretically calculation

The EO matrix of the KTP crystal is

$$[\gamma] = \begin{pmatrix} 0 & 0 & \gamma_{13} \\ 0 & 0 & \gamma_{23} \\ 0 & 0 & \gamma_{33} \\ 0 & \gamma_{42} & 0 \\ \gamma_{51} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \quad (1)$$

The value of each coefficient is shown in Table 1 [18].

Under the application of extra electric field, a phase difference is caused in the monitoring beam between the y -polarized components and the z -polarized components, which can be described as

$$\Gamma = \Gamma_1 + \Gamma_2 = \frac{2\pi L_x}{\lambda_0} (n_z - n_y) + (1 - 2D) \frac{\pi L_E E_z}{\lambda_0} (n_y^3 \gamma_{23} - n_z^3 \gamma_{33}). \quad (2)$$

Here, L_x is the length of the crystal. L_E is the effective EO interacting length (the whole length with electric field

Table 1 Electro-optical coefficients of KTiOPO_4 at 633 nm (unit: $\text{pm}\cdot\text{V}^{-1}$)

γ_{13}	γ_{23}	γ_{33}	γ_{42}	γ_{51}
9.5	15.7	36.3	9.3	7.3

applied). E_z is the voltage of the extra field. D is the duty-cycle (the ratio of reversed domain to the period).

In Eq. (2), the first term has no relation with EO effect, it is a constant during the poling process (the temperature change is not considered). The second term is related to EO effect and depends on the changing of the duty-cycle in the crystal. The refractive index n_y and n_z are defined by the Sellmeier Equation as

$$n_i^2 = a + b/(\lambda^2 - c) - d\lambda^2 \quad (i=x,y,z \text{ and } \lambda \text{ in } \mu\text{m}). \quad (3)$$

The coefficients in the Sellmeier Equation are defined in Table 2 [19].

Table 2 Coefficients of Sellmeier Equation

	a	b	c	d
x	3.00650	0.03901	0.04251	0.01327
y	3.03330	0.04154	0.04547	0.01408
z	3.31340	0.05694	0.05658	0.01682

The intensity received by the detector has the relation with the phase difference as

$$I \propto (1 - \cos \Gamma). \quad (4)$$

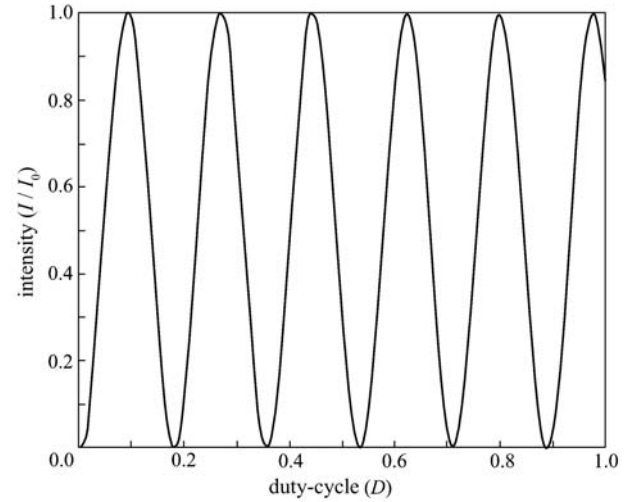
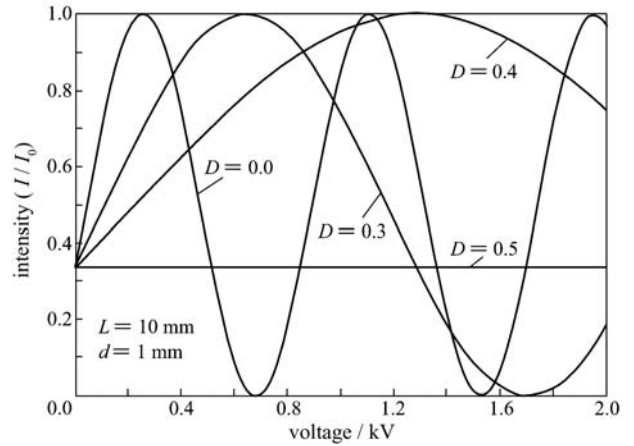
From Eqs. (2) and (4), it is easy to find that the detected intensity is determined by the duty-cycle and the voltage. Figures 3 and 4 show that the detected intensity is influenced by the duty-cycle and the voltage, respectively. In Fig. 3, the curve is obviously a cosine function. As long as the relative intensity is calculated at the determined duty-cycle, the poling process could be controlled effectively.

As shown in Fig. 4, as the value of D gets closer to 0.5, the detected intensity changes more slowly till the EO effect vanishes at $D = 0.5$ exactly.

With this characteristic the poling level of the crystal can be assessed. In other words, when a triangle pulse is applied on a periodically poled KTP crystal, the fluctuation of the detected intensity can reveal the quality of the crystal.

3 Experiment results and analysis

The KTP crystals used in this experiment are flux-grown KTP crystals after Rb-ion exchange pretreatment. The

**Fig. 3** Dependence between optical intensity and duty-cycle ($U = 2.4 \text{ kV}$, $L = 10 \text{ mm}$, $d = 1 \text{ mm}$)**Fig. 4** Dependence between electric field and optical intensity with different duty-cycle (D)

size of samples 1 and 2 are both $8 \text{ mm} \times 3 \text{ mm} \times 1 \text{ mm}$. Firstly, a triangle pulse is applied with the voltage lower than the coercive field to observe the EO effect of the crystal. Known from Eqs. (2) and (4), the detected intensity changes as a sine function, and there is a linear relation between phase retardation and the voltage. Figures 5 and 6 show that the experimental results fit well with the theoretical one, but the phase retardation has some errors because of the inhomogeneous conductivity of the crystal. Secondly, a trapezoid pulse is applied on the crystal. Figure 7 shows when the voltage is lower than the coercive field, which is 670 V/mm , the intensity curve dose not change during the flat top of the pulse, which is 22 ms . This means that there is no domain reversal occurring in the crystal.

The situation is different when the voltage is higher than the coercive field, as shown in Fig. 8. The detected intensity obviously changes as a sine function, just as described by Eq. (2), which means domain reversal

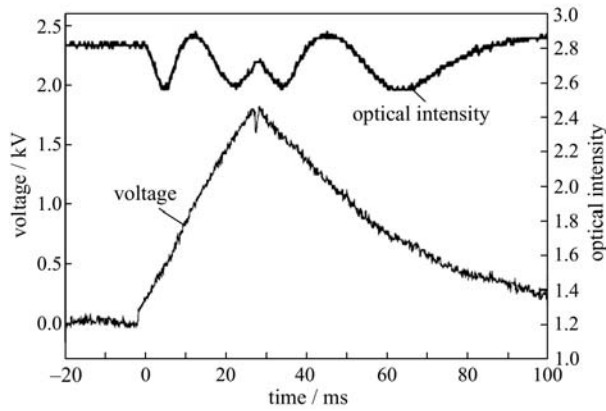


Fig. 5 Variety of optical intensity when the triangle electric pulse applied on sample 1

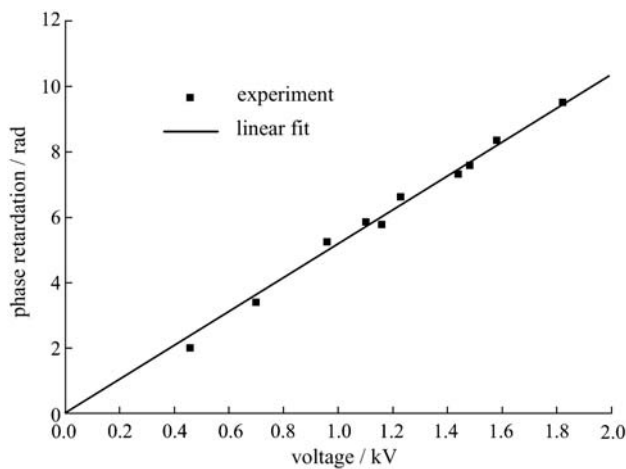


Fig. 6 Dependence between electric field and monitoring light phase retardation on sample 1

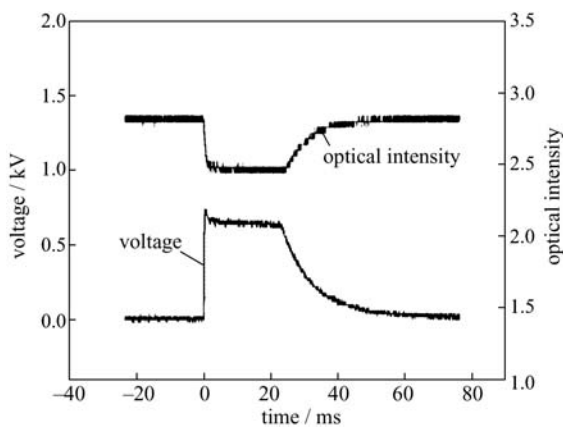


Fig. 7 Variety of optical intensity when the electric field below coercive field is applied on sample 2

happened in the crystal and reflected in the phase retardation.

By this means, the phase retardation from the intensity curve can be easily obtained to judge the quality of

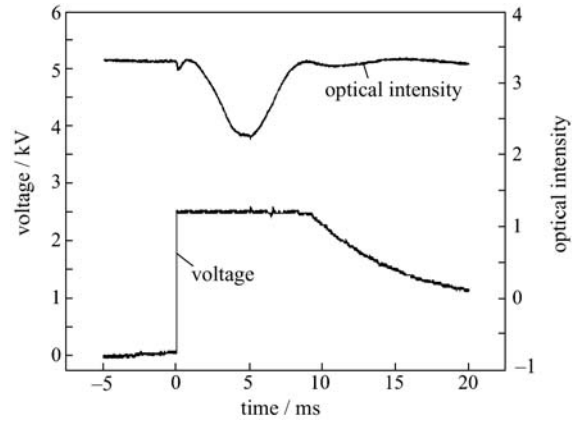


Fig. 8 Variety of optical intensity when the electric field over coercive field is applied on sample 2

poling, and then decide whether to apply another pulse to get a better domain reverse. It is noticeable that by observing the intensity change during the descending edge of the pulse, the degree of poling can be assumed. The more slowly the curve fluctuates, the better the crystal is poled.

4 Conclusions

The experimental results fit well with the theoretical calculation. All these work confirm the feasibility of the monitoring method using EO effect in the periodical poling process. This method can not only be used in the poling with duty-cycle of 0.5, but also in other situations. Further pulses applied can be stopped even if the EO effect dose not totally vanish, as long as the accumulated phase retardation reaches the predicted value.

Some KTP crystals have been poled under the real-time monitoring system depicted above. One of the best after-poled PPKTP crystals has been tested by its second harmonic generation of Nd:YAG laser. The transporting length of the sample is 8 mm, when the coupled incident power is 1 W, and SHG power output from the crystal is 13.5 mW. The single-pass SHG efficiency is 1.35%, and the normalized conversion efficiency reaches $1.69 \text{ (W} \cdot \text{cm)}^{-1}$, which is near the theoretical maximum value [20]. Compared to the former poling method without monitoring, the conversion efficiency is improved by several times.

Acknowledgements This work was supported by the National Nature Science Foundation of China (Grant No. 60377018) and the Key Science and Technology Research Project Foundation of Education Ministry of China (No. 02042).

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