Experiment of Measuring Half-wave Voltage and Electro-optic Coefficient of Crystal Based on KDP Crystal

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Abstract. The paper aims to measure half-wave voltage of KDP crystal irradiated by a 532 nm red laser. This paper explores a safe and easy way to measure the electro-optic coefficient, and then calculates the electro-optic coefficient of the KDP crystal. It provides a feasible way to measure the half-wave voltage and electro-optic coefficient of different electro-optic crystal materials by laser with different wavelengths.

Keywords: KDP crystal; half-wave voltage; electro-optic coefficient; birefringence; crystal optics.

1. Introduction
Potassium dihydrogen phosphate crystal (KH2PO4, hereinafter referred to as KDP) is a nonlinear optical crystal material with excellent performance [1-4], which has excellent electro-optical, piezoelectric and frequency doubling conversion performance [5-8]. After the laser technology has been widely developed, the application of KDP crystal has gradually attracted people's attention. Based on the wide application of KDP crystal, its growth method and parameter measurement become very important [9]. In the previous study, the various parameters of KDP are closely related to its growth method, so most of its parameters are provided by the producer. However, on the one hand, the parameters in the ideal environment often deviate from the actual application. On the other hand, the manufacturers may not provide the parameters needed. Therefore, the brief measurement method of parameters of KDP crystal becomes very important. There are many KDP crystal parameters, so this article mainly studies the measurement method of electro-optic coefficient from the perspective of the application of electro-optic switches. For the measurement method of electro-optic coefficient, there are usually interferometry and contrast method [10], and a more safe and convenient measurement method is proposed in this study.

2. Experimental materials
Optical path: a green laser with a wavelength of 532nm, two polarizers, a KDP crystal with electrodes, an optical power meter, and optical tool set
Circuit: a high-voltage DC module power supply adjustable between 0~15000V, two 20Ω sliding rheostats and two switching power supplies with DC5V and DC12V outputs respectively.

3. Experimental principle
When a light beam enters an anisotropic crystal, it is decomposed into two light beams (ordinary light \(o\) light and unusual light \(e\) light) and refracted in different directions. This phenomenon is called birefringence. Due to the electro-optical effect of anisotropic crystals, the refractive index of the crystal changes the original birefringence properties under the action of an external electric field\([11-12]\). The electro-optic coefficient is a constant that reflects the change in refractive index and quantitatively describes the electro-optic effect of crystals\([13]\).

When light propagates in a crystal, the propagation characteristics are described by the refractive index ellipsoid equation\((1)\):

\[
\frac{x^2}{n_x^2} + \frac{y^2}{n_y^2} + \frac{z^2}{n_z^2} = 1
\]

(1)

Because the KDP crystal is a single crystal axis crystal, so the refractive index of directions \(x\) and \(y\) is \(n_x = n_y = n_o\). The refractive index of direction \(z\) is \(n_z = n_e\). Under the action of an external electric field, the refractive index of the crystal changes, and the constants in the refractive index ellipsoid equation \(n_x, n_y\) and \(n_z\) change. Therefore, when an electric field is applied to the axis \(z\), the refractive index ellipsoid equation becomes:

\[
\frac{1}{(n_x')^2}(x')^2 + \frac{1}{(n_y')^2}(y')^2 + \frac{1}{(n_z')^2}(z')^2 = 1
\]

(2)

Among them, \(n_x', n_y'\) and \(n_z'\) are the changed refractive index. \(n_x'\) and \(n_y'\) are determined by the refractive index \(n_o\) of the light \(o\), light vector \(E_z\) of direction \(z\) and crystal electro-optic coefficient \(\gamma_{63}\):

\[
\begin{align*}
(n_x') &= n_x + \Delta n_x = n_o - \frac{n_o^3}{2} \gamma_{63} E_z \\
(n_y') &= n_y + \Delta n_y = n_o - \frac{n_o^3}{2} \gamma_{63} E_z
\end{align*}
\]

(3)

Figure 1. Light path diagram

As shown in Figure 1, when a beam of light enters the KDP crystal along the axis \(z\) (main optical axis), its light vector \(E\) (electric field strength) is along a certain direction, so the light vector at the
incident surface \( z = 0 \) can be decomposed for two mutually orthogonal components polarized in the directions of \( x' \) and \( y' \), the light waves in the directions of \( x' \) and \( y' \) propagate as follows:

\[
\begin{align*}
E_x' &= A_e e^{ \left[ \omega t - \frac{2\pi}{\lambda} (x_e', z) \right]} \\
E_y' &= A_e e^{ \left[ \omega t - \frac{2\pi}{\lambda} (x_y', z) \right]}
\end{align*}
\] (4)

At the exit end \( z = L \), the two light waves with different polarization directions produce a certain phase difference due to the difference in refractive index. This phase difference is the phase delay, which is recorded as \( \psi \):

\[
\psi = \frac{2\pi}{\lambda} n_o^3 \gamma_{63} E_z L = \frac{2\pi}{\lambda} n_o^3 \gamma_{63} U
\] (5)

Where \( U = E z L \) is the applied voltage along the z-axis. When the phase delay \( \psi = \pi \), the corresponding voltage \( U = \frac{\lambda}{2 n_o^3 \gamma_{63}} \) is the half-wave voltage [14-16].

According to theory, the half-wave voltage is determined by the electro-optic coefficient of crystal, which can be expressed as:

\[
U_{\pi} = \frac{\pi c}{\omega n_o^3 \gamma_{63}} = \frac{\lambda}{2 n_o^3 \gamma_{63}}
\] (6)

According to the production data provided by the manufacturer, at room temperature, when the wavelength of the laser is 532nm, the optical refractive index of light \( o \) through KDP crystal is 1.5129. Substituting it into the formula, the electro-optic coefficient of the KDP crystal can be obtained.

4. Experimental content

The core of the entire experimental device is a cylindrical KDP crystal and a circuit structure for applying a variable voltage on the crystal.

Fig. 2 is a diagram of the optical path device, in which P1 is a polarizer, P2 is an analyzer, and the cylinder represents the KDP crystal, which is fixed by an insulating clamp plate of the optical system.

First step is to turn on the optical power meter, measure the readout of the optical power meter under natural light and zero the readout of the optical power meter. Fix the experimental device according to Figure 2 and adjust the height and coaxiality of the components of the optical group to be the same. Then turn on the laser switch and turn P2 so that the angle between P1 and P2 is 90\(^\circ\). At this time, the readout of the optical power meter should be zero, indicating that the light passes through the crystal.
along the main optical axis. Keep the angle between P1 and P2 unchanged, and apply an external voltage along the z direction to the crystal. As the voltage increases, the readout displayed by the optical power meter increases first and then decreases to the initial value. Continue to increase the voltage, it will repeat the previous phenomenon. When the intensity of the outgoing light reaches the maximum for the first time, the z-direction bias is 1/4 wave voltage. When the intensity of the outgoing light returns to the initial value for the first time, the z-direction bias is a half-wave voltage.

The entire circuit is divided into a voltage regulation part and a voltage output part, and its schematic diagram is shown in FIG. 3. The voltage output part is connected to both ends of the KDP crystal to provide an applied voltage along the axis \( z \). According to the data, the half-wave voltage of the KDP crystal is about 5000–8000V. For this reason, the DC-DC boost module voltage is selected, which is powered by 12V. In the voltage regulation part, the high-voltage output is controlled by a voltage of 0-5V, that is, when the control voltage is 0V, the output of the high-voltage module power supply is 0V, when the control voltage is 5V, the output of the high-voltage module power supply is 15000V, the output voltage and the control voltage Proportional. In order to prevent the KDP crystal from being broken down due to high voltage, a switching power supply with an output of 5V and two sliding rheostats are connected in series, so that the voltage on each sliding rheostat is 2.5V. The control end of the high-voltage module power supply and one of the sliding rheostats form a voltage divider circuit to adjust the voltage across the KDP crystal. The physical connection diagram of the circuit is shown in Figure 4. Using this circuit can ensure that the output voltage of the high-voltage module power supply will not exceed 7500V, which prevents the breakdown of the KDP crystal and also ensures the safety of the experimental operation.

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5. Analysis and discussion

Recording the applied voltage at the maximum light intensity and the minimum light intensity, and substituting it into equation (6), the value of the electro-optic coefficient of the KDP crystal obtained by the solution is shown in Table 1.

| Half-wave voltage (V) | Intensity difference with the initial light (mW) | 1/4-wave voltage (V) | Intensity difference with the initial light (mW) | Electro-optic coefficient \( \gamma_{63} \) (pm/V) |
|----------------------|-----------------------------------------------|----------------------|-----------------------------------------------|-------------------------------------------|
| 6380                 | 0.00                                          | 3158                 | 0.47                                          | 12.04                                     |
| 6400                 | 0.01                                          | 3176                 | 0.49                                          | 12.00                                     |
| 6390                 | 0.01                                          | 3190                 | 0.35                                          | 12.02                                     |
| 6400                 | 0.00                                          | 3227                 | 0.35                                          | 12.00                                     |
| 6390                 | 0.01                                          | 3208                 | 0.35                                          | 12.02                                     |
| 6400                 | 0.00                                          | 3109                 | 0.48                                          | 12.00                                     |
| 6390                 | 0.01                                          | 3149                 | 0.45                                          | 12.02                                     |
It can be seen from Table 1 that when the applied voltage applied in the crystal is a half-wave voltage, the light intensity through the crystal is not 0, but the value is very small. This is mainly because the optical axis of the electro-optic sample does not completely coincide with the direction of the light during the measurement process. As a result, it is approximated to the initial light intensity value of the system, and the difference between the light intensity and the initial state light intensity is recorded. The average value of the electro-optic coefficient of this sample was $12.0143 \times 10^{-12} \text{m/V}$, and the maximum relative deviation was 0.21%. The crystal electro-optic coefficient $\gamma_{63}$ measured by this system is very close to the linear electro-optic coefficient $V_m/10^{11.12} \times 10^{-63}$ of the KDP crystal reported at room temperature in the literature, but the maximum relative deviation of this system is 0.21%. This is caused by the deviation of the measured value of the high-voltage DC power supply selected in the system from the actual output value, and the deviation of the reading of the optical power meter. In addition, the measurement accuracy of the crystal size also affects the measurement accuracy of the system. However, it can be seen from the standard deviation of the electro-optic coefficient that the electro-optic coefficient measurement method in this paper has higher measurement sensitivity.

6. Conclusion

A scheme for measuring the electro-optic coefficient of the crystal based on laser modulation is proposed in this paper. The electro-optic coefficient of the KDP crystal is measured by using the polarization characteristics of the laser. The high-voltage power supply module and low-voltage voltage divider circuit are used to safely control the high voltage required for the experiment. Using the above method, the half-wave voltage and electro-optic coefficient of the KDP crystal can be measured using a laser with a wavelength of 532 nm, which is further extended to measuring the half-wave voltage and electro-optic coefficient of KDP or other electro-optic crystal materials by using lasers of different wavelengths. The experimental device is simple and safe, the cost is relatively low, and the measurement is fast, which provides a feasible method for crystal electro-optic coefficient measurement.

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