Original Research Article

The Influence of Mechanical-angle on the Quartz Filter Features

***Abstract*—In this paper,by using the matrix optics, the transmission of quartz crystal birefringent filter with any direction of incidence angle,azmuth,mechanical rotation angle was derived .Through theoretical simulation obtained the laws of central wavelength and free spectral range of quartz crystal birefringent filter changing with the mechanical-angle .The results show that when rotated around the z-axis of the filter mostly influenced the features of the filter and the transmission spectrum of the designed filter is tested and investigated by using Ultra-6600 spectrophotometer. The experimental results are in good agreement with theoretical results and it is helpful for manufacturing, adjusting and designing of the quartz birefringent filter.**

***Index Terms*—optical devices,crystal optics, mechanical-angle, quartz crystal birefringent filters**

1. Introduction

Birefringent filter is one of the important passive components, including two classic types:Lyot filter[1,2] and Solc filter[3,4],which is widely used in the field of spectral images [5,6],laser tuning[7,8],remote sensing[9], astronomy[10,11], dense wavelength division multiplexing[12]. For a optical ,working in fixed transmission wavelength spectra is very important.For example,in the sunlight observation instrument application, output central wavelength is sensitive to incident angle [13-15] ,in the birefringent filter system ,mechanical stress is inevitable,due to the mechanical stress ,the filter will produce a tiny rotation angle ,thus the accuracy of birefringent filter system decreased,therefore study the function between tiny rotation mechanical-angle and the transmission of the filter is useful for manufacturing, designing and adjusting quartz birefringent filter.

In this paper, the quartz crystal wave plate rotated around the optical axis (x-axis) or y-axis or z-axis ,the spectral outputs of the filter are studied by the way of numerical simulation and experiment researchs in detail,through numerical analysis and experiments research,the changing of the central wavelength and the free spectral range of the filter are investigated by using Ultra-6600 series spectrophotometer in detail, and the results of theory are agreed to the results of experiment very well.

The structure of this paper is that, firstly theoretically analyzed the principle of quartz filter. Secondly, the additional phase of the filter under tiny mechanical-angle is discussed Thirdly,the spectral outputs of the filter with any direction of incidence angle,azmuth,mechanical rotation angle are studied , and analysis the experimental results in detail ,then make a conclusion in the end.

2. Numerical simulation and theory anlysis

A. Basic principle of quartz filter

A typical type optical filter is usually composed of several birefringent polarization devices and several polarizing devicesSchematic diagram of the unipolar filter is shown in figure 1 that consists of polaroids P1,P2 and the quartz plate L,the optical axis of the plate is parallel to its surface[16-17]..

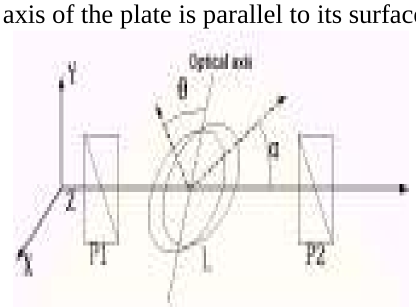

Fig.1 Schematic diagram of the unipolar birefringence filter

Where α is the angle between surface of crystal and the incident light,θ is the azimuth angle,L is the quartz plate.Based on the matrix optics,the Jones matrix of the quartz crystal given by:

$$M_B = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{1}$$

Where each element given by:

$$m_{11} = a_0\left[(1-\frac{\sin\alpha_i}{qn_e^2})\cos^2\theta\exp(\mathrm{i}\,\delta_e + \sin^2\theta\exp(\mathrm{i}\,\delta_0))\right] \tag{2}$$

$$m_{12} = m_{21} = a_0\left\{\sqrt{1-\frac{\sin^2\alpha_i}{qn_e^2}}\sin\theta\cos\theta[\exp(\mathrm{i}\,\delta_e)-\exp(\mathrm{i}\,\delta_o)]\right\} \tag{3}$$

$$m_{22} = a_0\left\{\sin^2\theta\exp(\mathrm{i}\,\delta_e) + \left[1+\frac{\sin^2\alpha_i}{qn_e^2}\right]\cos^2\theta\exp(\mathrm{i}\,\delta_o)\right\} \tag{4}$$

Where $a_0=\left(1-\frac{\cos^2\alpha\sin^2\alpha_i}{qn_e^2}\right)^{-1}\alpha_i$, $q=1-\left(\frac{1}{n_o^2}-\frac{1}{n_e^2}\right)\sin^2\alpha_i\cos^2\theta$, α_i is the incidence angle（$\alpha_i = \pi/2 - \alpha$）, n_e , n_o are the refractive indices of the extraordinary and ordinary of the quartz plate. Based on matrix optics, the transmittance of the filter given by:

$$T = |m_{22}|^2 = 1 - A\sin^2\frac{\delta'}{2} \tag{5}$$

Where $A = \dfrac{q^2 n_e^4 - q n_e^2 \sin^2 \alpha_i}{(q n_e^2 - \cos^2 \theta \sin^2 \alpha_i)^2} \sin^2 2\theta$, $\delta^{'}$ is the total phase delay of the quartz crystal plate with tiny mechanical-angle $\Delta\theta$, δ is the phase delay of the quartz crystal plate without mechanical-angle, $\Delta\delta$ is the additional phase with tiny mechanical-angle $\Delta\theta$,the function of the three given by :

$$\delta^{'} = \delta + \Delta\delta \tag{6}$$

Where

$$\delta = \frac{2\pi d}{\lambda}\left[\frac{\sqrt{n_e^2 n_o^2 - (n_e^2\cos^2\theta + n_o^2\sin^2\theta)\sin^2\alpha_i}}{n_o} - \sqrt{n_o^2 - \sin^2\alpha_i}\right] \tag{7}$$

λ is the wavelength of incident light, d is the thickness of the quartz plate, the additional phase $\Delta\delta$ of the filter with tiny mechanical-angle is discussed.

1).The quartz crystal rotated around the x-axis with tiny mechanical-angle

When the quartz crystal rotated around the x-axis of angle $\Delta\theta$, in the xy_1z_1 coordinate system ,the direction of x-axis did not change,the incidence angle was still α_i , rotation angle changed from θ to $\theta+\Delta\theta$,the total phase delay of the quartz crystal plate given by:

$$\delta_x^{'} = \frac{2\pi d}{\lambda}\left[\frac{\sqrt{n_e^2 n_o^2 - [n_e^2\cos^2(\theta+\Delta\theta) + n_o^2\sin^2(\theta+\Delta\theta)]\sin^2\alpha}}{n_o} - \sqrt{n_o^2 - \sin^2\alpha}\right] \tag{8}$$

and the additional phase give by:

$$\Delta\delta_x = \delta_x^{'} - \delta \tag{9}$$

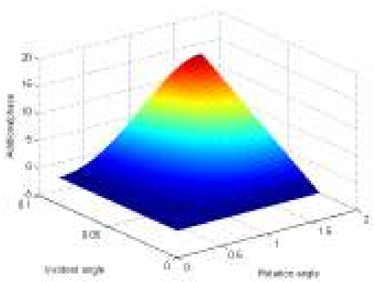

Fig.2 The additional phase $\Delta\delta_x$ of the quartz plate as a function α and $\Delta\theta$ when plate rotated around x-axis

2).The quartz crystal rotated around the y-axis with tiny mechanical-angle

When the quartz crystal rotated around the y-axis of angle $\Delta\theta$,in the x_2yz_2 coordinate system ,the direction of y-axis did not change,the incidence angle was still α_i rotation angle changed from θ to $\theta+\Delta\theta$,the total phase delay of the quartz crystal plate given by:

$$\delta_y^{'} = \frac{2\pi d}{\lambda}\left\{\frac{\sqrt{n_e^2 n_o^2 - n_e^2(\cos^2\theta\sin^2\alpha + n_o^2(\cos\alpha\sin\Delta\theta - \sin\alpha\sin\theta\cos\Delta\theta)^2}}{n_o} - \sqrt{n_o^2 - [(\cos\alpha\sin\Delta\theta - \sin\alpha\sin\theta\cos\Delta\theta)^2 + (\sin\alpha\cos\theta)^2]}\right\} \tag{10}$$

and the additional phase give by:

$$\Delta\delta_y = \delta_y^{'} - \delta \tag{11}$$

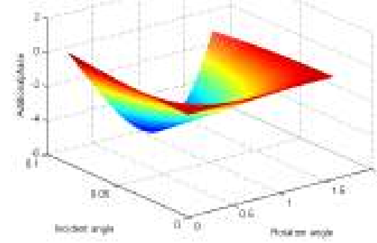

Fig.3 The additional phase $\Delta\delta_y$ of the quartz plate as a function α and $\Delta\theta$ when plate rotated around y-axis

3).The quartz crystal rotated around the z-axis with tiny mechanical-angle

When the quartz crystal rotated around the y-axis of angle $\Delta\theta$,in the x_3y_3z coordinate system ,the direction of y-axis did not change,the incidence angle was still α_i rotation angle changed from θ to $\theta+\Delta\theta$,the phase delay of the quartz crystal plate given by:

$$\delta_z^{'} = \frac{2\pi d}{\lambda}\left\{\frac{\sqrt{n_e^2 n_o^2 - n_e^2(\cos\alpha\sin\Delta\theta + \sin\alpha\cos\theta\cos\Delta\theta)^2 + n_o^2(\sin\alpha\sin\theta)^2}}{n_o} - \sqrt{n_o^2 - [(\cos\alpha\sin\Delta\theta - \sin\alpha\sin\theta\cos\Delta\theta)^2 + (\sin\alpha\cos\theta)^2]}\right\} \tag{12}$$

and the additional phase give by:

$$\Delta\delta_z = \delta_z^{'} - \delta \tag{13}$$

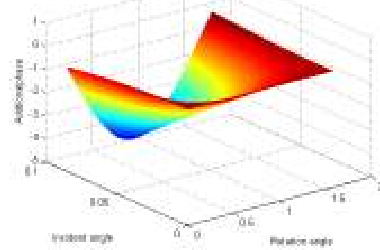

Fig.4 The additional phase $\Delta\delta_z$ of the quartz plate as a function α and $\Delta\theta$ when plate rotated around z-axis.

Thus the transmittance of the emergent light given by:

$$T = 1 - A\sin^2\frac{\delta + \Delta\delta}{2} \tag{14}$$

From formula(14)we can see that a certain wavelength λ of incident light, corresponding to a certain phase delay δ , we take a corresponding value δ ,can maximum value T ,for different wavelength value λ ,we need to change the $\Delta\delta$ in order to maximum value T ,and the output of quartz plate changed.

B. Numerical simulation analysis

Figure 3 show the theoretical transmission versus wavelength with different directions tiny mechanical angle with the wavelength range of 580~600nm.The thickness of quartz is 7mm the parameter of quartz used as follows: n_e , n_o are 1.55335 and 1.54424 [11] , α_i is 4^o , θ is 45^o ,the rotation angle $\Delta\theta$ is 3^o ,curve1 ,curve2, curve3, curve4 are the theoretical transmission curves with the same rotation angle

$\Delta\theta = 3^o$ that rotated around the z-axis , rotated around the y-axis, rotated around the x-axis, and without rotation angle.

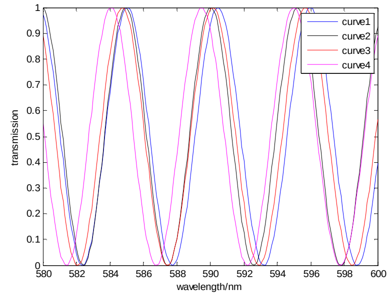

Fig.5 The simutation resules with tiny mechanical-angle at different axial directions

Form Figure 5 ,we can see that when the incidence angle $\alpha = 4^o$,the azimuth angle $\theta = 45^o$,and the quartz crystal rotated around the x-axis with tiny mechanical-angle $\Delta\theta = 3^o$,the central wavelength changed to shorter wavelength for about 0.1nm, the quartz crystal rotated around the y-axis with tiny mechanical-angle $\Delta\theta = 3^o$,the central wavelength changed to a shorter wavelength for about 0.3nm，the quartz crystal rotated around the z-axis with tiny mechanical-angle $\Delta\theta = 3^o$,the central wavelength changed to a longer wavelength for about 0.9nm.

Figure 6 show the curve between the mechanical-angle and FSR of the filter. The thickness of quartz is 7mm, α_i is 4^o , θ is 45^o, rotation angle $\Delta\theta = 0^o$: $+3^o$ .From figure 6 we can see that the quartz crystal rotated around the x-axis, y-axis,z-axis ,the maximum offsets of the free spectral range(FSR) are -0.001nm,0.003nm,0.009nm,the deviations are -0.02%, 0.05% 0.16%, we can conclude that when $\Delta\theta = 0^o$: $+3^o$,rotated around the z-axis mostly influence the FSR of the filter.

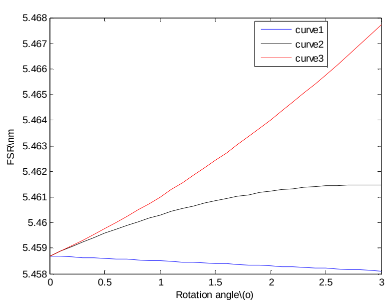

Fig.6 A The FSR of the filter as a function $\Delta\theta$ when $\alpha = 4^o, \theta = 45^o$

Figure 7 show the curve between the mechanical-angle and the central wavelength of the filter The thickness of quartz is 7mm, α_i is 4^o , θ is 45^o, the rotation angle $\Delta\theta = 0^o$: $+3^o$. From figure 4 we can see that the quartz crystal rotated around the x-axis, y-axis,z-axis the maximum offsets of the center wavelength are 0.1 nm,-0.3nm,-0.9nm,the deviations are 0.02% , -0.05% ,-0.15%,we can know that when $\Delta\theta = 0^o$: $+3^o$,rotated around the z-axis mostly influence the central wavelength of the filter. Therefore, by changing crystal obliquity angle can tune the central wavelength of the birefringent filter.

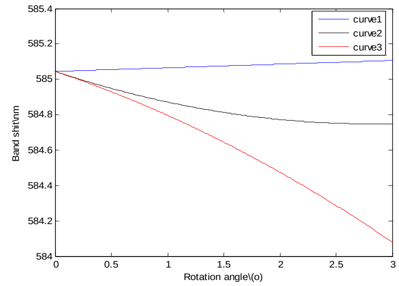

Fig. 7 The central wavelength of the filter as a function $\Delta\theta$ when $\alpha = 4^o, \theta = 45^o$

3. Experimental results and discussion

In order to verify the correctness of the above theory, the experimental system is set up by using Ultra-6600 spectro photometer with 0.1nm sweeping step and 190nm to 900nm sweeping range , and received the transmission spectrum of quartz birefringent filter .The transmission spectrum measure -ment system framework shown in figure.5.

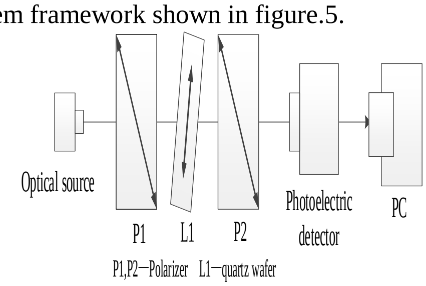

Fig.8 The structure of the measurement system

The thickness of quartz plate used in the test is 7mm, the incidence angle is about $\alpha = 4^o$,the azimuth angle is about $\theta = 45^o$,the transmission curves of quartz birefringent filter are shown in figure 9, the spectral range is 580~600nm,the spectral resolution is 0.1nm,curve1, curve2, curve3,curve4 are the transmission curves with the same rotation angle $\Delta\theta = 3^o$ that rotated around the z-axis , rotated around the y-axis, rotated around the x-axis,and without rotation angle.

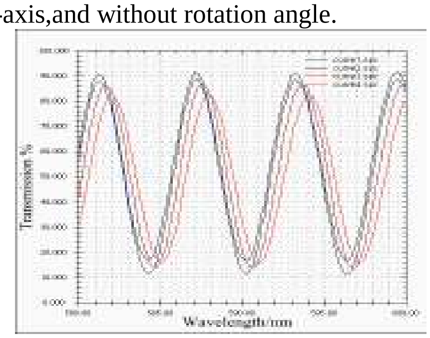

Fig.9 The results of the experiment

We can find the results of experiment are very similar to the results of figure 5 botained by numerical simulation.The experimental results show that : a). the central wavelength of quartz filter changed to a shorter wavelength for about 0.2nm,0.4nm,0.9nm with the same rotation angle of $\Delta\theta = 3^o$ when rotated around x-axis,y-axis,z-axis (theoretical values are 0.1 nm, 0.3nm, 1nm),the experiment results are in good agreement with the theoretical simulations,we believe that the presence of small differences are due to the thickness error of the measurement and the mechanical angle error. b).The maximum transmission value of the filter is about 92%, we believe that this is due to the scattering of quartz plate and the absorption of polarizer. c).The minimum transmission value of the filter is about 10%, we believe that this is due to the extinction ratio of the polarizers are not high and the angle between the polarizer and the crystal is not strictly 45^{o}.

4. Conclusion

By using the matrix optics, the transmission of quartz birefringent filter with any direction of incidence angle,azmuth,mechanical rotation angle,through computer programming simulation.the transmission spectrum of quartz birefringent filter with tiny mechanical-angle is investigated in detail, the experimental results verify the correctness of the theories, the results show that when rotated around different axises the outputs of the quartz filter are different, the offset is related to the direction of rotation, rotated around z-aixs mostly influence the the quartz filter features.It will has a certain application in stability output of optical filter when tiny mechanical-angle acts on filter .As a result ,by changing crystal obliquity angle can tune the center wavelength of the birefringent filter.The results can be useful for constructing high-performance birefrigent filter.

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