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The Influence of Mechanical-stress on the Quartz Filter Features

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

In order to study the effect of mechanical-stress on the quartz filter output, based on the elasto-optical effect of quartz crystal, the relationship between berifringent difference of quratz plate and mechanical-stress is deduced, the experimental system is set up by using Ultra-6600 UV spectrophotometer, and received the transmission spectrum of Lyot quartz birefringence filter, the transmission spectrum was investigated theoretically and experimentally in detail. The results show that when applied different mechanical stresses, the center wavelength of quartz birefringent filter changed, and the drifting direction of the center wavelength is related to the size of applied mechanical stress, the drifting size of the center wavelength is related to the direction of applied mechanical stress. It is helpful for the manufacturing, correct design and application of quartz birefringence filter.

Keywords: Optical devices; mechanical-stress; elasto-optical effect; quratz crystal berifringent filters.

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1. INTRODUCTION

Spectral imaging has been widely used in the fields of medical research [1,2], laser tuning [3,4], remote sensing [5,6], art painting reproduction, agriculture, astronomy [7,8] and dense wavelength division multiplexing [9,10]. In principle, there are two main methods for spectral selection, the one is a diffraction method and the other is an interference method [11,12].

Each method has theirs own advantages. Compared to other methods, the selection of a single wavelength can be easily realized by diffraction grating, and it has a high resolution, however, large volume, low efficiency, sensitive to polarization, and no ability for two-dimensional imaging are its shortage at the same time. Interference filters such as thin film interference filters, has a compact construction, but it provides a lower resolution, and it is difficult to achieve the particular wavelength selection. Birefringence filter has the capability of two-dimensional imaging, is easy to be adjusted, suitable for the specific polarization incident light and for large field angle imaging requirements. Moreover, quratz crystal berifringent filters have many characters such as tunability, flexible and simple structure, narrow band width and wide field of incidence so it has been extensively investigated [13-16].

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 stress. The analysis of stress effect on the output characteristic of the quartz birefringence filter has not still been reported to our knowledge. We investigate theoretically and experimentally this property in detail in this paper, the result of theory is agreed to the result of experiment very well.

2. NUMERICAL SIMULATION AND THEORY ANALYSIS

2.1 Basic Principle of Quartz Filter

A typical type optical filter is usually composed of several birefringence polarization devices and several polarizing devices. Schematic diagram of the Lyot filter is shown in Fig. 1 consist of polaroids P1,P2 and the quartz plate S, The azimuth angle between the polarization plane of P1 and the optical axis of the quartz plate is 45°, which as the same as P2, the optical axis of the plate is parallel to its surface.

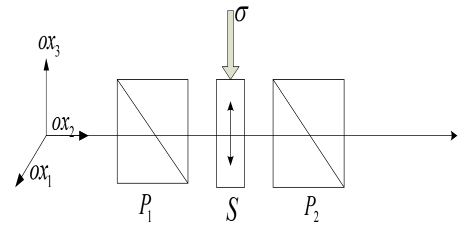

Fig. 1. The schematic diagram of the unipolar Loyt filter

The phase delay of incident light generated in the quartz crystal plate given by:

$$\delta = \frac{2\pi}{\lambda} \cdot \Delta n \cdot d \tag{1}$$

Where λ is the wavelength of incident light , Δn is refractive index difference, d is the thickness of the quartz wafer, the transmittance of the emergent light given by:

$$T = \cos^2(\frac{\delta}{2}) \tag{2}$$

The quartz crystal belongs to the crystal system ($3m, 32, \bar{3}m$) of trigonal system [17]. Without applying stress to the quartz filter, the optical indicatrix equation of quartz given by:

$$\beta_1^0 x_1^2 + \beta_2^0 x_2^2 + \beta_3^0 x_3^2 = 1 \tag{3}$$

$$\beta_1^0 = \beta_2^0 = \frac{1}{n_e^2}, \beta_3^0 = \frac{1}{n_o^2} \tag{4}$$

Where β_i^0 ($i = 1, 2, 3$) is inverse dielectric tensor of quartz, n_e, n_o are the refractive index of the extraordinary and ordinary of the quartz plate.

1). Applied mechanical stress σ_3 paralleled to the optical axis ox_3 to the quartz plate, elastic-optic coefficient matrix of quartz given by:

$$\begin{bmatrix} \Delta\beta_i \\ \Delta\beta_2 \\ \Delta\beta_3 \\ \Delta\beta_4 \\ \Delta\beta_5 \\ \Delta\beta_6 \end{bmatrix} = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{13} & \pi_{14} & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{13} & -\pi_{14} & 0 & 0 \\ \pi_{31} & \pi_{31} & \pi_{33} & 0 & 0 & 0 \\ \pi_{41} & -\pi_{41} & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 2\pi_{41} \\ 0 & 0 & 0 & 0 & \pi_{14} & (\pi_{11}-\pi_{12}) \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \sigma_3 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

Where $\pi_{ij}\,(\mathrm{i},\mathrm{j}=1,2,3,4,5,6)$ is elasto-optical coefficient, $\Delta\beta_j\left(\mathrm{j}=1,2,3,4,5,6\right)$ is the variation of inverse dielectric tensor, we can learn:

$$\begin{cases}\beta_1=\beta_1^0+\Delta\beta_1=\dfrac{1}{n_e^2}+\pi_{13}\sigma_3\\ \beta_2=\beta_2^0+\Delta\beta_3=\dfrac{1}{n_e^2}+\pi_{13}\sigma_3\\ \beta_3=\beta_3^0+\Delta\beta_3=\dfrac{1}{n_o^2}+\pi_{33}\sigma_3\\ \beta_4=\beta_5=\beta_6=0\end{cases} \quad (6)$$

The optical indicatrix equation of quartz has changed to:

$$\left(\frac{1}{n_e^2}+\pi_{13}\sigma_3\right)(x_1^2+x_2^2)+(\frac{1}{n_o^2}+\pi_{33}\sigma_3)=1 \quad (7)$$

The three main refractive indices give by:

$$\begin{cases}n_1=n_2=n_e-\dfrac{1}{2}n_e^3\pi_{13}\sigma_3\\ n_3=n_0-\dfrac{1}{2}n_0^3\pi_{33}\sigma_3\end{cases} \quad (8)$$

The refractive index difference given by:

$$\Delta n_3=(n_e-n_o)-\frac{1}{2}(n_e^3\pi_{13}-n_o^3\pi_{33})\sigma_3 \quad (9)$$

2). Applied mechanical stress σ_1 paralleled to the axis ox_1 to the quartz plate, The optical indicatrix equation of quartz given by:

$$(\frac{1}{n_e^2}+\pi_{11}\sigma_1)\;x_1^2+(\frac{1}{n_e^2}+\pi_{12}\sigma_1)x_2^2+(\frac{1}{n_o^2}+\pi_{31}\sigma_1)\;x_3^2+2\pi_{41}\sigma_1x_2x_3=1 \quad (10)$$

Where the cross terms emerge, we should seek new principal axis direction and proceed principal axis transformation. The figure of transformation shown in Fig. 2.

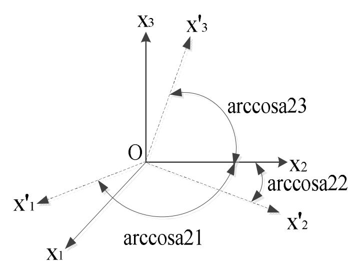

Fig. 2. The figure of coordinate system transformation

Where a_{ij} ($i,j=1,2,3$) are the direction cosine between the new i coordinate and the old j coordinate. The coordinate transformation matrix given by:

$$a_{ij}^{'}=\begin{bmatrix}\cos\theta_1 & \sin\theta_1 & 0\\ -\sin\theta_1 & \cos\theta_1 & 0\\ 0 & 0 & 1\end{bmatrix} \quad (11)$$

θ_1 is determined by:

$$\tan 2\theta_1=\frac{2\pi_{41}\sigma_1}{(\frac{1}{n_0^2})\;-(\frac{1}{n_e^2})} \quad (12)$$

The new optical indicatrix equation of quartz given by:

$$(\frac{1}{n_e^2}+\pi_{11}\sigma_1)\;x_1^{'2}+(\frac{1}{n_e^2}+\pi_{12}\sigma_1+\pi_{41}\sigma_1\tan\theta_1)x_2^{'2}+(\frac{1}{n_o^2}+\pi_{31}\sigma_1-\pi_{41}\sigma_1\tan\theta_1)\;x_3^{'2}+2\pi_{41}\sigma_1x_2x_3=1 \quad (13)$$

The refractive index difference given by:

$$\Delta n_1=n_2-n_3=(n_e-n_o)-\frac{1}{2}n_e^3\sigma_1(\pi_{11}-\pi_{31}+\pi_{41}\tan\theta_1) \quad (14)$$

3). Applied mechanical stress σ_2 paralleled to the axis ox_2 .

Through coordinate conversion, we can acquire the refractive index difference given by:

$$\Delta n_2 = n_1 - n_3 = (n_e - n_o) - \frac{1}{2} n_e^3 \sigma_2 (\pi_{12} - \pi_{31} + \pi_{41} \tan\theta_2) \quad (15)$$

θ_2 is determined by:

$$\tan 2\theta_2 = \frac{-2\pi_{41}\sigma_2}{\left(\frac{1}{n_0^2}\right) - \left(\frac{1}{n_e^2}\right)} \quad (16)$$

As discussed above, when applied stress σ_1 to the quartz plate paralleled to the axis, combine (2) and (14) can acquire the transmittance of the emergent ligh given by:

$$T_1 = \cos^2\left\{\frac{\pi}{\lambda} \cdot d \cdot \left[(n_e - n_o) - \frac{1}{2} n_e^3 \sigma_1 (\pi_{11} - \pi_{31} + \pi_{41} \tan\theta_1)\right]\right\} \quad (17)$$

When applied stress σ_2 to the quartz plate paralleled to the axis ox_2, combine (2) and (15) can acquire the transmittance of the emergent ligh given by:

$$T_2 = \cos^2\left\{\frac{\pi}{\lambda} \cdot d \cdot \left[(n_e - n_o) - \frac{1}{2} n_e^3 \sigma_2 (\pi_{12} - \pi_{31} + \pi_{41} \tan\theta_2)\right]\right\} \quad (18)$$

When applied stress to the quartz plate paralleled to the optical axis σ_3, combine (2) and (9) can acquire the transmittance of the emergent ligh given by :

$$T_3 = \cos^2\left\{\frac{\pi}{\lambda} \cdot d \cdot \left[(n_e - n_o) - \frac{1}{2}(n_e^3 \pi_{33} - n_o^3 \pi_{13})\sigma_3\right]\right\} \quad (19)$$

From formulas (17), (18) , (19) 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 of incident light ,we need to change the stress value σ in order to maximum value T ,and the output of quartz plate changed.

2.2 Numerical Simulation Analysis

Fig. 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 $\pi_{13} = 0.27, \pi_{33} = 0.1$ curve1, curve2, curve3, curve4 are the theoretical transmission curves that without stress and applied mechanical stress paralleled to the ox_1, ox_2, ox_3 axis with the size of 0.00025N/m^2.

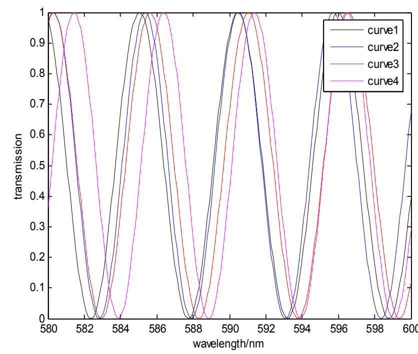

Fig. 3. Transmittance curves that without stress and applied mechanical stress paralleled to the ox_1, ox_2, ox_3 axis with the size of 0.00025N/m^2

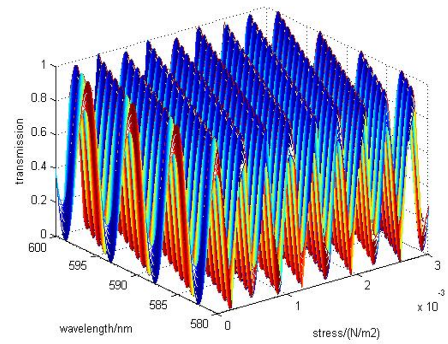

Fig. 4. The transmission of the filter as a function stress along axis ox_1

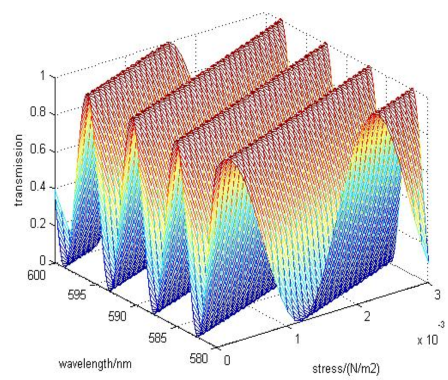

Fig. 5. The transmission of the filter as a function stress along optical axis ox_2

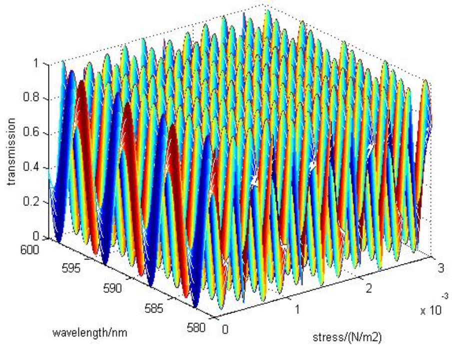

Fig. 6. The transmission of the filter as a function stress along optical axis ox_3

Form Fig. 3, we can see that when applied mechanical stresses paralleled to the ox_1, ox_2, ox_3 axis with the same size of 0.0025N / m^{2}the central wavelength will change to longer wavelength for about 0.4nm,0.6nm,1.2nm. Form Fig. 4 to Fig. 6 we can know that the direction of the center wavelength drifting is related to the size of applied mechanical stress, the drifting size of the center wavelength is related to the direction of applied mechanical stress, and the mechanical stress along the optics axis mostly influence the output features of the filter. We can change the size of mechanical stress to adjust the center wavelength drift of filter.

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 UV spectrophotometer with 0.1nm sweeping step and 190nm to 900nm sweeping range, and received the transmission spectrum of quartz birefringence filter. The structure of the transmission spectra mearsure system Fig. 7.

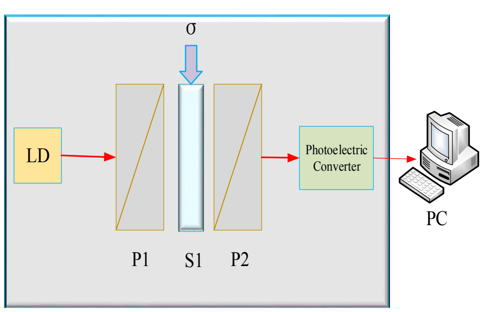

Fig. 7. The structure of the mearsure system

Where P_1,P_2 are polaroids and S_1 is the quartz plate, the optical axis of the plate is parallel to its surface, the azimuth angle is 45^o ,we can know that P_1 S_1,P_2 consist a typical Loyt filter, LD Lyot filter and optoelectronic converter formed the UV spectral measurement system The thickness of quartz wafer used in the test is 7mm.Applied the mechanical stress of specified axial to the quartz wafer by using weight and stress tester, the transmission curve obtained of Lyot quartz birefringent filter is shown in Fig. 8, the spectral range is 580~600nm, the spectral resolution is 0.1nm, curve1, curve2, curve3, curve4 are the transmission curves with the same stress of 0.00025N/m^2. that without stress and applied mechanical stress paralleled to the ox_1, ox_2, ox_3 axis.

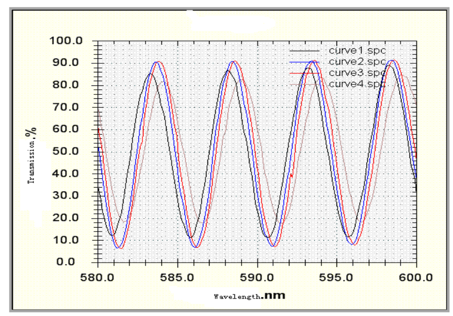

Fig. 8. The results of the experiment

We can find the results of experiment are very similar to the results of Fig. 5 botained by numerical simulation. The experimental results show that : a). the central of quartz filter will change to a longer wavelength for about 0.4nm,0.6nm,1nm with the same stress of 0.00025N/m^2 (theoretical values are 0.4 nm, 0.6nm, 1.2nm), 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 stress error. b). The maximum transmittance value of the filter is about 92%, we believe that this is due to the scattering of quartz wafer and the absorption of polarizer. c). The minimum transmittance value of the filter is about 10%, we believe that this is due to the extinction ratio of the polarizers is not high and the angle between the polarizer and the crystal is not strictly 45^o.

4. CONCLUSION

In this paper, based on the elasto-optical effect of quartz crystal, the transmission spectrum of quartz birefringence filter under stress is investigated in detail through numerical simulation and experiment research, the experimental results verify the correctness of the theories, the results show that the center wavelength of quartz birefringent filter change, and the drifting direction of the center wavelength is related to the size of applied mechanical stress to quartz birefringent filter, the offset is related to the direction of mechanical stress. This will has a certain application in stability output of optical filter when stress acts on filter and is helpful to correct design and application of quartz birefringence filter.

NOTE

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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