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The transfer matrix of the acousto-optic tunable filter

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A characteristic matrix is presented to describe an acousto-optic tunable filter (AOTF). An orthogonal polarizing optical method based on the matrix is developed to improve the spectral purity in the spectral measurement, which use an AOTF as an optical splitting system. An experiment is performed to validate the orthogonal polarizing method.

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1. Introduction

In recent years, AOTF has been very attractive because it offers fast tuning speed, broad filtering bandwidth, large angular aperture [1-5], especially for a fast growing near-infrared spectral monitoring, such as, a spectral discrimination of composition in the food industry, an on-line analysis of component in the chemical industry, a non-invasive measurement of blood sugar in the medicine [6-11], in which, an AOTF decides the key performances of the system as an optical splitting system. A design of the system is always desired to have higher spectral resolution and signal-to-noise ratio (SNR) in order to pick up more feeble information. Hence, an analytical model about AOTF will be very important as the key component of near-infrared spectral measurement.

However, although there are a lot of theory methods about AOTF [1-5,12-15], there is few method to describe an AOTF in the near-infrared spectral measurement. In this paper, a characteristic matrix is presented to design and analyze an AOTF. Based on it, a method is developed for the spectral measurement. And, an experiment is performed to validate the method.

2. The characteristic matrix of AOTF

The structure of AOTF is as shown in Fig. 1, which consists of a crystal and a transducer bonded on it. The transducer converses the electric signal to supersonic oscillation in crystal, which induces the spatial periodic modulation. When the Bragg diffraction condition is satisfied, the incident light produces Bragg diffraction. The wavelength of the diffraction is corresponding to the frequency of driven electric signal, therefore, changing the frequency can alter wavelength.

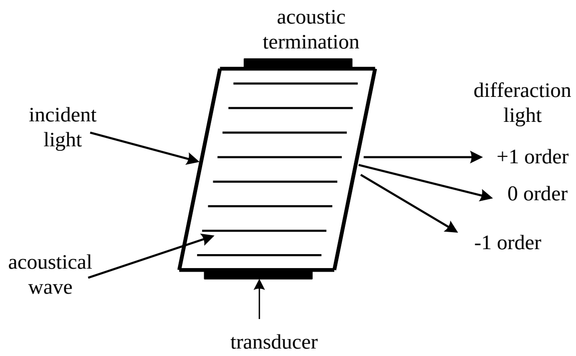


Fig. 1. The sketch of AOTF.

As an optical splitting device, AOTF is classically abnormal Bragg diffraction, which can change the polarization state of the incident light, i.e. if the ordinary light is incident, then the extraordinary light is emergent, on the contrary, the extraordinary light is incident, the ordinary light exits, and if the natural light is incident, the polarized light is emergent. It works in a similar way to the function of a combination of a linear polarizer and a 1/2 wave plate.

Under the condition of Bragg diffraction condition satisfied (momentum matching condition satisfied), zero-order-light incident diffracts and one-order diffraction light generates (the other diffraction light is too weak). One-order diffraction efficiency can express as the followed:

$$\eta = \sin^2(\frac{\xi}{2}), \xi = -\frac{2\pi}{\lambda_0}\Delta nL \tag{1}$$

where $\Delta n = -\frac{1}{2}(n_i n_d)^{3/2} ps$, n_i is the refractive index of the incident light, n_d is the index of the diffraction light.

Based on above analysis, actually, we can express the function of an AOTF using a matrix. The characteristic matrix of an AOTF is equal to the Miller matrix of linear polarizer multiplied in inverted sequence by that of 1/2 wave plate:

$$M = \eta \cdot M(\text{1/2 wave plate}) \cdot M(\text{linear polarizer}) + (1-\eta) \cdot M(\text{linear polarizer}) \tag{2}$$

where the coefficients stand for the energy variation, the first item of the right part of equ. (2) is the diffraction light, and the second of the right part of equ. (2) is the zero-order-light that don't diffract.

Hence, we can get the characteristic matrix of the AOTF as followed:

$$M = \frac{1}{2}\eta \begin{bmatrix} 1 & c_2 & s_2 & 0 \\ -A & -c_2 A & -s_2 A & 0 \\ -B & -c_2 B & -s_2 B & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} + \frac{1}{2}(1-\eta) \begin{bmatrix} 1 & c_2 & s_2 & 0 \\ c_2 & c_2^2 & c_2 s_2 & 0 \\ s_2 & c_2 s_2 & s_2^2 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{3}$$

where: $A=c_2c_4+s_2s_4$, $B=c_2s_4-c_4s_4$, $c_2=\cos(2\alpha)$, $c_4=\cos(4\alpha)$, $s_2=\sin(2\alpha)$, $s_4=\sin(4\alpha)$, α is the angle between the polarizing direction and the horizontal direction

As shown in Equ. (3), we can use the characteristic matrix of AOTF to show the variation of the polarization state and the energy of the incident light through the AOTF.

3. The orthogonal polarizing based on the AOTF optical splitting system

3.1 The transfer matrix of the system

As discussed above, when the incident light passes through the AOTF optical splitting system, actually, zero-order-light coexists with diffraction light, thus zero-order-light can also be receipted by the photo electrical sensor because the diffraction angle is very small, which leads to the reduced resolution of the spectral measurement. Hence, how to reject the zero-order-light in the sensor becomes a key problem to improve the separate purity and efficiency of transmitted light, consequently improving the system resolution?

According to the orthogonal polarizing characteristic of incident light and diffractive light of abnormal Bragg diffraction AO interaction, orthogonal polarizing method (as shown in Fig. 2) is adopted to get rid of the zero order light. This method will reduce the light intensity of diffractive light, but it can efficiently erase zero order light and imp rove the spectrum SNR.

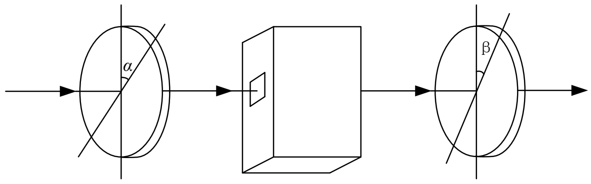


Fig. 2. Orthogonal polarzing method.

Firstly, we will analyze the orthogonal polarizing method theoretically using the characteristic matrix of AOTF. Assuming the angle between transmitting direction of polarizer and the x-axis is 0, the angle between transmitting direction of analyzer and the x-axis is α, the absorption coefficients of the polarizer and the analyzer are σ_1, σ_2, respectively.

So, the characteristic matrix of the orthogonal polarizing method can be expressed as followed:

$$M = M(analyzer) \cdot M(AOTF) \cdot M(ploarizer) \tag{4}$$

That is:

$$M = \frac{1}{2}\sigma_1\sigma_2\eta \begin{bmatrix} 1-c_2 & 1-c_2 & 0 & 0 \\ c_2-c_2^2 & c_2-c_2^2 & 0 & 0 \\ s_2-s_2^2 & s_2-s_2^2 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} + \frac{1}{2}\sigma_1\sigma_2(1-\eta) \begin{bmatrix} 1+c_2 & 1+c_2 & 0 & 0 \\ c_2+c_2^2 & c_2+c_2^2 & 0 & 0 \\ s_2+s_2^2 & s_2+s_2^2 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

where the first item of equation (5) is the diffraction light, the second of equation (5) is the zero-order-light.

From Equ. (5), in order to erase the zero-order-light, we should let the second item is equal to zero, which means $c_2=1$. And, $c_2=\cos(2\alpha)$, hence, we can get $\alpha=\pi/2$. Therefore, when the angle between the transmission direction of the analyzer and the x-axis is 90°, this can effectively reduce the zero-order-light, improve resolution and SNR.

3.2. The experimental results

In order to validate the orthogonal polarizing method, an experiment is performed (as shown in Fig. 3). One beam of natural light was introduced to a polarizer, and interacted in the AOTF system, then it was detected by Spectrum GX FT-IR.

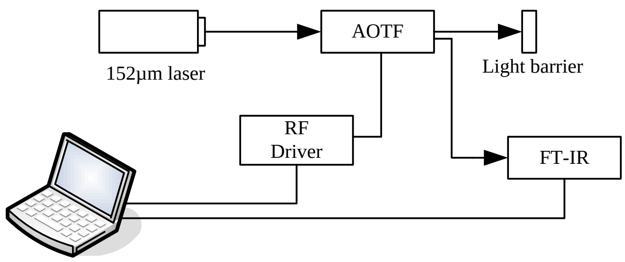
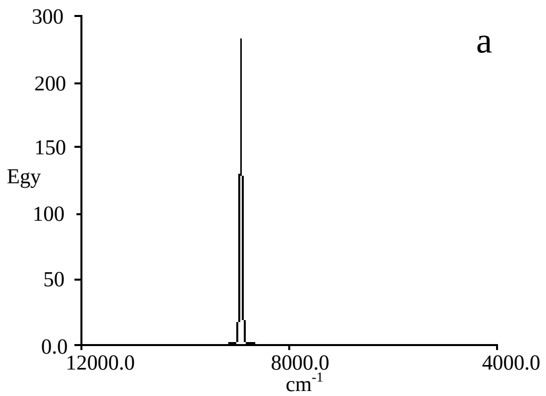
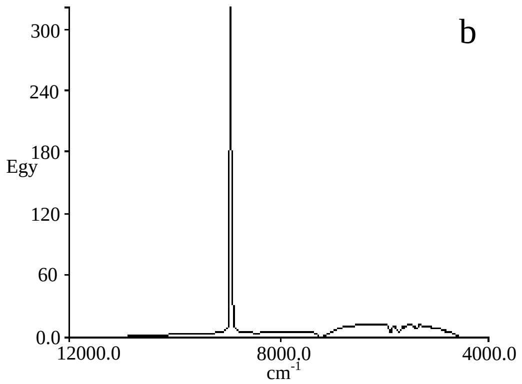


Fig. 3. Setup of experiment for diffraction efficiency of AOTF.

Fig. 4 shows the experimental results. Fig. 4(a) shows the results using the method, Fig. 4(b) shows the results without the method. It can be observed that this method reduces effectively the influence of zero-order-light, improve the resolution and the SNR. However, we can see this effect is gained as the sacrifice of the light intensity, which lowers the utilization ratio. There is a tradeoff between the utilization ratio and the SNR.



(a) adopting this method



(b)not adopting this method

Fig. 4. Effect of rejecting zero order light with orthogonal polarizing method.

4. Conclusion

In this paper, a matrix theory has been presented to analyze the AOTF. Furthermore, an orthogonal polarizing method based on the AOTF as an optical splitting system has been presented in theory and experiment to improve the spectral purity in spectral measurement.

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