Efficient double-filtering with a single acousto-optic tunable filter

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Abstract: We describe an efficient double-filtering method that uses a single acousto-optic tunable filter (AOTF) to improve the spectral resolution and intrinsic sidelobes for the spectral domain analysis systems. Double filtering with a single AOTF is realized by applying a unique feedback scheme based on the fact that incident light can be diffracted into two orthogonally polarized beams of light by an AOTF. Our theoretical explanation attempts to address and satisfy the main prerequisite for the proposed idea. The experimental results confirm that the proposed method achieves a 20% to 30% improvement in spectral resolution and 10 dB suppression of sidelobes with minimized light loss for the extraordinary incident light. We believe that the results of using an AOTF are comparable to the results achieved with two AOTFs in tandem.

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References and links

1. Introduction

Ever since the first studies on the background theory of the TeO₂-based non-collinear mode AOTF [1,2], the AOTF has been widely used in spectral and polarimetric imaging analysis because it enables the use of a large angular aperture and generates orthogonally polarized light with a rapid wavelength tuning capability [3-5]. Furthermore, when an AOTF is adapted to an interferometer, a tomographic thin-film thickness profile can be measured through a full-field spectral domain analysis [6,7].

The performance of an AOTF is characterized mainly by the wavelength tuning range, the spectral resolution, and the sidelobes. Researchers have tried to improve those features [8-10]. In spectral imaging applications, the spectral resolution is considered a key evaluation index of performance and related to the TeO₂ crystal design parameters, such as the optical wavelength and the length of the piezoelectric transducer. However, the enhancement of the spectral resolution is limited if we confine ourselves to the above-mentioned factors. Researchers have attempted to enhance the spectral resolution through “double filtering” based on two AOTFs in tandem [11]. The spectral resolution of an AOTF has a sinc² function; a second successive filtering process elicits a sinc⁴ function, which produces enhanced spectral resolution and suppressed sidelobes [12]. Instead of operating two AOTFs in series, some researchers have reported a double-filtering method based on a single AOTF; in this method, the diffracted light reenters the medium of interaction and is diffracted for a second time [13]. In a similar manner, Yaqoob and Riza reported a double-pass retroreflective mode that increases the sound-light interaction length by a factor of 2 [14].

In this letter, extending our previously reported research [15], we introduce an efficient double-filtering method that improves the spectral resolution and suppresses the sidelobes; the method involves an optical setup based on the unique feedback scheme with a single AOTF. We provide a detailed description of the system setup and its background theory. To confirm the feasibility of the proposed double-filtering method, we compare experimental results with the simulation results.

2. The double-filtering method with a single AOTF

Due to birefringence, randomly polarized incident light is divided inside the crystal into ordinary and extraordinary polarized light. Incident light interacts with the acoustic waves generated by the piezoelectric transducer attached to the crystal. The transducer creates sinusoidal modulation of the refractive index inside the crystal. As shown in Fig. 1(a), each polarized light is diffracted and changes its polarization by means of acousto-optic (A-O) interaction. Aside from the fact that the polarization of each diffracted light from the AOTF is orthogonal, the wavelengths differ slightly for a given acoustic frequency, \( f \). Thus, the tuning relation between the input, \( f \), and the central wavelengths of the diffracted light, \( \lambda_e \) and \( \lambda_o \), is generally not exactly the same as the relation described in the following equation and shown in Fig. 1(b) [16]:
Optic Axis

TeO$_2$

Index Ellipsoid

\( \theta_i \)

\( \theta_d \)

\( e \)

\( \theta_d \)

\( o \)

ka

\( \gamma \)

ki

kd

\( \gamma \)

\( \xi \)

\( \eta \)

\( \kappa \)

\( \lambda \)

\( f \)

\( \delta \)

\( \theta \)

\( r \)

\( n_o \)

\( n_e \)

\( B_e \)

\( B_o \)

\( C_o \)

\( C_e \)

\( D_o \)

\( D_e \)

\( i = o \) or \( e \) denotes the incident polarization. \( n_o \) and \( n_e \) are, respectively, the ordinary (o) and extraordinary (e) refractive indices of the crystal. The incident angle, \( \theta_i \), is the angle between the incident light and the optic axis of the crystal. \( \theta_o \) and \( \theta_e \) are the polar angles for the o- and e-polarized beams and \( \gamma \) is the acoustic angle.

The schematic setup of the proposed double-filtering method is described in Fig. 2. Any incident light that is polarized to an extraordinary state passes through a polarizing beam splitter and enters the AOTF. The light, which is diffracted and separated downward by A-O interaction, changes its polarization to the ordinary state. Its wavelength is determined by the acoustic frequency, \( f \), as defined in Eq. (1). The diffracted ordinary light is reflected by two mirrors and a polarizing beam splitter then reenters the AOTF. Finally, the ordinary light is diffracted again by the AOTF to the extraordinary state and separated upwards to be measured by a detector (double filtering). The light that is fed back to the AOTF should be accurately aligned so that the same incident angle is preserved.

### Fig. 1.
(a) Acousto-optic interaction inside a TeO$_2$ crystal; (b) theoretical \( f-\lambda \) relation for the orthogonally polarized light diffracted by an AOTF with experimental data

\[
 f_i = \left( V_e B_e / \lambda \right) \left[ C_z \pm \left[ C_{1} \mp \left[ C_{2} \mp \left[ n_e / n_o \right] - 1 \right] D_{1} \right] \right]^{1/2}
\]

with

\[
 B_e = \left( \cos^2 \gamma / n_e^2 + \sin^2 \gamma / n_o^2 \right)^{1/2},
\]

\[
 B_o = \left( \cos^2 \theta / n_o^2 + \sin^2 \theta / n_e^2 \right)^{1/2},
\]

\[
 C_o = \left( B_e / n_o \cos \gamma \cos \theta + \left( n_e / n_o \right) \sin \gamma \sin \theta \right),
\]

\[
 C_e = - \cos (\theta - \gamma),
\]

\[
 D_o = - \sin^2 \theta, \quad D_e = \sin^2 \theta
\]

### Fig. 2.
The proposed double-filtering method
Theoretically, the spectral response of the proposed double-filtering method is proportional to the multiple of two spectral responses diffracted from a single AOTF. It has a similar form to the equation in [11] and can be expressed as follows:

\[
F_{\text{double}}(k, \delta) \propto F_{\text{eo}}(k) \times F_{\text{eo}}(k + \delta),
\]

where \( F \) is the spectral response and \( \delta \) denotes the difference between the two central wavelengths of orthogonally polarized light. If \( \delta \) is greater than the width of each spectrum, nothing is filtered out through the proposed double-filtering method. However, a slight difference smaller than the width of a spectrum can induce an even better performance than when the \( f\lambda \) relation is exactly overlapped [11]. Thus, the value of \( \delta \) must be kept within the width of each spectrum.

We explain this problem as follows: Figure 3(a) shows the relation between \( f \) and \( \theta_i \) in Eq. (1) with an assumed constant wavelength of 632.8 nm [4,16,17]. At normal incident to the first front surface of an AOTF \((\theta_i=22.6^\circ)\), the wavelength is acquired at two different \( f \) values. However, at the crossing point in Fig. 3(a), it is possible to simultaneously collect light from both polarization states at the same wavelength from a given \( f \). After all, \( \delta \) is a function of \( \theta_i \), and we can control \( \theta_i \) by rotating the AOTF against the incident light. For example, \( \delta = 0 \) if \( \theta_i \) is changed precisely to the crossing point in Fig. 3(a). Thus, the initialization of the setup to make \( \delta \) near the crossing point can be accomplished easily by changing \( \theta_i \). The limit angles of operation where still the increase of resolution is achieved can be found where the spectrum of two diffracted light just starts to overlap as described in Fig. 3(b). The \( \delta \) is obtained by the difference between two curves in Fig. 3(a).

![Figure 3](image-url)

Fig. 3. (a) The \( f\theta_i \) relation at a constant wavelength (632.8 nm). As the incident angle decreases near the crossing point by the rotation of the AOTF, the value of \( \delta \) in Eq. (2) becomes smaller than the width of each spectrum, thereby satisfying the main prerequisite of the proposed double filtering (b) limit angles of operation where still the increase of resolution is achieved.

To find an appropriate value of \( \delta \) for the improved spectral resolution, we simulated \( F_{\text{double}} \) with \( F_{\text{eo}} \) and \( F_{\text{eo}} \), the values of which were experimentally measured and normalized. The numerical calculations of the spectral resolution and the peak intensity of the double filtering are shown in Figs. 4(a) and 4(b), respectively. As \( \delta \) increases, the spectral resolution is improved but the peak intensity of \( F_{\text{double}} \) decreases, possibly inducing a lower signal-to-noise ratio. Thus, \( \delta \) needs to be selected on the basis of the resolution and light throughput. The value of \( \delta \) in the experiment was set at 0.14 MHz.

The performance of the proposed double filtering with a single AOTF is expected to be comparable to that of a system with two AOTFs in tandem, and the light loss for the extraordinary incident light is expected to be minimized.
3. Experimental results

The AOTF (Brimrose, TEAF10-40-65) used here is commercially available, and the f-λ relation is provided via an electric driver. The main parameters of the AOTF are listed in Table 1. The crystal design parameters, such as $\theta_i$ and $\gamma$, are generally unknown; hence, these parameters were estimated experimentally with two light sources, a HeNe laser (632.8 nm) and a diode laser (532 nm). After ensuring that the light source enters the front surface of the AOTF normally, we measured the intensity of two orthogonally diffracted light beams by scanning $f$. The theoretical f-λ relation of Eq. (1) converges well with the experimental data, where, as shown in Fig. 1 (b), $\theta_i$ = 22.6° and $\gamma$ = 9.7°.

Table 1. Main parameters of the AOTF

<table>
<thead>
<tr>
<th>parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>115 ~ 180</td>
</tr>
<tr>
<td>tunable range (nm)</td>
<td>452 ~ 636</td>
</tr>
<tr>
<td>spectral resolution (nm)</td>
<td>0.6 ~ 1.6</td>
</tr>
<tr>
<td>deflection angle (°)</td>
<td>6 ~ 6.7</td>
</tr>
</tbody>
</table>

The angle between diffracted and undiffracted light which is referred as deflection angle in Table 1 changes as the wavelength is scanned; therefore, the incidence angle in the double-filtering configuration is affected. However, the maximum deviation of 0.7° is reduced to 0.3° inside the crystal of which the refractive index is 2.26 for the wavelength of 632.8 nm.

For the next step, we measured each diffracted light after single filtering to examine the spectral responses of $F_{eo}$, $F_{oe}$ and $\delta$ with a monochromatic light source (632.8 nm). Fig. 5 (a) shows the spectral resolution and sidelobes when the light enters the front surface of the AOTF normally ($\theta_i$ = 22.6°). The shape of the spectrum is determined by a convolution of the monochromatic source and the spectral response of the AOTF, and the horizontal axis can be changed to the wavelength by means of Eq. (1). Hence, the FWHM values of 0.36 MHz and 0.31 MHz from single filtering are interpreted as a resolution of 1.6 nm and 1.4 nm, respectively. With FWHMs determined experimentally, $\theta_{\text{min}}$ and $\theta_{\text{max}}$ are obtained as 20.9° and 22°, respectively, from Fig. 3(b).

Note that double filtering cannot be realized at the current state because the difference between the two peaks, $\delta$, is larger than the width of the single-filtered spectrum. We rotated the AOTF counterclockwise by 4° to change $\theta_i$ near the crossing point and measured each diffracted light again, the results of which are plotted in Fig. 5(b). The overlap of the $F_{eo}$ and...
$F_{\text{oo}}$ values with the previously determined value of $\delta$ enabled us to establish the proposed setup.

Finally, we measured the $F_{\text{double}}$ value and, as shown in Fig. 6(a), compared it with the calculated spectral response of Eq. (2). The biggest sidelobe of single-filtered light is suppressed by 9.8 dB through the double-filtering method. Figure 6(b) describes the calculated degree of sidelobe suppression against $\delta$. The experimental results confirm that when the proposed double-filtering method is used the spectral resolution improves from 0.36 MHz and 0.31 MHz for each single filtering to 0.25 MHz and the sidelobe is suppressed around 10 dB. In Fig. 6(a), the noise level of double-filtered curve is larger than the calculated one and only the largest sidelobe is observable because the calculated dynamic range of the double-filtered signal is higher than that of the detector. The photo-diode used for the experiment has a dark noise level of 33 mV and cannot measure a signal of which the dynamic range is over 25 dB. The proposed double filtering configuration can be generalized to different crystals at different wavelength ranges if the crystal generates two diffracted rays of orthogonally polarized and the spectrum of two diffracted light is fully or partially overlapped as shown in Fig. 5(b).
4. Conclusion

In this study, we propose an efficient double-filtering technique with a single AOTF. First, we investigate the initialization process in terms of the relation between the input acoustic frequency, \( f \), and the central wavelength of the two orthogonally diffracted light beams. We then describe the optical setup in detail in terms of the tradeoff between the spectral resolution and the signal intensity. The experimental results show that the improvement of spectral resolution ranges from 20\% to 30\% with more than one order of sidelobe suppression, a result that agrees well with the calculated value. In conclusion, we emphasize that the results from a single AOTF are comparable to the results achieved with two AOTFs in tandem. Moreover, the light loss is minimized for the extraordinary incident light.

Acknowledgment

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