Optimization Design of the Tellurium Dioxide Acousto-optic Tunable Filters For WDM system

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ABSTRACT

Acousto-optic tunable filter (AOTF) is one of important optical switch components in optical networks. The possibility of tellurium dioxide acousto-optic tunable filter (TeO$_2$ AOTF) as an optical add/drop multiplexer (OADM) is studied on the basis of the theory of the anomalous acousto-optic Bragg diffraction and the design principle of non-collinear AOTF. Its main performances and structure are analyzed and discussed, and the significance of incident angles and interaction lengths for its performances is presented. The model for optimization design is built under some limitation and the transducer areas is adopted as a regulator for performance, the designed example of the TeO$_2$ AOTF for WDM systems is given by the optimized method.

Keywords: TeO$_2$ AOTF, anomalous acousto-optic diffraction, optimized design, OADM

1. INTRODUCTION

As an optical switch device in wavelength division multiplexing (WDM) system, the acousto-optic tunable filter (AOTF) is one of powerfully several potential candidates [1][2], because that it has not only large wavelength range, but also dynamic and reconfigurable characteristics. That will make AOTF possible to play a critical role in WDM systems. The tellurium dioxide (TeO$_2$) AOTF with larger acousto-optic merit value and simpler fabricate technology is often used in the spectral analysis. Naturally, it should be study on if it has ability to perform the function of an optical add/drop multiplexer (OADM). The difference of its working mechanism from the integrated acousto-optic tunable filter (IAOTF) is related to incident angles. Thus, the design of a TeO$_2$ AOTF can be more flexible, but is more complicated. In 1999, Chieu D. Tran developed the collinear beam TeO$_2$ AOTF with the tuning range of 600nm and negligible sidelobe [3], which enables TeO$_2$ AOTF to have an attractive foreground in the optical transport networks. And I.C. Chang studied it as an optical add/drop multiplexer (OADM) on optical networks in 2000[4].

According to the diffraction theory and design principle of non-collinear AOTF, the main performances of the TeO$_2$ AOTF used in WDM system, such as diffraction efficiency and driving power, can be given by computer simulation, by which it is shown that the effect of optical incident angle and interaction length are significant on its performances, and how to choose them properly should be comprehensively considered when designing AOTF as an OADM, that the influence of the transducer areas is not negligible. So is the device structure, in which the crystal sizes and the distribution of acoustic energy is considered on the basis of the non-collinear TeO$_2$ AOTF structure for transforming o-light to e-light.

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In this paper, in order to realize multi-performance optimization, the mathematical model is build up, the confined conditions are presented, and the design variables are defined. Their reasonability and the feasible scheme are shown, the designed example of an TeO$_2$ AOTF with the optimized performances is gotten by the optimized way.

2. THE DIFFRACTION THEORY OF NON-COLLINEAR AOTF AND THE DESIGN PRINCIPLE

2.1 The design principle and the diffraction theory of non-collinear AOTF

The TeO$_2$ AOTF with the functions of filtering and mode conversion due to the periodic refractive index grating throughout the interaction length induced by the LiNbO$_3$ transducer is shown in Fig.1 (for transforming o-light to e-light). As an anisotropic crystal, the orientation of acoustic energy flow is different from that of wave vector and the former is more important for acousto-optic interaction, as indicated in the Fig.1. The mode conversion is commonly based on the design principle of non-collinear AOTF, and the following two relations can be deduced as [5]:

$$\theta_a = F(\theta_i) \quad (\text{e-light to o-light}) \quad (1)$$
$$\theta_a = \pi - F(\theta_i) \quad (\text{o-light to e-light}) \quad (2)$$

where $\theta_a$ and $\theta_i$ designate the acoustic and the optical incident angle respectively.

And the tuning relation is given by

$$\lambda_0 = (\Delta n / f)[\sin^2 2\theta_i + \sin^4 \theta_i]^{1/2} \quad (3)$$

where $\lambda_0$, $\Delta n$, $f$ and $\theta_i$ are the incident optical wavelength, the difference between o and e-optical effective refractive index, the acoustic velocity and the acoustic frequency, respectively. The formula (3) is fit for whichever optical mode transformation.

The basic theory for TeO$_2$ AOTF is that of the anomalous acousto-optic Bragg diffraction, which defines the optical diffraction performances, the amount of driving power and device bandwidth. They can be written as:

$$\eta = \sin^2[\Gamma L \sqrt{1 + (\Delta k_1 / 2\Gamma)^2}]/[1 + (\Delta k_1 / 2\Gamma)^2] \quad (4)$$

where $\eta$ is the diffraction efficiency; $\Delta k_1 = Q(\lambda, \theta, n)$ is the amount of momentum mismatch; $\Gamma = R(\lambda_0, \theta, n, A, P_a)$ is the coupling coefficient and $L$, $A$, $P_a$ is the interaction length, the transducer areas and the driving power respectively. Generally $\Gamma L = \pi/2$, there is the driving power as the following:

$$P_a = \frac{\lambda_0^2 A \sin^2 \theta_i n_d}{2 M_2(\theta) L^2 n_i} \quad (5)$$

where $M_2(\theta)$ is the acousto-optic merit number and the sub ‘d’ stands for ‘diffracted’.

And the bandwidth $\Delta \lambda$ can be inferred from the diffraction efficiency equation as:

$$\frac{\Delta \lambda}{\lambda_0} = \frac{1}{\eta}$$

Fig 1. Architecture of TeO$_2$ AOTF(O to E-light)

Fig.2 The relation curves of the diffraction efficiency vs the acoustic frequency:

(1)64°- solid line:A-2cm$^2$; dashed line: A-1cm$^2$
(2)65°- solid line:L-5cm; dashed line: L-7cm
\[ \Delta \lambda = 0.9 \lambda_0^2 / \Delta n \sin^2 \theta_i \]  

(6)

In order to realize narrow bandwidth, either interaction length or optical incident angle should be larger. And the longest wavelength in the tuning range should be used in the calculation of bandwidth because of the square law relation between them. In addition, the three equations based on the diffraction theory are irrelevant to mode transformation.

2.2 Design consideration for performances

These indexes above are important for an OADM and the application in WDM system. Because of the diffraction efficiency in connection with many factors, the curves of the diffraction efficiency versus acoustic frequency are simulated for a definite wavelength \( \lambda_0 \) (=1.554 \( \mu \)m) and a definite driving power \( P_\text{d} \) (= 83mw ), shown in Fig.2. In view of a larger optical incident angle, \( \Delta n \) varies with \( \theta_i \) must be considered. The influence of the interaction length and the transducer area on diffraction efficiency and the sidelobe is clearly shown in the curves \( (\theta_i = 64^\circ) \) and \( (\theta_i = 65^\circ) \) for the different transducer areas and the different interaction lengths.

In Fig.3 (a) and (b), it is shown in detail how the transducer area affects the diffraction efficiency and the sidelobes, in which the simulated conditions are \( \theta_i = 30^\circ \) in both figures, \( A = 2.0 \text{cm}^2, 2.5 \text{cm}^2 \) and 3.5 \( \text{cm}^2 \) in (a) and \( A = 2.0 \text{cm}^2, 1.2 \text{cm}^2 \) and 1.0 \( \text{cm}^2 \), in (b) and which is related to curve (1), (2) and (3) respectively. It can be found that there exists an extreme value of the transducer area, at which a higher diffraction efficiency and lower sidelobes can be acquired for a specified optical incident angle. The value of the area has to be found when a TeO2 AOTF is designed. The matching areas of the transducer may not be satisfied the considered requirement on the sidelobes of the diffracted light for an OADM. It can be matched easily by an electrical circuit as same as the integrated AOTF.

![Fig.3 (a) The relation of the diffraction efficiency vs the acoustic frequency with \( A=2.0, 2.5 \) and 3.5 \( \text{cm}^2 \) respectively](image)

![Fig.3 (b) The relation of the diffraction efficiency vs the acoustic frequency with \( A=2.0, 1.2 \) and 1.0 \( \text{cm}^2 \) respectively](image)

In Fig.4 it is shown that the diffraction efficiency changes along with optical wavelength within the tuning range of 200nm for the conditions in curve (1), \( P = 85 \text{mw}, L = 7 \text{cm}, A = 2 \text{cm}^2 \) and \( \theta_i = 64^\circ \), and for the different conditions in curve(2)-(5) respectively. The analysis on the wavelengths’ stability is also nessesary in the device design for the multi-wavelength operation as an OADM.
In Fig.5 the variation of the driving power with the optical incident angle is shown. It is clear that there is a maximum value of the driving power at the optical incident about 63° for different interaction length. It means the optical incident angle (about 63°) should be not applied. If the AOTF operates at a smaller or a larger angle, the driving power should be lower.

The result from an all-round consideration for the device performances is that a longer interaction length and a larger optical angle are beneficial. In the meantime, the sidelobe and wavelengths’ stability should be analyzed, but they can be independently dealt with for a given incident angle and interaction length.

3. CHOICE OF SOME PARAMETERS ACCORDING TO A TeO₂ AOTF STRUCTURE

The device structure, or the distribution of optical and acoustic beam, is decided by their incident angles and it is related to the crystal sizes. On the basis of usual non-collinear AOTF structure, whatever it changes o-light to e-light or not, by analyzing its geometrical structure, the relation equation between the interaction length \( L \) and the transducer length \( l \), which is in proportion to transducer area, can be described as follow:

\[
L = l \left\{ \cos(\theta_i - (\theta_a - 90^\circ)) - \frac{\sin(\theta_i - (\theta_a - 90^\circ))}{\tan(\theta_a + 90^\circ - \theta_f)} \right\}
\]

(7)

where \( \theta_i \) designates the orientation of the acoustic energy flow from the crystallographic axis [110]. For a given interaction length \( L \), the transducer area is usually adjusted by the transducer width. And the variation of \( l \) with the optical incident angle \( \theta_i \) can be gotten, from that the momentum-match should be met in the acoustic angle \( \theta_a \). In Fig.6, \( L \) is respectively 25, 35, 45, and 55mm, responding to curve (1)-(4) respectively. It can be seen that there is a maximum value of the incident angle about 72°. In addition, the formula above is not fitted for the collinear mode because of different structure.
It makes more efficiently utilize the material to choose the angle $\theta$ between the energy flow and transducer reasonably. The variation of the angle $\theta$ with the optical incident angle is shown in Fig. 7. It can be found that the angle $\theta$ doesn’t change basically at about $33^\circ$ within the range of the optical incident angle from $30^\circ$ to $72^\circ$, which makes the optical incident angle chosen more freely and widely in the usage of the crystal.

For a device’s structure, the length and the width of the crystal are the function of incident angle, interaction length and optical aperture. According to Fig. 1, their relationship is depicted in Fig. 8 for the optical aperture of 4mm, and with the interaction length of 55mm, 45mm and 25mm respond to the curve (1), (2) and (3) respectively. It can be found that the variation of the crystal length along [110] is not obvious for the different interaction length in the range of the optical incident angle of $0^\circ$-$90^\circ$, but there is a big change along [001], especially at the optical incident angle of $63^\circ$. It is necessary for the research of the crystal growth at [001] to acquire a higher performance device.

Considering the device size, it is more proper to choose a smaller or a larger angle, which is the same as the conclusion from driving power. The distribution stability of acoustic energy in a range of optical incident angle makes this choice possible. It is necessary to estimate the transducer length to calculate a transducer area with a lower sidelobe.

4. DESIGN VARIABLES, MATHEMATICAL MODEL AND OPTIMIZATION

From the discussion above, it is clearly seen that there are many factors to affect the performances of the device, such as optical incident angle, interaction length and transducer areas, and in the meantime, also to be decisive for the usage of the crystal in orientation and sizes. And it is reasonable that the optical incident angle and the interaction length are defined as the design variables. It can be written as:

$$X = [x_1, x_2]^2 = [\theta_i, L]^2 \tag{8}$$

where $X$ and $x$ are the symbols of design variable; ‘power 2’

Fig. 6 The relation curves of transducer length $l$ vs optical incident angle $\theta_i$ on a different interaction length $L$.

Fig. 7 The curve of the angle $\theta$ between the transducer and the acoustic energy vs the optical incident $\theta_i$.

Fig. 8 The relation between optical incident angle and crystal length. Solid line: the length at [001]; Dashed line: the length at [110].
show that there are two design variables.

Because there are a lot of limitations for the usage of TeO$_2$ AOTF in WDM system, for examples, high diffraction efficiency and narrow bandwidth, so that a multi-objective design should be made for it. It is so difficult to solve this design model that it has to simplify the model of device design. Considering the more comprehensive characteristics of diffraction efficiency, it has ability to play the role of a target function. According to the applied conditions, the bandwidth and the driving power are chosen as the confined conditions. Thus, there is a mathematical model of an AOTF optimized design as below:

\[
\min f(x) = 1 - \eta \quad \text{subject to } x \in R^2
\]

\[
g_1(x) = \Delta \lambda - 0.8 \leq 0 \quad \text{(9a)}
\]

\[
g_2(x) = P - 100 \leq 0 \quad \text{(9b)}
\]

\[
g_3(x) = L_{[001]} - 150 \leq 0 \quad \text{(9c)}
\]

\[
0^0 \leq \theta_1 \leq 90^0 ; \quad 0 \leq L \leq 5cm \quad \text{(9d)}
\]

where \(\min f(x)\) is the target function and the optimization should make \(f(x)\) value minimum, ‘s.t.’ stands for ‘subject to’, which includes all of the confined performance conditions (9a) –(9c) and a confined boundary (9d). As an example, \(g_1(x)\) means the bandwidth must be smaller than 0.8nm; \(g_2(x)\) means the driving power smaller than 100mw; \(g_3(x)\) means the length along [001] smaller than 150mm. These chosen values are just an example. The demand for the crystal length along [110] is not considered because it can be met easily in practice now.

With a program for optimization, we get the design variables [35$^0$, 45mm], responding to the acoustic angle about 75$^0$ for the device structure of o- transforming to e-light, and the results shown in the table1.

<table>
<thead>
<tr>
<th>Bandwidth (nm)</th>
<th>Driving power (mw)</th>
<th>Length along [001] (mm)</th>
<th>Diffraction efficiency (%)</th>
<th>Sidelobe (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.78</td>
<td>74</td>
<td>147</td>
<td>97</td>
<td>-10.4</td>
</tr>
</tbody>
</table>

The sidelobe is modeled after the other results are acquired. And it is about –10.4dB when transducer area is 1.5cm$^2$. The curves of the diffraction efficiency and the wavelength stability are separately given in Fig.9 (a) and (b). The relative stability of diffraction efficiency in the range of 200nm is evidently shown in Fig.9 (b), which is nearly about 95%. The optimized parameters of a TeO$_2$ AOTF can be gotten under some confined conditions by this way.
5. CONCLUSIONS

According to the diffraction theory and the design principle for non-collinear TeO$_2$ AOTF, the change of the performances and the device structure with the interaction length, the incident angle and the transducer area are discussed, including the distribution of acoustic energy and crystal size. The design variables, the confined conditions and the optimized model are defined on the basis of characteristics discussion. The conclusions are obtained as follow:

1. The major design parameters should be the interaction length, incident angle and transducer area because of their important influence on the performances and structure, in which the curve of diffraction efficiency is studied as a principle role in detail.

2. The optimized mathematical model for the device design has been constructed and simplified from a multi-objective function to a single objective. The reasonability of the model is demonstrated by analyzing performances and its structure.

3. With the optimization analysis program, the optimized characteristics of a TeO$_2$ AOTF have been gotten from the target function under some confinement and in the varying range of the variables.

4. In order to get lower sidelobes, the transducer area works as adjustment after the parameters from optimization analysis are firstly gotten. Then the feasibility is checked by the acoustic incident angle and the distribution of the energy flow.

Thus, the feasible and reasonable design can be found out by this optimization way.

REFERENCES


