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Acousto-Optical Tuneable Filter design for efficient diffraction of unpolarised light

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ABSTRACT

Diffraction of optical waves by an acoustic grating is a well-known phenomenon that enables the design of very versatile devices useful in photonic systems. For example, Acousto-Optic Tuneable Filters (AOTFs) can be dynamically tuned by radio-frequency signals. Among possible material choice, tellurium dioxide crystal is often used for practical applications due to its high efficiency. In such a birefringent material, the anisotropic configuration is often used. A feature of this configuration is the sensitivity to optical input polarisation: a selective coupling between polarized modes occurs. The incident must be polarised and the diffracted mode polarisation is orthogonal to the incident one.

However, during the design process a very specific operation point can be found that ensures the simultaneous diffraction of both the ordinary and the extraordinary optical modes. In this presentation, we introduce the design of AOTF in birefringent crystals and present the main parameters that are subject to trade-off. Acousto-optic diffraction efficiency is sensitive to the so-called phase matching condition between optical wave and the ultrasonic wave. The offset from synchronicity is considered introducing a phase mismatch parameter. Diffraction efficiency evolution with respect to Bragg condition offset are illustrated. A custom device is finally presented that ensures simultaneous diffraction of both polarisation modes and compared to experimental results.

Keywords: *AOTF, anisotropic diffraction, umpolarised light.*

1. INTRODUCTION

Acousto-Optic Tunable Filter (AOTF) are widely deployed in different industrial sectors with optical instrumentation (biomedical [1], spectroscopy [2-6], or hyperspectral imaging [7-10]). When designing an acousto-optical component, different parameters must be considered such as: the material used, the orientation of the optical faces, the acoustic section, the type of acoustic wave generated, or the polarization of the incident and diffracted optical beams. We introduce here briefly the main aspects of acousto-optic diffraction and AOTF devices design.

The physical principle of acousto-optical interaction consists of the diffraction of a light beam (usually a laser source of wavelength λ) by a harmonic ultrasonic wave of period Λ, generated by a piezoelectric transducer. These interactions take place within a crystal with photoelastic properties such as Quartz, or Paratellurite (TeO_2). The propagation of ultrasonic waves in this type of medium modifies the optical properties: the propagation of a sinusoidal ultrasonic wave leads to a periodic variation in the optical refractive index of the crystal, which leads to the creation of a "diffraction grating". There are two regimes of interaction: the Raman-Nath regime and the Bragg regime. The first corresponds to the theory of thin gratings and the

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second to the theory of thick gratings. We consider here the Bragg regime which is the most used because it gives rise to a single diffracted beam and for which in theory the efficiency can reach 100%. This regime takes place for a well-known angle of incidence which results from the analysis of the constructive interference conditions between two optical beams diffracted by two consecutive planes of the diffraction grating. Under these conditions, the diffraction angle between the incident beam and the diffracted beam is equal to twice the Bragg angle, θ_{Bragg} which is expressed in the isotropic case by:

$$\sin(\theta_{Bragg}) = \frac{\Lambda}{2*\lambda} \tag{1}$$

Most photoelastic crystals are optically and acoustically anisotropic. Optically, this means that the crystal is birefringent. In such a material, an optical wave of any polarization is decomposed into two eigenmodes of orthogonal polarizations. We are interested in the anisotropic interaction: the polarization of the transmitted optical beam is orthogonal to that of the diffracted beam. More specifically, we seek for conditions that allows the anisotropic light diffraction of unpolarised light.

2. ANISOTROPIC DIFFRACTION IN PARATELLURITE

The anisotropic diffraction regime corresponding to the Bragg conditions is shown in Figure 1: an incident optical beam of wave vector $\vec{k_i}$ is coupled to the ordinary wave and is diffracted to the extraordinary wave ($\vec{k_d}$) by the acoustic wave ($\vec{K}$). We then have the following relationship:

$$\vec{k_d} = \vec{K} + \vec{k_i} \tag{2}$$

An alternative situation exists: thanks to a rotation of its polarisation, the incident beam can be coupled to the extraordinary wave and then it is diffracted to the ordinary one. When the conditions of the interaction are not ideal, the interaction takes place with a small deviation from the Bragg conditions. This phenomenon occurs when, for example, there is an offset of the incident angle or of the acoustic frequency or of the optical wavelength with respect to the exact Bragg conditions. A phase shift is then introduced by $\overrightarrow{\Delta k_d}$ which reflects this discrepancy. The vector relation expressing the conservation of moment is then modified:

$$\vec{k_d} = \vec{K} + \vec{k_i} + \overrightarrow{\Delta k_d} \tag{3}$$

The diffraction efficiency is then expressed as:

$$\eta = \frac{P}{P_0} \frac{\sin^2\left(\frac{\pi}{2}\sqrt{\frac{P}{P_0}+\left(\frac{\Delta\Phi}{\pi}\right)^2}\right)}{\frac{P}{P_0}+\left(\frac{\Delta\Phi}{\pi}\right)^2} \tag{4}$$

With: $\Delta\Phi = \Delta k_d . W_{eff}$, the phase mismatch and W_{eff}, the effective interaction length, P the acoustic power and P_0 the power necessary to diffract completely the optical incident wave.

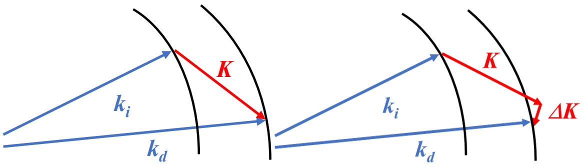

Figure 1. wave vector diagram of anisotropic acousto-optic Bragg diffraction, left. at synchronism and right. with phase mismatch.

3. ACOUSTO-OPTIC TUNEABLE FILTERS

In the case of a polychromatic incident optical beam, an AOTF makes it possible to extract a particular optical wavelength by selecting the corresponding acoustic frequency: an optical wavelength corresponds to an acoustic frequency. The work carried out by Yano, Watanabe [11] and Chang [12] has allowed the configuration of filters whose incident and diffracted beams are separated angularly (non-collinear). This kind of anisotropic interaction configuration is called NPM (for Narrow Phase Matching), it is favourable to a narrow spectral resolution. Moreover, a practical operation point with a high incident optical aperture is possible when the tangent to the incident and diffracted wave vector loci are parallel. Though, this case is polarisation sensitive and can not be exploited with unpolarised light which corresponds to the usual “natural” light.

When an unpolarised incident light is coupled to an anisotropic material such as paratellurite, it couples simultaneously the ordinary and extraordinary modes. In this case, the filtering ability can be maintained for a very specific operation point. It corresponds to the situation when the ordinary to extraordinary diffraction and the reverse situation are found to be at exact synchronism for the same acoustic wave vector. In this situation, the ordinary and the extraordinary beam are diffracted simultaneously in two distinct directions, respectively upside and downside with respect to the incident direction. This situation is illustrated in figure 2.

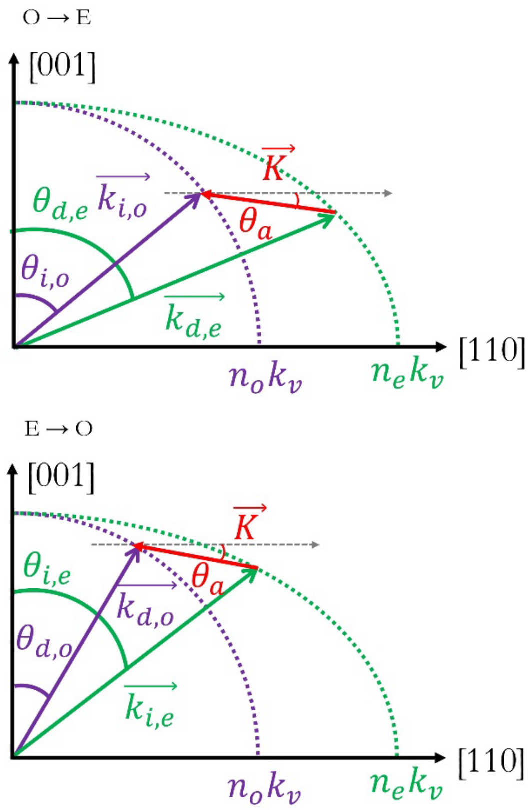

Figure 2. anisotropic diffraction, top: ordinary to extraordinary case, bottom: extraordinary to ordinary. Exact synchronism conditions are found with the same incident angle and the same acoustic wavevector $\vec{K}$.

When projecting the vectoral relation (1) on the crystallographic axis, a couple of equations are found that lead to the expression of the acoustic frequency:

$$f_S = \frac{V}{\lambda}\left(n_i(\theta_i)\sin(\theta_i-\theta_a) - \sqrt{n_d{}^2(\theta_d) - n_i{}^2(\theta_i)\cos^2(\theta_i-\theta_a)}\right) \tag{5}$$

With: the incident angle θ_i, the acoustic cut θ_a, the optic wavelength λ, the acoustic velocity V, θ_d the deflexion angle and the refractive index $n_i{}^2(\theta_i)$ et $n_d{}^2(\theta_d)$, that are calculated thanks to Sellmeier formulas [13].

The evolution of the acoustic frequency as a function of incident angle is depicted in figure 3. The high incident optical aperture corresponds to the point of this curve with a horizontal tangent. From figure 3, it is noticeable that the curve corresponding to the ordinary to extraordinary and the one corresponding to the extraordinary to the ordinary, intercept in one unique point. This point can be found for any optical wavelength and correspond to the simultaneous diffraction of the two polarisations: there is a dual diffraction (DD) for the couple of parameters of incident angle and acoustic frequency identified by: (θ_{DD}, f_{DD}).

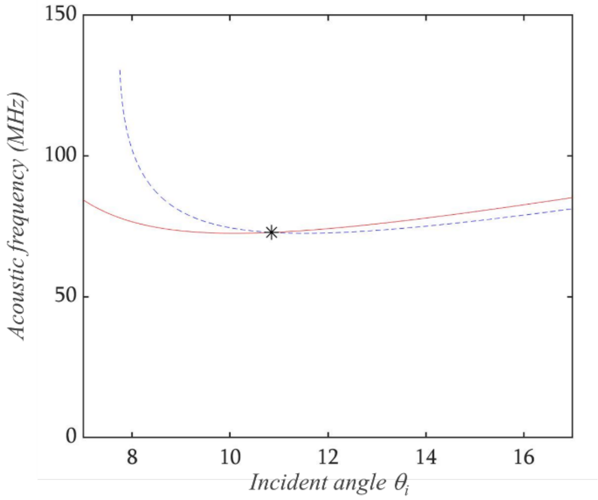

Figure 3. evolution of the acoustic frequency as a function of the incident angle for a wavelength of 515 nm, dashed line e→o, solid line o→e.

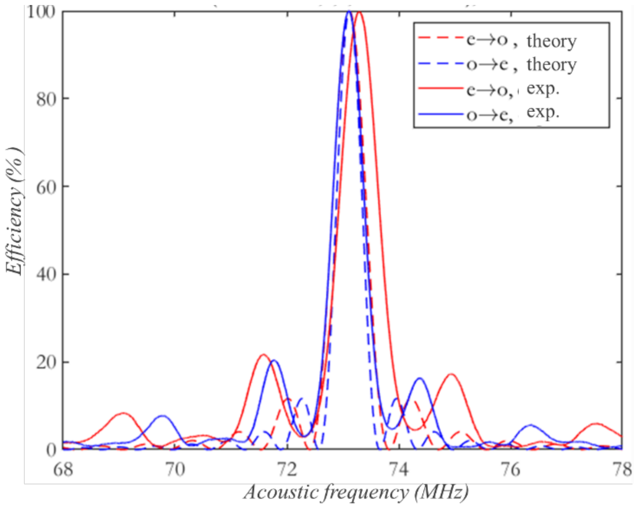

Figure 4. Designed AOTF filtering characteristics at 514 nm.

Table 1. Characteristics of the designed AOTF for the filtering of unpolarized light.

Acoustic cut	5°
Optical operation span	450 - 800 nm
Transducer total length	11 mm
Spectral resolution	< 10 nm
Incident angle (at 600 nm)	10.83°

We have designed a custom device that has been realised by AA optoelectronics according to the characteristics given in table 1. This filter is able to filter "natural" unpolarised light and to diffract it with a high efficiency, splitting the two orthogonal polarisations into two distinct directions. The filter has been tested, an example of filtering characteristics is given in figure 4: the filter response has a traditional cardinal sinus shape with visible sidelobes. As a perspective, it is possible to get an apodised response with multiple contacts transducer launching a Gaussian profile acoustic grating.

4. CONCLUSIONS

In this article, the design of acousto-optic tuneable filters has been recalled with an emphasis on the design of polarisation unsensitive devices. The parameters for such a filter have been given and its filtering characteristics both theoretical and experimental have been investigated. This filter can be used for spectral analysis of "natural" unpolarised light.

5. ACKNOWLEDGMENTS

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