INFLUENCE OF THE LIGHT DIVERGENCE ON COLLINEAR ACOUSTO-OPTIC INTERACTION

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Abstract
The wavelength resolution and the diffraction efficiency of an acousto-optic cell based on collinear interaction are analyzed as a function of the light beam collimation. Experimental results performed for radiations around 1550 nm are in complete agreement with theory. From these results, applications in the fields of Telecommunication and Fast Spectroscopy are proposed.

Introduction

Collinear acousto-optic interaction is obviously of great interest for fundamental and applied physics, since the interaction length between light and ultrasound can be substantially increased. Only electric powers of the order of a few tens of milliwatts are needed to implement the acousto-optic device in this case, with a 100% diffraction efficiency, and its light wavelength resolution can reach very high values. The undesirable side lobe intensities strongly diminish [1] in the collinear interaction, which is very favourable for application to tunable acousto-optic filters in WDM telecommunication systems, since it allows a drastic diaphoty reduction between the different channels [2]. Among all the parameters that influence the coupling phenomenon, the most remarkable and the less studied one, consists of the light beam divergence. Yet, this parameter can be easily modified by transformation of the beam diameter. In our experiments, a laser light at the telecommunication wavelength $\lambda = 1550$ nm was collimated by microlenses of different focal lengths, at the end of the input fibre. Accordingly, the incident light beam waist could take several values between 0.25 and 2.4 mm.

The TeO_2 acousto-optic cell [2] we used is oriented at Bragg angle. The direct and deflected beam intensities are measured as a function of the light beam diameter, at constant modulation index, and versus the modulation index values for five different beam waists. The results are interpreted in the light of the interaction theory by considering the light wavelength bandwidth variations induced by the beam divergence that breaks the acousto-optic selection rules. Complementary experiments of radiation selectivity measurements of the acousto-optic cell are also performed for confirmation with incident white light and a spectrum analyser at the device output.

Theoretical background

In the present study only the directions of propagation of the incident light (always ordinarily polarized) and acoustic energy are parallel. Yet, the wave vectors of the direct and diffracted optical beams are differently oriented, thus allowing an angular separation between them at the output. The TeO_2 acousto-optic cell based on collinear interaction is completely described in reference [2], where it characteristics result from an optimization of the device. We will give only a short recall here. The dimension L of the crystal along the light beam path represents also the acousto-optic interaction length. The use of the largest L compatible with high quality TeO_2 single crystals is hunted for, since it increases both the modulation index [3] and the resolution. We used L =40 mm, among the highest values of the literature. At Bragg incidence (or resonance conditions), the ultrasonic frequency F is related to the incidence θ_i according to:

$$F\lambda = V\,[(n_2^2 - n_o^2\cos^2\theta_i)^{0.5} - n_o\sin\theta_i]\,. \qquad (1)$$

Here, V is the acoustic phase velocity, n_o and n_2 the refractive indices of the incident and diffracted light, respectively. The Figure of Merit M_2 of the cell in our scattering geometry is given by:

$$M_2 = n_o^3 n_2^3 p_{eff}^2/(\rho V^3)\,. \qquad (2)$$

The effective photoelastic constant p_{eff} is a function of the crystal, the acoustic propagation and the light incidence.

The total filtration bandwidth $\delta\lambda$ is equal to:

$$\delta\lambda = [(\delta\lambda_L)^2 + (\delta\lambda_d)^2]^{0.5}\ , \qquad (3)$$

where $\delta\lambda_L$ is a function of the number of periods of the photoelastically induced grating intersected by the optical beam during its propagation in the crystal. As to $\delta\lambda_d$, it represents the bandwidth due to the light beam divergence that affects θ_i . One must keep in mind that $\delta\theta_i$ corresponding to a Gaussian light beam is equal to $\lambda/(\pi n_o\omega_0)$, where ω_0 is the waist radius. The influence of the acoustic column divergence [2] in this type of diffraction can be neglected in equation (3). Calculations give for our experimental conditions: θ_i = 54.52° ; θ_d = 56.03° ; V = 632 m/s; F = 41.76 MHz ; $R_L = \lambda / \delta\lambda_L$ = 2165; M_2 = 240 (calculated with respect to the maximum figure of merit of silica). Actually, the scattering geometry of the device was conceived in order to maximize the corresponding product M_2 x R_L .

For λ = 1550 nm, the bandwidth $\delta\lambda_L$ = 0.71 nm. This value corresponds to the utmost wavelength selection of the acousto-optic cell. Normally, one must add the $\delta\lambda_d$ contribution. From equation (1), we can determine $\delta\lambda_d/\delta\theta_i$ in our experimental conditions. We find: $\delta\lambda_d/\delta\theta_i$ = 26 nm/deg. For a typical value of ω = 650 µm, one obtains $\delta\lambda_d$ = 0.52 nm. Finally, equation (3) gives $\delta\lambda$ = 0.88 nm.

Experimental results

Incident light at 1550 nm comes from a tunable semiconductor laser TSL-210 from Scantec and is transported by a single- mode fibre collimator that delivers a Gaussian beam of waist ω. In most of our experiments, we used a collimation $2\omega_0$ = 1.3 mm that is substantially smaller than the acoustic beam section (3.5 mm x 3.5 mm) to avoid truncation effects, while benefiting from a rather high collimation. A high collimation of light increases the selectivity of the device as a function of λ, while increasing its light diffraction efficiency. At the device output we observed as much as 95% of diffracted light at the maximum figure 1. Actually 5% of the direct beam remains undiffracted since they correspond to the most external and inclined rays of the Gaussian beam that do not fulfil the Bragg matching conditions at the frequency F. One can notice in figure 1 that the sum of I_0 (transmitted) and I_1 (diffracted) intensities correspond exactly to 100%. It clearly means that all the incident light is deviated in a single direction. The filtered bandwidth $\delta\lambda$ (see figure 2) measured in these experimental conditions (L = 40 mm and w = 650 µm) is equal to 0.9 nm which is exactly equal to the predicted value 0.88 nm calculated here above in the limit of the experimental errors.

In the wavelength selectivity measurements, the diffraction efficiency is obtained as a function of λ by tuning the laser around the central wavelength λ = 1550 nm. Details of the measurements are given in the insert of figure 2. The bandwidth is determined at 3 dB of the maximum.

Measurements of intensity as a function of the beam waist radius ω_0 have been performed at λ = 1550 nm and for a rather weak Raman-Nath parameter (modulation index range where diffracted intensities are proportional to the acoustic power). Thus, maintaining the acoustic power constant in the acousto-optic cell, we chose ω_0 successively among the five values 0.125, 0.225, 0.3, 0.65, and 1.2 mm. The result is given in figure 3. One can observe both on I_0 and I_1 the favourable effect of light beam collimation on the diffraction efficiency. Yet one notices a saturation behaviour beyond a certain value of ω_0, due to truncation and edge effects of the acoustic beam.

The comparative influence of the light collimation on the diffraction efficiency is seen in figure 4, where a large domain of RF power on the piezoelectric transducer is explored. On each curve of figure 4, the intensity maximum that is rather flat occurs approximately at the same RF power. Only subtle

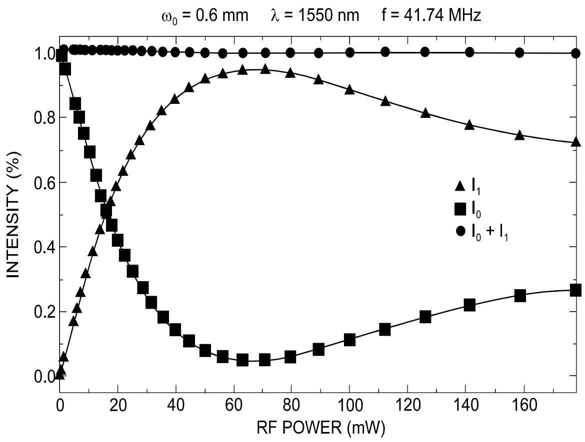

Figure1: Transmitted (I_0) and diffracted (I_1) intensities versus electric power

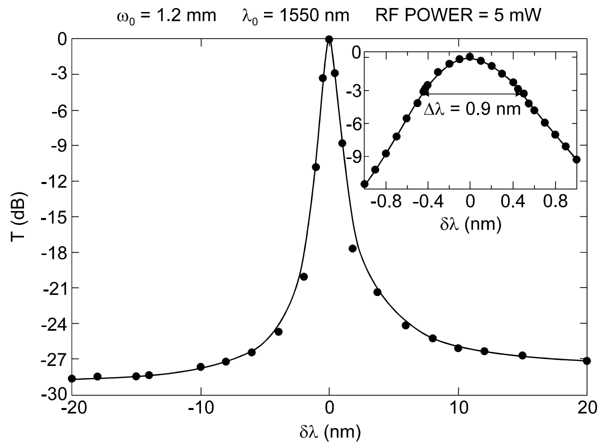

Figure 2 : Wavelength selectivity

modifications are evidenced between ω_0 = 0.65 mm and ω_0 = 1.2 mm. To explain the whole set of results, one must keep in mind that the Bragg condition are strictly respected only for the light rays which are directed along the light beam axis. Proportion of rays that do not fulfil this condition obviously increases with the beam divergence.

The presence of a multi-scattering processes cannot

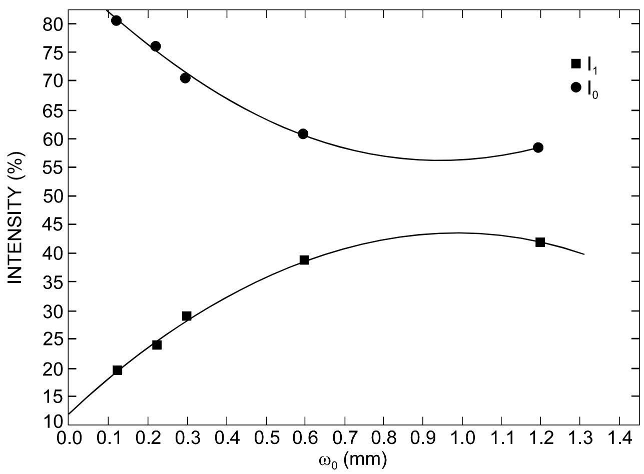

Figure 3: Intensities versus collimation at constant RF power.

be invoked here since we have checked that the intensity lost in the zero-order I_0 is entirely converted into the first order I_1. Actually we can notice that I_0 and I_1 are complementary over the whole RF range of

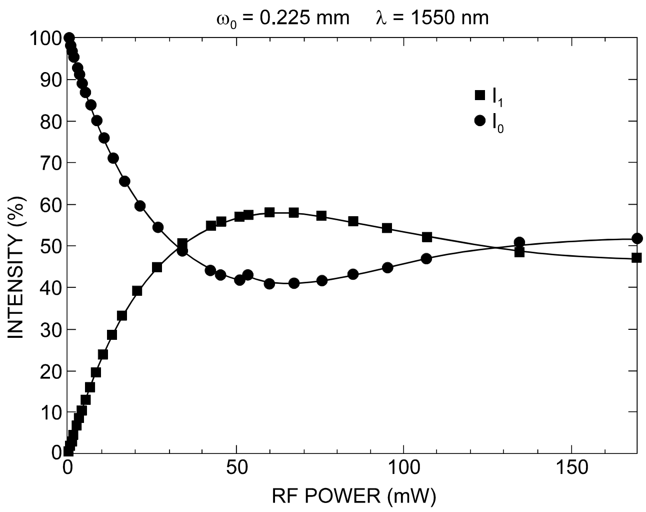

Figure5: Intensities versus RF power for ω_0 = 225 µm.

investigation (see figures 5 and 6) even for the smallest ω_0. The use of a fibre for the collection of light at the device output, since it eliminates the most inclined light rays is favourable to a resolution increase of the device [2]. Thus, for a white light beam with ω_0 = 0.65 mm and a fibre at the output connected to a spectrum analyser, we observed a noticeable reduction of the resolution (0.75 nm instead of the 0.9 nm) found here above.

Discussion:

In Reference [2] the potential applications of this acousto-optic cell using collinear interaction in TeO_2,

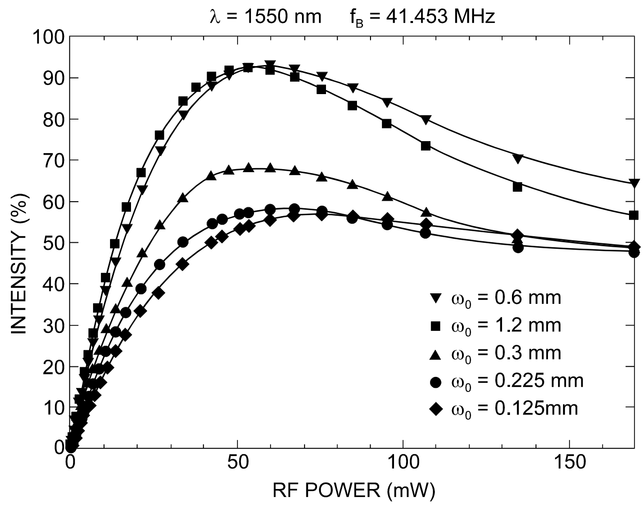

Figure 4: Diffraction versus RF power for different collimation.

a highly anisotropic crystal [4] , had been analyzed. We particularly focused on Telecommunication WDM systems. Yet, the use in fast spectroscopy had been also pointed out. Actually there are many

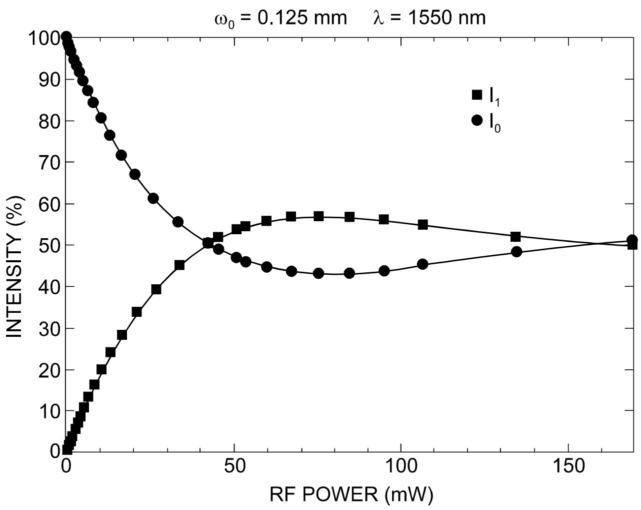

Figure 6: Intensities vs RF power (ω_0= 125 µm).

domains for which this technique is required, such as study of short-lived species, transitory states or imaging spectroscopy [5]. As a consequence of the lack of optical channel analysers for wavelengths around 1.5 µm, the solution consisting of utilizing acousto-optic cells of this kind, seems to be unavoidable. It is worthwhile pointing out that the reconfiguration time which is equal to the transit time τ of the acoustic waves across the crystal length L is independent of the light beam collimation. In the present cell one find τ = 53 µs. The study presented here, proposes among other things, a way to realize the best matching of the light beam to the cell in order to increase its performances. The characteristics of the investigated cell depend on the orientation of the acoustic planes. Modification of this orientation leads to modifications of the resolution and of the figure of merit and can be tailored according to the application.

Acknowledgment

It is a pleasure to thank V.Molchanov for the cell fabrication and for helpful discussions.

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