CONTROLLING THE SPATIAL COHERENCE DEGREE OF LIGHT BY SINGLE AND THREE PHONON ACOUSTO-OPTIC BRAGG DIFFRACTION

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Abstract
Different regimes of acousto-optic Bragg diffraction in a TeO_2 crystal @ λ=0.633 μm has been experimentally investigated to increase the spatial coherence degree of a laser beam. In particular we studied the influence of the acoustic power and the acoustic frequency on the spatial coherence degree of the different diffraction orders participating to the various acousto-optic interactions. A simple “effective thickness” model is proposed to explain the dependencies of the spatial coherence degree on the acoustic power and to compare in a quantitative way the behaviour of the different diffraction regimes. The highest coherence increase is obtained in the “far-off-axis” anisotropic single phonon acousto-optic diffraction at the highest acoustic frequencies and for low acoustic powers

Introduction

The spatial coherence degree of a laser beam has to be in accordance with the photonic application under consideration. When the available coherence degree is too high, many different methods have already been proposed and exploited to destroy the spatial coherence degree [1]. However, when one faces the problem that the spatial coherence degree needs to be increased, the number of methods is very limited. Such spatial coherence increase can be important for the extension of the measurement base of interferometers, for filtering optical signals which have propagated through optical fibres or through turbulent media, for decreasing the optical noise in images caused by the appearance of optical pulses with short coherence lengths. Practical solutions for the coherence increase can open the possibility to transmit optical signals not only by amplitude modulation but also by means of phase or frequency modulation.

Recently a theoretical paper was devoted to the increase of the spatial coherence degree by means of acousto-optic Bragg diffraction [2]. Tarn shows that tackling this problem in a general theoretical framework is very complicated and the derived results are only qualitatively indicative. Therefore at this early stage of the investigations on the coherence increase a much more simple approached is required for explaining experimental results. We propose here a novel very simple physical method of the “effective thickness” approach.

The effective thickness approach

AO Bragg gratings are analogues to multilayer mirrors [3] and have many of their properties. The interesting of multi-layer gratings lays in the property that the total reflected field is a result of the interference of a lot of beams reflected from different layers located at different depths. This factor determines both the strong angular selectivity of the reflected beam and the mutual coherence of neighbouring points of optical field. If the grating is formed by the periodic acoustic wave the characteristics of the reflection is determined by the acoustic frequency and acoustic power. The acoustic wave introduces a periodic refractive index pattern with changes $\Delta n = -\frac{1}{2} n^3 p \sqrt{\frac{2P_a}{\rho V^3 HL}}$ [4] as illustrated in figure 1.

Here n is the refractive index of material, p is the effective acousto-optic coefficient, P_a is the acoustic power, ρ is the density of material and V is the sound velocity, H and L are in fact the dimensions of piezo-transducer, so P_a/HL is the acoustic power density.

The electrical field at point “d” of the scattered light I_d is formed by the fields scattered from “n” different layers. At ‘d’ we have the following expression for the electrical field

$$E_d = E_1 + E_2 + \ldots + E_n. \quad (1)$$

The intensity in this point is

$$I_d = E_d \times E_d^* = \left(E_1 + E_2 + ..E_n\right) x \left(E_1 + E_2 + ..E_n\right)^*$$
$$= E_1 \times E_1^* + E_2 \times E_2^* + ...E_n \times E_n^* + \sum_{i \neq k}^{n} E_i \times E_k^* \quad (2)$$

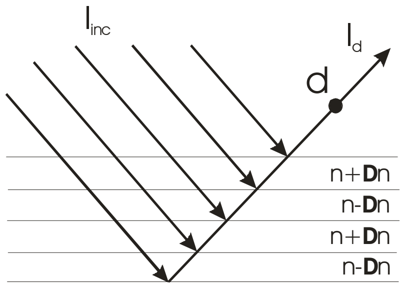

Figure 1: Optical scheme of the scattering process

In expression (2) the term $I_{in} = \sum_{i \neq k}^{n} E_i \times E_k^*$,where I_{in} is the interference part, is very important for the scattering process. When all fields $E_1, E_2, ...E_n$ are not mutual coherent, $I_{in}=0$, and $I_d = E_1^2 + E_2^2 + ... + E_n^2$. If we take for simplicity $E_1 = E_2 = ... = E_n$, then $I_d = nE_1^2$.

If all beams are coherent with respect to each other and all of them are in phase, $I_d = (nE_1).(nE_1) = n^2 E_1^2$. We see that the ratio of these two cases is 'n'. When n is big, the contrast between coherent and non-coherent interference is large. When the incident light is partially coherent, we have the intensity of reflected light between nE_1^2 and $n^2 E_1^2$. The angular width of the scattered light is $\Delta\varphi \sim 1/n$. Hence the coherence degree of a light beam interacting with a large number of layers of the acoustic grating can be strongly influenced.

Experiments

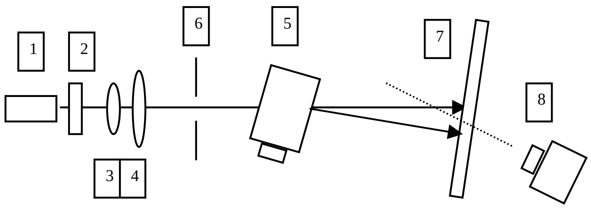

Figure 2: Optical set-up.

The physical model for the description of the coherence increase of a partially coherent beam by means of the AO interaction in the Bragg regime was verified with the set-up of figure 2. Highly coherent optical radiation generated by a He-Ne laser 1 (λ = 0.63 μm) is scattered by diffuser 2 made from a glass plate, of which one side was polished by powder M5, leading to a surface roughness of about $5\,\mu m$. The scattered radiation is collimated by lenses 3 and 4 into a convergent beam with beam waist ~ 0.5 cm. The AO cell 5 is made from a TeO_2 crystal with dimensions 8x8x10 mm along the directions $[110],[001],[1\bar{1}0]$, respectively, which was placed into the beam waist. In front of the AO cell diaphragm 6 is placed. Behind the AO cell the outgoing beams are directed towards the semitransparent screen 7. The beam spots on this screen are photographed by means of camera 8.

Figure 3: 0th (left) and 1st (right) orders of AO diffraction at different levels of acoustic power.

In Fig. 3 we shown typical photographs of the speckle structure of non-diffracted beams (left spot) and diffracted into 1st order (right spot) at different levels of acoustic power. The acoustic frequency is 46.8 MHz, the AO interaction length is 6 mm. It can be seen that at low acoustic power (upper picture) the grains of the diffracted beam are bigger and the background is suppressed. Therefore the degree of the spatial coherence is bigger in comparison with the non-diffracted light. With the increase of the acoustic power (middle at bottom, consequently) the level of noise increases, the degree of the coherence of diffracted and non diffracted beams starts to be equal to each other. This phenomenon can be explained by the fact that for increasing acoustic power, the refractive index change Δn increases and hence the number of layers participating to the diffraction pattern decrease. In other words the effective thickness of the acoustic grating decreases with the acoustic power.

Our model can explain the difference between isotropic and anisotropic diffraction in anisotropy media. In Figure 4 we shown the photographs of speckle structures of beams diffracted in 'close to axis' (a) and 'far off axis' (b) regimes in TeO_2. The acoustic power is chosen such that the intensities of the 0^{th} and -1^{st} orders are to equal each other. It can be clearly seen that the speckle structure of the -1^{st} order of anisotropic diffraction is more coherent, the dimensions of the grains are bigger, the small-grain noise is suppressed.

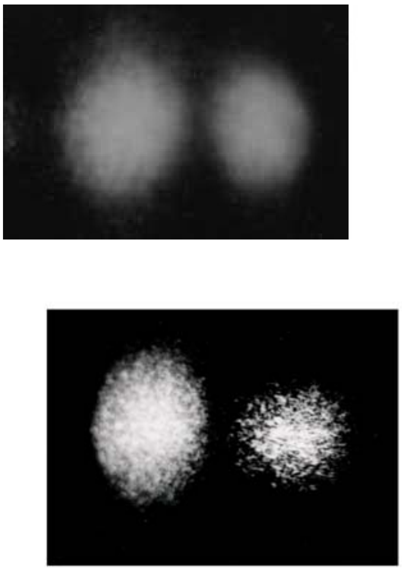

Figure 4: "Close to axis" (top) and "far off axis" (bottom) regimes of AO diffraction

We also investigated the influence of multi-phonon (three-phonon) AO diffraction on the degree of coherence. The vector diagram of the 3-phonon diffraction including the phase mismatch is shown in figure 5.

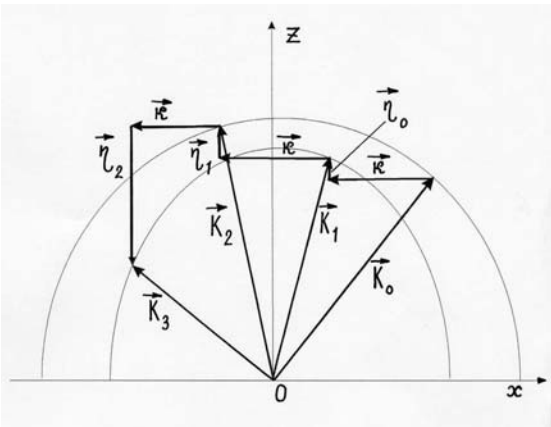

Figure 5: Vector diagram of 3-phonon AO diffraction

In figure 5 K_0,K_1,K_2,K_3, **k** are the wave vectors of 0^{th}, 1^{st}, 2^{nd}, 3^{rd} orders of light and acoustic wave vector, respectively. η_0, η_1, η_2 are the wave vectors of mismatch.

As the constraints on the matching is much tighter here, as illustrated in figure 6, the angular selectivity of 3-phonon diffraction is much higher than that of the common regimes.

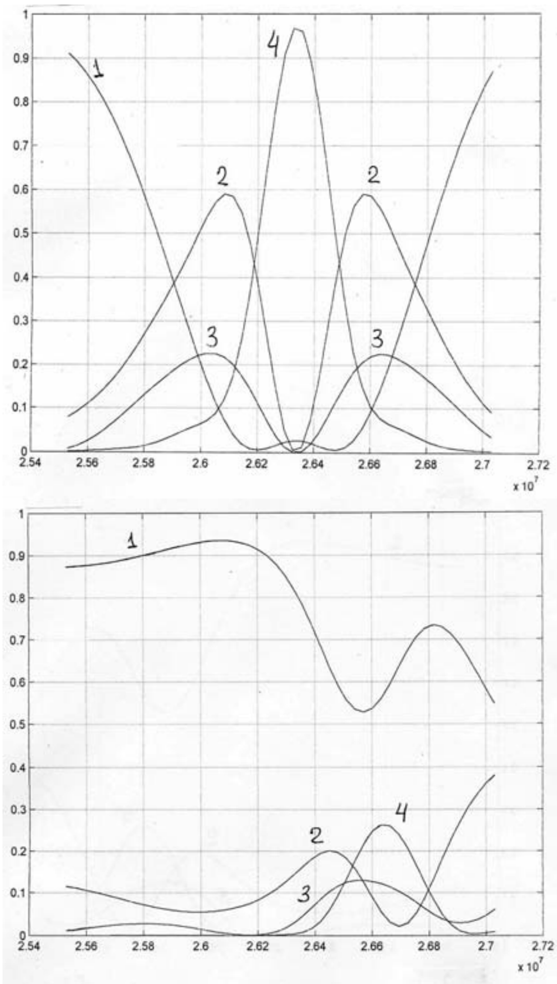

Figure 6: Relative intensities of the 0^{th}, 1^{st}, 2^{nd}, 3^{rd} diffracted orders (curves 1, 2, 3, 4 respectively) versus the acoustic frequency. Top figure corresponds to strong synchronisation, Bottom figure corresponds to an angular mismatch of 1 min.

One can deduce from Figure 6 that it should be possible to concentrate all optical energy in the highest (i.e. 3^{rd}) order. However, in our experiments we could not reach this situation, as the divergence of the beam is much higher that angular resonance of the 3-phonon AO interaction. Experiments of the 3-phonon diffraction are conducted for (λ = 0.63 μm) at the resonance frequency (28 MHz) of TeO_2. These experiments as shown in figure 7, reveal that by increasing the acoustic power the intensity of the higher orders gradually increase and always have the highest degree of coherence.

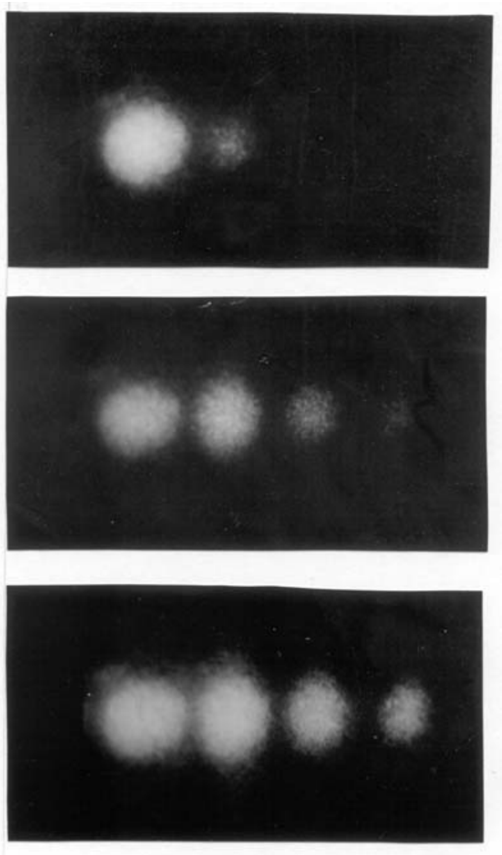

Figure 7: The 0^{th} (left), 1^{st}, 2^{nd}, 3^{rd} (right) diffraction orders of 3 phonon diffraction at different acoustic power levels. From top to bottom the acoustic power increases.

We also compared the three different regimes which can be realized at the same acoustic frequency of 28 MHz. In according with our investigations the regime of 3-phonon Bragg diffraction is the best among the investigated regimes at the 3-phonon resonance frequency. At higher acoustic frequencies, however, the anisotropic regime of diffraction is the best for the increase of the degree of spatial coherence.

Conclusions

The influence of the anisotropic AO Bragg diffraction in the uniaxial crystal TeO_2 on the degree of spatial coherence of the partially coherent light was experimentally investigated. It is shown that the largest increase of the degree of spatial coherence occurs at low levels of acoustic power. This phenomenon can be explained by the changes of the effective thickness of the scattering grating. For larger acoustic powers, the effective thickness decreases.

Two regimes of anisotropic Bragg diffraction where experimentally compared: when light propagates close to the optical axis (1^{st} regime) and far-off-axis (2^{nd} regime). It is shown that the 2^{nd} regime is much better. This can be explained in the framework of the scattering of light from a "thicker" multi-layer structure. This difference can be up to 15 times for an acoustic frequency around 60 MHz. Finally the 3-phonon regime of diffraction is also investigated and compared with two previous regimes of anisotropic diffraction. It is show that at resonance 3-phonon frequency the 3-phonon variant is the best for the increasing of the degree of the spatial coherence among all investigated AO regimes.

Acknowledgments

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