Two-Frequency Degeneracy of Acousto-Optic Interaction in Paratellurite

Alexander V. Yurchenko, Vladimir M. Moskalev

Department of Quantum Radiophysics, Kiev Taras Shevchenko University, 64, Vladimirskaya str., 252033 Kiev, Ukraine

Abstract: An effect of two-frequency acousto-optic degeneracy in paratellurite is predicted and grounded. Necessary calculations have been carried out. The found effect is shown to take place and to be important for real acousto-optic devices. Compared to the known mechanism, its essence consists in the fact that a light beam can be diffracted twice by acoustic waves of different frequencies instead of being typically diffracted twice by the same acoustic wave. It happens due to strong acoustic anisotropy of paratellurite. A light beam diffracted by one spectral component of a complex acoustic signal can be effectively diffracted again by another spectral component. In the studied case, the frequencies of acoustic waves interacting with a light beam were equal to 43.7 MHz and 44.2 MHz correspondingly.

The essence of an acousto-optic degeneracy in an anisotropic deflector using TeO$_2$ is that a light wave diffracted by a shear acoustic wave propagating exactly along the [110] axis, then can be diffracted once again by the same acoustic wave. It is getting possible because the synchronism conditions are satisfied simultaneously for two types of acousto-optic interactions - for a slow light wave and for a fast light wave, i.e. in this case wave-vector diagrams are completely symmetrical about the optic axis. First this effect was described and explained in (1). To avoid disadvantages of a deflector with this effect, a new deflector was suggested (2) in which a symmetry had been violated due to an acoustic wave propagating at a small angle (6°) to the [110] axis. Then such deflectors were investigated by many authors including thorough theoretical studies for a case of divergent sound wave carried out in (3). All of them dealt with cases where a light wave was diffracted twice by an acoustic wave of the same frequency. However the strong anisotropy of paratellurite makes it possible for a light wave to be diffracted twice by two acoustic waves of different frequencies. This case is considered in the present work.

The mechanism of two-frequency degeneracy in TeO$_2$ consists in the repeated diffraction of a light beam by acoustic waves with different frequencies instead of being typically diffracted twice by the same acoustic wave. Bragg conditions resulted in the degeneracy can be satisfied under a certain frequency correlation of two slow acoustic shear waves. A light beam diffracted by one spectral component of a complex acoustic signal can be effectively diffracted again by another spectral component. Thus, a physical mechanism of this effect is the same as in the ordinary case but it takes place under different conditions (different sound frequencies). To clarify conditions of two-frequency degeneracy arising and to find frequencies of acoustic waves by which incident light is scattered, let us consider a wave-vector diagram presented in Fig. 1. It shows an acousto-optic interaction in TeO$_2$ in the (001) plane. A case is considered similar to the one described in (2), i.e. the case when an acoustic wave is propagating at some angle $\alpha_C$ to the [110] axis. An incident light wave of a slow mode with a wave vector $k_1$ is diffracted by that acoustic wave with a wave vector $K_C$. The necessary condition for an effective interaction is the validity of the quasi-momentum law. Therefore there is no degeneracy in this case because the diffracted light wave of a fast mode with a wave vector $k_2$ can not be scattered again into a light wave with a wave vector $k_{1D}$ by an acoustic wave propagating in the same direction, for $AC \neq CD$, i.e. $|K_D| \neq |K_C|$. On the other hand, it is possible to find an acoustic wave for which such scattering can take place. This is an acoustic wave with a wave vector $K_E$, found from a condition $|K_E| = |K_C|$ which propagates at a different angle $\alpha_E$ to the [110] axis. Because of strong anisotropy of sound velocity in TeO$_2$ the difference between velocities of those acoustic waves can be noticeable. Thus, to satisfy the condition $|K_E| = |K_C|$ at different sound velocities, sound frequencies are to be different as well.

Calculations of degeneracy frequencies can be made using a wave-vector diagram in Fig. 1. At a given light wavelength $\lambda$ and an incident angle $\theta_1$, the length of an arbitrary acoustic vector $K$ depends only on an angle $\alpha$, which determines its direction. Thus, since $|K| = 2\pi f/v$, where $v$ and $f$ is a velocity and a frequency of an acoustic wave, one can say that the angle $\alpha$ is a function of $f$, i.e. $\alpha = \alpha(f)$. In this sense the angles $\alpha_C$ and $\alpha_E$ are also functions of $f$. Then for every operating wave vector $K$ and frequency $f$ there will be existing "a degeneracy wave.
vector $K_d$ and a degeneracy frequency $f_d$ exactly as for vectors $K_C$ and $K_E$ in Fig. 1.

That is a function $f_2(f, \theta_1)$ can be constructed, which will connect operating and degeneracy frequencies. An incident angle $\theta_1$ is a parameter in this case. Now considering triangles OAC and OBE and taking into account that AC=CE, necessary equations can be derived:

$$
\sqrt{n_1^2(\theta_1) + n_2^2(\theta_2) - n_1(\theta_1) n_2(\theta_2) \cos(\theta_2 - \theta_1)} = \sqrt{n_1^2(\theta_E) - n_2^2(\theta_2) \cos^2(\theta_2 - \alpha_E) - n_2(\theta_2) \sin(\theta_2 - \theta_E)},
$$

(1)

where $n_1$ and $n_2$ are indexes of refraction for slow and fast light waves correspondingly, and $\theta_2$, $\theta_E$ and $\alpha_E$ are functions of $f(\theta_1)$ is a parameter). Functions $\theta_2(f, \theta_1)$ and $\theta_E(f, \theta_1)$ can be found from the geometry since $n_1(\theta)$ and $n_2(\theta)$ are known. Then from the equation (1), one can calculate $\alpha_E(f, \theta_1)$, and ultimately write the degeneracy frequency $f_d$ as a function of an operating frequency $f$:

$$
f_d(f, \theta_1) = |K(f, \theta_1)| v(\alpha_E(f, \theta_1)) / 2\pi,
$$

(2)

where $v(\alpha)$ is a known dependence of sound velocity on direction in TeO$_2$.

In this way, there were made the estimations of mentioned frequencies for a device with parameters close to those of an acousto-optic modulator investigated in (4). Initial calculation data were: the transducer length, $L=0.8$ mm; $\lambda = 633$ nm; $\theta_1=2.87^\circ$; $\alpha_C=4^\circ$; $\alpha_E=3.1^\circ$. Calculated values of frequencies were $f_d=44.2$ MHz and $f=43.7$ MHz. Thus, in such a device the spectral component $f$ of a complex acoustic signal can be suppressed by another spectral component $f_d$ of the same signal.

Of course, a two-frequency degeneracy will take place if both vectors $K_E$ and $K_C$ are located within a transducer pattern. At the transducer mentioned length this condition is satisfied. Hence the effect described can be important in real devices.

REFERENCES