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Yano et al.

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- [54] **ACOUSTO-OPTIC FILTER**
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- [52] **U.S. Cl.**..... **350/161; 350/149**
- [51] **Int. Cl.²**..... **G02F 1/34**
- [58] **Field of Search**..... **350/161, 149**

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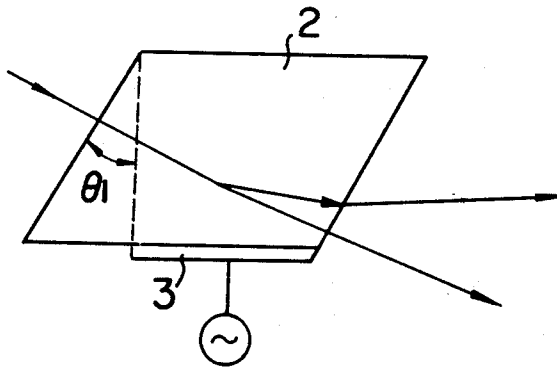
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[57] **ABSTRACT**

An acousto-optic filter utilizing the far-off-axis anisotropic Bragg diffraction comprising an optically anisotropic acousto-optic medium embodied by paratellurite. The light entrance surface is slanted to the crystalline axis to make a light beam incident perpendicularly to the surface. The light exit surface is slanted to the direction of the entrance surface to minimize the dispersion of diffracted angle due to light wave length.

6 Claims, 7 Drawing Figures



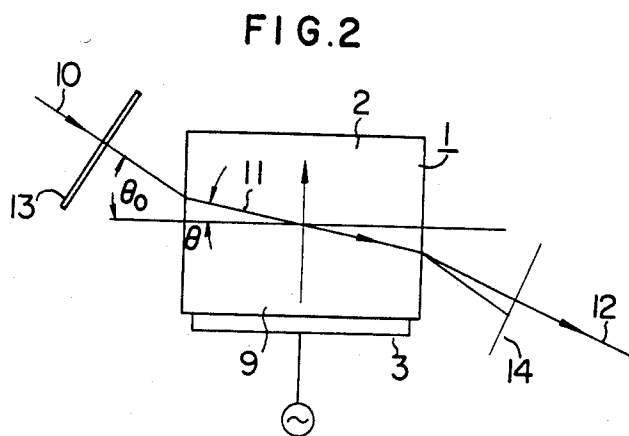
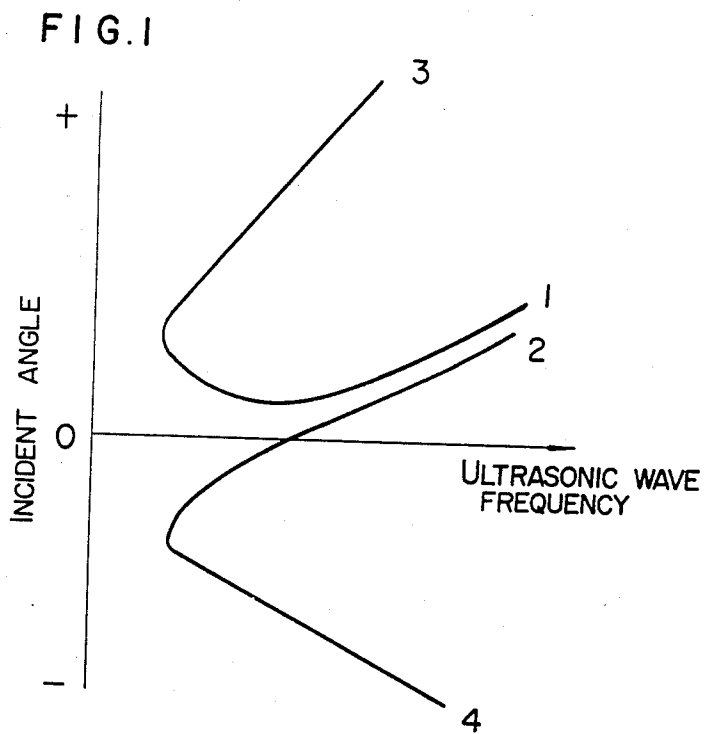


FIG. 3

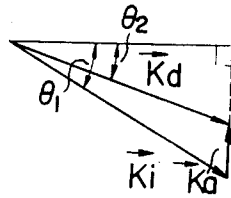


FIG. 4

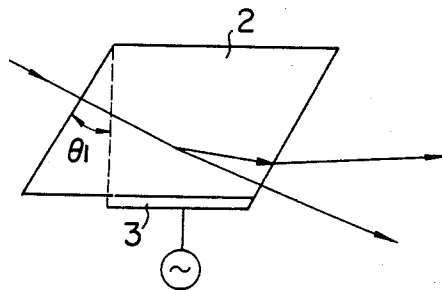


FIG. 5

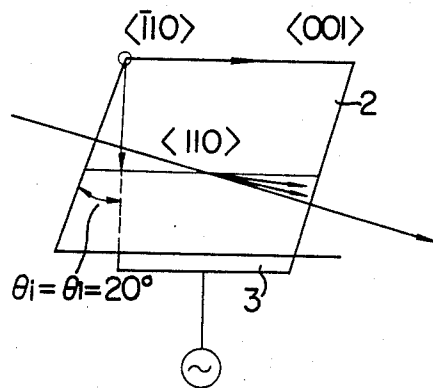


FIG. 6a

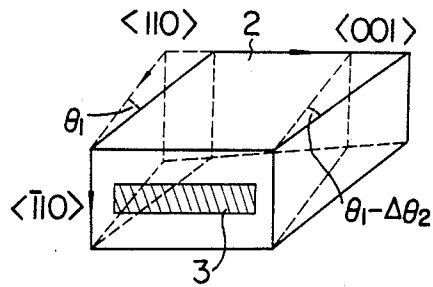
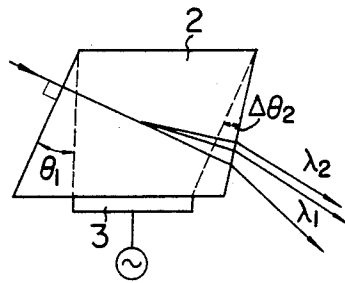


FIG. 6b



ACOUSTO-OPTIC FILTER

This invention relates to an acousto-optic filter for selecting light of an arbitrary wavelength from an incident light beam by changing the frequency of an ultrasonic wave appropriately, and more particularly to an acousto-optic filter in which incidence of light is normal to an incident surface.

An object of this invention is to provide an acousto-optic filter capable of reducing the variation in the angle of diffraction due to the wavelength change.

The above and other objects, features and advantages of this invention will become apparent from the following description when taken in conjunction with the accompanying drawings in which;

FIG. 1 is a diagram for illustrating the anisotropic Bragg diffraction;

FIG. 2 is a schematic cross-section of an acousto-optic filter utilizing the far-off-axis anisotropic Bragg diffraction;

FIG. 3 is a diagram of wave vectors for illustrating the operational conditions of the filter of FIG. 2;

FIGS. 4 and 5 are schematic cross-sections of acousto-optic filters; and

FIGS. 6a and 6b are a schematic perspective view and a schematic cross-section of a dispersionless embodiment of the acousto-optic filter according to this invention respectively.

Conventional acousto-optic filter may be classified into two broad classes. Namely, one is called the collinear type and the other the noncollinear type. In a collinear type acousto-optic filter, a light beam and an ultrasonic wave are propagated along the same linear line in an optically anisotropic medium to cause interaction therebetween. The non-collinear type includes the isotropic Bragg diffraction type and the far-off-axis anisotropic Bragg diffraction type. The latter has a far higher practical value. In an acousto-optic filter of the far-off-axis anisotropic Bragg diffraction type, a light beam and an ultrasonic wave are propagated at an angle different from the right angle therebetween to cause interaction. An example of a far-off-axis anisotropic Bragg diffraction type filter will be described with reference to FIG. 2 hereunder.

When an ultrasonic wave and a light beam are interacted in a crystal having two phase velocities of light in the propagating direction, diffracted light appears generally above a certain frequency of the ultrasonic wave when the Bragg's condition is satisfied. Here, the phase of the diffracted light varies by 180° from that of the incident light and the polarization changes. This is the so-called anisotropic Bragg diffraction. When the angle of incidence is further increased, another diffracted light appears at a certain angle.

The diffraction phenomenon at larger incident angles is called the far-off-axis anisotropic Bragg diffraction, and those at smaller incident angles are called the near-by-axis anisotropic Bragg diffraction. The relation between the angles of incidence and diffraction is as shown in FIG. 1. The far-off-axis anisotropic Bragg diffraction is generated above a certain frequency and the incident angle increases abruptly as indicated by curves 3 and 4. The near-by-axis anisotropic Bragg diffraction indicated by curves 1 and 2 is the phenomenon often utilized in conventional light deflectors and modulators.

In FIG. 2, a filter medium 1 comprises an acousto-optical medium 2 and a piezoelectric transducer 3. An electric signal is converted in the piezoelectric oscillator 3 to become an ultrasonic wave 9 propagating in a crystal. An incident light 10 is linearly polarized in a polarizer 13, is directed to the medium at an incident angle of θ_0 , propagates in the crystal in a direction forming an angle θ with respect to the optic axis, mutually interacts with the ultrasonic wave 9 propagating normal to the optic axis to generate a diffracted light 11. The diffracted light 11 emerges from the crystal as a linearly polarized beam having a plane of polarization rotated 90° from that of the incident light.

For generating the far-off-axis anisotropic diffraction, it is necessary to satisfy the relation of the wave vectors shown in FIG. 3. This can be expressed in the following formulae (1), (2) and (3).

$$\left. \begin{aligned} |\vec{K}_i| &= \frac{2\pi n_1}{\lambda_0} \\ |\vec{K}_d| &= \frac{2\pi n_2}{\lambda_0} \\ |\vec{K}_a| &= \frac{2\pi f_a}{v} \end{aligned} \right\} \quad (1)$$

Here, n_1 and n_2 are refractive indices for the extraordinary and ordinary rays when the normal of the light wave front is slanted by θ_1 and θ_2 from the optic axis, and can be expressed by the following equations.

$$\left. \begin{aligned} n_1^2 &= n_o^2 \left(1 + 2\delta \cos^2 \theta_1 + \frac{(n_e^2 - n_o^2)}{n_o^2} \sin^2 \theta_1 \right) \\ n_2^2 &= n_o^2 (1 - 2\delta \cos^2 \theta_2) \end{aligned} \right\} \quad (2)$$

In equations (1) and (2), λ_0 is the wavelength of light in vacuum, f_a the frequency of an ultrasonic wave, v the acoustic velocity of the medium, n_o and n_e refractive indices for the ordinary and extraordinary rays in the medium, and 2δ the gyration constant defined when the medium is optically active. Symbol \vec{K} represents a wave vector.

The angles of incidence and diffraction for a far-off-axis anisotropic Bragg diffraction can be obtained as the larger solutions of θ 's satisfying the following equations (3) from equations (1) and (2) or from FIG. 3.

$$\left. \begin{aligned} \frac{2\pi n_1}{\lambda_0} \cos \theta_1 &= \frac{2\pi n_2}{\lambda_0} \cos \theta_2 \\ \frac{2\pi n_1}{\lambda_0} \sin \theta_1 - \frac{2\pi n_2}{\lambda_0} \sin \theta_2 &= \frac{2\pi f_a}{v} \end{aligned} \right\} \quad (3)$$

An approximated solution of θ_1 can be expressed as

$$\sin \theta_1 = \frac{\lambda_0}{v(n_e - n_o)} f_a \quad (4)$$

In an acousto-optic filter, the angle of incidence θ_1 is fixed and the frequency of the ultrasonic acoustic wave f_a is changed to tune λ_0 .

Generally in acousto-optic filters according to this method, the entrance and exit surfaces are slanted by θ_1 to make normal entrance and exit of light as shown in FIG. 4. Here, the angle of diffraction θ_2 can be expressed from equations (3) as

$$\cos\theta_2 = \frac{n_1}{n_2} \cos\theta_1 \quad (3)'$$

When the wavelength is varied, n_1 and n_2 vary so that the angle of diffraction θ_2 varies depending on the wavelength as seen from FIG. 3. For example, when paratellurite is used as the medium, a transverse displacement wave is generated having an oscillation in the $\langle 110 \rangle$ direction and propagation along the $\langle 110 \rangle$ direction, and a light beam is directed with an angle θ_1 of 20° slanted from the $\langle 001 \rangle$ axis and with a polarization corresponding to the extraordinary ray as is shown in FIG. 5, the angle θ_2 is equal to $18^\circ 49'$ at a light wavelength of $\lambda = 6328\text{\AA}$ and outside the crystal the exit direction is shifted about $2^\circ 31'$ from the incident direction. For light of $\lambda = 4880\text{\AA}$, $\theta_2 = 18^\circ 44'$ and the shift is about $2^\circ 57'$ outside the crystal.

Since the diffraction angle changes depending on the wavelength of light in this way, when an acousto-optic filter is used for color separation or as a spectrometer, there is a drawback that a light detector should be moved depending on the wavelength.

According to a basic embodiment of this invention, the exit surface is not formed parallel to but slanted by a small angle from the direction incident surface, thereby eliminating the above drawback.

The embodiment utilizing paratellurite as the acousto-optic medium is shown in FIGS. 6a and 6b. In the figures, an acousto-optic filter comprises an acousto-optic medium 2 and a transducer 3. The normal direction of the exit surface is slightly slanted to the optic axis ($\langle 001 \rangle$ axis) by $\Delta\theta_2$ as compared with the incident surface. The relation between angles of incidence and diffraction can be expressed by the following equations by Snell's law and equation (3).

$$\left. \begin{aligned} n_1 \cos\theta_1 &= n_2 \cos\theta_2 \\ n_2 \sin(\theta_2 - \Delta\theta_2) &= \sin\theta_3 \end{aligned} \right\} \quad (5)$$

These equations (5) are solved over the whole wavelength region required and the most preferable value of $\sin\theta_3$ is determined to decide $\Delta\theta_2$.

Assuming the angle of incidence to be set at $\theta_1 = 20^\circ$, when the offset angle $\Delta\theta_2$ is set at $\Delta\theta_2 = 3^\circ 19'$, for light of $\lambda = 6328\text{\AA}$, the angle of incidence to the exit surface in the crystal is $2^\circ 8'$ and the exit angle outside the

crystal is $4^\circ 48'$, and for light of $\lambda = 4880\text{\AA}$ the values are $2^\circ 3'$ and $4^\circ 47'$.

In this case, the shift between the exit angles for light of 6328\AA and 4880\AA which was 18 minutes in the conventional arrangement is reduced to about 1 minute according to this invention. Here, the shift in the exit angle is within the same order for other wavelengths.

As is described above, the variation in the exit angle can be reduced and lights of various wavelengths can be obtained in substantially the same direction according to this invention.

What is claimed is:

1. An acousto-optic filter comprising: a medium in which light has two different phase velocities in a propagating direction, said medium having entrance and exit surfaces for light rays, transducer means for propagating an ultrasonic wave in said medium, and means for directing a light beam to the entrance surface of said medium so as to cause far-off-axis anisotropic Bragg diffraction with said ultrasonic wave, said diffraction occurring at a relatively large incident angle with respect to the plane of the wave front of said ultrasonic wave in said medium, the propagation direction of the diffracted light being displaced from the plane of the wave front of said ultrasonic wave in the same direction as that of undiffracted light to produce optical filtering, the entrance surface of said medium being slanted by a predetermined angle from the plane normal to the wave front of the ultrasonic wave.
2. An acousto-optic filter according to claim 1, wherein said medium is a paratellurite single crystal.
3. An acousto-optic filter according to claim 1, wherein the normal direction of the exit surface of said medium is slanted from the normal of the acoustic wave front by a different angle from that of the entrance surface so as to minimize the variation in the exit angle of a transmitted light beam due to variations in the wavelength.
4. An acousto-optic filter according to claim 3, wherein said medium is a paratellurite single crystal.
5. An acousto-optic filter according to claim 4, wherein said acoustic wave is propagated along the $\langle 110 \rangle$ direction of the paratellurite single crystal.
6. An acousto-optic filter according to claim 5, wherein the normals of the entrance surface and the acoustic wave front make an angle of 20° and the normals of the exit surface and the acoustic wave front make an angle of $16^\circ 41'$.

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