Physics Letters A 382 (2018) 2226–2229

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Opto-mechanic oscillatory system based on birefringent crystal

Vitaly B. Voloshinov *, Nataliya V. Polikarpova

Physics Faculty, Lomonosov Moscow State University, Moscow 119991, Russia

ARTICLE INFO

Article history:
Available online 13 October 2017
Communicated by S. Vyatchanin

Keywords:
Oscillatory system
Torsional pendulum
Photons
Momentum
Energy
Birefringence

ABSTRACT

The paper presents a proposal on a new concept of opto-mechanic oscillatory system applying an optic birefringent crystal and a laser. Additionally to the crystal and the laser, the system uses an optic modulator maintaining mechanic torsion oscillations in the system. The principle of the system operation is described using traditional theory of optic waves in crystals and also applying the corpuscular approach based on the concept of energy and momentum of photons. We prove that operation of the system is most efficient in case of optic crystals demonstrating strong birefringence.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

The authors of the paper represent Physics Faculty of Lomonosov Moscow State University. We prepared this contribution in memory of Professor Vladimir Braginsky. Professor Braginsky was our next-door neighbor and good old colleague at the Division of Oscillation Physics in the University. During a few decades, we have been working in close scientific contact with this outstanding person who used to discuss with us various problems of mutual interest. In the beginning of the paper, we specially note that the principal idea of this research was proposed after fruitful discussions with this prominent scientist.

It is known that various types of mechanical oscillatory systems have been successfully used in science and technology [1–6]. Recent progress in precise measurement of weak forces, spatial displacements and shift of frequency is related to the development of sensitive mechanical, electrical and optical instruments. Oscillatory devices and systems such as resonators, interferometers, probe masses, etc., may be mentioned in this context [2–6]. Novel modifications of traditional torsional pendulums and oscillatory systems of other types may be attributed to these systems used as sensors [1–10]. The instruments are usually characterized by the advantage of low dissipation of energy and high quality factors. It means that the instruments do not require much power to maintain and control oscillations.

In the paper, we describe a principally new concept of an opto-mechanic torsional pendulum intended to carry out precise measurements of external impact. The mechanical part of the pendulum is rather simple and consists of a birefringent optic crystal attached to a thin quartz thread used as the crystal suspension. The optical part of the device includes a laser source of light, mirrors and a laser modulator. The crystal is illuminated by the laser whose intensity of radiation is modulated at the mechanical fundamental frequency of the pendulum. The opto-mechanical oscillatory system allows remote regulation of its operation characteristics by control of intensity and polarization of the laser beam.

The layout of the paper is the following. Section 1 examines propagation of optical waves and photons in an isotropic glass plate. Section 2 briefly considers optical birefringence of crystals and discusses directions of phase and group velocities of optic waves. In Section 3 of the contribution, we analyze propagation of waves and photons in a birefringent medium. In Section 4, we discuss directions of phase and group velocities of optic waves in a birefringent crystal. Section 5 describes propagation of a photon in the birefringent plate. We also evaluate magnitudes of momentum and energy of photons propagating in the anisotropic medium. Finally, Sections 6 and 7 describe the operation of the torsional pendulum and explain the principle of operation of the designed oscillatory system.

2. Propagation of optic waves and photons in a glass plate

We start our analysis considering a simple plane parallel glass plate transparent to optic radiation. The optically isotropic plate is surrounded by the vacuum and illuminated by a plane optic wave. According to fundamentals of wave optics [11,12], we can

* Corresponding author.
E-mail addresses: volosh@phys.msu.ru (V.B. Voloshinov), polikarp@phys.msu.ru (N.V. Polikarpova).

https://doi.org/10.1016/j.physleta.2017.10.018
0375-9601/© 2017 Elsevier B.V. All rights reserved.

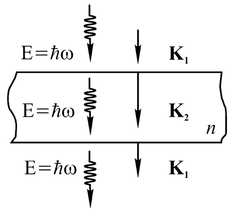

Fig. 1. Energy and momentum of photon propagating in the vacuum and in the glass plate.

state that wavelength and frequency of the wave in vacuum are correspondingly equal to λ and ν. The relation between these parameters is $\lambda = c/\nu$, where c is the speed of light in vacuum. If the optic wave is incident on the plate and propagates in it then both the wavelength and the optic phase velocity decrease correspondingly to λ/n and c/n, where n is the refractive index of the glass. It is also evident that the optic frequency in the glass remains unchanged with respect to the frequency ν of the wave in the vacuum. Finally, magnitudes of the optic wave vector in vacuum and in the glass may be written correspondingly as $|\mathbf{K}| = 2\pi/\lambda$ and $|\mathbf{K}| = 2\pi n/\lambda$.

The same effect of optic wave propagation in vacuum and in the glass plate may be treated on base of the corpuscular theory of light [1,11,12]. According to the theory, we can state that an optic beam is composed of photons. Each of them in the vacuum is characterized by the energy $E = h\nu = \hbar\omega$ and by the momentum $\mathbf{K}$. The momentum is a vector characteristic, absolute value of which is $|\mathbf{K}| = h\nu/c = \hbar\omega/c$. Normal incidence and propagation of the photon in the plate are illustrated in Fig. 1. As seen, the energy of the photon in the plate and in the vacuum remains unchanged $E = \hbar\omega$ while the momentum is changing from $\mathbf{K}_1$ to $\mathbf{K}_2$ and then back to $\mathbf{K}_1$, where $|\mathbf{K}_1| = \hbar\omega/c$ and $|\mathbf{K}_2| = \hbar\omega n/c$. It means that the magnitude of the momentum in the medium is increasing by a factor of n. However, leaving the medium, the photon looses part of its momentum so that the momentum magnitude changes back to the intrinsic value $|\mathbf{K}_1| = \hbar\omega/c$. The physical phenomenon of propagation and change of the momentum magnitude may quite reasonably be explained by the assumption that the glass-vacuum interface gets impact from the incident photon, absorbs it and then reradiates the photon in the volume of the glass [1,11]. Absorbing and reradiating the photon, the surface increases its momentum. However, leaving the medium, the reradiated photon returns the extra portion of the obtained momentum to the medium. All these effects take place at the input and output facets of the glass plate.

3. Optic waves propagating in birefringent crystals

It is known that two types of orthogonally polarized optic waves may propagate in a birefringent crystal. These waves are defined as the "ordinary" and "extraordinary" optic modes [11,12]. The index of refraction of the ordinary optic mode is equal to n_o and it does not change with direction of propagation in the crystal. As for the refraction index $n_e(\varphi)$ of the extraordinary mode, it depends on optic polar propagation angle φ that is usually evaluated relatively to the optic axis

$$n_e(\varphi) = \frac{n_o n_e}{\sqrt{n_e^2 \cos^2\varphi + n_o^2 \sin^2\varphi}}. \tag{1}$$

According to Eq. (1), this index varies from $n = n_o$, along the optic axis at $\varphi = 0$, to the magnitude $n = n_e$, observed at $\varphi = \pi/2$ in orthogonal directions. The birefringence exceeds zero $\Delta n = n_e - n_o > 0$ in a positive birefringent crystal while in a negative crystal, the birefringence is negative $\Delta n < 0$. In the majority of optic crystals, the relative birefringence $\Delta n/n_o$ is low and does not exceed 0.1, i.e., 10%. On the other hand, recent progress in development of new crystalline materials, periodic structures and metamaterials demonstrates that there are media characterized by amazingly high magnitudes of the birefringence, e.g., up to $\Delta n/n_o \le 0.6$ [13].

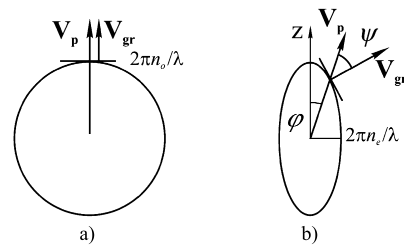

Fig. 2. Cross-section of wave vector surfaces for ordinary (a) and extraordinary (b) polarized waves.

It is known that optic waves in isotropic media propagate in such a manner that their phase $\mathbf{V}_\mathrm{p}$ and group $\mathbf{V}_\mathrm{gr}$ velocity vectors as well as their wave vectors $\mathbf{K}$ and Poynting vectors $\mathbf{S}$ coincide in space [11–13]. Data in Fig. 2a prove this general statement for the ordinary polarized waves. In the figure, we show the cross-section of an optic wave surface or a "slowness" surface, i.e., the surface of inverse velocity $(1/V_p)$ in a uniaxial negative crystal. We can treat the wave surface or the slowness curve $(1/V_p)$ just as the surface showing possible directions of the optic wave vectors $\mathbf{K}$. On the other hand, in every point of the slowness curve, a normal to its tangent shows direction of the corresponding group velocity vector $\mathbf{V}_\mathrm{gr}$ or the Pointing vector $\mathbf{S}$ [11,12]. As proved in Fig. 2a, the phase and group velocity vectors for the ordinary polarized waves coincide.

As for the extraordinary polarized light, the corresponding cross section of the wave surface in a negative crystal is presented in Fig. 2b. Using the above presented consideration, we can find directions of the group $\mathbf{V}_\mathrm{gr}$ and phase $\mathbf{V}_\mathrm{p}$ velocity vectors. As seen, the vectors are separated in space by the optic walkoff angle ψ. It means that the optic Poynting vector $\mathbf{S}$ deviates from the direction of the wave vector $\mathbf{K}$. It also means that the flow of optic energy in a birefringent medium is not orthogonal to the optic wave front [11–13].

4. Optic walkoff angle between phase and group velocity of light

It may be shown that the magnitude of the walkoff angle ψ in a negative crystal depends on indices of refraction according to the expression

$$\psi = \arctan\left[(n_e/n_o)^2 \tan\varphi\right] - \varphi, \tag{2}$$

where φ is the polar angle between optic axis Z of a crystal and the direction of the wave vector $\mathbf{K}$ [13]. In case of low birefringence, i.e., if the magnitude $\Delta n/n_o < 0.1$, the expression for the walkoff angle may be approximated as follows

$$\psi \approx \arctan\left[(1 - \Delta n/n_o)^2 \tan\varphi\right] - \varphi. \tag{3}$$

It means that the walkoff angle increases with the relative birefringence. The length of the wave vector in the plate for the extraordinary polarized radiation is written as $|\mathbf{K}_2| = 2\pi n_e(\varphi)/\lambda$. As seen, the length is dependent on the index of refraction $n_e(\varphi)$ along the propagation angle φ. According to results of our analysis, the walkoff angle ψ grows with the relative birefringence $\Delta n/n_o$, as illustrated in Fig. 3. The drawing proves that such single crystals as tellurium (Te), the crystalline compounds of mercury (Hg_2Cl_2 and Hg_2Br_2) as well as antimony sulfur-iodide (SbSI) possess walkoff angles exceeding $\psi = 15°$ and approaching $\psi = 25°$ [13].

Download English Version:

https://daneshyari.com/en/article/8203087

Download Persian Version:

https://daneshyari.com/article/8203087

Daneshyari.com