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The use of a ring laser to study the space isotropy

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Abstract. An experiment is suggested for high-precision verification of the assumption concerning isotropy of the ambient space. The key element of the experimental setup is a ring laser with the cavity partially filled with a condensed matter.

1. Introduction

The unique properties of ring lasers open up wide possibilities for their use in high-precision studies in fundamental and applied physics. Such lasers are promising for search for various gravitational and relativistic effects [1 – 3] and creation of quantum frequency standards [4]. Ring lasers have been already used in measurements of the irregularity of the Earth rotation in order to determine the origin of this effect [5, 6]. At present, laser gyroscopes based on the unique features of ring lasers are widely used in precise navigation systems [7].

In this paper, we would like to point to the possibility of using modern ring lasers for precise investigations of the space isotropy.

The assumption about the optical isotropy of space (i.e., the assumption that the velocity of light wave is independent of the direction in space from a light source to an observer) is a fundamental postulate of the theory of relativity [8]. Space is assumed isotropic with respect to other optical phenomena as well. If space is isotropic indeed, then nonreciprocal optical effects [9] that are sensitive to the direction of light propagation relative to a material medium must be independent of the orientation of the experimental setup.

Note that in most experiments on precise measurements of the velocity of light, the velocity averaged over two opposite directions of the light propagation has been in fact measured [10].

The concept of the optical isotropy of space is generally accepted now, however, the correctness of this assumption can be only verified experimentally. The optical isotropy of space has been tested repeatedly in experiments (see, e.g., [11 – 13]). The least inaccuracy $\Delta c/c$ of measuring the light velocity dependence on the direction of light propagation in space is reported in [14] and is as small as 3×10^{-9}. Note that the space isotropy with respect to the inertial properties of material bodies has been verified to a high degree of accuracy ($\Delta m/m = 10^{-22}$ [15]).

Therefore, improving the accuracy of experimental investigations of the space isotropy is, undoubtedly, of particular interest.

A schematic diagram of the experiment under discussion is shown in Fig. 1. A principal element of the scheme is a ring laser with the cavity shaped as a figure eight. The cavity is partially filled with transparent elements whose refractive index differs from unity. Such a cavity can be made of fused quartz (similarly to that of a laser gyroscope [7]) as a single block with channels drilled in it to place the active medium. Transparent elements cut off at the Brewster angle or having the antireflection coating are also inserted inside the channels.

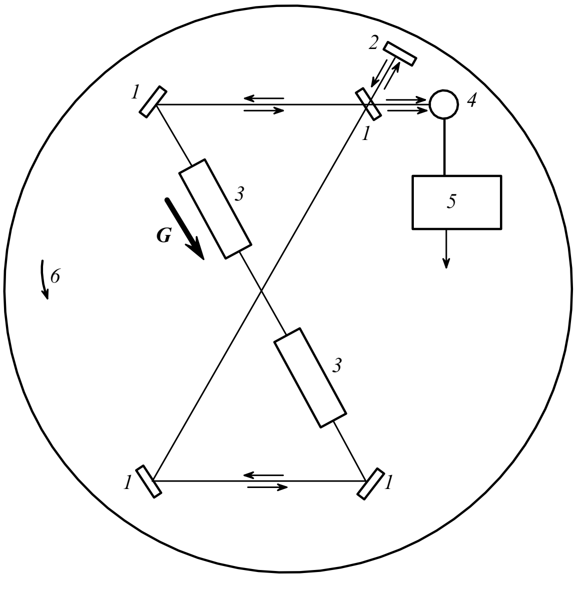

Figure 1. Schematic diagram of the experimental setup (active medium and elements providing the initial frequency offset are not shown): (1) mirrors of the laser cavity; (2) retrodirective mirror of the optical mixer; (3) transparent medium with the refractive index different from unity; (4) photodetector; (5) unit for measuring the frequency difference of counterpropagating waves; (6) rotary table.

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Let the space anisotropy be characterised by the vector $\boldsymbol{G}$ so that upon the propagation of the light wave along the direction of this vector the value of Δc is maximum, whereas upon the propagation of the light wave in the perpendicular direction, we have $\Delta c = 0$. For definiteness, we assume that the initial orientation of the cavity plane is parallel to the vector $\boldsymbol{G}$ and this vector is oriented as shown in Fig. 1.

The round-trip transit time for a light wave in the ring cavity partially filled with a material possessing the refractive index, which is different from that of the active medium, depends (in the presence of the space anisotropy) on the direction of the wave propagation [12]. As a result, the round-trip transit times for two counterpropagating light waves in the ring cavity will differ by the value

$$\Delta t = \frac{2(n-1)l\Delta c}{c^2} - \frac{l\Delta n}{c}. \tag{1}$$

Here, c is the velocity of light averaged over the two counterpropagating waves; Δc is a possible deviation of the velocity of the unidirectional wave from the average velocity of light; n is the refractive index of the condensed medium inside the cavity averaged over the two counterpropagating waves; l is the total length of two elements of this medium inserted inside the cavity; and Δn is the possible difference in the refractive indices of the condensed medium for the counterpropagating waves caused by the space anisotropy. In deriving (1), we used the fact that the refractive index of a conventionally used gas active medium is close to unity with a sufficient accuracy.

The difference Δt in the round-trip transit time for counterpropagating waves (whatever is the cause) results in the difference $\Delta\omega$ of the frequencies of these waves [16]

$$\Delta\omega = \frac{\omega\Delta t c}{L}, \tag{2}$$

where ω is the average frequency of the waves, and L is the optical length of the cavity. By combining (2) and (1), we obtain

$$\frac{\Delta\omega}{\omega} = 2(n-1)\frac{l}{L}\frac{\Delta c}{c} - \frac{l\Delta n}{L}. \tag{3}$$

It is obvious that the rotation of the laser in the plane of the cavity by 180° will change the sign of $\Delta\omega$. By comparing the values of $\Delta\omega$ for different laser orientations, one can determine whether or not the optical anisotropy of space is present. The dependence of $\Delta\omega/\omega$ on the refractive index of the medium allows one to separate effects caused by a possible deviation of the parameters Δc and Δn from zero. The experimental values of Δn are presented in [17].

It follows from the above discussion that the experimental setup should be placed on a table whose orientation in space (e.g., with respect to the direction to the centre of the Galaxy) can be changed. In this case, the search for the space anisotropy is reduced to precise measurements of the frequency difference between two counterpropagating light waves at various orientations of the table in space.

Turning back to a particular design of the ring laser (see Fig. 1), it should be noted that a figure eight cavity shape makes it possible to exclude the influence of the Sagnac effect on the radiation frequency of the space waves generated [16]. Such a cavity is insensitive to this effect if the areas of the triangles forming the ring cavity are equal and the transparent elements placed in different arms of the cavity are identical.

At present, the relative error $\Delta\omega/\omega$ of the frequency measurements in modern standard laser gyroscopes is 10^{-16}–10^{-17} [7], whereas in unique ring lasers this error can be reduced down to $10^{-21} - 10^{-22}$ [6]. Therefore, the experiment suggested can provide a record high accuracy (by several orders of magnitude higher than that obtained so far) of space anisotropy investigations.

Technical problems involved in carrying out these experiments (the necessity of providing a frequency-stable base, a magnetic shield, a rigid design of the ring laser and stable parameters of the latter, high-precision frequency measurements, etc.) can be solved on the basis of modern laser technologies (see, e.g., [3, 6]).

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