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A low-polarisation loss prism ring resonator

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***Abstract*. Polarisation losses are compared for three- and four-prism resonators and their origin is determined. The methods for reducing the resonator anisotropy and polarisation losses are considered.**

Keywords: *prism resonator, total internal reflection prism, polarisation losses.*

To reduce the errors of a laser gyroscope, which are caused to a great extent by nonlinear and thermal effects, it is necessary to provide its operation at a small gain in an active medium. Such an operating regime is possible at low losses in a resonator. In this connection the resonators formed by total internal reflection (TIR) prisms are of special interest [1]. In laser gyroscope of the KM type, a four-prism resonator is used (Fig. 1a). Each of the prisms has one TIR face and two refraction faces, which are oriented at the Brewster angle to incident radiation.

The prisms are fixed on a monoblock with soft solder and seal in pairs its vacuum channels in one of which a high-frequency discharge is initiated. The losses in such a resonator include losses due to scattering and absorption of radiation in surface layers and the prism material, diffraction and polarisation losses, as well as the useful losses due to radiation extracted from the resonator.

In an ideal case, radiation generated in a prism resonator should be linearly polarised, and the electric field strength vector $\boldsymbol{E}$ should lie in the plane of the axial contour (p polarisation). However, the distortion of the axial-contour planeness and the presence of stresses in the prism material result in the appearance of the s component, which is orthogonal to the contour plane. In this paper, we consider only polarisation losses and the methods for their reducing.

The polarisation losses are determined by three main reasons. The first one is errors in the manufacturing and assembling of the resonator. The modern level of technology makes it possible to reduce these errors to minimum.

The second reason is related to the fact that the wave front of a Gaussian beam is not plane but spherical and is determined by the optical scheme of the resonator. Because of this, radiation is incident on prism faces at the Brewster angle only in the axial part of the beam, so that the refraction faces of prisms represent polarisation-inhomogeneous elements.

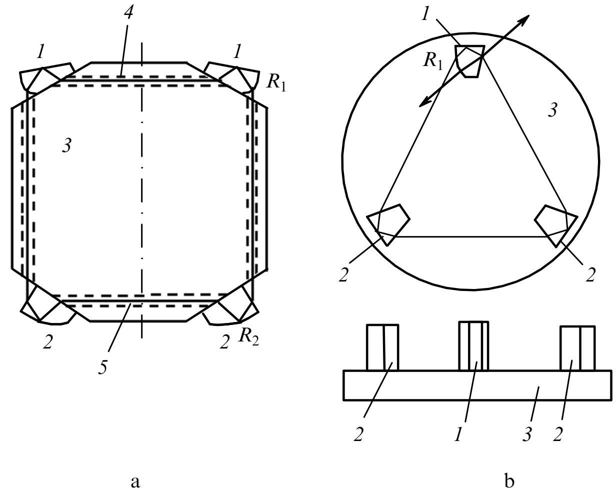

Figure 1. (a) Monoblock design with a four-prism resonator: (*1*) resonator prism with a spherical refraction face with $R_1 = 1$ m; (*2*) resonator prism with a spherical TIR face with $R_2 = 0.43$ m; (*3*) monoblock; (*4*) active channel; (*5*) passive vacuum channel and (b) planar design with a three-prism resonator: (*1*) resonator prism with a spherical refraction face with $R_1 = 1$ m and a plane refraction face to extract radiation; (*2*) resonator prisms with plane faces; (*3*) base plate.

The third reason is the stresses that are produced in prisms upon their fixing on a monoblock.

The polarisation losses caused by these reasons were calculated in Ref. [2]. According to these calculations, the polarisation losses in a properly manufactured and assembled ring prism resonator do not exceed 10^{-3} %. The total losses in such a resonator are of about 10^{-2} %, as follows from measurements. The real polarisation losses in a prism resonator can be estimated from the measurement of the intensity (power) of beams reflected from the refraction faces of TIR prisms.

To improve the design of a laser gyroscope from the point of view of the possible distortion of the planeness of the axial contour and the induced spatially inhomogeneous anisotropy of the prism material, we developed the so-called planar gyroscope with a three-prism resonator (Fig. 1b). Each of the prisms in this resonator, as in a four-prism resonator, has one TIR face and two plane refraction faces oriented at the Brewster angle relative to incident radiation.

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The exclusion is a prism mounted at the top of a triangle contour with one refraction face making angle 1° with the Brewster angle in order to increase the faction of the reflected p component and to extract radiation from the resonator. Another refraction face of this prism represents a sphere with the radius of curvature equal to 1 m.

The wave front in such a resonator proves to be more flat than that in a standard four-prism resonator containing four spherical faces: two of them with the radius of curvature equal to 1 m and two others, with the radius equal to 0.43 m.

Another specific feature of the planar design is the method of prism fixing. The prisms are fastened on a base plate by the method of optical contact. Unlike a monoblock design where prisms are mounted on a refraction face, here the fastening faces are not working ones. This method of prism fixing provides the remoteness of the caustic of light waves from the region of mechanical stresses produced in the prism upon its fixing, which also reduces the spatially inhomogeneous anisotropy of the resonator and its polarisation losses. It was shown in Ref. [3] that the stress in the prism at a distance of 10 mm from the optical contact was the same as in an unfastened prism.

We determined polarisation losses in resonators being compared by measuring the intensities of beams reflected from refraction faces of the prisms. To perform a comparative analysis of the planar and monoblock designs (we studied first of all the influence of stresses in the prisms on polarisation losses), we studied the resonator that was analogous to a standard monoblock resonator but was, however, formed by four identical TIR prisms, each of them having one spherical refraction face with the radius of curvature equal to 1 m. The three-prism resonator used in the planar design contained one spherical refraction prism of the same radius of curvature. Therefore, wave fronts in both resonators were sufficiently flat, which minimised the effect of their curvature on polarisation losses upon reflection from prism surfaces and the windows of a gas-discharge tube, allowing a comparative analysis to be made. Fig. 2 shows principal schemes for optical measurements.

In the monoblock design, we measured the intensities of beams reflected from spherical (beams *1* and *4*) and plane (beams *2* and *3*) faces of resonator prisms oriented an the Brewster angle to incident radiation. Beams (*1*) and (*2*) reflected from an unfastened prism, while beams (*3*) and (*4*) were reflected from a prism soldered to the monoblock surface with soft solder.

In the planar design, all the prisms are fastened on the base by the method of optical contact. In this case, we measured the intensities of beams reflected from the faces oriented at the Brewster angle (beams *2, 3, 4*) and from the face making an angle 1° with the Brewster angle to extract radiation from the resonator (beam *1*).

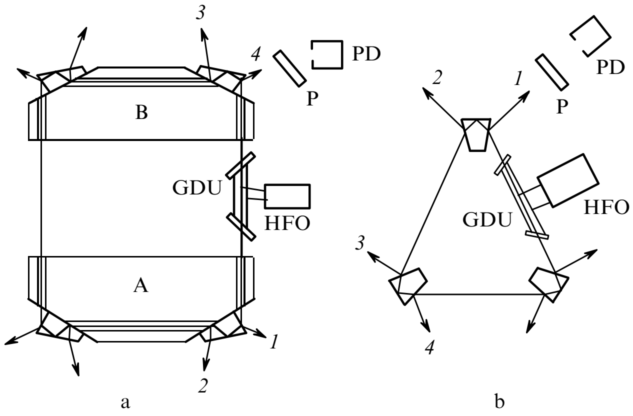

Figure 2. Principle schemes for measuring polarisation losses in ring monoblock lasers with (a) a four-prism resonator and (b) planar lasers with a three-prism resonator: (GDU) gas-discharge unit (discharge tube with Brewster windows); (HFO) high-frequency oscillator; (PD) photodetector for measuring the beam intensity; (A) block with unfastened prisms; (B) block with soldered prisms; (P) Polaroid; (*1–4*) beams reflected from the refraction faces of resonator prisms.

In front of a detector a Polaroid P was placed, which was used for separating, by rotating it, the p or s component of radiation. The active element in both cases was a gas-discharge tube with Brewster windows. A discharge in the tube was maintained with a high-frequency oscillator. We measured the dependence of the intensity of the p and s radiation components on the excess of the pump power over the threshold. To calibrate the losses, we used the fact that the angle φ_B of incidence of radiation on one of the prism faces in a three-prism resonator is 1°, which, according to calculations, provides the reflection of 0.0093 % of incident radiation. Knowing the intensity I_{pl} of the beam reflected from this face, we can find polarisation losses on another face:

$$\varkappa_{pol} = (0.0093/I_{p1})I_m,$$

where I_m is the power of the beam reflected from the refraction face.

For correctness, the measurements would be performed in the working regime of the laser gyroscope, i.e., in the single-frequency single-mode regime. However, an extremely low power of the beams reflected from refraction faces at the Brewster angle makes the measurements unreliable. Because the instability of external factors is less pronounced in the multimode regime, we performed measurements in the multimode regime when the pump power exceeded the threshold by five times. However, in this case, as follows

Table 1.

Resonator design	p-component losses				s-component losses			
	$\varkappa_{p1}/10^{-4}$ %	$\varkappa_{p2}/10^{-4}$ %	$\varkappa_{p3}/10^{-4}$ %	$\varkappa_{p4}/10^{-4}$ %	$\varkappa_{s1}/10^{-4}$ %	$\varkappa_{s2}/10^{-4}$ %	$\varkappa_{s3}/10^{-4}$ %	$\varkappa_{s4}10^{-4}$ %
Monoblock	3.4	1.84	2.2	5.6	1.78	17	16.8	11.2
Planar	93*	1.34	1.84	2.6	1.46	0.62	5.8	2.8

* Useful losses related to radiation emerging from the resonator

from our analysis, because of a larger diameter of the laser beam, the measurements of the power of reflected beams prove to be overstated for some reasons.

Let us compare polarisation losses in the resonators for the monoblock and planar designs. Table 1 presents reflection losses measured for the p and s components.

Because not all the reflected beams can be measured, taking into account the resonator symmetry, the losses for the monoblock design are described by the expression

$$\varkappa_{\text{pol}}^{\text{mon}} = 2(\varkappa_{\text{p1}} + \varkappa_{\text{p2}} + \varkappa_{\text{p3}} + \varkappa_{\text{p4}} + \varkappa_{\text{s1}} + \varkappa_{\text{s2}} + \varkappa_{\text{s3}} + \varkappa_{\text{s4}}).$$

It follows from Table 1 that

$$\varkappa_{\text{pol}}^{\text{mon}} = 11.96 \times 10^{-3}\,\%.$$

The losses for the planar design are (by neglecting useful losses)

$$\varkappa_{\text{pol}}^{\text{pl}} = 2(\varkappa_{\text{p2}} + \varkappa_{\text{p3}} + \varkappa_{\text{p4}} + \varkappa_{\text{s3}} + \varkappa_{\text{s4}}) + \varkappa_{\text{s1}} + \varkappa_{\text{s2}}.$$

It follows from Table 1 that

$$\varkappa_{\text{pol}}^{\text{pl}} = 2.96 \times 10^{-3}\,\%.$$

Here, $\varkappa_{\text{p}i}$ and $\varkappa_{\text{s}i}$ are losses for the p and s components and $i = 1 - 4$ (see Fig. 2). Therefore, in the case of the planar design, when prisms are fastened by the optical contact and the caustic is removed from the site of prism fixture, the reflection losses are lower by a factor of four than those in the monoblock design. The absolute difference of losses in these two cases is 9×10^{-3} %.

The mean polarisation losses at one refraction surface of a prism are 1.5×10^{-3} % for the monoblock design and 0.5×10^{-3} % for a prism fastened by the optical contact in the planar design.

It is important that the reflection losses for the s component in the four-prism resonator amount to 93.4×10^{-4} % (78 % of the total polarisation losses in this resonator), whereas these losses in the three-prism resonator are only 18×10^{-4} % (58 % of the total polarisation losses). Such a great difference (more than by four times) is explained by a greater path of light in prisms, a greater curvature of the wave front on plane refraction faces of the prisms, and by a greater anisotropy of the resonator in the monoblock design due to greater stresses in the prisms.

For the p components, the difference is not so considerable. The losses per refraction face are 3.26×10^{-4} and 1.93×10^{-4} % for the four- and three-prism resonator, respectively. The p component appears upon reflection from the refraction face for two reasons: because of the wave-front curvature and due to the presence of an intermediate layer at the quartz – air interface (the so-called Drude film [4]).

In Ref. [4], the results of the experimental verification of the Fresnel formulas are presented. In particular, it is shown that the vector E_{p} of the reflected p component does not vanish when the angle of incidence is equal to the Brewster angle, and the reflected light has the elliptic polarisation, the ellipticity $\rho = |E_{\text{p}}|/|E_{\text{s}}|$ achieving $10^{-3} - 10^{-2}$ and higher values. For a particular case of reflection from the surface of pure liquids, where there are no effects related to the mechanical processing of the surface, the ellipticity is not lower than 10^{-3}.

For comparison, we estimate the ellipticity of light reflected from the refraction face of a prism in the three-prism resonator. The mean reflection losses of the p component per prism face are 1.93×10^{-4} % (Table 1). The corresponding ellipticity can be found from the ratio of the intensities of the reflected components:

$$\rho = (|E_{\text{p}}|^2/|E_{\text{s}}|^2)^{1/2} = 3.9 \times 10^{-3},$$

which is of the order of magnitude of reflection from Drude films [4].

A greater reflection of the p component in the monoblock design is obviously explained by a greater curvature of the wave front in this resonator.

Therefore, the planar design proposed here allows us, first, to reduce the polarisation inhomogeneity of optical elements caused by mechanical stresses in the prism material, which reduced the sensitivity of the resonator to an external magnetic field. Second, the scattering of reflected beams from the resonator elements located near its optical elements also decreases.

Thus, the reflection losses for the p component per refraction face of the prism (1.9×10^{-4} %) in the three-prism resonator are close to the minimal losses caused by reflection from the Drude films. In the four-prism resonator, the reflection losses for the p component per refraction face of the prism (3.26×10^{-4} %) are greater by 70 %, which is probably explained by a greater curvature of the wave front (because of the presence of four spherical faces instead of one face in the three-prism resonator).

The total reflection losses for the s component in the three-prism resonator are 18×10^{-4} % and are caused by strains in the prism material and the wave-front curvature. The total reflection losses for the s component in the four-prism resonator are considerably greater (93.4×10^{-4} %). We suppose that such high losses are caused by the fact that, first, the total anisotropy produced by strains increases with the distance propagated by the beam in prisms. The path length in silica glass in the four-prism resonator is almost two times greater. Second, the fastening of the prisms over the perimeter results in the dependence of strains on transverse coordinates.

This circumstance should substantially increase reflection with increasing the beam diameter, which is observed in the multimode regime. In addition, the wave-front curvature produces mainly the loss in the form of the s component reflected from refraction faces. For this reason, polarisation losses increase with increasing order of the transverse modes because of the polarisation inhomogeneity of the refraction faces.

The estimates of polarisation losses in the multimode regime made above can be used for a comparative analysis of the four- and three-prism resonators. The losses related to the s component are overstated because they should be lower under real conditions upon generation of the fundamental mode.

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