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Polarisation losses in a ring prism cavity

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Abstract. The polarisation losses in a ring cavity, formed by total-internal-reflection prisms, were analysed. All the sources of the polarisation losses are indicated and expressions for their calculation are presented. The limit to loss reduction in cavities of this kind, set by the difference between the radii of curvature of the radiation wavefront and of the refracting prism faces, was determined.

1. Formulation of the problem

One of the main requirements which must be met in the development of an optical cavity of a laser gyroscope is the attainment of its maximum Q-factor. The low gain of the active medium in a high-Q cavity ensures low errors that are associated with the nonreciprocity resulting from nonlinear and thermal effects, and also promotes an increase in the service life and a reduction in the start-up time of a laser gyroscope. A cavity formed by four total-internal-reflection (TIR) prisms satisfies these conditions as a consequence of the virtual absence of the TIR losses [1]. A prism cavity is used in the type KM-11 laser gyroscope developed for civil aviation. Four TIR prisms, the refracting faces of which form the Brewster angle with the axial ray, are used in the cavity (see Fig. 1). A significant factor in the analysis carried out below is that the radii of curvature of the refracting faces of the prisms and of the radiation wavefront do not coincide.

The advantages of the cavity under consideration include its low losses, which can be reduced to 0.008% by adopting the best technology. The losses in such a cavity are determined primarily by the scattering and absorption of radiation in the surface layer and within the material of the prisms. The diffractive and useful losses, associated with the coupling out of the radiation from the cavity, as well as the polarisation losses, caused by the deviation of the angle of incidence from the Brewster angle throughout the beam cross section, are added to them. One part of the polarisation losses is caused by fabrication and cavity assembly errors. Another part is associated with the curvature of the radiation wavefront and is independent of the precision of fabrication of the cavity, but is determined by its optical system (by the radius of curvature of the optical surfaces of the prisms and by the cavity perimeter). The polarisation losses of this type are reduced by the fact that the incidence of radiation on the prism faces at the Brewster angle applies only to the axial ray of the radiation beam and not to the beam as a whole.

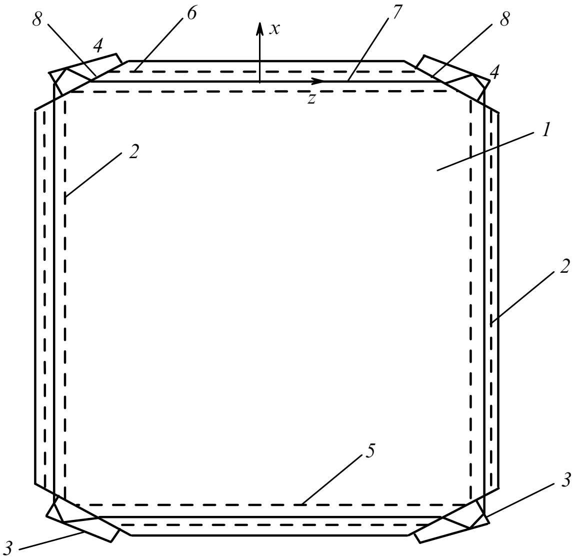

Figure 1. Schematic diagram of a ring cavity: (1) monolithic cavity base; (2) 'air' channels; (3) TIR prisms with a large focal length; (4) TIR prisms with a small focal length; (5) channel with the active medium; (6) 'vacuum' channel; (7) axial ray; (8) refracting prism faces with the maximum polarisation losses.

We note that the losses in cavities formed by interference mirrors are also determined by many factors (scattering, transmission, absorption, etc.) which are of a different nature than those in a prism cavity and have been examined, for example, by Kolodnyi et al. [2]. The aim of the present study was an analysis of the polarisation losses in a prism cavity.

2. Losses caused by the wavefront curvature

We shall examine initially the polarisation losses caused by the wavefront curvature, which determines their lower limit. Each point on the optical surface then acts as a partial polariser with a varying orientation of the axes. The refracting faces of the TIR prisms thus constitute polarisation-inhomogeneous components [3, 4]. Optical components with a variable anisotropy (caused, for example, by mechanical stresses) may also function in this way.

These factors make the radiation in a ring-prism cavity a polarisation-inhomogeneous wave. It is particularly noteworthy that the polarisation state of such a wave varies continuously not only in the transverse but also in the

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longitudinal direction because of the polarisation astigmatism of the orthogonal components of the vector ***E***. In particular, this leads to differences between the radii of curvature of the wavefronts and between the positions of the beam waists along the z axis. The ellipsometric and wave parameters of such a wave are transformed jointly and it is therefore not permissible to calculate them separately. The natural characteristics of a polarisation-inhomogeneous wave in a cavity may be determined by the method of polarisation-wave matrices [3, 4].

In the real KM-11 optical system, which ensures the absence of cavity misalignment in the specified temperature range, there are two cross sections where the radius of curvature R_x of the beam wavefront reaches an extremum value of ~ 53 mm in the meridional xz plane of the axial profile; in the sagittal yz plane, we then have the radius $R_y \approx 2139$ mm. In the vicinity of these cross sections on the prisms (4) (the faces labelled 8 in Fig. 1), the angle of incidence at each point of the laser-beam cross section differs most from the Brewster angle.

Suppose that a linearly polarised Gaussian beam, the wavefront of which is characterised by the radii of curvature R_x and R_y, is incident at the Brewster angle on a plane optical face of a prism. The intensities of the orthogonal components of the reflected light are given by the expressions

$$I_x = \left(\frac{1-n^4}{2n^3}\right)^2 \frac{x^2}{R_x^2} \exp\left(\frac{-2x^2}{w_x^2}\right) \exp\left(\frac{-2y^2}{w_y^2}\right),$$
$$I_y = \left(\frac{1-n^2}{1+n^2}\right)^2 \frac{y^2}{R_y^2 n^2} \exp\left(\frac{-2x^2}{w_x^2}\right) \exp\left(\frac{-2y^2}{w_y^2}\right), \tag{1}$$

where w_x and w_y are the transverse beam radii in a given cross section in the xz and yz planes, respectively; n is the refractive index of the prism material (in the calculations, it was assumed that $n = 1.45703$). Hence, by integrating over the beam cross section, we obtain the polarisation losses on one prism face:

$$A = \frac{(n^4-1)^2}{16n^2} \frac{w_x^2}{R_x^2} + \frac{(n^2-1)^2}{4n^2(n^2+1)^2} \frac{w_y^2}{R_y^2}. \tag{2}$$

Taking into account the real values of R_x and R_y, and $w_x = 0.301$ mm and $w_y = 0.265$ mm corresponding to them, we find $A = 2.3 \times 10^{-4}\%$. The losses on other prism faces are two orders of magnitude lower. Thus the total polarisation losses in the cavity, caused by the wavefront curvature, are determined virtually by only two faces and amount to $5 \times 10^{-4}\%$. This value may be regarded as representing the minimum losses in a ring cavity of this type.

Calculations show that the polarisation losses of the TEM_{10} mode on a plane refracting face of a prism exceed by a factor of three the fundamental-mode losses and by a factor of five the TEM_{20}-mode losses. Consequently, this face serves as the 'soft' aperture for the transmitted radiation and is an additional transverse-mode selector.

The polarisation losses in a prism cavity may be inferred from the intensities of the lines reflected by the refracting prism faces. When these rays are scattered within the cavity, they may enlarge the region of trapping in the ring laser. We note that these rays are precisely those used in the adjustment of the cavity. Practice has confirmed the dependence of the intensity of the 'Brewster' rays on the wavefront curvature: the intensity of the rays reflected from the faces (8 in Fig. 1) is significantly greater.

3. Losses caused by the appearance of the s-component

In the ideal case, the radiation from a prism cavity should be linearly polarised and the vector ***E*** should then be located in the plane of the axial cavity contour (p-component). On the beam axis, the s-component of the vector ***E*** arises as a consequence of two main causes: the nonplanarity of the axial contour and the stresses in the prisms. The 'classical' method for calculation of the polarisation losses ignores the relationship between the polarisation and wave parameters and involves their separate determination, for example by the ray and Jones matrix methods. The losses on each refracting prism face are found from the relationship $A_i = (1 - T_\mathrm{s}{}^2/T_\mathrm{p}^2)|\Gamma_i|^2$, where Γ_i is the polarisation variable of the normal wave incident on the ith surface, whereas T_s and T_p are the transmission coefficients of the p- and s-components; in our case, $T_\mathrm{s}/T_\mathrm{p} = 0.9331$.

In order to calculate the losses associated with the misalignments in the sagittal cavity plane (off-centre positioning, prism tilt), which lead to nonplanarity of the axial contour, it is necessary to evaluate the coordinates of the axial ray and the angles between the planes of incidence on each prism face [5, 6]. To a first approximation, these angles of tilt of the polarisation plane may be regarded as independent perturbations and the values of Γ_i, associated with each of the twelve angles of tilt at the vertices of the axial contour, may be added together linearly. Our calculations made it possible to obtain the relationships between the parameters with an arbitrary misalignment and the polarisation losses in the cavity, for example $A \approx 2 \times 10^{-6}\,\sigma^2$ for a tilt angle σ, where A is a percentage and σ is expressed in angular minutes. If $\sigma = 5'$, then the losses in the cavity are $5 \times 10^{-5}\%$.

The s-component arises also from the stresses in a prism attached to the monolithic cavity block. The contribution to the losses by one prism (in percent) is $A = 4.4\,a^2(\Delta y)^2$, where Δy (in millimetres) is the shift of the laser beam relative to an isotropic point in the prism at which there is no birefringence [7], while a (in radians per millimetre) is a coefficient which takes into account the change in the linear phase anisotropy from zero at the isotropic point to the maximum value at the prism edge. This coefficient is evaluated by measuring the path difference Δ of the orthogonal component of the vector ***E***. This is done on a polarimeter, the axes of which coincide with the x and y axes of the prism (see Fig. 1). For example, $\Delta = 6$ nm at a distance of 4 mm from the isotropic point of the prism corresponds to $a = 8.7 \times 10^{-3}$ rad mm^{-1}. If $\Delta y = 0.5$ mm under these conditions, then $A = 8.3 \times 10^{-5}\%$. One may assume that the stresses in all the prisms lead to additional polarisation losses in the cavity not greater than $5 \times 10^{-4}\%$.

4. Losses caused by the appearance of the p-component

The losses of the active p-component, caused by the misalignments in the meridional cavity plane, are in practice lower than the losses of the s-component, which follows, in particular, from an analysis of the polarisation state of the 'Brewster' rays. Calculations show that for the error in the fabrication of the monolithic block (tilt of the base plane by $1'$) these losses are $\sim 10^{-6}\%$.

5. Conclusions

Our analysis thus shows that the polarisation losses do not exceed 10^{-3}% when the existing technologies for the fabrication and assembly of a ring prism cavity are used. The fundamental fact is the existence of a lower limit to the polarisation losses, which results from the curvature of the laser-radiation wavefront and amounts to $\sim 5 \times 10^{-4}$%.

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