Journal of Engineering Physics and Thermophysics, Vol. 74, No. 5, 2001

OPTICAL JOINT OF OPTOELECTRONIC RADIATION CONVERTERS WITH IMMERSION LIGHT GUIDES AND CALCULATION OF THEIR CHARACTERISTICS

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UDC 621.745.5.06./.07:536.5

In the present work, equations are obtained that establish relationships between the optical characteristics of optoelectronic radiation converters and straight cylindrical immersion light guides with straight faces manufactured from isotropic and anisotropic materials with different refractive indices. Engineering procedures to calculate the schemes of optical joint of pyrometric converters with light guides that improve the metrological characteristics of the immersion light-guide thermometry of radiation are developed.

For the high-temperature light-guide immersion thermometry of liquid and gaseous media one mainly uses straight cylindrical light guides with straight faces manufactured from optically transparent refractory materials with high chemical stability, for example, quartz or sapphire. To perform measurements, the light guides are brought into contact with the medium subjected to thermometry; then radiation is formed and transferred to the primary optoelectronic pyrometric converter, whose thermometric parameters are uniquely related to the temperature of this medium.

The metrological characteristics of the light-guide pyrometry of radiation under the above conditions are largely determined by the optical joint of pyrometric converters with light guides. Therefore, the study of this problem has received particular attention in light-guide thermometry. For example, in [1–4], methods of optical jointing are described, which, however, have some disadvantages; in particular, they require application of additional elements (lenses and flexible light guides), impose rigid demands on the stability of the reflectivity of a side surface of immersion light guides (it is essential to use coatings made of platinum, rhodium, and other, expensive, as a rule, materials), and complicate the design and operation of thermometric equipment, since the need arises for the forced cooling of optical-joint devices and converters, it becomes difficult to control the state of the light guide, etc.

As a result of theoretical and experimental investigations, the author has developed a variant of solution of this problem free of the indicated disadvantages. According to this new method, the converter is sighted to the central part of the immersion face so that the light guide cannot restrict its visual field and cannot vignette the luminous flux (Fig. 1). With such a joint the influence of the optical characteristics of the side surface of the light guide on the results of thermometry is virtually completely eliminated [5].

Procedures for determining the characteristics of light guides and pyrometric converters are developed [6] which implement this method of jointing.

For $d_{\text{en.port}} > d_{\text{en.pup}}$ (Fig. 1a) and $n_{21} = 1$ we have the following relations:

$$\tan\varphi = \frac{d_{\text{en.port}} - d_{\text{en.pup}}}{2L_{\text{en.port–en.pup}}}\,; \quad \tan\varphi = \frac{d_{\text{v.f}} - d_{\text{en.pup}}}{2L_{\text{im.f–en.pup}}}\,; \quad \tan\omega = \frac{d_{\text{en.port}}}{2L_{\text{en.port–en.pup}}}\,, \tag{1}$$

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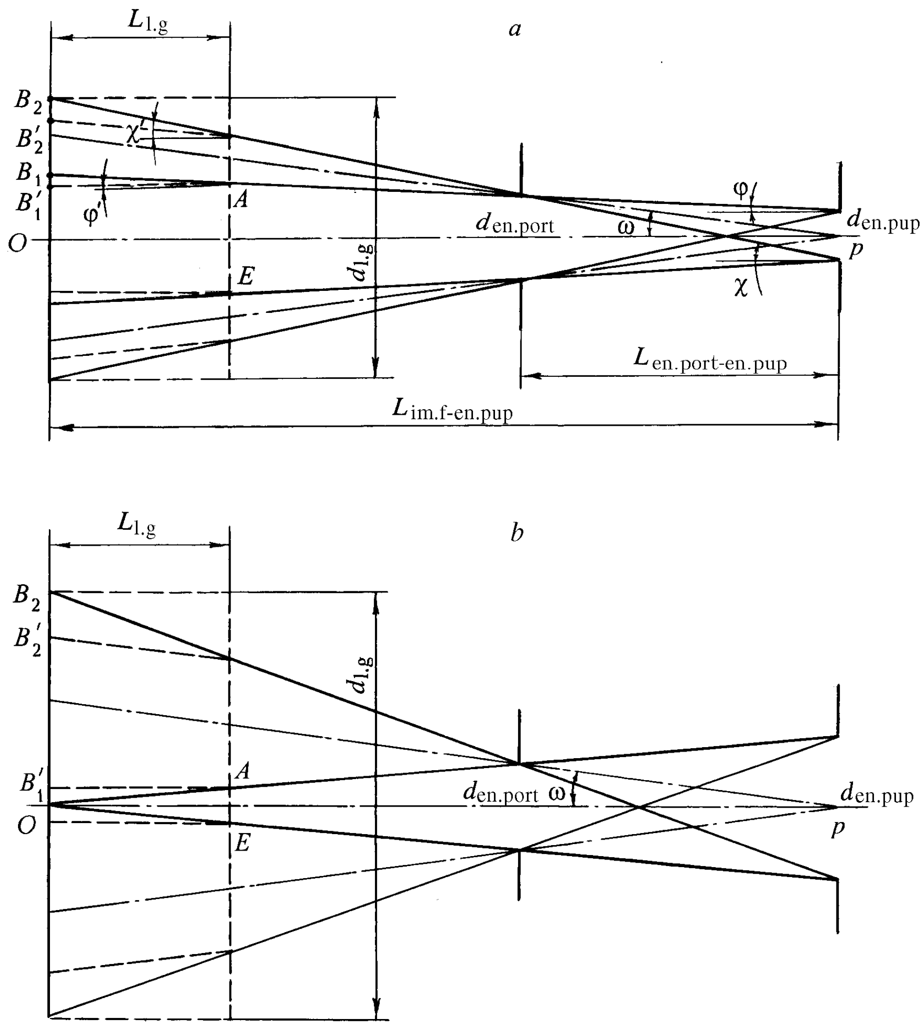

Fig. 1. Optical scheme of joint of pyrometric converters with light guides: a) $d_{en.port} > d_{en.pup}$; b) $d_{en.port} < d_{en.pup}$.

where $d_{v.f} = 2OB_1$.

Taking into account that $L_{en.port-en.pup} = d_{en.port}/(2 \tan \omega)$, from the given relations it is possible to obtain the calculated expression

$$d_{l.g} > d_{v.f} = 2L_{im.f-en.pup}\left(1 - \frac{d_{en.pup}}{d_{en.port}}\right)\tan \omega + d_{en.pup} . \tag{2}$$

If the entire radiation transmitted by the optical system of the converter arrives at the detector, then the following equalities hold:

$$\tan \chi = \frac{D_{v.f} + d_{en.pup}}{2L_{im.f-en.pup}}; \quad \tan \chi = \frac{d_{en.port} + d_{en.pup}}{2L_{en.port-en.pup}}; \quad \tan \omega = \frac{d_{en.port}}{2L_{en.port-en.pup}}, \tag{3}$$

from which we find the calculated formula

$$d_{l.g} > D_{v.f} = 2L_{im.f-en.pup}\left(1 + \frac{d_{en.pup}}{d_{en.port}}\right)\tan \omega - d_{en.pup}, \tag{4}$$

where $D_{v.f} = 2OB_2$ is the diameter of the visual field, m.

In the case $n_{21} > 1$

$$d_{v.f} = 2\,(OB_1 - B_1B_1^{\prime})\,. \tag{4a}$$

Taking into account that $n_{21} = \sin\varphi/\sin\varphi^{\prime}$ and $\tan\varphi = (1 - d_{en.pup}/d_{en.port})\tan\omega$, we obtain the following expression for $B_1B_1^{\prime}$:

$$B_1B_1^{\prime} = L_{l.g}\left(1 - \frac{d_{en.pup}}{d_{en.port}}\right)\left[1 - \frac{1}{n_{21}^2 + (n_{21}^2 + 1)\left(1 - \frac{d_{en.pup}}{d_{en.port}}\right)^2 \tan^2\omega}\right]. \tag{4á}$$

Having substituted Eq. (4b) into Eq. (4a), we obtain

$$d_{v.f} = 2\left(1 - \frac{d_{en.pup}}{d_{en.port}}\right)\left[L_{im.f-en.pup} - L_{l.g}\left(1 - \frac{1}{\sqrt{n_{21}^2 + (n_{21}^2 + 1)\left(1 + \frac{d_{en.pup}}{d_{en.port}}\right)^2 \tan^2\omega}}\right)\right]\tan\omega + d_{en.pup}. \tag{5}$$

If the entire radiation transmitted by the optical system of the converter arrives at the detector, then the diameter of the visual field is determined by the expression

$$D_{v.f} = 2\,(OB_2 - B_2B_2^{\prime})\,,$$

where, taking into account that $n_{21} = \sin\chi/\sin\chi^{\prime}$ and $\tan\chi = 1 + (d_{en.pup}/d_{en.port})\tan\omega$, we have

$$B_2B_2^{\prime} = L_{l.g}\left(1 + \frac{d_{en.pup}}{d_{en.port}}\right)\left[1 - \frac{1}{\sqrt{n_{21}^2 + (n_{21}^2 + 1)\left(1 + \frac{d_{en.pup}}{d_{en.port}}\right)^2 \tan^2\omega}}\right]\tan\omega\,.$$

The resultant expression for calculating has the form

$$d_{l.g} > D_{v.f} = 2\left(1 + \frac{d_{en.pup}}{d_{en.port}}\right)\left[L_{im.f-en.pup} - L_{l.g}\left(1 - \frac{1}{\sqrt{n_{21}^2\,(n_{21}^2 + 1)\left(1 + \frac{d_{en.pup}}{d_{en.port}}\right)^2 \tan^2\omega}}\right)\right]\tan\omega - d_{en.pup}\,. \tag{6}$$

Calculation for $n_{21} < 1$ is carried out using the expressions that hold for $n_{21} > 1$.

If the light guide is manufactured from a uniaxial crystal, whose optical axis does not coincide with the geometrical axis of a bar, then

$$d_{l.g} > d_{v.f} + L_{ord.r-extr.r}\,.$$

To calculate $L_{ord.r-extr.r}$, we use the Huygens principle of construction that describes the propagation of light in uniaxial crystals. The behavior of rays in a uniaxial crystal for which $n_{extr.r} > n_{ord.r}$ is depicted in Fig. 2. The drawing plane coincides with the plane of the principal cross section of the crystal; therefore, the projection of the wave surfaces consists of a circle of radius $1/n_{ord.r}$ and an ellipse with axes of $1/n_{ord.r}$ and $1/n_{extr.r}$ that is described by the equation

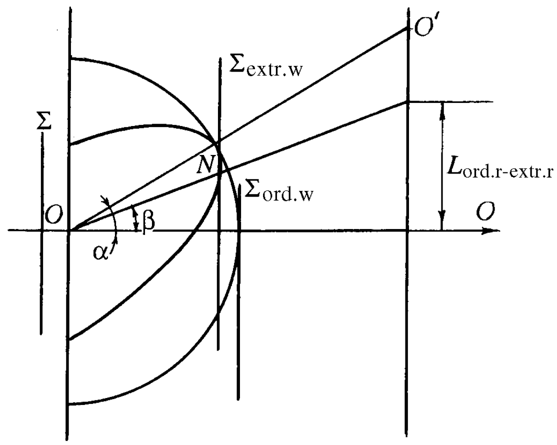

Fig. 2. Behavior of rays in a uniaxial crystal.

$$n_{ord.r}^2 x^2 + n_{extr.r}^2 y^2 = 1 . \tag{7}$$

The point of tangency of these curves lies on the optical axis of the crystal OO' that makes an angle α with the geometrical axis OO of the light guide.

The normally incident wave Σ inside the crystal is divided into the ordinary wave $\Sigma_{ord.w}$ and extraordinary wave $\Sigma_{extr.w}$. The ordinary wave $\Sigma_{ord.w}$ travels in the same direction as the incident wave Σ, i.e., parallel to the geometrical axis OO of the light guide, whereas the extraordinary wave $\Sigma_{extr.w}$ is deflected to the optical axis OO' of the crystal. The extraordinary ray passes through the point of tangency N of the ellipse and the front of the extraordinary wave $\Sigma_{extr.w}$, i.e., its position is determined by the angle β.

Having differentiated Eq. (7), we find the quantity tan β

$$\frac{dy}{dx} = -\frac{n_{ord.r}^2}{n_{extr.r}^2} \frac{x}{y} . \tag{8}$$

Here $dy/dx = -\tan(90 - \alpha)$ is the tangent of the slope at the point N; therefore,

$$\frac{dy}{dx} = \text{ctan}\,\alpha . \tag{9}$$

Proceeding from Fig. 2, we have

$$\frac{x}{y} = \text{ctan}\,(\alpha - \beta) . \tag{10}$$

Substitution of Eqs. (9) and (10) into Eq. (8) gives

$$\tan\beta = \frac{(n_{extr.r}^2 - n_{ord.r}^2)\tan\alpha}{n_{ord.r}^2 \tan^2\alpha + n_{extr.r}^2} . \tag{11}$$

Thus,

$$L_{ord.r\text{–}extr.r} = L_{l.g}\tan\beta = L_{l.g}\frac{(n_{extr.r}^2 - n_{ord.r}^2)\tan\alpha}{n_{ord.r}^2 \tan^2\alpha + n_{extr.r}^2} . \tag{12}$$

Expression (12) also holds for negative crystals in which $n_{extr.r} < n_{ord.r}$.

In the case where $d_{en.port} < d_{en.pup}$ (Fig. 1b), $d_{l.g}$ is calculated from the formulas obtained for $d_{en.port} > d_{en.pup}$.

However, when the point O of intersection of the rays OA and OE is closer to the immersion face, the radiation flux can be restricted by the side surface of the outer part of the light guide. Therefore, the following additional condition must be fulfilled:

$$d_{\text{l.g}} \geq AE = 2\,(L_{\text{im.f–en.pup}} - L_{\text{l.g}})\left(1 - \frac{d_{\text{en.pup}}}{d_{\text{en.port}}}\right)\tan\omega + d_{\text{en.pup}}\,. \tag{13}$$

Thus, by using the Huygens principle and the laws of geometrical optics and crystal optics, an expression is obtained for the distance between the ordinary and extraordinary rays leaving a crystal and engineering procedures are developed for calculating the schemes of optical joint of optoelectronic radiation converters with light guides made of isotropic and anisotropic materials with different refractive indices. Computational procedures provide technical implementation of the optical joint of pyrometric converters with straight immersion light guides having straight faces, which improves the metrological characteristics of light-guide radiation thermometry owing to elimination of the limitation on the visual field of converters, vignetting of a luminous flux, and the influence of the background radiation of a side surface of the immersion light guides.

NOTATION

$d_{\text{en.port}}$, diameter of the converter entrance port, m; $d_{\text{en.pup}}$, diameter of the converter entrance pupil, m; $L_{\text{ord.r–extr.r}}$, distance between the ordinary and extraordinary rays leaving the light guide, m; $L_{\text{en.port–en.pup}}$, distance between the entrance port and entrance pupil, m; $d_{\text{v.f}}$, diameter of the converter visual field on the immersion face, whose radiation is not vignetted by the entrance port, m; $L_{\text{im.f–en.pup}}$, distance from the light-guide immersion face to the entrance pupil, m; 2ω, angle of the converter visual field, ... $^{\circ}$; $d_{\text{l.g}}$, diameter of the light guide, m; $D_{\text{v.f}}$, diameter of the converter visual field, m; $L_{\text{l.g}}$, light-guide length, m; n_{21}, refractive index of the light-guide material relative to the intermediate medium; $n_{\text{extr.r}}$, refractive index of the extraordinary ray; $n_{\text{ord.r}}$, refractive index of the ordinary ray; Σ, incident wave; $\Sigma_{\text{ord.w}}$, ordinary wave; $\Sigma_{\text{extr.w}}$, extraordinary wave; φ and φ', angles between the rim ray for $d_{\text{v.f}}$ and the geometrical axis outside the light guide and inside it, respectively, ... $^{\circ}$; χ and χ', angles between the rim ray for $D_{\text{v.f}}$ and the geometrical axis of the light guide and converter outside the light guide and inside it, respectively, ... $^{\circ}$; α, angle between the optical and geometrical axes of the crystal, ... $^{\circ}$; β, angle between the extraordinary ray and the geometrical axis of the crystal, ... $^{\circ}$; p, center of the entrance pupil.

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