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Cube-corner reflectors with interference dielectric coating

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***Abstract.* The cube-corner reflectors (CCRs) with a special interference dielectric coating intended for ring retroreflector systems of space vehicles with uniaxial orientation are considered. The diffraction patterns of radiation reflected from the CCRs with different face coatings are studied. It is shown that the choice of the angle between the faces, the size and the coating of CCR faces allow essential variation in the diffraction pattern, thereby providing its optimisation for solving different navigation problems.**

Keywords: *cube-corner reflector, diffraction pattern, ring retroreflector system, radiation pattern, interference dielectric coating.*

1. Introduction

Retroreflector systems [1–8] consisting of cube-corner reflectors (CCRs) (Fig. 1) are used for installation on geodesic and navigation satellites to reflect the beam of a laser ranger. Measuring the time of laser pulse propagation allows high-precision determination of the distance to the satellite and calculation of the orbit parameters [3].

The radiation reflected from a retroreflector system is characterised by a certain radiation pattern, i.e., the dependence of the energy on the angle between the optical axis and the direction of observation. A specific feature of exploiting CCRs in the systems of satellite ranging is that the reflected laser beam is deflected from the direction towards the transmitter due to the so called effect of velocity aberration, the value of deviation angle amounting to $2u/c$, where u is the tangent component of the satellite motion velocity, and c is the velocity of light. This deviation depends on the satellite orbit height and varies from $1''$ for the Moon to $10''$ for low-orbit satellites. Therefore, in the general case the energy of reflected laser beam must be concentrated not on the optical axis, i.e., in the central lobe, but in the side lobes. Correspondingly, the intensity maximum in the diffraction pattern should be shifted from the axis by the angular distance equal to the angular aberration for the given satellite. For a triaxially oriented satellite (not changing its position with respect to the plane of the orbit) the optimal far-field diffraction pattern (FFDP) has the shape of two spots, separated by the required distance, and for uniaxially oriented satellites (e.g., GLONASS) the optimal FFDP shape is a ring.

First of all, the far-field diffraction pattern depends on the size of prismatic corner reflectors that form the retroreflector system of the satellite, and on the angle between their faces. In the case of CCRs with metallised faces the change in the dihedral angle by the value ϕ with respect to $\pi/2$ yields the angular distance between the spots of the diffraction pattern amounting to $4\sqrt{6}n\phi/3$, where n is the refractive index of the CCR material.

One of the efficient methods for changing and optimising the radiation pattern is the control of the phase shift of the vector $\boldsymbol{E}$ components in the process of refraction and reflection at the CCR faces, which is determined by the kind of the face coating or its absence [8].

The number of CCRs in the retroreflector system is a compromise between the necessary value of the equivalent scattering surface, which in the present case amounts to 10^7–10^9 m^2, and the admissible weight of the system. The ring retroreflector system possesses a number of advantages, and the aim of the present paper is the analysis of the parameters of different CCRs and the discussion of the criteria, using which one can choose the optimal CCR for such system.

2. Polarisation structure of radiation reflected from a CCR

A specific feature of the CCR polarisation characteristics is determined by the fact that the beam on its way inside the CCR experiences three reflections, each being characterised by a phase shift between the orthogonal components of the vector $\boldsymbol{E}$: $\delta = \delta_{\rm s} - \delta_{\rm p}$, the planes of the beam incidence on the faces being not coincident.

Let us define the coordinate system with the longitudinal axis z along the incident beam and the transverse axes that can be rotated to fit the planes of the beam incidence on the reflecting faces of the CCR so that the x axis lies in the plane of incidence. After the reflection the coordinate system remains right. At the exit from the CCR the positive direction of the z axis is changed for the opposite one.

For the normal incidence of light on the CCR the angle of incidence onto each face is $\arctan\sqrt{2} \approx 54.7°$, and the angle α between the planes of incidence on the adjacent faces is equal to $\pm 60°$. Besides it is necessary to account for the angle between the x axis and the planes of incidence at the entry into the CCR and exit from it.

The ray can travel inside the CCR via six different ways depending on which of the six sectors of the entry face it falls initially. For example, the ray enters sector 2; is successively reflected from the faces C, A, and B (see Fig. 1); and exits from sector 6. The sequence of twist angles for six possible combinations of reflecting faces met by the ray on its path is described in [5–8].

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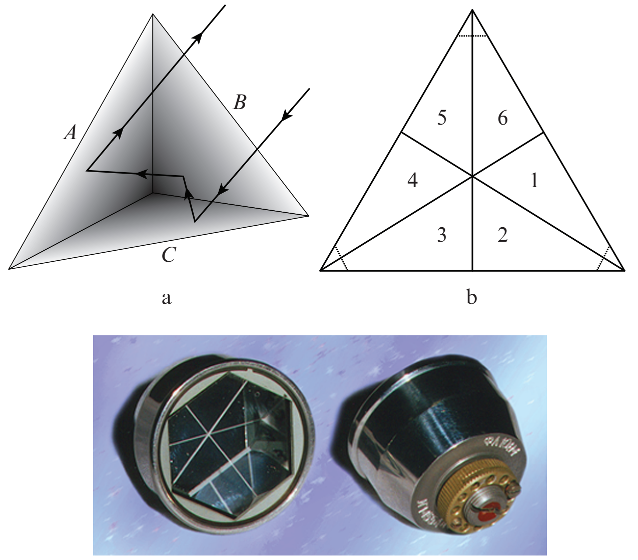


a b

c

Figure 1. (a) Ray paths in the CCR, (b) sectors of the entrance CCR face, hitting which determines six different versions of ray paths in the CCR, and (c) the exterior view of the CCRs, manufactured by Scientific-Research Institute for Precision Instrument Making.

The complex amplitudes of the orthogonal components of the vector ***E*** in the near field of the CCR are calculated using the Jones method. To describe the CCR polarisation properties it is necessary to consider six resulting Jones matrices for different combinations of the beam path elements with the rotations of the coordinate system and the phase shift by δ at the reflecting faces taken into account. The corresponding six sectors, into which the CCR aperture is divided, are characterised by definite amplitude – phase transmission coefficients for the orthogonal components of the vector ***E***. Thus, the wave front of the incident plane wave is divided into six parts as a result of reflection from the CCR. These beams with different polarisation states and phase shifts spread due to the diffraction, interfere, and produce a complicated diffraction pattern in the far-field zone. The spatial polarisation structure of radiation is this case depends upon both the polarisation state of the incident light and the CCR parameters [1 – 8].

3. Radiation pattern of a CCR with interference dielectric coating.

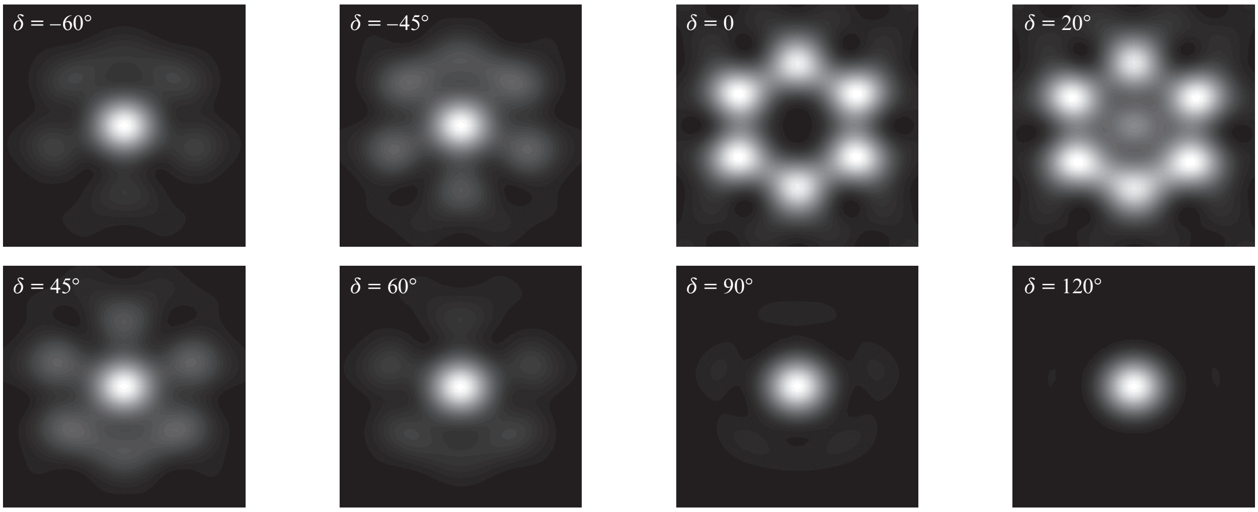
The far-field diffraction pattern essentially depends on the phase shift between the orthogonal components at the reflection, which is determined by the kind of the CCR face coating. For example, when the coating is absent (under the conditions of total internal reflection, TIR) $\delta \approx -40°$ (in the coordinate system chosen by us); for a metal face coating $\delta = 150° - 170°$, and for an interference coating the phase shift can be smoothly varied within a wide range from 0 to 180°. Hence, all types of CCRs should be classified with respect to the phase shift at each face δ_A, δ_B, δ_C. A certain far-field diffraction pattern corresponds to each particular combination of δ_i [8].

The results of calculation of the diffraction pattern depending on the phase shift of the orthogonal components at the CCR faces for linear horizontal polarisation state of the initial light polarisation are presented in Table 1. Note that at the zero phase shift ($\delta_A = \delta_B = \delta_C = 0$) the central spot is absent in the middle of the picture.

The coatings based on thin dielectric layers, including gradient ones, deposited onto the reflecting CCR faces, can provide any required phase shift. The first dielectric layer, adjacent to the prism surface, must have a greater refractive index than the prism material, e.g., $n_{\mathrm{h}} = 2$. At the interface between the last layer and the air the TIR is always observed, and in this case an essential phase shift between the orthogonal components of the vector ***E*** is known to arise, namely, $|\delta| = 20° - 50°$ (depending on the incidence angle and the refractive index of the medium). In a multilayer medium the division of waves with p- and s-components of the vector ***E*** into the secondary waves occurs in a different way because of different transmission coefficients at the media interfaces, and the results of summation also appear to be different. For example, in the case when the wave is incident of the reflecting face of the prism at the Brewster angle, the wave with p-component passes to the last layer practically without reflection and returns into the prism with a certain phase shift accumulated. At the same time the wave with s-component experiences multiple reflections and the resulting wave in the prism is a superposition of coherent waves with different phase shifts.

Therefore, in the CCR with an interference dielectric coating (IDC) the multiple-beam interference of waves with dif-

Table 1. Diffraction patterns in the far field for the CCR with different phase shifts between the field components at the faces.

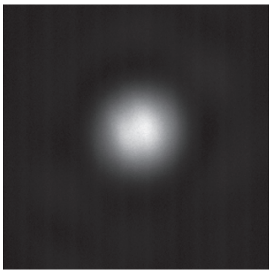
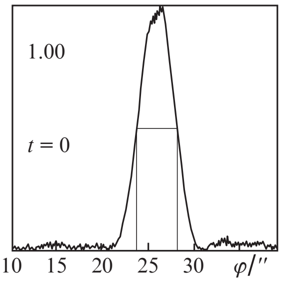
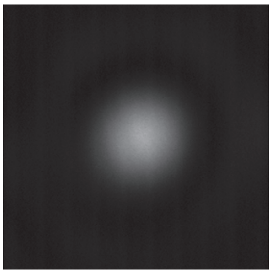
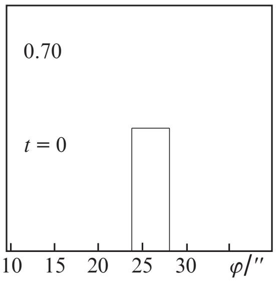
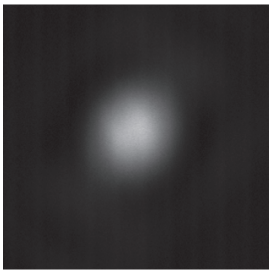
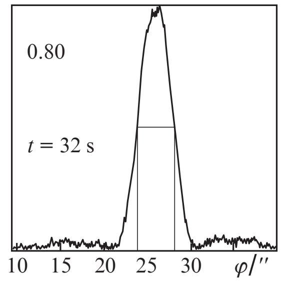
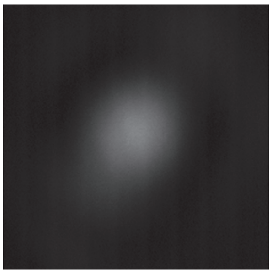
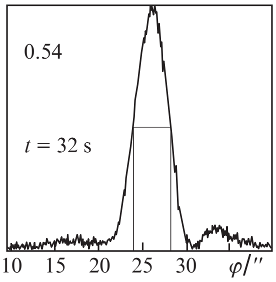
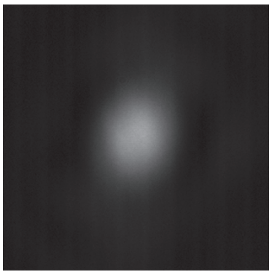
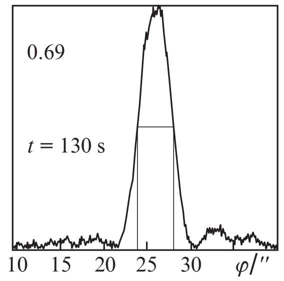
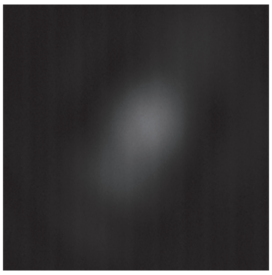
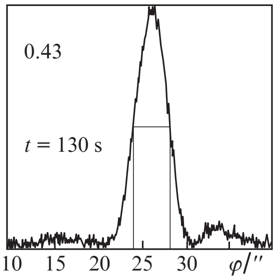
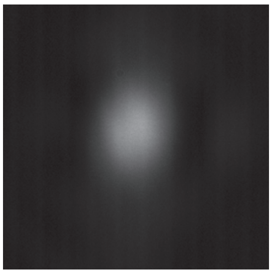
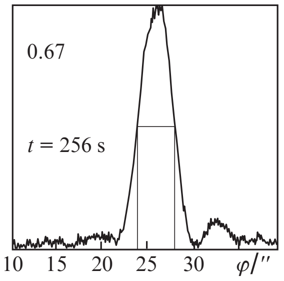
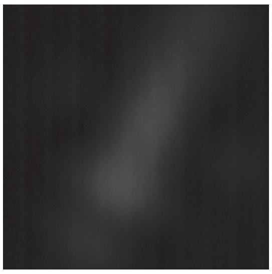
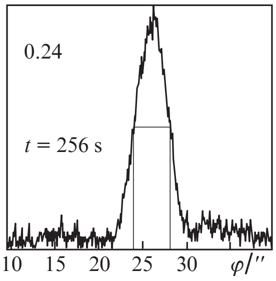


ferent amplitude and phase, reflected from the boundaries of the coating layers, leads to the additional phase shift between the orthogonal components at each face of the CCR [9]. By choosing a various number of layers any required phase shift can be provided (with only one layer the value of the shift is limited). For such a coating the CCR losses are zero in the ideal case, because at the last boundary the TIR conditions are provided. However, practically the losses amount to a few per cent. In this connection the use of a gradient coating seems to be a rather promising method to reduce the losses caused by the scattering.

In a number of cases (geostationary satellites, the Moon) the retroreflector system must produce the Airy diffraction pattern in the far field of the reflected radiation. As follows from Table 1, to obtain such a pattern the phase shift $|\delta| \geqslant 90°$ (in the chosen coordinate system) is necessary, which is usually provided by deposition of metallic coating on the reflecting faces.

The advantages of using a dielectric coating instead of a metal one are caused by several factors. First, on average, the reflection coefficient of the dielectric coating is by 30%–40% greater than for the aluminium coating, and by 5% greater than for the silver one. Second, the dielectric coating possesses better resistance to external mechanical effects than the silver one. The silver coating is particularly sensitive to wet atmosphere in the presence of smallest damage of the protective layer (silicon oxide, bakelite lacquer). Third, the thermal distortions of the radiation pattern are significantly smaller for a dielectric coating, since it weakly absorbs the visible radiation from the Sun. Table 2 shows diffraction patterns of light, reflected from the CCR with silver and aluminium coating at different moments of time in the process of heating by the radiation of a xenon lamp with the spectrum, close the solar one. The diffraction pattern of the light, reflected by the dielectric coating, does not change under the analogous conditions.

Table 2. Diffraction patterns for the light reflected from the CR with silver and aluminium coatings under the heating conditions at different moments of time, and the corresponding angular distributions of intensity in the diffraction maxima.

Silver coating		Aluminium coating	
			
			
			
			

Note: The figures at the distributions show the ratio of the intensity in the centre of diffraction pattern to the corresponding intensity in the case of using a silver-coated CR at the moment of time $t = 0$.

A disadvantage of dielectric coatings is the dependence of the phase shift between the orthogonal components of the vector ***E*** on the wavelength and the angle of light incidence on the CCR entrance face. Besides there is a limitation of the admissible angles of light incidence, namely, at the incidence angle exceeding 18° the TIR condition is, generally, violated. However, for high-orbit satellites (GLONASS, geostationary satellites, the Moon) this problem is not so essential. Just in these cases the dielectric coating may be successfully exploited instead of a metal one, because the angle of incidence on the CCR of these satellites does not exceed ±15°. As to the wavelength of light for laser rangers, it has, as a rule, a fixed value of 0.532 or 10.06 μm.

As a result, the effect of single-lobe radiation pattern formation is already achieved using only three interference layers. Figure 2 shows the dependence of the phase shift δ on the optical thickness of layers $\Delta = n_{\mathrm{h}}h_{\mathrm{h}} = n_{\mathrm{s}}h_{\mathrm{s}}$, chosen to be similar for the layer with high (n_{h}) and low (n_{s}) refractive indices at three angles of incidence on the entry face of the CCR (the normal incidence and the deviation by ±8° from it).

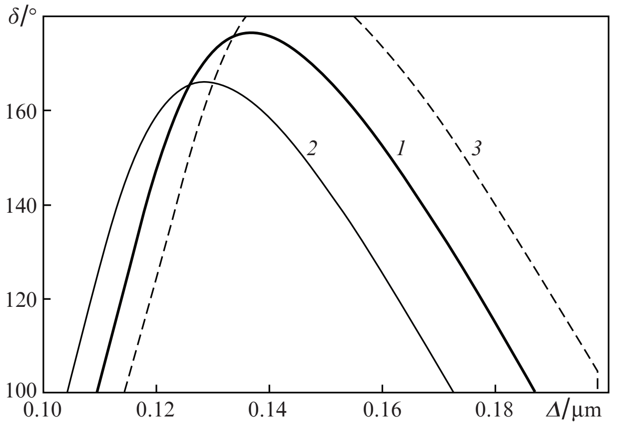


Figure 2. Phase shift between the orthogonal components of the vector ***E*** for the reflection of light from dielectric coatings having different optical thickness Δ: (*1*) normal incidence; (*2*, *3*) deviation from the normal by ±8°.

4. Optimal CCR parameters for double-spot diffraction pattern formation

The principle of operation of the promising ring retroreflector system (RRS) consists in the following. The reflected signal of the laser ranger is formed not by all CCRs of the system, as in the planar panel with uncoated CCRs, but only by a few CCRs, ideally, two of them located at the opposite sides of the RRS (Fig. 3). As was found at the Scientific-Research Institute for Precision Instrument Making, this feature allows a more precise determination of the distance to the geometric centre of the panel and, thus, of the distance from the given point of the laser ranger to the centre of mass of the space vehicle.

Non-standard CCRs should be used in constructing the RRS, namely, it is necessary to change one of the dihedral angles by the given small value with the precision up to 0.2″, which leads to the appearance of two spots instead of one in the far field diffraction pattern. Generally, for a long time such double-spot CCRs are already being exploited in triaxially-oriented low-orbit space vehicles using aluminium coating for the reflecting CCR faces. In this case the angle of deviation from 90° is sufficiently large and amounts to 4″–5″, so that instead of one Airy spot one gets two spots separated by the distance required to compensate the velocity aberration.

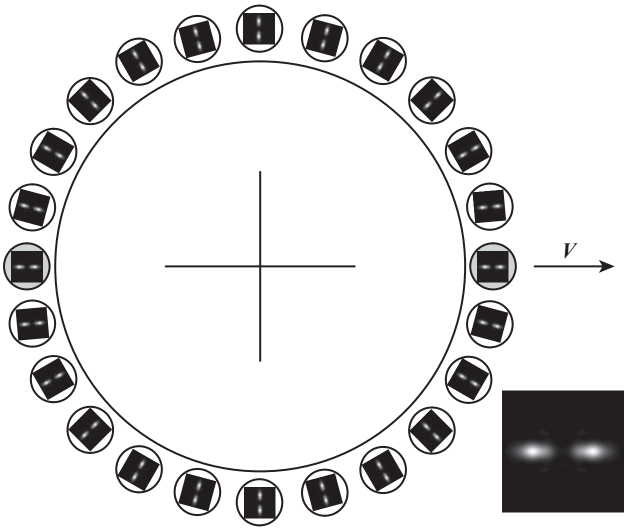


Figure 3. Ring retroreflector system. It is shown how the radiation patterns are oriented for each CCR. For the direction towards the receiver the reflected radiation is formed by only two CCRs (some intensity can be also contributed by the adjacent CCRs); ***V*** is the velocity vector of the space vehicle.

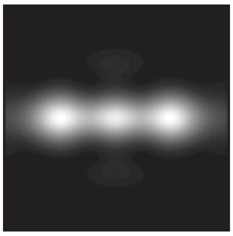
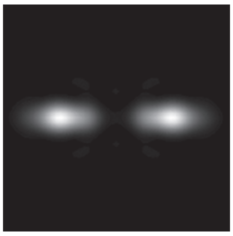
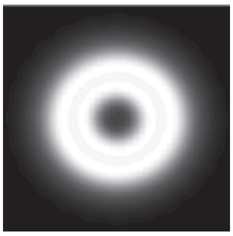
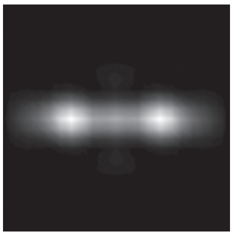
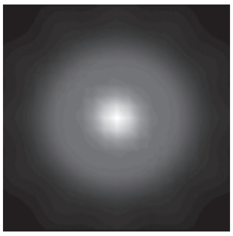
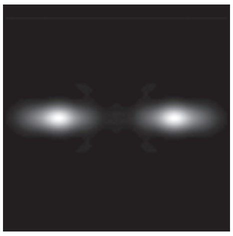
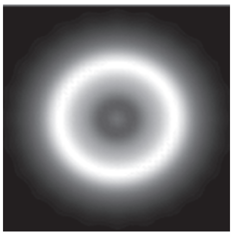
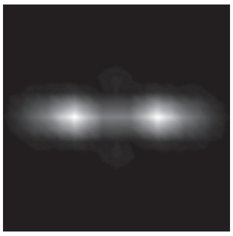
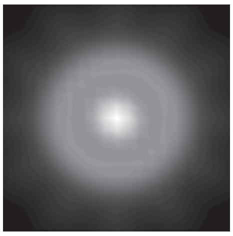
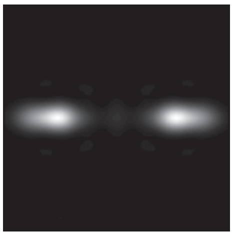
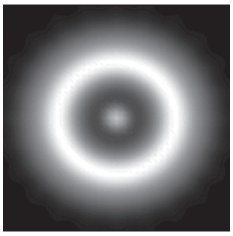
A specific feature of RRS is that since for the GLONASS navigation satellites the angular velocity aberration is nearly 5″, the aberration compensating angle should be only as small as ~2.5″. In this case for the CCR with the aperture of nearly 28 mm instead of two spots one observes a dumbbell diffraction pattern, and a significant part of the reflected energy is lost, hitting beside the receiver.

Obviously, the increase in the CCR size leads to a decrease in the angular size of the spots, thus giving rise to the required double-spot radiation pattern of the scattered radiation (Table 3). At the same time the CCR size should be optimal, since its excessive enlargement leads to the growth of the RRS mass and increases its sensitivity to temperature effects. The calculations show that the optimal size of the CCR aperture lies within the limits of 42–48 mm.

The KU-1 silica is an ideal material for CCRs due to a number of important characteristics, such as high homogeneity, small linear expansion coefficient, radiation resistance, etc. The absorption lines of KU-1 lie in the IR spectral region; therefore, at solar irradiation only a small fraction of light energy is absorbed in the CCR material. The main heating occurs in the case when the reflecting faces of the CCR are metallised. As a result the difference of temperatures between the entry face and the CCR vortex (2–4 °C) leads to the change in the refractive index inside the CCR, which can be described using the model of a lens located at the exit of radiation from the CCR. The lens has a rather small focal power (a few hundredths of a dioptre); however, this is sufficient to increase the angular size of the radiation pattern by two times or more, the intensity of the spot centre being able to decrease by an order of magnitude [10, 11].

The silver coating is in this sense preferable as compared to the aluminium one, because the radiation losses in the

Table 3. Diffraction patterns in the far-field zone upon reflection of light from the RRS and from individual CRs with different parameters.

Deviation of the CR dihedral angle from 90°	The CR aperture diameter 28 mm		The CR aperture diameter 50 mm	
	Single CR	RRS	Single CR	RRS
2.2″				
2.4″				
2.6″				

CCR in the first case amount to 20% as against 40% in the second case. As shown experimentally [11] the use of interference dielectric coating leads to essential reduction of the temperature gradient and radiation pattern distortions.

5. Conclusions

The distribution of the radiation intensity reflected from a corner reflector in the far-field zone is essentially dependent on the kind of the CCR face coating or its absence (in this case the reflection occurs due to the TIR effect). This is caused by different phase shift between the orthogonal components of the vector ***E*** acquired as a result of reflection. A radical method to control the radiation pattern is the use of IDCs that, particularly, allows the formation of a single-lobe reflected radiation pattern (the Airy spot in the diffraction pattern), which is usually provided by deposition of metallic coating on the reflecting faces of the CCR. The use of IDCs leads to the reduction of thermal effects on the CCR. This is particularly important for double-spot CCRs of enlarged size, used in the ring retroreflector system with improved precision and energy characteristics.

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