Formation of scattering indicatrix of retroreflective coatings with microspheres

E R Galimov, Yu A Pryakhin, E E Tukbaev, N Ya Galimova and L R Fazlyev
Kazan National Research Technical University named after A N Tupolev, Kazan, Russian Federation

kstu-material@mail.ru, morenko@imm.knc.ru

Abstract. The problems of calculation based on the third-order aberration and Fraunhofer approximation and in the ray approximation of reflection indicatrixes of retroreflective coatings containing the catadioptric system on the basis of glass microballoons are considered. The fundamental relations are formulated the experimental studies of indicatrix are carried out.

1. Introduction
Light reflectors of retroreflective type are widespread first of all at traffic management as coatings of road signs and vehicles numbers. They are also used in military and space technologies as the element of measuring systems [1]. Microspherical lens determining the light reflector optical properties is its main element. The light rays passing through the lens are reflected at its outer and inner surfaces and go out in directions including the opposite direction to the propagation of the incident beam [3]. A number of papers, for example [3, 4], are devoted to the research of retroreflective coatings based on the corner reflectors, but only a few works are devoted to the research of the microspherical retroreflective coatings [1-3].

2. Research part
The coating structure (variant) can be represented as a planar multilayer structure with microspheres situated in it (figure 1).

Peculiarities of retroreflective coatings reflection are determined by the optical properties of the radiation reflection by the microspheres which is characterized by the scattering indicatrix – angular dependence of the radiation flow of reflected (scattered) light. The light reflection from microspheres is well known in the phenomena of rainbow and halo – back reflection of light from water droplets [5]. When solving the plane wave diffraction problem, for example, on a homogeneous dielectric cylinder the expression for the scattered field can be written as a series over cylindrical waves – Debye series [5] with coefficients that take into account the (p-1) multiple internal reflections from the cylinder surface. If we consider only the first term of the Debye expansion (p=0) then it can be shown that in geometric optics a field is easy to find by multiplying the field of the corresponding beam on Fresnel reflection coefficient [5, 6].

Scattered field can be thought of as consisting of two parts – one of which is caused by the reflection and refraction on the sphere the other – by the diffraction of the wavefront at the external boundary of the scattering sphere. Interference between the various components leads to the appearance of fast oscillations of the intensity when changing the direction of observation. If the
sphere radius \( r \) is much greater than the wavelength \( \lambda \) (in our case \( 2r/\lambda = 200 \)) then the scattering field of such a sphere can be found using the geometrical optics approximation [6, p. 469].

The expression for the angles and the scattering indicatrix at diffraction on large spheres is given in [5].

Sphere as an optical lens system (figure 2) is given by the surface radius \( r \), the refractive indexes of the environment and the sphere \((n_1, n_2, n_3)\) and is also characterized by the paraxial parameters – focal length \( f' \) and back-focal distance \( S'_{F'} \). The back-focal distance of the sphere

\[
f' = \frac{n_2 n_3 r_1 r_2}{n_2 r_2 (n_2 - n_1) + n_2 r_1 (n_3 - n_2) - d(n_2 - n_1)(n_3 - n_2)},
\]

\[
S'_{F'} = f' \left\{ 1 - \frac{(n_2 - n_1)d}{n_2 n_1} \right\},
\]

where \( n_i, i = 1, 2, 3 \) – refractive indexes of environments, \( r_1, r_2 \) – radiiuses of the front and rear surfaces of the lens.

Rear surface of the sphere along the rays in the catadioptric reflector has a mirror coating. The angle of the ray reflected in the opposite hemisphere (\( \varphi \)) can be found from the condition of rays’ propagation at reflection in the microsphere at a given angle of incidence (\( \varepsilon \))

\[
\varphi(\varepsilon, n_1, n_2) = 4 \arcsin \left( n_1 \frac{\sin(\varepsilon)}{n_2} \right) - 2\varepsilon.
\]

The sphere has catadioptric properties – a parallel beam of incident rays turns into a parallel beam of reflected rays – if its refractive index \( n_2 = 2 \) (at \( n_1 = 1, \) air).
In the studied scheme where an additional layer with a mirror surface is formed on the rear hemisphere of the ball the catadioptric reflector acquires catadioptric properties (figure 3).

In order to determine the axial light intensity the spherical aberration of the third order was calculated, from the principal ray paths (normalization $\alpha_1 = 0$, $n_1 = 0$) [4] we find the longitudinal ($\Delta y_1$) and spherical aberration ($\Delta S$), the focal length within the catadioptric reflector ($F$), Seidel sum $S_1$, the wave aberration as a function of change of $n_3$ and $d_2L = L (\Delta n_3, \Delta d_2)$. The intensity distribution of the reflected radiation is described by the Fresnel-Kirchhoff integral in the Fraunhofer approximation for the exit pupil plane of the catadioptric reflector which is proportional to the Fourier transformation of the complex amplitude distribution of the reflected wave in the exit pupil plane. The maximum value of the indicatrix of reflection (scattering) is found by moving from the spatial frequencies in this plane to the spatial angular spectrum.
Measurements of the optical properties of different according to the technology retroreflective coatings were made some experimental scattering indicatrixes are presented in figure 4.

![Scattering indicatrixes of different samples](image)

**Figure 4.** Scattering indicatrixes of different samples: $I(\phi)$ – intensity, $\phi$ – scattering angle

In Figure 4, curve 1 – the scattering indicatrix of the "diamond type" of the retroreflective film of "3M" company, curve 2 – the scattering indicatrix of film of company "3M" (white, engineer grade), curve 3 – the scattering indicatrix of coating, developed in KNRTU-KAI.

It should be noted that the half-width of the scattering indicatrix of different designs' reflective coatings are quite close to each other. Maximum reflection scattering phase of the developed coating (curve 3) is close to the maximum reflection of the «3M» film company (curve 2) at about the same viewing angles.

3. Conclusions

Thus, on the basis of the conducted research it was found that the main optical characteristics (the maximum intensity of the reflected signal, the width of the reflection chart) the developed light-return coverage correspond to foreign models film of the company "3M" engineering type.

The findings served as the basis for the development of new reflective coatings based on polymer powder compositions, filled with microsphere reflectors. As a result of comprehensive experimental and theoretical studies of the regularities of changes in optical coatings defined by the structure, the nature of the components, dispersion and uniformity of the microsphere reflectors and regime parameters of applying and the formation of functional coating layers were defined.

References

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