

**DIFFRACTIVE ELEMENTS IN THE OPTICAL SYSTEM: SUCCESSES,  
CHALLENGES, AND SOLUTIONS****G. I. Greisukh,\* E. G. Ezhov, I. A. Levin, S. V. Kazin,  
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*Correction of aberrations is regarded as one of the most successful applications of diffractive optical elements in the optical system. The ways of overcoming these negative properties of the diffractive elements as spherochromatism and power spectral selectivity are presented. Using the technique given in this paper, a compact plastic–lens refractive–diffractive objective, which can operate in a wide spectral range including the visible and near-infrared radiation, has been designed.*

**1. INTRODUCTION**

One of the most promising lines of using diffractive optical elements in optical systems is correction of aberrations in the system as a whole, primarily the correction of chromatism. The correcting diffractive optical elements have a rotationally symmetric quasiperiodic relief–phase microstructure with multistage or sawtooth relief. If the optical power is nonzero and its microstructure in the first approximation is similar to the microstructure of the Fresnel-zone plate, then such an element is called a diffractive lens.

The efficiency of correcting aberrations in the optical systems using diffractive lenses is stipulated by the unique aberration properties of such lenses. For monochromatic aberrations, these include fast convergence of the aberration expansion and automatic fulfillment of the Petzval condition, which permit one to remove simultaneously the field curvature and the third-order astigmatism. For the first-order chromatism, we should mention the linear dependence of the optical power of a diffractive lens on the wavelength of the diffracted wave [1, 2].

The main objective of this study is to demonstrate the ways and possibilities for correction of chromatism, as well as to achieve high optical performance of the optical systems, whose refractive lenses are made of technological and commercially available plastics, by inclusion of a single diffractive lens into the system. The problem is that, unlike the optical glasses, the choice of such plastics is very limited, and their dispersion characteristics are very close. A similar problem is also observed in radio optics since in the microwave range of electromagnetic radiation the dispersion characteristics of radio-transparent materials only slightly differ, as well. The solution requiring the simultaneous use of two phenomena, refraction and diffraction, for transformation of the wave fronts is universal. This solution can effectively be used both in the optical and radio-frequency ranges of electromagnetic radiation.

**2. CHROMATISM OF THE REFRACTIVE AND DIFFRACTIVE LENSES**

Primary axial chromatism (i. e., dependence of the optical power and system image distance on the wavelength) of a regular refractive lens is determined by the dispersion properties of its material and is

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characterized by the dispersion coefficient

$$\nu_{\text{R}}^{(\bar{\lambda})} = (n_{\bar{\lambda}} - 1)/(n_{\lambda_{\text{min}}} - n_{\lambda_{\text{max}}}), \quad (1)$$

where  $n_{\lambda_{\text{min}}}$ ,  $n_{\bar{\lambda}}$ ,  $n_{\lambda_{\text{max}}}$  is the refractive index of the material of the refractive lens for the minimum  $\lambda_{\text{min}}$ , center  $\bar{\lambda}$ , and maximum  $\lambda_{\text{max}}$  wavelengths of a given spectral range. The definition of a similar parameter describing the primary chromatism of a diffractive lens includes only the wavelengths themselves:

$$\nu_{\text{D}}^{(\lambda^*)} = \lambda^*/(\lambda_{\text{min}} - \lambda_{\text{max}}). \quad (2)$$

Here,  $\lambda^*$  is the wavelength for which the structure of the diffractive lens is calculated and which is chosen, as a rule, from the condition  $\lambda^* = \bar{\lambda}$ .

Addressing Eq. (2) and the optical glass catalogues, it can easily be seen that in the visible wavelength range from 0.49 to 0.66  $\mu\text{m}$  the dispersion coefficient of a diffractive lens is  $-4.5$ . In a refractive lens, this coefficient ranges from 16 to 85, depending on the glass brand. In the extended spectral range, which includes the near infrared (IR) region, i. e., from 0.4 to 0.9  $\mu\text{m}$ , the dispersion coefficient of a diffractive lens is  $-1.3$ , and for a refractive lens it lies in the range 6.5–25. Hence, having the same optical power, the primary axial chromatism of the diffraction lens is significantly greater in absolute value and is opposite in sign compared with the refractive lens. It is exactly this fact that makes a diffractive lens one of the most effective chromatism correctors in the refractive-lens optical systems.

Along with the optical-power variation of a diffractive lens due to the deflection of the wavelength  $\lambda$  of the incident radiation from the calculated wavelength  $\lambda^*$ , its spherical aberration also changes drastically. This phenomenon, known in optics as spherochromatism, was considered in detail in [3]. Here we give only an expression for the third-order spherical-aberration coefficient of a diffractive lens on a curvilinear surface. In the particular case where the aperture-stop plane passes through the apex of the surface on which the microstructure of the diffractive lens is located, this expression has the form

$$S_{\text{D}}^{(3)} = \frac{4m\lambda A_2}{\pi} - \left(\frac{m\lambda A_1}{\pi}\right)^2 \left(-\frac{m\lambda A_1}{\pi} + \frac{2}{s} - 2c\right). \quad (3)$$

Here,  $s$  is the distance from the apical tangent plane to the carrier surface of the microstructure of a diffractive lens to the plane of the object,  $c$  is the curvature of the carrier surface of a diffractive lens,  $A_1$  and  $A_2$  are the first expansion coefficients of phase delay of a diffractive lens, which are determined by a power series of the form

$$\Psi(\rho) = m \sum_{j=1} A_j \rho^{2j}, \quad (4)$$

with  $m$  as the number of the operating diffraction order and  $\rho$  as the distance reckoned from the optical axis. Power series (4) was adopted to describe the diffractive lenses in ZEMAX, one of the most widely used commercial software for optical design [4].

It is seen from Eq. (4) that the dependence of the spherical aberration on the wavelength can be excluded only in one trivial case where all the coefficients  $A_j = 0$ , i. e., where the diffractive microstructure is absent. The case is different for the refractive lens. General expressions for the coefficients of wave spherical aberration of the third, fifth, and seventh orders of an aspherical refracting surface are given in [2]. Using these expressions, it is easy to obtain the corresponding coefficients for a thick refractive lens. However, in view of the abruptly increasing cumbersomeness of the formulas with increasing number of the aberration order, we use the approximation of a thin refractive lens only for the third-order spherical aberration coefficient,

$$S_{\text{R}}^{(3)} = - \left[ \frac{n_{\lambda} (c_1 s_1' - 1)^2}{s_1'^3} \left( 1 - \frac{n_{\lambda} s_1'}{s_1} \right) + (n_{\lambda} - 1) (8\alpha_{2,1} + c_1^3 \kappa_1) \right]$$

$$+ \frac{(c_2 s'_2 - 1)^2}{s'_2{}^3} \left( 1 - \frac{s'_2}{n_\lambda s_2} \right) - (n_\lambda - 1) (8\alpha_{2,2} + c_2^3 \kappa_2) \Big]. \quad (5)$$

Here,  $c_i$ ,  $s_i$ ,  $s'_i$ ,  $\alpha_{2,i}$ , and  $\kappa_i$  are the curvature, conjugate sections, aspheric deformation coefficient, and the conical constant of the front ( $i = 1$ ) and rear ( $i = 2$ ) refracting surfaces of a refractive lens, respectively. It is assumed that the aperture stop is matched with the lens itself, and the aspheric surfaces of a refractive lens are described by equations of the form [4]

$$z(\rho) = \frac{c_i \rho^2}{1 + \sqrt{1 - (1 + \kappa_i) c_i^2 \rho^2}} + \sum_{p=2}^P \alpha_{p,i} \rho^{2p}, \quad (6)$$

where  $z$  is the coordinate of the point on the surface at a distance  $\rho$  from the optical axis in the coordinate system bound with the apex of that surface,  $c = 1/r$  is the surface curvature at the apex,  $k$  is the conical constant, and  $\alpha_p$  are the coefficients of aspheric deformation for  $p = 2, 3, 4, \dots$

To ensure that the power of a refractive lens remains constant with the variation in the ratio of curvatures of its refracting surfaces, a parameter  $\sigma$  is generally used, which is called the deflection of a lens and is connected with its surface curvatures by the relations [3]

$$c_1 = (\sigma + 1)/a, \quad c_2 = (\sigma - 1)/a, \quad (7)$$

where  $a = 2(n_\lambda - 1) f'_\lambda$ . The subscripts of the refractive index and focal length of a refractive lens show that these quantities are calculated at the center wavelength  $\bar{\lambda}$  of a given spectral range.

The studies performed in [5] have shown that independently of the glass brand and the magnification of a refractive lens, by choosing the deflection and the aspheric deformation coefficient of one of the lens surfaces it is possible to change, depending on the wavelength, the shape of the curve determining the third-order spherical aberration or even remove this aberration at two arbitrary chosen wavelengths. If the deformation of a lens is already utilized for control of the third-order spherical aberration, then, as in the case of a diffractive lens, the fifth-order spherical aberration of a refractive lens can be removed only at one wavelength.

### 3. SUPPRESSION OF THE POWER SPECTRAL SELECTIVITY OF DIFFRACTIVE LENSES

The above-considered chromatism of a diffractive lens is a consequence of the dependence of the microstructure diffraction angle on the incident-radiation wavelength. Moreover, the diffraction efficiency, by which we mean the ratio between the flux of the radiation diffracted into one operation order and the flux of the radiation incident on the microstructure, is wavelength dependent, as well. It can easily be shown that in the case of a relief-phase sawtooth microstructure that ensures a diffraction efficiency close to 100% at the center wavelength of the extended spectral range, the diffraction efficiency falls down to 57% at the edge of that range, i. e., at wavelengths of 0.4 and 0.9  $\mu\text{m}$ . This phenomenon, called the power spectral selectivity, plays a fairly negative role in the case where the diffractive lens is used as an aberration corrector in the optical system.

To attenuate the spectral selectivity of the diffraction structure operated for transmission, and to level off, to a certain degree of accuracy, the diffraction efficiency in a given spectral range, we make use of the solution proposed by A. V. Lukin, K. S. Mustafin, and R. A. Rafikov [6, 7] in 1987. This requires the creation of a multilayer (in particular, two-layer) relief-phase microstructure designed as a plane-parallel plate of two optical materials, each being limited by plane and relief surfaces. Relief surfaces are similar, have an identical depth of relief, and are in optical contact with each other. A similar solution was also proposed in the later papers (see, e. g., [8]). The method of attenuating the spectral selectivity of the relief-phase diffraction microstructures on optical plastics is given in [9]. The positive effect is reached by using two or

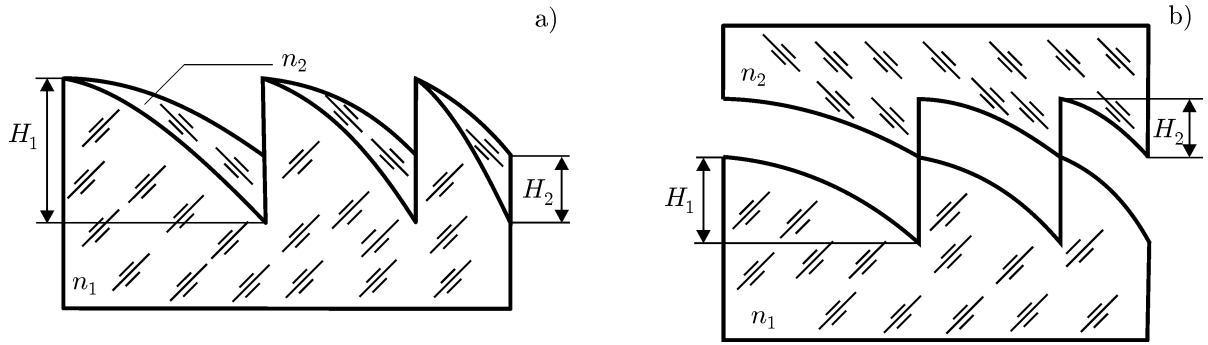


Fig. 1. Two-layer matched-relief microstructures ensuring a high diffraction efficiency in a wide spectral range (the case of a diffraction lens with positive spectral power for  $n_1 < n_2$ ): a) the structure with inner and outer reliefs and b) the structure with two inner reliefs.

more reliefs with different depths.

Besides the wavelength of the incident radiation, the diffraction efficiency also depends on the shape and depth of the relief, as well as on the number of Fresnel zones of a diffractive lens. By the term “Fresnel zone” we mean the part of the diffractive-lens microstructure, within which the phase delay introduced into the incident wave front varies from 0 to  $2\pi$ . For a relatively large number of Fresnel zones (more than 100) the high diffraction efficiency is provided by the linear-sawtooth relief. For a small number of Fresnel zones, the optimal shape of the relief depends on the shape of the incident wave front, the optical power of the diffractive lens, and the form of the surface on which the microstructure of the diffractive lens is located. In [10, 11], the reliefs having an optimal shape and providing, besides the maximum diffraction efficiency, the shape of generated wave front coinciding with the calculated one are called correlated, or matched reliefs. The same papers also give equations of the matched reliefs of one- and two-layer double-relief microstructures located on the plane and curvilinear interfaces. It is shown that in the case of two-layer double-relief microstructures with matched reliefs, the diffraction efficiency within the entire extended spectral range can be no less than 93% independently of the number of Fresnel zones in the microstructure of a diffractive lens.

Figure 1 presents two-layer double-relief microstructures with matched reliefs. The optimal depths  $H_1$  and  $H_2$  of the reliefs in optical media with the refractive indices  $n_1$  and  $n_2$  can be found using the procedures given in [12, 13].

Concluding this section, we note that the diffractive lenses with two-layer, and the more so, double-relief microstructure are technologically inferior to those with one-layer microstructure. However, the Canon company has already organized serial production of a high-quality teleobjective with a two-layer double-relief diffraction element [14].

#### 4. DIFFRACTIVE-REFRACTIVE CORRECTOR

Primary chromatism and spherochromatism of the optical system can be reduced to an admissible level simultaneously by using a diffractive-refractive corrector, namely, the component proposed in [15] and composed of one diffractive lens and one or two refractive lenses. The minimum number of refractive lenses included in the corrector depends on the degree of correction of primary color. Achromatization requires one refractive lens made of an identical or similar optical material of the optical system as a whole. Apochromatization requires one refractive lens, too, but the latter is made of a flint-like material. Superachromatization requires that at least two refractive lenses, whose materials make up a crown-flint pair, should be used in the diffractive-refractive corrector.

We note at once that crown-like materials are the optical materials whose dispersion coefficient for the visible spectral range  $\nu_R^{(\lambda)} \geq 50$ , and flint-like materials are those in which  $\nu_R^{(\lambda)} \leq 50$ . We then recall that the state at which equal image distances of the optical system,  $s'_{\lambda_{\min}} = s'_{\lambda_{\max}}$ , are provided at two wavelengths,  $\lambda_{\min}$  and  $\lambda_{\max}$ , of a given spectral range is called achromatization [16, 17]. Apochromatic correction of the

optical system (i. e., correction of the secondary spectrum) is generally the elimination of chromatism for three wavelengths,  $\lambda_{\min}$ ,  $\bar{\lambda}$ , and  $\lambda_{\max}$  of the chosen spectral range. The aim of this correction is to make the system image distance equal at three wavelengths,  $s'_{\lambda_{\min}} = s'_{\bar{\lambda}} = s'_{\lambda_{\max}}$  [16, 18].

Superachromatic correction (correction of the tertiary spectrum) is the elimination of axial color for four wavelengths of a given spectral range and aims at making the system image distances equal at these wavelengths [19–21]. The purpose of the transition from achromatization to apochromatization and then to superachromatization is to reduce defocusing at the intermediate wavelengths.

The above-formulated conditions for the achievement of the given degree of correction of chromatism with a minimum number of refractive lenses in the diffractive–refractive corrector can be explained using the achievement of apochromatic correction of the optical system as an example. Simultaneously, we single out the basic elements of the procedure we developed to calculate the diffractive–refractive corrector for provision of the given degree of correction of chromatism. The method includes two stages. At the first stage, the diffractive–refractive corrector is assumed to be infinitely thin and the axial chromatism is described by the first chromatic sum. We take into account that the optical power  $\Phi$  of an infinitely thin diffractive–refractive corrector at the center wavelength  $\bar{\lambda}$  should have a fixed value. Then the condition of achievement of apochromatization of an optical system that includes a diffractive–refractive corrector can be written in the form of the system of equations

$$\begin{aligned} \varphi_D + \sum_{i=1}^I \varphi_{Ri} &= \Phi, \\ \frac{\varphi_D}{\nu_D} + \sum_{i=1}^I \frac{\varphi_{Ri}}{\nu_{Ri}} &= \frac{S_{\text{ch}}^{[\lambda_{\min}, \lambda_{\max}]}}{h_A^2}, \quad \frac{\gamma_D \varphi_D}{\nu_D} + \sum_{i=1}^I \frac{\gamma_{Ri} \varphi_{Ri}}{\nu_{Ri}} = \frac{S_{\text{ch}}^{[\lambda_{\min}, \bar{\lambda}]}}{h_A^2}. \end{aligned} \quad (8)$$

Here,  $\varphi_D$  and  $\varphi_R$  are the optical powers of the diffractive and refractive lenses of the corrector at the wavelength  $\bar{\lambda}$ ,  $h_A$  is the height of the aperture zero ray in the plane of the diffractive–refractive corrector, which was calculated at the same wavelength,  $I$  is the number of refractive lenses included in the corrector,  $S_{\text{ch}}^{[\lambda_{\min}, \lambda_{\max}]}$  and  $S_{\text{ch}}^{[\lambda_{\min}, \bar{\lambda}]}$  are the contributions to the first chromatic sums of all elements of the optical system except for the diffractive–refractive corrector, which were calculated for the spectral ranges  $[\lambda_{\min}, \lambda_{\max}]$  and  $[\lambda_{\min}, \bar{\lambda}]$ , respectively,  $\gamma_D$  and  $\gamma_R$  are the relative partial dispersions for the diffractive lens and the materials of a refractive lens, which were calculated by the formulas

$$\gamma_D = (\lambda_{\min} - \bar{\lambda}) / (\lambda_{\min} - \lambda_{\max}), \quad (9)$$

$$\gamma_R = (n_{\lambda_{\min}} - n_{\bar{\lambda}}) / (n_{\lambda_{\min}} - n_{\lambda_{\max}}). \quad (10)$$

In the case where the diffractive–refractive corrector comprises one refractive lens, the system of equations (8) is overdetermined, and the condition for the existence of its solution is that the determinant of the extended matrix be equal to zero,

$$\begin{vmatrix} 1 & 1 & \Phi \\ 1/\nu_D & 1/\nu_{R1} & S_{\text{ch}}^{[\lambda_{\min}, \lambda_{\max}]} / h_A^2 \\ \gamma_{2D} / \nu_D & \gamma_{2R1} / \nu_{R1} & S_{\text{ch}}^{[\lambda_{\min}, \bar{\lambda}]} / h_A^2 \end{vmatrix} = 0. \quad (11)$$

The absolute value of the left-hand side of Eq. (11) is minimized by choosing the optical material of a refractive lens and is set to zero by additional correction of the parameters of the last column of the determinant due to the redistribution of optical powers among the diffractive–refractive corrector and other refractive lenses of the optical system.

By virtue of the nonlinear refractive index of the material as a function of the wavelength, the conditions of vanishing of the first chromatic sum and the absence of axial color for the given pair of wavelengths, rigorously speaking, do not coincide. Therefore, at the second stage of calculation of the

diffractive–refractive corrector, the optical powers of its elements obtained when solving the system of equations (8) are considered as the zero approximation. Then the optical powers are determined more precisely through iterative solution of the system of equations, some of which ensure the given focal length  $f'$  of the optical system with the diffractive–refractive corrector set at the wavelength  $\bar{\lambda}$  and other ensure that the image distances of the optical system are equal at the corresponding wavelengths of the chosen spectral range [22]. In the case of apochromatization, this system of equations has the form

$$f'_{\bar{\lambda}} = f', \quad s'_{\lambda_{\min}} = s'_{\lambda_{\max}}, \quad s'_{\lambda_{\min}} = s'_{\bar{\lambda}}. \quad (12)$$

The transition from the system of equations (8) to system (12) also makes it possible to introduce thicknesses of the elements and air gaps and operate with the “actual optical materials,” describing them not by the parameters  $\nu_R$  and  $\gamma_R$ , which are based on the linearization of the dependence of the refractive index on the wavelength, but using appropriate dispersion formulas.

When choosing the materials for manufacturing of refractive lenses for the diffractive–refractive corrector, one should also take into account that the chosen pair of materials determines the radius  $R$  of the Petzval surface [3] on which the optical system can form a stigmatic image,

$$R = \left( \sum_i \varphi_{Ri}/n_i \right)^{-1}, \quad (13)$$

where

$$\varphi_{Ri} = (n_i - 1)(c_{2i} - c_{1i}) \quad (14)$$

is the “fine” component of the optical power of the refractive lens with number  $i$ . The summation is performed over all lenses of the optical system except for the diffractive lens since its Petzval curvature is equal to zero [1, 2].

It should be mentioned that the introduction of a diffractive–refractive corrector into the preliminarily calculated optical system can break the previously reached correction of monochromatic aberrations. The level of these aberrations can generally be restored or even reduced at the optimization stage by using the deflection of the refractive lens, the coefficients of asphericity of the refracting surfaces, the coefficients of aspheric additions of the diffractive lens, and thicknesses of the elements and air gaps.

## 5. CALCULATION OF THE PLASTIC–LENS APOCHROMATIC OBJECT GLASS WITH A DIFFRACTIVE–REFRACTIVE CORRECTOR

One of the categories of the optical systems for mass production and in huge amount is the objectives of cell phones and compact security video cameras. The combining of low cost requirements and fairly high optical performance of these objectives makes it expedient to use plastics for manufacturing the elements of these optical schemes. Indeed, the advanced shaping techniques based on high-precision stamping permit easy copying of plastic lenses with aspheric refracting surfaces. Moreover, a diffraction microrelief [23, 24] can be stamped, if necessary, on these surfaces. As concerns the chromatism of plastic–lens objectives, the diffractive–refractive correctors ensure that the required degree of correction of primary chromatism is reached even when the refractive lenses of such objectives are manufactured of the most technological and commercially available optical plastics of only two brands, e. g., crown-like polymethyl methacrylate and flint-like polycarbonate.

The problem of the high-quality image formation is significantly complicated when it is needed to calculate the objectives of compact systems of exterior video monitoring intended for work in a wide spectral range, i. e., under natural daytime and twilight illumination, as well as under artificial illumination created, e. g., by a LED IR search light [25]. As a result, for example, the resolution of the plastic–lens achromatic objective described in [26], when operated in the extended spectral range, decreases from 140 to 35 mm<sup>-1</sup>. Now, to increase the resolution, one should compensate for at least the secondary spectrum as well, i. e.,

ensure the apochromatization of the objective.

Following the method of making the diffractive–refractive corrector a part of the objective, it is needed to choose the original scheme of the optical system with not fully corrected chromatism. As the system, we used the already mentioned plastic–lens achromatic objective. The refractive part of the diffractive–refractive corrector of this objective is a single refractive lens which is made, as the other refractive lenses of the objective, of crown-like polymethyl methacrylate. If the problem of apochromatization with increasing number of elements of the diffractive–refractive corrector is posed, then the material of its single refractive lens should be chosen depending on the condition. The minimization of the absolute value of the left-hand side of Eq. (11) requires that the refractive lens as part of the diffractive–refractive corrector be made of a material with greater dispersion than the dispersion of the materials of all other lenses of the objective, i. e., a flint-like optical material (in this case, flint-like polycarbonate). As was mentioned before, the vanishing of the determinant of the extended matrix on the left-hand side of Eq. (11) can be reached not only due to the material of the refractive lens, but also by redistribution of the optical powers between the lenses of the diffractive–refractive corrector and other lenses of the objective.

The introduction of a refractive lens made of flint-like polycarbonate into the scheme of the apochromatic objective has reduced the radius of the Petzval surface. In order to increase this radius and, simultaneously, create conditions for reducing the field monochromatic aberrations, the power refractive lens of the objective, which follows behind the diffractive–refractive corrector, was replaced by a doublet made of the same crown-like material, i. e., polymethyl methacrylate. Note at once that this effect cannot be achieved by introducing an additional lens into the diffractive–refractive corrector. Then the optical powers and the curvature radii of the refracting surfaces of refractive lenses were determined more accurately by solving the system of equations (12).

The final stage of calculation of a plastic–lens apochromatic objective was the optimization using the ZEMAX optical design software [4]. The optimization was performed over the parameters not affecting the optical powers of the lens and, therefore, without breaking the objective apochromatization condition that was achieved. Such parameters in this case were deflections of the refractive lenses, coefficients of asphericity of the refracting surfaces, and coefficients of aspheric additions of the diffractive lenses.

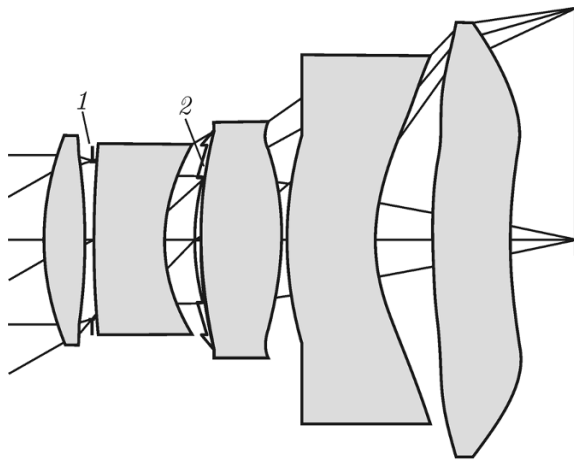


Fig. 2. Optical scheme of a plastic–lens refractive–diffractive apochromatic objective: 1 aperture stop and 2 diffractive lens.

Figure 2 shows a block diagram of the plastic–lens refractive–diffractive apochromatic objective calculated by the above-described method. The diffractive–refractive corrector of the objective includes the second refractive lens and a diffractive lens, whose microstructure is located on the frontal surface of the third refractive lens, i. e., the first lens of the power doublet. The latter correction refractive lens reduces the angles of incidence of rays on the peripheral elements of the matrix photo detector and therefore provides its more uniform illumination.

The objective for the focal length  $f' = 3.71$  mm, relative aperture 1:2.4 within the angular field  $2\omega \leq 60^\circ$ , and maximum angle of incidence of the chief ray in the image space, which is less than  $20^\circ$ , provides a spatial resolution of no less than  $N = 150 \text{ mm}^{-1}$  for the contrast  $T = 0.5$  in the visible range of  $\lambda_F = 0.48613 \text{ } \mu\text{m}$  to  $\lambda_C = 0.65626 \text{ } \mu\text{m}$ . In the spectral range of  $\lambda_{\min} = 0.4 \text{ } \mu\text{m}$  of

$\lambda_{\max} = 0.9 \text{ } \mu\text{m}$ , which corresponds to the natural twilight illumination, the spatial resolution is no less than  $N = 140 \text{ mm}^{-1}$ . In the night-time operation using artificial IR illumination by a LED search light with the maximum radiation at the wavelength  $\lambda = 0.85 \text{ } \mu\text{m}$ , the spatial resolution is no less than  $N = 127 \text{ mm}^{-1}$ . Distortion of the calculated apochromatic objective for all types of illumination does not exceed 1%, and

the residual axial color turns out to be no more than  $5.5 \mu\text{m}$ .

Thus, in all the three above-mentioned regimes, this objective exceeds in resolution the glass-lens objectives of this class that are currently issued by the leading producers by at least 30% [27–29].

## 6. CONCLUSIONS

The fundamental possibilities for correction of aberrations of refractive-lens optical systems using diffractive lenses have been demonstrated by comparing the properties of such lenses with the properties of the conventional refractive lenses. It is shown that the diffractive–refractive corrector included in one diffractive or two refractive lenses is the component which permits the fundamental possibilities mentioned above to be implemented. Particular attention is paid to the capability of suppressing the power spectral selectivity of diffractive lenses and reach a diffraction efficiency close to 100% in a fairly wide spectral range by using a two-layer double-relief microstructure with matched reliefs. The proposed method for calculation of the objective ensures that the required degree of correction of chromatism is reached due to the diffractive–refractive corrector with a minimum number of refractive lenses in it. A plastic–lens apochromatic objective, which by its optical performance exceeds the known glass-lens objectives of this class is calculated.

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