# DIFFRACTIVE ELEMENTS FOR IMAGING OPTICS OF MOBILE COMMUNICATION DEVICES

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***Abstract***

An estimate of the permissible width of the working spectral range of optical systems with diffractive elements is given. It takes into account the interval of the angles of incidence of the radiation on the microstructure of the element and it proceeds from the requirement that there is no halo in the image that is visualized by the LCD monitor. It is shown that the design parameters of diffractive elements intended for mobile device cameras are quite achievable for today's technologies of mass production of plastic optics.

Keywords: diffraction efficiency, relief-phase diffraction microstructure, halo, diffractive lens.
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## *Introduction*

Broad opportunities of aberration correction and, first of all, of chromatic aberration of an imaging optical system are well known due to inclusion of a diffraction optical element into the system diagram [1 – 10]. In particular, the element consisting of a diffractive lens (DL) with a small optical power helps achieve a high degree of chromatic correction required to get a high-quality color image even when using a limited set of optical materials, for instance, technologically efficient and commercially available optical plastics. Thereby, today's technologies of mass production of plastic refraction lenses, one of the spherical or aspheric surfaces of which bears a sawtooth relief-phase diffraction microstructure (see Fig. 1), remove almost all previously existed constraints on the design parameters of such hybrid elements.

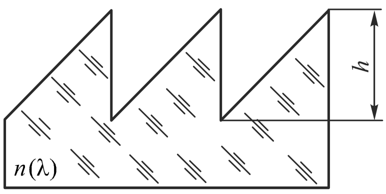


*Fig. 1. A sawtooth relief-phase diffraction microstructure*

Hence, almost the only serious challenge that restricts common use of diffractive elements with the sawtooth relief-phase microstructure is supposed to be considerable probability of the occurred color fringe (halo) that provides the most striking image fragments being formed by the optical system in polychromatic radiation. The responsibility for halo is taken by the radiation diffracted onto the microstructure in indirect diffractive orders [11]. Integrally, their level is usually estimated by the difference of the diffraction efficiency (DE) in the first working order $\eta$ of unity.

The conditions imposed on the diffraction efficiency of the microstructure and guaranteeing the absence of the visually observable halo in the image recorded by a photodetector array are shown in paper [12]. They demand that the DE-wavelength influence curves, being smooth and convex at all angles of incidence of the radiation of the microstructure ($-\theta_{max} \le \theta \le \theta_{max}$) and within the whole working spectral range ($\lambda_{min} \le \lambda \le \lambda_{max}$), should fulfill the following condition: $\eta \approx 1$ at one of the wave-lengths within the spectral range and $\eta \ge 0.85$ on its edges. These conditions have been obtained by theoretical analysis of experimental results given in paper [13] with the use of the Plastic Hybrid Aspheric Lens No 65-999, a commercial product by Edmund Optics [14].

## *1. Estimate of the permissible width of the spectral range*

We may accurately estimate DE of the sawtooth relief-phase microstructure of the diffractive lens within the framework of the scalar theory provided that the relation between the minimum period of the microstructure and the relief depth is $\Lambda_{min} / h \ge 10$. In fact, as shown in papers [15 – 17], the DE values obtained within the framework of the rigorous diffraction theory based on solutions of Maxwell's equations with respective boundary conditions are, in general, lower than the values given by the scalar theory. However, during the relative microstructure period $\Lambda_{min} / h \ge 10$ this difference in the DE values is not large and may be neglected.

Within the framework of the scalar theory, DE of the sawtooth relief-phase microstructure of the diffractive lens in the first diffractive order is described as follows [18]:

$$\eta = \left\{ \sin\left[ \pi\left(1 - \Delta l/\lambda\right) \right] / \pi\left(1 - \Delta l/\lambda\right) \right\}^2 . \quad (1)$$

Here $\Delta l$ is an increment of the optical distance in one period (in one annular area) of the sawtooth profile being dependent on the refraction index of the microstructure material $n(\lambda)$, on the relief depth, and also on the wavelength and the angel of incidence of the radiation of the microstructure from the air:

$$\Delta l = h\left( \sqrt{n^2(\lambda) - \sin^2\theta} - \cos\theta \right). \quad (2)$$

Having selected the maximum wavelength of the working spectral range and using the equations (1) and (2), it is easy to obtain the dependence $\lambda_{min}(\theta_{max})$ that provides the above no-halo condition ($\eta \approx 1$ at one of the wavelengths inside of the working spectral range and $\eta \ge 0.85$ on its edges at all angles of incidence of the radiation of the microstructure not exceeding θmax in absolute magnitude). However, the best values of the relief depth *h* will be obtained thereby which provide the least value of $\lambda_{min}$ for each angle of incidence.

Defining the working spectral range of a photo- or video camera, we will assume that it may be displayed by a modern LCD monitor. We can select the maximum wavelength of the working spectral range having referred to the CIE chromaticity diagram with an applied color triangle or, that is more obvious, to the spectral response function of an LED highlight block of the LCD monitor, for instance, a modern budget-type model SynsMaster XL20 by Samsung [19] (see Fig. 2). Taking into account the fact that the relative radiant intensity of R LEDs of the RGB-triplet drops rapidly from 0.15 almost to zero at the wavelengths of over 0.65 μm, particularly this wavelength ($\lambda_{max} = 0.65$ μm) may be taken as the maximum wavelength of the working spectral range of mobile device photo- or video cameras.

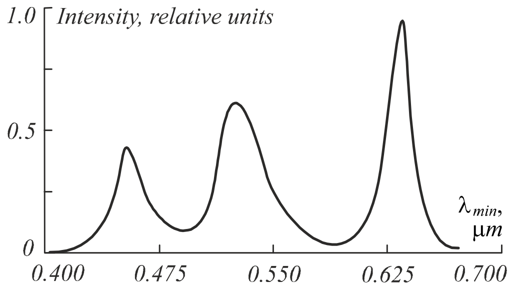


*Fig. 2. Spectral characteristic of an LED highlight block of the LCD monitor SynsMaster XL20*

Having the above chosen long wavelength limit of the working spectral range and using the microstructure made of the crown-alike optical plastic E48R [20], we have drawn up the dependency graph $\lambda_{min}(\theta_{max})$ given in Fig. 3. It shows that when the angles of incidence of the radiation are $0 \le \theta_{max} \le 15°$, the minimum permissible wavelength is $0.427 \le \lambda_{min} \le 0.436$ μm.

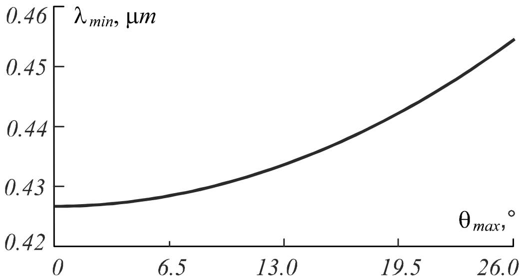


*Fig. 3. Dependence of the permissible short wavelength of the working spectral range from the angle of incidence of the radiation of the microstructure*

Having referred again to Fig. 2, we will note that when the wavelengths are from 0.427 to 0.436 μm, the radiant intensity of B LEDs referred to the relevant maximum grows from 0.05 up to no more than 0.2. Hence, elimination of the radiation from the working spectrum at the wavelengths of less than $\lambda_{min}$ by using a proper optical radiation filter won't be visually perceived and won't involve any additional digital color correction.

The situation with large angels of incidence of the radiation is quite different. For instance, when $\theta_{max} = 25°$, the minimum permissible wavelength is $\lambda_{min} = 0.452$ μm.

This spectrum constraint may be achieved using a yellow optical filter "ZhS12" usually applied at black-and-white photography [21]. In this case, the filter blocks all wavelengths being left-handed from the maximum radiation of R LEDs that encolors the image displayed on the monitor in yellow (Fig. 4). If required, this color gradation may be removed, as noted in paper [12], by digital correction using a white-balance tool in any paintbrush software, for instance, Adobe Photoshop [22]. Besides, it is possible to anticipate an automatic white-balance shift by a predefined value in the mobile device camera software.


*Fig. 4. Example of digital correction of the image formed by the photo camera when being installed in front of the lens of the yellow optical filter "ZhS12": 1– with the optical filter; 2 – without the optical filter; 3 – the corrected white balance in software*

In conclusion, thereof we would like to note that limiting the angles of incidence of the radiation of the microstructure of the diffractive lens in refractive-and-diffractive optical systems is provided by the design technique actual for these systems. In particular, the procedure noted in [23] helped limit the angles of incidence of the radiation of the microstructure in periscope and variable focus lenses up to ±15° at angular fields of view of the optical system up to ±37° [24, 25]. The same technique used in objective lenses of smart phones helps limit the angles of incidence of the radiation of the microstructure up to ±25° at angular fields of view of the optical system up to ±32° [12].

### *2. Estimate of technological effectiveness of the sawtooth relief-phase DL microstructure*

In Introduction we have mentioned that today's technologies of mass production of elements with the sawtooth microstructure remove almost all previously existed constraints on the design parameters of diffractive elements. This is due to the fact that the main critical parameter, that is the width of the microstructure's narrowest annular area, is restricted with the following condition: $\Lambda_{min} / h \ge 10$. The very width of the narrowest area at the given focal length of the diffractive lens determines exactly the maximum clear aperture. We will demonstrate this with the example of two types of elements: the diffractive lens, the coefficients of a spherical aberration component of which at the effective wavelength are inversely proportional to the focal length of proper degree, and the diffractive lens with the spherical aberration completely removed at the estimated wavelength.

The first type of the diffractive lens causes the following phase delay to the normally incident plane wavefront:

$$\phi = \pi\rho^2/\lambda_0 f', \tag{3}$$

where $\lambda_0$ is the estimated wavelength; $\rho$ is the length measured relative to the optical axis; $f'$ is the focal length.

The microstructure of this diffractive lens is similar to the microstructure of the geometrical Fresnel zone plate whose boundary radii of annular areas are proportional to the square root of whole numbers. The outer radius of a boundary annular area of the geometrical Fresnel zone plate, i.e. the half of the clear aperture, is relevant to the width of this zone with the following approximate relationship:

$$0.5D_{cl} = \rho_{\max} \approx (\lambda_0/\Lambda_{\min}) f'. \tag{4}$$

Taking into account the fact that the best relief depths of the diffractive lens at the angles of incidence of the radiation up to 25° slightly differ from the depth that provides the unit diffraction efficiency ($\eta = 1$) at $\theta = 0$ at the estimated wavelength $\lambda_0$, we use the following:

$$h = \lambda_0 \big/ \left(n(\lambda_0) - 1\right), \tag{5}$$

and assuming that $\Lambda_{\min} / h = K$ for the half of the clear aperture, we receive the following:

$$0.5D_{cl} \approx \frac{n(\lambda_0) - 1}{K} f'. \tag{6}$$

When $K \geq 10$, the clear aperture will be restricted with the following condition:

$$D_{cl} \leq 0.2\left(n(\lambda_0) - 1\right) f', \tag{7}$$

and the width of the narrowest area is as follow:

$$\Lambda_{\min} \geq \frac{10\lambda_0}{\left(n(\lambda_0) - 1\right)} \tag{8}$$

In consideration of $\lambda_0$ being the central wavelength of the visible spectral range ($\lambda_0 = 0.55$ μm) and assuming $n(\lambda_0) \approx 1.5$, it is not difficult to see that $\Lambda_{\min} \geq 11$ μm and $D_{cl} \leq 0.1f'$. These design parameters are actually no problem for today's technologies of mass production of plastic optics (see, for instance [26]).

The second type of the diffractive lens causes the phase delay to the normally incident plane wavefront described by the following equation:

$$\phi = \frac{2\pi}{\lambda_0}\left(\sqrt{\rho^2 + f'^2} - f'\right). \tag{9}$$

The microstructure of this diffractive lens is similar to the microstructure of an interference zone plate. The relationship of its clear aperture with the focal length at low numerical apertures ($D_{cl} \leq 0.1f'$) is also described with a reasonable degree of accuracy by the following formulae (4) and (6). In this way, the design parameters of this diffractive lens are completely achievable for today's technologies.

## *Conclusion*

This paper presents recommendations on selection of the working spectral range of photo- and video cameras for mobile communication devices. These recommendations are grounded on the analysis of the spectral and angular dependence of the diffraction efficiency of the saw-tooth relief-phase microstructure and on the experimental estimate of quality influence of the image being formed by the optical system with the diffractive lens and the radiation having been diffracted on its microstructure in indirect orders. In addition, they also take into consideration the color gamut of the LCD monitor which is supposedly to be used for image visualization.

According to these recommendations, the whole visible spectral range may be considered as the working spectral range of the optical system at the angles of incidence of the radiation of the microstructure of the diffractive lens not exceeding 15° in absolute magnitude. When the incidence angles come up to 25° in absolute magnitude the visually observed halo occurred within the image shall be omitted only by cutting-off a short wave-end of the spectrum, for instance, by means of the yellow optical filter "ZhS12".

The paper shows that restrictions on the microstructure design parameters caused by electromagnetic wave diffraction on the relief-phase microstructure of finite depth are more severe than today's technological constraints in mass production of such structures.

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