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Hybrid apochromatic lens

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In the paper, it has been shown that an apochromatic triplet can be designed without employing special glasses. This possibility is offered when optical system is composed of two lenses, *i.e.*, hybrid and glass ones. Such a system is proposed and its spherochromatic aberration is determined. Aberration characteristic of the system is compared with that of conventional glass apochromat.

1. Introduction

Correction of chromatic aberration is usually one of the most significant conditions for usability of an optical system. The simplest achromatic correction can be obtained in a doublet which is created by two lenses produced with the use of conventional optical glasses. A more complete correction of chromatic aberrations, *i.e.*, apochromatic or superachromatic corrections, can be obtained in a triplet if, at least, one of the glasses applied is a special glass [1]–[3]. In the contemporaty optics the diffraction optical elements (DOE) or hybrid lenses are used more and more frequently; the hybrid lenses being a combination of a glass lens and diffraction element located on one of the refracting surfaces of the glass lens. The design parameters of the hybrid lens, in addition to the curvature radii and the lens thickness, are the positions of sources of the waves creating the diffraction pattern on the refractive surface of the lens. The distances of the waves sources from the lens will be denoted by z_α and z_β, respectively. Since the contemporary structures of hybrid lenses are produced synthetically, the distances z_α and z_β are essentially the parameters defining the topology of the structure. The hybrid lens produced in this way is characterized by an axial symmetry. It can be an achromatic lens [3], [4], but the secondary spectrum of such a lens is significant and therefore it has found no broader application in praxis. For illustration of achromatic correction possibilities, *i.e.*, Abbe numbers, partial dispersions for λ_D, as well as converging powers of lenses creating classical achromatic lens and hybrid lens are given in Tab. 1. For DOE the Abbe number and partial dispersion (for λ_D line) are defined as follows:

$$\nu = \frac{\lambda_D}{\lambda_F - \lambda_C}, \tag{1a}$$

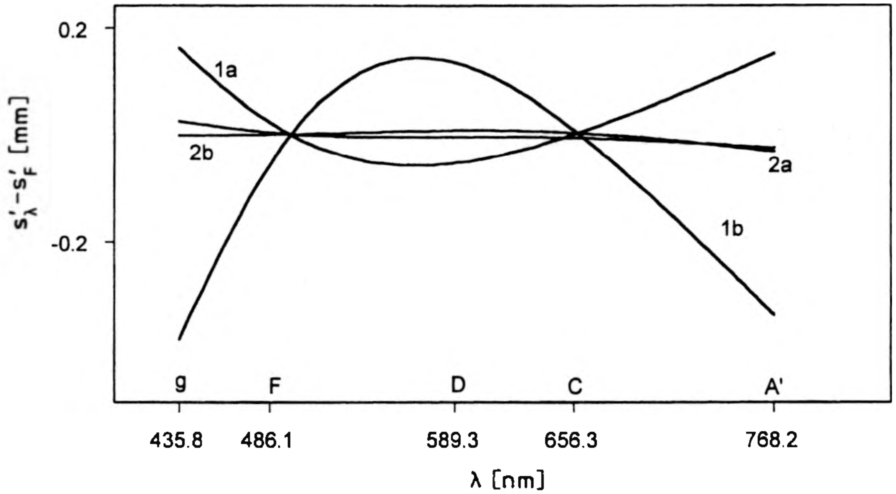


Fig. 1. Chromatism of position of achromatic and apochromatic lenses ($f' = 100$ mm).

Table 1. Converging powers of selected achromatic and apochromatic lenses ($f' = 100$ mm).

No.	Type of lens	Type of glass	φ	ν	P_D
1a	Glass achromat	BK3	0.0199	65.63	0.69935
		SF5	−0.0099	32.12	0.71730
1b	Hybrid achromat	DOE	0.0005	−3.4624	0.60635
		BK3	0.0095	65.63	0.69935
2a	Glass apochromat	F2	0.0253	36.36	0.71496
		KzFSN5	−0.0393	39.62	0.71121
		FK51	0.0240	84.46	0.703125
2b	Hybrid apochromat	DOE	0.00015	−3.4624	0.60635
		BK3	0.01684	65.63	0.69935
		SF5	−0.00699	32.12	0.71730

Table 2. Chromatism of position for selected achromatic and apochromatic lenses ($f' = 100$ mm).

No.	$S'_\lambda - S'_F$ [mm]				
	A'	C	D	F	g
1a	0.154	0.005	−0.050	0	0.181
1b	−0.341	0.001	0.136	0	−0.426
2a	−0.031	0.007	0.010	0	0.002
2b	−0.024	−0.003	−0.001	0	0.031

$$P_D = \frac{\lambda_F - \lambda_D}{\lambda_F - \lambda_C} \tag{1b}$$

where λ is the wavelength for: $\lambda_D = 0.5893$ µm, $\lambda_F = 0.4861$ µm, $\lambda_C = 0.6563$ µm, respectively. It can be seen that a conventional achromat is of definitely better correction for position chromatism than the hybrid lens (Tab. 2, Fig. 1). In spite of the large secondary spectrum of the latter it allows us to design hybrid achromat working in a smaller range of wavelengths [6].

2. Apochromatic correction

In order to make a three-lens optical system an apochromat the following conditions must be fulfilled [2], [3]:

$$\frac{\varphi_1}{\nu_1}+\frac{\varphi_2}{\nu_2}+\frac{\varphi_3}{\nu_3}=0, \tag{2a}$$

$$\frac{\varphi_1}{\nu_1}P_1+\frac{\varphi_2}{\nu_2}P_2+\frac{\varphi_3}{\nu_3}P_3=0, \tag{2b}$$

$$\varphi_1+\varphi_2+\varphi_3=1. \tag{2c}$$

This set of equations will be solvable if the condition

$$\begin{vmatrix} 1 & 1 & 1 \\ P_1 & P_2 & P_3 \\ \nu_1 & \nu_2 & \nu_3 \end{vmatrix} \neq 0. \tag{3}$$

is satisfied. This condition requires at least one special glass to be applied. The converging powers of the respective single lenses are determined by the formulae:

$$\varphi_1=-\frac{C_D\nu_1}{C_D(\nu_3-\nu_1)+\nu_2-\nu_3}, \tag{4a}$$

$$\varphi_2=\frac{\nu_2}{C_D(\nu_3-\nu_1)+\nu_2-\nu_3}, \tag{4b}$$

$$\varphi_3=\frac{\nu_3(C_D-1)}{C_D(\nu_3-\nu_1)+\nu_2-\nu_3} \tag{4c}$$

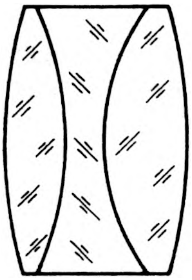
where

$$C_D=\frac{P_{2D}-P_{3D}}{P_{D1}-P_{3D}}. \tag{5}$$

The locations of the foci for three wavelengths, λ_F, λ_C, λ_D in this case, are identical. Our task was to design an apochromat taking advantage of a hybrid lens. We assume that the first lens is replaced by diffractive lens with converging power determined by the formula

$$\varphi_1=\left(\frac{1}{z_\alpha}-\frac{1}{z_\beta}\right). \tag{6}$$

a



R [mm]	d [mm]	Type of glass
63.434		
	2.5	F2
−40.00		
	2.0	KzFSN5
28.54		
	2.8	FK51
−68.50		

b

R [mm]	d [mm]	Type of glass
45.395		
	3.0	BK3
−83.100		
	1.0	SF5
−723.04		

$z_\alpha = 13.500$ mm
$z_\beta = -13.475$ mm

Fig. 2. Constructional data for apochromats: **a** — glass type 2a, **b** — hybrid type 2b.

In this case, we do not have to apply special glasses. The constructional data, chromatism of position and spherochromatic aberration of a hybrid apochromat are presented in Tabs. 1 and 2, and Figs. 1 and 2 (lens 2b). The values of z_α and z_β, radii of curvature and thicknesses of the lenses are chosen in such a way that the spherochromatic aberration is corrected. For comparison analogous magnitudes were given for conventional apochromat (lens 2a), [7]. When analysing the values of image distance differences $S_\lambda - S_F$ for the two lenses it can be seen that the correction of chromatic aberration within the interval $\lambda_F \leqslant \lambda \leqslant \lambda_C$ is very similar, see Tab. 2.

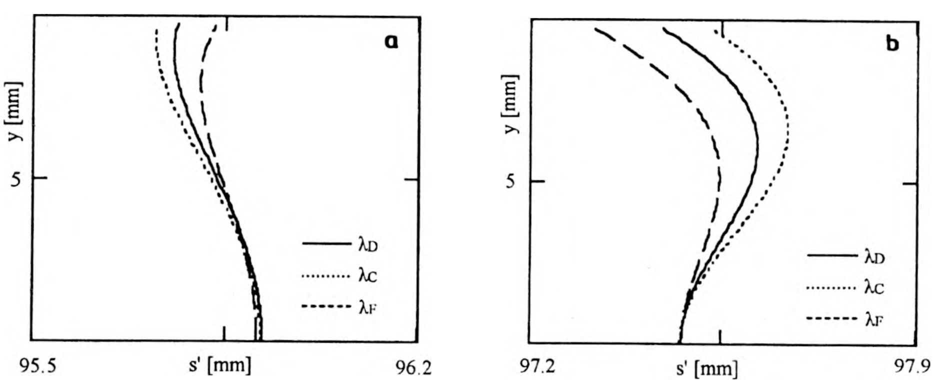


Fig. 3. Spherochromatic aberration of apochromatic objectives: **a** — glass type 2a, **b** — hybrid type 2b. s — image distance, y — height of the ray incidence on the lens surface.

For both the lenses the f-number was assumed to be equal to 5. From the course of spherochromatic aberration it is visible that the hybrid apochromat should not be applied f-number higher than those mentioned above while the conventional one could have f-number as high as 4 (Fig. 3).

3. Conclusions

Summing up, we note that while the correction of chromatic aberration of position in a hybrid achromatic lens is much worse than that in conventional one the correction of this aberration in an apochromatic hybrid lens is analogous to that in a glass triplet. Therefore, when assuming not too high f-numbers ($f'/D \leqslant 5$) there is a possibility to design hybrid apochromatic systems without necessity of using special glasses.

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