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Hybrid objective with corrected chromatism in visible spectrum

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The possibilities of chromatic aberration correction in a hybrid (diffractive-refractive) objective are discussed. It is possible to design a hybrid triplet objective free from chromatic aberration in the wavelength range 0.45–0.85 μm practically covering the whole visible spectrum. To that end one of the lenses should be made of special glass, but not necessarily of fluorite. For illustration purposes objectives of relative aperture 1:3 and maximum field-of-view angle $w = 5°$ have been designed and their aberrations presented.

Keywords: hybrid objective, chromatic aberration, apochromatic correction, superachromatic correction.

1. Introduction

A very good correction of chromatic aberration is of major importance in designing optical imaging element (objective). The quality of chromatic correction depends on the complexity of optical system considered. In particular, in three-element objective apochromatic correction and superachromatic correction are possible. As shown by HERZBERGER [1] superachromatic correction, *i.e.*, equality of focal lengths for four wavelengths: $\lambda_t = 1014.0$ nm, $\lambda_F = 486.1$ nm, $\lambda_C = 656.3$ nm and $\lambda_j = 365.0$ nm, assures that secondary spectrum is practically equal to zero in the whole visible spectrum. Unfortunately, both types of corrections require using a special glass. Moreover, in the case of superachromatic correction special condition concerning parameters of glasses used has to be satisfied.

In this paper, we discuss the feasibility of chromatic aberration correction in a hybrid objective in the widest possible range of wavelength spectrum.

A hybrid triplet objective is understood here as an optical system composed of two classic (refractive) lenses with spherical surfaces and a diffractive microstructure deposited either on one of the above-mentioned lens surfaces or on a separate, stand

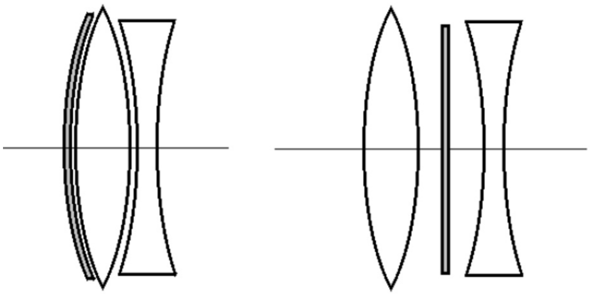

Fig. 1. Possible designs of hybrid triplet objective.

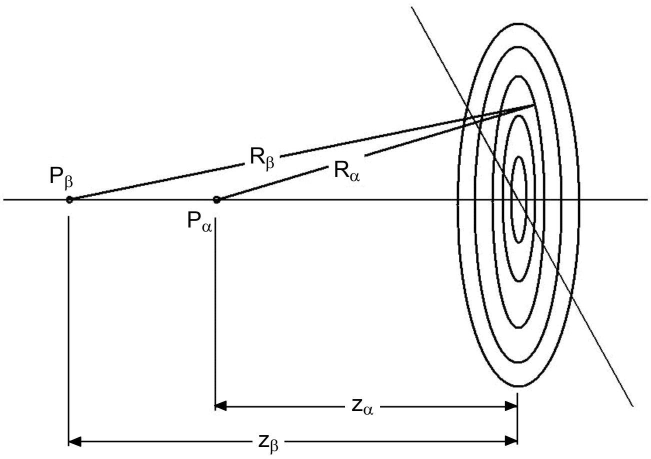

Fig. 2. Geometry of diffractive microstructure.

alone, thin surface (Fig. 1). The diffractive structure has geometry analogous to the interference pattern obtained by interference of two spherical waves having different radii of curvature [2], [3]. Imaging properties of a such structure is fully defined by two parameters: z_α and z_β (Fig. 2), corresponding to the radii of curvature.

2. Apochromatic correction

Let us consider an infinitely thin triplet objective of focal length normalized to unity. The apochromatic correction means that focal distances for three wavelengths: λ_F, λ_C and λ_d are equal. The necessary conditions assuring such corrections are as follows [4]–[6]:

$$\frac{\Phi_1}{\nu_1} + \frac{\Phi_2}{\nu_2} + \frac{\Phi_3}{\nu_3} = 0, \tag{1}$$

$$\frac{\Phi_1}{\nu_1} P_{1,\,d} + \frac{\Phi_2}{\nu_2} P_{2,\,d} + \frac{\Phi_3}{\nu_3} P_{3,\,d} = 0, \tag{2}$$

$$\Phi_1 + \Phi_2 + \Phi_3 = 1 \tag{3}$$

where Φ, ν and $P_{\lambda d}$ denote focusing power, Abbe number and partial dispersion for the wavelength λ_d, respectively. Subscripts 1, 2, 3 denote the number of optical element constituting triplet objective. The analog of Abbe number and partial dispersion for diffractive structure are defined as [4]–[6]:

$$\nu = \frac{\lambda_d}{\lambda_F - \lambda_C}, \tag{4}$$

$$P_d = \frac{\lambda_F - \lambda_d}{\lambda_F - \lambda_C}. \tag{5}$$

The set of Eqs. (1)–(3) has non-zero solutions if the following condition is met

$$W_1 = \begin{vmatrix} 1 & 1 & 1 \\ P_{1,\,d} & P_{2,\,d} & P_{3,\,d} \\ \nu_1 & \nu_2 & \nu_3 \end{vmatrix} \neq 0, \tag{6}$$

and the solutions are given by:

$$\Phi_1 = \frac{-c\,\nu_1}{c(\nu_3 - \nu_1) + \nu_2 - \nu_3}, \tag{7}$$

$$\Phi_2 = \frac{\nu_2}{c(\nu_3 - \nu_1) + \nu_2 - \nu_3}, \tag{8}$$

$$\Phi_3 = \frac{(c-1)\,\nu_3}{c(\nu_3 - \nu_1) + \nu_2 - \nu_3} \tag{9}$$

where

$$c = \frac{P_{2,\,d} - P_{3,\,d}}{P_{1,\,d} - P_{3,\,d}}. \tag{10}$$

In Table 1 four hybrid objectives made of different sets of optical glasses and designed according to formulas (7)–(10), *i.e.*, fulfilling the condition of apochromatic correction, are presented. In columns 3 and 4 of the table the values of determinant W_1

T a b l e 1. Values of determinants W_1 and W_2 and focusing powers of particular components of selected triplet objectives designed as apochromats or superachromats.

		Apochromatic correction		Superachromatic correction	
No.	DOE/glass	W_1	Φ	W_2	Φ
1	DOE		7.531×10^{-3}		
	BK3	4.046	1.826	2.00×10^{-2}	
	SF5		–0.834		
2	DOE		7.611×10^{-3}		
	FK54	7.212	1.429	2.00×10^{-2}	
	SF5		–0.436		
3	DOE		4.619×10^{-3}		5.578×10^{-3}
	fluorite	6.592	1.574	5.70×10^{-5}	1.559
	LaSFN15		–0.579		–0.564
4	DOE		6.039×10^{-3}		8.703×10^{-3}
	fluorite	7.626	1.417	5.69×10^{-3}	1.558
	SF5		–0.422		–0.566

as well as focusing powers of particular components are given. The dependence of focal length on the wavelength illustrating chromatic aberration for all objectives mentioned above is plotted in Fig. 3.

Objective No. 1 is a classic hybrid apochromate designed without use of special glasses [6]. In the next three objectives the glass BK3 (Schott) is substituted by special glass FK54 (Schott) or fluorite. From the curves presented in Fig. 3 we conclude that chromatic aberration of hybrid objectives including the lens made of special glass or fluorite is compensated in a much wider wavelength range than in typical apochromate. In practice, secondary spectrum is negligible in the wavelength range

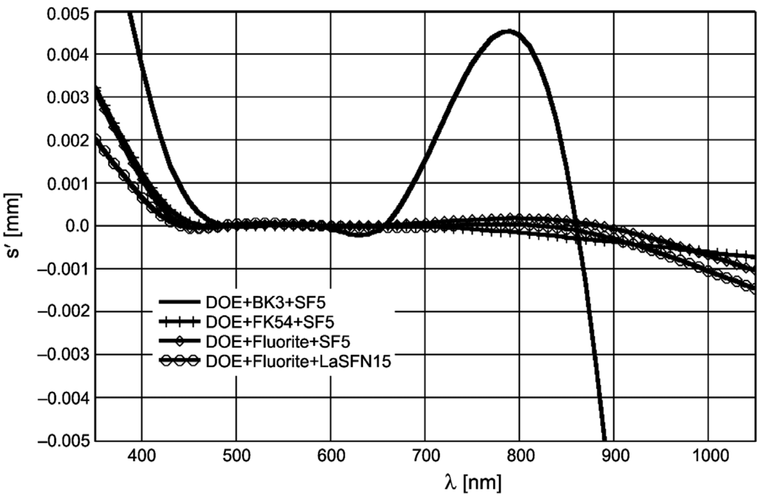

Fig. 3. Longitudinal chromatic aberration curves for triplet hybrid objectives designed as apochromates.

0.45 nm ≤ λ ≤ 0.95 nm. Moreover, we notice that focusing powers of the objective components are relatively small, which is very promising for monochromatic aberration correction.

3. Superachromatic correction

After Herzberger we define apochromatic correction as identity of effective focal lengths for four wavelengths

$$f'_1 = f'_F = f'_c = f'_2 \tag{11}$$

where $\lambda_1 = \lambda_t = 1014.0$ nm, and $\lambda_2 = \lambda_j = 365.0$ nm.

The set of equations assuring such correction has the form [6]

$$\frac{\Phi_1}{\nu_1} + \frac{\Phi_2}{\nu_2} + \frac{\Phi_3}{\nu_3} = 0, \tag{12}$$

$$\frac{\Phi_1}{\nu_1} P_{1, \lambda 1} + \frac{\Phi_2}{\nu_2} P_{2, \lambda 1} + \frac{\Phi_3}{\nu_3} P_{3, \lambda 1} = 0, \tag{13}$$

$$\frac{\Phi_1}{\nu_1} P_{1, \lambda 2} + \frac{\Phi_2}{\nu_2} P_{2, \lambda 2} + \frac{\Phi_3}{\nu_3} P_{3, \lambda 2} = 0, \tag{14}$$

$$\Phi_1 + \Phi_2 + \Phi_3 = 1 \tag{15}$$

where $P_{\lambda 1}$ and $P_{\lambda 2}$ are partial dispersions for the wavelengths λ_1 and λ_2, respectively. The necessary condition for Eqs. (12)–(15) to have non-zero solutions is

$$W_2 = \begin{vmatrix} 1 & 1 & 1 \\ P_{1, \lambda 1} & P_{2, \lambda 1} & P_{3, \lambda 1} \\ P_{1, \lambda 2} & P_{2, \lambda 2} & P_{3, \lambda 2} \end{vmatrix} = 0. \tag{16}$$

As already mentioned it is possible to find sets of three glasses (including fluorite) assuring superachromatic correction. In the present work we want to find two glasses, which, together with diffractive structure, give similar correction. To do this we have calculated the determinant W_2 (see Eq. (16)) for all glasses from Schott catalogue (including fluorite) plus diffractive structure in the wavelength range typical of superachromate and we found that none of the combinations investigated gives satisfactory result. We conclude that it is impossible to find exact solution for hybrid lens assuring superachromatic correction in the wavelength range $\lambda_t \le \lambda \le \lambda_j$.

We can, however, limit the wavelength of interest to the slightly narrower range extended from $\lambda_1 = \lambda_g = 0.435$ nm to $\lambda_2 = \lambda_s = 0.852$ nm, which in practice covers the whole visible spectrum. In the following part of this paper we call such correction (equity of focal lengths for four wavelengths, but in smaller spectral range) "quasi -superachromatic". To assure such correction the focusing powers of particular components of hybrid objective are calculated from Eqs. (7)–(9), where

$$c = \frac{P_{2,s} - P_{3,s}}{P_{1,s} - P_{3,s}}. \tag{17}$$

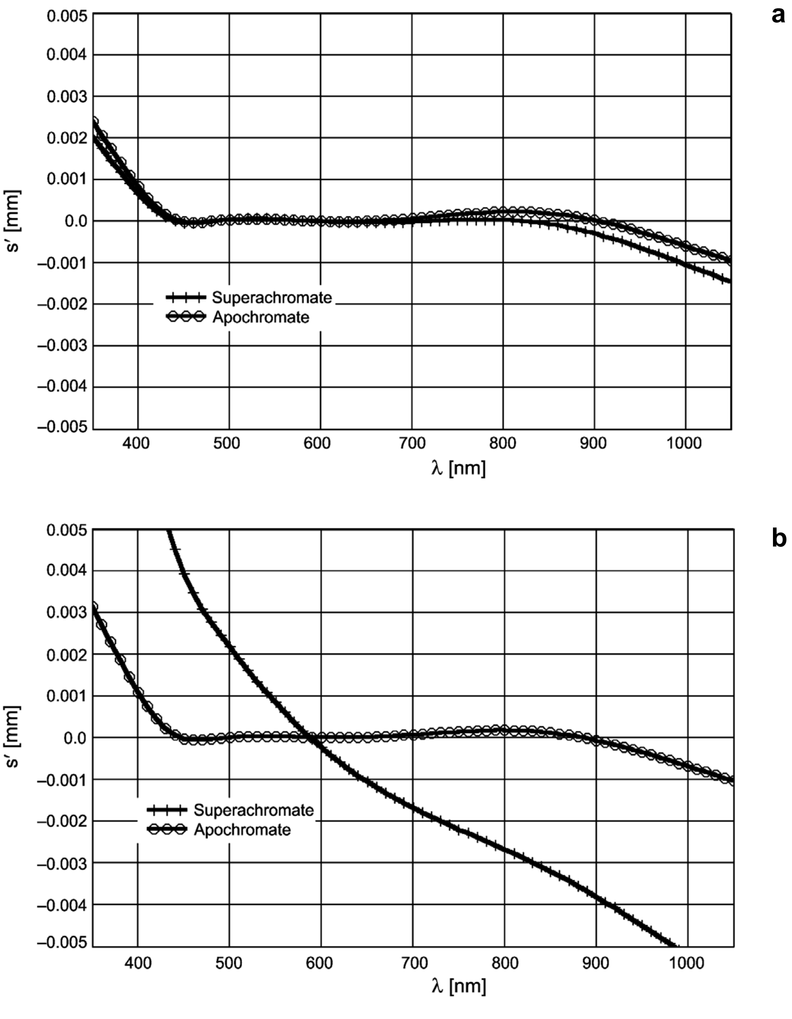

Fig. 4. Longitudinal chromatic aberration curves for triplet hybrid objective on: fluorite and LaSFN15 glass (**a**) and fluorite and SF5 glass (**b**) designed as apochromate and quasi-superachromate.

For further analysis we select pairs of glasses and diffractive structure for which determinant W_2 (see Eq. (16)) calculated in limited wavelength range is as small as possible, and simultaneously focusing powers of particular optical elements are not substantially greater than 1. Two best combinations are given in Tab. 1 as lens no. 3 and lens no. 4. In column 5 the values of determinant W_2 are given, and column 6 contains focusing powers of particular components of hybrid quasi-superachromate objectives.

The differences between apochromatic and quasi-superachromatic solutions for the objectives No. 3 and No. 4 are illustrated in the graphs of longitudinal chromatic aberration presented in Fig. 4**a** and **b**. Figure 4**a** presents chromatic aberration of the hybrid objective built from the fluorite and LaSFN15 glass. It can be seen that irrespective of whether the design is based on apochromatic or quasi-superachromatic solutions the secondary spectrum is practically the same. In the case of the objective built from fluorite and SF5 glass the design according to quasi-superachromatic solution does not assure correction of chromatic aberration at all. This means that the value of determinant W_2 is too great and the focusing powers calculated from Eqs. (13)–(16) are in fact completely accidental, and do not assure proper correction of chromatic aberration.

The above results suggest that quasi-superachromatic correction is possible if the value of determinat W_2 is not greater than $\sim 5\times 10^{-4}$. The secondary spectrum in the whole wavelength range under consideration is negligibly small. Moreover, the values of focusing powers of all elements are very close to those calculated from apochromatic condition.

4. Examples oh hybrid objectives with corrected chromatic aberration and conclusions

In order to verify the presented solutions and their practical usefulness we designed several real objectives based on the data presented in Tab. 1. For practical reasons all the design objectives have focal length equal to 100 mm. Monochromatic aberrations are minimized as much as possible by appropriate choice of the curvatures of refractive lenses as well as parameters describing the diffractive structure. The construction parameters of these objectives are presented in Tab. 2. Their imaging quality can be evaluated from the aberration characteristics presented in Figs. 5–8. The curves describing spherochromatic aberration for the wavelengths from the range λ_g to λ_s as well as meridional and sagittal curvature are presented there. The amount of comma can be deduced from spot diagrams.

The analysis of imaging characteristics of the lenses designed on the basis of the presented solutions allows us to conclude that:

– by substituting one of the normal glasses with special glass or fluorite the correction of spherochromatic aberration can be better – the relative aperture as high as 1:3 can be obtained;

T a b l e 2a Construction parameters of apochromatic objective No. 1.

R [mm]	d [mm]	
+45.40		
	0	DOE: $z_\alpha = -13.50$ mm, $z_\beta = -14.469$ mm
+45.40		
	8.0	BK3
–83.10		
	1.0	SF5
42.48		
	36	
∞		aperture stop

T a b l e 2b Construction parameters of apochromatic objective No. 2.

R [mm]	d [mm]	
∞		aperture stop
	0	
+49.98		
	0	DOE: $z_\alpha = -20.00$ mm, $z_\beta = -19.974$ mm
+49.98		
	6.0	FK54
–79.00		
	0.5	air
–65.00		
	1.0	SF5
–117.00		

T a b l e 2c Construction parameters of superachromatic objective No. 3.

R [mm]	d [mm]	
∞		aperture stop
	0	
+49.90		
	0	DOE: $z_\alpha = -20.00$ mm, $z_\beta = -19.976$ mm
+49.90		
	7.0	fluorite
–63.22		
	0.5	air
–58.50		
	2.0	LaSFN15
–95.90		

T a b l e 2d Construction parameters of apochromatic objective No. 4.

R [mm]	d [mm]	
42.48		
	0	DOE: $z_\alpha = -19.00$ mm, $z_\beta = -18.978$ mm
42.48		
	5.5	fluorite
–125.00		
	0.8	air
–76.50		
	1.0	SF5
–150.87		
	39.0	
∞		aperture stop

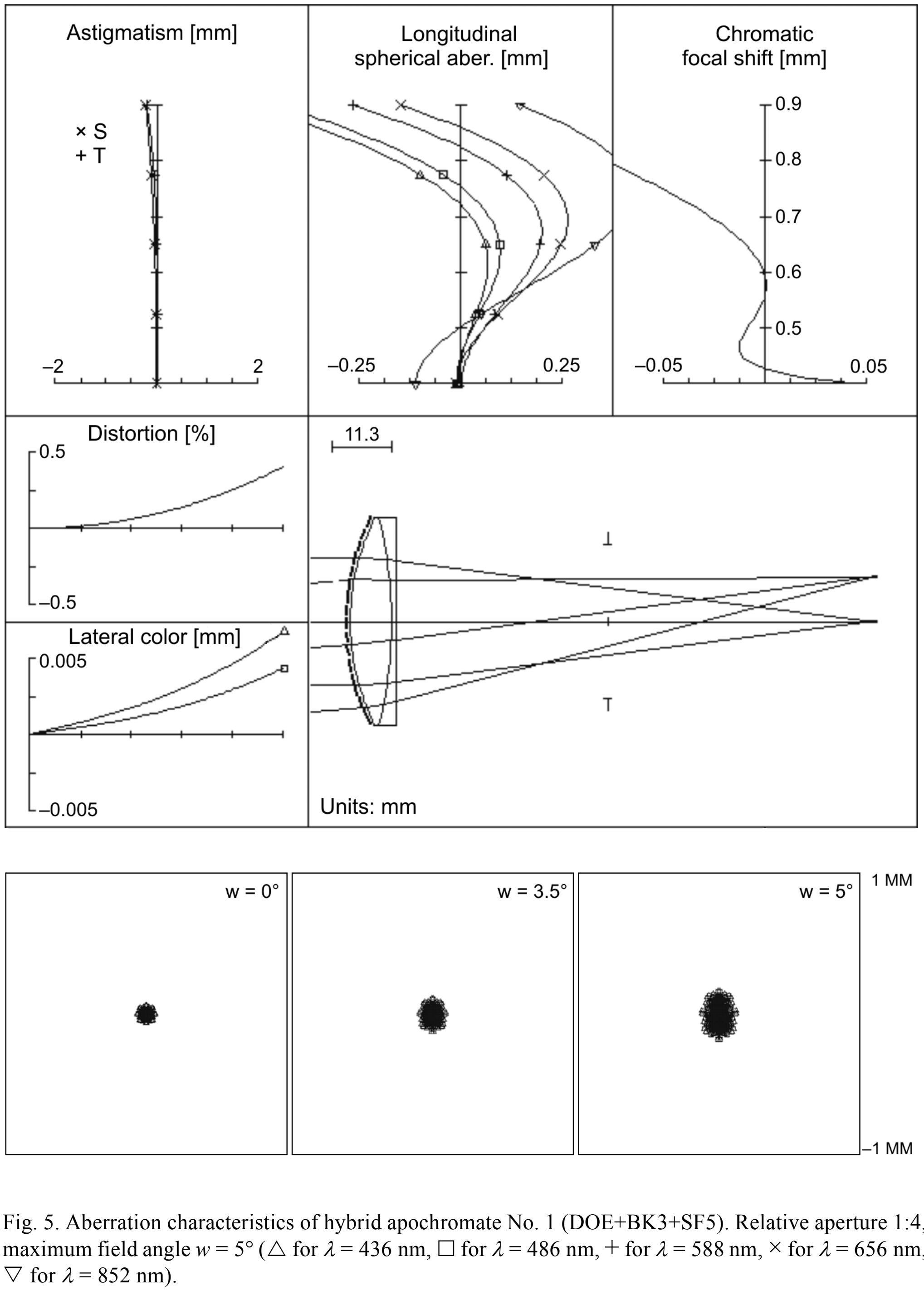

Fig. 5. Aberration characteristics of hybrid apochromate No. 1 (DOE+BK3+SF5). Relative aperture 1:4, maximum field angle $w = 5°$ (△ for $\lambda = 436$ nm, □ for $\lambda = 486$ nm, + for $\lambda = 588$ nm, × for $\lambda = 656$ nm, ▽ for $\lambda = 852$ nm).

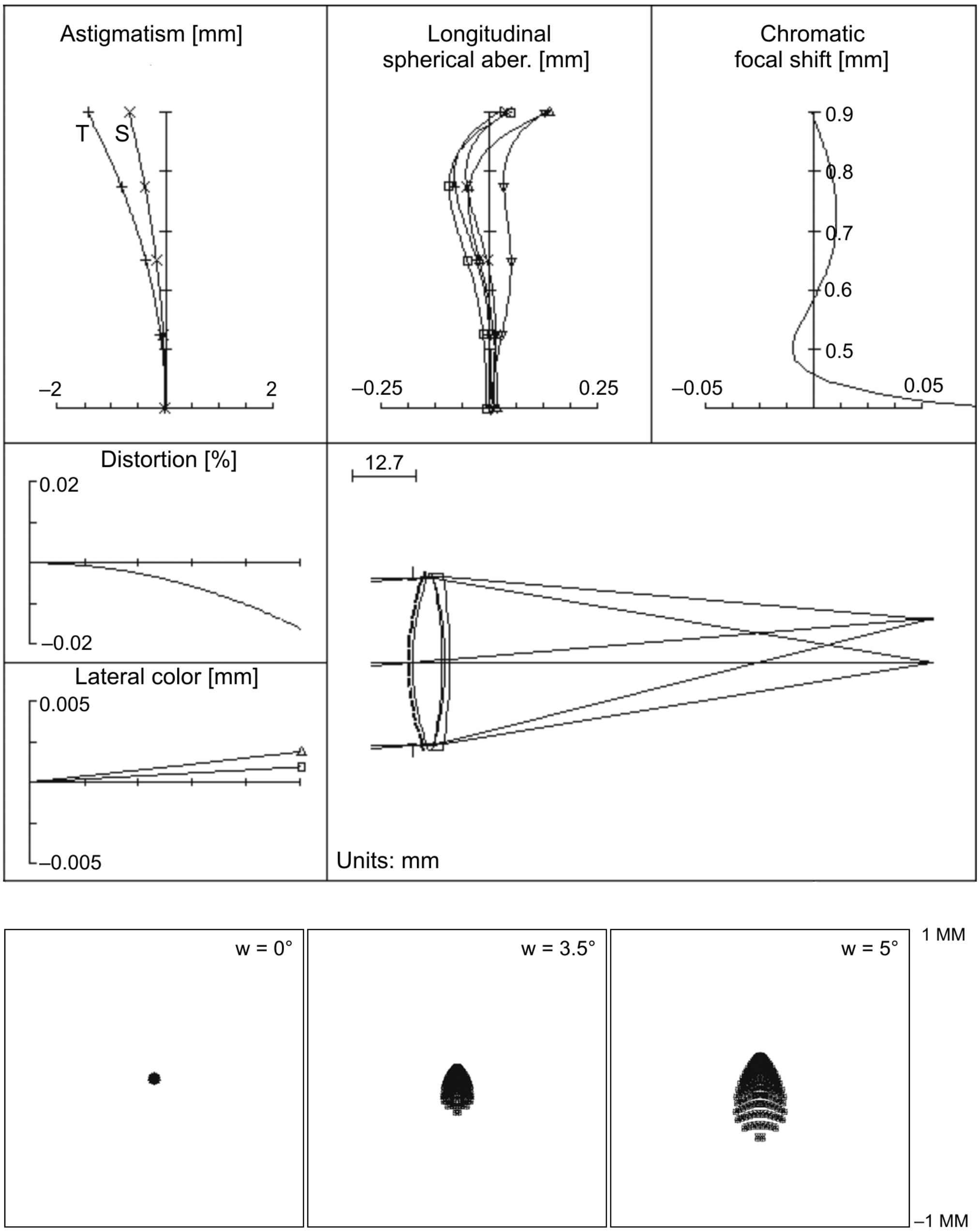

Fig. 6. Aberration characteristics of hybrid apochromate No. 2 (DOE + FK54+SF5). Relative aperture 1:3, maximum field angle $w = 5°$ (△ for $\lambda = 436$ nm, □ for $\lambda = 486$ nm, + for $\lambda = 588$ nm, × for $\lambda = 656$ nm, ▽ for $\lambda = 852$ nm).

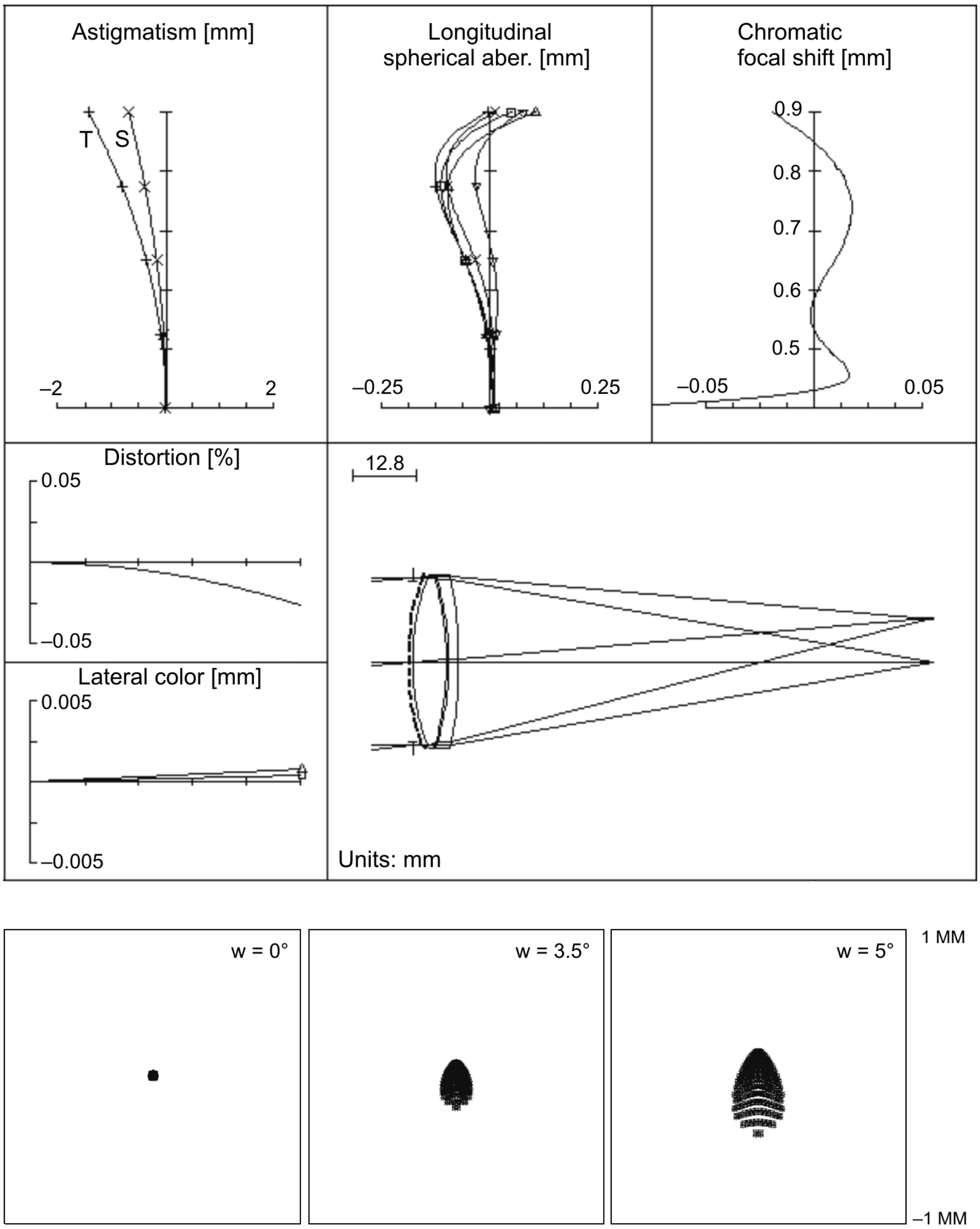

Fig. 7. Aberration characteristics of hybrid quasi-superachromate No. 3 (DOE+fluorite+LaSFN15). Relative aperture 1:3, maximum field angle $w = 5°$ (△ for $\lambda = 436$ nm, □ for $\lambda = 486$ nm, + for $\lambda = 588$ nm, × for $\lambda = 656$ nm, ▽ for $\lambda = 852$ nm).

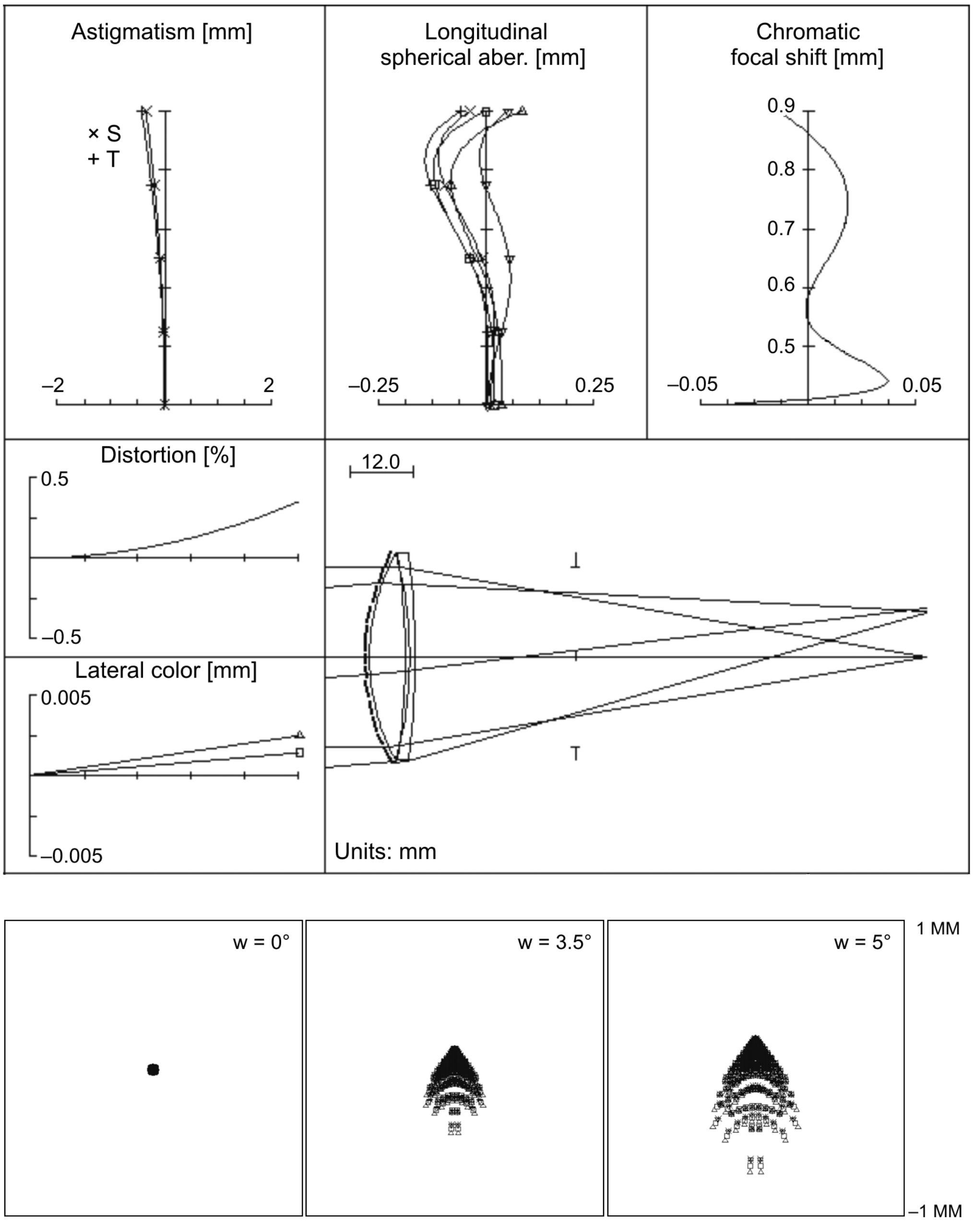

Fig. 8. Aberration characteristics of hybrid apochromate No. 4 (DOE+fluorite+SF5). Relative aperture 1:3, maximum field angle $w = 5°$ (△ for $\lambda = 436$ nm, □ for $\lambda = 486$ nm, + for $\lambda = 588$ nm, × for $\lambda = 656$ nm, ▽ for $\lambda = 852$ nm).

– the secondary spectrum of the objectives designed is similar and very small irrespective of whether the objective was designed according to apochromatic or superachromatic formulas. Full correction of chromatic aberration in the wavelength range 0.45–0.85 μm is obtained;

– in practice, the use of fluorite is not necessary, however it is not possible to find formal solution for superachromatic correction without fluorite.

Concluding we would like to express an opinion that in hybrid triplet objective it is possible to obtain very good correction of chromatic aberration in the wavelength range practically covering the whole visual spectrum. Depending on the glasses used as a starting point for design process two alternative conditions can be used: apochromatic or superachromatic correction. The imaging quality of the final objective depends on the value of secondary spectrum and not on the formal type of correction.

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