Simple achromatic hybrid lens

MAREK ZAJĄC, JERZY NOWAK

Institute of Physics, Technical University of Wrocław,
Wybrzeże Wyspiańskiego 27, 50–370 Wrocław, Poland, e-mail: marek.zajac@pwr.wroc.pl.

The simplest achromatic hybrid lens consists of a refractive (glass) lens with a diffractive microstructure deposited on one of its surfaces. In such lens the reasonable aberration correction is possible only for very limited aperture and field angles. Better possibilities of aberration correction appear if we split the refractive lens onto two identical parts separated by certain distance and locate the diffractive element between the glass lenses. We show that in a such way it is possible to obtain a hybrid lens of the same or even smaller aberrations for substantially greater aperture and field angles.

Keywords: hybrid lens, diffractive element, aberrations.

1. Achromatic hybrid lens

By a hybrid lens we mean an optical system composed of a classic refractive (glass) lens and a diffractive element (DOE) [1]–[4]. The essence of DOE is a periodic or quasi-periodic structure deposited on a surface, *e.g.*, on one of the refractive lens surface. Imaging properties of such element depend on the geometry of fringes making its structure. In our considerations we assume that the fringes are analogous to those obtained by the interference of two spherical waves originating from point sources located on an optical axis. Independently of the technology of DOE manufacturing the geometry of fringes can be uniquely described by the distances from these points to the center of DOE z_α and z_β. Focusing power of DOE is given by

$$\Phi_D = \frac{\lambda}{\lambda_d}\left(\frac{1}{z_\alpha} - \frac{1}{z_\beta}\right) \tag{1}$$

where λ_d is a wavelength for which the structure is designed and λ is the actual wavelength. We can also define an analog of Abbe number

$$\nu_D = \frac{\lambda_d}{\lambda_F - \lambda_C}. \tag{2}$$

Thanks to combining the refractive lens with DOE it is possible to correct the chromatic aberration. For such single hybrid lens we can also correct spherochromatic aberration and, to some extent, field aberrations. In paper [1] we described a single hybrid lens having satisfactorily corrected aberrations for aperture 1:10 and field angle 0.05.

2. Correction of chromatic aberration in a compound system

For a single hybrid lens case it was possible to compensate monochromatic aberrations only for limited aperture and field angles. A substantial increase in the aperture and field-of-view can be obtained thanks to the slight development of an optical system. In this paper we discuss a hybrid objective composed of two identical refractive lenses separated by some distance d and a diffractive optical element located close to the second lens (Fig. 1). This optical system is achromatic if the following equation is fulfilled:

$$\frac{\Phi_R}{\nu_R} + (1 - d\Phi_R)^2 \left(\frac{\Phi_R}{\nu_R} + \frac{\Phi_D}{\nu_D} \right) = 0 \tag{3}$$

where d is the overall system length and Φ_R , Φ_D , ν_R , ν_D are focusing powers and Abbe numbers of refractive and diffractive parts, respectively.

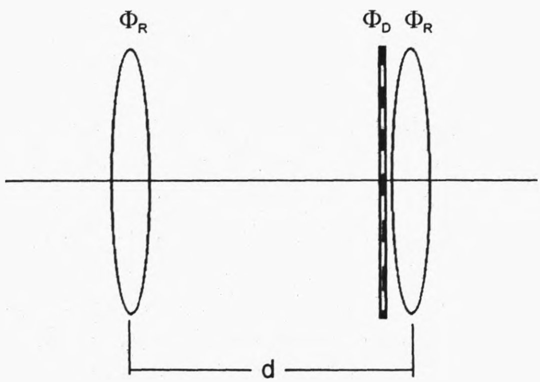

Fig. 1. Three-element hybrid lens.

Additionally we assume the normalization condition

$$\Phi_R + (1 - d\Phi_R)(\Phi_D + \Phi_R) = 1. \tag{4}$$

Solving a set of Eqs. (3), (4) gives

$$\Phi_R + \left[1 - d\Phi_R(\Phi_R + \eta) \frac{\Phi_R(2 - 2d\Phi_R + d^2\Phi_R^2)}{(d\Phi_R - 1)^2} \right] = 0 \tag{5}$$

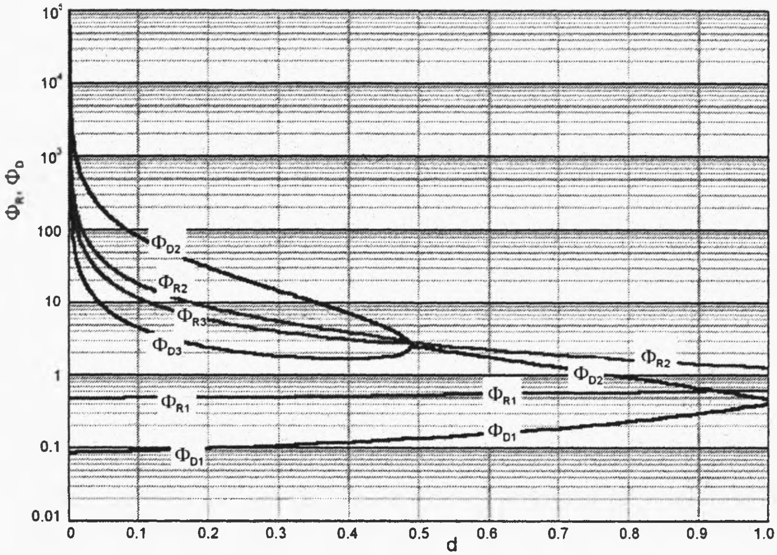

Fig. 2. Solutions of Eq. (5).

where

$$\eta = \frac{-v_D}{v_R} \tag{6}$$

is an achromatisation parameter.

The solutions of Eq. (5) for a selected glass type (here BK3 according to Schott glass catalogue) are presented in Fig. 2. Particular curves correspond to focusing powers of refractive lenses Φ_R and diffractive element Φ_D calculated from Eqs. (5) and (4), depending on the normalized distance d between refractive lenses. As it can be seen, several solutions exist. If the distance d is small we have three solutions (Φ_{R1}, Φ_{D1}, Φ_{R2}, Φ_{D2}, Φ_{R3}, Φ_{D3}), if the distance d is greater (close to the overall focal length) we have only two solutions (Φ_{R1}, Φ_{D1}, Φ_{R2}, Φ_{D2}). However, only one solution has a practical meaning: this of the smallest focusing powers (Φ_{R1}, Φ_{D1}).

3. Numerical illustration

We will illustrate by two examples the possibilities of using the discussed formulae for designing the achromatic hybrid objective. One is a "short" lens (denoted LENS #1) in which the distance between refractive parts is close to zero. In the other one – a "long" objective (denoted LENS #2) – this distance equals 60% of the overall focal length. The distribution of the focusing power between refractive and diffractive parts is in a "short" lens $\Phi_R = 0.48$, $\Phi_D = 0.052$, and in a "long" lens $\Phi_R = 0.562$, $\Phi_D = 0.098$.

The construction parameters of both objectives were found numerically [5]. We were guided by the optimum correction of spherochromatic aberration as well as selected field aberrations (astigmatism and field curvature, as well as lateral chromatic aberration). As an additional free parameter we used a location of an input pupil.

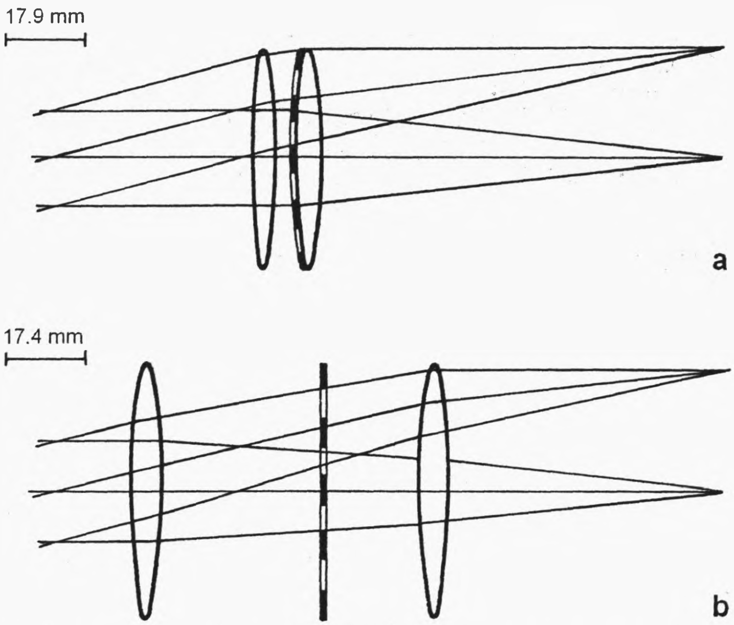

Fig. 3. Two exemplary achromatic hybrid objectives: "short" (**a**) and "long" (**b**).

Table. Construction data of two exemplary achromatic hybrid objectives (all dimensions in millimeters).

		LENS #1	LENS #2
Refractive part	R_1	+177.5	+160.0
	R_2	–250.0	–200.0
	t	5.0	5.0
	Glass	BK3	BK3
Diffractive part	z_α	–32.56	–24.42
	z_β	–32.00	–24.00
	l	0	38.0
	d	5.0	60.0
	z_t	–45.0	–17.0

In the case of a "short" objective we assumed that the diffractive structure is deposited directly on one of the lens surface (curved) – see Fig. 3**a**. This assumption does not alter substantially the achromatisation condition. In the case of a "long" objective we allowed a shift of DOE along an optical axis between both refractive lenses. This caused slight deviation from achromatisation Eqs. (3), (4), however the correction of chromatic aberration can be easily restored by small changes in Φ_R and Φ_D. Location of DOE assuring the best correction of the above mentioned field aberration was found numerically.

Final construction parameters of both investigated lenses are presented in Fig. 3 and in the Table. The achieved correction of aberrations is presented in Figs. 4 and 5

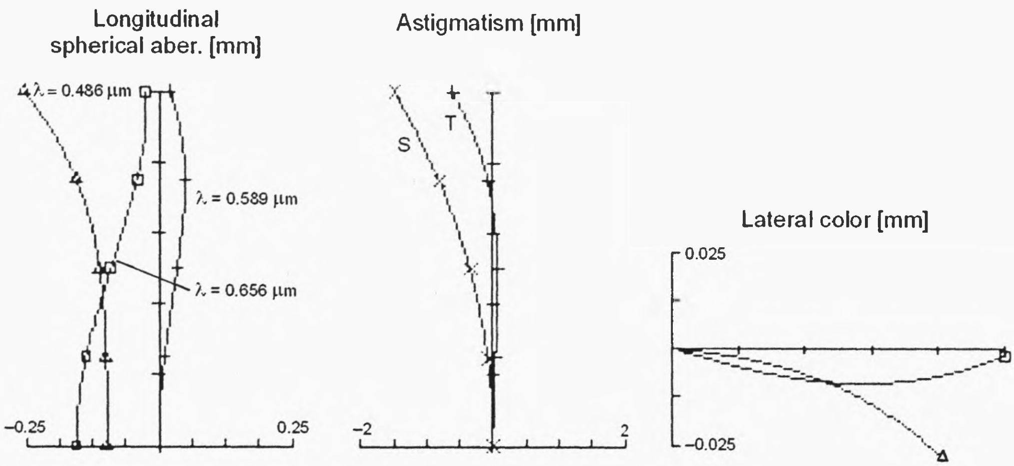

Fig. 4. Aberrations of LENS #1.

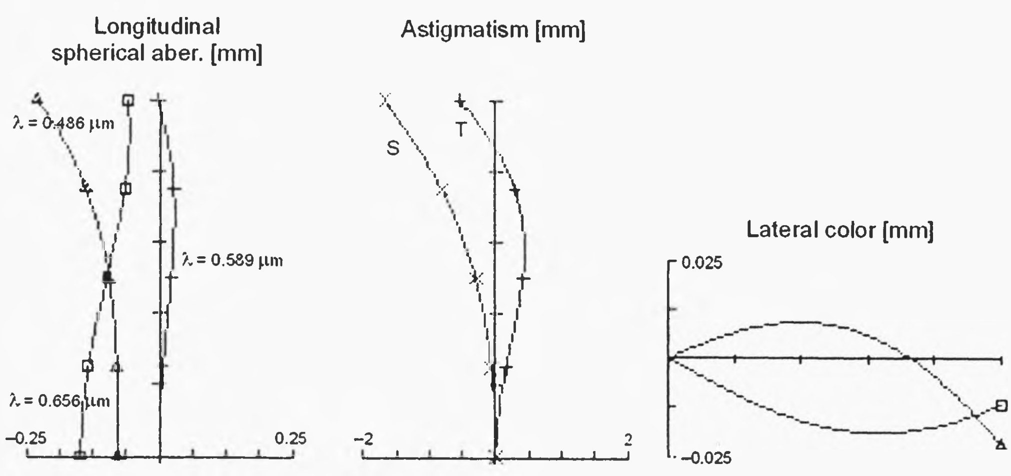

Fig. 5. Aberrations of LENS #2.

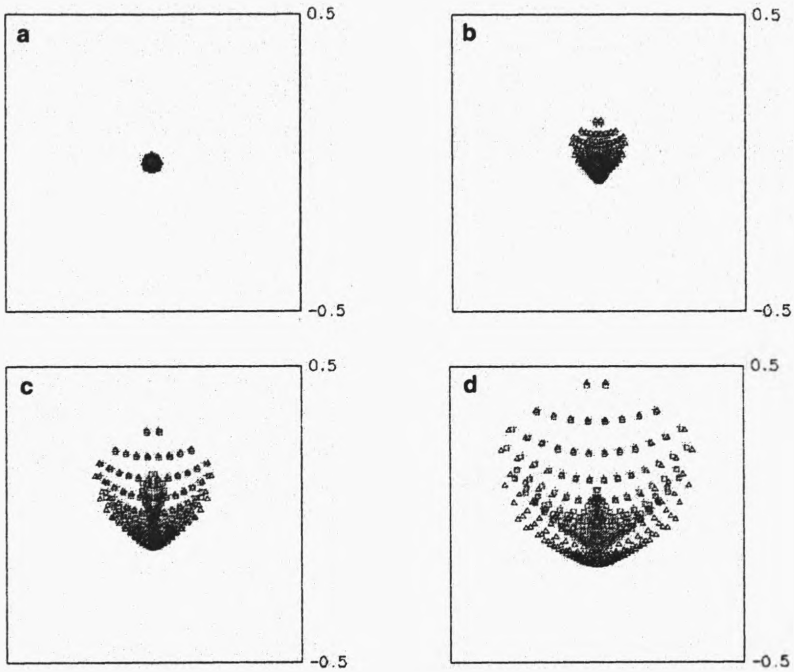

Fig. 6. Spot-diagram for LENS #1: $w = 0°$ (**a**), $w = 5°$ (**b**), $w = 10°$ (**c**), $w = 15°$ (**d**).

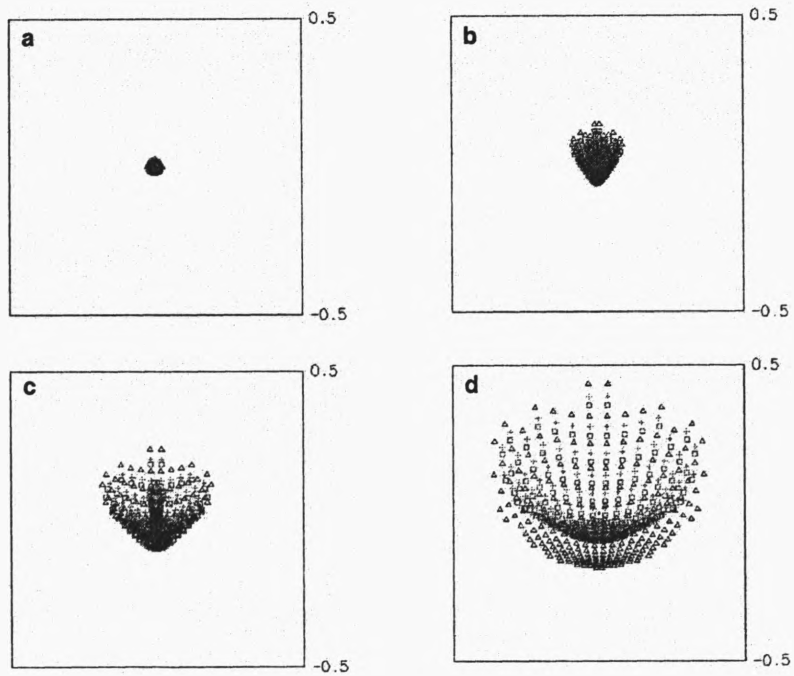

Fig. 7. Spot-diagram for LENS #2: $w = 0°$ (**a**), $w = 5°$ (**b**), $w = 10°$ (**c**), $w = 15°$ (**d**).

where respective curves illustrate spherochromatic aberration for the wavelengths λ_C, λ_F and λ_d, astigmatism and field curvature, as well as lateral chromatism for both lenses. Relative aperture equals 1:4.5 and maximum field angle $w = 15°$.

In both cases some uncompensated coma exists what can be noticed on spot-diagrams presented in Figs. 6 and 7.

4. Conclusions

Presented examples prove that it is possible to design a hybrid achromatic objective of a very simple construction – composed of two identical refractive lenses and a diffractive optical element having relative aperture 1:4.5. This objective has satisfactorily compensated field aberrations, including lateral color for the maximum field-of-view angle as high as $w = 15°$ (comp. [6]).

References

[1] KOTH S., NOWAK J., ZAJĄC M., Optik **106** (1997), 63.
[2] SMITH W.J., *Modern Optical Engineering*, McGraw Hill, New York 2000.
[3] NOWAK J., Opt. Appl. **30** (2000), 213.
[4] ZAJĄC M., NOWAK J., Optik **9** (2002), 299.
[5] OSLO LIGHT Program (Sinclair Optics, Ltd).
[6] SMITH W.J., *Modern Lens Design – a Resource Manual*, McGraw Hill, New York 1992.

Received October 29, 2002
in revised form January 14, 2003