[10] Modeling and investigation of color correction in optical systems with constituent elements synthesized by precision molding

G.I. Greisukh, E.G. Ezhov, S.V. Kazin, S.A. Stepanov
Penza State University of Architecture and Construction, Penza, Russia

Abstract

Color correction in optical systems with constituent elements synthesized by precision molding is investigated. Advantages associated with the use of the technique are demonstrated.

Keywords: chromatic corrector, refractive lens, diffractive lens, molding glass, apochromatic correction, superachromatic correction.

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Introduction

In the work [1] a model was proposed of an infinitely thin objective- superachromat, consisting of axial color corrector (ACC) and a power positive lens (PPL). It was assumed that ACC can only consist of refractive lenses (RL) or include along with RL one diffraction lens (DL). Using this model, the effect of the PL corrector of these RL materials on the maximum modulus optical power (i.e. the value, inverse to the focal length) was studied. The study involved nearly twenty optical plastics and more than a thousand brands of optical glass, which were serially produced by the world`s leading manufacturers.

In a few years that have passed since the publication of the cited work in the manufacture of optical plastics and components from these no fundamental changes happened. At the same time traditional methods of making glass components by grinding and polishing were supplemented by new technology of production high-precision optical components. This technology of precision glass pressing opens the possibility of a mass and cost effective production of aspherical lenses or even lenses with the surfaces of any form. Its extensive introduction will allow, in particular, to improve significantly the optical characteristics of photo and video cameras of all kinds of gadgets, while maintaining or even reducing their cost. It should be noted that the appearance of precision optical glass pressing technology in no way eliminates or reduces the role of optical plastics in optical instrument production. This is in particular due to the fact that optical plastics pressing technology is now more developed, and plastic elements themselves have more predictable optical and physical and mechanical properties [2, 3].

Precision pressing technology is based on a specially developed class of optical glass [moldable glasses (MG)]. One of its distinguishing features is that viscosity required for pressing the glass is achieved at a relatively low temperature of about 500 ° C [2]. A rather wide range of MG-class brands glasses today is serially produced by Schott Group [3] and Hoya Corporation [4], while the latter has already submitted in their catalogs dispersion formulas of glasses made in this class This fact allowed to produce research, the results of which are presented in this article.

Terms and results of research

By adding MG class of glasses with optical plastics group and using the previously proposed model of the optical system, consisting of infinitely thin ACC and PPL, were investigated potential properties of ACC, including RL, each of which may have aspherical surfaces and, therefore, along with the correction of chromaticity of the first order, may take part in correction of both monochromatic and poly-chromatic aberration of the third and higher orders [5-12]. The above mentioned potential opportunities of ACC are determined by the radii of curvature of its RL surfaces Indeed, all the radiation, involved in the formation of an image, should pass through the ACC , and the small radii of RL surfaces curvature will limit the objective light diameter and introduce unwanted aberrations of the third and higher orders.

Obviously, the greater (by the module) are the radii of curvature of the surfaces, and hence the smaller are optical RL power included in the ACC, with respect to the optical power of objective in general, the greater are the opportunities to increase the aperture of objective and its high-quality image field.. Therefore, one of the determining factors in choosing a combination of optical RL ACC materials is their impact on the maximum by the module optical power of RL corrector. This article presents the results of a study of this influence while apochromatization and superahromatization of an optical system, while the same as in [1], options were considered with ACC, consisting only of RL or including one DL along with RL. Here we recall that kinds of correction of longitudinal chromatism differ in the number of wavelengths of operating spectral range which provide equality of rear segments of the optical system. At ahromatization this equality is provided at two, when apochromatization - at three, and when superachromatization - at four wavelengths. With the increase in the number of wavelengths at which equality of the rear sections is provided, image defocusing is decreased at intermediate wavelengths, not involved in correction of longitudinal chromatism.

Apochromatization and super achromatization, providing lower level of remaining chromatism compared to achromatization, is used when seeking high quality polychromatic image, formed by the optical system, in a wide spectral range, for example as in this article and in the paper [1], which includes the visible and near infrared radiation (λ_{min}=0.4 μm, λ_{max}=0.9 μm). At apochromatization the spectral range from λ_{min} to λ_{max} is split into two, and at superachromatization – into three approximately equal intervals [13].

Assuming that the optical power of objective model at a central wavelength λ' of the given spectral range must be equal to one (unity), the condition of its apohromatization can be written as a system of three equations [14]

$$\left.\begin{aligned} &\sum_{i=1}^{I}\varphi_i = 1-\varphi_{PL} \\ &\sum_{i=1}^{I}\frac{1}{\nu_i}\varphi_i = -\frac{\varphi_{PL}}{\nu_{PL}} \\ &\sum_{i=1}^{I}\frac{\gamma_i}{\nu_i}\varphi_i = -\frac{\varphi_{PL}}{\nu_{PL}}\gamma_{PL} \end{aligned}\right\} \qquad (1)$$

Here φ_{PL}, ν_{PL}, γ_{PL} and φ_i, ν_i, γ_i is a normalized optical power at a wavelength λ', coefficient of dispersion and relative particular dispersion of PPL and ACC lenses, respectively. The coefficient of dispersion and relative particular dispersion of DL (ν_D, γ_D) and RL materials (ν_R, γ_R) are calculated according to the formulas [7]

$$\nu_D = \lambda'/(\lambda_{min}-\lambda_{max}), \qquad (2)$$

$$\gamma_D = (\lambda_{min}-\lambda')/(\lambda_{min}-\lambda_{max}) \qquad (3)$$

and

$$\nu_R = (n_{\lambda'}-1)/(n_{\lambda_{min}}-n_{\lambda_{max}}), \qquad (4)$$

$$\gamma_R = (n_{\lambda_{min}}-n_{\lambda'})/(n_{\lambda_{min}}-n_{\lambda_{max}}) \quad , \qquad (5)$$

where $n_{\lambda'}$, $n_{\lambda min}$ и $n_{\lambda max}$ are values of the refractive index of the RL material at wavelengths λ', λ_{min} and λ_{max}, respectively.

Conditions to achieve super achromatization can be written as a system of four equations [1]

$$\left.\begin{aligned} &\sum_{i=1}^{I}\varphi_i = 1-\varphi_{PL} \\ &\sum_{i=1}^{I}\frac{1}{\nu_i}\varphi_i = -\frac{\varphi_{PL}}{\nu_{PL}} \\ &\sum_{i=1}^{I}\frac{\gamma_{k}}{\nu_i}\varphi_i = -\frac{\varphi_{PL}}{\nu_{PL}}\gamma_{k,PL} \qquad (k=1;2) \end{aligned}\right\} \qquad (6)$$

where γ_{ki} are relative partial dispersions, which for DL and RL materials are calculated, respectively, by the formulas [1, 8]

$$\gamma_D = (\lambda_1-\lambda_{max})/(\lambda_{min}-\lambda_{max}), \qquad (7)$$

$$\gamma_D = (\lambda_{min}-\lambda_2)/(\lambda_{min}-\lambda_{max}) \qquad (8)$$

and

$$\gamma_R = (n_{\lambda_1}-n_{\lambda_{max}})/(n_{\lambda_{min}}-n_{\lambda_{max}}), \qquad (9)$$

$$\gamma_R = (n_{\lambda_{min}}-n_{\lambda_2})/(n_{\lambda_{min}}-n_{\lambda_{max}}). \qquad (10)$$

Here vawelengths λ_{min}, λ_1, λ_2 and λ_{max} satisfy the condition $\lambda_{min}<\lambda_1<\lambda_2<\lambda_{max}$.

Systems of equations (1) and (6) are linear and definite with respect to normalized optical forces of three (I=3) or four (I=4) ACC lenses, respectively.

Experience of chromatism correction of real optical systems, consisting of glass or plastic RL, using techniques that involve replacement of one of the optical system RL with ACC showed that chromatism of the remaining (non-replaceable) part of optical system is comparable to chromatism of a single RL having the same optical power as that of non-replaceable part of the system. Moreover, this chromatism is usually intermediate between chromatism of a single RL made of krone (krone like plastics), and from flint (flint like plastics) [15-17]. Therefore, choosing for the PPL model some krone (krone-like plastic) or flint (flint-like plastic) and by searching the optimal combination of optical ACC materials for a range of values of ratio of PPL and ACC optical power, it is possible to cover a very wide range of possible situations, typical for design of real lenses.

In studies, the results of which are presented in this paper, optical materials for PPL and ACC lenses were chosen from the catalogs Misc and Zeon , included in the Glasscat database of a computer program of optical design Zemax [18] in the section Glass Molded Lens of the catalog Hoya Group Optics Division [4] and in the section Optical Plastic For molded lenses, the catalog of the Fiber Optic Center company [19].

Table. 1 and 2 show the optimal combination of optical RL ACC materials for seven options of layout of model objective-apochromate and superahromate, respectively.

Table. 1. The optimum combinations of optical RL materials constituting the ACC of model objective apochromate

Type of ACC	Plastic of PPL	Normalized optical power of PPL	$\|\varphi\|_{max}$	Optical material of ACC RL		
				RL1	RL2	RL3
3RL	PMMA	0.9	1.0	M-FCD1	AL-6265 (OKP-850)	M-FDS2
		0.8	0.98			
		0.5	0.94			
		0	1.18			
	POLYCARB	0.9	1.37			
		0.8	1.31			
		0.5	1.15			
2RL+DL	PMMA	0.9	0.40	M-FDS2	M-FCD1	-
		0.8	0.49			-
		0.5	0.76			-
		0	1.2			-
	POLYCARB	0.9	0.77			-
		0.8	0.81			-
		0.5	0.96			-

Table 2. Optimal combinations of optical RL materials that make up the ACC of model superahromate objective

Type of ACC	Plastic of PPL	Normalized optical power of PPL	$\lvert\varphi\rvert_{max}$	Optical material of ACC RL			
				RL1	RL2	RL3	RL4
4RL	PMMA	0.9	0.72	M-BACD15	AL-6265 (OKP-850)	M-FDS1	M-FDS910
		0.8	0.73	M-FDS2		M-FDS910	M-PCD51
		0.5	0.90	M-BACD5N	M-FDS2	M-FCD1	AL-6265 (OKP-850)
	POLYCARB	0	0.92	AL-6265 (OKP-850)	M-FCD1	M-FDS2	480R
		0.9	1.13		M-BACD12		M-FDS910
		0.8	1.08		M-FCD1	M-TAFD307	M-FDS2
		0.5	1.15	M-TAF1		M-FDS2	AL-6265 (OKP-850)
3RL+DL	PMMA	0.9	0.79	M-TAF1	M-FCD1	AL-6263 (OKP4HT)	-
		0.8	0.79	M-FCD1	AL-6261 (OKP4)	AL-6265 (OKP-850)	-
		0.5	0.90		AL-6265 (OKP-850)	AL-6263 (OKP4HT)	-
	POLYCARB	0	1.11	M-FD80	AL-6261 (OKP4)	M-FCD1	-
		0.9	1.10	M-FCD1	AL-6265 (OKP-850)	AL-6263 (OKP4HT)	-
		0.8	1.04	AL-6263 (OKP4HT)		M-FCD1	-
		0.5	1.09	POLYSTYR	M-FCD500		-

Presented in Tables 1 and 2 layout options are different for the material and the normalized optical power of PPL. ACC of model objective- apochromate in Table 1 consists of three RL or two RL and a DL, and ACC of model objective - superahromate in Table 2 - of four RL or three RL and a DL. Both tables show what will be in the best case a maximum modulus of the normalized optical power of ACC lenses $\lvert\varphi\rvert_{max}$, if corrector would carry apohromatization or superahromatization of an objective, whose power component in its chromatic properties is equivalent to a single lens, made from krone like (PMMA) or flintlike (POLYCARB) plastics. The choice of PMMA и POLYCAB plastics is related to the fact that their dispersion coefficients allow to overlap a very wide range of residual chromatism of real objectives, lenses of which are made of materials that allow precision molding.

Fig. 1 and 2 give examples of optical schemes of model objective-apochromate and superahromate, while infinitely thin air gaps between the elements are shown here for clarity as if having a finite thickness.

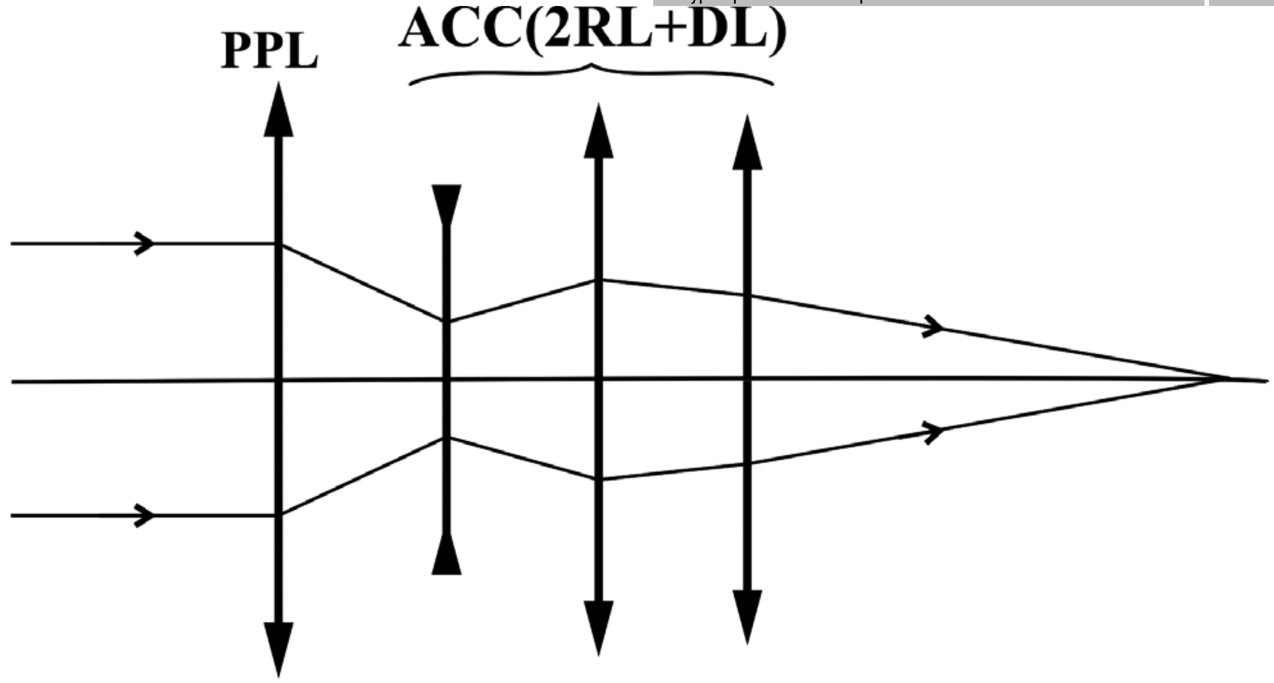

Fig. 1. Optical scheme of the model achromatic objective , whose ACC consists of two RL and DL, and PPL is made of PMMA and has normalized optical force equal to 0.50 (see. Table 1). Normalized optical forces of two RL and DL are respectively -0.27; 0.76; 0.01

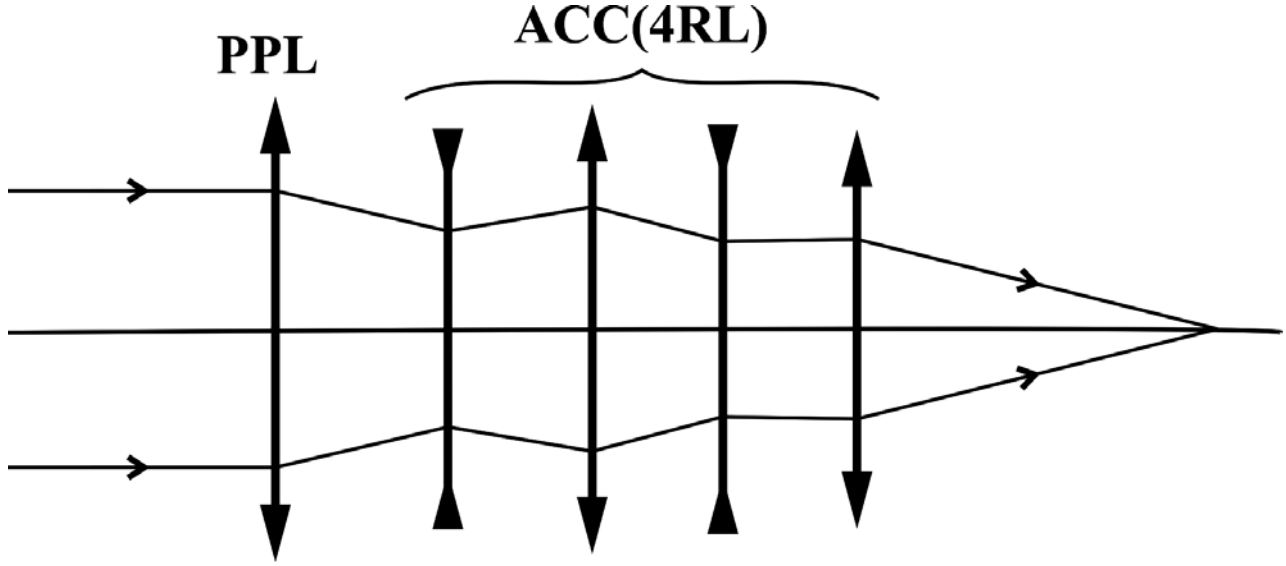

Fig. 2. Optical scheme of model objective- superachromate, whose ACC consists of four RL, and PPL is made of POLYCARB and has a normalized optical power equal to 0.80 (see. Table. 2). The normalized optical power of four RL are respectively -1.08; 1.07; -0.39; 0.60

Table. 3 shows the basic optical characteristics of RL materials shown in Tables 1 and 2. In this case dispersion coefficient ν_R is obtained by the formula (4) for the extended spectral range considered in this article, which includes visible and near infrared radiation (λ_{min}=0.4 мкм, λ_{max}=0.9 мкм).
From Table. 1 it is easy to see that at apochromatization depending on the material and the optical power of the PPL replacement of one RL to the DL allows to reduce the maximum optical power in RL ACC in 1.2÷2.5 times. It should be noted that the optical power of DL is at least an order less than the optical power of the weakest RL ACC. At the same time Tab. 2 shows that at superachromatization the replacement of one of the four RL ACC for DL does not lead to any tangible reduction in the maximum optical RL power.

Table 3.Optic characteristics of the materials included in the Table 12.

Component	Brand of Optical material	Catalog	$n_{\lambda'}$	ν_R
PPL	PMMA	Misc	1.4893999	21.2899
	POLYCARB	Misc	1.5802963	10.5987
ACC	M-FCD1	Hoya Group	1.4953891	30.1383
	480R	Zeon	1.5227177	21.0343
	M-FCD500	Hoya Group	1.5511577	26.5512
	M-BACD12	Hoya Group	1.5803758	21.8943
	POLYSTYR	Misc	1.5853759	11.2193
	M-BACD5N	Hoya Group	1.5864168	22.4933
	M-PCD51	Hoya Group	1.5895242	24.7170
	AL-6261 (OKP4)	Fiber Optic Center	1.6012884	9.5576
	M-BACD15	Hoya Group	1.6196105	21.3693
	AL-6263 (OKP4HT)	Fiber Optic Center	1.6250213	8.3797
	AL-6265 (OKP-850)	Fiber Optic Center	1.6433915	7.5437
	M-FD80	Hoya Group	1.6830174	11.0616
	M-TAF1	Hoya Group	1.7681758	19.5309
	M-FDS910	Hoya Group	1.8121523	8.4189
	M-TAFD307	Hoya Group	1.8755809	13.5331
	M-FDS1	Hoya Group	1.9113227	7.2270
	M-FDS2	Hoya Group	1.9883254	6.6445

Conclusion

The results presented in this paper show that if ACC consists only from RL made of optical materials which allow precise pressing, the maximum optical powers of these RL while superachromatization and apochromatization are comparable (at achromatization they are 20÷25% more). At the same time the maximum RL optical powers at superachromatization are at least 35-40% less than of the corresponding optical powers of RL ACC made of conventional optical glasses included in the catalogs of the leading world producers (see. Table 2 [1]).

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