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Investigation and calculation of two-component chromatic aberration compensator

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The chromatic aberrations compensator from two hyperchromatic lenses has been investigated. Dependencies of values of chromatic aberrations from parameters of the two-component compensator have been obtained. On the basis of theoretical data, an aberration compensator for high-aperture immersion achromatic microscope lenses has been calculated.

Keywords: microscope lens, achromate, chromatic aberration, hyperchromatic lenses, chromatism of magnification - transverse chromatic aberration.

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Introduction

Microscopes are now widely used in medicine and various industries [1–4]. The object lens is the most important component of the microscope [5–7]. The quality of the optical system as a whole [8,9] depends on its characteristics and the degree of aberration correction. The most common are achromatic lenses, with the sufficient for most cases degree of correction of aberrations and relatively low cost [10]. Despite the fact that achromatic object lenses of small and medium numerical apertures and magnifications can almost completely correct most of the aberrations, for highly aperture object lenses with a large magnification this problem remains. The elimination of chromatic aberrations remains one of the main problems. Compensation eyepieces [11,12], having a complex optical scheme, are usually used for this purpose in microscopes. However, if the radiation receiver is a matrix, it is not possible to compensate for chromatic aberrations with the eyepiece.

Therefore, the use of a special two-component compensator, the scheme of which is represented in Fig. 1, is very effective. Components — hyperchromatic lenses — are flat parallel plates consisting of two glued lenses made of glass with refractive indices close to the main wavelength but with significantly different mean dispersion factors [13,14]. The components are separated from each other by an air span d of significant magnitude. The two-component compensator makes it possible to simultaneously correct the transverse and longitudinal chromatic aberration. Introduced into the system in parallel or loosely convergent beams, it has little effect on monochromatic aberrations.

If the distance from the object to the first component of the compensator is $s_1 = \infty$, transverse chromatic aberration is determined by the expression [15]:

$$\frac{dy'}{y'_{1,2}} = \frac{d}{r_1}(dn_1 - dn_2), \tag{1}$$

where $\frac{dy'}{y'_{1,2}}$ — is the first order transverse chromatic aberration defined by formula

$$\frac{dy'}{y'_{1,2}} = \frac{y'_{\lambda_2} - y'_{\lambda_1}}{y'_{\lambda_0}}, \tag{2}$$

where $y'_{\lambda_1}, y'_{\lambda_2}, y'_{\lambda_0}$ — the image value for the appropriate wavelength, λ_0, λ_1 and λ_3 — the primary and extreme wavelength of the selected spectral range;
d — the distance between hyperchromatic lenses;
r_1 — chromatic radius;

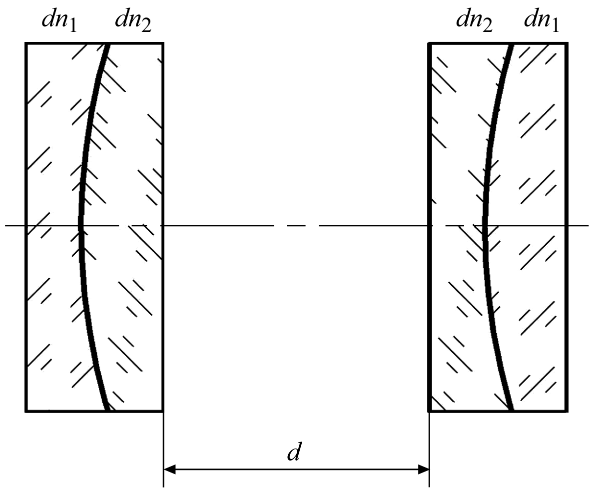

Figure 1. The chromatic aberrations compensator from two hyperchromatic lenses is investigated.

dn_1 and dn_2 — mean glass dispersions determined by the formula

$$dn = n_{\lambda_2} - n_{\lambda_1}, \tag{3}$$

wheren_{λ_1}, n_{λ_2} — glass refraction indices for the extreme wavelengths of the selected spectral range.

By specifying the desired transverse chromatic aberration value, the expression (1) gives an analytic value of the chromatic radius r_1. The calculation of the two-component compensator is limited to the choice of a chromatic pair of glasses and to finding the value of the „chromatic" radius at specified component thicknesses, the distance between the components and the distance between the lens and the first component [15].

Investigation and calculation of the two-component chromatic aberration compensator

The study and calculation of the two-component chromatic aberration compensator was carried out for the serial achromatic lens OM-41 with a magnification of $90^{\times}$, numerical aperture 1.25 and a focal length of 1.96 mm [16], in the spectrum F−d−C.

The study considered 50 pairs of glass recommended in the literature as chromatic, various combinations of them and several combinations of glass from the Trubko table [17,18]. Using optimization tools and target functions in the Zemax OpticStudio program, compensators for the OM-41 lens were calculated from each pair and the values of aberrations were obtained. In Table 1 there are five pairs of glasses with a minimum absolute transverse chromatic aberration. For all pairs of glass presented, the wavelength aberration on the pupil edge for the primary wavelength W_d is 0 to the nearest hundredth.

The best result of the correct transverse chromatic aberration was shown by a pair of LZ_TK14−LZ_F1 glasses from the LZOS catalog. Therefore, further studies were conducted on the basis of a compensator from this pair of glasses. Various variations in the location of hyperchromatic lenses were considered. In each combination of the mean variance differences of the first and second components have opposite signs, and the chromatic radii are equal in modulo. The values of aberrations for different combinations are presented in Table 2. It can be seen that the compensator,

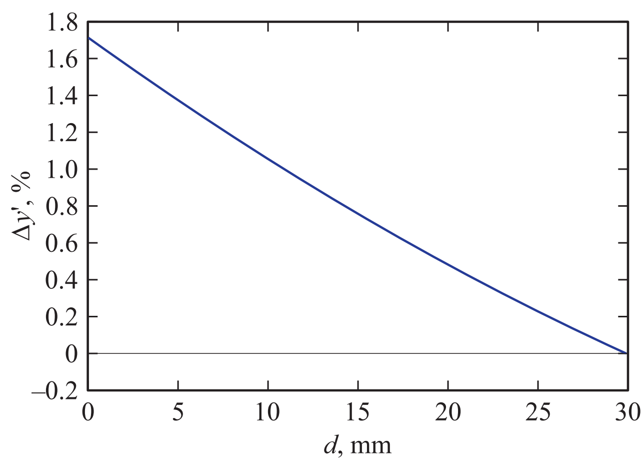

Figure 2. Graph of transverse chromatic aberration dependence on the distance between hyperchromatic compensator lenses.

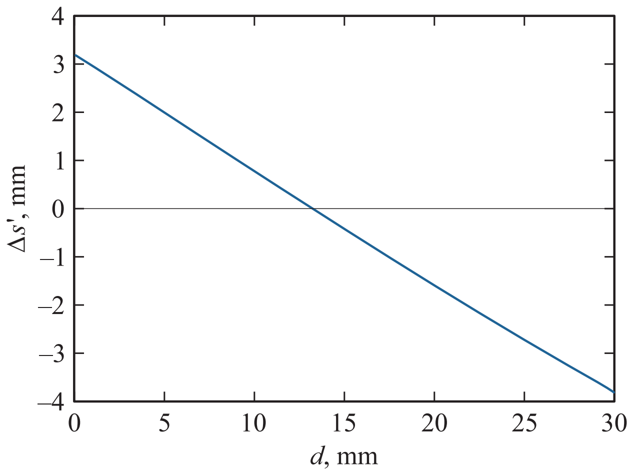

Figure 3. Graph of longitudinal chromatic aberration dependence on the distance between hyperchromatic compensator lenses.

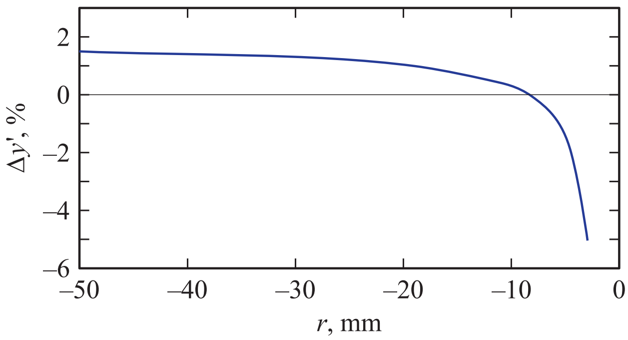

Figure 4. Graph of transverse chromatic aberration dependence on chromatic radius.

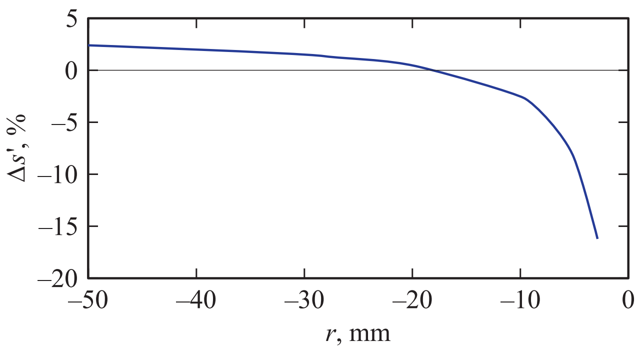

Figure 5. Graph of longitudinal chromatic aberration dependence on chromatic radius.

Table 1. Pairs of glasses with minimum absolute Transverse chromatic aberration

№	1	2	3	4	5
Glass grade	LZ_TK14/LZ_F1	LZ_TK16/LZ_F1	LZ_CTK9/LZ_TF4	LZ_FK24/LZ_LF9	LZ_CTK12/LZ_TF8
Chromatic radius r_1, mm	−8.36	−8.08	−15.30	−8.58	−13.22
Transverse chromatic aberration for maximum field point $\Delta y'$, %	0.00	0.04	0.11	0.12	0.16
Longitudinal chromatic aberration for on-axis point $\Delta s'$, mm	−3.74	−3.51	−3.61	−3.49	−3.42
Wave aberration on the edge of the pupil-for wavelength F W_F, waves	−1.65	−1.61	−1.61	−1.61	−1.58
Wave aberration on the edge of the pupil-for wavelength C W_C, waves	−0.18	−0.19	−0.19	−0.19	−0.20
2nd Zeidel sum S_{II}	1.01	0.97	1.03	1.12	1.06
3nd Zeidel sum S_{III}	0.11	0.11	0.12	0.11	0.12
Distortion for maximum field point, %	0.70	0.70	0.70	0.71	0.70

Table 2. Comparison of different versions of a compensator made of a pair of glasses TC14-F1

Glass grade	LZ_TK14/LZ_F1−LZ_F1/LZ_TK14		LZ_F1/LZ_TK14−LZ_TK14/LZ_F1	
Conditions applied to radii	$r_1 = r_2$, $r_1 < 0$	$r_1 = -r_2$, $r_1 > 0$	$r_1 = r_2$, $r_1 > 0$	$r_1 = -r_2$, $r_1 < 0$
Chromatic radius r_1, mm	−8.35964	14.26610	8.60148	−14.41250
Transverse chromatic aberration for maximum field point $\Delta y'$, %	−0.00112	0.11280	−0.00114	0.10956
Longitudinal chromatic aberration for on-axis point $\Delta s'$, mm	−3.74350	24.54295	−3.55347	24.33285
Wave aberration on the edge of the pupil for wavelength F W_F, waves	−1.64912	2.49267	−1.61189	2.46255
Wave aberration on the edge of the pupil for wavelength d W_d, waves	−0.00002	0.00149	−0.00002	0.00143
Wave aberration on the edge of the pupil for wavelength C W_C, waves	−0.17760	−1.34485	−0.18911	−1.33660
2nd Zeidel sum S_{II}	1.00563	0.99330	0.99623	0.99023
2nd Zeidel sum S_{III}	0.11240	0.11197	0.11238	0.11196
Distortion for maximum field point, %	0.69954	0.69831	0.70080	0.69878

consisting of components with two equal negative chromatic radii, exceeds the degree of correction of transverse chromatic aberration of other compensators considered.

Further investigation of this compensator analyzed the dependence of chromatic aberrations on its parameters - the distance between the components of the compensator and „chromatic" radius. According to graphs presented on Fig. 2−5, you can see that by changing any of these parameters, it is possible to achieve optimal values of transverse and longitudinal chromatic aberration.

As a result, a compensator of transverse chromatic aberration was calculated for the OM-41 lens with a magnification of $90^\times$, a numerical aperture of 1.25 and a linear object-side field of vision 0.2 mm. In Table 3,

Table 3. Monochromatic and chromatic lens aberrations OM-41 (magnification of $90^{\times}$, numeric aperture 1.25 and linear field of view space objects 0.2 mm) with and without compensator

Aberration	Without Compensator	With Compensator
Wave aberration on the edge of the pupil for wavelength d W_d, waves	0.00	0.00
Wave aberration on the edge of the pupil for wavelength F W_F, waves	−0.55	−1.65
Wave aberration on the edge of the pupil for wavelength C W_C, waves	−0.52	−0.18
Coma in the tangential plane for maximum field point of s'_{coma}, mm	0.03	0.03
Astigmatic tangential shift for maximum field point of the field $s'_{\tan}$, mm	−20.95	−20.82
Astigmatic sagittal shift for maximum field point of s'_{sag}, mm	−15.96	−15.85
Distortion for maximum field point of the field, %	0.71	0.70
Transverse chromatic aberration for maximum field point of the field $\Delta y'$, %	1.83	0.00
Longitudinal chromatic aberration for on-axis point of the field $\Delta s'$, mm	3.68	−3.74

Table 4. Monochromatic and chromatic lens aberrations OX-32 (magnification of $100^{\times}$, numeric aperture 1.25 and linear object-side field of view 0.2;mm) without and with compensator

Aberration	Without Compensator	With compensator	
		$d = 29.45$ mm	$d = 22.45$ mm
Wave aberration on the edge of the pupil for wavelength d W_d, waves	0.10	0.25	0.25
Wave aberration on the edge of the pupil for wavelength F W_F, waves	−0.46	−1.25	−1.05
Wave aberration on the edge of the pupil for wavelength C W_C, waves	−0.41	0.01	−0.05
Coma in the tangential plane for maximum field point of s'_{coma}, mm	0.21	0.21	0.21
Astigmatic tangential shift for maximum field point of $s'_{\tan}$, mm	−33.06	−34.11	−34.13
Astigmatic sagittal shift for maximum field point of s'_{sag}, mm	−29.59	−30.66	−30.68
Distortion for maximum field point, %	0.71	0.72	0.71
Transverse chromatic aberration for maximum field point of the field $\Delta y'$, %	2.02	0.01	0.40
Longitudinal chromatic aberration for on-axis point $\Delta s'$, mm	2.87	−5.47	−3.71

a comparison of the values of monochromatic and chromatic aberrations before and after the application of the compensator is presented. The optical scheme of the OM-41 lens with chromatic aberration compensator is presented on Fig. 6.

The calculated compensator was used to correct the transverse chromatic aberration in the achromatic objective lens OX-32 with magnification of $100^{\times}$, the numeric aperture 1.25 and the focal length 1.89 mm [19].

For the compensator, the chromatic radius and the distance between the components were recalculated. As a result, the residual transverse chromatic aberration was 0.01%. However, the fact that the compensator was placed in a loosely convergent beam caused the longitudinal chromatic aberration to deteriorate. By reducing the distance between the components and, therefore, slightly worsening the transverse chromatic aberration value, the longitudinal chromatic aberration value was improved. The residual transverse chromatic aberration was 0.4%. The values of monochromatic and chromatic aberrations at each stage of calculation are presented in Table 4. The optical scheme of

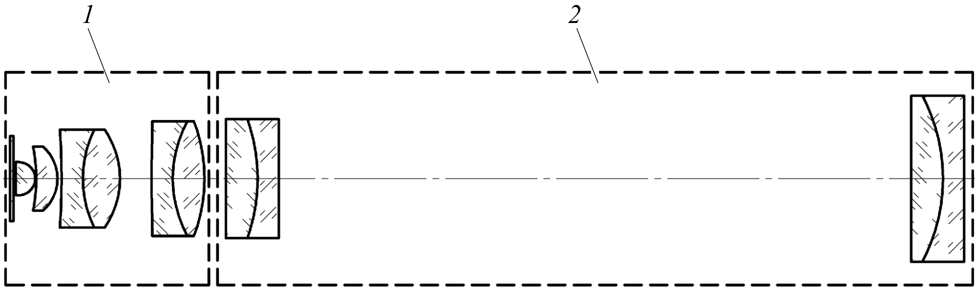

Figure 6. Optical scheme of OM-41 lens objective (magnification of $90^{\times}$, numerical aperture 1.25 and linear field of view in object space 0.2 mm) with the chromatic aberrations compensator: *1* — objective lens, *2* — chromatic aberrations compensator.

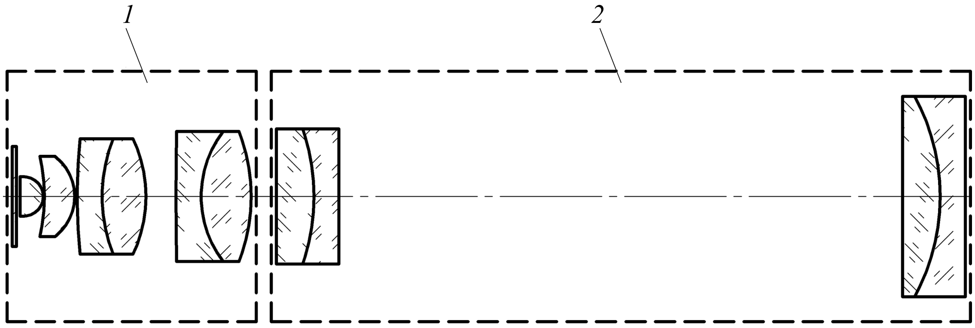

Figure 7. Optical scheme of OX-32 objective lens (magnification of $100^{\times}$, numerical aperture 1.25 and linear field of view in object space 0.2 mm) with chromatic aberrations compensator: *1* — objective lens, *2* — chromatic aberration compensator.

the objective lens with a compensator is represented on Fig. 7.

Conclusion

For two highly aperture immersion achromatic objective lenses OM-41 and OX-32, a transverse chromatic aberration compensator was calculated during the operation; with its help in OM-41 lens objective while maintaining the overall quality of the lens objective we were able to completely correct the transverse chromatic aberration at its initial value of 1.83%; in OX-32 lens objective the transverse chromatic aberration was reduced from 2.02 to 0.40%. This will allow the use of objective lenses with conventional eyepieces or use the CCD matrix in a microscope as a receiver.

In addition, the proposed method of calculation of the compensator makes it possible to design a compensator with any necessary magnification chromatism values, both in size and in sign, without the introduction of other aberrations. This allows to use it not only for the correction of aberrations of most micro lenses, but also for other optical systems requiring minimization of chromatic aberrations, for example, when working with digital optical radiation receivers.

Conflict of interest

The authors declare that they have no conflict of interest.

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