Design of apochromatic telescope without anomalous dispersion glasses

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A novel lens system with correction of secondary spectrum without using anomalous glasses is presented. The lens system comprises four separated lens components, with three of them being subapertures. Two examples of apochromatic telescope are presented, both with the use of typical normal glasses, namely crown K9 and flint F5 glasses, and low-cost slightly anomalous dispersion glasses. Secondary spectrum and other chromatic aberrations of the two design examples are corrected.

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Secondary longitudinal chromatic aberration is often the limiting factor in refracting optical systems. In conventional apochromats the secondary spectrum is corrected by using optical materials having anomalous dispersion. These are special optical glasses, for example fluor crowns or short flints, as well as some crystals and optical liquids[1]. In this way it is possible to correct secondary spectrum with very small residual longitudinal chromatic aberration.

Unfortunately, there are a lot of problems with anomalous dispersion optical materials[1]. They are extremely expensive, unavailable in large pieces, fragile and difficult to work with, so it is preferable to avoid the use of them. However, McCarthy[2] and later Wynne[3,4] showed that this assumption was incorrect. They presented examples of lens systems which demonstrate the secondary spectrum correction with normal glasses. Moreover, Wynne proposed the extended first-order chromatic theory. As shown by other researcher[5], these optical systems are nearly equivalent.

The above results are of great importance because they open the way for a new type of apochromatic refracting optical systems. Unfortunately, although in these designs the secondary spectrum is indeed reduced without resorting to anomalous dispersion glasses, many harmful aberrations remain. For this reason such optical systems are generally impractical. In this paper, we present a new and more practical apochromatic lens system with non-anomalous dispersion glasses.

The disadvantages of the designs of McCarthy and Wynne are caused by their constructions. Both optical systems consist of two widely spaced lens groups with different functions. The front lens group has nearly zero refractive power at the mean wavelength and it acts as a corrector of secondary spectrum for the rear lens group. The power of the lens systems is contributed by the rear lens group. These designs are optical systems of two separated components where the front one is not color-corrected. Such kind of optical systems suffer from a chromatic difference of magnification. This aberration can be reduced by making the front component nearly afocal, and that is exactly the way it works in these designs.

However, a chromatic difference of magnification can also be avoided by using four-component design. In the proposed system the widely spaced third and fourth components mainly help in elimination of the lateral color of the first and the second components. Although every separate component is not corrected for chromatic aberration, the whole system is. In contrast with the designs of McCarthy and Wynne, the front component has large positive refraction power. As a result, the second, third and fourth components are subapertures, the effect of this construction is a reduction of manufacturing cost. Further, the four-component design has good correction of various chromatic and monochromatic aberrations. Due to these improvements, the present system is able to compete with conventional apochromats in some applications.

Considering a refracting surface S, whose paraxial radius of curvature is p, bounded by refractive indices n and n' for some mean wavelength. Let u and u' be the angles of the paraxial marginal ray coming from O measured with respect to the optical axis before and after refraction respectively, see Fig. 1.

The paraxial longitudinal chromatic aberration of a Gaussian image of an axial object point, including all orders in the glass dispersion for a single surface,is given by[6−9]

$$\mathrm{Lchr} = Ah\Delta\left(\frac{\delta n}{n}\right) + hk\delta h + h\Delta\left(\delta n \delta u\right), \qquad (1)$$

where A is the refraction invariant, h is the incidence height of the paraxial marginal ray coming from O, and

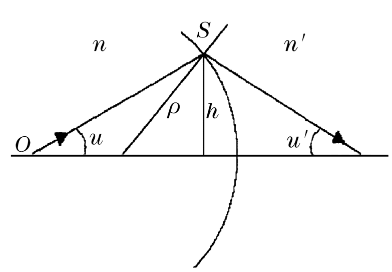

Fig. 1. Parameters for the evaluation of longitudinal chromatic aberrations.

Δ signifies the difference on refraction. The refraction invariant can be written as $A = n(\frac{h}{\rho} + u)$; the Δ-term is given by $\Delta\left(\frac{\delta n}{n}\right) = \left(\frac{\delta n'}{n'} - \frac{\delta n}{n}\right)$; and k is given by $k = \Delta(\delta n)/\rho$.

Evaluating the paraxial longitudinal chromatic aberration between the short wavelength F and the long wavelength C, we have

$$\begin{aligned}\mathrm{Lchr}_{(C-F)} = n_F\left(\frac{h_F}{\rho} + u_F\right) h_F \left(\frac{n'_C - n'_F}{n'_F} - \frac{n_C - n_F}{n_F}\right) \\ + h_F\left[\frac{(n'_C - n'_F) - (n_C - n_F)}{\rho}\right] \\ + h_F\{[(n'_C - n'_F) - (n_C - n_F)] \\ \times [(u'_C - u'_F) - (u_C - u_F)]\}. \qquad (2)\end{aligned}$$

Equation (2) gives the individual surface contribution to paraxial longitudinal chromatic aberration as a wavefront aberration including all orders in the glass dispersion. For an optical system, the total contribution to paraxial longitudinal chromatic aberration is given by the sum of the individual surface contributions.

If the system is already corrected for primary longitudinal chromatic aberration, then the focus for the short and long wavelengths will be the same under this approximation. Then the difference between the focus positions for the long wavelength and the mean wavelength will give a measure of secondary spectrum, that is[4,5],

$$\begin{aligned}\mathrm{SSpec}_{(C-d)} = n_d\left(\frac{h_d}{\rho} + u_d\right) h_d \left(\frac{n'_C - n'_d}{n'_d} - \frac{n_C - n_d}{n_d}\right) \\ + h_d\left[\frac{(n'_C - n'_d) - (n_C - n_d)}{\rho}\right] \\ + h_d\{[(n'_C - n'_d) - (n_C - n_d)] \\ \times [(u'_C - u'_d) - (u_C - u_d)]\}, \qquad (3)\end{aligned}$$

where the subscripts C and d refer to long and middle wavelengths.

The first term in Eq. (3) is the conventional secondary spectrum evaluated by the classical first-order chromatic aberration theory. The other two terms in Eq. (3) involve the second and higher-order terms in the glass dispersion δn. For an optical system, the total contribution to secondary longitudinal chromatic aberration including all terms in glass dispersion is given by the sum of the individual surface contributions.

Performance of the present optical system will be illustrated with examples of apochromatic telescopes because the performance of refracting telescopes is usually limited by residual longitudinal chromatic aberration. Two examples are presented here, selected to show different types of glass combination. The secondary spectrum correction can be greatly improved by the use of low-cost slightly anomalous dispersion glasses (for example some dense flints). The partial dispersion of these glasses has only small deviations from normal values when compared with highly anomalous fluor crowns and special short flints.

The sample designs were optimized to produce minimum polychromatic root-mean-square (RMS) spot size over a field of view of $2\omega = 1°$. They are intended for wavelength range of 370 − 750 nm and the design wavelength is 555 nm.

The first design example having an aperture of 90 mm with an aperture ratio of $f/7$ is shown in Fig. 2. It has a cemented triplet as the second component and a cemented doublet as the third one. This design employs the typical normal glasses, namely crown K9 and flint F5, and an inexpensive slightly anomalous optical glass, namely QK3.

To illustrate the color correction of this telescope, the chromatic focal shift is shown in Fig. 3. The curve demonstrates the paraxial color correction at three wavelengths, which is typical for apochromats. Figure 4 shows the modulation transfer function (MTF) curve of this design. We can find that the MTF value approaches to the diffraction limit.

The second design example having an aperture of 100 mm with an aperture ratio of $f/4.5$ is shown in Fig. 5. It has a cemented doublet as the second component. The glasses K9, F5, ZK9, ZF3, ZF5 are used in this design.

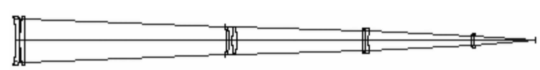

Fig. 2. Schematic of the first design example.

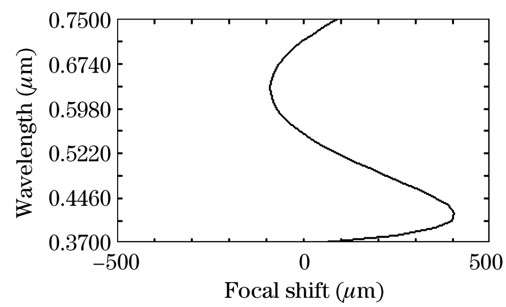

Fig. 3. Paraxial color curve of the first design example.

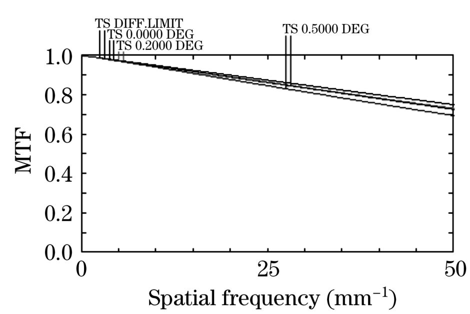

Fig. 4. MTF of the first design example. TS DIFF. LIMIT indicates the diffraction limit of this configuration, TS 0.0000 DEG means the field of view of 0°, TS 0.2000 DEG and TS 0.5000 DEG present the angles of half-field of view of 0.2° and 0.5°, respectively.

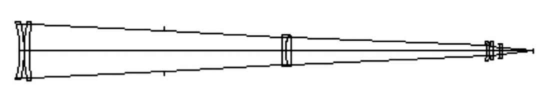

Fig. 5. Schematic of the second design example.

The chromatic focal shift of this design is shown in Fig. 6. Figure 7 shows the MTF curve, indicating that the MTF value approaches to the diffraction limit value. The improvement in optical performance is more evident here than in the previous example. It has a small tertiary spectrum along with a very high relative aperture.

All the above examples employ the combination of typical normal glasses with the slightly anomalous dispersion glasses and have good correction of secondary spectrum, other chromatic aberrations and various monochromatic aberrations. The secondary spectrum for the two design examples is about several ten microns. It is much smaller than the secondary spectrum for a standard apochromat of the same aperture and focal length. Furthermore, the two examples demonstrate that the present optical system is over a much wider range of wavelengths than a standard apochromat. To conclude, the fact that apochromatic lens systems of practical size are possible with non-anomalous dispersion optical materials.

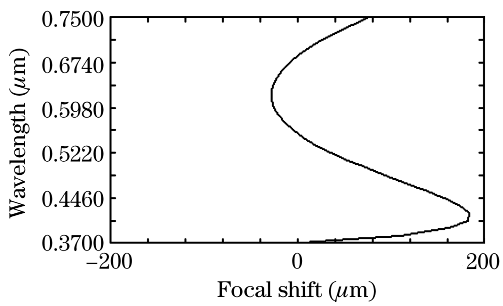

Fig. 6. Paraxial color curve of the second design example.

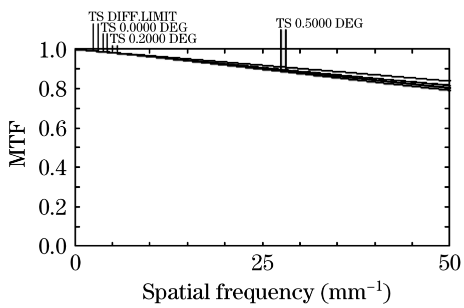

Fig. 7. MTF of the second design example.

The presented optical system can be used in various imaging devices other than telescopes or as a part of a more complex optical system, for example as a subaperture corrector for spherical or aspherical mirrors, or as a prepositive optical system for imaging spectrometer.

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