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Apochromatic telescope without anomalous dispersion glasses

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In order to correct secondary longitudinal chromatic aberration in conventional refracting optical systems it is necessary to use at least one optical material having anomalous partial dispersion. This paper presents a novel lens system with correction of secondary spectrum by using only normal glasses. The lens system comprises three widely separated lens components, both second and third components are subaperture. The presented example of an apochromatic telescope demonstrates secondary spectrum correction with the use of only crown BK7 and flint F2, which are among the most inexpensive optical glasses available at the market. Two more similar designs are presented, both with the use of low-cost slightly anomalous dispersion glasses. These telescopes have a higher relative aperture and a smaller tertiary spectrum.

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1. Introduction

Secondary longitudinal chromatic aberration is often the limiting aberration 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. 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. They are extremely expensive, unavailable in large pieces, fragile and difficult to work with. For these and other reasons, it is preferable to avoid the use of them. Until the middle of the 20th century, it had been accepted that the elimination or considerable reduction of the secondary longitudinal chromatic aberration in refracting optical systems is not possible without the use of materials having anomalous dispersion. However, McCarthy ¹ and later Wynne ^{2,3} showed that this assumption was incorrect. Both authors presented examples of lens systems which demonstrate the secondary spectrum correction with normal glasses. Moreover, Wynne pointed out the defects in the accepted theory of first order chromatic aberrations and developed the extended first-order chromatic theory. As was shown by other authors ⁴⁻⁶ these optical systems are nearly equivalent.

The results obtained by these investigators are of great importance because they clever the way for a new type of apochromatic refracting optical systems. Unfortunately, while in both McCarthy and Wynne designs the secondary spectrum is indeed reduced without resort to anomalous dispersion glasses, many harmful aberrations remain. For this reason such optical systems are generally impractical. Perhaps this is why the normal glass apochromats are so little known. The goal of this paper is to present a new and more practical apochromatic lens system without the use of anomalous dispersion glasses.

2. Three-component design

The disadvantages of McCarthy and Wynne designs are caused by their construction. Both optical systems consist of two widely airspaced 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. Both McCarthy and Wynne designs per se 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 designs in question.

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

3. Examples

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. Three examples are presented here, selected to show different types of glass combination. The sample designs were optimized to produce minimum polychromatic RMS spot size over a field of view of 0.5° . They are intended for visual use and the design wavelength is 555 nm. All the telescopes are of the same length but different apertures, their section drawings are shown in Fig. 1.

In the first example we consider an apochromatic telescope with the use of typical normal glasses, namely crown BK7 and flint F2, which are among the most inexpensive optical glasses

available at the market. These materials are from SCHOTT catalog but other manufacturers make nearly equivalent glass types. The first design having an aperture of 70 mm with an aperture ratio of $f/7$ is shown in Fig. 1(a) and the specifications are summarized in Table 1.

To illustrate the color correction of this telescope the chromatic focal shift plot is shown in Fig. 2. The color curve demonstrates the paraxial color correction at three wavelengths, which is typical for apochromats. Note, that the tertiary spectrum in blue-violet region is significantly smaller than in red one. Such type of color correction is uncommon for conventional apochromatic lens systems.

Fig. 3 shows the Strehl ratio as a function of wavelength for the first example and for a standard achromat of the same aperture and length. This plot clearly demonstrates that the present lens system significantly outperforms a standard achromat due to the improvement in color correction. The performance of such normal glass apochromats can be considerably improved by adding lens elements or using other glass combinations.

Although the secondary spectrum correction in the above example is obtained with the use of the most common optical glasses, many other glasses can be successfully applied. By a proper choice of glass combination it is possible to either improve optical performance or increase relative aperture, or both. It is important that the secondary spectrum correction can be greatly improved by the use of low-cost slightly anomalous dispersion glasses (for instance some dense flints). The partial dispersions of these glasses have only small deviations from normal values when compared to highly anomalous fluor crowns and special short flints. Normally, the partial dispersions of such slightly abnormal optical glasses are not anomalous enough to produce competitive conventional apochromats.

The next design example having an aperture of 90 mm with an aperture ratio of $f/7$ is shown in Fig. 1(b) and the specifications are listed in Table 2. It is a little more complex, it has a cemented triplet as the middle component and a cemented doublet as the rear one. This design employs an inexpensive and slightly anomalous optical glass, namely N-FK5. The combinations of this crown glass with other normal glasses do not result in significant

reduction of the secondary spectrum when used in conventional lens systems. However, in the presented optical system the use of N-FK5 yields the solid apochromatic color correction. Fig. 4 shows the Strehl ratio as a function of wavelength for this design and for a standard achromat of the same aperture and length.

The last design having an aperture of 100 mm with an aperture ratio of $f/4.5$ is shown in Fig. 1(c) and the specifications are summarized in Table 3. This design exploits the slightly anomalous dispersion and high refractive indices of some dense flint glasses. Dense flints are relatively inexpensive optical glasses that are widely used in the industry for many decades. Fig. 5 shows the Strehl ratio as a function of wavelength for this design and for a standard achromat of the same aperture and length. The improvement in optical performance is more evident here than in the previous examples, although the design is simple. This apochromatic telescope has a small tertiary spectrum along with a very high relative aperture.

4. Discussion

Thus, all the above examples demonstrate that the present optical system is diffraction limited over a much wider range of wavelengths than a standard achromat. To conclude, the fact that diffraction-limited apochromatic lens systems of practical size are possible without the use of anomalous dispersion optical materials. Actually, the correction of secondary spectrum can be obtained with only two optical glasses of different relative dispersions regardless of their partial dispersions. It is especially important at a different waveband from the visible because in UV and IR spectral regions there are a lot less optical materials to choose from. This feature also leaves considerable freedom to designers in choosing designs with optimum balance between cost and performance for various specific applications.

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

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Table 1. Prescription of 70 mm f/7 apochromatic telescope with the use of normal glasses. The dimensions are given in millimeters.

| Radius of curvature | Axial thickness | Material | Clear diameter |
|---------------------|-----------------|----------|----------------|
| -168.7614 | 6.0 | BK7 | 72.0 |
| -458.8111 | 0.0 | Air | 72.0 |
| 211.0389 | 7.0 | F2 | 72.0 |
| Infinity | 343.0 | Air | 72.0 |
| 90.3161 | 12.0 | BK7 | 51.0 |
| -77.3368 | 0.0 | Air | 51.0 |
| -78.3952 | 6.0 | F2 | 51.0 |
| 114.4303 | 540.0 | Air | 51.0 |
| 82.7580 | 6.0 | F2 | 30.6 |
| 4135.3424 | 80.003 | Air | 30.6 |
| | image plane | | |

Table 2. Prescription of 90 mm f/7 apochromatic telescope with the use of normal glasses and N-FK5.

| Radius of curvature | Axial thickness | Material | Clear diameter |
|---------------------|-----------------|----------|----------------|
| -186.8514 | 8.0 | BK7 | 92.6 |
| -288.5483 | 0.0 | Air | 92.6 |
| 223.9165 | 10.0 | F2 | 92.6 |
| 913.3273 | 391.5 | Air | 92.6 |
| -254.6844 | 7.0 | BK7 | 57.4 |
| -81.9085 | 6.0 | F2 | 57.4 |
| 102.4033 | 10.0 | N-FK5 | 57.4 |
| -129.1499 | 430.5 | Air | 57.4 |
| 93.3023 | 6.0 | F2 | 37.0 |
| -127.1627 | 6.0 | BK7 | 37.0 |
| 128.6485 | 125.002 | Air | 37.0 |
| image plane | | | |

Table 3. Prescription of 100 mm f/4.5 apochromatic telescope with the use of dense flint glasses.

| Radius of curvature | Axial thickness | Material | Clear diameter |
|---------------------|-----------------|----------|----------------|
| -182.2961 | 9.0 | BK7 | 103.0 |
| -243.5326 | 0.0 | Air | 103.0 |
| 213.7035 | 10.0 | SF1 | 103.0 |
| 456.0384 | 385.0 | Air | 103.0 |
| -223.9607 | 6.0 | SF1 | 64.4 |
| 88.1108 | 12.0 | SK16 | 64.4 |
| -181.6369 | 472.0 | Air | 64.4 |
| 80.8862 | 6.0 | SF2 | 41.6 |
| 425.7558 | 100.001 | Air | 41.6 |
| | image plane | | |

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Fig. 4. Strehl ratio as a function of wavelength for the 90mm f/7 apochromatic telescope with the use of normal glasses and N-FK5.

Fig. 5. Strehl ratio as a function of wavelength for the 100mm f/4.5 apochromatic telescope with the use of dense flint glasses.

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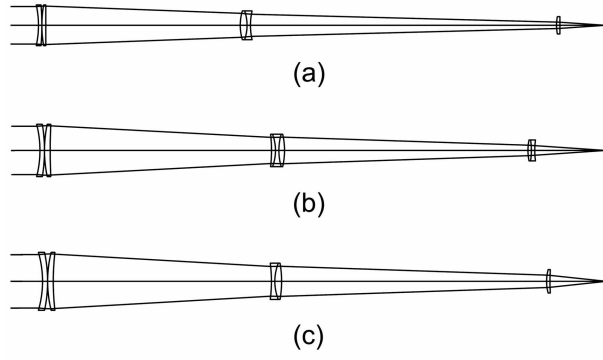


Fig. 1. Section drawings of the design examples. duplovF1.eps

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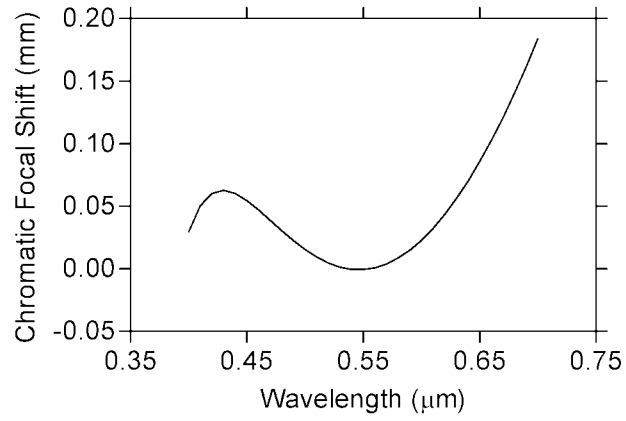


Fig. 2. Paraxial color curve of the 70mm f/7 apochromatic telescope with the use of normal glasses. duplovF2.eps

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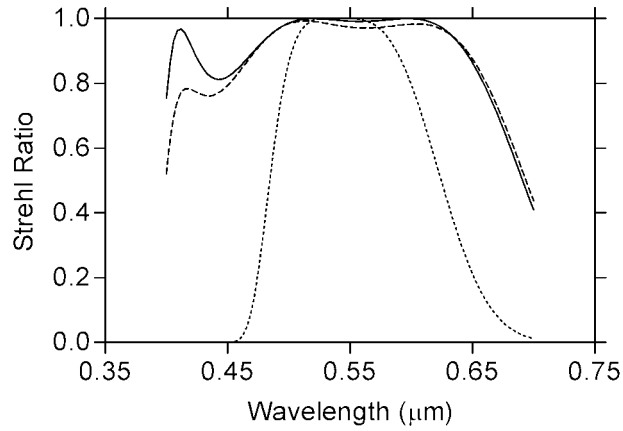


Fig. 3. Strehl ratio as a function of wavelength for the 70mm f/7 apochromatic telescope with the use of normal glasses. The solid line corresponds to on-axis Strehl ratio and the dashed line to 0.25° off-axis. The dotted reference line shows on-axis Strehl ratio for a standard achromat of the same aperture and length. duplovF3.eps

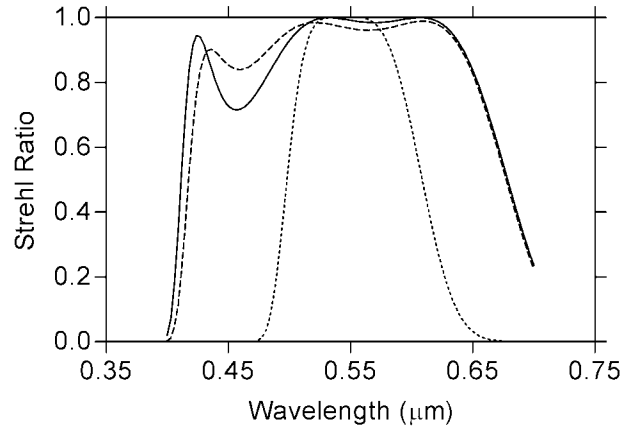


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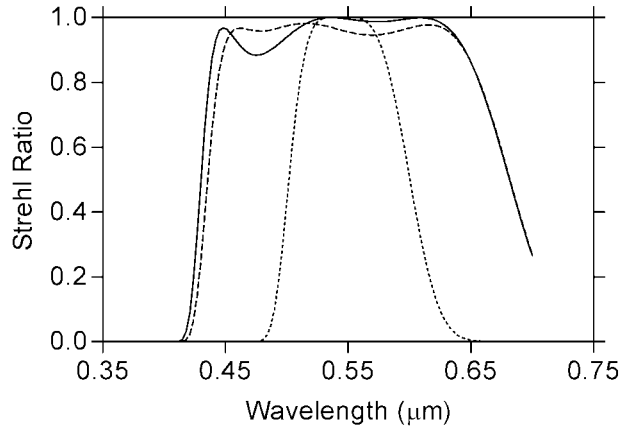


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