International Research Journal of Natural Sciences

Vol.2, No.4, pp.1-9, December 2014

Published by European Centre for Research Training and Development UK (www.eajournals.org)

DESIGN OF TWO-GLASS FOR APOCHROMATIC OPTICAL SYSTEM

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ABSTRACT: *Apochromatic designs of lens systems utilizing two optical materials are described. A method of glass selection for apochromatic optical systems with reduced chromatic aberration is present. This method is based on the glass maps by using a glass database (Schott glass) and an optical design program (OSLO) to help the optical designer to select optical glass types in a more efficient way. 'Active' glass maps can be used to compare glasses for special properties and to change glasses in the optical design process , and then using computer program(OSLO) to aid in the design of a lens and the validation results. The goal for this paper is to make glass selection easier to understand.*

KEYWORDS: Design, Glass, Apochromatic, Optical System

INTRODUCTION

Chromatic aberration of a single lens causes different wavelength (FIG. 1). Apochromatic lenses are designed to bring three wavelengths (typically red, green, and blue) into focus in the same plane. The residual color error (secondary spectrum) can be up to an order of magnitude less than for an achromatic lens of equivalent aperture and focal length. Apochromatic lenses are also corrected for spherical aberration at two wavelengths, rather than one as in achromatic lenses. Apochromatic designs require optical glasses with special dispersive properties to achieve three color crossings [1].

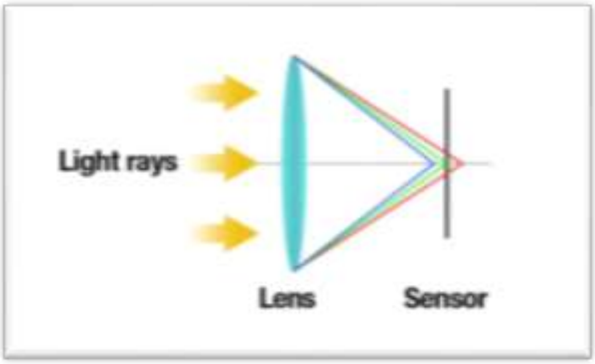

FIG. 1: Chromatic aberration of a single lens causes different wavelengths or frequencies to have differing focal lengths [2].

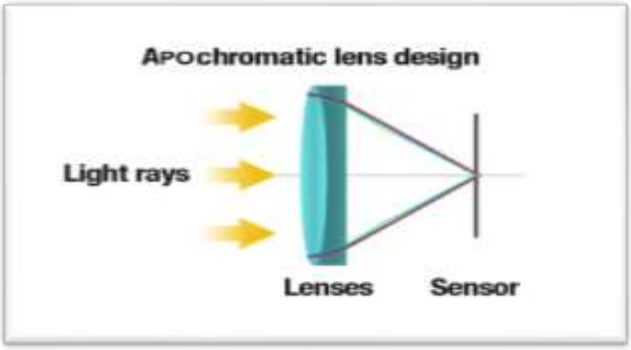

FIG.2: apochromatic lens of two elements and brings light of three different frequencies to a common focus.

Apochromatic optical systems need a specific combination of optical glass sorts, whose dispersive properties insure correction of the longitudinal chromatic aberration and secondary spectrum. An apochromatic system accomplishes the superposition of image abscissas for three wavelengths, so that the secondary spectrum is much lower than for any other optical entity. The design algorithm supposes that the operator has already chosen the glass sorts [2]. The apochromatic lens is usually of three elements ,But, in this paper used two element (Fig. 2) and brings light of three different frequencies to a common focus .A simple cemented doublet can be made apochromatic if suitable glasses are chosen in which the partial dispersion ratios are equal. The large V difference keeps the elements weak and reduces the zonal aberration [3]. The apochromatic lens is used more conservatively in astronomy-related optics, as for example, in telescopes, more than in photography. Graphic arts process (copy) cameras generally use apochromatic lenses for sharpest possible imagery as well [2].

The correction of secondary color and higher order spectrum in lens design has been the subject of investigations since the design of the first achromatic doublet by Hall in 1733, Historically, the temi- apochromat or apochromatic was initially introduced by Abbe [4] in his study of microscope objectives to mean color correction at three wavelengths and the correction of the sine condition at two colors. In recent years, the renewed interest among optical designers in the design of apochromatic and arise from the developments of new types of optical materials which include glasses, liquids, and crystals as well as developments in diffractive optics. Mercado and Ryzhikov presented a review of the simple methods of selecting optical materials for designing apochromats and superachromats [5]. In 2005 Volker Witt used two materials like (LAK10-FK54) to design apochromatic optical system [6]. Recently,[7] A method of glass selection for triplet apochromatic optical systems with reduced chromatic aberration were described. in this paper, we will use the terms apochromatic to mean color correction at three wavelengths, and the additional requirements of aplanaticity as defined by Abbe to be optimal depending on the application of the lens system, Design examples of medium aperture optical systems are discussed and the optical performance evaluations of these designs are shown.

Theoretical basis

When we initially understand an Apochromatic only as achromatic with reduced secondary spectrum, since the magnitude of secondary spectrum depends on the specific dispersive properties of the glasses combined, some combinations will produce significantly more of it than common crown/flint combinations. To get a better color correction, secondary spectrum must be reduced using special glasses.The degree of reduction in secondary spectrum is determined by the ratio of their respective dispersion differentials between the blue (F) and red (C) line; if it is inversely proportional to the lens' powers, blue and red will be brought to a common (paraxial) focus [8].

If we choose to cancel chromatism for the F (486nm blue) and C (656 nm red) lines, then the curvatures of the front and rear lens need to relate as:

$$\frac{k_2}{k_1} = -\frac{n_{F1} - n_{C1}}{n_{F2} - n_{C2}} \qquad (1)$$

With k=(1/R1)-(1/R2), where R1,2 is the front and rear lens radius of curvature, respectively, and n_{F1}, n_{c1} and n_{F2}, n_{c2} refractive index of the selected distant wavelengths for the front and rear lens, respectively. This relation tells that for bringing F and C to a common focus, the magnitude of dispersive powers of two glasses in F and C for two glasses needs to relate as the inverse of their optical power (since the curvature k is directly proportional to the optical power). For instance, if the positive element in a doublet has 50% greater optical power than the negative element, its dispersive differential between F and C has to be as much smaller [8, 9].

In other words, secondary spectrum of a doublet does not depend of lens shape, only their power. This leaves enough room for lens "bending", so that other (monochromatic) aberrations are also corrected or minimized.

But bringing two widely separated wavelengths to a common focus does not make all the wavelengths over the visual range nearly par focal. Those in between will still focus shorter, and those closer to the end of range will focus longer. This form of residual chromatic defocus is called secondary spectrum. In order for a doublet to have identical focal length for an additional, third wavelength in the mid-range (e-line here), it also needs to satisfy the relation as in equation:

$$\frac{k_2}{k_1} = -\frac{n_{F1} - n_{e1}}{n_{F2} - n_{e2}} \qquad (2)$$

This implies that any two different glasses with their F-C dispersion differentials ratio sufficiently deviating from 1 can bring these two wavelengths to a common focus (obviously, two lenses made of the same glass will achieve this only for collimated beam). Since the formation of a real focus requires the positive element to be of greater optical power than the negative element, the former needs to have its C-F dispersion lower by the same ratio; in other words, the positive element of an achromat – or, for that matter, doublet objective – is always of weaker dispersion than the negative one[8,9,10].

But other wavelengths will still deviate from this common focus, creating secondary spectrum. The measure of its magnitude is, for the standard achromat with a common F/C focus, the axial separation between it and the e-line focus, which focuses the shortest. Its magnitude is directly proportional to how much the ratio between F-e dispersion differential between two glasses deviates from their F-C differential in equation below.

$$1/f_{FC} - 1/f_e = \Delta/f = (n_{F1} - n_{e1})k_1 + (n_{F2} - n_{e2})k_2 \qquad (3)$$

If the ratio of the elements' respective dispersion differentials between the blue (F) and green e line is proportional to their F-C differential ratio, e line will be also brought to a common focus. This practically ensures that all other wavelengths will come to focus near to this common F-e-C focus as well. Such objectives qualify as apochromatic. Glass combinations that do not achieve this level of secondary spectrum correction, but are better corrected in that respect than standard achromats, are often referred to as semi-apochromats objectives.

The significance of Abbe (dispersion) differential between two glass elements is implied by equation:

$$-\frac{f_1}{f_2} = \frac{V_2}{V_1} \qquad (4)$$

With $f_{1,2}$ being the lens focal lengths in the e-line, and $V_{1,2}$ their respective Abbe numbers (dispersion), with the subscripts 1 and 2 referring to the front and rear lens, respectively. The equation implies that the two lenses need to have opposite powers, and that the weaker lens (normally, the negative element of a telescope objective) needs to have proportionally stronger dispersion in order to offset chromatism induced by the stronger lens [9].

Their respective Abbe numbers need to relate as the inverse of their focal lengths. Thus, the closer V_1 and V_2, the less of a relative differential between their focal length as well. And since the combined focal length is given by:

$$(1/f) = (1/f1) + (1/f2), \qquad (5)$$

The longer wavelength always numerically negative, the smaller specific values for $f1$ and $f2$ need to be to generate a given combined focal length. And that means more strongly curved lens surfaces.

An important parameter in this context is the relative partial dispersion (Ve) as in equation:

$$\vartheta_e = \frac{n_F - n_e}{n_F - n_C}. \qquad (6)$$

Thus, the dispersion between the F -line (480.0 nm, blue) and the e-line (546.1 nm, green) relative to the base dispersion n_F - n_C referred [6] .

In an attempt to define an apochromatic as instrument meeting specific minimum correction level, it was stated by Ernst Abbe himself that an objective is apochromatic if its secondary spectrum is canceled and if its correction of spherochromatism - or tertiary spectrum - is also satisfactory.

RESULT AND DISCUSSION

Glass combinations that were identified by the simple methods described in this paper have been tried to achieve the design of apochromatic microscope objectives . In most cases, the combination of these pairs of materials yields excellent chromatic aberration correction toward the short end of the visible spectral region [5]. these pairs of glasses are chosen relative to the closeness of the values of their partial dispersion ratios and The large V difference keeps the elements weak and reduces the zonal aberration, then A simple cemented doublet can be made apochromatic if suitable glasses are chosen in which the partial dispersion ratios are equal and The large V difference between two glass[3,6].So we can directly choose suitable pairs of glasses from the plot of partial dispersion ratios versus Abbe number as shown in Fig.3. Graphically, two glasses will have near-zero secondary spectrum if the line connecting them on a relative partial dispersion diagram is near horizontal, i.e. if their respective relative partial dispersion values are nearly identical.

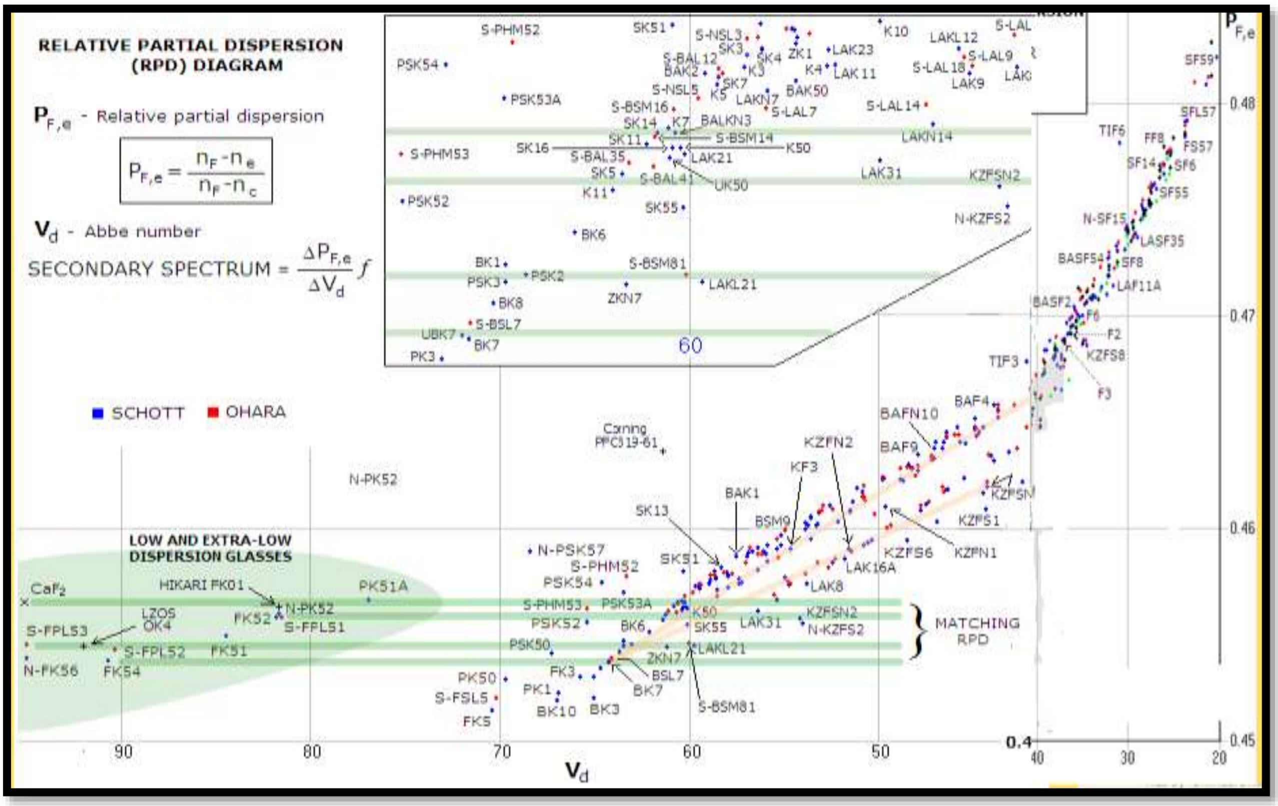

FIG.3: Shows partial dispersion ratios versus Abbe number [9].

As FIG. 3 shows, some ten extra low-dispersion glasses by two major glass manufacturers, Schott[11] can be matched by roughly twice as many higher dispersion ("normal" or slightly "abnormal") glasses for cancelling secondary spectrum. However, while they'll bring blue, green and red to a common focus, their dispersion properties toward violet and deep red vary, making some combinations better than others with respect to the degree of correction in that spectral range. Cancelling out secondary spectrum requires two glass elements with nearly identical relative partial dispersion (RPD) value. Since one of them is of positive, and the other of negative power, their refractive variation with the wavelength offsets one another. On the RPD graph, it translates into near horizontal line connecting two glasses. Thus, the greater slope of the connecting line, the more of secondary spectrum produced; for instance, top orange line connects BK7 crown and F2 flint, the standard achromat, while the lower orange line, connecting BK7 and KZFSN4 indicates nearly 30% smaller secondary spectrum (FIG.3). For given RPD differential, secondary spectrum is inversely proportional to the Abbe number differential between two glasses. The Abbe differential is also important because it determines lens power needed for achieving the minimum secondary spectrum level for the two glasses: the smaller differential, the stronger lenses required [9].The suitable pairs of glasses are partially illustrated from the plots of partial dispersion ratios versus Abbe number in FIG.3 and With the help of the data summarized from Schott glass (data sheet)[11] as shown in table (1)

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Table 1

Depression and Partial Depression for Glasses Used in a Double -Lens Apochromatic.

Number of Double Apochromatic lens	Glass	n_e(refractive index)	P_{Fe}(partial dispersion)	V_d(abbe number)
1-	FK_5	1.48914	0.4520	**70.41**
	F_5	1.60718	0.4682	**38.03**
2-	BK_7	1.51872	0.5103	**64.17**
	N-$BaSF_2$	1.66853	0.4865	**36.00**
3-	BK_3	1.50014	0.4522	**65.1**
	F_6	1.636359	0.4680	**35.34**
4-	FK_5	1.48914	0.4520	**70.41**
	F_2	1.62408	0.4692	**36.37**
5-	BK_7	1.51872	0.5103	**64.17**
	N-SF_5	1.67764	0.4721	**32.25**

After finding the shaded alternative materials in Table 3 for double design, the design of double –lens must be used to validate it for use is free of the chromatic aberration, the possibility of system brought three colors to a common focus through the analysis provided by the program OSLO-EDU [12] free download from (Lambd ResearchCorporation) Accords as shown in FIG. 4.

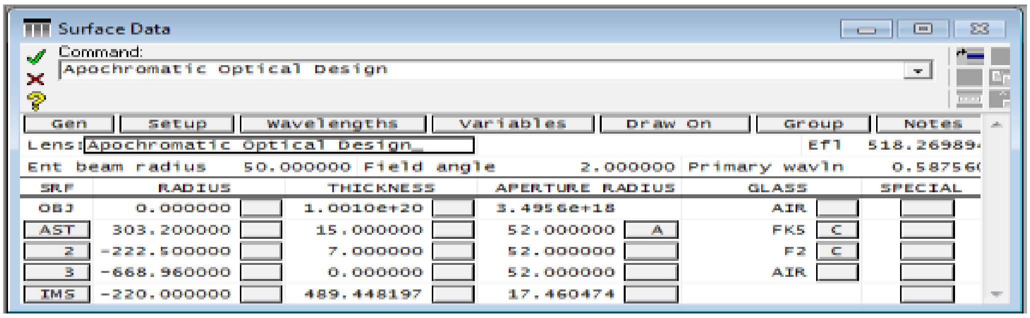
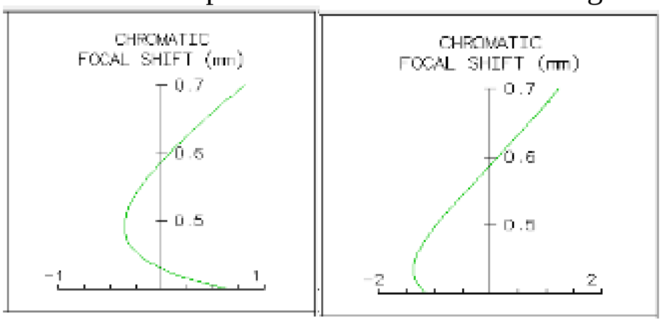


FIG.4: Input the data in the OSLO program for the lens optical system.

There are a couple of things we want to draw your attention to. The first one is the Chromatic Focal Shift .Chromatic focal shift shows where the different colors come to a focus. The vertical scale show the wavelengths, 0.4 on the bottom is violet, and 0.7 on the top is red. The horizontal scale shows the focal position for different wavelengths as shown in FIG .5.



(a) (b)

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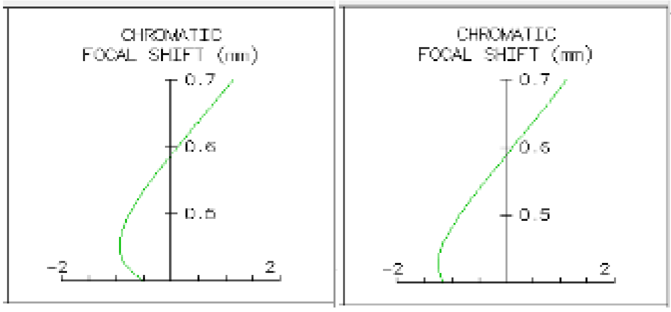


(c) (d)

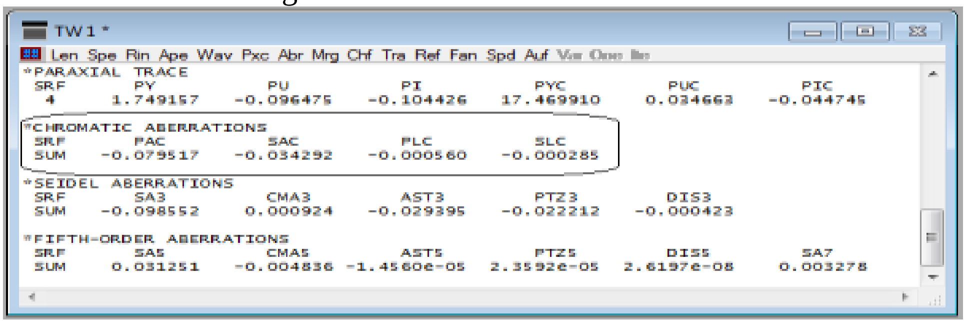
(a)FK5-F2; (b) BK7- N-BASF2; (c) BK3-F6; (d) FK5-F5

FIG. 5: Longitudinal chromatic aberration of two-element apochromatic.

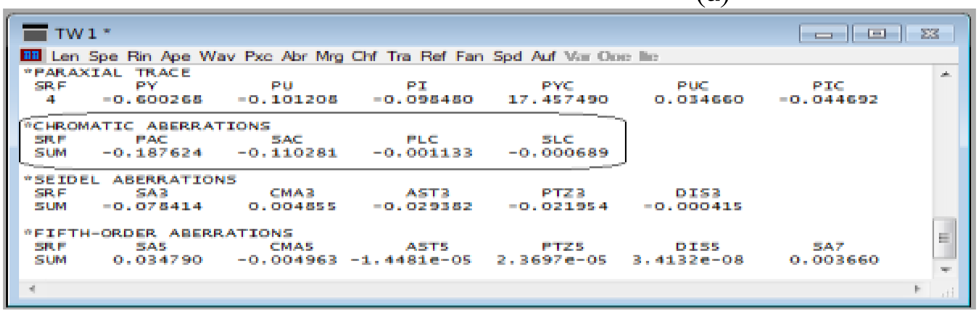
In FIG .5(a) Remember that the chromatic focal shift shows where the different wavelengths come to a focus. The 0.400 wavelength (violet) comes to a focus about 0.8mm behind the best focus. This is very good, especially compared with a normal achromatic refractor's color correction which is about 10mm. Red light (0.7 microns) focuses about 1 mm behind the green light. This color balance is typical for a visual objective lens. So the improvement here is about 10 times better color correction for the violet compared with a normal refractor lens .

In FIG.5 (b-d) the violet light (0.4 microns) focuses about 1.5mm farther away from the lens than green light of 0.588 microns. Having the blue line on the left of center means that in this design the violet light will have less longitudinal chromatic aberration. Red light (0.7 microns) focuses about 2 mm behind the green light. This color balance is typical for a visual objective lens. So the improvement here is about 5 times better color correction for the violet compared with a normal refractor lens. This color correction is the key to why apochromatic lenses can have such good images. Selecting the right glass types is very important. There are many combinations which can give good results.

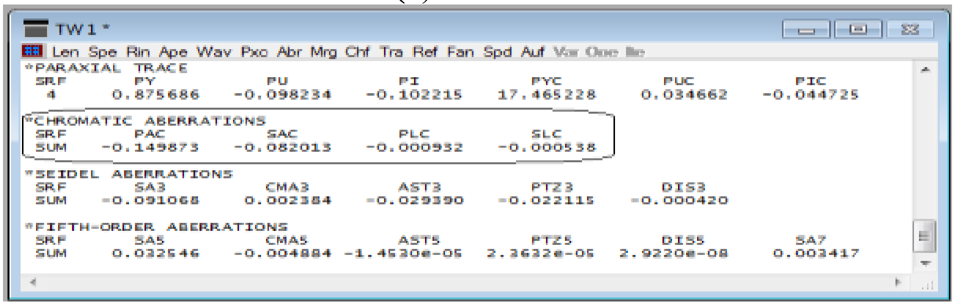
The other thing to notice is the chromatic Aberration graph. Notice that the scale is small compared with a normal achromatic design as shown in FIG. 6.



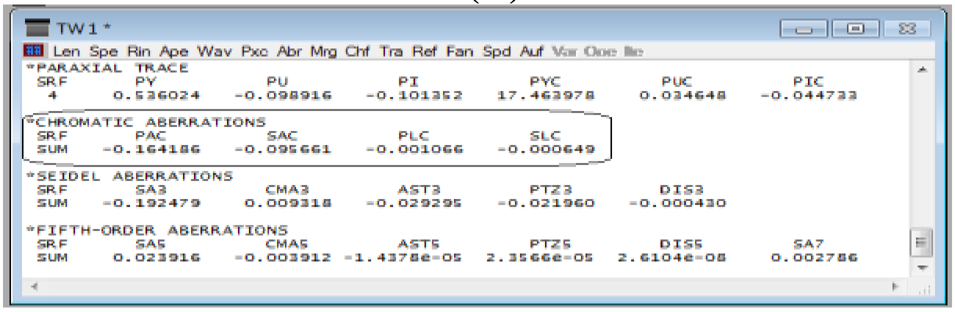
(a)



(b)



(c)



(d)

(a)FK5-F2; (b) BK7- N-BASF2; (c) BK3-F6; (d) FK5-F5

FIG. 6: Chromatic Aberration of two-element Apochromatic

Note that all kinds of chromatic aberration (PAC, SAC, PLC, SLC) in Aberration(Abr) command is very small and approximating the apochromatic design.

CONCLUSIONS

We presented a review of the simple methods of selecting optical materials for designing apochromats. These methods were derived from simple refractive index interpolation formulas that are well known to optical designers. Pairs of optical glasses selected by these simple methods yield designs of lens systems having paraxial color correction at three wavelengths .Recent development of new optical materials which include optical glasses, liquids, and crystals enable us to design apochromatic lenses by using only two materials.

We validity and successful implementation of color corrected designs depends on the accuracy of refractive index measurement data for optical materials. It was shown that apochromatic lens systems can be designed using two optical material if the two materials have the partial dispersion ratios are equal and the large V difference between them.

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