(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
31 August 2006 (31.08.2006)

PCT

(10) International Publication Number
WO 2006/091181 A1

(51) International Patent Classification:
*G02B 9/34* (2006.01) *G02B 11/16* (2006.01)

(21) International Application Number: PCT/UA2005/000028

(22) International Filing Date: 1 July 2005 (01.07.2005)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicant and
(72) Inventor: DUPLOV, Roman [UA/UA]; Kvartal 103-14A/71, Yasinovataya, Donetskaya oblast, 86006 (UA).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

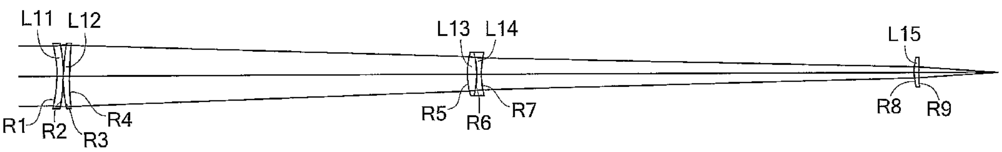
(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

**Declaration under Rule 4.17:**
— *of inventorship (Rule 4.17(iv))*

**Published:**
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*
— *upon request of the applicant, before the expiration of the time limit referred to in Article 21(2)(a)*

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

**(54) Title:** LENS SYSTEM WITH CORRECTED SECONDARY SPECTRUM




**(57) Abstract:** The invention discloses the lens system with corrected secondary spectrum without the use of anomalous dispersion optical glasses. The lens system comprises three widely separated lens components. The front lens component of positive refractive power comprises at least two lenses. The middle lens component comprises at least two lenses. The rear lens component of positive refractive power comprises at least one lens. In the present invention the correction of secondary spectrum is obtained with the use of the most inexpensive optical glasses. The illustrative designs with the use of ordinary crown (BK7) and flint (F2) glasses are presented. Additionally, the illustrative designs with the use of slightly abnormal dense flint glasses are also presented.

WO 2006/091181 A1

# LENS SYSTEM WITH CORRECTED SECONDARY SPECTRUM

## Technical Field

The present invention relates generally to color-corrected optical systems. More particularly, this invention relates to refractive objective lenses with reduced residual longitudinal chromatic aberration. Such lens systems are particularly suitable for use in telescopes.

## Background Art

The optical properties of a lens depend on the refractive index of the optical material. The dispersion of optical material causes the properties of a lens vary with wavelength of the light transmitted by it. Effect of the dispersion is to produce various chromatic aberrations. Most refractive optical systems deal with white light and, therefore, suffer from chromatic aberrations. One of the most difficult aberration to control is secondary longitudinal chromatic aberration.

It is conventional to specify the dispersion properties of the optical material by its Abbe number and partial dispersions. Manufacturers usually provide refractive indexes, Abbe numbers and partial dispersions of optical materials. The crown glass has relatively low dispersion and high Abbe number. The flint glass has relatively high dispersion and low Abbe number. Optical glass catalogs also provide plots of a relative partial dispersion versus Abbe number. In such plot most glasses fall close to a nearly straight line known as Abbe normal line or normal glass line. These glasses are called normal glasses or glasses with normal partial dispersions. Many of them are inexpensive, easy to fabricate and readily available. The glasses that fall significantly away from the normal glass line are the glasses with anomalous partial dispersion, also called anomalous dispersion glasses or abnormal glasses.

To correct longitudinal chromatic aberration in the refractive telescope it is usually necessary to have at least two lenses made of optical materials with different dispersion. By combining lenses made of different optical materials it is possible to correct the longitudinal chromatic aberration for two wavelength. Such kind of lens systems is called achromatic. The typical example is an achromatic doublet consisting of two lenses made of crown and flint glasses. However, an achromatic lens brings only two given colors to the same focus. The focal points of other wavelengths do not coincide with the common focal point of the two colors mentioned above. The residual color error at wavelengths other than these two is called secondary longitudinal chromatic aberration, secondary spectrum or secondary color. The secondary spectrum of a typical achromat is about 0.05% of the focal length over the spectral range from Fraunhofer spectral line F (486 nm) to spectral line C (656 nm).

Secondary spectrum often is a limiting aberration in refractive telescopes, large photographic objectives, collimators and other refractive optical systems. There are different strategies in controlling of this aberration. Almost all conventional refractive optical systems with corrected secondary spectrum require the use at least one optical material having anomalous partial dispersion. These anomalous dispersion optical materials are abnormal glasses, crystals or special optical liquids. In this way it is possible to obtain color correction for three or more wavelengths with very small residual chromatic aberrations. Such kind of color correction is called apochromatic. There are different levels of the secondary spectrum correction. Lens systems with a reduced but still significant secondary spectrum is sometimes called semiapochromatic. The secondary spectrum in semiapochromatic telescopes is reduced at least by half, when compared with a typical achromat. The term "corrected secondary spectrum" is used herein in the wide sense, including not only the elimination of secondary spectrum, but the significant reduction of secondary spectrum as well.

The correction of the secondary spectrum in conventional apochromatic doublets is obtained by appropriate choice of optical glasses. The basic idea is to choose optical materials with equal, or close to equal, relative partial dispersions. On the other hand, Abbe numbers of these optical materials should be as different as possible in order to avoid steep surface curvatures. However, the normal glasses approximately satisfy the linear relationship between relative partial dispersions and Abbe numbers. For this reason, the pair of normal glasses can not be used in apochromatic doublet. At least one lens of apochromatic doublet should be made of optical material with anomalous partial dispersion. This rule is also applied to more complex conventional apochromatic lens systems.

Probably the first practical apochromatic telescope objective was suggested by H.D. Taylor in 1892 . His air spaced triplet was disclosed in British patent 17,994/1892. In the original design an anomalous dispersion flint glass was used. The main disadvantage of Taylor design is that the curvatures of interior refractive surfaces are very steep. Taylor apochromatic telescopes are very long since a typical relative aperture is about f/18.

In the middle of the 20th century dense flint glasses were developed. Dense flints have high refractive index, low Abbe number and many of them display slightly anomalous dispersion. By using these optical glasses, it became possible to build so-called dense flint apochromats with a typical f-number of F/15 (Reference. A. König and H. Köhler, *Die Fernrohre und Entfernungsmesser*, published by Springer Verlag in 1959, p. 135, nr. 12).

Better performance can be obtained with the use of short flint glasses. These abnormal glasses are widely used in various apochromatic lenses. However, short flints are very expensive and sensitive.

Nowadays, most of apochromatic telescopes utilize so-called fluor-crowns. This is another kind of special optical glasses with highly anomalous dispersion like Schott FK51, FK54, FK56, Ohara FPL51, FPL52, FPL53 glasses or similar products of other manufacturers. Typical fluor-crown apochromatic telescopes have relative aperture about F/7. Alternatively, it is possible to obtain even better optical performance with use of fluorite (calcium fluoride). This crystalline material has large anomalous dispersion.

It is also possible to combine different kinds of optical glasses having anomalous dispersion in order to design apochromatic lens. The example of such apochromatic triplet is given by Michael J. Kidger in *Intermediate Optical Design*, SPIE Press (2004), pp.104-105.

However, there are a lot of problems with anomalous glasses and crystals. These optical materials are extremely expensive, unobtainable in large pieces, fragile and difficult to work with. In addition, it is difficult to fabricate anomalous dispersion materials with high homogeneity. For these reasons, in general, the use of normal glasses is preferable.

Thus, a need exists in the art for lens systems with corrected secondary spectrum without the use of anomalous dispersion glasses.

For a long time it had generally been accepted that the elimination or considerable reduction of the secondary spectrum in refracting optical systems requires the use of optical materials having anomalous dispersion. However, in 1955 E.L. McCarthy in United States patent 2698555 disclosed optical system with corrected secondary spectrum by using only normal glasses. Years later, in 1977, C.G. Wynne published the paper "Secondary spectrum correction with normal glasses" in *Optics Communication* **21** (3). In the next 1978 year C.G. Wynne published the paper "A comprehensive first-order theory of chromatic aberration secondary spectrum correction without special glasses" in *Optica Acta* **25** (8). In these papers C.G. Wynne explained new extended theory of first-order chromatic aberration. According with this theory the correction of secondary spectrum is possible without abnormal glasses. C.G. Wynne also described example of such optical system. These achievements of McCarthy and Wynne demonstrate the possibility of secondary spectrum correction by using only normal glasses.

McCarthy's patent depicts optical system with corrected secondary spectrum having a zero-power doublet with over-corrected longitudinal chromatic aberration is placed a long distance in front of positive doublet with under-corrected longitudinal chromatic aberration. The separation between the doublets is given approximately by the focal length of the second doublet.

The lens system disclosed by C.G. Wynne comprises a multi-lens corrector placed in front of an achromatic doublet. The corrector comprises widely separated components and it has substantially zero optical power at the mean wavelength. The original Wynne design is relatively complicated.

Although McCarthy and Wynne designs look different, in fact they are very close. In both of these designs, substantially afocal correctors are placed in front of doublets and the power of the lens system is contributed by the last component. Moreover, in both of these designs, components are widely separated. Additional discussion of McCarthy and Wynne designs can be found in a number of publications, including: M. Rosete-Aguilar, "Correction of secondary spectrum using standard glasses", *SPIE Proc.*, Vol.

2774 (1996), pp.378-386; M. Rosete-Aguilar, "Application of the extended first-order chromatic theory to the correction of secondary spectrum", *Revista Mexicana de Física*, **43**, No. 6 (1997), pp.895-905; Michael J. Kidger, *Intermediate Optical Design*, SPIE Press (2004), pp.109-112.

While in both McCarthy and Wynne designs secondary spectrum is indeed reduced without resort of abnormal glasses, many other harmful aberrations remain. These aberrations limit applicability of the lens systems to low apertures if diffraction limited performance is assumed. For this reason, telescopes designed according McCarthy patent or Wynne papers are generally not practical.

# Disclosure of Invention

## Technical Problem

The technical problem to be solved by the present invention consists in providing a lens system with corrected secondary spectrum by using inexpensive glasses. It is another object of the present invention to provide a color-corrected lens system with relatively high relative aperture.

## Technical Solution

The lens system with corrected secondary spectrum of the present invention comprises three widely spaced lens components. The front lens component of positive refractive power comprises at least two lens elements. The middle lens component comprises at least two lens elements. The rear lens component of positive refractive power comprises at least one lens element. Both the middle and rear lens components have significantly smaller clear aperture than the front lens component. All lens elements of the lens system are made of inexpensive glasses.

## Advantageous Effects

The lens system of the present invention deliver high optical performance without the use of expensive optical materials. The lens system of the present invention can be made with high relative aperture. This is important advantage for photography and CCD imaging. The lenses of the middle and rear components of the lens system have smaller size than lenses of the front component. This is a further advantage because the lens system can be manufactured in a more economical manner. In addition, in the present invention the secondary spectrum correction extends over a wider spectral range than in conventional apochromats.

## Description of Drawings

**Fig. 1** is a schematic illustration of the lens system according to Embodiment 1 of the present invention.

**Fig. 2** is a schematic illustration of the lens system according to Embodiment 2 of the present invention.

**Fig. 3** is a schematic illustration of the lens system according to Embodiment 3 of the present invention.

**Fig. 4** is a schematic illustration of the lens system according to Embodiment 4 of the present invention.

**Fig. 5** is a schematic illustration of the lens system according to Embodiment 5 of the present invention.

**Fig. 6** is a schematic illustration of the lens system according to Embodiment 6 of the present invention.

**Fig. 7** is a schematic illustration of the lens system according to Embodiment 7 of the present invention.

**Fig. 8** shows the on-axis OPD curves of the achromatic doublet with an aperture of 80 mm and an f-number of f/15.

**Fig. 9** shows the on-axis OPD curves of the lens system depicted in **Fig. 1**.

**Fig. 10** shows the on-axis OPD curves of the lens system depicted in **Fig. 2**.

**Fig. 11** shows the on-axis OPD curves of the lens system depicted in **Fig. 3**.

**Fig. 12** shows the on-axis OPD curves of the achromatic doublet with an aperture of 100 mm and an f-number of f/12.

**Fig. 13** shows the on-axis OPD curves of the lens system depicted in **Fig. 4**.

**Fig. 14** shows the on-axis OPD curves of the lens system depicted in **Fig. 5**.

**Fig. 15** shows the on-axis OPD curves of the achromatic doublet with an aperture of 120 mm and an f-number of f/10.

**Fig. 16** shows the on-axis OPD curves of the lens system depicted in **Fig. 6**.

**Fig. 17** shows the on-axis OPD curves of the achromatic doublet with an aperture of 100 mm and an f-number of f/10.

**Fig. 18** shows the on-axis OPD curves of the lens system depicted in **Fig. 7**.

## Best Mode for Carrying Out the Invention

In conventional apochromatic lens systems the correction of secondary spectrum is obtained owing to anomalous dispersion of optical glasses. This is a generic feature of conventional apochromats regardless what kind of anomalous material is used. In contrast, a generic feature of known normal glass apochromats is a presence of wide air spaces between lens components. However, in two-component optical systems a wide air space between components results in difficulties with the correction of the chromatic difference of magnification. In order to reduce this aberration the front component of McCarthy lens system has virtually zero optical power at the mean wavelength. In other words, the requirement of the correction of the chromatic difference of magnification causes constraints on shape of all lenses of McCarthy lens system. As a result of these constraints, McCarthy design is unfavorable for correction of other aberrations. Since Wynne design is very close to McCarthy one, it suffers from the same problem.

In the present invention the lens system with corrected secondary spectrum comprises three widely air spaced lens components. In contrast with McCarthy and Wynne designs, in the present invention the front lens component has large positive refractive power. The widely separated third lens component of small size mainly helps in elimination of the chromatic difference of magnification. As a result, the middle and rear components of the lens system of the present invention are of significantly smaller size than the front component. The effect of this is a reduction of manufacturing costs. Moreover, the three-component design of the present invention has good correction of longitudinal and transverse chromatic aberrations, spherical aberration, spherochromatism and coma. In the present invention the correction of secondary spectrum can be obtained with the use of only two different optical materials with normal partial dispersion, for instance with most common crown and flint glasses.

Illustrative embodiments will now be described with reference to the accompanying drawings and tables. While the present invention is described herein with reference to the embodiments for particular applications, it should be understood that the invention is not limited thereto.

All optical glasses listed in the embodiments are from Schott glass catalog, but other glass manufacturers make nearly equivalent glass types. Along with Schott glass type designation, the descriptions of the embodiments will show the internationally recognized six-digit glass code for each glass type. In the six-digit glass code the first three digits indicate the refractive index after the decimal point and last three digits indicate the Abbe number (Example: BK7 with a refractive index $n_d = 1.51680$ and Abbe number $V_d = 64.17$ has the six-digit glass code 517642). All refractive surfaces in the following embodiments are spherical and the dimensions are given in millimeters. The effective focal lengths are calculated at the design wavelength of 555 nm.

The specifications for all embodiments are summarized in Tables I through VII. These tables list, in order from the object side, the lens element identifiers, the surface identifiers, the radii of curvature of refractive surfaces, the on-axis lens thicknesses or separations, as well as the material of each lens element.

Embodiment 1

Reference should now be made to **Fig. 1**, which is a schematic illustration of the telescope objective with reduced secondary spectrum having an aperture of 80 mm, an effective focal length of 560 mm and an f-number of f/7.

As shown on **Fig. 1**, the objective comprises three widely separated lens components.

The front lens component has a positive refractive power and comprises lens elements **L11** and **L12**. The lens element **L11** is a meniscus lens having negative refractive power with its concave surface on the object side. The lens element **L11** is on the object end of the objective. The lens element **L12** is a meniscus lens having positive refractive power with its convex surface on the object side.

The middle lens component has a negative refractive power and comprises lens elements **L13** and **L14**. The lens element **L13** is a biconvex lens. The lens element **L14** is a biconcave lens. The lens elements **L13** and **L14** are cemented together.

The rear lens component consists of the lens element **L15**. The lens element **L15** is a meniscus lens having positive refractive power with its convex surface on the object side.

The lens elements **L11** and **L13** are made of BK7 glass (six-digit glass code 517642). The lens elements **L12**, **L14** and **L15** are made of F2 glass (six-digit glass code 620364).

As shown on **Fig. 1**, both the middle and rear lens components have significantly smaller clear apertures than the front lens component.

The specifications for this design are summarized in Table I.

Embodiment 2

Reference should now be made to **Fig. 2**, which is a schematic illustration of the telescope objective with reduced secondary spectrum having an aperture of 80 mm, an effective focal length of 640 mm and an f-number of f/8.

As shown on **Fig. 2**, the objective comprises three widely separated lens components.

The front lens component has a positive refractive power and comprises lens elements **L21** and **L22**. The lens element **L21** is a meniscus lens having negative refractive power with its convex surface on the object side. The lens element **L21** is on the object end of the objective. The lens element **L22** is a meniscus lens having positive refractive power with its convex surface on the object side.

The middle lens component comprises lens elements **L23** and **L24**. The lens element **L23** is a biconvex lens. The lens element **L24** is a biconcave lens. The lens elements **L23** and **L24** are cemented together.

The rear lens component consists of the lens element **L25**. The lens element **L25** is a meniscus lens having positive refractive power with its convex surface on the object side.

The lens elements **L21** and **L23** are made of BK7 glass (six-digit glass code 517642). The lens elements **L22**, **L24** and **L25** are made of F2 glass (six-digit glass code 620364).

The specifications for this design are summarized in Table II.

Embodiment 3

Reference should now be made to **Fig. 3**, which is a schematic illustration of the telescope objective with corrected secondary spectrum having an aperture of 80 mm, an effective focal length of 560 mm and an f-number of f/7.

As shown on **Fig. 3**, the objective comprises three widely separated lens components.

The front lens component has a positive refractive power and comprises lens elements L**31** and L**32**. The lens element L**31** is a meniscus lens having negative refractive power with its concave surface on the object side. The lens element L**31** is on the object end of the objective. The lens element L**32** is a biconvex lens.

The middle lens component has a negative refractive power and comprises lens elements L**33** and L**34**. The lens element L**33** is a biconvex lens. The lens element L**34** is a biconcave lens.

The rear lens component consists of the lens element L**35**. The lens element L**35** is a meniscus lens having positive refractive power with its convex surface on the object side.

The lens elements L**31** and L**33** are made of BK7 glass (six-digit glass code 517642). The lens elements L**32**, L**34** and L**35** are made of F2 glass (six-digit glass code 620364).

The specifications for this design are summarized in Table III.

Although in the above embodiments the middle lens components consist of crown-in-front doublets, the opposite order of the crown and flint lenses is possible. In such case, the optical performance is similar to the above presented embodiments. The lens systems with the middle lens components consisting of flint-in-front doublets will be described in the Embodiment 6 and Embodiment 7.

The lens systems of Embodiments 1 through 3 of the present invention demonstrate a significant reduction of the residual chromatic aberration by using of crown glass BK7 and flint glass F2, which are among the most inexpensive optical glasses available at the market. Nevertheless, many other optical glasses can be used in order to obtain better performance or other advantages. Moreover, different optical materials can be used in the present invention, for example plastics.

The performance of the above lens systems can be significantly improved by adding lens elements. For instance, the front lens component can be formed of three or more lens elements. Such modifications are obvious for those having ordinary skill in the art.

To illustrate these possibilities, the slightly more complex design will be now described.

Embodiment 4

Reference should now be made to **Fig. 4**, which is a schematic illustration of the telescope objective with corrected secondary spectrum having an aperture of 100 mm, an effective focal length of 700 mm and an f-number of f/7.

As shown on **Fig. 4**, the objective comprises three widely separated lens components. The front lens component has a positive refractive power and comprises lens elements **L41** and **L42**. The lens element **L41** is a meniscus lens having negative refractive power with its concave surface on the object side. The lens element **L41** is on the object end of the objective. The lens element **L42** is a meniscus lens having positive refractive power with its convex surface on the object side.

The middle lens component has a negative refractive power and comprises lens elements **L43**, **L44** and **L45**. The lens element **L43** is a meniscus lens having positive refractive power with its concave surface on the object side. The lens element **L44** is a biconcave lens. The lens element **L45** is a biconvex lens. The lens elements **L43**, **L44** and **L45** are cemented together.

The rear lens component comprises the lens elements **L46** and **L47**. The lens element **L46** is a biconvex lens. The lens element **L47** is a biconcave lens.

The lens elements **L41**, **L43** and **L47** are made of BK7 glass (six-digit glass code 517642). The lens elements **L42**, **L44** and **L46** are made of F2 glass (six-digit glass code 620364). The lens element **L45** is made of inexpensive fluor-crown N-FK5 (six-digit glass code 487704).

The specifications for this design are summarized in Table IV.

Sometimes it is advantageous to use in the present invention glasses with some kind of anomalous dispersion. In this case, extra cost can be compensated by better color correction or other advantages. There are different categories of optical materials with respect to their partial dispersions. Most glasses have nearly normal partial dispersions. Most fluor-crowns and short flint glasses have highly anomalous partial dispersions. However, there are optical glasses which are placed in an intermediate position between normal and highly abnormal glasses. These glasses are often relatively inexpensive when compared to highly abnormal fluor-crowns or short-flints. Usually, the partial dispersions of such glasses are not anomalous enough to produce competitive conventional apochromats. Though, these glasses with slightly anomalous partial dispersions can be successfully used in the present invention. This important feature of the present invention leaves considerable freedom to designer in choosing the design with optimum cost-performance combination. Therefore, by using the present invention it is possible to achieve optimum balance of performance and cost for various specific applications. In order to illustrate this feature three additional designs will be described.

In the following embodiments some dense flint glasses and dense barium crown glasses are utilized. These dense flint glasses have slightly anomalous partial dispersions. Although said glasses are not so cheap as most common crowns and flints but they are inexpensive when compared to highly abnormal glasses. It is also possible to use in the present invention many other types of slightly anomalous glasses, for example some dense barium flints or lanthanum flints and crowns.

Embodiment 5

Reference should now be made to **Fig. 5**, which is a schematic illustration of the telescope objective with corrected secondary spectrum having an aperture of 100 mm, an effective focal length of 550 mm and an f-number of f/5.5.

As shown on **Fig. 5**, the objective comprises three widely separated lens components.

The front lens component has a positive refractive power and comprises lens elements L**51** and L**52**. The lens element L**51** is a meniscus lens having negative refractive power with its concave surface on the object side. The lens element L**51** is on the object end of the objective. The lens element L**52** is a meniscus lens having positive refractive power with its convex surface on the object side.

The middle lens component has a negative refractive power and comprises lens elements L**53** and L**54**. The lens element L**53** is a biconvex lens. The lens element L**54** is a biconcave lens. The lens elements L**53** and L**54** are cemented together.

The rear lens component comprises the lens element L**55**. The lens element L**55** is a meniscus lens having positive refractive power with its convex surface on the object side.

The lens element L**51** is made of BK7 glass (six-digit glass code 517642). The lens elements L**52** and L**54** are made of SF1 glass (six-digit glass code 717295). The lens element L**53** is made of SK16 glass (six-digit glass code 620603). The lens element L**55** is made of SF4 glass (six-digit glass code 755276) of relatively high refractive index. The use of high-index glasses in the rear lens component is often advantageous.

The specifications for this design are summarized in Table V.

Embodiment 6

Reference should now be made to **Fig. 6**, which is a schematic illustration of the telescope objective with corrected secondary spectrum having an aperture of 120 mm, an effective focal length of 540 mm and an f-number of f/4.5. The objective comprises three widely separated lens components.

The front lens component has a positive refractive power and comprises lens elements L**61** and L**62**. The lens element **L61** is a meniscus lens having negative refractive power with its concave surface on the object side. The lens element L**61** is on the object end of the objective. The lens element **L62** is a meniscus lens having positive refractive power with its convex surface on the object side.

The middle lens component has a negative refractive power and comprises lens elements L**63** and **L64**. The lens element L**63** is a biconcave lens. The lens element **L64** is a biconvex lens. The lens elements L**63** and L**64** are cemented together.

The rear lens component comprises the lens element L**65**. The lens element **L65** is a meniscus lens having positive refractive power with its convex surface on the object side.

The lens element **L61** is made of BK7 glass (six-digit glass code 517642). The lens elements L**62** and L**63** are made of SF1 glass (six-digit glass code 717295). The lens element L**64** is made of SK16 glass (six-digit glass code 620603). The lens element L**65** is made of SF2 glass (six-digit glass code 648339).

The specifications for this design are summarized in Table VI.

Embodiment 7

Reference should now be made to **Fig. 7**, which is a schematic illustration of the telescope objective with corrected secondary spectrum having an aperture of 100 mm, an effective focal length of 400 mm and an f-number of f/4. The objective comprises three widely separated lens components.

The front lens component has a positive refractive power and comprises lens elements L**71** and L**72**. The lens element **L71** is a meniscus lens having negative refractive power with its concave surface on the object side. The lens element L**71** is on the object end of the objective. The lens element L**72** is a meniscus lens having positive refractive power with its convex surface on the object side.

The middle lens component comprises lens elements L**73** and L**74**. The lens element L**73** is a biconcave lens. The lens element L**74** is a biconvex lens.

The rear lens component comprises the lens element L**75**. The lens element **L75** is a biconvex lens.

The lens element **L71** is made of BK7 glass (six-digit glass code 517642). The lens elements L**72** and L**73** are made of SF4 glass (six-digit glass code 755276) . The lens element **L74** is made of N-SSK5 glass (six-digit glass code 658509). The lens element **L75** is made of SF2 glass (six-digit glass code 648339).

The specifications for this design are summarized in Table VII.

The optical performance of the above embodiments will now be discussed in comparison with equivalent achromatic telescopes.

It is conventional to measure secondary spectrum as a longitudinal, a transverse or an wavefront aberration. However, the effective focal length of the lens system accordingly the present invention is usually significantly shorter than the effective focal length of the equivalent achromat. In this case it is reasonable to use wavefront aberrations. In order to illustrate the correction of the secondary spectrum in the present invention, optical path differences (OPD) plots are shown in **Figs. 8** through **18**. The term "equivalent achromat" as used herein means a typical achromatic doublet having the same aperture and overall length as the lens system according the present invention. The term "overall length" as used herein means the length as measured by the separation between the vertex of the front surface and the focus of the optical system.

In the presented OPD plots the vertical axis represents the normalized entrance pupil coordinate and the horizontal axis represents the on-axis optical path difference in waves. The OPD curves are presented for four wavelengths, namely Fraunhofer lines g (436 nm), F (486 nm), e (546 nm) and C (656 nm). The reduction of the residual longitudinal chromatic aberration is clearly visible in the OPD plots because the secondary spectrum is the dominant aberration in achromatic telescopes of this size.

Although in the lens systems of Embodiment 1 and Embodiment 2 the paraxial longitudinal chromatic aberration is corrected for two wavelengths, the secondary spectrum is significantly reduced. In the lens systems of Embodiments 3 through 7 the longitudinal chromatic aberration is corrected for three wavelengths.

**Fig. 8** shows OPD plot of the achromatic doublet which is the equivalent achromat for the lens systems of Embodiment 1, Embodiment 2 and Embodiment 3. This equivalent achromat has an aperture of 80 mm, an f-number of f/15 and an overall length of 1200 mm. **Fig. 9** shows OPD plot of the lens system of Embodiment 1. The curves of

**Fig. 9** demonstrate that the wavefront aberrations of the lens system of Embodiment 1 are considerably reduced, compared with the aberrations of the equivalent achromat. This is the effect of the reduction of secondary spectrum in the lens system of Embodiment 1. This telescope can be rated as semiapochromatic. **Fig. 10** shows OPD plot of the lens system of Embodiment 2, which has somewhat better color correction than the lens system of Embodiment 1. **Fig. 11** shows OPD plot of the lens system of Embodiment 3. This telescope has better performance than the previous designs because the lenses of the middle component are air spaced.

**Fig. 12** shows OPD plot of the achromatic doublet which is the equivalent achromat for the lens systems of Embodiment 4 and Embodiment 5. This equivalent achromat has an aperture of 100 mm, an f-number of f/12 and an overall length of 1200 mm. Although the equivalent achromat is relatively long-focus telescope, it has a large secondary spectrum. This causes serious degradation of the image quality. In contrast, **Fig. 13** demonstrates that the lens system of Embodiment 4 has a good correction of the secondary chromatic aberration, especially in the violet region. This telescope has apochromatic-type color correction. **Fig. 14** shows OPD plot of the lens system of Embodiment 5. The curves of **Fig. 14** demonstrate that the aberrations of the lens system of Embodiment 5 are much better corrected, compared with the aberrations of the equivalent achromat.

**Fig. 15** shows OPD plot of the achromatic doublet which is the equivalent achromat for the lens system of Embodiment 6. This equivalent achromat has an aperture of 120 mm, an f-number of f/10 and an overall length of 1200 mm. **Fig. 16** shows OPD plot of the lens system of Embodiment 6. The curves of **Fig. 16** show a great improvement in color correction of the lens system of Embodiment 6 over the equivalent achromat. With an f-number of f/4.5, the lens system of Embodiment 6 has a high relative aperture for a refractive telescope.

**Fig. 17** shows OPD plot of the achromatic doublet which is the equivalent achromat for the lens system of Embodiment 7. This equivalent achromat has an aperture of 100 mm, an f-number of f/10 and an overall length of 1000 mm. **Fig. 18** demonstrates that the lens system of Embodiment 7 has a good correction of the secondary chromatic aberration, compared with the equivalent achromat. With an f-number of f/4, the lens system of Embodiment 7 is a very fast refractor.

The presented illustrative embodiments of the present invention are intended for use in the visible range. However, the present invention can be applied at a different waveband from the visible. If appropriate optical materials are used the present invention can be applied in the infrared (IR) and ultraviolet (UV) parts of spectrum. The ability to correct secondary spectrum even with only two optical materials of different relative partial dispersions is a very important feature of the present invention. This feature is especially important for IR and UV wavebands because in these spectral regions there are a lot less optical material to choose from.

The presented OPD plots show that the correction of the secondary spectrum in the present invention is especially good when the wide wavelength range is considered. This is another important feature because it is uncommon for conventional apochromats. Due to the ability to correct secondary spectrum for a wide spectral range the present invention is useful in lens systems for use over extended wavebands.

The present invention is not limited to the aforementioned embodiments, as it will be obvious that various alternative implementations are possible. For example, values such as the number of lens elements, the radii of curvature of each of the lens, the air spaces between the lenses are not limited to the examples indicated in aforementioned embodiments, as other values can be adopted. Other embodiments of the presented invention could be designed using other optical materials, as well as their order in the construction. The present invention has been described herein with reference to particular embodiments for a particular applications but the lens system with corrected secondary spectrum of the present invention may be used in various image forming devices other than the telescopes for amateur astronomers discussed above.

Table I

| Lens Element | Surface | Radius of Curvature [mm] | Axial Thickness or Separation [mm] | Material |
|---|---|---|---|---|
| | R1 | -160.574844 | | |
| L11 | | | 8.0 | BK7 |
| | R2 | -219.970251 | | |
| | | | 0.0 | Air |
| | R3 | 186.491866 | | |
| L12 | | | 8.0 | F2 |
| | R4 | 363.704856 | | |
| | | | 508.0 | Air |
| | R5 | 93.474949 | | |
| L13 | | | 12.0 | BK7 |
| | R6 | -100.895511 | | |
| L14 | | | 6.0 | F2 |
| | R7 | 116.035487 | | |
| | | | 552.0 | Air |
| | R8 | 76.145743 | | |
| L15 | | | 6.0 | F2 |
| | R9 | 306.731135 | | |

Table II

| Lens Element | Surface | Radius of Curvature [mm] | Axial Thickness or Separation [mm] | Material |
|---|---|---|---|---|
| | R1 | 239.525901 | | |
| L21 | | | 8.0 | BK7 |
| | R2 | 97.320119 | | |
| | | | 6.0 | Air |
| | R3 | 100.623083 | | |
| L22 | | | 11.0 | F2 |
| | R4 | 250.223223 | | |
| | | | 265.0 | Air |
| | R5 | 116.980731 | | |
| L23 | | | 14.0 | BK7 |
| | R6 | -113.232474 | | |
| L24 | | | 6.0 | F2 |
| | R7 | 168.400990 | | |
| | | | 784.0 | Air |
| | R8 | 98.463859 | | |
| L25 | | | 6.0 | F2 |
| | R9 | 440.206389 | | |

Table III

| Lens Element | Surface | Radius of Curvature [mm] | Axial Thickness or Separation [mm] | Material |
|---|---|---|---|---|
| | R1 | -192.666950 | | |
| L31 | | | 8.0 | BK7 |
| | R2 | -548.714866 | | |
| | | | 0.0 | Air |
| | R3 | 253.856058 | | |
| L32 | | | 8.0 | F2 |
| | R4 | -6041.312075 | | |
| | | | 428.0 | Air |
| | R5 | 104.765524 | | |
| L33 | | | 11.0 | BK7 |
| | R6 | -91.128065 | | |
| | | | 0.0 | Air |
| | R7 | -92.428494 | | |
| L34 | | | 8.0 | F2 |
| | R8 | 136.346584 | | |
| | | | 641.0 | Air |
| | R9 | 83.236079 | | |
| L35 | | | 6.0 | F2 |
| | R10 | 725.044549 | | |

Table IV

| Lens Element | Surface | Radius of Curvature [mm] | Axial Thickness or Separation [mm] | Material |
|---|---|---|---|---|
| | R1 | -223.756186 | | |
| L41 | | | 10.0 | BK7 |
| | R2 | -384.483551 | | |
| | | | 0.0 | Air |
| | R3 | 282.148910 | | |
| L42 | | | 10.0 | F2 |
| | R4 | 1789.474870 | | |
| | | | 484.0 | Air |
| | R5 | -315.045519 | | |
| L43 | | | 8.0 | BK7 |
| | R6 | -97.487083 | | |
| L44 | | | 5.0 | F2 |
| | R7 | 125.408973 | | |
| L45 | | | 10.0 | N-FK5 |
| | R8 | -152.631047 | | |
| | | | 513.0 | Air |
| | R9 | 100.642667 | | |
| L46 | | | 5.0 | F2 |
| | R10 | -214.494838 | | |
| L47 | | | 5.0 | BK7 |
| | R11 | 150.711452 | | |

Table V

| Lens Element | Surface | Radius of Curvature [mm] | Axial Thickness or Separation [mm] | Material |
|---|---|---|---|---|
| | R1 | -214.397621 | | |
| L51 | | | 10.0 | BK7 |
| | R2 | -275.710819 | | |
| | | | 0.0 | Air |
| | R3 | 246.204550 | | |
| L52 | | | 10.0 | SF1 |
| | R4 | 439.301959 | | |
| | | | 555.0 | Air |
| | R5 | 141.172343 | | |
| L53 | | | 10.0 | SK16 |
| | R6 | -131.699095 | | |
| L54 | | | 6.0 | SF1 |
| | R7 | 170.008970 | | |
| | | | 503.0 | Air |
| | R8 | 81.234625 | | |
| L55 | | | 6.0 | SF4 |
| | R9 | 228.667280 | | |

Table VI

| Lens Element | Surface | Radius of Curvature [mm] | Axial Thickness or Separation [mm] | Material |
|---|---|---|---|---|
| | R1 | -228.965183 | | |
| L61 | | | 10.0 | BK7 |
| | R2 | -312.338420 | | |
| | | | 0.0 | Air |
| | R3 | 269.106060 | | |
| L62 | | | 10.0 | SF1 |
| | R4 | 606.960178 | | |
| | | | 470.0 | Air |
| | R5 | -338.215090 | | |
| L63 | | | 6.0 | SF1 |
| | R6 | 105.318391 | | |
| L64 | | | 14.0 | SK16 |
| | R7 | -251.247215 | | |
| | | | 584.0 | Air |
| | R8 | 82.372040 | | |
| L65 | | | 6.0 | SF2 |
| | R9 | 391.722212 | | |

Table VII

| Lens Element | Surface | Radius of Curvature [mm] | Axial Thickness or Separation [mm] | Material |
|---|---|---|---|---|
| | R1 | -220.531921 | | |
| L71 | | | 10.0 | BK7 |
| | R2 | -411.603804 | | |
| | | | 0.0 | Air |
| | R3 | 266.174867 | | |
| L72 | | | 10.0 | SF4 |
| | R4 | 873.360907 | | |
| | | | 383.0 | Air |
| | R5 | -413.983997 | | |
| L73 | | | 6.0 | SF4 |
| | R6 | 90.825373 | | |
| | | | 0.43 | Air |
| | R7 | 91.395641 | | |
| L74 | | | 13.0 | N-SSK5 |
| | R8 | -243.507952 | | |
| | | | 472.0 | Air |
| | R9 | 101.842955 | | |
| L75 | | | 6.0 | SF2 |
| | R10 | -8251.459018 | | |

# CLAIMS

1. A lens system with corrected secondary spectrum comprising three widely spaced lens components, in order from the object side, as follows:
a front lens component of positive refractive power;
a middle lens component;
a rear lens component of positive refractive power;
wherein
said front lens component includes at least two lens elements;
said middle lens component includes at least two lens elements;
said rear lens component includes at least one lens element;
said lens elements are made of only two different optical materials;
said optical materials have substantially different relative partial dispersions.

2. The lens system of claim **1**, wherein said middle lens component and said rear lens component have substantially smaller clear apertures than said front lens component.

3. The lens system of claim **1**, wherein said middle lens component has a negative refractive power.

4. A lens system with corrected secondary spectrum comprising three widely spaced lens components, in order from the object side, as follows:
a front lens component of positive refractive power;
a middle lens component;
a rear lens component of positive refractive power;
wherein
said front lens component includes at least two lens elements;
said middle lens component includes at least two lens elements;
said rear lens component includes at least one lens element;
said lens elements are made of at least two different optical materials;
all said optical materials have substantially normal partial dispersions.

5. The lens system of claim **4**, wherein said middle lens component and said rear lens component have substantially smaller clear apertures than said front lens component.

6. The lens system of claim **4**, wherein said optical materials are ordinary crown glasses and flint glasses, for example Schott BK7 and Schott F2.

7. The lens system of claim **4**, wherein said middle lens component has a negative refractive power.

8. The lens system of claim **7**, wherein
said front lens component consists of two lens elements;
said middle lens component consists of two lens elements;
said rear lens component consists of a single lens element.

9. The lens system of claim **8**, wherein
the first lens of said front lens component consists of a meniscus lens having negative refractive power with its concave surface on the object side;
the second lens of said front lens component consists of a meniscus lens having positive refractive power with its convex surface on the object side;
said first lens is made of first optical material;
said second lens is made of second optical material;
Abbe number is greater for said first optical material than for said second optical material.

10. The lens system of claim **8**, wherein
the first lens of said middle lens component consists of a biconvex lens;
the second lens of said middle lens component consists of a biconcave lens;
said first lens is made of first optical material;
said second lens is made of second optical material;
Abbe number is greater for said first optical material than for said second optical material.

11. The lens system of claim **8**, wherein
the first lens of said middle lens component consists of a biconcave lens;

the second lens of said middle lens component consists of a biconvex lens;
said first lens is made of first optical material;
said second lens is made of second optical material;
Abbe number is greater for said second optical material than for said first optical material.

12. The lens system of claim **8**, wherein said rear lens component is made of glass with high refractive index.

13. A lens system with corrected secondary spectrum comprising three widely spaced lens components, in order from the object side, as follows:
a front lens component of positive refractive power;
a middle lens component;
a rear lens component of positive refractive power;
wherein
said front lens component includes at least two lens elements;
said middle lens component includes at least two lens elements;
said rear lens component includes at least one lens element;
said lens elements are made of at least two different optical materials;
said optical materials are selected from the group consisting of optical materials having substantially normal partial dispersions, optical materials having slightly anomalous partial dispersions, and combinations thereof;
at least one of said optical materials has slightly anomalous partial dispersions.

14. The lens system of claim **13**, wherein said middle lens component and said rear lens component have substantially smaller clear apertures than said front lens component.

15. The lens system of claim **13**, wherein said middle lens component has a negative refractive power.

16. The lens system of claim **13**, wherein said optical materials having slightly anomalous partial dispersions comprises slightly anomalous fluor-crown glasses, for example Schott N-FK5 or Ohara S-FSL5.

17. The lens system of claim **13**, wherein said optical materials having slightly anomalous partial dispersions comprises dense flint glasses, for example Schott SF1 glass.

18. The lens system of claim **13**, wherein said optical materials having slightly anomalous partial dispersions comprises dense barium flint glasses.

19. The lens system of claim **13**, wherein said optical materials having slightly anomalous partial dispersions comprises lanthanum flint or lanthanum crown glasses.

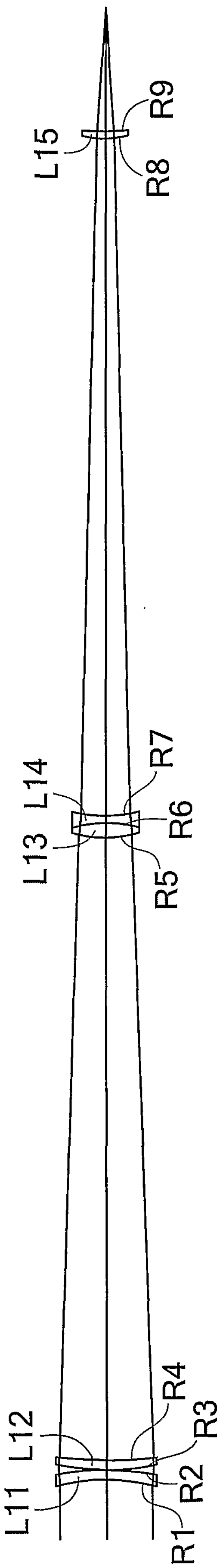

L15
R8
R9
L13
L14
R5
R6
R7
L11
L12
R1
R2
R3
R4

Fig. 1

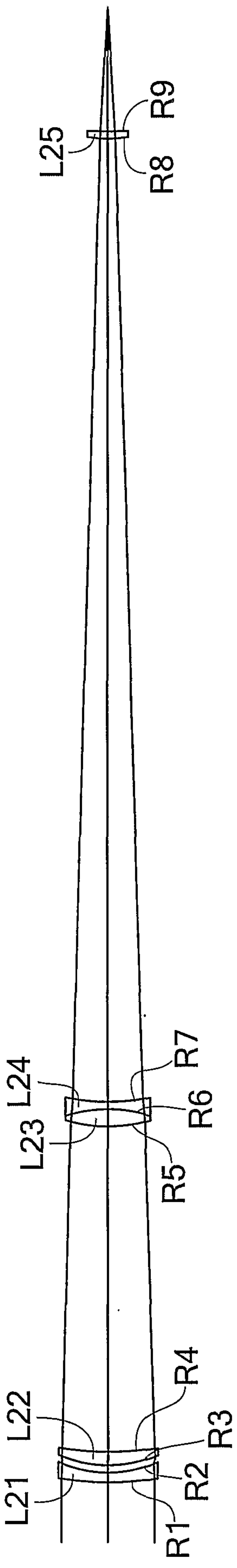

L25
R8
R9
L23
L24
R5
R6
R7
L21
L22
R1
R2
R3
R4

Fig. 2

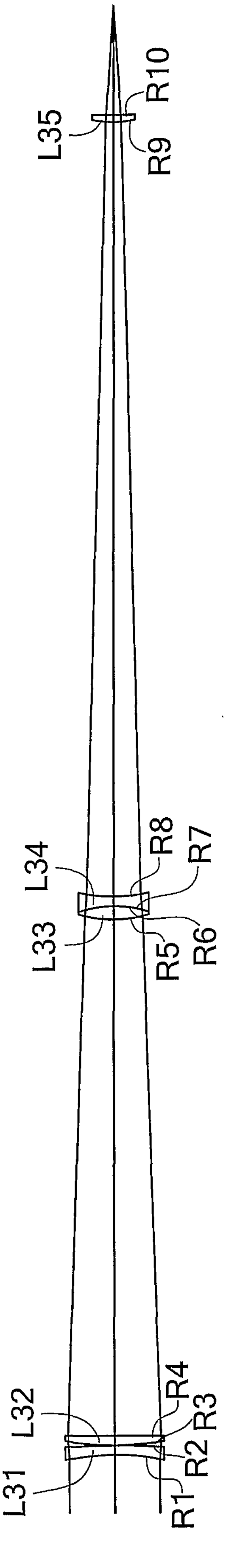

L35
R10
R9
L34
R8
R7
L33
R5
R6
L32
R4
R3
L31
R2
R1

Fig. 3

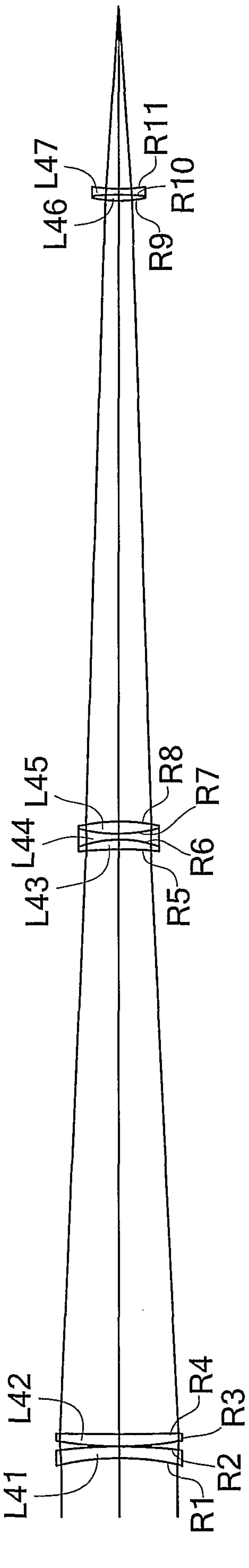

L47
R11
R10
L46
R9
L45
R8
R7
L44
L43
R6
R5
L42
R4
R3
L41
R2
R1

Fig. 4

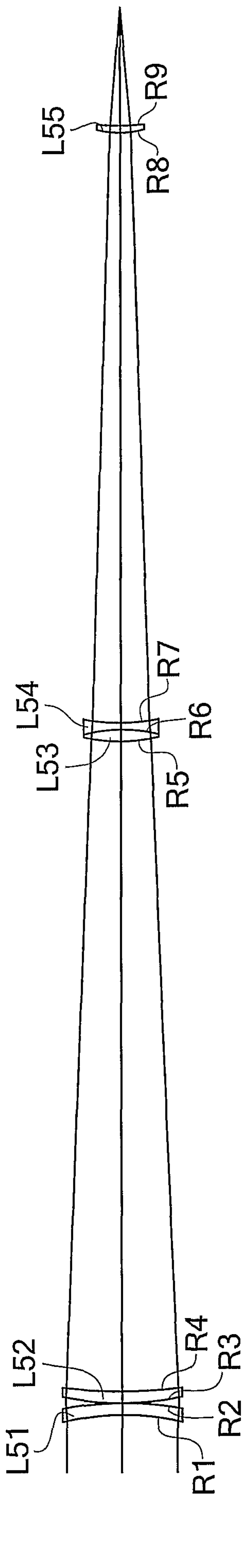

L55
R9
R8
L54
R7
R6
L53
R5
L52
R4
R3
L51
R2
R1

Fig. 5

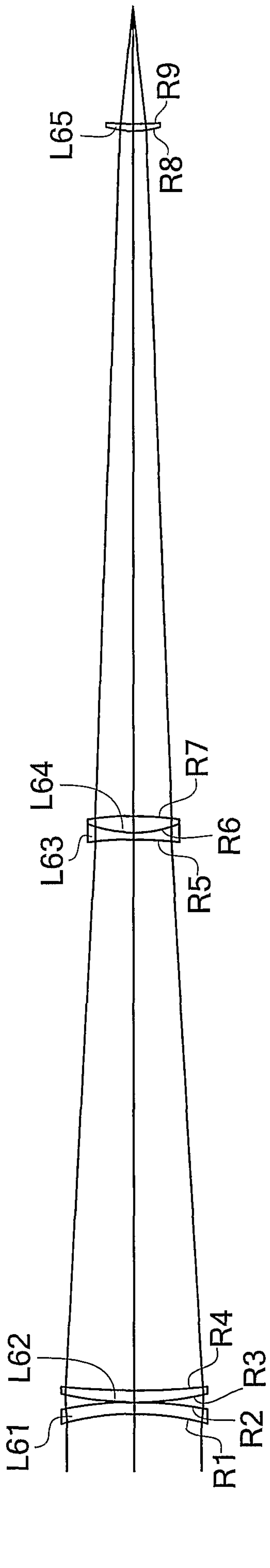

L65
R9
R8
L64
R7
L63
R6
R5
L62
R4
R3
L61
R2
R1

Fig. 6

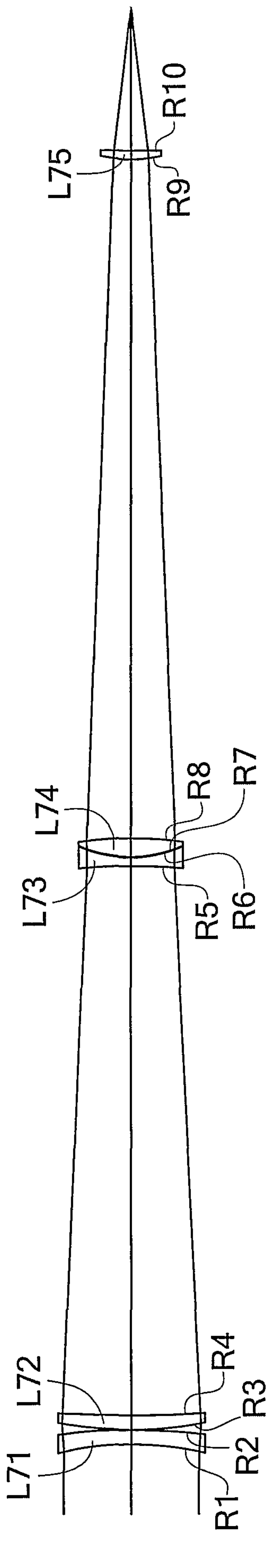



Fig. 7

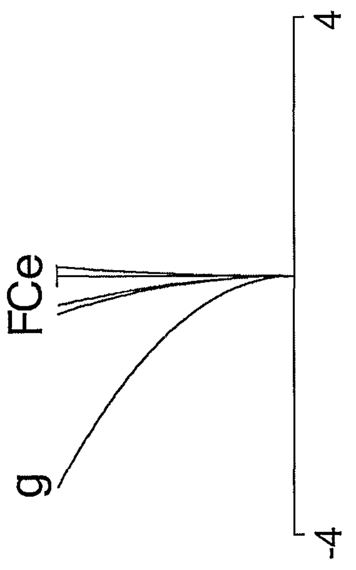



Fig. 8

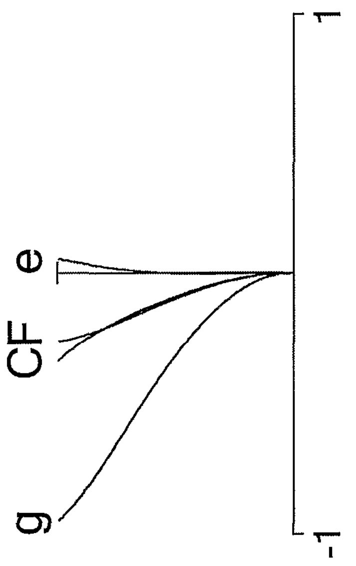



Fig. 9

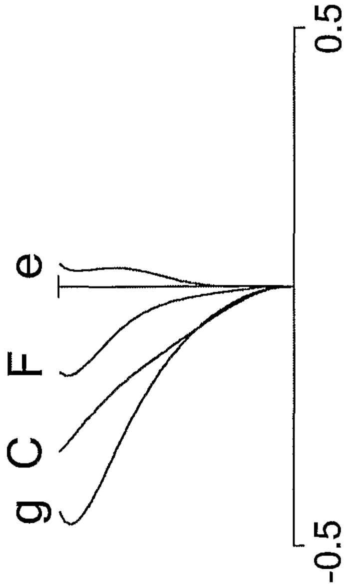



Fig. 10

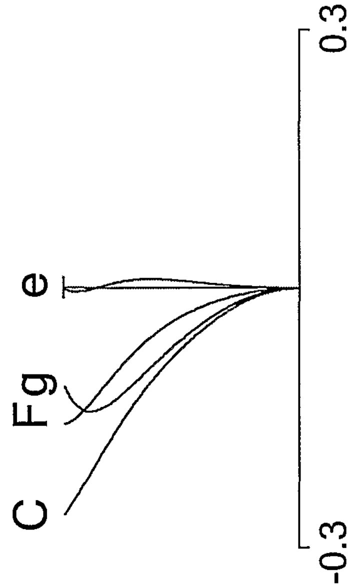



Fig. 11

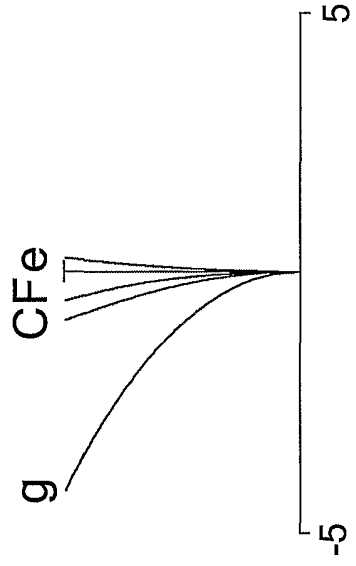



Fig. 12

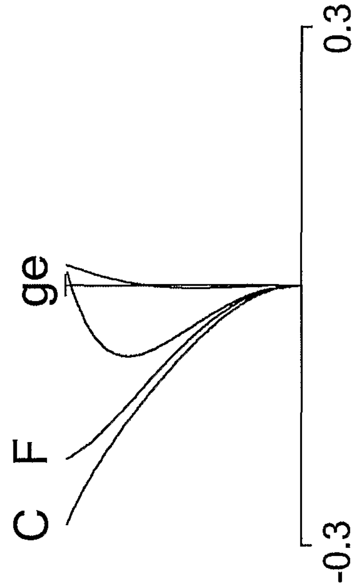



Fig. 13

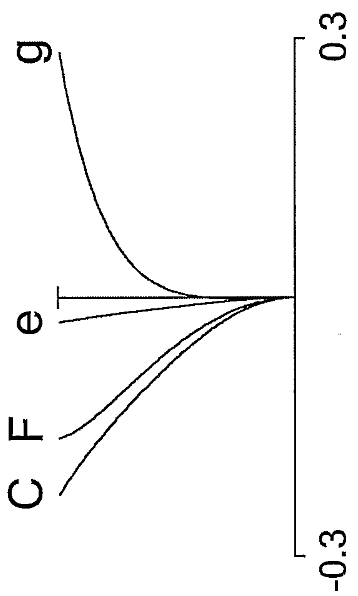


Fig. 14

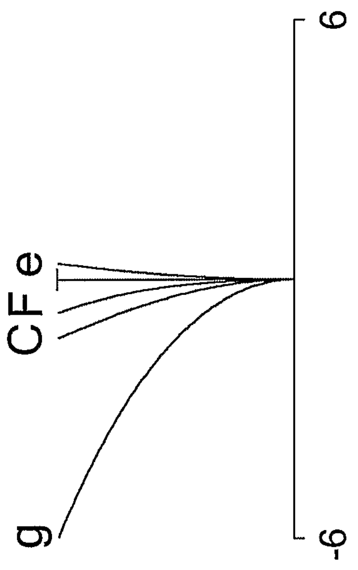


Fig. 15

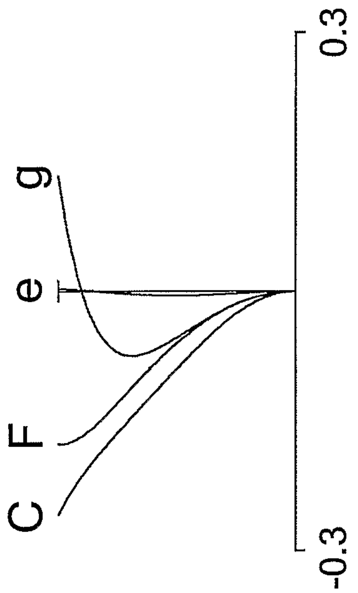


Fig. 16

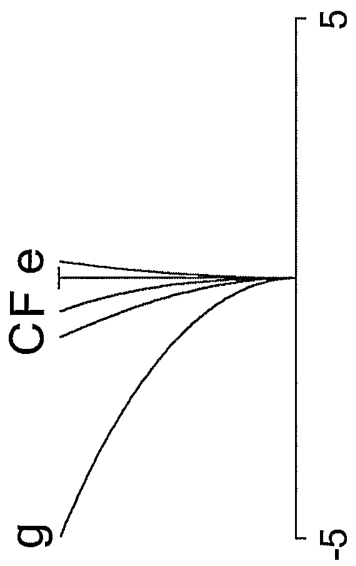


Fig. 17

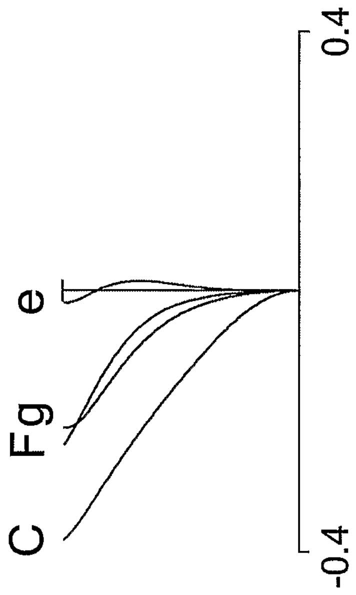


Fig. 18

## INTERNATIONAL SEARCH REPORT

International application No.
PCT/UA 2005/000028

A. CLASSIFICATION OF SUBJECT MATTER ***G02B 9/34 (2006.01)***
***G02B 11/16(2006.01)***

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B 3/00-3/14, 5/00-5/06, 9/00-9/64, 11/00-11/34, 13/00-13/26, 17/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | GB 893653 A (KODAK LIMITED) 11.04.1962 | 1-19 |
| A | RU 2239855 C2 (SIBIRSKAYA GOSUDARSTVENNAYA GEODEZICHESKAYA AKADEMIYA) 10.11.2004 | 1-19 |
| A | DE 3637310 A1 (JENOPTIK JENA GMBH) 06.08.1987 | 1-19 |
| A | JP 60129720 A (SIGMA KK) 11.07.1985 | 1-19 |

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is nit considered to be of particular relevance
"E" earlier application or document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 20 February 2006 (20.02.2006) | 02 March 2006 (02.03.2006) |

| Name and mailing address of the ISA/RU FIPS | Authorized officer |
|---|---|
| Russia, 123995, Moscow, G-59, GSP-5, Berezhkovskaya nab., 30-1 | A. Kotov |
| Facsimile No. | Telephone No. |