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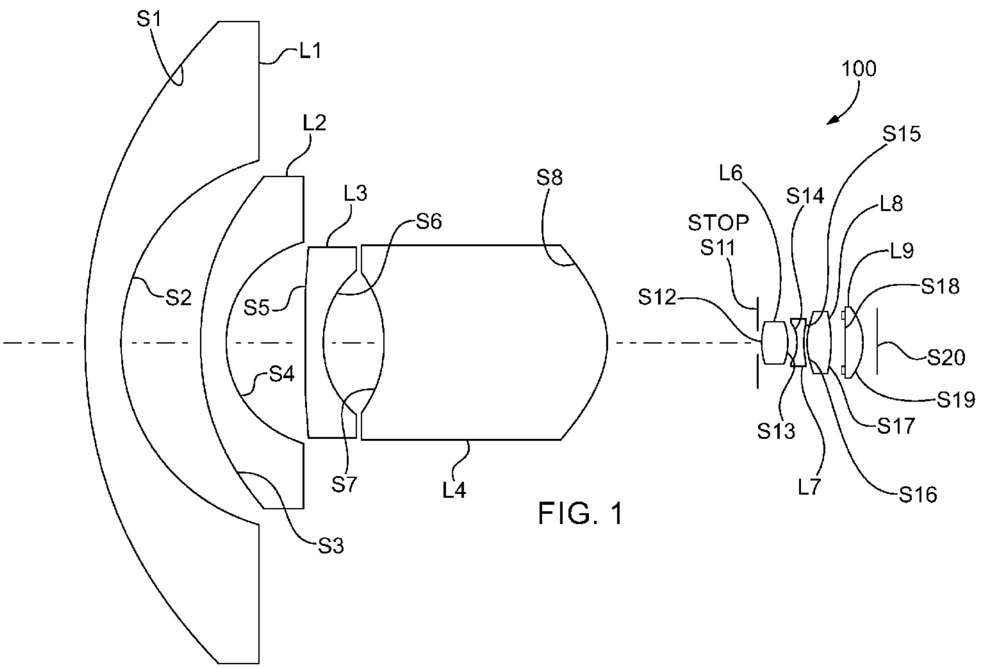

FIG. 1

(57) **Abstract:** Wide angle lens for imaging objects disposed away from the optical axis towards the periphery of the field of view.

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[Continued on next page]

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WIDE ANGLE LENS AND CAMERA SYSTEM FOR PERIPHERAL FIELD OF VIEW IMAGING

Related Applications

This application claims the benefit of priority of U.S. Provisional Application No. 62/514,080, filed on June 2, 2017, the entire contents of which application(s) are incorporated herein by reference.

Field of the Invention

[0001] The present invention relates generally to wide angle lenses, and more particularly, but not exclusively, to lenses configured to preferentially image objects located towards the periphery of the field of view, as well as camera systems incorporating such lenses.

Background of the Invention

[0002] Axiomatic to optical imaging systems is the principle that such systems are designed with the expectation that objects of primary interest will be located on the optical axis of the imaging system, and therefore lenses of such systems must be designed to provide high quality imaging on-axis. Indeed, one will typically accept reduced optical performance at the edges of the field of view in favor of enhanced performance on-axis. Photography, microscopy, and astronomy are all examples of fields in which the observer often endeavors to position the optical system so that at least one object of interest is disposed centrally in the field of view on the optical axis.

[0003] In contrast, Applicant has conceived of applications in which all objects of interest will be disposed away from the optical axis towards the periphery of the field of view. Consequently, Applicant has recognized that existing lenses which are optimized for on-axis performance are not well-suited to peripheral field of view imaging in part due to the unneeded optimization of on-axis-performance. Accordingly, it would be an advance in the state-of-the-art to provide wide angle lenses which are optimized for imaging objects located at the periphery of the field of view rather than on-axis.

Summary

[0004] In accordance with one of its aspects, the present invention may provide a wide angle lens for imaging objects disposed in a peripheral region of interest of the field of view. An exemplary wide angle lens in accordance with the present invention may include, in order along an optical axis from object to image space, a first group of lens elements, an aperture stop, and a second

group of lens elements. The region of interest may be an annular cone that extends between a first angle of at least 30 degrees from the optical axis to a second angle of at least 75 degrees from the optical axis, where the first and second lens groups are configured for imaging of objects disposed within the region of interest. The wide angle lens may have a ratio of the first angle to the second angle in the range of R=1.67:1 to 2.5:1. In particular, the first angle may be 50 degrees and the second angle may be 100 degrees. The lens may be configured and constructed such that a ray of the second angle in object space intersects the lens image plane at a distance, H, from the optical axis and a ray of the first angle in object space intersects the lens image plane at a distance, h, from the optical axis such that $H/h > R$, or preferably $H/h \geq 1.1xR$, or more preferably $H/h \geq 1.5xR$ The angular mapping of the field of view in the region of interest onto the image plane may be substantially linear.

[0005] The first and second groups of lens elements may be configured for imaging of objects disposed within the region of interest by having certain performance metrics in the region of interest. For example, the first and second groups of lens elements may cooperate to provide: a longitudinal spherical aberration on-axis greater than the longitudinal spherical aberration throughout the region of interest; a longitudinal spherical aberration throughout the region of interest less than half of the longitudinal spherical aberration on-axis; a field curvature for tangential rays on-axis greater than the field curvature for tangential rays throughout the region of interest; and/or a field curvature for tangential rays throughout the region of interest less than one quarter of the field curvature for tangential rays on-axis.

[0006] Further, the first and second groups of lens elements may cooperate to provide: a modulation transfer function of at least 55% at 187 lp/mm for sagittal rays in the region of interest; a modulation transfer function of at least 76% at 93 lp/mm for sagittal rays in the region of interest; a modulation transfer function of at least 36% at 187 lp/mm for tangential rays in the region of interest; and/or a modulation transfer function of at least 65% at 93 lp/mm for tangential rays in the region of interest. Also of note, exemplary wide angle lenses in accordance with the present invention may be optimized without the use of aspherical surfaces; the lens elements of the first and second groups may all have spherical surfaces. The first group of lens elements may consist of four or five lenses, while the second group of lens elements may consist of four lenses. The effective focal length may be 1 mm or less with an f-number of 2.4 or less.

[0007] In another of its aspects, the present invention may provide a wide angle lens having an angular field of view, FOV, of more than 150 degrees spanning the optical axis and a central half-field of view, $FOV_{1/2}$, spanning the optical axis. The ratio of the angular range $FOV_{1/2}$ of the central half field of view versus the angular range of the field of view FOV may be $FOV/FOV_{1/2} = 2$, with the lens being constructed and arranged such that a ratio of a diameter (D_1) at the image plane of an image circle of the field of view versus the diameter ($D_{1/2}$) of an image circle of the central half-field of view is $D_1 / D_{1/2} > 2$. The ratio of $D1 / D1/2 \geq 2.2$, or preferably $D1 / D1/2 \geq 2.5$, or more preferably $D1 / D1/2 \geq 3$. The lens may comprise a region of interest disposed between the $FOV_{1/2}$ and FOV, wherein angular mapping of the field of view in the region of interest onto the image plane is substantially linear. Additionally, the present invention may provide a camera system comprising wide angle lens of the present invention.

Brief Description of the Drawings

[0008] The foregoing summary and the following detailed description of exemplary embodiments of the present invention may be further understood when read in conjunction with the appended drawings, in which:

[0009] Figure 1 schematically illustrates an exemplary eight element lens in accordance with the present invention;

[0010] Figures 2A – 2C illustrate the calculated longitudinal spherical aberration, field curvature, and f-theta distortion, respectively, of the lens of Fig. 1;

[0011] Figure 3 schematically illustrates an exemplary nine element lens in accordance with the present invention;

[0012] Figures 4A – 4C illustrate the calculated longitudinal spherical aberration, field curvature, and f-theta distortion, respectively of the lens of Fig. 3;

[0013] Figure 5 illustrates the calculated modulation transfer function versus field for the lens of Fig. 3;

[0014] Figure 6 illustrates the calculated polychromatic diffraction modulation transfer function versus spatial frequency for the lens of Fig. 3;

[0015] Figure 7 illustrates calculated spot diagrams for the lens of Fig. 3;

[0016] Figure 8 illustrates the calculated polychromatic diffraction through focus modulation transfer function versus focus shift for the lens of Fig. 3;

[0017] Figure 9 illustrates the calculated relative illumination of the image plane versus field for the lens of Fig. 3;

[0018] Figure 10 illustrates the calculated lens chief ray angle versus field for the lens of Fig. 3 along with the target chief ray angles for an exemplary image sensor (detector); and

[0019] Figure 11 illustrates field height versus field of view for the lens of Fig. 3 as designed and fabricated.

Detailed Description of the Invention

[0020] Referring now to the figures, wherein like elements are numbered alike throughout, Figures 1 and 3 schematically illustrate configurations of exemplary wide angle lenses 100, 200 optimized for performance towards the outer half of the field-of-view in accordance with the present invention. The lenses 100, 200 may have a wide field-of-view of 210° (± 105° on either side of the optical axis), and may be optimized for optical performance within a region of interest of the field-of-view. Specifically, with the goal of imaging objects disposed in the periphery of the field-of-view, the region of interest may comprise an annular cone beginning at 50° from the optical axis and extending to 100° from the optical axis. Optical performance outside of the region of interest, e.g., a cone between 0° and 50° field-of-view, may be relaxed and have inferior optical performance to that found in the region of interest. For example, the spherical aberration of the lenses 100, 200 may be well corrected for 50° and above as compared to 50° and below. In addition, by relaxing the requirements for optical performance outside of the region of interest, Applicant has been able to achieve designs in which all optical surfaces are spherical, avoiding the manufacturing complexities and cost associated with aspherical surfaces.

[0021] Turning to the configuration of lens 100 of Fig. 1 more particularly, the lens 100 may include a first group of four optical elements L1 – L4 disposed on the object side of an aperture stop S11 and may include a second group of four optical elements L6 – L9 disposed on the image side of the stop S11, with first-order design properties shown in Table 1. The first two lenses, L1, L2, are meniscus-type lenses having surfaces which are convex to the object side, and introduce negative power to decrease entering ray angles to be more parallel to the optical axis. Optionally, lens L4 of the lens 100 of Fig. 1 may be replaced by two lens elements L4a, L5, with all other lenses L1 – L3 and L6 – L9 remaining the same, as shown in Table 2 and Fig. 3. The optical glasses provided in Tables 1, 2 refer to glasses from Schott North America, Inc, Elmsford, NY, USA, and Nd refers to a wavelength of 587.6 nm. The cyclic olefin copolymer “COC” in Tables 1, 2 may be APEL™ Cyclo olefin copolymer APL5014CL (Mitsui Chemicals, Inc., Tokyo, Japan).

Surface	R(mm)	d(mm)	Nd	Vd	Note	Material
S1	29.2909	2.3865	1.806	41.00	L1	N-LASF43
S2	12.2744	5.1328				
S3	16.1766	1.6535	1.804	46.6	L2	N-LASF44
S4	6.7924	5.1229				
S5	82.6538	1.2012	1.64	60.2	L3	N-LAK21
S6	6.2407	4.1457				
S7	-6.7625	15.1741	1.544	56.00	L4	COC
S8	-6.0836	10.2985				
S11	infinity	0.2611			Stop	
S12	4.4027	1.6888	1.589	61.3	L6	P-SK58A
S13	-3.8501	0.7362				
S14	-2.6508	0.3804	1.642	22.5	L7	PC
S15	4.0385	0.2402				
S16	6.1489	1.5593	1.544	56.00	L8	COC
S17	-3.6755	0.7822				
S18	-37.2014	1.1781	1.544	56.00	L9	COC
S19	-3.3096	0.9428				
S20	Infinity	-			Image	

Table 1. Eight element design

Surface	R(mm)	d(mm)	Nd	Vd	Note	Material
S1	29.2909	2.3865	1.806	41.00	L1	N-LASF43
S2	12.2744	5.1328				
S3	16.1766	1.6535	1.804	46.6	L2	N-LASF44
S4	6.7924	5.1229				
S5	82.6538	1.2012	1.64	60.2	L3	N-LAK21
S6	6.2407	4.2648				
S7	-5.5241	7.4709	1.544	56.00	L4a	COC
S8	-8.6995	0.3750				
S9	-12.5165	6.3058	1.544	56.00	L5	COC
S10	-6.2516	9.8205				
S11	infinity	0.2426			Stop	
S12	4.4027	1.6888	1.589	61.3	L6	P-SK58A
S13	-3.8501	0.7362				
S14	-2.6508	0.3804	1.642	22.5	L7	PC
S15	4.0385	0.2402				
S16	6.1489	1.5593	1.544	56.00	L8	COC
S17	-3.6755	0.7822				
S18	-37.2014	1.1781	1.544	56.00	L9	COC
S19	-3.3096	0.9428				
S20	Infinity	-			Image	

Table 2. Nine element design

[0022] Regarding the optical performance, since designs in accordance with the present invention are focused on performance in a region of interest comprising an annular cone extending to the edge of the field-of-view, performance near the optical axis may be reduced. For example, in terms of classically defined aberrations, as illustrated in Figs. 2A, 4A the longitudinal spherical aberration may be well corrected in the region of interest between 50° and 100°, while a relatively large spherical aberration on-axis of 40 μm may be tolerated. In particular, the longitudinal spherical aberration may be so well corrected in the region of interest that the value in the region of interest may be less than one quarter of that present on-axis. Similarly, field curvature, especially for tangential rays, may be minimized in the region of interest while being comparatively larger on-axis, Figs. 2B, 4B. Like the spherical aberration, the field curvature for tangential rays in the region of interest may be less than one quarter of that present on-axis. While not intending to be bound by any particular theory, it is believed that third order field curvature may be corrected by introducing compensating higher order field curvature via lens element L5 of lens 200, and via lens elements L7, L8. F-theta distortion, unlike longitudinal spherical aberration and field curvature, may increase with field height without correction, but may be constrained to be less than 34% at full field, Figs. 2C, 4C.

[0023] Specified in terms of modulation transfer function (MTF) rather than third order aberrations, exemplary target values for the MTF in the region of interest are provided in Table 3, which may be selected with regard to the detector to be used at the image plane. Specifically, the size and spacing of the pixels on the detector can establish the Nyquist frequency for the MTF design targets. For example, in the case of an exemplary detector having a pixel size of 1.34 µm x 1.34 µm (OV16825 16-megapixel CameraChip™ sensor, OmniVision Technologies, Inc., Santa Clara, California, USA), one quarter of the Nyquist frequency would correspond to 93 lp/mm, and one half of the Nyquist frequency would correspond to 187 lp/mm. The calculated performance for the design of the lens 200 of Fig. 3 with regard to MTF is illustrated in Figs. 5, 6, and 8, as well as Table 4. Performance of the design of the lens 200 of Fig. 3 in terms of spot diagrams as illustrated in Fig. 7. In addition, the ability to properly illuminate the detector at the image plane is illustrated in terms of relative illumination in Fig. 9, which illustrates that 80% relative illumination is maintained out to 105°. This result is consistent with proper control of the chief ray angles as illustrated in Fig. 10, which shows that the lens chief ray angle may be maintained ± 2° from the target detector chief ray angle over 60% of field.

[0024] In addition, designs in accordance with the present invention, including that of lens 200, may seek to optimize mapping of the angular field-of-view onto the detector in a manner that is both linear in the region of interest (*e.g.*, annular cone beginning at 50° from the optical axis and extending to 100° from the optical axis) and maximizes the number of pixels on the image sensor S20 onto which the region of interest of the field-of-view is mapped. In particular, Fig. 11 illustrates that the field of view over the region of interest is substantially linearly mapped onto the field at the image sensor S20, with 50° field of view mapping to h=0.4 relative field height and 100° mapping to H=0.95 relative field height, for a ratio of H/h = 2.375 on the image detector. The number of pixels covered on the image sensor may also be optimized in this region, with roughly 970 pixels disposed within the field-of-view between 50° and 100° for the exemplary sensor model OV16825 mentioned above, where the number of pixels is counted along a line taken along one of the two orthogonal directions on which the 1.34 µm x 1.34 µm grid of pixels of the image sensor is organized. For this pixel size, 970 pixels corresponds to 1.3 mm (970×1.34

μm). Thus, the annular field-of-view between 50° and 100° maps to a linear distance of about 1.3 mm taken along one of the two orthogonal axes of the sensor grid.

[0025] Specified more generally, the region of interest may extend between a first angle and a second angle from the optical axis in object space, where the ratio of the second angle to the first angle is R and may be in the range of R=1.67:1 to 2.5:1. The lens may be configured and constructed such that a ray of the second angle in object space intersects the lens image plane at a distance, H, from the optical axis and a ray of the first angle in object space intersects the lens image plane at a distance, h, from the optical axis such that $H/h > R$, or preferably $H/h \geq 1.1xR$, or more preferably $H/h \geq 1.5xR$.

[0026] Another metric for specifying the angular mapping of the region of interest onto the image plane may be provided with respect to the full field-of-view, FOV, and half field-of-view, $FOV_{1/2}$, that is $FOV/FOV_{1/2} = 2$. The lens may be constructed and arranged such that a ratio of a diameter (D_1) at the image plane of an image circle of the full field-of-view versus the diameter ($D_{1/2}$) of an image circle of the central half field-of-view is $D_1 / D_{1/2} > 2$. Also $D_1 / D_{1/2} \geq 2.2$, or preferably $D_1 / D_{1/2} \geq 2.5$, or more preferably $D_1 / D_{1/2} \geq 3$. For example, seventy-five percent or more of pixel sensor elements of the image sensor may be disposed in the image region corresponding to the annular field-of-view between 50° and 100°. Again, the angular mapping of the field of view in the region of interest onto the image plane may be substantially linear.

FOV (deg)	MTF at 95 lp/mm	MTF at 190 lp/mm
50	0.8	0.6
60	0.8	0.6
70	0.75	0.55
80	0.7	0.5
90	0.6	0.4
100	0.5	0.3

Table 3. MTF design target values

<table>
<tr><th colspan="2">Item</th><th colspan="2">Specification</th><th>Notes</th></tr>
<tr><td colspan="2">Image Sensor Resolution</td><td colspan="2">4608 * 3456</td><td>(1/2.3 inch)</td></tr>
<tr><td colspan="2">Image Sensor Pixel Size</td><td colspan="2">1.34 µm * 1.34 µm</td><td></td></tr>
<tr><td colspan="2">Effective Focal Length</td><td colspan="2">0.93 mm</td><td></td></tr>
<tr><td colspan="2">F. No.</td><td colspan="2">2.4</td><td></td></tr>
<tr><td colspan="2">Object Distance</td><td colspan="2">10 cm to infinity</td><td></td></tr>
<tr><td rowspan="3">View Angle</td><td>Horizontal</td><td colspan="2">-</td><td>Image Height = 3.087 mm</td></tr>
<tr><td>Vertical</td><td colspan="2">210 deg.</td><td>Image Height = 2.271mm</td></tr>
<tr><td>Diagonal</td><td colspan="2">-</td><td>Image Height = 3.859 mm</td></tr>
<tr><td rowspan="12">Resolution (MTF)</td><td>50 deg</td><td>44.9%(T)</td><td>59.5%(S)</td><td rowspan="6">at 187 lp/mm (1/2 Nyquist freq.)</td></tr>
<tr><td>60 deg</td><td>40.8%(T)</td><td>58.6%(S)</td></tr>
<tr><td>70 deg</td><td>39.5%(T)</td><td>56.8%(S)</td></tr>
<tr><td>80 deg</td><td>39.3%(T)</td><td>56.7%(S)</td></tr>
<tr><td>90 deg</td><td>37.4%(T)</td><td>57.9%(S)</td></tr>
<tr><td>100 deg</td><td>36.9%(T)</td><td>55.4%(S)</td></tr>
<tr><td>50 deg</td><td>73.1%(T)</td><td>78.9%(S)</td><td rowspan="6">at 93 lp/mm (1/4 Nyquist freq.)</td></tr>
<tr><td>60 deg</td><td>70%(T)</td><td>78.1%(S)</td></tr>
<tr><td>70 deg</td><td>68.3%(T)</td><td>77.1%(S)</td></tr>
<tr><td>80 deg</td><td>67.8%(T)</td><td>77.2%(S)</td></tr>
<tr><td>90 deg</td><td>67.2%(T)</td><td>77.9%(S)</td></tr>
<tr><td>100 deg</td><td>64.8%(T)</td><td>75.9%(S)</td></tr>
<tr><td colspan="2">F-theta Distortion</td><td colspan="2">33%</td><td></td></tr>
<tr><td colspan="2">Relative Illumination</td><td colspan="2">82 %</td><td>at full image height</td></tr>
<tr><td colspan="2">CRA on Sensor</td><td colspan="2">< 4.44 deg.</td><td></td></tr>
<tr><td colspan="2">Total Track Length</td><td colspan="2">54.07 mm</td><td></td></tr>
<tr><td colspan="2">Optical Length</td><td colspan="2">54.07 mm</td><td></td></tr>
<tr><td colspan="2">Max. Image Circle</td><td colspan="2">4.6 mm</td><td></td></tr>
</table>

Table 4. Nine element design Results

Lens Chief Ray Angle (CRA)		
Image	Field	CRA (deg.)
0.000	0	0.00
0.389	0.1	0.14
0.778	0.2	0.97
1.167	0.3	2.40
1.556	0.4	3.60
1.945	0.5	4.05
2.271	0.6	4.44

Table 5.

Sensor Chief Ray Angle (CRA)		
Image	Field	CRA (deg.)
0.000	0	0.00
0.389	0.1	0.69
0.778	0.2	1.43
1.167	0.3	2.27
1.556	0.4	3.20
1.945	0.5	4.22
2.334	0.6	5.27

Table 6.

Lens		Image sensor	
210 deg FOV		OV16825(1/2.3")	
		4608 X 3456, 1.34μm	
FOV (degree)	Real Height	Field	Pixel
0	0	0	0
10	0.163	0.070	122
20	0.333	0.144	248
30	0.515	0.222	384
40	0.712	0.307	531
50	0.925	0.400	690
60	1.154	0.498	861
70	1.393	0.602	1040
80	1.640	0.708	1224
90	1.894	0.818	1413
100	2.143	0.926	1599
105	2.271	0.981	1694

Table 7.

[0027] These and other advantages of the present invention will be apparent to those skilled in the art from the foregoing specification. Accordingly, it will be recognized by those skilled in the art that changes or modifications may be made to the above-described embodiments without departing from the broad inventive concepts of the invention. It should therefore be understood that this invention is not limited to the particular embodiments described herein, but is intended to include all changes and modifications that are within the scope and spirit of the invention as set forth in the claims. Furthermore, the transitional terms "comprising" and "consisting of" when used in the appended claims define the claim scope with respect to what unrecited additional claim elements or steps, if any, are excluded from the scope of the claims. The term “comprising” is intended to be inclusive or open-ended and does not exclude any additional unrecited element or material. The term “consisting of” excludes any element or material other than those used in connection therewith as specified in the claims.

Claims

What is claimed is:

1. A wide angle lens for imaging objects disposed in a region of interest of the field of view, comprising in order along an optical axis from object to image space: a first group of lens elements, an aperture stop, and a second group of lens elements, wherein the region of interest is an annular cone that extends between a first angle of at least 30 degrees from the optical axis to a second angle of at least 75 degrees from the optical axis, and wherein the first and second lens groups are configured for imaging of objects disposed within the region of interest.
2. The wide angle lens of claim 1, wherein the second angle is at least twice the first angle.
3. The wide angle lens of any of the preceding claims, wherein the ratio of the second angle to the first angle, R, is in the range of R=1.67:1 to 2.5:1.
4. The wide angle lens of claim 3, wherein the lens in configured and constructed such that a ray of the second angle in object space intersects the lens image plane at a distance, H, from the optical axis and a ray of the first angle in object space intersects the lens image plane at a distance, h, from the optical axis such that $H/h > R$, or preferably $H/h \geq 1.1xR$, or more preferably $H/h \geq 1.5xR$.
5. The wide angle lens of claim 3 or 4, wherein R=2.
6. The wide angle lens of any of the preceding claims, wherein the first angle is 45 degrees.
7. The wide angle lens of any of the preceding claims, wherein the first angle is 50 degrees.
8. The wide angle lens of any of the preceding claims, wherein the first angle is 50 degrees and the second angle is 100 degrees.
9. The wide angle lens of any of the preceding claims, wherein the first and second groups of lens elements are configured for imaging of objects disposed within the region of interest by having a longitudinal spherical aberration on-axis is greater than the longitudinal spherical aberration throughout the region of interest.
10. The wide angle lens of any of the preceding claims, wherein the first and second groups of lens elements are configured for imaging of objects disposed within the region of interest by having a longitudinal spherical aberration throughout the region of interest less than half of the longitudinal spherical aberration on-axis.

11. The wide angle lens of any of the preceding claims, wherein the first and second groups of lens elements are configured for imaging of objects disposed within the region of interest by having a field curvature for tangential rays on-axis greater than the field curvature for tangential rays throughout the region of interest.
12. The wide angle lens of any of the preceding claims, wherein the first and second groups of lens elements are configured for imaging of objects disposed within the region of interest by having a field curvature for tangential rays throughout the region of interest less than one quarter of the field curvature for tangential rays on-axis.
13. The wide angle lens of any of the preceding claims, wherein the first and second groups of lens elements are configured for imaging of objects disposed within the region of interest by having a modulation transfer function of at least 55% at 187 lp/mm for sagittal rays in the region of interest.
14. The wide angle lens of any of the preceding claims, wherein the first and second groups of lens elements are configured for imaging of objects disposed within the region of interest by having a modulation transfer function of at least 76% at 93 lp/mm for sagittal rays in the region of interest.
15. The wide angle lens of any of the preceding claims, wherein the first and second groups of lens elements are configured for imaging of objects disposed within the region of interest by having a modulation transfer function of at least 36% at 187 lp/mm for tangential rays in the region of interest.
16. The wide angle lens of any of the preceding claims, wherein the first and second groups of lens elements are configured for imaging of objects disposed within the region of interest by having a modulation transfer function of at least 65% at 93 lp/mm for tangential rays in the region of interest.
17. The wide angle lens of any of the preceding claims, wherein the lens elements of the first and second groups all have spherical surfaces.
18. The wide angle lens of any of the preceding claims, wherein the first group of lens elements consists of four or five lenses.
19. The wide angle lens of any of the preceding claims, wherein the second group of lens elements consists of four lenses.

20. The wide angle lens of any of the preceding claims, wherein the effective focal length is 1 mm or less.
21. The wide angle lens of any of the preceding claims, wherein the f-number is 2.4 or less.
22. The wide angle lens of any of the preceding claims, wherein the f-theta distortion is 34% or less at full field.
23. The wide angle lens of any of the preceding claims, wherein the chief ray angle at the image plane of the wide angle lens is less than 4.5 degrees from a normal to the surface at the image plane.
24. The wide angle lens of any of the preceding claims, wherein the back focal length is 1 mm or less.
25. The wide angle lens of any of the preceding claims, wherein a lens element closest to the aperture stop from the first group of elements contributes to the correction of third order field curvature.
26. The wide angle lens of any of the preceding claims, wherein a lens element of the second group of elements contributes to the correction of third order field curvature.
27. The wide angle lens of any of the preceding claims, wherein angular mapping of the field of view in the region of interest onto the image plane is substantially linear.
28. A wide angle lens having an angular field of view, FOV, of more than 150 degrees spanning the optical axis and a central half-field of view, $FOV_{1/2}$, spanning the optical axis such that a ratio of the angular range $FOV_{1/2}$ of the central half field of view versus the angular range of the field of view FOV is $FOV/FOV_{1/2} = 2$, the lens being constructed and arranged such that a ratio of a diameter (D_1) at the image plane of an image circle of the field of view versus the diameter ($D_{1/2}$) of an image circle of the central half-field of view is $D_1 / D_{1/2} > 2$.
29. A wide angle lens of claim 28 wherein $D_1 / D_{1/2} \geq 2.2$, or preferably $D_1 / D_{1/2} \geq 2.5$, or more preferably $D_1 / D_{1/2} \geq 3$.
30. The wide angle lens of claims 28–29, comprising a region of interest disposed between the $FOV_{1/2}$ and FOV, wherein angular mapping of the field of view in the region of interest onto the image plane is substantially linear.

31. The wide angle lens of claims 28–30, comprising a region of interest disposed between the $FOV_{1/2}$ and FOV, wherein the lens has a longitudinal spherical aberration on-axis greater than the longitudinal spherical aberration throughout the region of interest.
32. The wide angle lens of claims 28–30, comprising a region of interest disposed between the $FOV_{1/2}$ and FOV, wherein the lens has a longitudinal spherical aberration throughout the region of interest less than half of the longitudinal spherical aberration on-axis.
33. The wide angle lens of claims 28–30, comprising a region of interest disposed between the $FOV_{1/2}$ and FOV, wherein the lens has a field curvature for tangential rays on-axis greater than the field curvature for tangential rays throughout the region of interest.
34. The wide angle lens of claims 28–30, comprising a region of interest disposed between the $FOV_{1/2}$ and FOV, wherein the lens has a field curvature for tangential rays throughout the region of interest less than one quarter of the field curvature for tangential rays on-axis.
35. The wide angle lens of claims 28–30, comprising a region of interest disposed between the $FOV_{1/2}$ and FOV, wherein the lens has a modulation transfer function of at least 55% at 187 lp/mm for sagittal rays in the region of interest.
36. The wide angle lens of claims 28–30, comprising a region of interest disposed between the $FOV_{1/2}$ and FOV, wherein the lens has a modulation transfer function of at least 76% at 93 lp/mm for sagittal rays in the region of interest.
37. The wide angle lens of claims 28–30, comprising a region of interest disposed between the $FOV_{1/2}$ and FOV, wherein the lens has a modulation transfer function of at least 36% at 187 lp/mm for tangential rays in the region of interest.
38. The wide angle lens of claims 28–30, comprising a region of interest disposed between the $FOV_{1/2}$ and FOV, wherein the lens has a modulation transfer function of at least 65% at 93 lp/mm for tangential rays in the region of interest.
39. The wide angle lens of claims 28–38, wherein the lens comprises all spherical surfaces.
40. The wide angle lens of claims 28–39, wherein the effective focal length is 1 mm or less.
41. The wide angle lens of claims 28–40, wherein the f-number is 2.4 or less.
42. The wide angle lens of claims 28–41, wherein the f-theta distortion is 34% or less at full field.

43. The wide angle lens of claims 28–42, wherein the chief ray angle at an image plane of the wide angle lens is less than 4.5 degrees from a normal to the surface at the image plane.
44. The wide angle lens of claims 28–43, wherein the back focal length is 1 mm or less.
45. The wide angle lens of claims 28–44, wherein the full field of view spanning the optical axis is 200 degrees.
46. A camera system comprising the wide angle lens according to any of the preceding claims and comprising an image sensor having an imaging surface area placed at the back focal length of the lens.

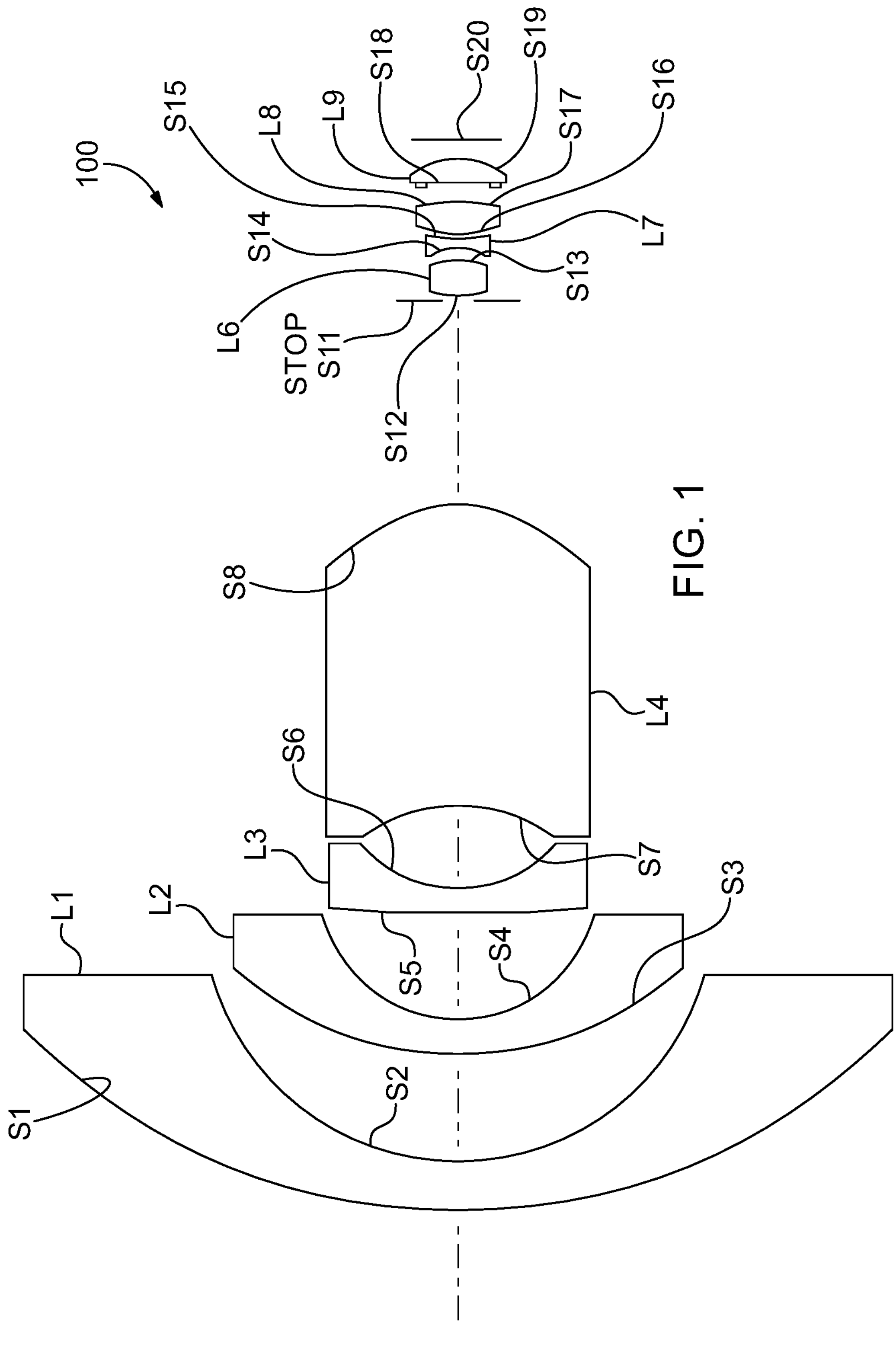

100
S15
L8
L9
S18
S20
S19
S17
S16
L7
S13
S14
L6
STOP
S11
S12
S8
L4
S6
L3
S7
L2
L1
S5
S4
S3
S2
S1

FIG. 1

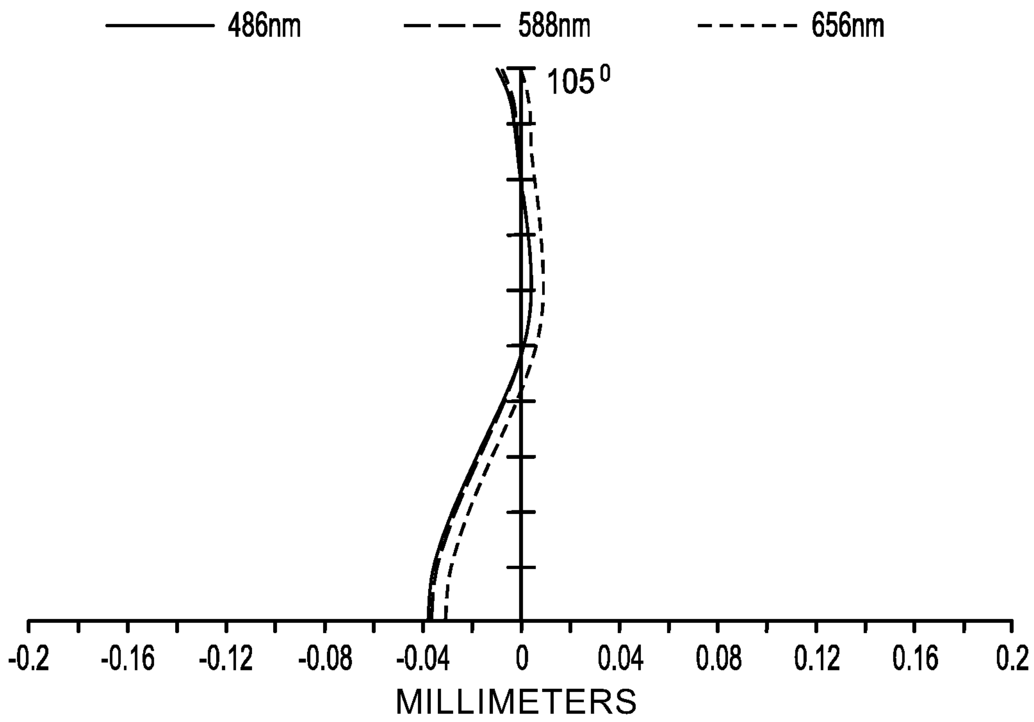

486nm
588nm
656nm
105°
-0.2
-0.16
-0.12
-0.08
-0.04
0
0.04
0.08
0.12
0.16
0.2
MILLIMETERS

FIG. 2A

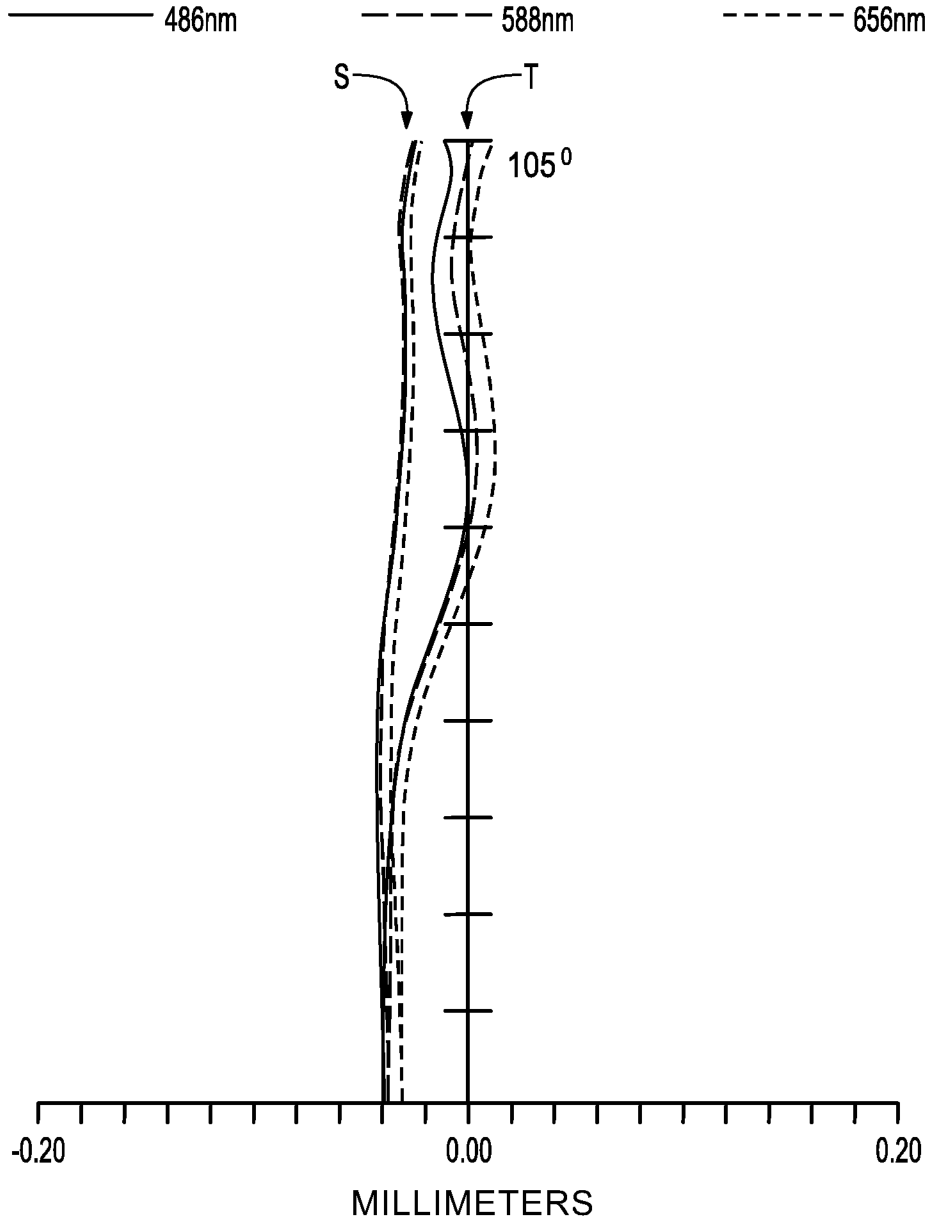


FIG. 2B

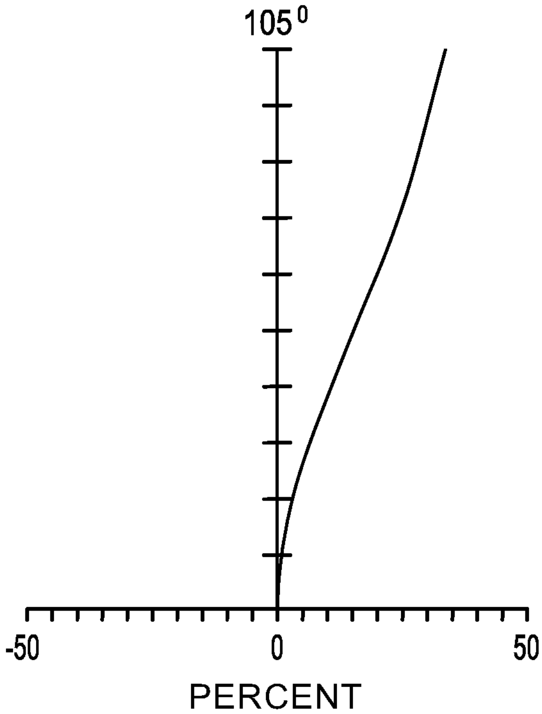


FIG. 2C

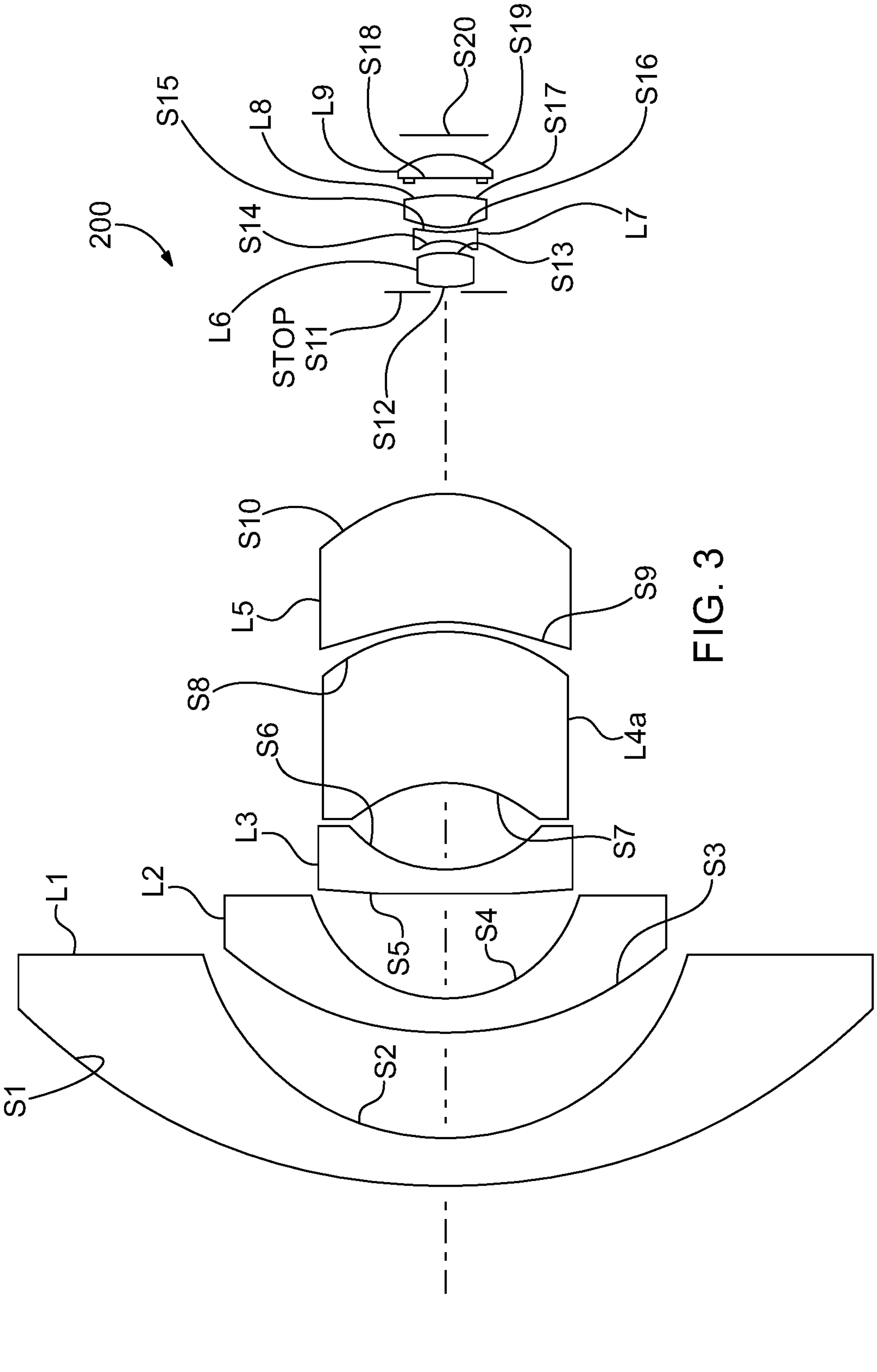

200
S15
L8
L9
S18
S20
S19
S17
S16
L7
S14
S13
L6
STOP
S11
S12
S10
L5
S9
S8
L4a
S6
L3
S7
L1
L2
S3
S5
S4
S2
S1

FIG. 3

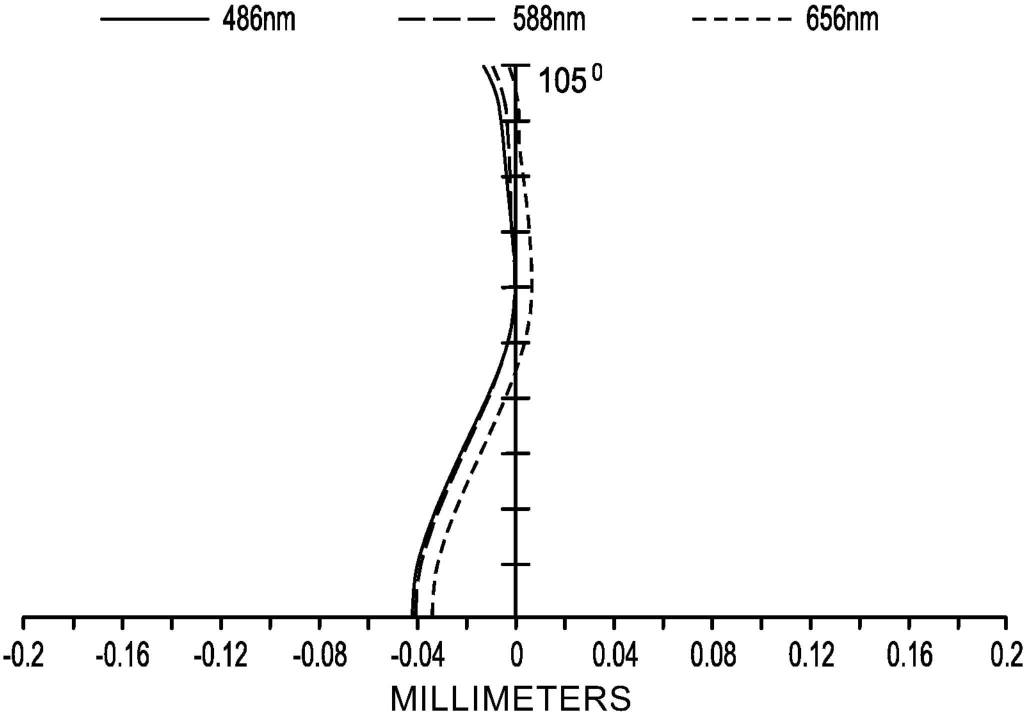

486nm
588nm
656nm
105⁰
-0.2
-0.16
-0.12
-0.08
-0.04
0
0.04
0.08
0.12
0.16
0.2
MILLIMETERS

FIG. 4A

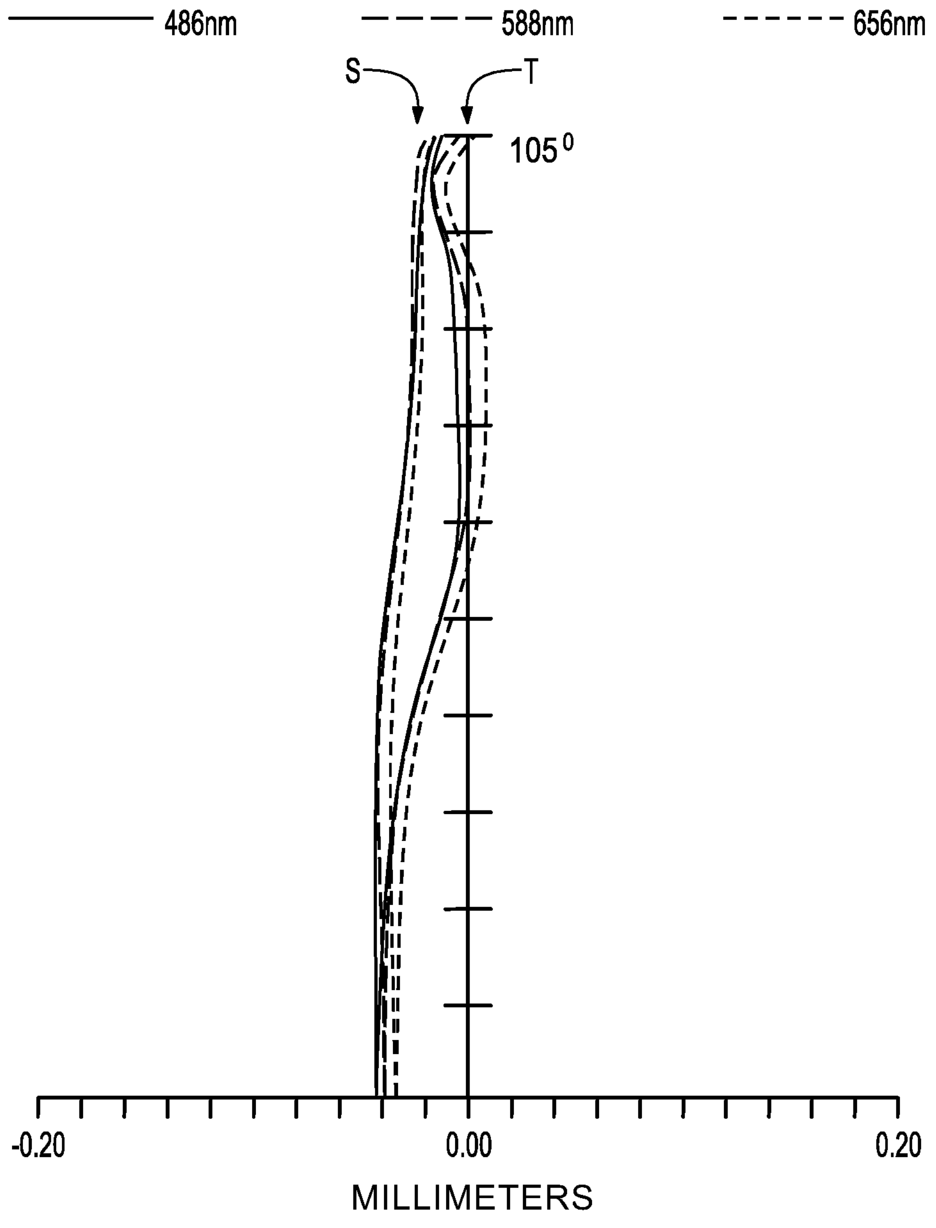


FIG. 4B

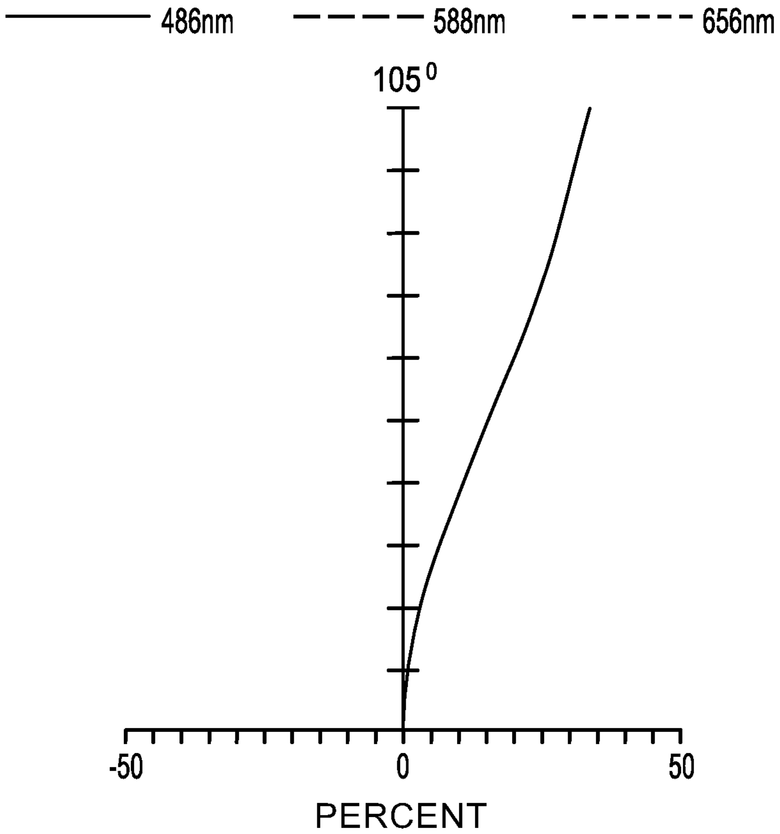


FIG. 4C

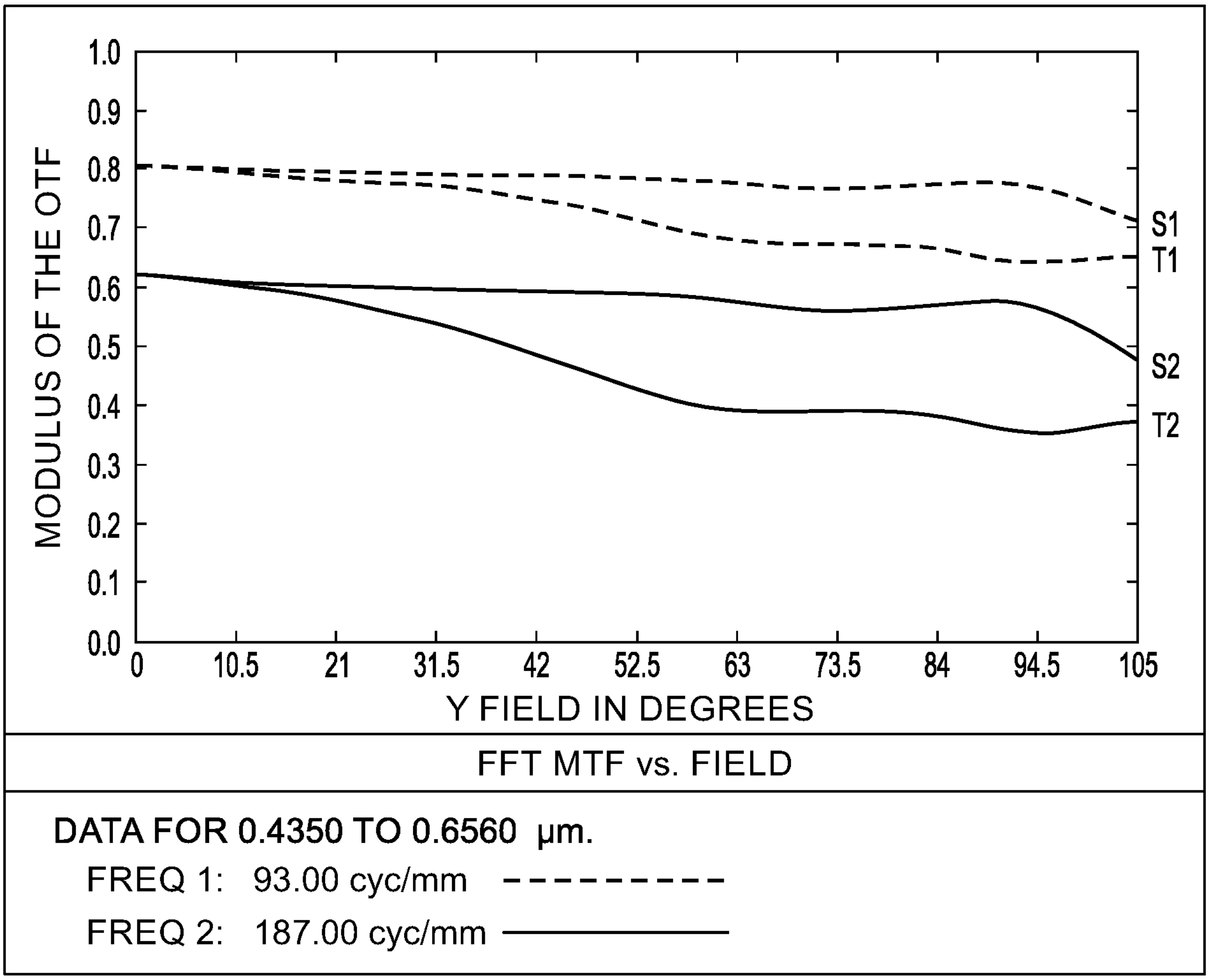

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
MODULUS OF THE OTF
0
10.5
21
31.5
42
52.5
63
73.5
84
94.5
105
Y FIELD IN DEGREES
S1
T1
S2
T2
FFT MTF vs. FIELD
DATA FOR 0.4350 TO 0.6560 µm.
FREQ 1: 93.00 cyc/mm
FREQ 2: 187.00 cyc/mm

FIG. 5

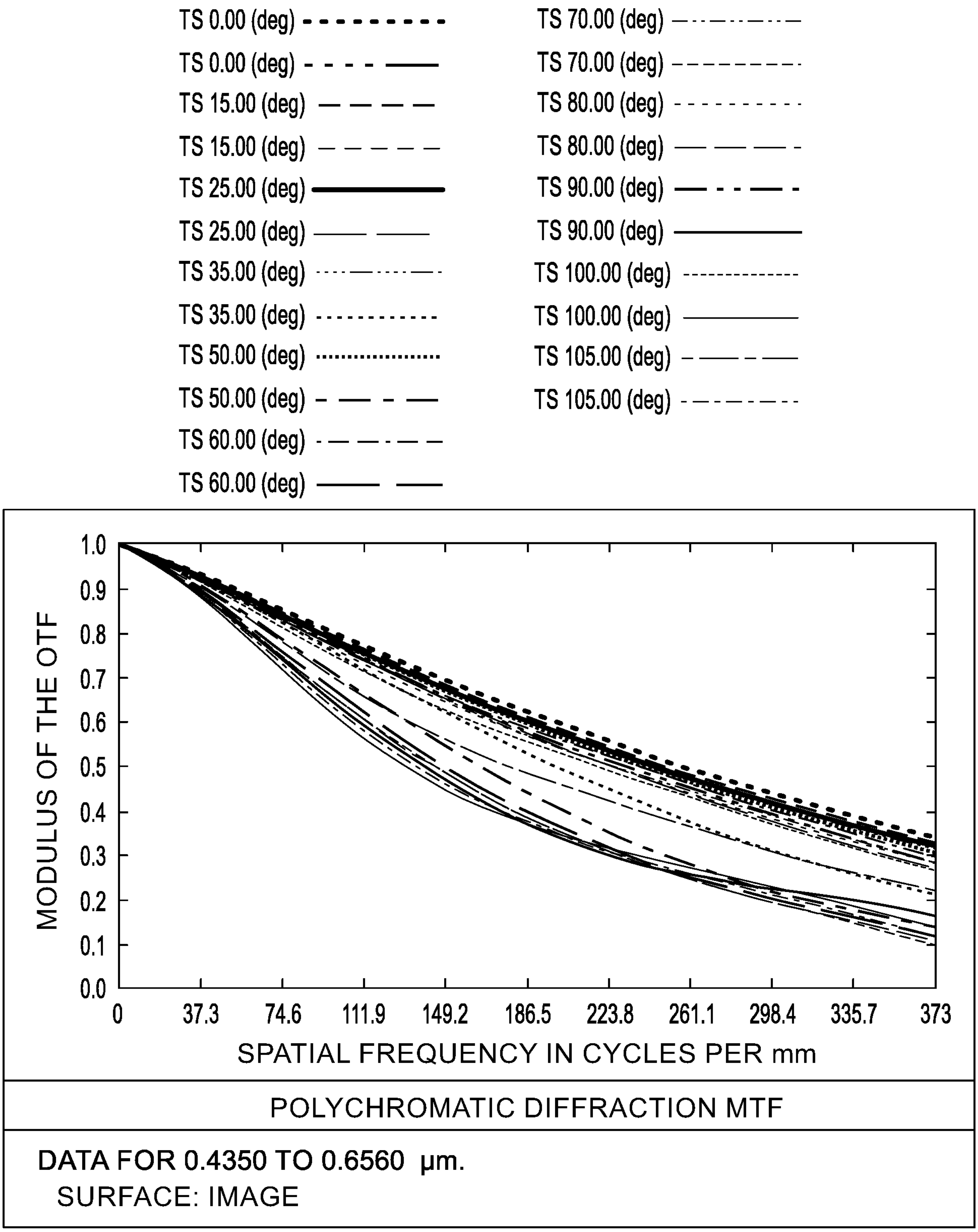
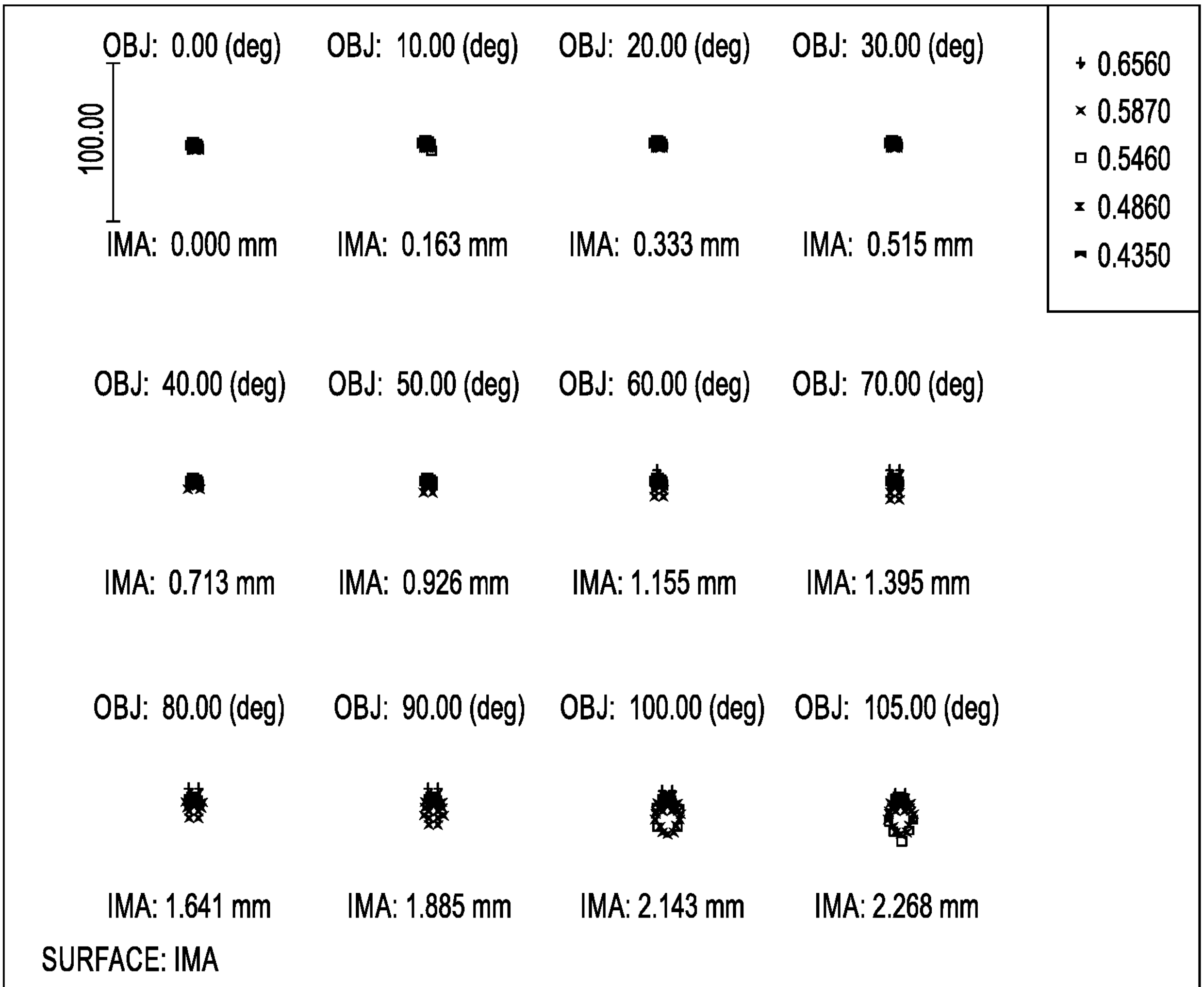

TS 0.00 (deg)
TS 0.00 (deg)
TS 15.00 (deg)
TS 15.00 (deg)
TS 25.00 (deg)
TS 25.00 (deg)
TS 35.00 (deg)
TS 35.00 (deg)
TS 50.00 (deg)
TS 50.00 (deg)
TS 60.00 (deg)
TS 60.00 (deg)
TS 70.00 (deg)
TS 70.00 (deg)
TS 80.00 (deg)
TS 80.00 (deg)
TS 90.00 (deg)
TS 90.00 (deg)
TS 100.00 (deg)
TS 100.00 (deg)
TS 105.00 (deg)
TS 105.00 (deg)
MODULUS OF THE OTF
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
37.3
74.6
111.9
149.2
186.5
223.8
261.1
298.4
335.7
373
SPATIAL FREQUENCY IN CYCLES PER mm
POLYCHROMATIC DIFFRACTION MTF
DATA FOR 0.4350 TO 0.6560 μm.
SURFACE: IMAGE

FIG. 6



SPOT DIAGRAM

UNITS ARE μm.

FIELD:	1	2	3	4	5	6	7	8	9	10	11	12
RMS RADIUS:	1.130	1.261	1.358	1.269	1.330	1.596	1.996	2.348	2.583	3.020	3.546	3.997
GEO RADIUS:	2.177	3.062	3.900	3.295	3.351	5.257	6.116	7.299	9.848	10.786	15.765	24.053

SCALE BAR: 100 REFERENCE: CHIEF RAY

FIG. 7

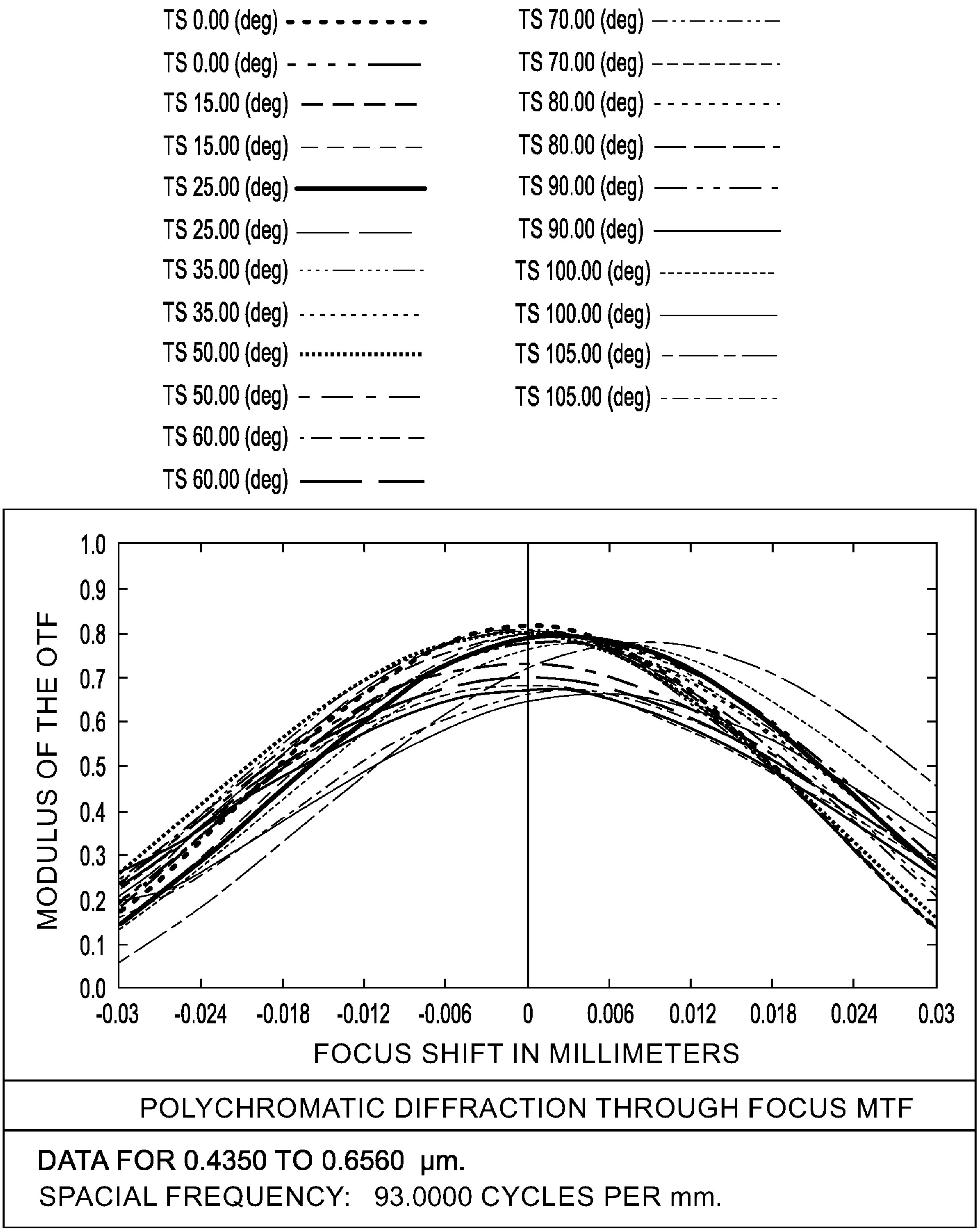

TS 0.00 (deg)
TS 0.00 (deg)
TS 15.00 (deg)
TS 15.00 (deg)
TS 25.00 (deg)
TS 25.00 (deg)
TS 35.00 (deg)
TS 35.00 (deg)
TS 50.00 (deg)
TS 50.00 (deg)
TS 60.00 (deg)
TS 60.00 (deg)
TS 70.00 (deg)
TS 70.00 (deg)
TS 80.00 (deg)
TS 80.00 (deg)
TS 90.00 (deg)
TS 90.00 (deg)
TS 100.00 (deg)
TS 100.00 (deg)
TS 105.00 (deg)
TS 105.00 (deg)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
MODULUS OF THE OTF
-0.03
-0.024
-0.018
-0.012
-0.006
0
0.006
0.012
0.018
0.024
0.03
FOCUS SHIFT IN MILLIMETERS
POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF
DATA FOR 0.4350 TO 0.6560 μm.
SPACIAL FREQUENCY: 93.0000 CYCLES PER mm.

FIG. 8

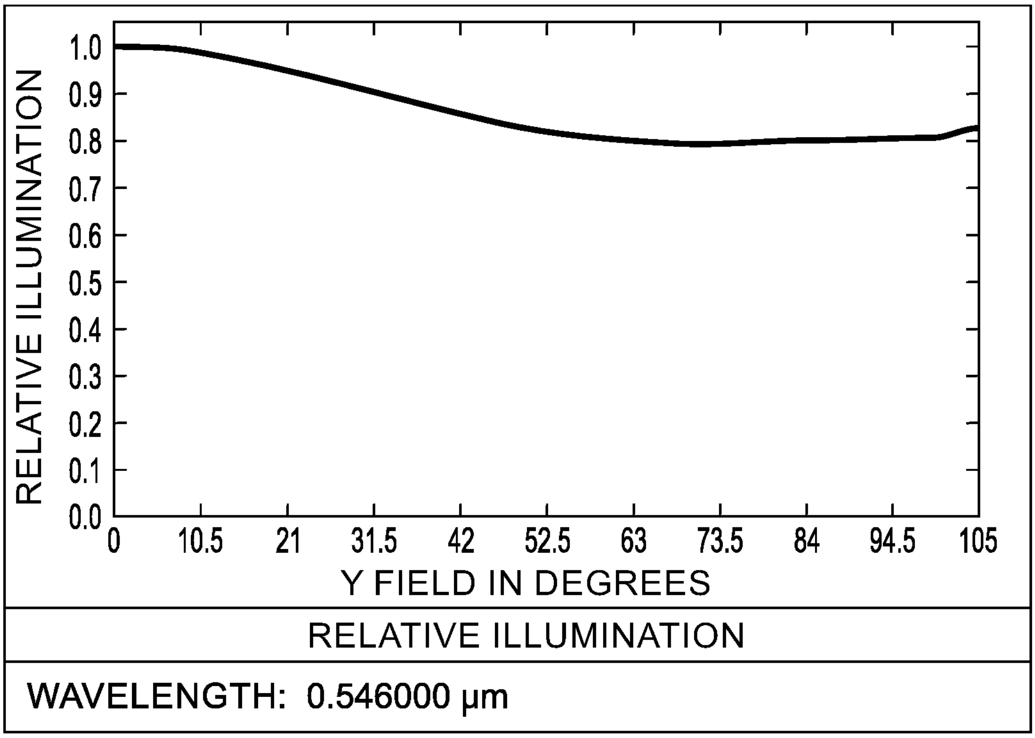

RELATIVE ILLUMINATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10.5
21
31.5
42
52.5
63
73.5
84
94.5
105
Y FIELD IN DEGREES
RELATIVE ILLUMINATION
WAVELENGTH: 0.546000 µm

FIG. 9

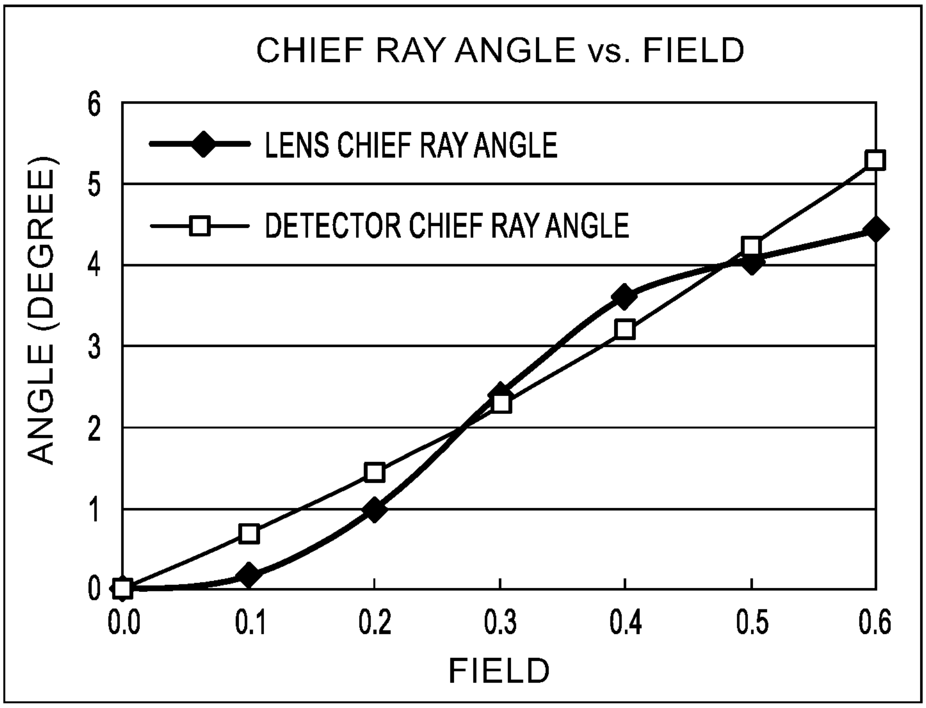

CHIEF RAY ANGLE vs. FIELD
ANGLE (DEGREE)
6
5
4
3
2
1
0
LENS CHIEF RAY ANGLE
DETECTOR CHIEF RAY ANGLE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
FIELD

FIG. 10

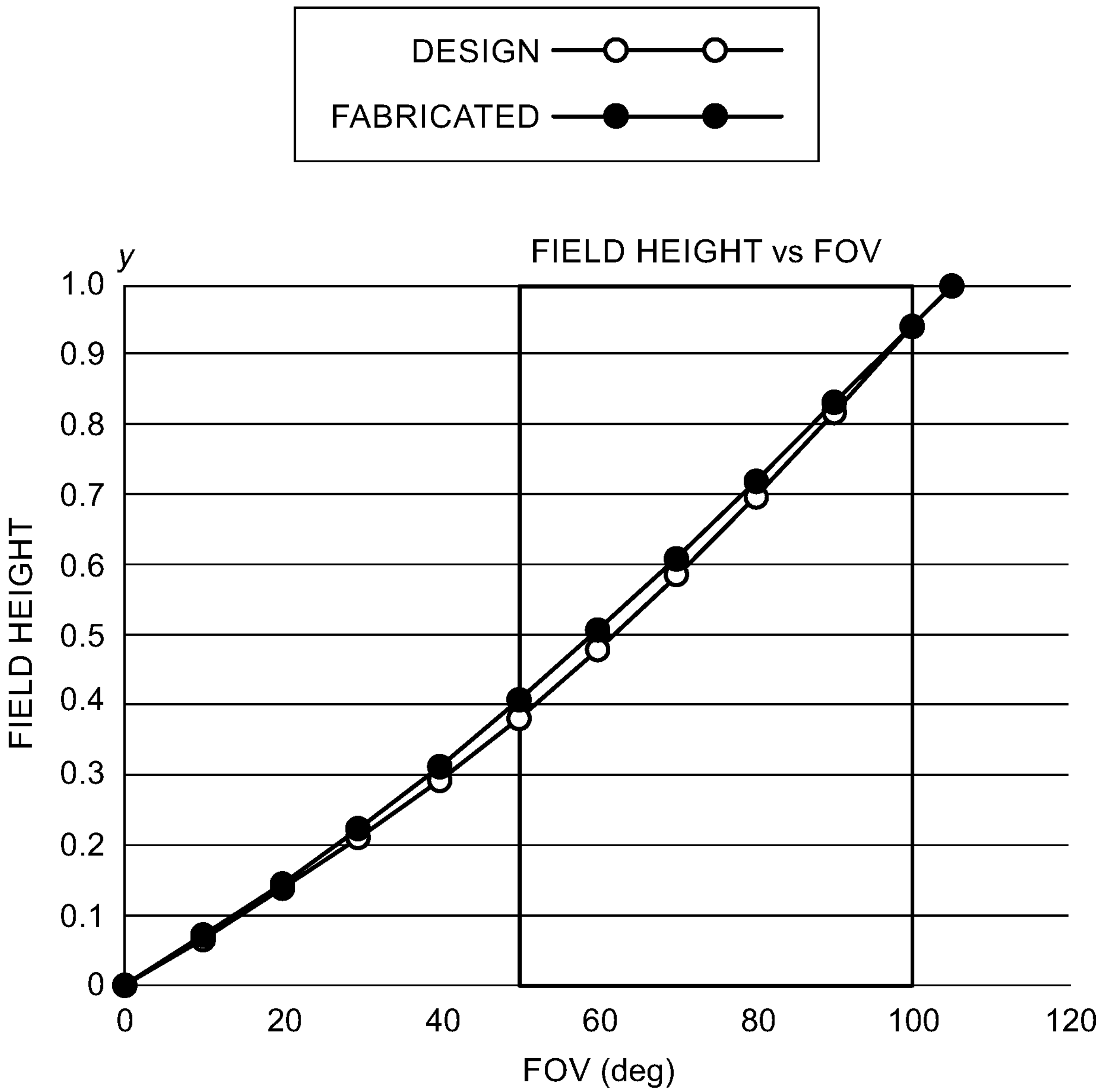

DESIGN
FABRICATED
FIELD HEIGHT vs FOV
y
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
FIELD HEIGHT
0
20
40
60
80
100
120
FOV (deg)

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2018/035328

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G02B 13/18; G02B 3/02; G02B 9/10; G02B 13/04; G02B 13/06 (2018.01)
CPC - G02B 13/18; G02B 9/06; G02B 9/34; G02B 9/64; G02B 13/003; G02B 13/06 (2018.05)

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)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 359/716; 359/717; 359/754; 359/755; 359/793; 359/798 (keyword delimited)

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2009/0052059 A1 (LIN) 26 February 2009 (26.02.2009) entire document	1-4
A	US 2003/0107820 A1 (NANBA) 12 June 2003 (12.06.2003) entire document	1-4
A	US 2004/0257677 A1 (MATSUSAKA) 23 December 2004 (23.12.2004) entire document	1-4
A	US 2012/0120505 A1 (NAKAI et al) 17 May 2012 (17.05.2012) entire document	1-4
A	US 2004/0211907 A1 (WELLMAN et al) 28 October 2004 (28.10.2004) entire document	1-4

☐ 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 not considered to be of particular relevance
"E" earlier application or patent 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
31 July 2018	17 SEP 2018

Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2018/035328

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 5-46
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.