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(19)

(54) ANNULAR FIELD OPTICAL SYSTEM

(71) We, THE PERKIN ELMER CORPORATION, a Body Corporate organised and existing under the laws of the State of New York, United States of America, having a principal place of business at Main Avenue, Norwalk, Connecticut 06856, United States of America do hereby declare the invention, for which we pray that a patent may be granted to and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to optical projection systems for projecting an image of an object at unit magnification and with high resolution, such as used for exposing a semiconductor wafer to the image of a master in micro-circuit fabrication.

The optical system of the present invention is closely related to annular projection systems of the type disclosed in U S patent no: 3 748 015. While this optical system has many advantages, the present invention enables additional advantages to be realised within the said system and systems of the same general type, as will become apparent from the description that follows.

An optical projection system for wafer exposure must ensure the very best image fidelity to the master that the optical art can provide. High resolution and flatness of field are of course of paramount importance since it is quite common in present day micro-circuit design to allow for spacing between contiguous elements of the order of a micron. In order to alleviate the optical design problem in achieving such a high peak of performance, the useful field has had to be severely restricted and the projection system designed for the scanning mode of exposure. In this a considerable advancement in the art was brought about by the recognition that off-axis fields could be used to best advantage, whereas traditionally designers had concentrated on paraxial fields. In fact, the system disclosed in the U S patent referred to above provides a narrow annular field highly corrected against optical aberrations, including of course field curvature.

It is well known that the monochromatic aberrations that may afflict an optical system are of five different kinds and that no system can ever be perfectly corrected for all of them simultaneously. The design problem is further compounded if the light to be used for image projection is not monochromatic and the system includes refracting elements. In such case, it becomes necessary to take into account the chromatic aberration arising from the fact that the index of refraction of optical material such as glass changes with the wavelength of the light traversing it. Since a common factor of the five monochromatic aberrations is the index of refraction, it follows that chromatic aberration modifies each of the monochromatic aberrations. In other words, chromatic aberration is always something to be contended with in optical design, unless the imaging light is monochromatic or the imaging optics is all-reflecting. The use of monochromatic light is of course a severe limitation, since suitable high intensity light sources are either unavailable or very inconvenient; and all reflecting optical systems such as the one described in the aforesaid U S patent, have their limitations, which, as we shall presently disclose, may be overcome in accordance with the present invention by introducing refracting elements, albeit at the cost of bringing back and then defeating the chromatic aberration problem.

There are occasions in optical design when in an attempt to refine the performance of a high resolution optical system a change is introduced in the effect of the chromatic aberration present which actually results in variation of focus or wavelength being introduced or increased. In this situation, the present invention recognises that the problem can be overcome by generating a counteracting chromatic aberration the effect of the disturbing chromatic aberration that gives rise to chromatic variation of focus with field position.

According to the present invention an optical projection system adapted to provide a discrete off-axis field zone which, as generated, is annular in shape, said field zone having a substantially flat focal surface within a range of projection light wavelengths comprises two halves, each including an optical system having an optical axis and having conjugate planes normal to that axis for which the system is of substantially unit power, the two halves being co-axially disposed in back-to-back relationship so that the conjugate planes are superposed on one side of the optical axis to form an intermediate image location but not on the other side of the optical axis to thereby space the object and final image locations from one another, the optical system of each half including reflecting means and refracting means comprising a meniscus element whose convex radius is larger than its concave radius and whose thickness is greater than the difference between its convex and concave radii so as to be nearly concentric and being so constructed and arranged that the Petzval sum is substantially zero and including provision for balancing the effects of the variation in the Petzval sum due to variation in colour by introducing axial chromatic aberration of the opposite sense so that the positions of focus at the annular field portions of the conjugate planes remain substantially constant. The term "Petzval sum" used above is a well known one meaning the algebraic sum of the quantities obtained by dividing the power of each surface by its index of refraction, the index of refraction of a reflecting surface being defined as negative one for this computation.

Different forms of optical system in accordance with the invention will now be described with reference to the accompanying drawings, in which:—

Figure 1 is a schematic representation of one half of an optical system, constructed in accordance with the concepts of the present invention and itself the subject of the copending application 5682/78.

Figure 2 is a schematic representation of a double optical system, wherein two optical systems similar to the system of Figure 1 are mounted in back-to-back relationship;

Figure 3 is a schematic representation of an optical system similar to the system of Figure 2, but simplified by removing the requirement that each half of the system be symmetrical, while keeping the system symmetrical as a whole;

Figure 4 is a schematic representation of an optical system similar to the system of Figure 3, but simplified by combining the two color correcting plates into a single element of the same form and by eliminating the folding flats required to separate the object and final image by making the conjugate distances of the two-mirror components unequal;

Figures 5 to 7 are schematic representations of other embodiments, respectively, of optical systems according to the invention; and Figure 8 is a graphic representation showing the variation of the focal position as a function of the distance from the axis and the wavelength of the image forming light.

For a proper appreciation of the present embodiment as a practical application of the inventive concept disclosed herein, reference should be made to the optical system illustrated in Figure 2 of U S specification no: 3 748 015 wherein the concave mirror shown forms an image of the object point 0 at I and the convex mirror forms a virtual image of I at 0, the latter being re-imaged by the concave mirror at I.

A limitation of that prior art system imposed by the fifth order astigmatism inherent in the design, is the comparatively narrow width of the corrected annular field that can be achieved. The cause of the astigmatism is the spherical aberration suffered by the principal rays parallel to the optical axis, which may be minimised in known manner by introducing (at a location presently to be indicated) a pair of meniscus elements concentric with the mirrors. Unfortunately, when so arranged the elements introduce third order field curvature, which is, of course, a severe penalty but is not accompanied by any other third order aberration.

The reason why the meniscus elements introduce field curvature is that the index of refraction of the material used in their construction, along with that of any transparent media, changes with the wavelength of the light transversing it, and field curvature is related to said index. In fact, the necessary condition for the absence of field curvature, i.e. for a flat image surface, in an optical system is that the algebraic sum of the quantities obtained by dividing the power (in diopters) of each surface encountered from an object point by the index of refraction of the surface be zero, the index of refraction of a reflecting surface being defined as negative one for this computation. The said sum is known in the art as the Petzval sum. It follows that if the index of refraction for one particular wavelength causes the Petzval sum to be zero, and therefore the field to be flat, that for a different wavelength will give a value different from zero and thus introduce field curvature.

Naturally, if a monochromatic projection light were used, the problem would not arise, since the optical system would be designed to meet the Petzval condition at the single wavelength chosen. However, in terms of the energy that can be passed through it, the system is far more efficient in practice if it can be made to accept a spectral band that is reasonably broad compared with a monochromatic line.

It is thus seen that, in attempting to increase the width of the corrected annular field in the prior art system referred to by resorting to a pair of concentric meniscus elements for removing the spherical aberration that limited the width in the first place, a disturbing chromatic aberration is introduced where none existed. However, since no other third order aberration is introduced at the same time, the attainment of the wider annular field becomes possible if some means is found of combating the adverse effect of chromatic aberration on field flatness.

The disturbing chromatic aberration will not affect the position of a focal point in the lateral direction, i.e. perpendicular to the optical axis in the image space because of the symmetry of the system.

The effect in the longitudinal direction, i.e.

parallel to said optical axis, is another matter entirely. Taking as a datum the position of a focal point for a given wavelength, that position will shift in one direction along a path parallel to the optical axis for a longer wavelength, and in the opposite direction for a shorter wavelength. In other words, a longitudinal spread of the focal position will take place, and this is where the application of the inventive concept disclosed herein comes into play. This concept, as already stated, involves the generation of a counteracting chromatic aberration, the effect of which is substantially to neutralise the effect of the disturbing chromatic aberration. In the application under review, the disturbing aberration we are concerned about is the component thereof operating in the longitudinal or axial direction and therefore the counteracting aberration will be made to have a longitudinal effect.

For an introductory appreciation of how the present invention is applied to the refinement of an optical system as depicted in Figure 2 of the U S patent hereinbefore referred to, we need to emphasise the well known fact that the prior art solution of introducing a concentric meniscus with a conjugate at the centre of curvature causes no longitudinal chromatic aberration (which means that the focal point along the optical axis of the system is the same for all wavelengths within the spectrum of the projection light) but does cause an increasing spreading out of the focal positions as between long and short wavelengths for discrete off-axis field zones of increasing separation from the optical axis.

If we assume that the whole system, including the concentric meniscus, has been so designed that the Petzval sum is zero for a chosen datum wavelength, which for the purposes of this explanation we shall take as the middle wavelength in the spectral range of the projection light, the focal surface at the discrete off-axis zone will naturally be substantially flat. For the purposes of this explanation, we shall call that surface the datum focal surface.

Now the concentric meniscus has a slight negative power and consequently a slight contribution to the Petzval sum of the system. The Petzval contribution is more negative for wavelengths shorter than the chosen datum wavelength and less negative for wavelengths longer than the chosen datum wavelength because the index of refraction of the refracting material of which the meniscus is made increases with decreasing wavelength. As a result of this, the focus for short wavelengths will be downstream of the datum focal surface and the long wavelengths upstream. This clearly cannot be tolerated in a high resolution system.

The situation may be remedied by applying the concept of the present invention. In fact, by giving the convex surface of the meniscus a controlled amount of positive power, and ending up therefore with a non-concentric meniscus (the negative power of which is, incidentally, reduced as compared to a concentric meniscus of the same thickness) longitudinal chromatic aberration is introduced by virtue of which the focal position separation between short and long wavelengths is at its maximum along the optical axis and decreases in an off-axis direction. Positive power naturally means that the shorter wavelengths focus upstream of the datum focal surface and lower downstream.

We thus have an effect which is opposite to that of the concentric meniscus of the prior art. By selecting the right amount of positive power in relation to the chosen discrete off-axis zone, a balance is established whereby all the wavelengths within the spectral range of the projection light may be brought to a substantially common focus at the datum focal surface.

Figure 1 illustrates one half of the new and improved optical system indicated generally at 10, which comprises two spherical mirrors, a convex mirror 12 and a concave mirror 14, arranged to provide three reflections within the system. The mirrors are arranged with their centres of curvature along the system axis SA and to have off axis conjugate areas centered at points 0 and I. The points 0 and I are each a distance H from the reference axis SA at opposite sides thereof.

A pair of symmetrically disposed meniscus elements 16 are provided for reducing the spherical aberration of the principal rays. It is noted that the meniscus elements would also be effective for reducing the spherical aberration of the principal rays if they were mounted directly adjacent to the convex mirror 12 so that the surface of the mirror 12 and the convex surface of the meniscus elements 16 are parts of the same spherical surface. It will be appreciated that the high order astigmatism has been greatly reduced with the result that the width of the corrected annulus is increased by an order of magnitude.

The small aberrations arising from the departure of the meniscus elements 16 from concentricity are compensated for by introducing a small departure from concentricity in the mirror pair 12 and 14. That is, the concave mirror 14 and the convex mirror 12 are supported with a distance between their centres of curvature of less than about two percent of the length of the shorter radius. Colour correcting plates 18 operate in the manner subsequently described. Other suitable arrangements of these mirrors are shown and described in the prior U S patent no: 3 748 015.

A necessary condition for the absence of field curvature, i.e. for a flat image surface, in the resultant system is that the algebraic sum of the quantities obtained by dividing the power of each surface by its index of refraction be substantially zero, the index of refraction of a reflecting surface being defined as negative one for this computation. Since the index of refraction of the meniscus elements varies with the wavelength of the image forming light, it will be appreciated that the incorporation of these elements in the optical system results in a variation of field curvature with wavelength. This results in a variation of the focal position as a function of the distance from the axis and as a function of the wavelength of the image forming light, as shown in Figure 3. In an annular field optical system, the variation with distance from the axis is effectively removed by restricting the field to an annulus whose distance from the axis is constant. The variation of field curvature with wavelength is such a system becomes a variation of focal position with wavelength and it can be balanced by the introduction of color aberration of the opposite sense. To accomplish this in accordance with the invention, the refracting meniscus departs from exact concentricity by having its convex radius of curvature shorter than the sum of its concave radius and its thickness. That is, its thickness is greater than the difference between the radii of its convex and concave surfaces. The way in which this works can be explained as follows:

The variation of field curvature with wavelength introduced by a nearly concentric meniscus whose power is negative is such that the back focus is greater for short wavelength than for long wavelengths. A concentric meniscus with conjugate at its center of curvature does not introduce any longitudinal color aberration. The same is substantially true of such a meniscus with a conjugate near its center of curvature. The addition of a positive lens to such a meniscus introduces longitudinal color of the sense required to balance the variation in focus with wavelength resulting from the variation of the field curvature (contributed by the meniscus) with wavelength. This can be accomplished by making the convex radius of the meniscus shorter than the sum of its concave radius and its thickness. The meniscus is then equivalent to two lenses, one being a fictitious concentric meniscus with convex radius equal to the sum of the concave radius and the thickness, while the second is a zero thickness positive meniscus whose concave radius is the convex radius of the fictitious meniscus and whose convex radius is the convex radius of the actual meniscus. For a nearly concentric meniscus with concave radius R_1, convex radius R_2, thickness t, and refractive index N, the longitudinal color compensates for the change in focus due to the variation of field curvature with wavelength in an annulus of radius H when

$$R_2 > R^1 \qquad (1)$$

$$\text{and } t \simeq R_2 - R_1 + (H^2/2N^2)(1/R_1 - 1/R_2)$$

It has been found that the introduction of a pair of menisci whose parameters substantially satisfy equation (1) into an optical system of the type disclosed in the aforementioned U S Patent No. 3 748 015, together with accompanying modifications which will be discussed more fully hereinafter, results in a reduction in the high order astigmatism over a wide spectral band.

The resultant system can be improved considerably by modifying the menisci so that their thicknesses are greater than the values given by equation (1). This results in a variation of focus of an annular field system whose sense is such that it can be compensated for by the introduction of a plane parallel plate of appropriate thickness, as indicated at 18 in Figure 1. The extra degrees of freedom provided by the additional element makes possible a much greater degree of correction.

Further improvement can be obtained by modifying the plane parallel plates in one of two ways:

(1) One of the faces of the plane parallel plate may be made aspheric.

(2) The plane parallel plate may be "bent" resulting in a meniscus element.

The highest degree of correction has been obtained with a system in which the thickness of the menisci is greater than the value given by equation (1) and in which colour compensation is obtained by adding plane parallel plates modified in accordance with one of the two ways described above.

Table 1 is an example, indicating the construction data, of the annular field optical system of Figure 1. As is well known in the art, a plus sign is used to denote that a surface is convex to the object and that distance is measured from left to right whereas a minus sign is used to denote that a surface is concave to the object and that a distance is measured from right to left.

Table II is a table of the computed performance of the annular field optical system of Table I over an extended spectral range 2800 Å to 5461 Å) in terms of the rms wave aberration at various annular radii. The width of the usable annulus is the difference between the values of the upper and lower radii for which the performance is adequate for the application. It is noted that a system is usually called "diffraction limited", or more precisely "aperture limited" when the rms wave aberration is less than 0.07. For a scanning system, the rms wave aberration may be as high as 0.09 or 0.1 at the edges of the annulus.

It is noted that annular field optical systems of the type described are usually used in a scanning mode and, for this purpose it is highly desirable that the orientation of the object and image be the same so that their physical supports can be maintained in fixed relation to each other while being moved relative to the optical system for scanning and so that the accuracy requirements of the scanning motion are minimized. An arrangement that achieves this by incorporating three flat mirrors in the optical system was shown in the U S Patent No. 3 951 596. Another means of achieving this effect, in accordance with the present invention by using two optical systems 10 and 10′, each being of the type shown in Figure 1, disposed in back-to-

TABLE I

RADIUS OF ANNULUS = 100 mm.

SURFACE NO. FROM OBJECT TO IMAGE	*RADIUS (mm)*	*DISTANCE TO NEXT SURFACE (mm)*	*MATERIAL*	*NOTE*
0	(PLANE)	144.92	AIR	OBJECT
1	-144.96	11.03	FUSED SILICA	
2	-151.75	88.70	AIR	
3	-975.30	16.75	FUSED SILICA	
4	-967.84	295.25	AIR	
5	-551.15	-279.07	AIR	MIRROR
6	-267.18	297.07	AIR	MIRROR
7	-551.15	-295.25	AIR	MIRROR
8	-967.84	-16.75	FUSED SILICA	
9	-957.30	-88.70	AIR	
10	-151.75	-11.03	FUSED SILICA	
11	-144.96	-144.92	AIR	
12	(PLANE)			IMAGE

TABLE II

N.A. = 0.17 AT OBJECT AND IMAGE

RADIUS OF ANNULUS (mm)	*RMS WAVE ABERRATION (WAVELENGTH UNITS)*					
	WAVELENGTH (ANGSTROM UNITS)					
	2800	*3200*	*3650*	*4000*	*4358*	*5461*
105	-09	-12	-13	-13	-13	-12
104	-05	-08	-09	-09	-09	-08
103	-02	-04	-05	-06	-06	-05
100	-02	-01	-01	-01	-01	-01
97	-04	-01	-02	-02	-02	-03
96	-06	-02	-02	-03	-03	-03
95	-08	-04	-04	-04	-04	-04
94	-11	-05	-05	-05	-05	-05
93	-13	-08	-07	-07	-06	-06

back relationship so that the object and image planes are superposed, as illustrated in Figure 2. Thus, the optical system 10 includes two spherical mirrors 12 and 14, a pair of meniscus elements 16 and a color correcting plate 18, and the symmetrical optical system 10′ includes two spherical mirrors 12′ and 14′, a pair of meniscus elements 16′ and a color correcting plate 18′. The physical separation between the object and final image required for a practical arrangement is obtained by the addition of folding mirrors 20 and 20′ shown by broken lines in Figure 2, to move the actual object and image to O′ and I′, respectively. In this arrangement the separation between the folding mirrors must be sufficient to provide clearance for scanning. It will, or course, be appreciated that other arrangements of folding flats, which retain the relative orientation of the object and image, are within the scope of this invention.

In the optical system of Figure 2, the intermediate image, indicated at 22, is highly corrected because it is formed by the indicated at 22, is highly corrected because it is formed by the optical system 10 of Figure 1. In this arrangement, each half 10 and 10′, of the system is longitudinally symmetrical and thus reversible. Since for most applications a high degree of correction at the intermediate image is not required, the system can be simplified by removing the requirements that each half of the system be symmetrical, while keeping the system or at least the refractive components thereof symmetrical as a whole, and thereby reduce the number of compensating menisci and correcting plates to two each, as illustrated in the embodiment of Figure 3. Thus, a half of the optical system, indicated at 10a, comprises two spherical mirrors 12 and 14, a meniscus element 16a and a color correcting plate 18a disposed on the side of the intermediate image 22, all of said elements being symmetrically disposed about the optical axis SA. The other half of the optical system, indicated at 10a′, comprises two spherical mirrors 12′ and 14′ a meniscus element 16a′ and a color correcting Plate 18a′ disposed on the side of the intermediate image 22, all of said elements being symmetrical about the optical axis SA. For the same reasons indicated hereinbefore, each half of the optical system is provided with a folding mirror 20 and 20′ shown by the broken lines in Figure 3, to move the actual object and final image to 0′ and I′, respectively.

Referring next to the embodiment of Figure 4, it will be appreciated that systems with an intermediate image, indicated at 22, can be further simplified by combining the two color correcting plates 18a and 18a′ of the embodiment of Figure 3 into a single element of the same form as indicated at 18b in Figure 4. Symmetry is maintained by placing the single color corrector 18b at or closely adjacent the intermediate image 22. Further, the folding mirrors 20 and 20′ of Figure 3 can also be eliminated by making unequal the conjugate distance of at least one of the two-mirror components 12b, 14b, and 12b′, 14b′. That is, the intermediate image distance to the two-mirror component is made greater than the object and/or image distances, to thereby space the final image I from the object 0. In this system, the color correcting plate 18b at the intermediate image can be true plane parallel.

In a truly afocal system, the magnification is the same for all conjugate positions. However, this desirable feature is not achieved in practical applications because real systems do not in general remain truly afocal for all field positions. In the unit magnification system of Figure 4, for example, if the object 0 and image I are moved together longitudinally by 1mm., the magnification of a 4mm. radial annulus varies from unity by ± .00032. This variation, which results in tracking smear during scanning, can be reduced to ± .00001 by aspherizing one of the faces of the color correcting plate 18b.

A modification of the optical system of Figure 4 is illustrated in Figure 5, wherein the correcting menisci are moved from the intermediate image side of the system to the object-image side thereof. In the embodiment of Figure 5, one half of the system includes two spherical mirrors 12b and 14b and a meniscus element 16c disposed on the object-image side and symmetrically about the system axis SA, and the other half of the system includes two spherical mirrors 12b′ and 14b′ and a meniscus element 16c′ also disposed on the object-image side and symmetrically about the system axis SA. A single color correcting plate 18b is disposed symmetrically about the system axis at or closely adjacent the intermediate image 22. As in the embodiment of Figure 4, one of the faces of this plate is aspherized. Further, as in the embodiment of Figure 4, the intermediate image distances to the two-mirror components are made greater than the object and image distances, to thereby space and the final image I from the object 0 for scanning purposes.

Table III is an example, indicating the construction data, of the annular field optical system of Figure 5.

Table IV is a table for the computed

TABLE III

RADIUS OF ANNULUS = 100 mm.

SURFACE NO. FROM OBJECT TO IMAGE	*RADIUS (mm)*	*DISTANCE TO SURFACE (mm)*	*MATERIAL*	*NOTE*
0	(PLANE)	107.13	AIR	OBJECT
1	-128.18	10.48	FUSED SILICA	
2	-135.29	378.48	AIR	
3	-541.32	-273.56	AIR	MIRROR
4	-264.61	273.56	AIR	MIRROR
5	-541.32	-590.28	AIR	MIRROR
6	-1772.58*	-7.01	FUSED SILICA	ASPHERIC
7	(PLANE)	-587.26	AIR	
8	541.32	273.56	AIR	MIRROR
9	264.61	-273.56	AIR	MIRROR
10	541.32	378.48	AIR	MIRROR
11	135.29	10.48	FUSED SILICA	
12	128.18	107.13	AIR	
13	(PLANE)			IMAGE

* Aspheric surface symmetrical about optical axis.

Departure, X from plane surface at distance r from axis:

$$X = 1772.58 + \sqrt{1772.58 - r^2} + 1.732 \times 10^{-8} r^4 + 4.210 \times 10^{-13} r^6 + 8.278 \times 10^{-18} r^8 - 4.078 \times 10^{-21} r^{10}$$

TABLE IV

N.A. = 0.17 AT OBJECT AND IMAGE

RADIUS OF ANNULUS (mm)	*RMS WAVE ABERRATION (WAVELENGTH UNITS)* WAVELENGTH (ÅNGSTROM UNITS) 2800	3200	3650	4000	4358	5461
103	.08	.08	.08	.08	.08	.07
102	.06	.05	.05	.05	.04	.04
100	.05	.04	.04	.03	.03	.03
98	.06	.04	.04	.04	.04	.05
97	.09	.06	.05	.05	.05	.06
96	.13	.09	.08	.07	.07	.07

TABLE V

RADIUS OF ANNULUS = 100 mm.

SURFACE NO.	*RADIUS (mm)*	*DISTANCE TO NEXT SURFACE (mm)*	*MATERIAL*	*NOTE*
0	(PLANE)	151.33	AIR	OBJECT
1	- 726.89	28.69	FUSED SILICA	
2	- 730.32	410.82	AIR	
3	- 552.06	-280.16	AIR	MIRROR
4	- 267.18	280.16	AIR	MIRROR
5	- 552.06	-363.25	AIR	MIRROR
6	- 160.78	- 24.03	FUSED SILICA	
7	- 145.19	-272.77	AIR	
8	145.19	24.03	FUSED SILICA	
9	160.78	-363.25	AIR	
10	-552.06	280.16	AIR	MIRROR
11	267.18	-280.16	AIR	MIRROR
12	-552.06	410.82	AIR	MIRROR
13	730.32	28.69	FUSED SILICA	
14	726.89	151.33	AIR	
15	(PLANE)			IMAGE

performance of the annular field optical system of Table III over an extended spectral range (2800 Å to 5461 Å) in terms of the rms wave abberation at various annular radii. The width of the usable annulus is the difference between the values of the upper and lower radii for which the performance is adequate for the application.

An optical system in which the distances from the intermediate image 22 to the two-mirror components 12d-14d and 12d′-14d′ are less than the distances from the object 0 and final image I is shown in Figure 6. In the embodiment of Figure 6, one half of the system includes two spherical mirrors 12d and 14d and a meniscus element 16a disposed on the intermediate image side and symmetrically about the system axis SA, and the other half of the system includes two spherical mirrors 12d′ and 14d′ and a meniscus element 16a′ also disposed on the intermediate image side and symmetrically about the system axis SA. A single color correcting plate 18b is disposed at or closely adjacent the intermediate image 22. Parallel folding flats, as in the systems of Figures 2 and 3 are introduced between the two crossed conjugate positions 0 and I to make them accessible for scanning purposes. However, in the embodiment of Figure 6, the two folding flats are the front and back surfaces of a plane parallel plate 20d, whose thickness is determined by mechanical considerations, in contrast to the arrangements of Figures 2 and 3 in which other considerations determined the separation between the reflecting surfaces. Thus, in the embodiment of Figure 6, the front and back surfaces of the plate 20d serve to deflect the object 0 to 0′ and the final image I to I′, thereby providing the spacing therebetween necessary for scanning.

Another embodiment of the invention utilizing crossed object and image planes is shown in Figure 7, wherein the single color correcting plate 18b of Figure 6 at the intermediate image has been replaced by two spaced, color correcting plates 18e and 18e′ on the object-image side of the system. In this embodiment, the

TABLE VI

N.A. = 0.17 AT OBJECT AND IMAGE

RADIUS OF ANNULUS (mm)	*RMS WAVE ABERRATION (WAVELENGTH UNITS)*					
	WAVELENGTH (ÅNGSTROM UNITS)					
	2800	*3200*	*3650*	*4000*	*4358*	*5461*
104	.08	.07	.09	.10	.10	.11
103	.06	.04	.05	.06	.07	.08
102	.05	.02	.03	.04	.05	.06
100	.03	.02	.02	.02	.03	.04
98	.07	.04	.03	.03	.02	.03
97	.10	.06	.05	.04	.04	.04
96	.14	.09	.07	.06	.06	.05

substantially plane parallel plates have been "bent" to form a meniscus element. The remainder of the system of Figure 7 is similar to that of Figure 6. That is, one half of the system includes two spherical mirrors 12d and 14d and a meniscus element 16a disposed on the intermediate image side, and the other half of the system includes two spherical mirrors 12d′ and 14d′ and a meniscus element 16a′ also disposed on the intermediate image side. As described hereinbefore in connection with the embodiment of Figure 6, plate 20d having mirror front and back surfaces serves to move the object 0 to 0′ and the final image I to I′ to provide physical separation between the object and image as required for a practical arrangement.

Table V is an example, indicating the construction data, of the annular field optical system of Figure 7.

Table VI is a table for the computed performance of the annular field optical system of Table V over an extended spectral range (2800 Å to 5461 Å) in terms of the rms wave aberration at various annular radii. The width of the usable annulus is the difference between the values of the upper and lower radii for which the performance is adequate for the application,

It is noted that with the arrangement of Figure 7 and with the configuration of Figure 5, the refracting or meniscus elements 18e, 18e′, 16c and 16C′ can be used as windows for sealing the portions of the optical system therebetween.

WHAT WE CLAIM IS:—

1. An optional projection system adapted to provide a discrete off-axis field zone which, as generated, is annular in shape, said field zone having a substantially flat focal surface within a range of projection light wavelengths, the system comprising two halves, each including an optical system having an optical axis and having conjugate planes normal to that axis for which the system is of substantially unit power, the two halves being co-axially disposed in back-to-back ralationship so that the conjugate planes are superposed on one side of the optical axis to form an intermediate image location but not on the other side of the optical axis to thereby space the object and final image locations from one another, the optical system of each half including reflecting means and refracting means comprising a meniscus element whose convex radius is larger than its concave radius and whose thickness is greater than the difference between its convex and concave radii so as to be nearly concentric and being so constructed and arranged that the Petzval sum is substantially zero and including provision for balancing the effects of the variation in the Petzval sum due to variation in color by introducing axial chromatic aberration of the opposite sense so that the positions of focus at the annular field portions of the conjugate planes remain substantially constant.

2. An optical system according to Claim 1, in which the reflecting means in each half of the optical system includes a concave mirror and a convex mirror supported with their centres of curvature substantially coincident.

3. An optical projection system according to Claim 1 or Claim 2 in which the optical systems of the two halves are substantially symmetrical with respect to an axis in the superposed conjugate planes.

4. An optical projection system according to Claim 1 in which each meniscus element is on the same side of the optical axis as the intermediate image location.

5. An optical projection system according to Claim 1 in which each meniscus element is on the same side of the optical axis as the object and final image locations.

6. An optical projection system according to Claim 1 in which the refracting means in each half of the optical system includes a pair of such meniscus elements, disposed symmetrically with respect to the optical axis.

7. An optical projection system according to any one of the preceeding claims and including a colour correcting plate disposed substantially at the intermediate image location.

8. An optical projection system according to any one of Claims 1 to 6 and including one colour correction plate associated with each meniscus.

9. An optical projection system according to Claim 8 in which each colour correction plate is in the form of a meniscus mounted normal to the optical axis.

10. An optical projection system according to Claim 7 or Claim 8 in which each colour correcting plate is a plane parallel plate.

11. A modification from optical projection system according to Claim 10 in which one of the faces of each plate is aspheric.

12. An optical system according to any one of the preceding claims in which the spacing between the object and final image locations is obtained by the inclusion of means for positioning the conjugate planes on that side of the optical axis.

13. An optical system according to Claim 12 in which the positioning means comprises folding mirrors.

14. An optical system according to Claim 12 in which the final image location and the object location are crossed and positioning reflecting means are included between these two locations to render them physically accessible.

15. An annular field optical system substantially as described with reference to Figure 5 of the accompanying drawings and having construction data as set out in Table III herein.

16. An annular field optical system substantially as described with reference to Figure 7 of the accompanying drawings and having construction data as set out in Table V herein.

17. An annular field optical system substantially as described with reference to any one of Figures 2 to 7 of the accompanying drawings.

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1605161 **PROVISIONAL SPECIFICATION**

7 SHEETS *This drawing is a reproduction of the Original on a reduced scale.*

Sheet 1

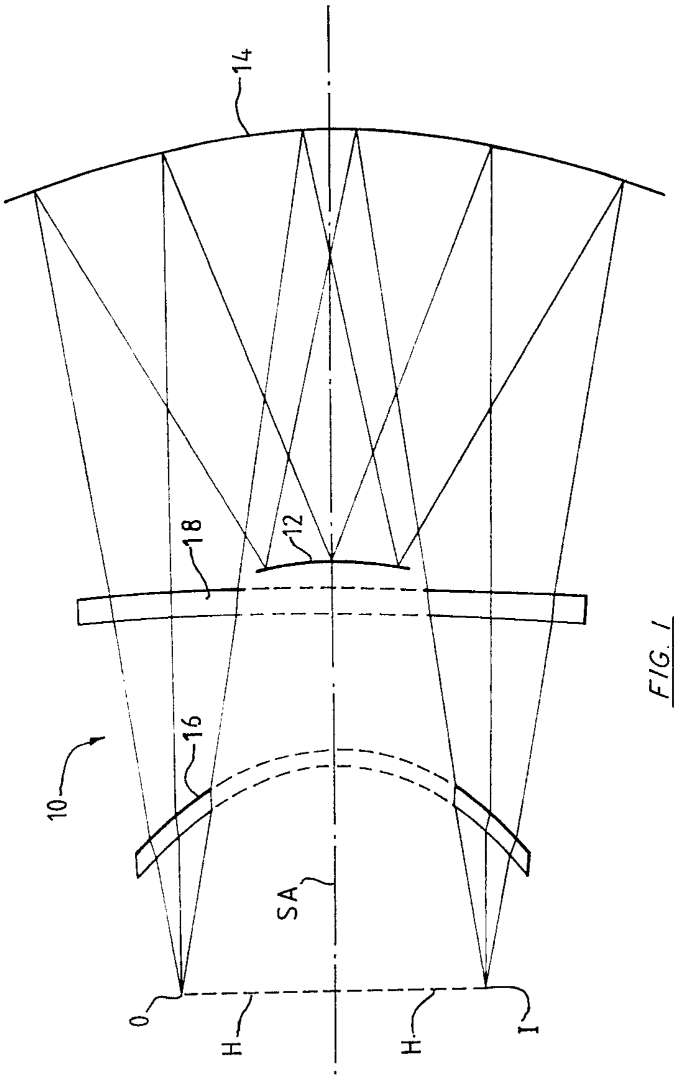

FIG. 1

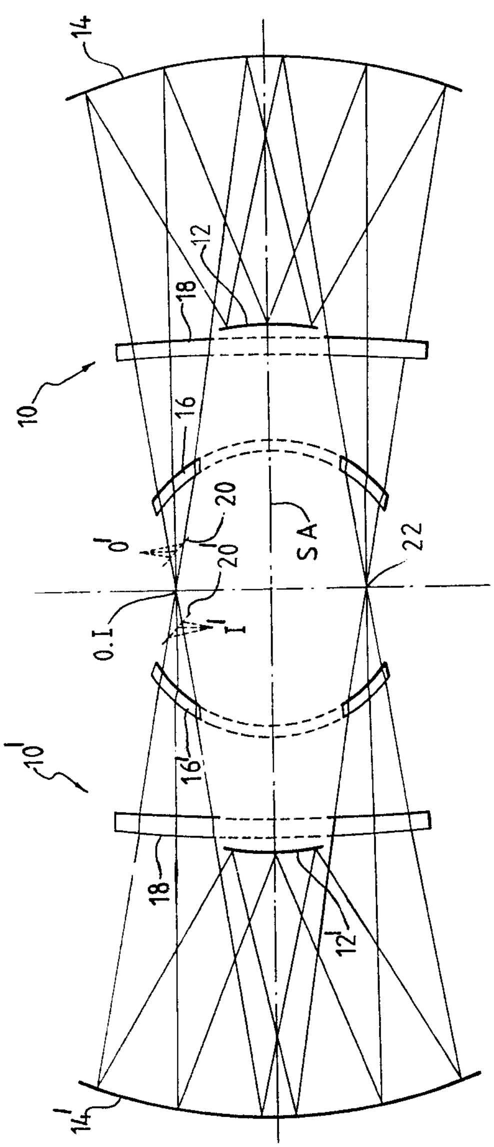

FIG. 2

1605161 **PROVISIONAL SPECIFICATION**

7 SHEETS *This drawing is a reproduction of the Original on a reduced scale.*
Sheet 3

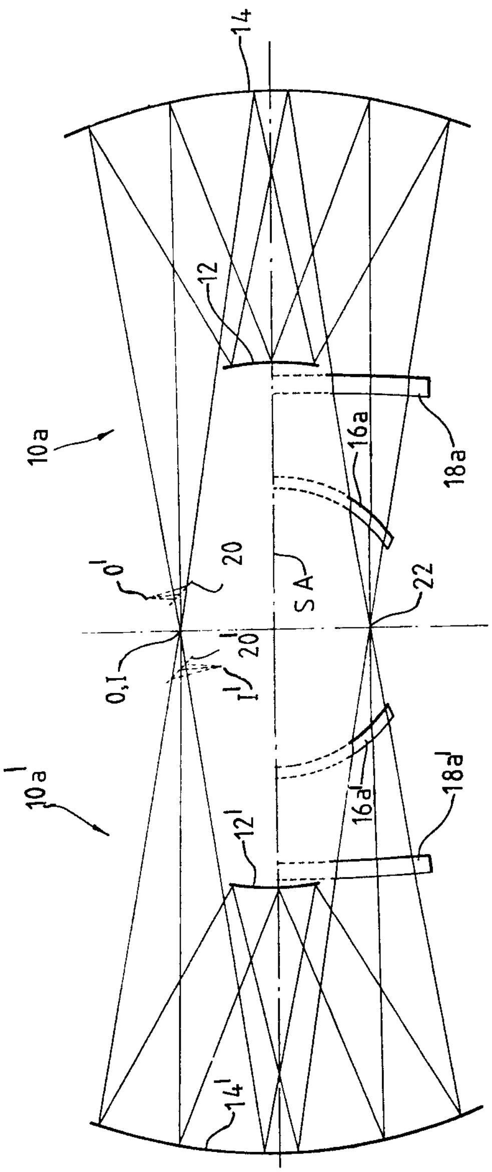

FIG. 3

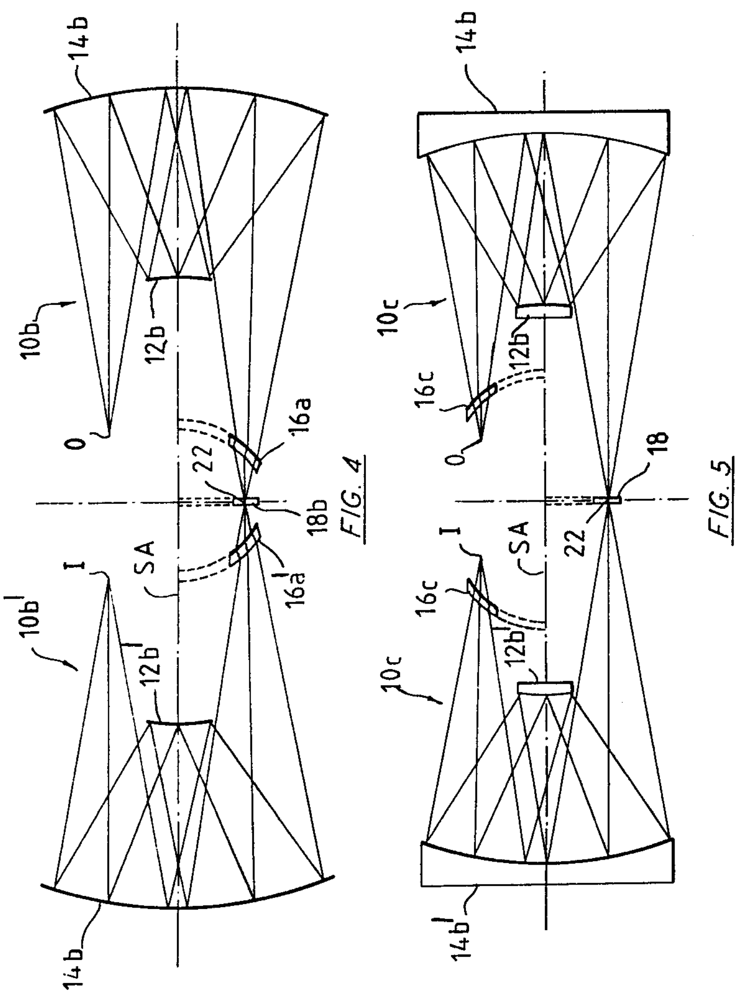
14b
10b
12b
0
16a
22
18b
SA
16a
I
10b
12b
14b
10c
12b
16c
0
18
22
SA
I
16c
12b
10c
14b

FIG. 4

FIG. 5

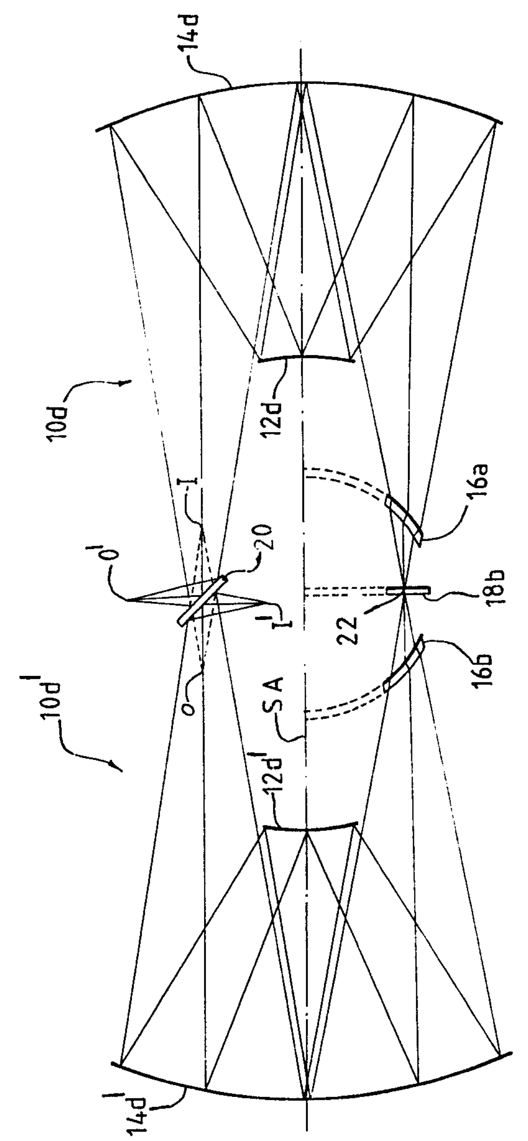

FIG. 6

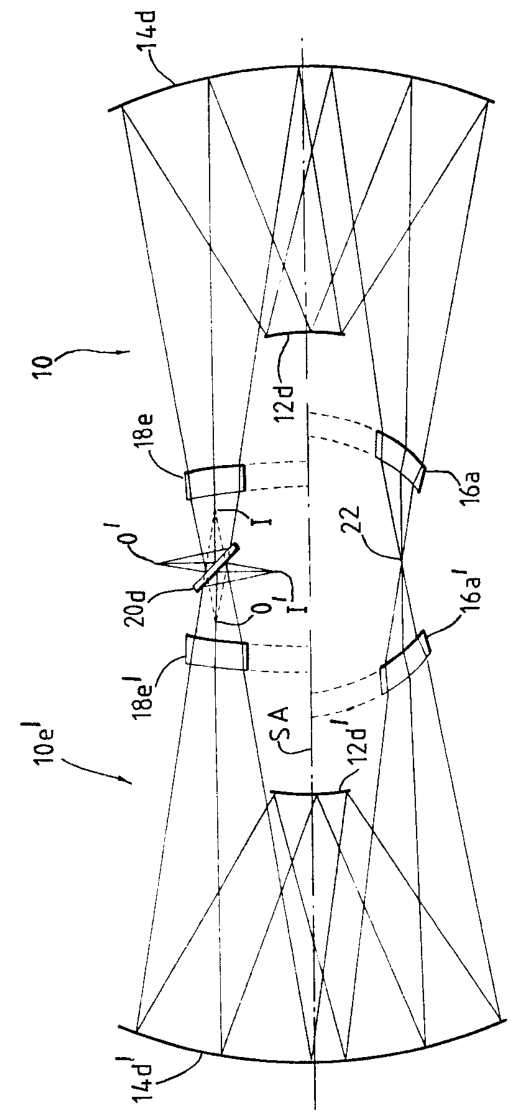

FIG. 7

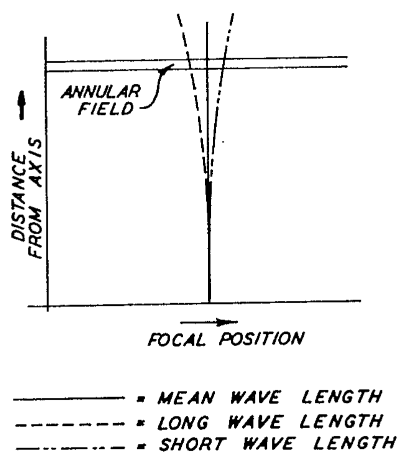
ANNULAR FIELD
DISTANCE FROM AXIS
FOCAL POSITION
= MEAN WAVE LENGTH
= LONG WAVE LENGTH
= SHORT WAVE LENGTH

FIG. 8