ABSTRACT: The present invention relates to a lens system having variable reduction and more particularly to a lens system having variable magnification and constant high correction. The lens system consists of eight lens elements and changes in reduction are produced by varying the shape of one lens element and changing one airspace while the remaining lens elements and air spaces remain constant.

2 Claims, 28 Drawing Figs.
FIG. 1

FIG. 2

<table>
<thead>
<tr>
<th>LENS</th>
<th>RADIUS</th>
<th>THICKNESS (t) OR AIRSPACE (S)</th>
<th>N_D</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>R_1+ 0.9840 F</td>
<td>t_1 = 0.0691 F, S_1 = 0.0044 F</td>
<td>1.69089</td>
<td>54.80</td>
</tr>
<tr>
<td></td>
<td>R_2+ 3.8081 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>R_3+ 0.6089 F</td>
<td>t_2 = 0.0616 F, S_2 = 0.0044 F</td>
<td>1.69089</td>
<td>54.80</td>
</tr>
<tr>
<td></td>
<td>R_4+ 0.8903 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>R_5+ 0.3461 F</td>
<td>t_3 = 0.0995 F, S_3 = 0.1329 F</td>
<td>1.69089</td>
<td>54.80</td>
</tr>
<tr>
<td></td>
<td>R_6+ 2.4406 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R_7+ 0.2320 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>R_8+ 1.6228 F</td>
<td>t_5 = 0.0299 F, S_4 = 0.1294 F</td>
<td>1.64752</td>
<td>33.80</td>
</tr>
<tr>
<td></td>
<td>R_9+ 0.6295 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>R_10+ 0.2813 F</td>
<td>t_6 = 0.0396 F, S_5 = 0.0044 F</td>
<td>1.60328</td>
<td>38.02</td>
</tr>
<tr>
<td></td>
<td>R_11+ 2.3989 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R_12+ 0.3923 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>R_13+ 1.3630 F</td>
<td>t_8 = 0.0792 F, S_6 = 0.0044 F</td>
<td>1.69089</td>
<td>54.80</td>
</tr>
<tr>
<td></td>
<td>R_14+ 0.8917 F</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

REDUCTION = 20X
**FIG. 3**

% MODULATION TRANSFER FUNCTION

Spatial Frequency 580 lines/mm

**FIG. 4**

% MODULATION TRANSFER FUNCTION

Sagittal
Tangential
Tangential (imaginary part)

Spatial Frequency 580 lines/mm

**FIG. 5**

% MODULATION TRANSFER FUNCTION

Full Field

Spatial Frequency 580 lines/mm
Diffraction Limit

**Fig. 6**

**Fig. 7**

Sagittal
Tangential
Tangential (imaginary part)

**Fig. 8**

Spatial Frequency
576 Lines/MM

Spatial Frequency
576 Lines/MM

Spatial Frequency
576 Lines/MM
FIG. 9

FIG. 10
FIG. 11

% MODULATION TRANSFER FUNCTION

DIFFRACTION LIMIT

AXIS

SPATIAL FREQUENCY
572 LINES/MM

FIG. 12

% MODULATION TRANSFER FUNCTION

SAGITTAL TANGENTIAL TANGENTIAL

IMAGINARY PART

.7 FIELD

SPATIAL FREQUENCY
572 LINES/MM

FIG. 13

% MODULATION TRANSFER FUNCTION

FULL FIELD

SPATIAL FREQUENCY
572 LINES/MM
FIG. 14

% MODULATION TRANSFER FUNCTION

DIFFRACTION LIMIT

AXIS

SPATIAL FREQUENCY

590 LINES/MM

FIG. 15

% MODULATION TRANSFER FUNCTION

SAGITTAL

TANGENTIAL

TANGENTIAL (IMAGINARY PART)

.7 FIELD

SPATIAL FREQUENCY

590 LINES/MM

FIG. 16

% MODULATION TRANSFER FUNCTION

FULL FIELD

SPATIAL FREQUENCY

590 LINES/MM
FIG. 17

% MODULATION TRANSFER FUNCTION

DIFFRACTION LIMIT

FIG. 18

SAGITTAL
TANGENTIAL
TANGENTIAL
(IMAGINARY PART)

FIG. 19

% MODULATION TRANSFER FUNCTION

FULL FIELD
\[ \delta \chi = 0.031 \text{ millimeters} \]
\[ \lambda = 5461 \text{ angstroms} \]

**FIG. 20**

- % Modulation Transfer Function
- Spatial Frequency: 598 lines/mm
- Axis
- Diffraction Limit

**FIG. 21**

- % Modulation Transfer Function
- Spatial Frequency: 598 lines/mm
- Sagittal Tangential
- Tangential (imaginary part)
- Field

**FIG. 22**

- % Modulation Transfer Function
- Spatial Frequency: 598 lines/mm
- Full Field
FIG. 23

% MODULATION TRANSFER FUNCTION

DIFFRACTION LIMIT

AXIS

SPATIAL FREQUENCY

610 LINES/MM

FIG. 24

% MODULATION TRANSFER FUNCTION

SAGITTAL

TANGENTIAL

TANGENTIAL (IMAGINARY PART)

.7 FIELD

SPATIAL FREQUENCY

610 LINES/MM

FIG. 25

% MODULATION TRANSFER FUNCTION

FULL FIELD

SPATIAL FREQUENCY

610 LINES/MM
VARIABLE REDUCTION LENS SYSTEM

This application is a continuation-in-part of copending parent U.S. Pat. application, Ser. No. 600,158 filed Dec. 8, 1966, now abandoned.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention is in the field of optics and more particularly relates to a lens group including lens elements.

SUMMARY OF THE INVENTION

It is well known that a given lens exceedingly well corrected at one working magnification will exhibit very poor performance at a different magnification (or reduction). In the production of miniature integrated circuits, by optical means, or in microfilming, the mask or document is reduced the desired amount by the lens producing the circuit or copy on some type of photoreceptive surface. If it is necessary to change this reduction by some desired amount, say from 20x to 17x, the same lens cannot be used at the new reduction and yet yield the usual high quality results, the two most offending aberrations being coma and astigmatism. For optimum results, a new lens especially corrected for the new reduction must be designed and employed. Versatility together with higher performance is therefore generally unattainable with one lens.

An object of the present invention is to provide a versatile lens system which may be used over a relatively large range of reductions with no appreciable loss in image quality.

Another object of the present invention is to provide a lens system wherein changes in reduction with constant high image quality may be accomplished with two simple adjustments.

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings.

In the drawings:

FIG. 1 is an optical diagram of a variable reduction lens system constructed according to the present invention.

FIG. 2 shows a chart of the constructional data for the lens system of FIG. 1.

FIGS. 3, 4 and 5 show curves of the modulation transfer function of the lens system of FIG. 1 calculated for a reduction value of 20X at the optical axis, at 0.7 field, and at full field, respectively.

FIGS. 6, 7 and 8 show curves of the modulation transfer function of the lens system of FIG. 1 calculated for a reduction value of 17x at the optical axis, at 0.7 field, and at full field, respectively, when said lens is not modified according to the present invention.

FIG. 9 is a curve of the astigmatism of the lens of FIG. 1 for a reduction of 17x when not modified according to the present invention.

FIG. 10 is a curve of one air space on one reciprocal radius of curvature of the lens system of FIG. 1 plotted as functions of reciprocal reduction.

FIGS. 11, 12 and 13 are curves of the modulation transfer function of the lens system of FIG. 1 calculated at the optical axis, 0.7 field, and full field, respectively, for a reduction of 15x.

FIGS. 14, 15 and 16 are similar modulation transfer function curves for a reduction of 30x.

FIGS. 17, 18 and 19 are similar modulation transfer function curves for a reduction of 40x.

FIGS. 20, 21 and 22 are similar modulation transfer function curves for a reduction of 50x.

FIGS. 23, 24 and 25 are similar modulation transfer function curves of an object at infinity.

FIG. 26 shows curves of the astigmatism for the lens of the present invention for reductions of 15x, 20x, 30x, 40x and 50x.

FIG. 27 shows curves of the distortion for the lens of the present invention for reductions of 15x, 20x, 30x, 40x, and 50x.

FIG. 28 is a schematic drawing of an adjustable reduction camera including the lens system of the present invention.

Referencing FIG. 1 an embodiment of a variable reduction lens is shown including eight lens elements designated as elements I, II, III, IV, V, VI, VII and VIII. Elements I and II are meniscus singlet lenses, lens elements III and IV are cemented together to form a meniscus doublet lens element V is a negative meniscus singlet lens; lens elements VI and VII are cemented together to form a meniscus doublet lens, and lens element VIII is a biconvex lens. The lenses are optically aligned on axis 10, and a diaphragm 12 is provided between lens elements V and VI.

At 5461 Angstroms, the lens system of FIG. 1 has an effective focal length of 113.62 millimeters, a back focal length of 59.26 millimeters, and a front focal length of 46.78 millimeters designed for a reduction of 20x.

The following table sets forth the constructional data for an embodiment of the present invention.

<table>
<thead>
<tr>
<th>Lens</th>
<th>Radius</th>
<th>Thickness (t) or airspace (s)</th>
<th>Np</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>R1 = -0.940F</td>
<td>t1 = 0.005F</td>
<td>1.69089</td>
<td>54.80</td>
</tr>
<tr>
<td>II</td>
<td>R2 = -3.081F</td>
<td>s1 = 0.004F</td>
<td>1.69089</td>
<td>54.80</td>
</tr>
<tr>
<td>III</td>
<td>R3 = -0.903F</td>
<td>s1 = 0.004F</td>
<td>1.69089</td>
<td>54.80</td>
</tr>
<tr>
<td>IV</td>
<td>R4 = 1.3401F</td>
<td>s1 = 0.004F</td>
<td>1.69089</td>
<td>54.80</td>
</tr>
<tr>
<td>V</td>
<td>R5 = 2.406F</td>
<td>s1 = 0.003F</td>
<td>1.04752</td>
<td>33.80</td>
</tr>
<tr>
<td>VI</td>
<td>R6 = 1.220F</td>
<td>s1 = 1.320F</td>
<td>1.04752</td>
<td>33.80</td>
</tr>
<tr>
<td>VII</td>
<td>R7 = 1.623F</td>
<td>s1 = 0.009F</td>
<td>1.04752</td>
<td>33.80</td>
</tr>
<tr>
<td>VIII</td>
<td>R8 = 2.393F</td>
<td>s1 = 0.009F</td>
<td>1.04752</td>
<td>33.80</td>
</tr>
</tbody>
</table>

wherein R1 through R8 represent the radii of curvature of the associated individual lens elements; t1 through t8 represent the axial thicknesses of the associated lens elements; S1 through S8 represent the axial spacing between the associated lens elements; Np represents the refractive index and V represents the Abbe number of each lens element.

The following Table I of mathematical statements lists the range of constructional data of the lens system of FIG. 1.

<table>
<thead>
<tr>
<th>R1 through R8</th>
<th>t1 through t8</th>
<th>s1 through S8</th>
<th>Np</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.92F &lt; R1 &lt; 1.06F</td>
<td>0.005F &lt; t1 &lt; 0.007F</td>
<td>1.69089 &lt; Np &lt; 1.69091</td>
<td>54.80 &lt; V &lt; 54.82</td>
<td></td>
</tr>
<tr>
<td>0.90F &lt; R2 &lt; 0.94F</td>
<td>0.003F &lt; t2 &lt; 0.005F</td>
<td>1.69089 &lt; Np &lt; 1.69091</td>
<td>54.80 &lt; V &lt; 54.82</td>
<td></td>
</tr>
<tr>
<td>0.90F &lt; R3 &lt; 0.96F</td>
<td>0.003F &lt; t3 &lt; 0.005F</td>
<td>1.69089 &lt; Np &lt; 1.69091</td>
<td>54.80 &lt; V &lt; 54.82</td>
<td></td>
</tr>
<tr>
<td>0.90F &lt; R4 &lt; 0.96F</td>
<td>0.003F &lt; t4 &lt; 0.005F</td>
<td>1.69089 &lt; Np &lt; 1.69091</td>
<td>54.80 &lt; V &lt; 54.82</td>
<td></td>
</tr>
<tr>
<td>0.90F &lt; R5 &lt; 0.96F</td>
<td>0.003F &lt; t5 &lt; 0.005F</td>
<td>1.69089 &lt; Np &lt; 1.69091</td>
<td>54.80 &lt; V &lt; 54.82</td>
<td></td>
</tr>
<tr>
<td>0.90F &lt; R6 &lt; 0.96F</td>
<td>0.003F &lt; t6 &lt; 0.005F</td>
<td>1.69089 &lt; Np &lt; 1.69091</td>
<td>54.80 &lt; V &lt; 54.82</td>
<td></td>
</tr>
<tr>
<td>0.90F &lt; R7 &lt; 0.96F</td>
<td>0.003F &lt; t7 &lt; 0.005F</td>
<td>1.69089 &lt; Np &lt; 1.69091</td>
<td>54.80 &lt; V &lt; 54.82</td>
<td></td>
</tr>
<tr>
<td>0.90F &lt; R8 &lt; 0.96F</td>
<td>0.003F &lt; t8 &lt; 0.005F</td>
<td>1.69089 &lt; Np &lt; 1.69091</td>
<td>54.80 &lt; V &lt; 54.82</td>
<td></td>
</tr>
</tbody>
</table>

R1 through R8 represent the respective radii of the lenses as designated in FIG. 1. t1 through t8 represent the respective thickness of the lenses along axis 10. S1 through S8 represent the airspaces between the respective lenses along the axis 10, all set forth as functions of the effective focal length F (113.62 millimeters). The fixed diaphragm of 20.8 millimeters diameter at f/3 is located 3.7 millimeters to the right of lens element V.

FIGS. 3, 4 and 5 are curves of the modulation transfer function of the lens system of FIG. 1 calculated at the axis 10, at
0.7 field, and at full field, respectively. The calculations were done at a of 5461 Angstroms and F=113.62 millimeters covering a linear field of ±16 millimeters reduced from ±320 millimeters.

The uniform high correction is illustrated in FIGS. 3, 4 and 5 by the slight departure of all curves from the diffusion limit. The magnitude of the imaginary part of the tangential fan is quite small and its reversal of sign denotes a balance of the residual coma. On the other hand when the lens system of FIG. 1 is used at a reduction of 17X, the modulation transfer function curves calculated at this new reduction shown in FIGS. 6, 7 and 8 readily show how the performance drops when the lens is not used at its designed reduction. The imaginary part of the tangential fan is extremely large, causing the lens to be useless at even this small change in reduction. The astigmatism at 17X reduction as shown in FIG. 9 is also far too large to yield acceptable performance. The maximum value of Y in FIG. 9 (and FIGS. 26 and 27) is 16.0 millimeters.

The present invention is directed to the manner in which the lens system of FIG. 1 can be slightly modified so as to provide a lens arrangement which can be used over a wide range of reductions while still maintaining the same high correction at each reduction. It has been found that by adjusting merely the shape associated with just one lens element (element V) of FIG. 1, such a lens system is obtainable rather than the usual requirement of redesigning an entire new lens system for each reduction. Thus the seven lens elements and their spacings (lens elements I through IV and VI through VIII) with the exception of spacing S, remain the same over a wide range of reductions. Furthermore, the adjustment of lens element V is in accordance with a given procedure as follows:

When the reduction of a lens system is changed form the initial design value, the main cause of the poor performance of the lens system is due to two aberrations; coma and astigmatism. In the present invention the coma and astigmatism aberrations can be rebalanced by changing only two parameters, the coma being rebalanced by changing the shape of element V and the astigmatism being rebalanced by changing airspage S.

Considering first coma correction, since element V is relatively thin and close to the diaphragm of the system, its astigmatic contribution is mainly a function of the lens power and almost independent of its shape. Also, since the nominal shape of lens element V is such that the lens is working close to minimum deviation for the axial bundle, the spherical aberration changes slowly as a function of bending. The Seidel coma contribution of lens element V, however, changes rapidly with bending, and since the higher order comatic aberrations of the entire lens system change slowly at different reductions, bending lens element V as a function of reduction thus balances all orders of coma with very small zonal residuals.

The modulation transfer function curves of the lens system of FIG. 1 at a reduction of 20X is shown in FIGS. 3, 4 and 5. The modulation transfer function curves for the lens system with element V adjusted at a reduction of 15X is shown in FIGS. 11, 12 and 13. A comparison of the curves at the two reductions illustrates at both reductions the imaginary parts of the tangential fan are quite small. The correction can be appreciated by contrasting the curves of FIGS. 11, 12 and 13 at a reduction of 15X with those of FIGS. 6, 7 and 8 for the unmodified lens system at a reduction of 17X. The total curvature of lens element V of FIG. 1 is represented by the expression

\[ C = C_0 - \frac{1}{R_s} \]

\[ C = -0.0085566 \text{ (millimeters)}^{1/2} \]

Thus, when the curvature \( C_0 \) (i.e., \( 1/R_s \)) is properly specified for a desired reduction power the curvature \( C_0 \) (i.e., \( 1/R_s \)) may be calculated.

Referring to FIG. 10, the proper value of \( C_0 \) is plotted as a function of the reduction powers and reciprocal of the reduction powers. Presume that the lens system of FIG. 1 is desired to be used at a reduction of 30X. In FIG. 10, an abscissa of 30X (or reciprocal reduction 0.033) for curvature \( C_0 \) has an ordinate of 0.005586 millimeters which is an effective focal length F of 113.62 millimeters in R = 1.5019F.

Also since \( C = 1/R_a = 1/R_s \) and

\[ C = -0.0085566, \text{ then} \]

\[ 1/R_0 = 0.0085566/0.005586 = 0.144166 \text{ millimeters}^{1/2} \]

which for F of 113.62 millimeters is 0.6105 F. In like manner the values of \( R_a \) and \( R_s \) can be calculated for any reduction power thereby specifying the curvature of lens element V.

To re-establish the astigmatism aberration the airspace S is changed. Referring again to FIG. 10, the airspace S is plotted as a function of the reduction power and its reciprocal.

For a reduction of 30X the abscissa of curve S has an ordinate 0.533 millimeters which means \( S = 0.533 \text{ millimeters or} \]

\[ 0.00469 \text{ F where} \ F = 113.62 \text{ millimeters.} \]

Using the curves of FIG. 10 the constructional data for the shape of lens element V and airspace S can be determined for each reduction. The following table lists the values of \( S \) and \( 1/R_0 \) for various reductions.

<table>
<thead>
<tr>
<th>Reduction</th>
<th>( S ) millimeters</th>
<th>( 1/R_0 ) millimeters</th>
</tr>
</thead>
<tbody>
<tr>
<td>30X</td>
<td>0.400</td>
<td>0.004588</td>
</tr>
<tr>
<td>25X</td>
<td>0.390</td>
<td>0.004557</td>
</tr>
<tr>
<td>30X</td>
<td>0.393</td>
<td>0.004589</td>
</tr>
<tr>
<td>40X</td>
<td>0.376</td>
<td>0.004530</td>
</tr>
<tr>
<td>50X</td>
<td>0.316</td>
<td>0.003659</td>
</tr>
<tr>
<td>Object at infinity</td>
<td>0.080</td>
<td>0.00952</td>
</tr>
</tbody>
</table>

It is to be particularly noted that lens elements I, II, III, IV, VI, VII and VIII and airspaces \( S_1 \), \( S_2 \), \( S_3 \), \( S_4 \) and \( S_5 \) of the embodiment were not changed. To illustrate that the lens system has constant high correction at the various reductions, the modulation transfer function curves were plotted for the lens system at the different reductions. FIGS. 11, 12 and 13 show the curves for a reduction of 15X, FIGS. 14, 15 and 16 show the curves for a reduction of 30X, FIGS. 17, 18 and 19 show the curves for a reduction of 40X, FIGS. 20, 21 and 22 show the curves for a reduction of 50X, and FIGS. 23, 24 and 25 show the curves for an object at infinity. The limiting case of object at infinity is provided to demonstrate the scope of the lens of the present invention. All curves denote extremely high performance over this range, with the residual coma quite small in magnitude and again of a balanced state. The astigmatism is also quite small (as shown in FIG. 26) and the distortion in no case exceeds 0.1 percent (as shown in FIG. 27). The reduction for the astigmatism curves and the distortion curves are set forth in FIGS. 26 and 27. The calculations for all reductions were done at F=113.62 millimeters covering a linear image field of ±16 millimeters.

Other embodiments of lens systems in accordance with the present invention may be selected from the ranges previously set forth in Table I. The other embodiments will have the same extremely high resolution over a relatively small field as set forth for the embodiment of FIG. 1. In particular, five additional embodiments of lens systems for reductions of 20X will be hereinafter set forth as embodiments two through six. The embodiments have different constructional data than that of FIG. 1 and particular parameters have been selected to be at or beyond the limits of the ranges previously set forth in Table I. After specifying the six additional embodiments, the modulation transfer functions of the embodiments at axis, at 0.7 field and at full field will be set forth in Table II and compared in tabular form with the modulation transfer functions of the embodiment of FIG. 1 illustrated in FIGS. 3, 4 and 5. The modulation transfer functions of embodiments two through six cannot be compared graphically with those shown in FIGS. 7, 8 and 9 because the scale used would not show any distinction. This in itself is an indication that all six embodiments provide the same high resolution as will other embodi-
ments of the invention with the ranges set forth in Table I and will illustrate to one skilled in the art that lens systems in accordance with the present invention can be selected from the ranges of Table I.

<table>
<thead>
<tr>
<th>Embodiment</th>
<th>Radii</th>
<th>S</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Third</td>
<td>R1 = -1.9463F</td>
<td>S1 = -0.044F</td>
<td>t1 = 0.061F</td>
</tr>
<tr>
<td></td>
<td>R2 = -1.351F</td>
<td>S2 = -0.044F</td>
<td>t2 = 0.061F</td>
</tr>
<tr>
<td></td>
<td>R3 = -1.32F</td>
<td>S3 = 0.023F</td>
<td>t3 = 0.023F</td>
</tr>
<tr>
<td></td>
<td>R4 = -0.216F</td>
<td>S4 = 0.084F</td>
<td>t4 = 0.084F</td>
</tr>
</tbody>
</table>

R4 is changed and is below the range 3.60F < +R4 < 4.00F

<table>
<thead>
<tr>
<th>Embodiment</th>
<th>Radii</th>
<th>S</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fourth</td>
<td>R1 = -1.011F</td>
<td>S1 = -0.041F</td>
<td>t1 = 0.061F</td>
</tr>
<tr>
<td></td>
<td>R2 = -1.357F</td>
<td>S2 = 0.044F</td>
<td>t2 = 0.044F</td>
</tr>
<tr>
<td></td>
<td>R3 = -1.32F</td>
<td>S3 = 0.025F</td>
<td>t3 = 0.025F</td>
</tr>
<tr>
<td></td>
<td>R4 = -0.214F</td>
<td>S4 = 0.084F</td>
<td>t4 = 0.084F</td>
</tr>
</tbody>
</table>

R4 is changed and is above the range 0.66F < t < 0.72F

<table>
<thead>
<tr>
<th>Embodiment</th>
<th>Radii</th>
<th>S</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fifth</td>
<td>R1 = -1.026F</td>
<td>S1 = -0.049F</td>
<td>t1 = 0.061F</td>
</tr>
<tr>
<td></td>
<td>R2 = -1.35F</td>
<td>S2 = -0.044F</td>
<td>t2 = 0.061F</td>
</tr>
<tr>
<td></td>
<td>R3 = -1.32F</td>
<td>S3 = 0.025F</td>
<td>t3 = 0.025F</td>
</tr>
<tr>
<td></td>
<td>R4 = -0.21F</td>
<td>S4 = 0.084F</td>
<td>t4 = 0.084F</td>
</tr>
</tbody>
</table>

R4 is changed above upper limits and R3 and R4 are at their respective lower limits.

<table>
<thead>
<tr>
<th>Embodiment</th>
<th>Radii</th>
<th>S</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sixth</td>
<td>R1 = -1.030F</td>
<td>S1 = -0.069F</td>
<td>t1 = 0.069F</td>
</tr>
<tr>
<td></td>
<td>R2 = -1.661F</td>
<td>S2 = -0.044F</td>
<td>t2 = 0.061F</td>
</tr>
<tr>
<td></td>
<td>R3 = -0.036F</td>
<td>S3 = 0.025F</td>
<td>t3 = 0.025F</td>
</tr>
<tr>
<td></td>
<td>R4 = -0.21F</td>
<td>S4 = 0.084F</td>
<td>t4 = 0.084F</td>
</tr>
</tbody>
</table>

R4 is changed to beyond upper range. t4 changed to its upper limit.

<table>
<thead>
<tr>
<th>Table II</th>
<th>Radii</th>
<th>S</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>25</td>
<td>62.3</td>
<td>61.4</td>
</tr>
<tr>
<td>75</td>
<td>15.6</td>
<td>12.7</td>
<td>10.4</td>
</tr>
<tr>
<td>35</td>
<td>80.7</td>
<td>58.6</td>
<td>58.6</td>
</tr>
<tr>
<td>75</td>
<td>14.8</td>
<td>12.7</td>
<td>10.8</td>
</tr>
<tr>
<td>45</td>
<td>80.0</td>
<td>58.6</td>
<td>58.6</td>
</tr>
<tr>
<td>75</td>
<td>14.8</td>
<td>12.7</td>
<td>10.8</td>
</tr>
</tbody>
</table>

The lens system of the present invention is extremely versatile, being capable of replacing an almost infinite number of conventional fixed design reduction lenses. In operation, the lens system may be embodied in a camera. Referring to FIG. 28, a schematic drawing of the mechanical elements of such camera are shown. In FIG. 28 in lens elements I, II, III, IV, VI, VII and VIII and their spacing (with the exception of S0) are identical to those shown in FIG. 1 and as described in FIG. 2. A turret A is provided which contains a plurality of different lens elements V, each one designed for a different reduction power as previously described. A selected lens element V for a desired reduction is introduced into the lens system by rotation of the turret 14 by handle 16. For each of the lens elements V a corresponding airspace S0 distance must be established. This is accomplished by a lead screw arrangement 18 which moves lens elements I and II in unison toward or away from lens element III so that a desired distance S0 may be established while the remaining airspaces of the lens system remain constant. It should be noted that lens element V is also the least expensive lens element.

While the invention has been particularly shown and described with reference to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention.

We claim:
1. A variable reduction lens system comprising first, second, third, fourth, fifth, sixth, seventh and eighth optically aligned lens elements wherein said first and second lens elements are meniscus singlet lenses, said third and fourth lens elements are meniscus singlet lenses cemented together to form a meniscus doublet, said fifth lens element is a negative meniscus singlet lens, said sixth and seventh lens elements are meniscus singlet lenses;
lenses cemented together to form a meniscus doublet, and said eighth lens element is a biconvex lens, and wherein said first lens element has radii of curvature \( R_1 \) and \( R_2 \) and thickness \( t_1 \), said second lens element has radii of curvature \( R_3 \) and \( R_4 \) and thickness \( t_2 \), said third lens element has radii of curvature \( R_5 \) and \( R_6 \) and thickness \( t_3 \), said fourth lens element has radii of curvature \( R_7 \) and \( R_8 \) and thickness \( t_4 \), said sixth lens element has radii of curvature \( R_{10} \) and \( R_{11} \) and thickness \( t_6 \), said seventh lens element has radii \( R_{12} \) and \( R_{13} \) and thickness \( t_7 \), and said eighth lens element has radii \( R_{14} \) and \( R_{15} \) and thickness \( t_8 \), wherein said first and second lens elements are axially separated by a distance \( S_1 \), said fourth and fifth lens elements are separated by an axial distance \( S_2 \), said fifth and sixth lens elements are separated by an axial distance \( S_3 \), and said seventh and eighth lens elements are separated by an axial distance \( S_4 \), wherein said radii, thicknesses and spacings are within limits as follows where \( F \) is the effective focal length of the lens group:

\[
0.9F < R_1 < 1.0F \\
3.60F < R_1 < 4.00F \\
0.8F < R_2 < 0.9F \\
0.4F < R_2 < 0.6F \\
2.2F < R_2 < 2.8F \\
2.0F < R_2 < 3.0F \\
2.0F < R_2 < 2.6F \\
1.5F < R_2 < 1.8F \\
0.8F < R_2 < 1.0F \\
0.5F < R_2 < 0.6F
\]

\[
0.9F < t_1 < 0.9F \\
0.9F < t_2 < 0.9F \\
0.9F < t_3 < 0.9F \\
0.9F < t_4 < 0.9F \\
0.9F < t_5 < 0.9F \\
0.9F < t_6 < 0.9F \\
0.9F < t_7 < 0.9F \\
0.9F < t_8 < 0.9F
\]

wherein said fifth lens element has radii of curvature \( R_9 \) and \( R_4 \) having values which are a function of the reduction power of said lens system, and wherein said second and third lens elements are axially separated by a distance \( S_5 \) having a value which is a function of the reduction power of said lens group.

2. A variable reduction lens system according to claim 1 having numerical data substantially as follows:

<table>
<thead>
<tr>
<th>Lens</th>
<th>Radius</th>
<th>Thickness (t) or airspace (s)</th>
<th>( N_D )</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>I...</td>
<td>( R_1 = +0.9840F )</td>
<td>( t_1 = .0591F )</td>
<td>1.60989</td>
<td>54.80</td>
</tr>
<tr>
<td>I...</td>
<td>( R_2 = +3.8081F )</td>
<td>( t_2 = .0548F )</td>
<td>1.60989</td>
<td>54.80</td>
</tr>
<tr>
<td>I...</td>
<td>( R_3 = +0.6089F )</td>
<td>( t_3 = .0571F )</td>
<td>1.60989</td>
<td>54.80</td>
</tr>
<tr>
<td>I...</td>
<td>( R_4 = +0.3461F )</td>
<td>( t_4 = .0595F )</td>
<td>1.60989</td>
<td>54.80</td>
</tr>
<tr>
<td>II...</td>
<td>( R_4 = +1.4003F )</td>
<td>( t_4 = .0392F )</td>
<td>1.64752</td>
<td>33.80</td>
</tr>
<tr>
<td>IV...</td>
<td>( R_4 = +0.2320F )</td>
<td>( t_4 = .1329F )</td>
<td>1.64752</td>
<td>33.80</td>
</tr>
<tr>
<td>II...</td>
<td>( R_4 = +1.2229F )</td>
<td>( t_4 = .0299F )</td>
<td>1.64752</td>
<td>33.80</td>
</tr>
<tr>
<td>VI...</td>
<td>( R_4 = -0.2833F )</td>
<td>( t_4 = .2896F )</td>
<td>1.60328</td>
<td>38.02</td>
</tr>
<tr>
<td>VII...</td>
<td>( R_{11} = -2.3999F )</td>
<td>( t_4 = .2894F )</td>
<td>1.60089</td>
<td>54.80</td>
</tr>
<tr>
<td>VIII...</td>
<td>( R_{11} = +1.3830F )</td>
<td>( t_4 = .0044F )</td>
<td>1.60089</td>
<td>54.80</td>
</tr>
<tr>
<td>VIII...</td>
<td>( R_{14} = -0.8977F )</td>
<td>( t_4 = .2792F )</td>
<td>1.60089</td>
<td>54.80</td>
</tr>
</tbody>
</table>

wherein \( R_1 \) through \( R_4 \) represent the radii of curvature of the associated individual lens elements, \( t_1 \) through \( t_4 \) represent the axial thicknesses of the associated lens elements, \( S_1 \) through \( S_4 \) represent the axial spacing between the associated lens elements, \( N_D \) represents the refractive index and \( V \) represents the Abbe number of each lens element.
Patent No. 3,588,228  Dated June 28, 1971
Inventor(s) Janusz S. Wilczynski; Raymond E. Tibbetts

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In the Patent:
Section 3, line 40  "S" should be --S2--

In the Application:
Page 7, line 20  States "S2".

In the Patent:
Section 7, line 5  "thickness t1" should be --thickness t2--

In the Application:
Amendment A, page 5, line 13 states "thickness t2".

In the Patent:
Section 7, line 6  "thickness t2" should be --thickness t3--

In the Application:
Amendment A, page 5, line 15 states "thickness t3".

Signed and sealed this 27th day of June 1972.

(SEAL)
Attest:
EDWARD M. FLETCHER, JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents