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(54) **Method of and apparatus for forming focusing diffraction gratings for integrated optics.**

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US - A - 3 578 845
US - A - 3 864 130
US - A - 3 991 386

OPTICS COMMUNICATIONS, vol. 20, nr. 1, January 1977, Publ. North Holland, Amsterdam (NL)
A. LIVANOS et al. "Fabrication of grating structures with variable Period", pages 179—182

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Method of and apparatus for forming focusing diffraction gratings for integrated optics

The invention relates to methods and apparatus for producing holographic diffraction gratings and the like. Gratings that have substantially equal spacing between their lines are referred to as being unchirped. They are especially useful for focusing as well as diffracting light in integrated optical devices.

Gratings have been incorporated in integrated optics devices for several purposes, including the fabrication of distributed feedback lasers, light-wave couplers, and band-rejection filters. Integrated-optics gratings known to the prior art were composed of straight lines, and therefore could not focus the light being processed. Gratings that combine focusing and diffraction were known to be desirable, but the prior art was unable to produce them.

U.S. Patent 3,578,845 discloses a method and apparatus for producing curved-line holographic gratings that have unequally spaced, or chirped, lines. This patent teaches the production of gratings that focus light that propagates into and out of the plane of the grating. It does not teach the relative orientation of laser beams and focal lines that are required in order to produce curved-line gratings that will function in integrated optics devices.

With the invention as claimed one of two coplanar beams which form an interference pattern on a planar surface perpendicular to the plane of the beams is focused to a focal line in the plane of the beams so that the interference pattern comprises substantially equispaced curved fringes. The other beam may be focused to infinity or it may also be focused to a focal line in the plane of the beams.

The invention is particularly applicable to the production of unchirped, curved-line, holographic diffraction gratings in thin films, which gratings will focus as well as diffract light that is confined to the film in which the grating is formed. (In integrated optics, the film containing the light is called optical waveguide, and the waveguide with a grating in it is called a corrugated waveguide.) The gratings are made by forming an interference pattern in a photosensitive material, photographically processing the interference pattern so formed such as by developing and fixing, and then using the fixed pattern as a mask for ion or chemical etching processes of conventional type to form corrugated waveguides.

In one embodiment of the invention two cylindrically focused beams of coherent optical radiation are provided for writing holographic diffraction gratings. The focal lines of the beams are oriented in a predetermined manner with respect to each other and with respect to the grating being written. The focal lines of the two beams are coplanar and are oriented so that the plane which contains the focal lines also contains the axis of the grating, thereby providing uniform spacing between the grating lines.

Some embodiments of the invention will now be described by way of example with reference to the accompanying drawings, in which

FIGS. 1A, 1B and 1C show apparatus for forming gratings according to an embodiment of the invention and

FIGS. 2A to 2L show different gratings according to embodiments of the invention and the methods employed in forming these gratings.

An optical system used to form curved-line gratings is shown in FIG. 1A. It involves two oblique coherent light beams 1 and 2, generated by conventional means not shown, focused by two cylindrical lenses 3 and 4, respectively. A curved-line grating is formed by recording the interference pattern of the two light beams on a photoresist plate 5. Plate 5 is in the (x, z) vertical plane with $y = 0$. Lenses 3 and 4 are centered in a horizontal plane at $z = 0$, and the beams are also horizontal. Lines bc and ac, along the center of the two beams are thus also horizontal, and planes adce and bdce are vertical. Note that in this invention, lines f—f and g—g, the focal lines of beams 1 and 2 respectively, are horizontal and are not necessarily parallel to the plate. This is in contrast with the prior art apparatus of U.S. Patent 3,578,845 referred to above in which focal lines would be oriented in the vertical direction and parallel to the photosensitive plate (see FIGS. 4 and 6 of Patent 3,578,845). The relative orientation of these focal lines and their relationship with the plate 5 determine the form of grating that will be formed and are the key to the invention.

In FIG. 1A, the beams are shown as being centered in a horizontal plane at $z = 0$. The particular value of z and the choice of a horizontal plane are, of course, arbitrarily chosen in order to make the illustration more comprehensible. The essential point is that the two incident beams are coplanar, i.e. they are centered about the same plane (the "beam plane"), and that plane is substantially perpendicular to the plane of the photosensitive material. Since the focal lines f—f and g—g and lenses 3 and 4 are centered in their respective beams, they lie in the "beam plane" also. The above remarks hold true even if one or more of the beams is collimated and the corresponding focal line is theoretically at infinity. If one focal line lies at a great distance from the photosensitive plate, the beam plane is still unambiguously defined by the centers of the beams, the centers of the lenses and the other focal line.

In designing a grating, the curvature of each fringe and the spacing between fringes on the *x* axis must be specified. The curvature is specified by the formula:

C(incident) + C(reflection) = 2C(fringe), (1)
where incident and reflection refers to the light being processed. The inter-fringe spacing is specified by the Bragg-reflection condition:

$$2\,\beta\,.\,\hat{x} = m\,G \qquad (2)$$

where

$$\beta = 2\pi/\lambda,\ G = 2\,\pi/d, \qquad (3)$$

d is the inter-fringe spacing, $\hat{x}$ is the unit vector in the positive *x*-direction, *m* is an integer specifying the diffraction order, and λ is the wavelength of the light beams 1 and 2.

The curvature of the fringe may also be expressed in terms of the beams 1 and 2 used to write the grating. In FIG. 1B, which shows a view looking down on the x, y plane of FIG. 1A, $\overline{ac}$ is the distance along the direction of propagation of beam 1 from focal line f—f to the *x* axis, and $\overline{bc}$ is the corresponding distance for beam 2.

The curvature of the fringes may be expressed in terms of the wavefront curvatures of the two beams.

$$C = C_A - C_B$$

$$= \frac{1}{2\cos\alpha}\left(\frac{1}{ac} - \frac{1}{bc}\right)$$

$$= \frac{-1}{2\cot\alpha}\left[\frac{\cot\alpha - \cot\beta_A}{x - \Delta} + \frac{\cot\alpha + \cot\beta_B}{x}\right] \qquad (4)$$

where x = o at G, Δ = the distance $\overline{\text{F—G}}$, and α is the angle between the direction of propagation of beam 1 and the x-axis. Equations 1 through 4 permit the design of gratings to accomplish the various tasks disclosed above.

FIG. 1C shows a plan view looking down on the x, y plane of the apparatus shown in FIG. 1A, further including the source of beams 1 and 2. For ease of illustration, the particular case where the beams intersect the x-axis at an angle α of 45 degrees is shown. Other configurations of beam angle and therefore of mirror position will be required to form gratings for various purposes and may be readily calculated by those skilled in the art from the information disclosed in this application.

In FIG. 1C, laser 9 generates a parallel beam of coherent optical radiation. It may be desired to employ a mask 10 to define the shape of the beam envelope (rectangular, square, et cetera). The beam from laser 9 is split by beam splitter 8, forming beams 1 and 2. These two beams are reflected by mirrors 6 and 7 into lenses 3 and 4 respectively. The position of all these elements will, of course, be adjusted to give the angles between beams 1 and 2 and plate 5 and the positions of focal lines f—f and g—g that are required by Equations 1 to 4 to provide the grating parameters that are desired.

In the first example of gratings design, shown in FIG. 2A, a grating is used to reflect and focus light emitting from a point source G in a waveguide back to that same point. FIG. 2B illustrates the optics used, looking down on the x—y plane. In this and the following cases, the first figure shows the grating in operation, and the next figure shows the parameters used to write the grating. Beam 1, focused at infinity, crosses the *x* axis at an angle α. Beam 2 is focused at line g—g, which crosses the *x* axis at point G, the same point as the focus, at an angle β_B. In general, line g—g is not at right angles to the direction of propagation of beam 2, which is 180 — α. Note that in FIG. 2B, the lines 1 and 2 illustrate the center lines of the beams 1 and 2, respectively. The beams are wide and they overlap one another as they are projected to the plate forming an interference pattern.

In the second grating, a plane parallel beam in a waveguide is focused to a point, at G in the same waveguide (FIG. 2C). In FIG. 2D, we see that beam 1 (plane-parallel) is oriented as before, and that g—g is at right angles to the $\hat{x}$ axis, passing through point G. Beam 2 has the same direction of propagation as in FIG. 2B.

In the third grating as shown in FIG. 2E, we use the grating to form a lens-like medium, in which all the grating lines have the same curvature. To produce the grating of FIG. 2E, we place the focal line g—g parallel to the *x* axis as shown in FIG. 2F. The other parameters of the two beams are the same as in the previous examples of FIGS. 2B and 2D.

In the fourth grating (FIG. 2G), light in a waveguide is focused from point G on the *x* axis to point F, also on the *x* axis. To produce the grating of FIG. 2G, both beams 1 and 2 are focused at finite distances, both focal lines being perpendicular to the *x* axis as shown in FIG. 2H. Line f—f intersects the axis at point F, the image point, and line g—g intersects the axis at point G, the object point.

In addition to the above, embodiment gratings may be used to form resonators in diode-lasers. Consider a Hermite-Gaussian beam propagating in a waveguide along the *x* axis, the curvature of the wave front varies in *x* as

$$C = \frac{x}{N^2\beta^2a_o^4 + x^2} \qquad (5)$$

where N is the mode index of the waveguide,

$$\beta = \frac{2\pi}{\lambda},$$

and a_o is the radius of the beam at x = 0. A requirement for the formation of a grating resonator for such a beam is that the curvatures of the incident and reflected waves, given by Equation 5 as well as the curvatures of the fringes in the grating, agree with Equation 4.

As an illustration, we consider a resonator for an Al Ga As Sb Bragg-reflector laser shown in FIG. 2I. The gratings used as left and right reflectors are each 100 μ_m long. The center of the left reflector is located at $x = 0$, where $C = 0$, and the center of the right reflector is located at $x = D = 600\ \mu m$. The two reflectors are formed separately, the parameters of the right reflector being shown for purposes of illustration. Putting $x = D + \Delta x$ in Equation 5, and taking $D = 600\ \mu m$, $N = 3.6$, $\lambda = 1.3\ \mu m$ and $a_0 = 4\ \mu m$, we find $C \approx -1.37 \times 10^{-3}\ (1 - 0.93 \times 10^{-3} \Delta x)\ \mu m^{-1}$. This curvature may be realized by the arrangement shown in FIG. 2J. Here, $C_A = 0$, $\alpha = 40.13$, $\beta_B = 28.53$, and G is located 931 μm from D.

FIG. 2K shows another grating-resonator designed for a distributed feedback laser. The grating is 350 μm long and centered at $x = 0$. Two cylindrically focused beams are used, as shown in FIG. 2L. The parameters that match the requirements of Equation 4 satisfactorily are: $N = 3.6$, $\lambda = 1.3\ \mu m$, $a_0 = 5\ \mu m$, $\alpha = 40.1$, $\beta_A = -156.33$, $\beta_B = -23.67$, and G and F are located at $x = -583.33\ \mu m$ and $+583.33\ \mu m$.

The method discussed above applies equally well to forming unstable resonators, in which the light being reflected travels along a different path on each pass between the two ends of the grating.

One practical problem that may be overcome arises from the distortions that are introduced in the cylindrical wavefront by placing the focal line at an angle other than normal to the direction of propagation. The use of only the center portion of the grating reduces this effect. Secondly, the intensities of the beams vary somewhat along the *x* axis, tending to overexpose parts of the photoresist plate. This effect may be reduced by the use of spatially varied neutral density filters that may be empirically adjusted to provide a uniform exposure.

Claims

1. A method of forming an interference pattern with curved fringes in a planar piece of photosensitive material wherein a first beam (2) and a second beam (1) of coherent optical radiation, the centres of the beams being coplanar and defining a first plane (X, Y) are directed onto the piece of photosensitive material (5) lying in a second plane (X, Z) perpendicular to the first plane to form the interference pattern, the first beam being focused to a focal line (g—g) characterised in that the focal line lines in the first plane so that the interference pattern comprises substantially equispaced curved fringes.

2. A method as claimed in claim 1 wherein the second beam is focused to infinity.

3. A method as claimed in claim 1 wherein the second beam is focused towards a second focal line (f—f) lying in the first plane.

4. A method as claimed in claim 2 or claim 3 wherein the or each focal line is perpendicular to the second plane.

5. A method as claimed in any of the preceding claims wherein the or each focal line lies in front of the photosensitive material.

6. A method as claimed in any of claims 1 to 4 wherein the or each focal line lies behind the photosensitive material.

7. Apparatus for forming an optical interference pattern with curved fringes in a planar piece of photosensitive material comprising means arranged to provide a first beam (2) and a second beam (1) of coherent optical radiation such that the centres of the beams are coplanar and define a first plane (X, Y) and the first beam is focused to a focal line (g—g) and means arranged to support the photosensitive material (5) in a second plane (X, Z perpendicular to the first plane so that the beams form an interference pattern in the material characterised in that the focal line lies in the first plane so that the interference pattern comprises substantially equispaced curved fringes.

8. Apparatus as claimed in claim 7 wherein the beam-providing means are arranged so that the second beam is focused to infinity.

9. Apparatus as claimed in claim 7 wherein the beam-providing means are arranged so that the second beam is focused to a second focal line (f—f) lying in the first plane.

10. Apparatus as claimed in claim 8 or 9 wherein the or each focal line is perpendicular to the second plane.

11. Apparatus as claimed in any of claims 7 to 10 wherein the or each focal line lies in front of the second plane.

12. Apparatus as claimed in any of claims 7 to 10 wherein the or each focal line lies behind the second plane.

Patentansprüche

1. Verfahren zum Erzeugen eines Interferenzmusters mit gekrümmten Streifen in einem planaren lichtempfindlichen Materialstück, wobei ein erstes (2) und ein zweites (1) Strahlenbündel aus kohärenter optischer Strahlung, deren Strahlmitten koplanar sind und eine erste Ebene (X, Y) definieren, auf das lichtempfindliche Materialstück (5), das in einer zweiten, zur ersten Ebene senkrechten Ebene (X, Z) liegt, gerichtet werden, um ein Interferenzmuster zu erzeugen, und das erste Strahlenbündel in eine Brennlinie (g—g) fokussiert wird, dadurch gekennzeichnet, daß die Brennlinie in der ersten Ebene liegt, so

gleich beabstandete gekrümmte Streifen umfaßt.

2. Verfahren wie in Anspruch 1 beansprucht, wobei das zweite Strahlenbündel auf Unendlich fokussiert wird.

3. Verfahren wie in Anspruch 1 beansprucht, wobei das zweite Strahlenbündel auf eine zweite Brennlinie (f—f), die in der ersten Ebene liegt, fokussiert wird.

4. Verfahren wie in Anspruch 2 oder 3 beansprucht, wobei die oder jede Brennlinie senkrecht zur zweiten Ebene ist.

5. Verfahren wie in einem der vorangehenden Ansprüche beansprucht, wobei die oder jede Brennlinie vor dem lichtempfindlichen Material liegt.

6. Verfahren wie in einem der Ansprüche 1 bis 4 beansprucht, wobei die oder jede Brennlinie hinter dem lichtempfindlichen Material liegt.

7. Apparatus zum Erzeugen eines optischen Interferenzmusters mit gekrümmten Streifen in einem planaren lichtempfindlichen Materialstück, mit Mitteln, die dafür ausgelegt sind, ein erstes (2) und ein zweites (1) Strahlenbündel aus kohärenter optischer Strahlung so zu erzeugen, daß die Mitten der Strahlenbündel koplanar sind und eine erste Ebene (X, Y) definieren und das erste Strahlenbündel auf eine Brennebene (g—g) fokussiert ist, sowie mit Mitteln, die dafür ausgelegt sind, das lichtempfindliche Material (5) in einer zweiten, zur ersten Ebene senkrechten Ebene (X, Z) zu halten, so daß die Strahlenbündel ein Interferenzmuster in dem Material erzeugen, dadurch gekennzeichnet, daß die Brennlinie in der ersten Ebene liegt, so daß das Interferenzmuster im wesentlichen gleich beabstandete gekrümmte Streifen umfaßt.

8. Apparatur wie in Anspruch 7 beansprucht, wobei die Strahlenbündelerzeugungsmittel so ausgelegt sind, daß das zweite Strahlenbündel auf Unendlich fokussiert wird.

9. Apparatur wie in Anspruch 7 beansprucht, wobei die Strahlenbündelerzeugungsmittel so ausgelegt sind, daß das zweite Strahlenbündel auf eine zweite Brennlinie (f—f), die in der ersten Ebene liegt, fokussiert wird.

10. Apparatur wie in Anspruch 8 oder 9 beansprucht, wobei die oder jede Brennlinie senkrecht zur zweiten Ebene ist.

11. Apparatur wie in einem der Ansprüche 7 bis 10 beansprucht, wobei die oder jede Brennlinie vor der zweiten Ebene liegt.

12. Apparatur wie in einem der Ansprüche 7 bis 10 beansprucht, wobei die oder jede Brennlinie hinter der zweiten Ebene liegt.

Revendications

1. Procédé de formation d'une figure d'interférences avec franges courbes dans un élément plan de matière photosensible, dans lequel un premier faisceau (2) et un second faisceau (1) de rayonnement optique cohérent, les centre de ces faisceaux étant coplanaires et définissant un premier plan (X, Y), sont dirigés vers l'élément de matière photosensible (5) qui se trouve dans un second plan (X, Z) perpendiculaire au premier plan, pour former la figure d'interférences, le premier faisceau étant focalisé vers une ligne focale (g—g), caractérisé en ce que la ligne focale se trouve dans le premier plan, afin que la figure d'interférences soit constituée par des franges courbes pratiquement équidistantes.

2. Procédé selon la revendication 1, dans lequel le second faisceau est focalisé à l'infini.

3. Procédé selon la revendication 1, dans lequel le second faisceau est focalisé vers une seconde ligne focale (f—f) qui se trouve dans le premier plan.

4. Procédé selon la revendication 2 ou 3, dans lequel la ligne focale, ou chaque ligne focale, est perpendiculaire au second plan.

5. Procédé selon l'une quelconque des revendications précédentes, dans lequel la ligne focale ou chaque ligne focale se trouve devant la matière photosensible.

6. Procédé selon l'une quelconque des revendications 1 à 4, dans lequel la ligne focale, ou chaque ligne focale, se trouve derrière la matière photosensible.

7. Dispositif destiné à former une figure d'interférences optiques avec des franges courbes dans un élément plan de matière photosensible comprenant des moyens conçus de façon à produire un premier faisceau (2) et un second faisceau (1) de rayonnement optique cohérent, de façon que les centres des faisceaux soient coplanaires et définissent un premier plan (X, Y) et que le premier faisceau soit focalisé vers une ligne focale (g—g), et des moyens conçus de façon à supporter la matiere photosensible (5) dans un second plan (X, Z) perpendiculaire au premier plan, de façon que les faisceaux forment une figure d'interférences dans la matière, caractérisé en ce que la ligne focale se trouve dans le premier plan de façon que la figure d'interférences soit constituée par des franges courbes pratiquement équidistantes.

8. Dispositif selon la revendication 7, dans lequel les moyens qui produisent les faisceaux sont conçus de façon que le second faisceau soit focalisé à l'infini.

9. Dispositif selon la revendication 7, dans lequel les moyens qui produisent les faisceaux sont conçus de façon que le second faisceau soit focalisé vers une seconde ligne focale (f—f) qui se trouve dans le premier plan.

10. Dispositif selon la revendication 8 ou 9, dans lequel la ligne focale, ou chaque ligne focale, est perpendiculaire au second plan.

11. Dispositif selon l'une quelconque des revendications 7 à 10, dans lequel la ligne focale, ou chaque ligne focale, se trouve devant le second plan.

12. Dispositif selon l'une quelconque des revendications 7 à 10, dans lequel la ligne focale, ou chaque ligne focale, se trouve derrière le second plan.

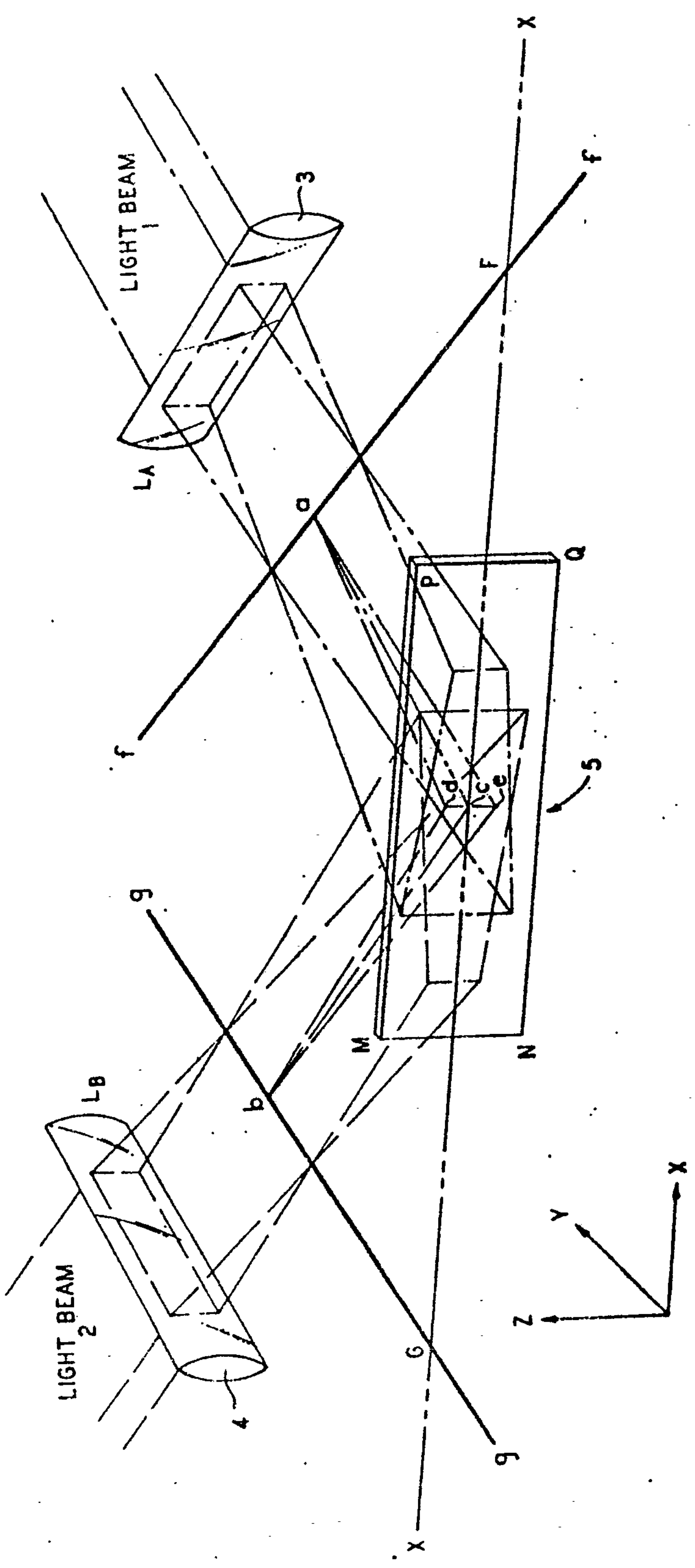

FIG. 1A
OPTICAL SYSTEM

FIG. 1B

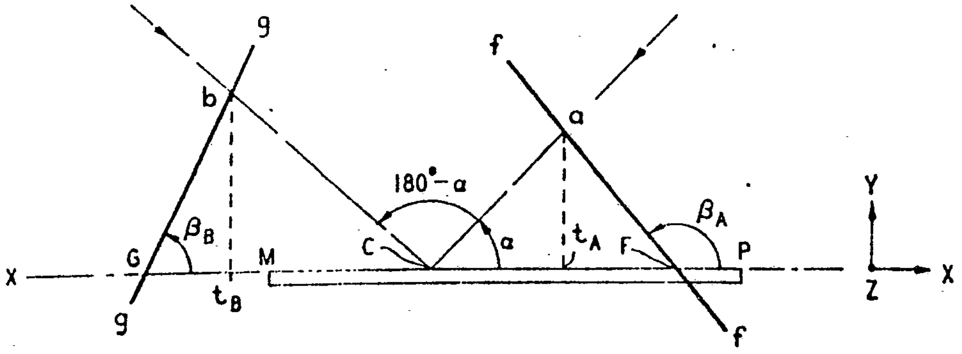
g
b
f
a
180°-α
β_A
Y
X
G
β_B
M
C
α
t_A
F
P
X
Z
t_B
g
f

FIG. 1C

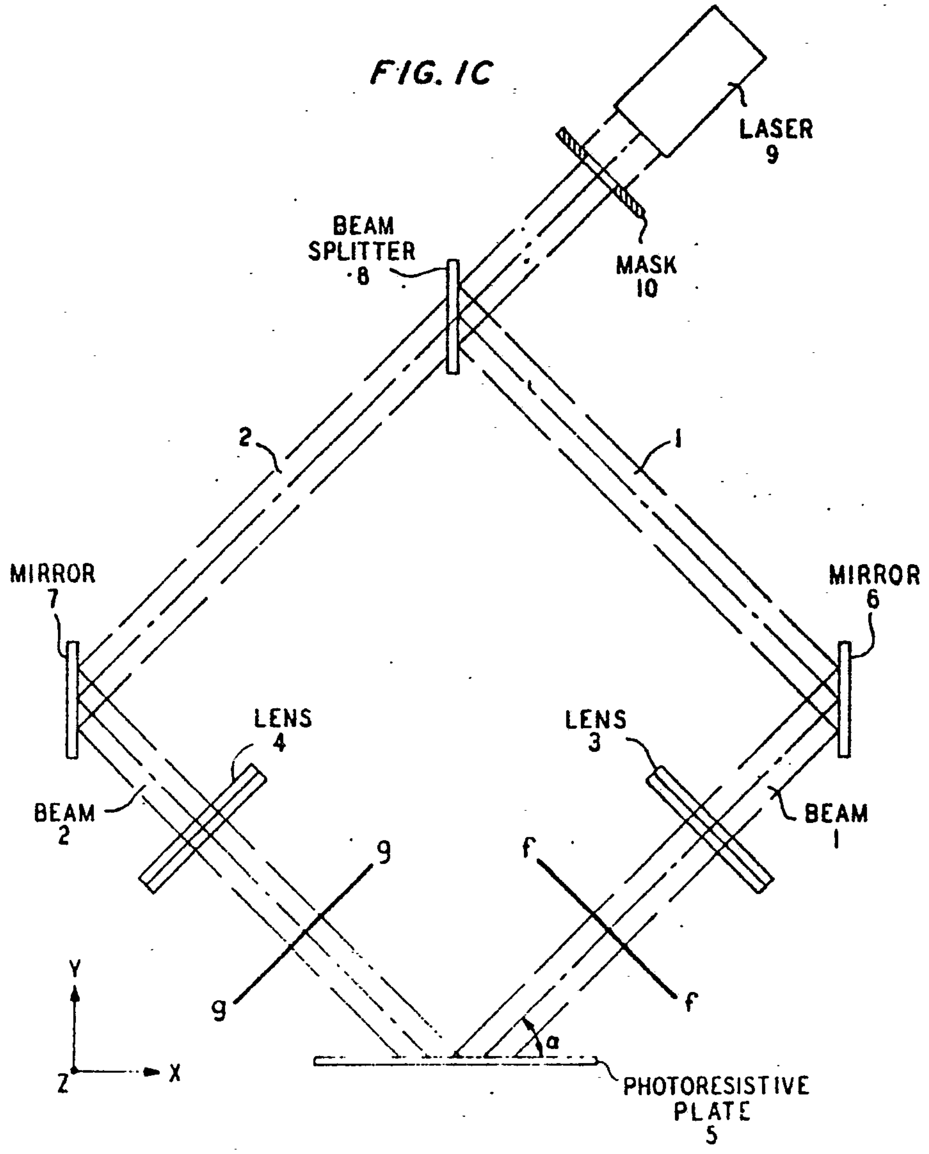
LASER 9
BEAM SPLITTER 8
MASK 10
2
1
MIRROR 7
MIRROR 6
LENS 4
LENS 3
BEAM 2
BEAM 1
g
f
g
f
α
Y
X
Z
PHOTORESISTIVE PLATE 5

FIG. 2A

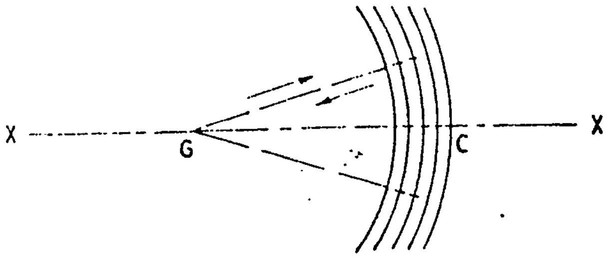

FIG. 2B

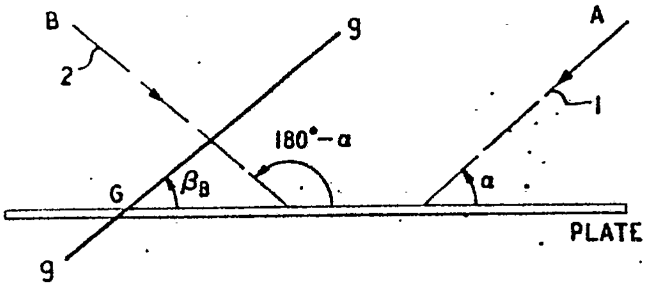

FIG. 2C

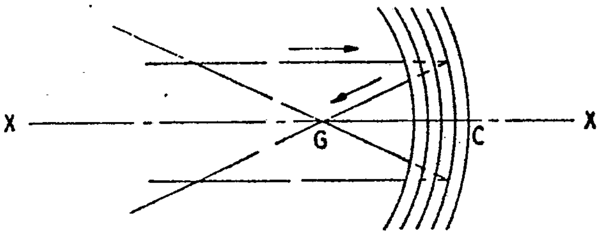

FIG. 2D

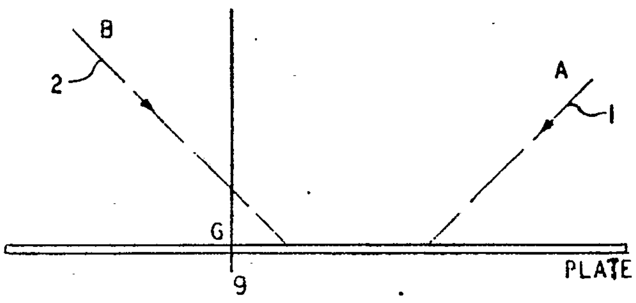

FIG. 2E

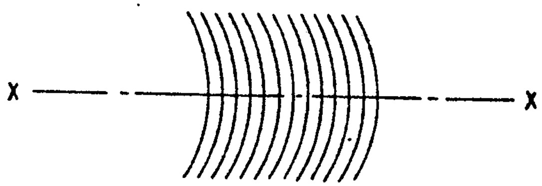

FIG. 2F

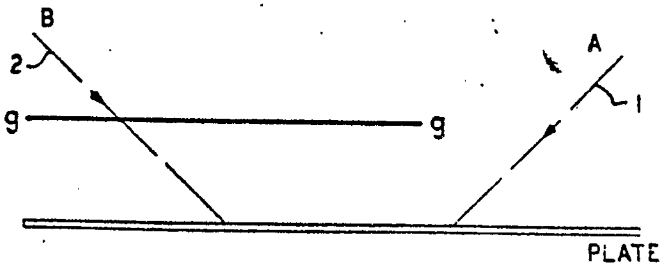

FIG. 2G

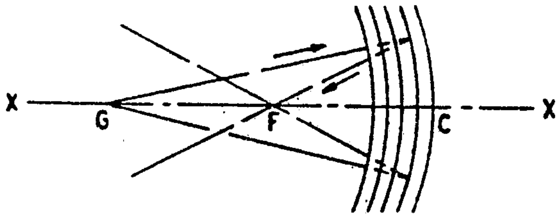

FIG. 2H

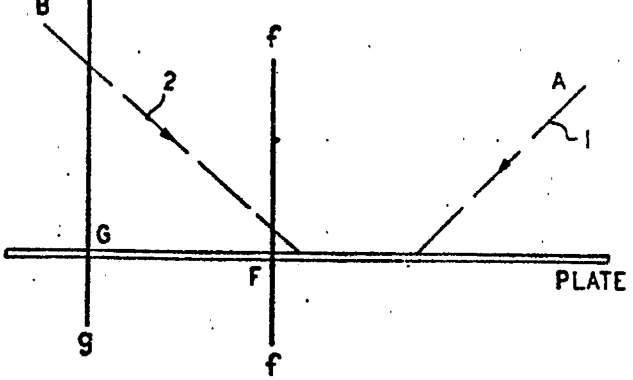

FIG. 2I

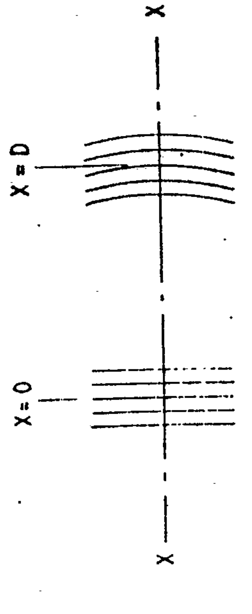

FIG. 2J

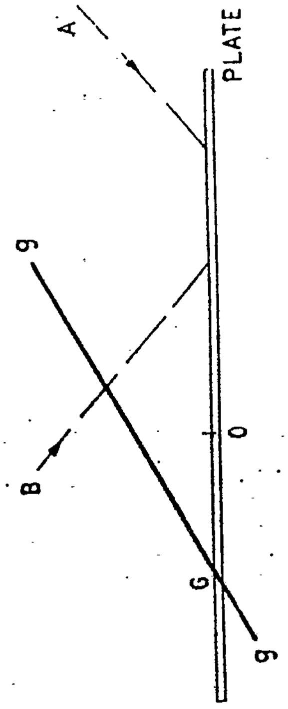

FIG. 2K

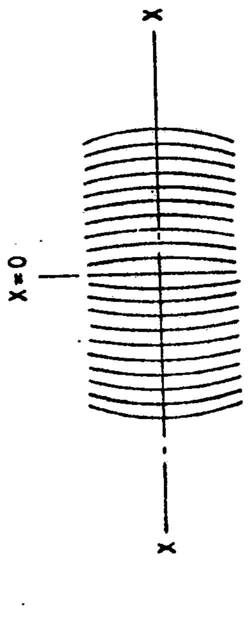

FIG. 2L