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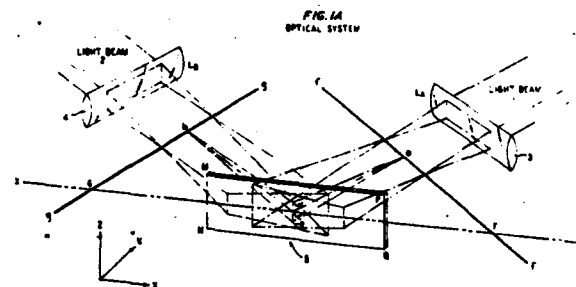
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54 **Method of and apparatus for forming focusing diffraction gratings for integrated optics.**

57 An apparatus and method is disclosed for making unchirped holographic diffraction gratings that are formed from curved lines in a thin film. First and second beams of coherent optical radiation are respectively focused to first and second focal lines (g,f) which lie in plane (x,y) that is substantially perpendicular to a planar photo-sensitive material (5) upon which the two beams interact to form an interference pattern.



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(P.K. Tien 43)

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

The invention relates to methods and apparatus for
5 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.
10 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
15 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
20 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
25 relative orientation of laser beams and focal lines
that are required in order to produce curved-line
gratings that will function in integrated optics
28 devices.

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According to one aspect of the present invention there is provided a method of forming a holographic diffraction grating having lines of substantially equal spacing, said method comprising generating first and
5 second beams of coherent optical radiation, causing the first and second beams to interfere with each other on a planar piece of photosensitive material to form an interference pattern in the photosensitive material, and processing to form the interference pattern, characterised
10 in that the first and second beams are coplanar in a first plane, and in that the planar piece of photosensitive material lies in a second plane oriented substantially perpendicular to the first plane.

According to another aspect of the present invention
15 there is provided an apparatus for forming an optical interference pattern with curved equally spaced lines in a planar photosensitive material, said apparatus comprising means for generating first and second beams of coherent optical radiation, each beam being focussed to a
20 respective focal line (ff,gg) at a predetermined position, characterised in that the focal lines are coplanar and define a first plane (Y, X), and in that the apparatus further comprises means for supporting a planar piece of photosensitive material (5) oriented in a second plane
25 (Z, X) substantially perpendicular to the first plane.

The present invention relates to a method and apparatus for producing unchirped, curved-line, holographic diffraction gratings in a thin film, which gratings will focus as well as diffract light that is confined to the
30 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,
35 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
38 processes of conventional type to form corrugated

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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.

The invention will become apparent from a study of the detailed description and of the accompanying drawings, in which

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

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

The basic optical system used to form the embodiment 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

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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
5 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
10 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 photo-sensitive 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
15 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
20 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 lens formula:

$$C(\text{incident}) + C(\text{reflection}) = 2C(\text{fringe}), (1)$$

25 where incident and reflection refers to the light being processed. The inter-fringe spacing is specified by the Bragg-reflection condition:

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$$1 \quad 2 \beta \cdot \hat{x} = m G \quad (2)$$

where

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

d is the inter-fringe spacing, 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 curvatures of the two beams.

$$\begin{aligned}
 15 \quad C &= C_A - C_B \\
 &= \frac{1}{2\cos\alpha} \left(\frac{1}{ac} - \frac{1}{bc} \right) \\
 &= \frac{-1}{2\cot\alpha} \left[\frac{\cot\alpha - \cot\beta_A}{x - \Delta} + \frac{\cot\alpha + \cot\beta_B}{x} \right] \quad (4)
 \end{aligned}$$

where $x = 0$ at G , $\Delta =$ the distance $F-G$, 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

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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 $180 - \alpha$. 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

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is focused from point G on the $\underline{x}$ axis to point F, also on the $\underline{x}$ 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 $\underline{x}$ axis as shown in FIG.

- 5 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
10 Hermite-Gaussian beam propagating in a waveguide along the $\underline{x}$ axis, the curvature of the wave front varies in $\underline{x}$ as

$$C = \frac{x}{N^2 \beta^2 a_0^4 + x^2} \quad (5)$$

- 15 where N is the mode index of the waveguide, $\beta = \frac{2\pi}{\lambda}$, and a_0 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
20 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 AlGaSb Bragg-reflector laser shown in FIG. 2I. The gratings used as left and right reflectors are each
25 $100 \mu_m$ 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.

- 30 Putting $x = D + \Delta x$ in Equation 4, 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 C is
35 located $931 \mu_m$ from D.

FIG. 2K shows another grating-resonator designed for a distributed feedback laser. The grating is $350 \mu_m$
38 long and centered at $x = 0$. Two cylindrically focused

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beams are used, as shown in FIG. 2L. The parameters that match the requirements of Equation 4 satisfactorily are: $N = 36$, $\lambda = 1.3 \mu\text{m}$, $a_0 = 5 \mu\text{m}$, $\alpha = 40.1$, $\beta_A = -156.33$, $\beta_A = -23.67$, and G and F are located at $x = 583.33 \mu$ and
5 +583.33 μm .

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.

10 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.
15 Secondly, the intensities of the beams vary somewhat along the x axis, tending to overexpose parts of the photo-resist 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.

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CLAIMS

1. Method of forming a holographic diffraction grating having lines of substantially equal spacing, said method comprising generating first and second beams of
5 coherent optical radiation, causing the first and second beams to interfere with each other on a planar piece of photosensitive material to form an interference pattern in the photosensitive material, and processing to form the interference pattern, characterised in that the first and
10 second beams are coplanar in a first plane, and in that the planar piece of photosensitive material lies in a second plane oriented substantially perpendicular to the first plane.

2. Method according to claim 1, characterised in that the first and second beams are focused to first and second focal lines lying in predetermined positions relative to the photosensitive material.

3. Method according to claim 2, characterised in that the first beam is focused to the first focal line before the first beam strikes the photosensitive material and the second beam is focused at infinity.

4. Method according to claim 2, characterised in that the first beam and/or the second beam are focused respectively to first and second focal lines oriented
25 substantially perpendicular to the second plane.

5. Method according to claim 2, characterised in that the first and the second beams are focused to first and second focal lines lying substantially behind the photosensitive material.

30 6. Focusing and diffracting grating made using the method of any one of claims 1-5.

7. Apparatus for forming an optical interference pattern with curved equally spaced lines in a planar photosensitive material, said apparatus comprising means
35 for generating first and second beams of coherent optical radiation, each beam being focused to a respective focal line (ff, gg) at a predetermined position, characterised in that
38 in that the focal lines are coplanar and

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plane (Y, X), and in that the apparatus further comprises means for supporting a planar piece of photo-sensitive material (5) oriented in a second plane (Z, X) substantially perpendicular to the first plane.

5 8. Apparatus according to claim 7, characterised
in that means (3) for focusing the first beam (1) serves
to focus the first focal line (ff) between the means (3)
for focusing the first beam and the photosensitive
material (5), and means (4) for focusing the second beam
10 (2) serves to focus the second beam at infinity.

 9. Apparatus according to claim 7 or 8,
characterised in that means (3) for focusing the first
beam (1) serves to focus the first focal line (ff)
substantially perpendicularly to the second plane (Z, X).
15 10. Apparatus according to claim 7, characterised
in that means (3, 4) for focusing the first (1) and
second (2) beams serve to focus the first (ff) and second
(gg) focal lines respectively perpendicularly to the
second plane (Z, X).

20 11. Apparatus according to claim 7, characterised
in that means (3, 4) for focusing the first (1) and
second (2) beams are adapted to focus the first (ff) and
second (gg) focal lines respectively so that they lie
substantially behind the photosensitive material (5).

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FIG. 1A
OPTICAL SYSTEM

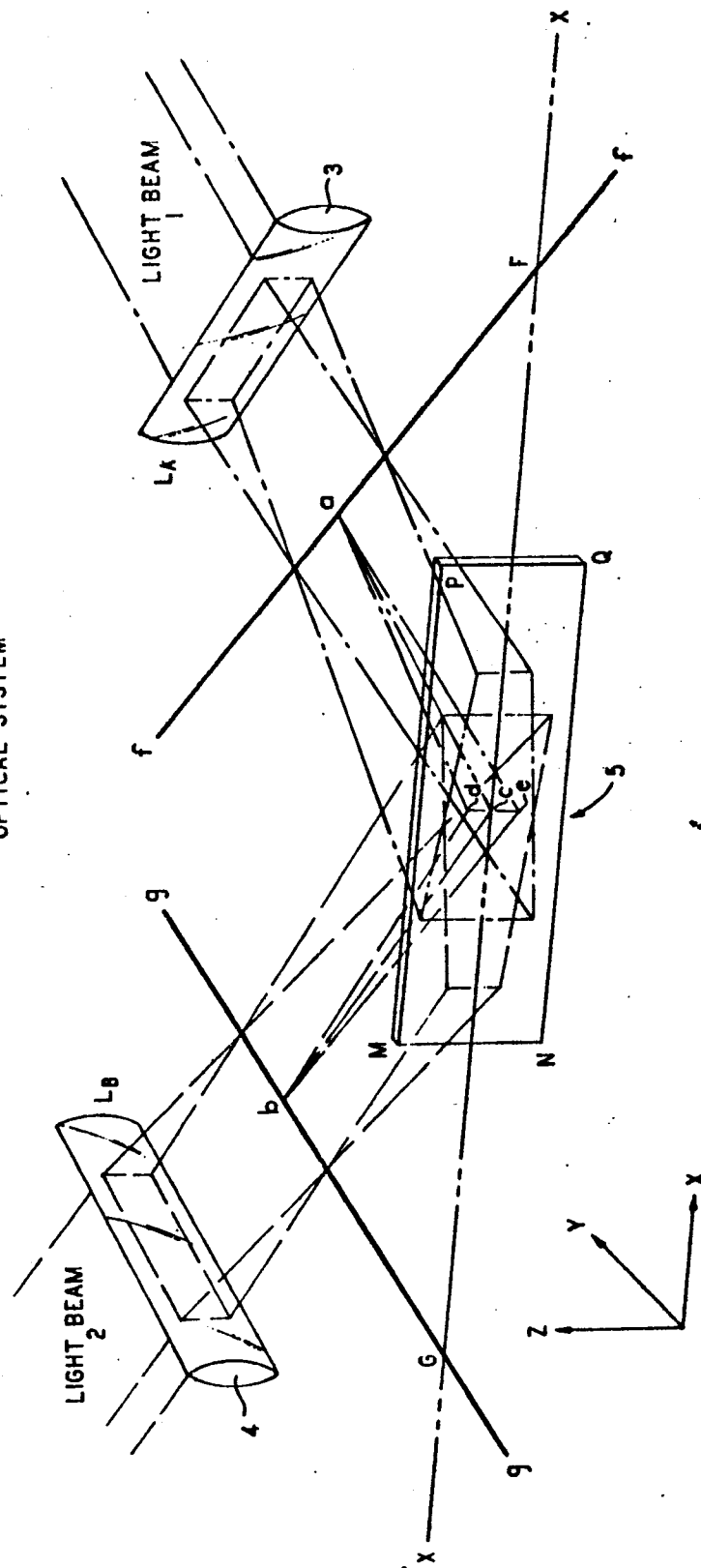


FIG. 2A

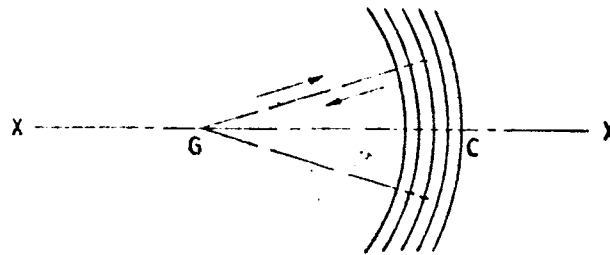


FIG. 2B

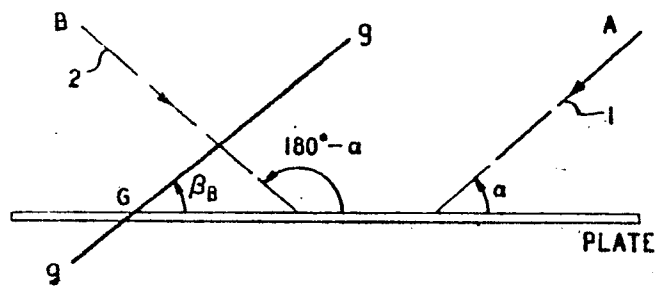


FIG. 2C

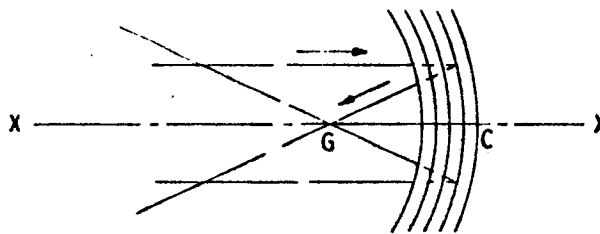


FIG. 2D

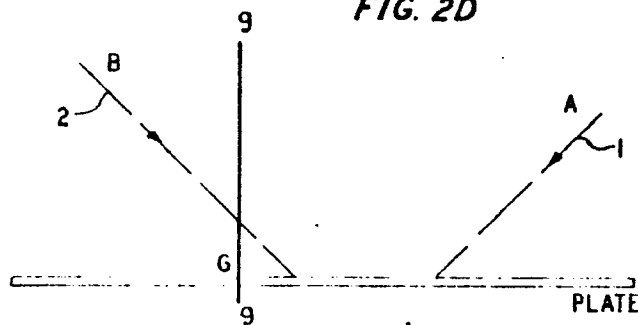


FIG. 2F

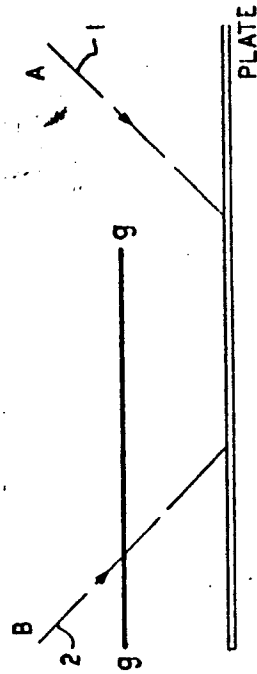


FIG. 2H

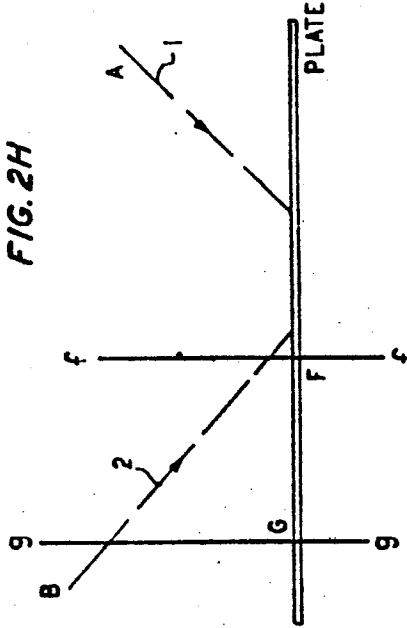


FIG. 2E

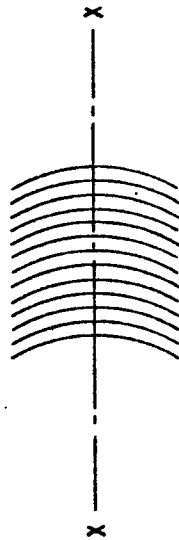


FIG. 2G

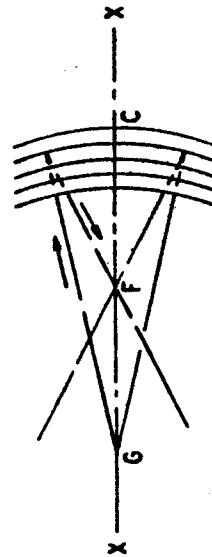


FIG. 2J

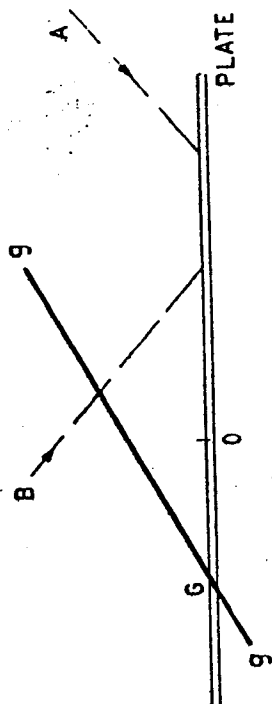


FIG. 2L

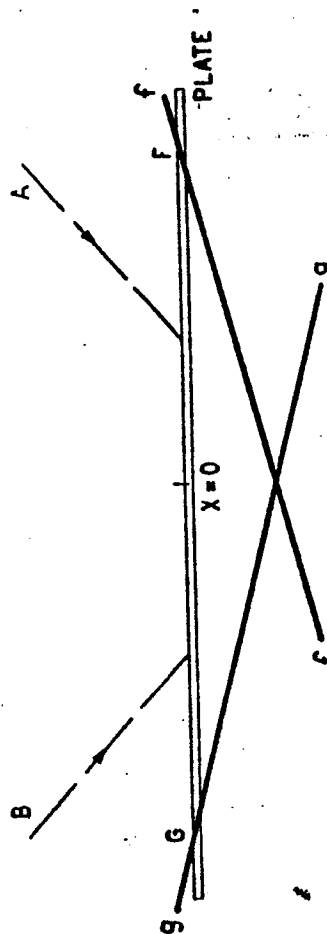


FIG. 2I

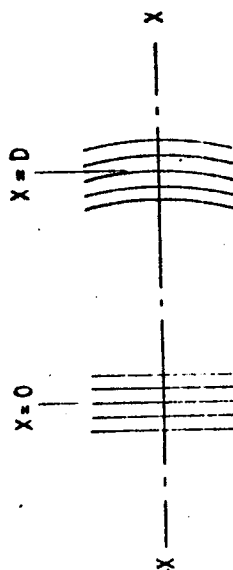
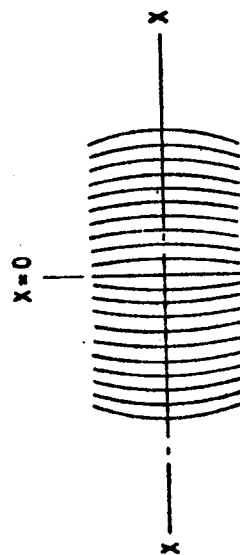


FIG. 2K





European Patent
Office

EUROPEAN SEARCH REPORT

Application number
EP 78 30 0156

DOCUMENTS CONSIDERED TO BE RELEVANT			CLASSIFICATION OF THE APPLICATION (Int. Cl. ³)
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	
	<u>US - A - 3 991 386</u> (G.BJORKLUND et al.) * Columns 3-4; figure 2 * ---	1	G 02 B 5/32 // H 01 S 3/06 G 02 B 5/17
D	<u>US - A - 3 578 845</u> (R.BROOKS et al.) * Whole document * ---	1	
A	<u>US - A - 3 864 130</u> (H.NASSENSTEIN et al.) * Column 3, figures 2-4 * ---	1	TECHNICAL FIELDS SEARCHED (Int.Cl.³) G 02 B 5/32 H 01 S 3/06 G 02 B 5/14 G 02 B 5/17
A	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 * Page 179 * ----	1	CATEGORY OF CITED DOCUMENTS X: particularly relevant A: technological background O: non-written disclosure P: intermediate document T: theory or principle underlying the invention E: conflicting application D: document cited in the application L: citation for other reasons
☒ The present search report has been drawn up for all claims			&: member of the same patent family, corresponding document
Place of search The Hague		Date of completion of the search 19-10-1978	Examiner BOEHM