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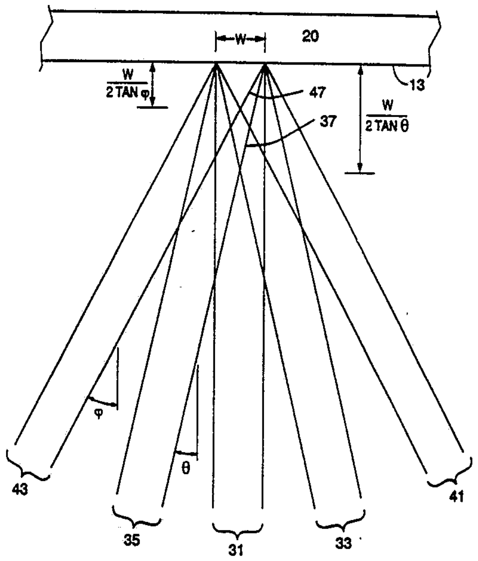

(57) Abstract

The apparatus disclosed herein employs a grating or scale (13) which concentrates light at a preselected wavelength into the positive (33) and negative (35) first orders while minimizing the zeroth order (31). The scale (13) is illuminated with monochromatic light of the selected wavelength and a poly-phase periodic detector (25) has its sensing plane spaced from the scale a distance less than W: 2 tan Θ where Θ = arcsin [λ: P], where W is the width of the illuminated region of the scale. The period of the poly-phase detector is equal to P/2 so that each detector element (51) or phase responds principally to interference between the positive and negative first orders without requiring magnification or redirection of the diffracted light. Preferably, the distance of the sensing plane from the scale (13) is greater than W: 2 tan φ where φ = arcsin [3λ: P], so that the detector response does not include substantial components from diffraction orders higher than the first.

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APPARATUS FOR DETECTING RELATIVE MOVEMENT

Background of the Invention

The present invention relates to an optical instrument for measuring displacement and more particularly to such an instrument which utilizes diffraction of monochromatic light from a scale or grating which is movable relative to a light source or sensing head.

A number of systems have been proposed heretofore for measuring relative displacement utilizing diffraction of light from an optical grating. Examples of such prior art systems may be seen in the Pettigrew patent 4,776,701; the Kanayama et al. patent 4,815,850; and the Taniguchi et al. patent 4,676,645. A commercially available system of this type is sold by Optra, Inc. of Beverly, MA under its trademark "Nanoscale". Each of these prior art systems, however, involves magnification or separation of the different diffraction orders obtained back from the diffraction grating which are then brought back together and interfered. Typically, fairly large numbers of optical components are required and the several components must be accurately spaced and aligned in order for the instruments to perform in accordance with their respective designs.

Among the several objects of the present invention may be noted the provision of apparatus for detecting relative displacement which employs a minimum of components; the provision of such a system in which tolerance of spacing and alignment of system components is relatively great; the provision of such an apparatus which is easily manufactured; the provision of such apparatus in which sensing components can be implemented using integrated circuit techniques; the provision of such apparatus which can provide measurement with high accuracy; the provision of such apparatus which is highly reliable and which is of relatively simple and inexpensive construction. Other objects and features are in part apparent and in part pointed out hereinafter.

Summary of the Invention

The apparatus of the present invention utilizes a scale or grating (hereafter collectively referred to as "scale") which, for a preselected wavelength, concentrates diffracted light into the positive and negative first orders. The scale is relatively movable with respect to a source providing monochromatic light of the selected wavelength and which illuminates a region of the scale having a width W along the length of the scale. A poly-phase periodic detector is spaced close to the scale so that each detector phase or element responds principally to interference between the positive and negative first orders diffracted from the scale without intermediate reflection or magnification.

Brief Description of the Drawings

Fig. 1 is a top diagrammatic view of displacement sensing apparatus in accordance with the present invention;

Fig. 2 is a diagram illustrating where different orders interfere in regions close to a diffraction scale employed in the apparatus of Fig. 1;

Fig. 3 is a diagrammatic illustration, with exaggerated scale spacing and diffraction angles, illustrating the operation of a periodic multi-phase detector employed in the apparatus of Fig. 1 in relation to light diffracted from a scale or grating; and

Fig. 4 is a diagram of the front of the detector of Fig. 3.

Corresponding reference characters indicate corresponding parts throughout the several views of the drawings.

Description of the Preferred Embodiment

For convenience in description, Fig. 1 is described as being a top view although, as will be apparent to those skilled in the art, the apparatus can be operated in any orientation. As indicated previously, the apparatus of the present invention operates to detect or sense relative movement or displacement between a sensing head, designated generally by reference character 11, and a scale or grating 13. The sensing head 11 incorporates a monochromatic light source, preferably a semiconductor laser as indicated by reference character 15. Semiconductor laser 15 provides essentially monochromatic light having a wavelength designated λ. Again, for convenience in description only, the direction of relative movement is designated the X-axis, this being along the length of the scale, while distance from the face of the scale is considered to be measured along the Y-axis. Correspondingly, the Z-axis is considered to be vertical or orthogonal to the plane of the drawing. The scale 13 is ruled parallel to the Z-axis.

As will be apparent from the description following, the scale 13 employed in the embodiment illustrated operates in reflection and is tailored to concentrate light diffracted at a selected wavelength into the positive and negative first orders and to minimize the zeroth order. As is understood by those skilled in the art, such a characteristic is obtained principally by employing a depth which is $\lambda/4$, i.e. a quarter wavelength, as well as by shaping the surface as is shown in Fig. 3. It should be understood that an essentially equivalent scale can be designed to operate in transmission.

Light from the semiconductor laser 15 is essentially collimated by a lens 17 and directed by a mirror 19 approximately orthogonally toward the face of the scale 13 illuminating a region 20 having a width W along the length of the scale. Light diffracted back from the scale 13 is detected by a poly-phase periodic detector 25. The period of the detector along the X-axis corresponds to the period of the interference pattern generated by interference of the positive and negative first orders diffracted from the scale 13 and is thus equal to P/2. The width of the active area of the detector 25 is preferably substantially smaller than the width of the illuminated region on the scale 13. While the detector 25 is shown as though being in the path of the light beam proceeding from the mirror 15 to the scale 13, it can in fact be located above or below the beam since exact orthogonality of the beam to the scale surface in the Z direction is not required.

Referring now to Fig. 2, a region of width W along the length of the scale 13 is illuminated by the beam from the laser light source. The zeroth order is reflected essentially directly back, this beam being indicated by reference character 31. The positive first order is illustrated as being diffracted at an angle θ to the right, this beam being indicated by reference character 33 while the negative first order, designated by reference character 35, is diffracted to the left by the same angle. As is understood by those skilled in the art, the angle θ is equal to arcsin (λ/P) where P is the period of the scale along the X-axis.

As may be seen, there exists a triangular region, designated by reference character 37, where the positive and negative first orders will interfere directly without any intermediate reflection or magnification. This region extends to a distance from the scale equal to $W/(2 \tan \theta)$ and may be considered a region of near field interference. To avoid confusion with the term "near field interference" in the Fresnel interference sense, the region of interference utilized in the present invention is more accurately described as a "pre-separation" interference, i.e. interference before the plus and minus orders diverge. In this region, the plus and minus orders interfere directly. In accordance with the present invention, the detector 25 is located within this region.

While the characteristics can be tailored to substantially eliminate the zeroth and even orders of diffraction from the scale 13, some appreciable energy will typically remain in the odd orders. With reference to Fig. 2, the positive and negative third order beams are designated by reference characters 41 and 43, respectively. As is understood by those skilled in the art, the angle from normal at which each of these beams depart is φ where $\varphi = \arcsin(3\lambda/P)$. There correspondingly exists a triangular region of pre-separation interference, this region being designated by reference character 47. This region extends from the scale for a distance of

$$\frac{W}{2 \tan \varphi}$$

Preferably, the detector 25 is located further from the scale than the region of pre-separation interference from the positive and negative third orders so that the signals obtained correspond most closely with the sine wave characteristic of the pure first order interference pattern. Preferably, the detector 25 is located just outside of the apex of the region 47 so as to allow maximum detector width. As will be apparent, the whole active area of the detector should be within the region of the desired interference.

In view of this explanation, it can be seen that it is desirable that the designed width of the illuminated region 20 correspond to the designed spacing of the sensing plane from the diffraction scale. However, it should be understood that illumination beyond the designed width does not prevent the desired interference but, rather, only allows some contribution from higher diffraction orders since portions of a broadened region of illumination may allow light leaving at a larger diffraction angle to reach the detector. Thus, the problem of mismatching of illuminated region width to detector spacing is more in the nature of a gradual degradation rather than a failure to function as intended. Thus, it is a feature of the design of the present invention that spacing is not highly critical.

As indicated previously, the width of the active area of the detector 25 is smaller than the width of the illuminated region on the scale. Thus, as illustrated in Fig. 3, positive first order diffraction from a region on the left hand side of the region 20 can meet and interfere with negative first order diffracted light from a zone on the right hand side of the region 20 and the meeting light components can interfere at the sensing plane of the detector 25.

As indicated, the dimensions and angles are exaggerated in Figures 2 and 3 for the purpose of explanation. Dimensions and angles for a practical design may, for example be as follows. The light source is a semiconductor laser providing light at a wavelength of 780 nanometers. The scale 13 is ruled at 424 lines per inch (16.64 lines per millimeter) so that the period P is 60 microns. Accordingly, the angle of first order diffraction θ is 1.7 degrees, and the angle of third order diffraction φ is 2.2 degrees. Assuming that the width of the illuminated region is 1.0 millimeter, the pre-separation first order region of interference extends 38.5 millimeters from the scale while the pre-separation third order region of interference extends 12.8 millimeters from the scale.

As is understood by those skilled in the art, the pattern of light intensity produced by interference of the positive and negative first order diffraction components will have a periodicity which is twice that of the scale itself. The detector 25 is constructed to have a matching periodicity, i.e. P/2 so that the contributions from the several elements in each phase of the detector combine additively. Preferably, the detector 25 is constructed as an integrated circuit comprising an array of narrow elongate photodiodes. Such an array of photodiodes is illustrated in Fig. 4. The individual photodiodes are indicated by reference character 51. As indicated previously, the array should be poly-phased. For example, two arrays providing Quadrature signals could define the relative displacement. An arrangement simpler to fabricate can be implemented by offsetting the two phases in the Z-axis direction so as to simplify the interconnection of the various photodetector elements. Another alternative is to employ relatively large area photodetectors, each of which is provided with a respective mask for admitting light of the appropriate phase. Again, while this construction is simpler to implement, it is less efficient in the utilization of the available light energy.

A still further alternative is to provide a lenticular screen at the sensing plane which disperses the different phases at different angles after interference at the sensing plane so that spaced apart detectors can be utilized. The lenticular screen will thus have a periodicity of P/2 along the X-axis. In this case, the photo-electric detectors themselves need not be placed within the so-called region of pre-separation interference 37 but, rather, the sensing plane and the point of interference is at the lenticular screen which is within the region.

Similarly, while it is preferable that pure first order interference be achieved so as to provide the purest possible sinewave out of each of the detector phases, some interference by other orders will not be overly objectionable in some applications and, by use of matching pattern tables, sufficiently accurate interpolations may be provided.

While the embodiment disclosed by way of example provides for sensing along a single axis, it should be understood that the technique of the present invention can be applied to a combined two-axis sensing device by utilizing a scale ruled in orthogonal directions, together with a respective detector for each direction. A single light source can serve both axes. Due to the orthogonality, there will be minimal interaction between movement along one axis with the sensing signals generated by movement along the other axis.

If the detectors and gratings are properly shaped to provide matching curvatures for the diffracted signal, or sufficiently narrow gratings were used, this invention can be effectively applied to a rotary encoder.

In view of the foregoing it may be seen that several objects of the present invention are achieved and other advantageous results have been attained.

As various changes could be made in the above constructions without departing from the scope of the invention, it should be understood that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

CLAIMS

What is claimed is:

1. Apparatus for detecting relative movement comprising a diffraction scale relatively movable with respect to said source and having a period P and a characteristic which concentrates light diffracted at a preselected wavelength λ into the positive and negative first orders;

means for illuminating with light of wavelength λ a region of said scale having a width W along the length of the scale;

a periodic detector having a sensing plane spaced from said scale a distance less than

$$\frac{W}{2 \tan \theta}$$

where

$$\theta = \arcsin \left(\frac{\lambda}{P}\right)$$

the period of said detector being equal to P/2 whereby said detector responds principally to interference at said sensing plane between the positive and negative first orders diffracted from said scale.

2. Apparatus as set forth in claim 1 wherein said sensing plane is spaced from said scale a distance greater than

$$\frac{W}{2 \tan \varphi} \quad \text{where } \varphi = \arcsin \left(\frac{3\lambda}{P}\right)$$

3. Apparatus for detecting relative movement comprising;

a source of monochromatic light of wavelength λ;

a reflection diffraction scale relatively movable with respect to said source and having a period P and a characteristic which concentrates light diffracted at said wavelength λ into the positive and negative first orders and which minimizes the zeroth order;

means for directing light from said source onto a region of said scale having a width W along the length of the scale;

a poly-phase periodic detector having a sensing plane spaced from said scale a distance less than

$$\frac{W}{2 \tan \theta}$$

where

$$\theta = \arcsin \left(\frac{\lambda}{P}\right)$$

the period of said detector being equal to P/2 whereby said detector responds principally to interference at said sensing plane between the positive and negative first orders diffracted from said scale.

4. Apparatus as set forth in claim 3 wherein said detector comprises an array of parallel elongate photodiodes.

5. Apparatus as set forth in claim 3 wherein said sensing plane is spaced from said scale a distance greater than

$$\frac{W}{2 \tan \varphi} \quad \text{where } \varphi = \arcsin \left(\frac{3\lambda}{P}\right)$$

6. Apparatus for detecting relative movement comprising:

a semiconductor laser providing monochromatic light of wavelength λ;

an elongate reflective diffraction scale longitudinally relatively movable with respect to said laser, said scale being ruled transversely to its length with a period P and a characteristic which concentrates light diffracted at said wavelength λ into the positive and negative first orders and which minimizes the zeroth order;

means for directing light from said laser onto a region of said scale having a width W along the length of the scale;

a plurality of elongate photoelectric detectors arranged in a planer parallel array spaced from said scale a distance less than

$$\frac{W}{2 \tan \theta}$$

where

$$\theta = \arcsin \left(\frac{\lambda}{P}\right)$$

said detectors being interconnected in a periodic multiphase array with the period being equal to P/2 whereby said detector responds principally to interference at said sensing plane between the positive and negative first orders diffracted from said scale.

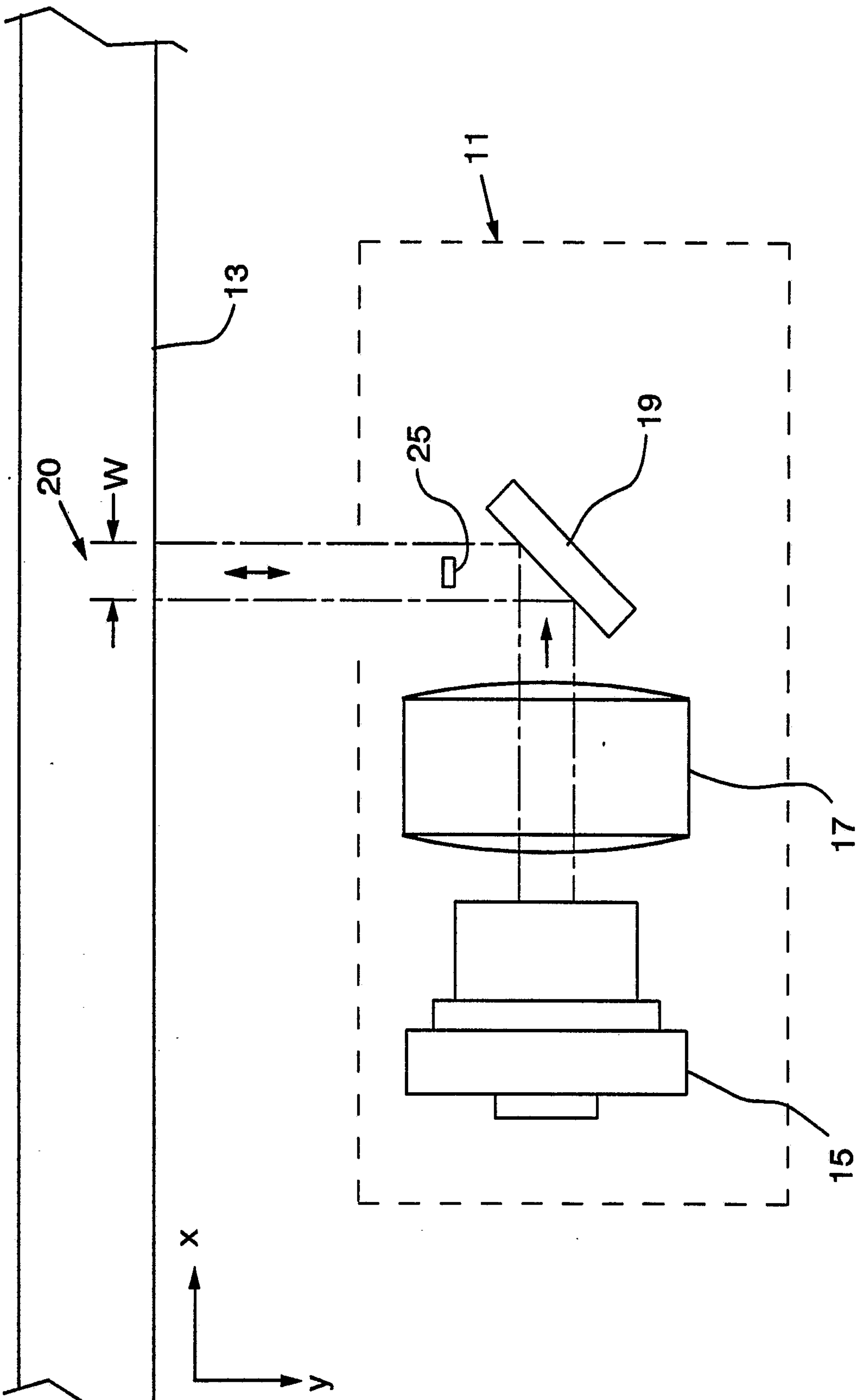

FIG. 1

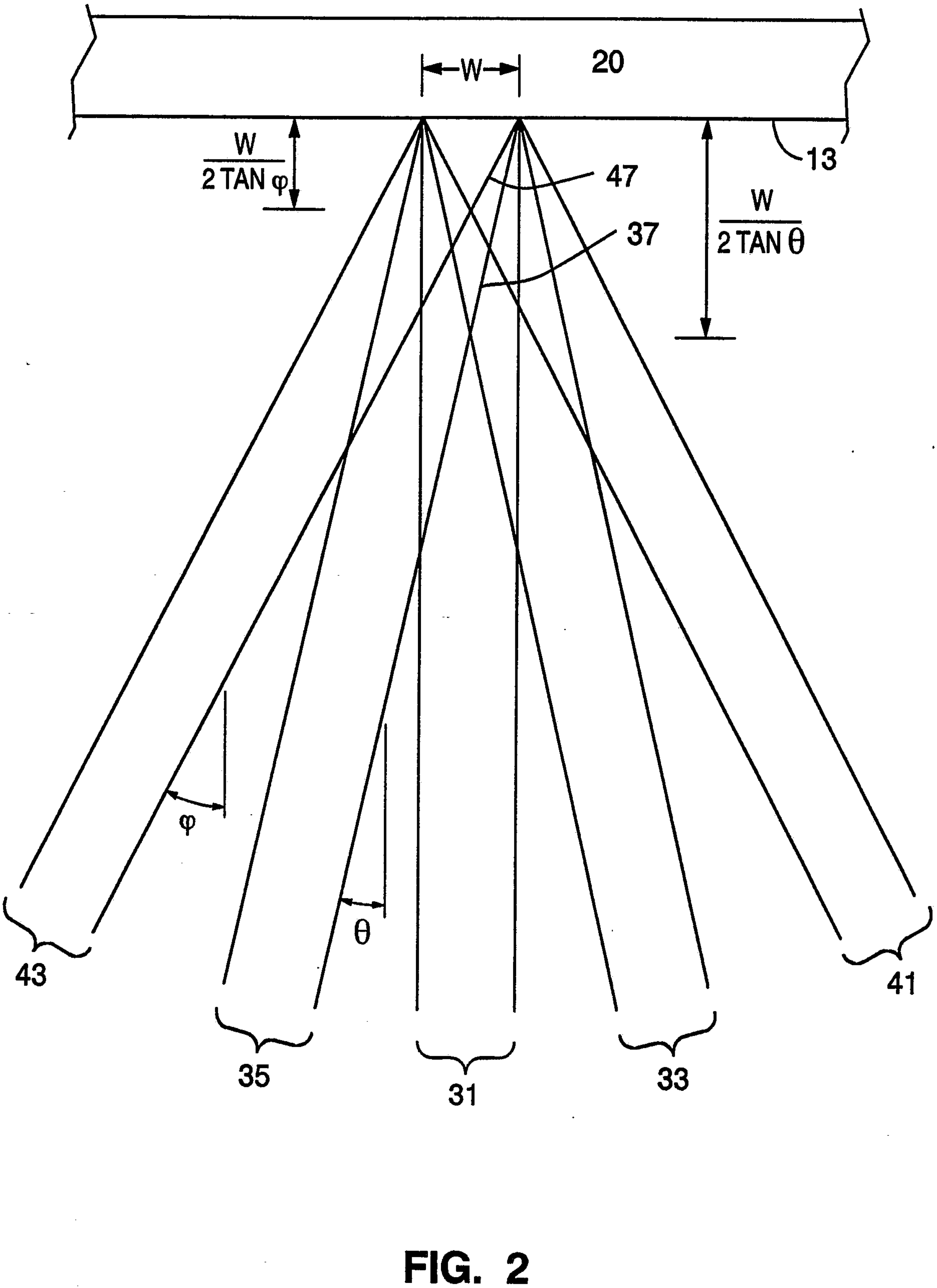

FIG. 2

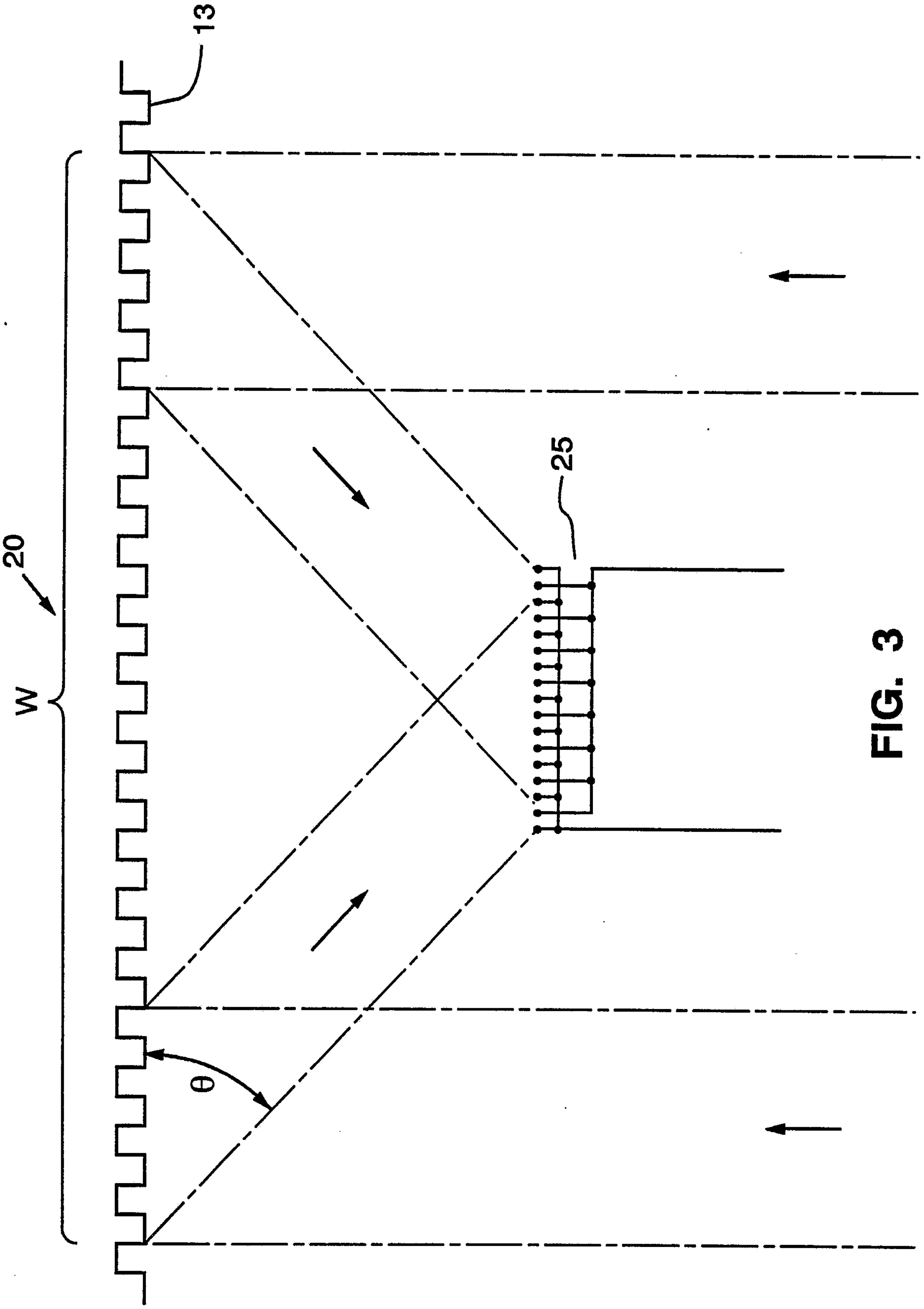

FIG. 3

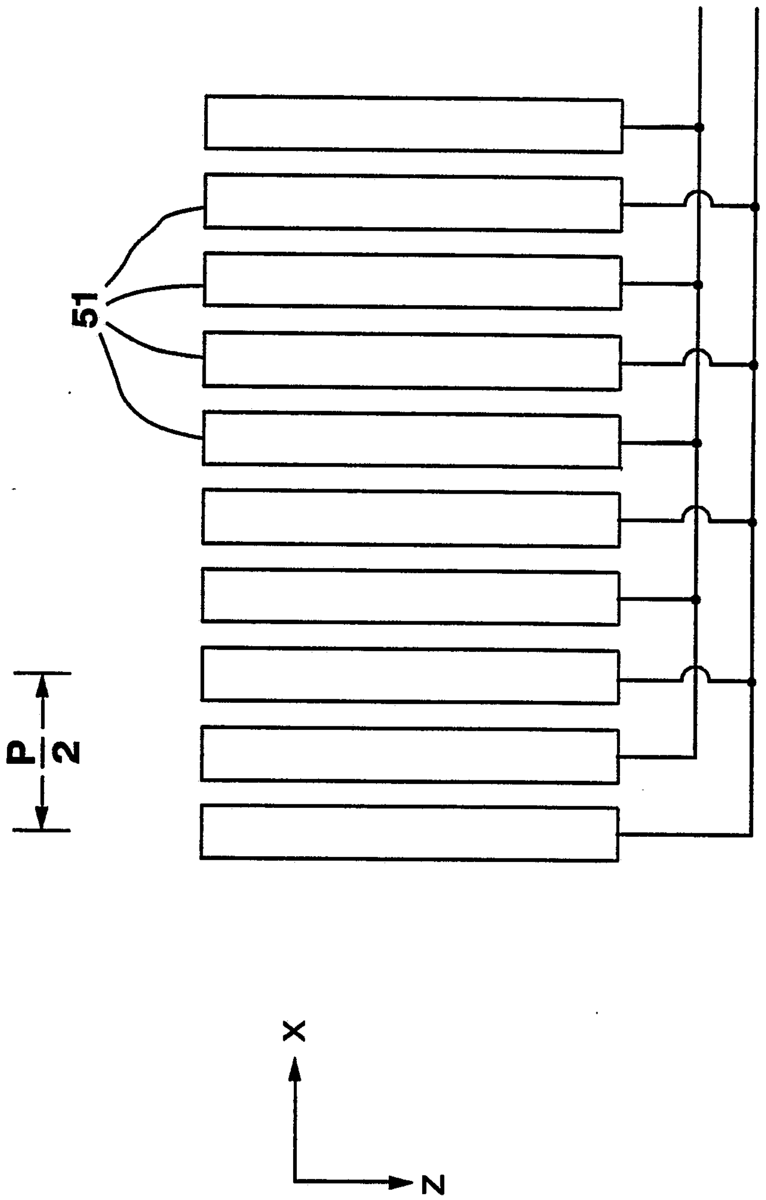

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/04260

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :G01B 9/02
US CL :356/356, 353, 363
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/356, 363, 353; 250/237G, 231.14, 231.16

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 4,776,701 (Pettigrew) 11 October 1988, see the summary of the invention.	1-6
Y	US, A, 4,815,850 (Kanayama et al.) 28 March 1989, see entire document.	1-6
A	US, A, 5,098,190 (Wijntjes et al.) 24 March 1992, see entire document.	1-6
A,P	US, A, 5,182,610 (Shibata) 26 January 1993, see Claims 1-22.	1-6
A	US, A, 5,104,225 (Masreliez) 14 April 1992, see entire document.	1-6

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
01 August 1993	06 AUG 1993

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 5,066,130 (Tsukiji et al.) 19 November 1991, see entire document.	1-6
A	US, A, 4,970,388 (Nishimura et al.) 13 November 1990, see entire document.	1-6
A	US, A, 4,168,908 (Cubalchini) 25 September 1979, see entire document.	1-6
A	APPLIED OPTICS, Volume 22, No. 10, issued 15 May 1983, Lawrence Mertz, "Complex Interferometry", pages 1530-1534.	1-6