An optical device and a method of utilizing such device, based on the idea of interferometry, for optically examining objects where the optical device comprises a pair of diffraction gratings (G1, G2) with each of the gratings designed to reduce substantially all the diffraction orders except the +1 and -1 diffraction orders by the evanescent wave phenomenon and zero order cancellation.
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AN OPTICAL DEVICE AND A METHOD OF UTILIZING SUCH DEVICE FOR OPTICALLY EXAMINING OBJECTS

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to optical devices and also to a method of utilizing such devices for optically examining objects.

One approach employed for optically examining objects is by the use of classical interferometry which measures phase retardation between two light beams. Examples based on this approach include interferometers (schlieren, shearing interferometry), shadowgraphy, moire interferometry, etc. This approach is generally characterized by very high accuracy, which is desirable; however, this approach is also characterized by high sensitivity and fixed sensitivity, which are considered as serious drawbacks.

A more recent approach for optically examining objects is based on moire deflectometry. According to this approach, a collimated beam deflected from the object is used to generate a moire pattern by directing the collimated beam through first and second gratings at a preselected angular orientation and separation with respect to one another, the moire pattern so produced providing an indication of the properties of the examined object. This approach was developed only during the mid-seventies and is
best applied to medium-low accuracy metrology. It has two main advantages over the classical interferometry approach: high stability (low sensitivity to shock and vibration), and tunable sensitivity over a very large dynamic range. Unfortunately, when stretching moire deflectometry to a high accuracy range, high order optical effects, that are residual for medium-low ranges, become dominant. The technology therefore becomes impractical for the high accuracy range.

**BRIEF SUMMARY OF THE PRESENT INVENTION**

The present invention provides an optical device, and a method of testing utilizing such optical device, which combine the high accuracy of interferometry with the tunable sensitivity and the high stability of the moire deflectometer.

According to a broad aspect of the present invention, there is provided an optical device characterized in that it includes a diffraction phase grating substantially reducing towards elimination all the diffraction orders except the -1 and the +1 diffraction orders by the evanescent wave phenomenon and zero order cancellation.

The evanescent wave phenomenon and cancellation of the zero order are both well known phenomena; see for example "Introduction to Fourier Optics", by Joseph Goodman, pages 50-51 and 69-70. The invention, as will be described
more particularly below, resides in the combination of the above two effects to produce a grating with just two diffraction orders. The optical device described below includes two such diffraction gratings in tandem.

According to further aspects of the invention, the optical device is a shearing interferometer, or more particularly a moire shearometer using phase gratings. Such an interferometer provides a number of important advantages when used for optically examining objects as will be described below.

**BRIEF DESCRIPTION OF THE DRAWINGS**

The invention is herein described, somewhat diagrammatically and by way of example only, with reference to the accompanying drawings, wherein:

Fig. 1 is a diagram illustrating the operation of a classic moire deflectometer;

Fig. 2 illustrates the diffraction orders of one grid as observed on the second grid in the moire deflectometer of Fig. 1;

Fig. 3 illustrates the diffraction orders in a shearing interferometer;

Fig. 4 is a diagram illustrating a square wave phase grating;

Fig. 5 is a diagram illustrating the diffraction orders produced by two gratings having a pitch of between two and three wavelengths;
Fig. 6 is a diagram illustrating a clean shearogram produced when the pitch is between one and two wavelengths;

Fig. 7 illustrates one form of shearing device constructed in accordance with the present invention;

and Figs. 8-10 illustrate three further forms of shearing devices constructed in accordance with the invention.

TECHNOLOGICAL BACKGROUND

The moire deflectometer (Patent No. USA 4,459,027, French Patent 8,120,331) is a practical tool for examining optical components and other phase objects in the medium to low accuracy range. The most basic configuration comprises two square-wave transmission gratings perpendicular to the optical axis with a gap "d" between them (Fig. 1). A simple description ignoring diffraction effects considers the geometric shadow of grating G1 on grating G2 observed with a collimated beam incident on grating G1 from the left. A perfect beam produces a shadow that is a perfect replica of grating G1 so that the moire pattern observed on the screen attached to grating G2 is identical to the contact (d=0) situation. For example when grating G2 is slightly rotated around the optical axis with respect to grating G1, a pattern of straight equidistant fringes (called tilt fringes) normal to the bisector of the angle between the directions of gratings G1 and G2 will be seen.
Insertion of a test object, such as a lens or an imperfect glass sheet, will spoil the beam collimation causing various rays to propagate in different directions thus producing distorted fringes. Analysis of the fringe data provides valuable information on the optical properties and aberrations of the test object. Many applications of this technique, including testing of reflective surfaces, are reported in the literature.

A serious disadvantage of the moire deflectometer is the effect of diffraction. A wave description of the system considers grating G1 as a source of multiple beams travelling in the directions of the various diffraction orders. The field at grating G2 is dominated by interference among these beams producing shadow blurring in some places. When the gap "d" equals an integral number of the Talbot distance \( p^2 \lambda \) ("p" is the pitch or period of the grating, and "\( \lambda \)" is the wavelength), all the diffraction orders are in phase, and the original field is recovered. Relying on the Talbot effect forces us to use monochromatic, or at least a narrowband beam source. Also the conditions for Fresnel diffraction must prevail.

The perfect reproduction of the grating shadow at the Talbot planes is observed only when the field is exactly periodic, namely grating G1 and the perfectly collimated beam are of infinite aperture. Introducing a test object with a finite aperture and/or distortions changes the picture. Consider the circular aperture, whose image of
-6-
grating G2 is shown in Fig. 2. The various diffraction
orders produce laterally shifted replicas of the radiation
field. A reasonable fringe pattern will be seen only where
the zeroth order overlaps either or both of the ±1 orders.
The fringe contrast is not perfect and depends locally on
the number of diffraction orders contributing at each
point.

The situation would be much better if the beams
could be somehow filtered such that only the two orders +1,
-1 are allowed to pass. A picture similar to that of a
shearing interferometer would result as shown in Fig. 3.
Here the two beams are of equal amplitude and produce a
clean interference pattern with maximum contrast. The fringe
shifts (in waves) are the phase differences between two
points separated by the shear distance 2λd/p [or with large
angles 2λd(p^2 - λ^2)^{-1/2}], which is the spatial resolution of
the method. It is seen here that the sensitivity cannot be
increased indefinitely since when the shear is larger than
the aperture, the circular areas will no longer overlap.
This constraint is called the diffraction limited
resolution.

Comparing the shearing interferometer (Fig. 3)
with the moire deflectometer (Fig. 2) shows that the spatial
resolution of the moire interferometer is poorer by at least
a factor of 2. This happens because the selection of the +1,
-1 diffraction orders allows to reduce the gap "d" by half
in order to achieve the same angular (or ray deviation)
sensitivity as that of a standard moire deflectometer. Furthermore, the fringes of the shearing interferometer do not suffer from the multiple diffraction effects because they are formed by just two beams. Thus the gap "d" between the gratings may be arbitrary, and the fringes are sharp and well-defined even when the object exhibits severe distortions.

The spatial resolution of the moire deflectometer is limited from below by the pitch "p", which suggests the use of gratings with the smallest possible "p". However, when "p" is below about 25 microns, the Talbot planes become so close together such as to make the position of grating G2 at an exact Talbot plane very difficult. In addition, the aberrations of the test object cause the Talbot plane to distort because of local deviations, such that the positioning task is practically impossible.

The shearing interferometer is free from this limitation, and one can select any shear (or sensitivity) value from zero (touching gratings) to the diffraction limit. However, the disadvantage of the shearing interferometer is that there is no known configuration which attains all the advantages of the moire deflectometer, especially the ease of construction, tunable sensitivity and tilt, and low susceptibility to noise. The commercial uses of the shearing interferometer are practically null compared to the widespread use of the moire deflectometer, especially in the ophthalmic industry.
THE PRESENT INVENTION

The present invention achieves the flexibility of the moire deflectometer with gratings of pitch \((p)\) much smaller than hitherto possible, limited from below only by the wavelength \(\lambda\) of the radiation used. By combining the phenomenon of evanescent waves with the method of phase gratings, all the unwanted diffraction orders are substantially eliminated. Furthermore, the new technique eliminates also unwanted orders from the second grating, so that the interference pattern can be observed directly without the diffusive screen.

The angle \(\alpha_m\) corresponding to the direction of the \(m^{th}\) order emanating from a diffraction grating is given by

\[
\sin \alpha_m = m \lambda / p. \hspace{1em} m = 0, \pm 1, \pm 2, \ldots
\]  

(1)

It is clear that \(|m|\) (the absolute value of \(m\)) cannot be larger than \(p/\lambda\); otherwise a sine larger than one will result. The radiation that would go into these high orders is channeled into the so-called evanescent waves. The evanescent waves behave in a way similar to the phenomenon of internal reflection, and their energy is either dissipated or scattered sideways. For the present purpose it is sufficient to note that these orders cannot progress forward into the measuring area.

A square wave amplitude transmission grating, also known as Ronchi ruling, contains the following orders:
m=0,±1,±3\ldots \tag{2}

Selecting the pitch "p" to be smaller than \(3\lambda\) ensures that all the waves with \(|m|=3\) and above will be evanescent, so that only the -1, 0 and +1 orders propagate in the forward direction. The zeroth order can be eliminated by replacing the amplitude grating with a phase grating of appropriate modulation depth.

A square wave phase grating (Fig. 4) has a phase difference \(\Delta \phi\) between the two half-periods proportional to the optical path difference determined by the height difference between the two half-periods. When this height difference equals \(\lambda n\) (where "n" is the refractive index of the grating material), the phase difference between the half periods is "\(\pi\)". In this case the wavefront is described by a square wave extending from \(-\pi/2\) to \(+\pi/2\), this contrasts the situation with an amplitude transmission square wave grating, whose two sections are given by \(\pi\) and 0. The average value of the phase grating wavefront is zero, while that of the amplitude grating is \(\pi/2\).

In short, with an appropriate height difference (or modulation depth) the phase grating produces no zero order. Zero order cancellation can be achieved not only by square waves, but also with other phase profiles, such as a sine wave.

The two effects, namely the evanescent wave phenomenon, and zero order cancellation by a phase grating,
combine to produce a novel kind of diffraction grating, which produces two diffraction orders exclusively. These two orders are of equal magnitude, and propagate symmetrically on either side of the optical axis. These features are ideal for the construction of a simple shearing interferometer. Furthermore, with the addition of a second phase grating, a moire shearerometer with all the advantages of both shearing interferometer and moire deflectometer emerges.

Consider the +1 order from the first grating, incident on the second at an angle \( \alpha_1 = \sin^{-1}(\lambda/p) \). The +/-1 orders of the second grating propagate in the directions corresponding to the +2 and 0 order of the first grating, respectively (Fig. 5). With this angle of incidence, the -3 order could also emerge in the direction of the original -2 order. When the pitch "p" is selected such that \( p<2\lambda \), these second orders are also eliminated through evanescence. The only emerging radiation propagates forward at an angle 0 through the combination of the +1 and -1 diffraction orders of G1 and G2, respectively.

A second beam, corresponding to -1 and +1, respectively, also travels in the forward direction and combines with the first to produce the desired interference pattern (Fig. 6). The two beams are shifted laterally by the shear distance

\[
s = 2d \tan \alpha_1 = 2d(p^2-\lambda^2)^{-1/2}
\]
Clearly, \( p \) must be larger than \( \lambda \); otherwise the first orders will also be evanescent thus effectively producing an opaque screen.

The interference fringes produced by this device are the loci of points whose wavefront values at the two points separated by the distance \( s \), differ by an amount equal to an integral number of wavelengths. For example, one fringe shift corresponds to a situation where:

\[
\frac{s}{2} - \frac{s}{2} = \lambda
\]

where \( W \) is the wavefront and \( y \) is the direction of the shear. When \( s \) is small, this expression can be approximated by the derivative

\[
\frac{\partial W}{\partial y} \approx \lambda.
\]

Thus the fringes are contours where the derivative is:

\[
\frac{\partial W}{\partial y} \approx \frac{\lambda}{s} = m \frac{(p^2 - \lambda^2)^{1/2}}{2d}
\]

\( m = 0, 1, 2, \ldots \)

This value is half the analogous expression in moire deflectometry. This factor of "2" difference in sensitivity results from the presence of the zeroth order in plain gratings, where the basic shear is \( d \tan \alpha_1 \). Two pairs of
orders (0,1 and -1,0) contribute to the fringe pattern, so that the spatial resolution, determined by the distance between the ±1 orders, is the same in both cases. Higher orders contribute some noise, which further reduces the resolution.

In short, for a given spatial resolution, the new shearometer is at least twice as sensitive as the standard moire deflectometer. However, the ease with which the sensitivity and tilt can be tuned is preserved.

Another important drawback of the moire deflectometer is also overcome by the present invention, i.e., the diffusivity of the image that results from the matt screen. The moire deflectometer employs a diffusive screen attached to grating G2 to prevent diffraction effects originating in that grating. The camera used to view the pattern must be focused on the screen. To obtain a good image of the test object the diffusive screen should be optically conjugate to the object.

In the system of the present invention, no unwanted orders are produced, and the screen with its degrading effects (grain, scratches, etc.) may therefore be avoided. The camera can be focused through the gratings directly on the object, adding more flexibility to the instrument.
DESCRIPTION OF PREFERRED EMBODIMENTS

Fig. 7 illustrates, for purposes of example, one form of shearing device constructed in accordance with the present invention. The device illustrated in Fig. 7 is a configuration where the shearometer module (which comprises the two phase gratings in tandem as described above) is used to characterize the optical parameters of transparent objects.

The shearing device illustrated in Fig. 7 includes a diode laser 2 producing a beam of coherent light which is expanded by a beam expander 4. The expanded collimated beam is directed toward the tested object which may be a sheet of glass, a lens, or any transparent object which may change the degree of beam collimation. The beam coming out of the tested object is directed toward the shearometer module, including a pair of diffraction gratings G1, G2, which produce an output in the form of a fringe pattern recorded in camera 10. Analysis of the fringe pattern indicates the extent to which the tested object has changed the beam collimation, and thereby indicates the optical properties of the tested object.

Fig. 8 illustrates an example wherein the tested object 6 is a diverging (negative) lens. This lens converts the collimated beam into a diverging spherical beam. The shearometer responds to this spherical beam by tilting the fringes so that they form an angle with respect to the direction of the unperturbed fringes displayed when
the beam is collimated. The slope of the fringes is proportional to the power of the lens and can be used to calculate the lens power.

Fig. 8 also illustrates the alternative wherein the diode laser light source can be moved backward, e.g., by a motor schematically indicated at M₁, until a point is reached where the beam exiting the tested lens and entering the shearometer is once again collimated. The distance by which the source has moved is used to calculate the power of the lens. The correct position is detected by observing the fringes and noting the location where the fringes return to the original position. Any difference between the resulting fringes and the unperturbed fringes (such as curved as opposed to the straight equidistant unperturbed fringes) is indicative of aberrations or imperfections in the tested lens. When the tested lens is positive, a reference fringe pattern is recovered by moving the source forward to the position where the beam entering the shearometer is once again collimated.

In a similar fashion the shearometer can detect non-parallelism in a nominally flat transparent sheet, non-uniformities in the material, etc.

Fig. 9 illustrates the use of the shearometer to measure deviations of reflective surfaces from a flat surface, such as roughness, waviness and strain. The collimated expanded beam from the light source 12 and beam expander 14 is directed toward a beam splitter 15. The part
of the beam that passes through is reflected by the tested surface 16. The reflected beam is once again divided by the beam splitter 15 into a part which continues in the original direction, and a second part reflected at right angles. The latter part is directed toward the shearometer module, including the part of diffraction gratings $G_1$, $G_2$, and the camera 20. Any changes in fringe position is proportional to the local slope of the tested object.

For purposes of example, consider a case where the surface is slightly curved in the form of a spherical section with a small curvature. The reflected beam is diverging or converging instead of parallel, and the resulting fringes will be tilted relative to the direction of the unperturbed fringe in the same way as noted above for a lens.

Fig. 10 illustrates another apparatus based on the same principle used to measure the curvatures of spherical or near spherical surfaces. The collimated beam from the light source 22 and beam expander 24 exiting from the beam splitter 25 is converged by an objective lens 23 and is directed toward the tested surface 26.

A search is made for a configuration where the return beam is collimated when entering the shearometer module including the diffraction gratings $G_1$, $G_2$, and the camera 30. Inspection of Fig. 10 reveals that this occurs when the tested object is located in either one of two points along the optical axis: (1) the object vertex
-16-

coincides with the focal point of the objective lens; or (2) the object center of curvature coincides with the focal point. In both cases, fringes will be observed oriented along the original direction. The distance between the two vertex positions is identical to the radius of curvature of the tested surface. Any remaining difference between the fringe pattern and the unperturbed pattern is used to measure deviation from an ideal spherical shape, as would be the case when the object is aspheric or toric, or contains another non-spherical feature such as waviness.

In either of the above modes (transmission or reflection), the shearometer unit can be used to measure the optical transfer function (OTF) or its modulus, the modulation transfer function (MTF). The measurement is based on the autocorrelation method for measuring the OTF (see for example Joseph Goodman, "Fourier Optics" secs. 6-3, 6-4). In this method one determines the overlap area between the two shifted pupils (see Figs. 3 and 6), and evaluates an integral of the light intensity within the overlap area. This integrated intensity provides a single entry into the OTF curve, which corresponds to a particular value of the spatial frequency scale equal to \( s/\lambda \) in units of cycles per radian. Conversion to cycles per mm is done by further dividing \( s/\lambda \) by the focal length of the tested lens. To recover the entire OTF vs. spatial frequency curve, it is necessary to repeat the above overlap integral measurement with different values of the shear distance \( s \).
With a typical shearing interferometer, tuning the shear is difficult if not impossible. The shearometer module allows simple scanning over $s$ by sliding one grating relative to the other (see eq. 3).

An example for the operation of an OTF measuring instrument can be described with reference to Fig. 8 above. The only modifications required to the setup of Fig. 8 is the addition of a means (such as a motor shown schematically at $M_2$) for continuously changing the gap $d$ between the two gratings $G_1, G_2$ in the shearometer module. Motor $M_2$ may also change the angle between the gratings. The OTF is constructed by evaluating the intensity over the overlap area as a function of $d$.

A related quantity, called through focus MTF, can be calculated by fixing $d$ to a prescribed value, and sliding the laser source around the point where the beam entering the shearometer is recollimated. When the source is out-of-focus, the MTF value is lower, so that the best focus is found at the maximum of the through focus MTF curve.

While the invention has been described with respect to several configurations, it will be appreciated that these are set forth merely for purposes of example, and that many other variations, modifications and applications of the invention may be made.
CLAIMS

1. An optical device including a diffraction phase grating substantially reducing towards elimination all the diffraction orders except the -1 and the +1 diffraction orders by the evanescent wave phenomenon and zero order cancellation.

2. The optical device according to Claim 1, wherein there are two of said diffraction phase gratings in tandem.

3. The optical device according to Claim 2, further including means for changing the distance between the two diffraction phase gratings.

4. The optical device according to either of Claims 2 or 3, further including means for changing the angle between the two diffraction phase gratings.

5. The optical device according to any one of Claims 2-4, further including a holder for an object to be optically examined; and a light source of collimated light oriented to pass a beam of collimated light through an object to be examined held by the holder to produce an emerging wavefront; said diffraction gratings being located to receive said emerging wavefront and to produce fringes indicative of the optical properties of the object being examined.

6. The optical device according to Claim 5, wherein said light source is a source of coherent light.
7. The optical device according to either of Claims 5 or 6, further including a camera for recording said fringes.

8. The optical device according to any one of Claims 5-7, further including a beam expander for expanding the beam of light before being passed through the object to be examined.

9. The optical device according to Claim 8, further including means for moving said light source towards or away from said beam expander.

10. The optical device according to any one of Claims 5-9, further including a beam splitter for passing part of said collimated beam to said examined object, which object reflects said collimated beam back to the beam splitter, said beam splitter reflecting another part of the collimated beam, together with the light reflected back from said examined object, to said diffraction phase gratings.

11. The optical device according to Claim 10, further including a converging lens between the beam splitter and the examined object.

12. A method of optically examining an object, comprising: passing a beam of collimated light to the object being examined and then through a diffraction grating substantially reducing towards elimination, by the evanescent wave phenomenon and zero order cancellation, all diffraction orders except the -1 and the +1 diffraction
orders; and observing the fringes produced by said
diffraction grating.

13. The method according to Claim 12, wherein said
beam of collimated light is passed through two of said
diffraction gratings in tandem.

14. The method according to Claim 13, wherein said
beam of collimated light is coherent light.

15. The method according to either of Claims 13 or
14, wherein the beam of collimated light is passed through a
beam expander before being directed to the examined object.

16. The method according to any one of Claims
12-15, wherein the distortions in the fringes produced by
said diffraction phase gratings are used to calculate the
deviation from collimation of the beam from the examined
object.

17. The method according to any one of Claims
12-15, wherein degree of beam collimation is evaluated from
the change in fringe density or orientation.

18. The method according to any one of Claims
12-18, wherein the examined object includes a reflective
surface, a part of the collimated beam being passed through
a beam splitter to the examined object and reflected back by
the examined object to the beam splitter, another part of
the collimated beam being passed by the beam splitter with
the beam reflected back from the examined object through
said diffraction phase gratings.
19. The method according to any one of Claims 13-18, further including changing the distance between said diffraction phase gratings for measuring the optical transfer function of the examined object.

20. The method according to any one of Claims 13-18, further including changing the distance between said diffraction phase gratings for measuring the modulation transfer function of the examined object.
**FIG. 1**

[Diagram of an object with optical components labeled: G1, G2, and distance d.]

**FIG. 2**

[Diagram of multiple overlapping circles with labels: -3, -1, 0, +1, +3.]

**FIG. 3**

[Diagram of two overlapping circles with labels: -1, +1.]

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**FIG. 4**

\[ \Delta \varphi = \pi \]

```
\[ p \rightarrow \text{GLASS} \]
```

**FIG. 5**

\[ +1, +1 \]

\[ -1, +3 \]

\[ +1, -1 \]

\[ -1, +1 \]

\[ +1, -3 \]

\[ -1, -1 \]

**FIG. 6**

\[ a_1 \]

\[ s \]

```
\[ \text{OVERLAP AREA} \]
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SUBSTITUTE SHEET (RULE 26)
**INTERNATIONAL SEARCH REPORT**

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(6) : G01B 9/02, 11/26; G02B 5/18, 27/44; G01C 1/00;

US CL: 356/152.3, 354, 359/566

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.: 356/128, 152.3, 305, 354, 374, 376; 359/558, 559, 563, 566, 569, 571

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

NONE

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

APS

search terms: phase gratings, deflectometer

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>US, A, 5,122,903 (ANOYAMA ET AL) 16 June, 1992, Figure 5, column 4, lines 38-69.</td>
<td>1-20</td>
</tr>
<tr>
<td>Y</td>
<td>US, A, 4,670,646 (SPIVEY) 2 June 1987, Figure 1, column 2, lines 33-54.</td>
<td>2-10, 13-20.</td>
</tr>
<tr>
<td>Y</td>
<td>US, A, 5,046,843 (KEREN) 10 September 1991, Figure 9, columns 5 and 6.</td>
<td>2-11, 13-20.</td>
</tr>
</tbody>
</table>

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

Date of the actual completion of the international search: 16 MAY 1996

Date of mailing of the international search report: 29 MAY 1996

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