

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
10 May 2007 (10.05.2007)

PCT

(10) International Publication Number
WO 2007/052019 A1

(51) International Patent Classification:
G01J 9/02 (2006.01)

(21) International Application Number:
PCT/GB2006/004070

(22) International Filing Date:
1 November 2006 (01.11.2006)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
0522398.7 3 November 2005 (03.11.2005) GB

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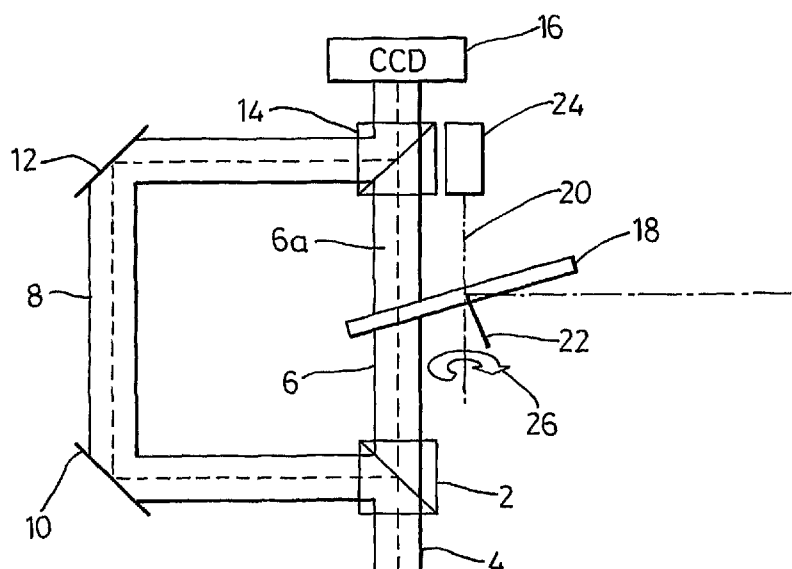
(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— with international search report

[Continued on next page]

(54) Title: APPARATUS FOR AND METHOD OF DETECTING THE PHASE OF A WAVEFRONT



(57) Abstract: An apparatus for detecting the phase of a wavefront in a beam of electromagnetic radiation includes divider (2) for dividing an original beam (4) into a reference beam (8) and a measurement beam (6,6a), a shearing device (18) for displacing the measurement beam (6) laterally according to a shearing vector and a rotator (24) for rotating the direction of the shearing vector. The apparatus also includes a detector (16) for detecting an interference pattern caused by superposition of the measurement beam (6a) and the reference beam (8), and a processor for ascertaining the phase and magnitude of temporal modulations in the interference pattern caused by rotation of the shearing vector.



For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

Apparatus for and method of detecting the phase of a wavefront

The present invention relates to an apparatus for detecting the phase of a wavefront in a
5 beam of electromagnetic radiation, and a method of detecting the same. In particular,
but not exclusively, the invention relates to measuring the phase distribution within a
beam of light. The invention also relates to a microscope system including such an
apparatus or operable according to such a method.

Sensing the phase of a wavefront is a key issue in optics since it enables the alignment
10 and performance of optical systems to be tested. It is of importance to industrial
applications, such as quality and alignment control. Other applications include adaptive
optics, where it is necessary to measure the wavefront that requires correction.

There are several wavefront measurement principles known from the literature. One
approach uses an interferometric measurement combined with fringe analysis or phase
15 shifting to extract the phase of the wavefront. In general this method can be very
accurate and is not too difficult to implement. However, it requires a separate reference
beam of known, preferably high quality. Another wavefront measurement principle is
modal wavefront sensing (See M.J. Booth, M.A.A. Neil, and T. Wilson: New modal
wave-front sensor: application to adaptive confocal fluorescence microscopy and two-
20 photon excitation fluorescence microscopy. *J. Opt. Soc. Am. A*, 19(10):2112-2120,
2002. & M.J. Booth. Direct measurement of Zernike aberration modes with a modal
wave front sensor. *Proc. SPIE, Advanced Wavefront Control: Methods, Devices, and
Applications*, 5162:79-90, 2003). This method requires the ability to bias the wavefront
with certain aberration modes in order to measure the modal content of the wavefront.

25 Another and perhaps the most common method for wavefront measurement is the
Hartmann or the Shack-Hartmann method. In the Hartmann method a mask with an
array of pinholes is used and the displacement of the spots is measured after some

propagation distance to infer the local tilt of the wavefront and after some computation the wavefront itself.

- The Shack-Hartmann principle is somewhat similar but here the array of pinholes is replaced by an array of microlenses which leads to higher light efficiency (see B.C. Platt and R. Shack. History and principles of Shack-Hartmann wavefront sensing. *Journal of Refractive Surgery*, 17:573-577, 2001). Usually a charge coupled device (CCD) is used to measure the displacement of the focal spots. The choice of the lenslet array (e.g. number of lenslets) determines the accuracy and also the dynamic range of the measurement. An advantage of the Shack-Hartmann setup is the relatively high speed, with more than 100 wavefront measurements per second reported. However, calibration of the apparatus is not always straightforward. Further, the cost of a Shack Hartmann system is currently about \$10,000 where the largest fraction is the CCD. For accurate measurements an expensive high resolution CCD sensor with good signal to noise ratio is required.
- US 6,115,126 (Chen et al) describes an optical wavefront analyser based on a phase-shearing interferometry technique. The analyser includes an adjustable phase shifter, a pattern receiving device and a phase reconstructing device that calculates the phase of a wavefront by analysing the interference patterns produced at five different settings of the phase shifter. The analyser is then rotated through 90° to analyse the interference pattern in the orthogonal direction.

According to the present invention there is provided an apparatus for detecting the phase of a wavefront in a beam of electromagnetic radiation, the apparatus including:

- divider means for dividing an original beam into a reference beam and a measurement beam,
- shearing means for displacing the measurement beam laterally according to a shearing vector,
- rotator means for rotating the direction of the shearing vector,
- detector means for detecting an interference pattern caused by superposition of the measurement beam and the reference beam, and

- processor means for ascertaining the phase and magnitude of modulations in the interference pattern caused by rotation of the shearing vector.

It should be noted that two or more of the elements recited in the preceding statement of invention may be combined into a single component. For example, a single optical
5 component may serve as both the divider means and the shearing means.

In the present document, references to the phase of modulations in the interference pattern relate to temporal modulations as caused by rotation of the shearing vector, rather than spatial modulations in the intensity of the pattern.

In comparison to a Shack-Hartmann system, the present invention allows the same or
10 better measurement accuracy with a CCD of much lower resolution. This provides a competitive advantage in both cost and performance. Because phase information is extracted purely from temporal intensity modulation, CCD resolution becomes an unimportant parameter. In addition, the Shack Hartmann sensor can have alignment problems that may lead to measurement errors, which are avoided in the present
15 invention. The invention also requires smaller algorithm and data processing complexity. Therefore, although the invention is not superior to the prior art under all conditions, (for example, when measurements at very high speeds are required), there are many applications where the measurement speed is not the main criterion and an instrument according to the invention can be used to provide excellent measurement
20 accuracy, simplicity and low cost.

Advantageously, the rotator means is constructed and arranged to provide continuous rotation of the shearing vector. Alternatively, the shearing vector can be rotated discontinuously (for example, in steps).

Advantageously, the rotator means is constructed and arranged to rotate the shearing
25 vector at a constant angular velocity. This simplifies operation of the apparatus.

Advantageously, the apparatus includes means for selecting the angular velocity of the shearing vector by adjusting the rotator.

Advantageously, the shearing vector has a constant magnitude, so that the measurement beam moves in a circle.

Advantageously, the apparatus includes means for selecting the magnitude of the shearing vector. This allows the sensitivity of the apparatus to be adjusted.

- 5 Advantageously, the shearing vector lies in a plane perpendicular to the optical axis of the measurement beam.

Advantageously, the processor means is constructed and arranged to detect the phase difference between the modulations in the interference pattern and a reference signal.

Advantageously, the reference signal is related to the phase angle of the shear vector.

- 10 This may be sensed for example by using an angular position encoder or a switch that is sensitive to the orientation of the rotator.

Advantageously, the detector means includes an array of detector elements. For example, the detector may be a CCD.

- 15 Advantageously, the processor means is constructed and arranged to record the interference pattern at a plurality of rotational directions of the shearing vector. If the rotator means is arranged to rotate continuously, this may be achieved by capturing an image at selected time intervals. Alternatively, if the rotator rotates in steps, an image may be captured after each step.

- 20 Advantageously, the processor means is constructed and arranged to extract the local slope and the local orientation of the wavefront from the interference patterns recorded at a plurality of rotational directions of the shearing vector.

Advantageously, the local slope and the local orientation of the wavefront are extracted by determining the phase and amplitude of temporal modulations in interference patterns recorded at a plurality of rotational directions of the shearing vector.

- 25 Advantageously, the phase and amplitude of the interference patterns are determined using a Fourier technique.

Advantageously, the processor means is constructed and arranged to reconstruct the wavefront from the local slope of the wavefront.

Advantageously, according to a first embodiment of the invention, the shearing means includes a parallel plate element that is positioned such that its surface normal is at an acute angle γ relative to the optical axis of the measurement beam (i.e. where $0^\circ < \gamma < 90^\circ$).

Advantageously, the rotator means is constructed and arranged to rotate the parallel plate element about an axis that is substantially parallel to the optical axis of the measurement beam. Preferably, the tilt angle γ remains constant relative as the normal line rotates around the optical axis.

Advantageously, the divider means includes a beam splitter.

Advantageously, according to a second embodiment of the invention, the apparatus includes an optical element for dividing the original beam into a reference beam and a measurement beam and for displacing the measurement beam laterally according to a shearing vector. The optical element thus serves as both the divider means and the shearing means. Advantageously, the optical element includes a birefringent material. Alternatively, the optical element may include a diffractive element.

Advantageously, the rotator means is constructed and arranged to rotate the optical element.

According to a second aspect of the invention there is provided a method of detecting the phase of a wavefront in a beam of electromagnetic radiation, the method including:

- dividing an original beam into a reference beam and a measurement beam,
- displacing the measurement beam laterally according to a shearing vector,
- rotating the direction of the shearing vector,
- detecting an interference pattern caused by superposition of the measurement beam and the reference beam, and
- ascertaining the phase and magnitude of modulations in the interference pattern caused by rotation of the shearing vector.

Advantageously, the shearing vector is rotated continuously.

Advantageously, the shearing vector is rotated at a constant angular velocity.

Advantageously, the shearing vector has a constant magnitude.

Advantageously, the shearing vector lies in a plane perpendicular to the optical axis of
5 the measurement beam.

Advantageously, the phase difference between the temporal modulations in the interference pattern and a reference signal is detected.

Advantageously, the reference signal is related to the phase angle of the shear vector.

Advantageously, the interference pattern is recorded at a plurality of rotational
10 directions of the shearing vector.

Advantageously, the local slope and the local orientation of the wavefront are extracted from the interference patterns recorded at a plurality of rotational directions of the shearing vector.

Advantageously, the local slope and the local orientation of the wavefront are extracted
15 by determining the phase and amplitude of temporal modulations in interference patterns recorded at a plurality of rotational directions of the shearing vector.

Advantageously, the phase and amplitude of temporal modulations in the interference patterns are determined using a Fourier technique.

Advantageously, the wavefront is reconstructed from the local slope of the wavefront.

20 In one suitable application of the invention, the wavefront to be measured may originate from a microscope setup and the information about the local wavefront slope may be used to establish a representation of the microscopic object. In another application of the invention, the obtained information about the wavefront may be used to measure the quality and/or alignment of optical components.

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

Figure 1 is a schematic diagram in plan view of an apparatus for detecting the phase of a wavefront in a beam of electromagnetic radiation, according to a first embodiment of the invention,

Figure 2 is a schematic isometric diagram of an apparatus for detecting the phase of a wavefront in a beam of electromagnetic radiation, according to a second embodiment of the invention, and

Figure 3 is a graph illustrating the temporal modulation in a detected interference pattern, in a method according to the invention.

Before describing a particular implementation of the device we describe the generalised measurement principle. We wish to measure the phase $\phi(x, y)$ of the beam Ψ_1 which may have amplitude non-uniformities described by the real parameter $A(x, y)$:

$$\Psi_1(x, y) = A(x, y) \exp(j\phi(x, y)). \quad (1)$$

In order to achieve this, we create a sheared version of this beam:

$$\Psi_2(x, y) = vA(x, y) \exp(j\phi_s(x, y)). \quad (2)$$

Here, the real parameter v denotes the relative balance between the amplitudes of the two beams. In the following, to simplify the calculations, two beams of equal amplitude are chosen so that $v = 1$. Operation of the system is not however limited to this case.

The phase of the second, sheared beam is

$$\phi_s(x, y) = \phi(x + \Delta x, y + \Delta y) \quad (3)$$

where the vector $(\Delta x, \Delta y)$ describes the lateral displacement of the sheared beam in respect to the original beam. Further we denote the local slopes of the wavefront with

$$s_x(x, y) = \frac{\partial}{\partial x'} \phi(x', y')_{x'=x; y'=y}, \quad \text{and} \quad s_y(x, y) = \frac{\partial}{\partial y'} \phi(x', y')_{x'=x; y'=y} \quad (4)$$

and the absolute value of the slope is given by

$$s(x, y) = \sqrt{s_x^2(x, y) + s_y^2(x, y)}. \quad (5)$$

For small shearing distances we can neglect higher orders and Equation (3) becomes:

$$\phi_s(x, y) = \phi(x, y) + \Delta x s_x + \Delta y s_y. \quad (6)$$

5

For brevity, the dependence of the slopes $s_x(x, y)$ and $s_y(x, y)$ on the coordinates (x, y) has been omitted.

Now we make the shear vector $(\Delta x, \Delta y)$ follow a circular modulation, which may be expressed as:

$$(\Delta x, \Delta y) = (r \cos(\omega t), r \sin(\omega t)), \quad (7)$$

10

where r is the total shear distance, ω refers to the angular velocity and t is the time. The difference between sheared and original wavefront then reads

$$\begin{aligned} \phi_s(x, y, t) - \phi(x, y) &= r s_x \cos(\omega t) + r s_y \sin(\omega t) + \delta \\ &= r s(x, y) (\cos \alpha \cos(\omega t) + \sin \alpha \sin(\omega t)) + \delta \\ &= r s(x, y) \cos(\omega t - \alpha) + \delta. \end{aligned} \quad (8)$$

15 The phase difference δ has been accommodated in this equation to account for any constant phase offset between Ψ_1 and Ψ_2 and to include the possibility of a deliberately introduced phase difference. We have also introduced the angle α that describes the orientation of the normal vector of the wavefront such that

$$s_x(x, y) = s(x, y) \cos \alpha \quad \text{and} \quad s_y(x, y) = s(x, y) \sin \alpha. \quad (9)$$

The existing dependence of α on the coordinates (x, y) is not spelled out for clarity. For our measurement task we now examine the intensity pattern produced by the interference of the beams,

$$I(x, y) = |\Psi_1 + \Psi_2|^2, \quad (10)$$

which leads to

$$\begin{aligned} I(x, y) &= A^2 |\exp(j\phi(x, y)) + \exp(j(\phi_s(x, y)))|^2 \\ &= 2A^2 [1 + \cos(\phi_s(x, y) - \phi(x, y))]. \end{aligned} \quad (11)$$

In the next step Equation (8) is combined with Equation (11) to give for the interferogram intensity:

$$I(x, y, t) = 2A^2 [1 + \cos(\delta + rs(x, y) \cos(\omega t - \alpha))] \quad (12)$$

The phase shift between the two beams has not been specified yet and we are free to set this parameter. If we choose $\delta = \pi/2$ and consider that $\cos(\pi/2 + \epsilon) = -\sin \epsilon$, we find from (12):

$$\begin{aligned} I(x, y, t) &= 2A^2 [1 - \sin(rs(x, y) \cos(\omega t - \alpha))] \\ &= 2A^2 [1 - rs(x, y) \cos(\omega t - \alpha)]. \end{aligned} \quad (13)$$

Here we made the approximation that the product of the local slope $s(x, y)$ and the shearing distance r in the argument of the sine function is small enough that we can use $\sin \alpha \approx \alpha$. Remembering that we discarded the location dependence of $\alpha(x, y)$ for clarity we can rewrite the previous equation:

$$I(x, y, t) = I_0(x, y) - m(x, y) \cos(\omega t - \alpha(x, y))], \quad (14)$$

where the following substitutions were made:

$$\begin{aligned} I_0(x, y) &= 2A^2 \\ m(x, y) &= 2A^2 rs(x, y). \end{aligned} \quad (15)$$

The previous equation (14) describes the measured intensity $I(x, y, t)$ of the interferogram and also reveals the measurement principle: we need to create a shearing interferometry setup where the lateral shearing vector of constant magnitude r rotates at constant angular velocity ω . Then, for each location (x, y) within the shearing interferogram the intensity will be modulated with ωt . It is straightforward to obtain the average $I_0(x, y)$ over one period, the phase-shift $\alpha(x, y)$ of the signal in respect to the modulation and the amplitude $m(x, y)$ using Fourier techniques. This demodulation process is a common task in signal processing and algorithms can be found (see for example Y. Surrel. Additive noise effect in digital phase detection. *Applied Optics*, 36(1):271-276, 1997. In the following, we will show how the wavefront slope $s(x, y)$ can be extracted from these parameters and explain the calibration of the system.

At first we calculate the normalised modulation

$$M(x, y) = \frac{m(x, y)}{I_0(x, y)} = rs(x, y). \quad (16)$$

In some cases the shearing distance r will be known a priori from the construction of the device. However, if it is not known we can perform a calibration procedure to obtain r comprising the following steps:

- supply a flat reference wavefront, for example by overexpanding a laser beam
- remove the remaining tilt of the wavefront entering the sensor by adjusting the tilt such that the modulation of the recorded interferogram is zero

- introduce an optical gauge element that produces a known tilt of the wavefront, for example a common wedge plate
- measure the average intensity $I_0(x, y)$ and the modulation amplitude of the interferogram, $rs(x, y)I_0(x, y)$ and deduce r from the known value of the tilt $s(x, y)$ induced by the gauge element.

Once the value of r is known, the wavefront sensor is ready to use. In each location of the interferogram, the average intensity value $I_0(x, y)$, the modulation

$$M(x, y) = rs(x, y)I_0(x, y) \quad (17)$$

and the phase shift $\alpha(x, y)$ are extracted by means of a Fourier analysis of the recorded time series. Now it is straightforward to extract the slope of the wavefront in each location:

$$s_x(x, y) = \frac{M(x, y) \cos \alpha(x, y)}{r} \quad \text{and} \quad s_y(x, y) = \frac{M(x, y) \sin \alpha(x, y)}{r}. \quad (18)$$

Certain embodiments of apparatus for use in measuring the phase of a wavefront according to the procedure described above will now be described.

The apparatus shown in figure 1 consists essentially of a modified Mach-Zehnder interferometer, which includes a first beam splitter 2 that divides an original input beam 4 into a measurement beam 6 and a reference beam 8, two mirrors 10,12 in the path of the reference beam 8, a second beam splitter 14 that recombines the measurement beam and the reference beam, and a CCD detector 16 that detects the interference pattern caused by the superimposed beams. A processor, for example a signal processing unit or computer, (not shown) is connected to the detector to record the images of the interference pattern. The processor extracts the local slope and the local orientation of the wavefront from the interference patterns recorded at a plurality of rotational directions of the shearing vector. The processor also performs the task of reconstructing the wavefront from its local slope measurements and is able to communicate and/or store and/or display information about the reconstructed wavefront.

The apparatus also includes a parallel-sided flat glass plate 18 of thickness d that is positioned in the path of the measurement beam 6 and mounted for rotation about an axis 20 that extends parallel to the axis of the measurement beam 6. The plate 18 is tilted so that a line 22 normal to its surface is at a tilt angle γ relative to the axis of the measurement beam 6. This causes the axis of the measurement beam to be offset laterally (sheared) from its original position. The axis of the sheared part 6a of the measurement beam is thus offset by a shear distance r that depends on the refractive index of the plate 18, the plate thickness d and the tilt angle γ . The sensitivity of the apparatus depends on the shear distance r and can be adjusted easily by changing the tilt angle γ .

The apparatus includes a drive motor 24 that is connected to the plate 18 and arranged in use to cause rotation of the plate about the rotation axis 20 in the direction of arrow 26. The direction of offset depends on the rotational position of the plate 18. Therefore, as the plate 18 rotates, the axis of the sheared measurement beam 6a rotates in a circle of radius r .

In use, the plate 18 rotates with angular velocity ω . This causes the sheared measurement beam 6a to rotate at the same angular velocity ω . The position of the sheared measurement beam may thus be represented by a shearing vector of magnitude r that rotates at an angular velocity ω . The interference pattern created by superposition of the sheared measurement beam 6a and the reference beam 8 will therefore be modulated at a frequency $f = \omega/2\pi$.

The interference pattern is detected by the CCD detector 16. This includes a two-dimensional array of pixels, each of which senses the varying intensity of light in one part of the modulated interference pattern. By way of example, figure 3 shows the temporal modulation in intensity that might be detected by three typical pixels, and a comparative reference signal, which may for example be the phase angle of the rotating plate or the shearing vector. It can be seen that the light intensity detected by each pixel is modulated, the frequency of modulation being equal to the frequency of the reference signal. However, the amplitude and the phase of the modulated intensity detected by each of the pixels is different. In the present invention, the amplitude and phase

information of the modulated interference pattern detected by the array of pixels is used to calculate the phase of the wavefront, as described above.

One advantage of this implementation is that it can be built from standard and relatively cheap components that are likely to be found in most laboratories. In addition, the apparatus is independent of wavelength. Also, by adjusting the angle γ , the sensitivity of the device can be set according to the dynamic range of the tilt contained in the wavefront one intends to measure. It should be noted that a small lateral offset between the reference beam and the sheared measurement beam is not a problem. In this case the measurement beam would probe a circular area of the wavefront and interfere it with another, further offset but constant region of the reference wavefront. Hence slight misalignment of the lateral adjustment of the reference beam has no influence on the modulation.

A second embodiment of apparatus for use in measuring the phase of a wavefront is shown in figure 2.

The second implementation is shown in Figure 2. Here the apparatus includes four optical elements: two quarter wave plates 30,32, a birefringent image separation crystal 34 and a linear polarisation analyser 36, as well as a CCD detector 38. These elements are arranged along the axis of an original beam 40. The second quarter wave plate 32, the image separation crystal 34 and the analyser 36 are mounted within a rotatable unit 42, which is rotatable about the axis of the original beam 40, as illustrated by arrow 44. A drive motor for rotating the rotatable unit and a processor for processing signals from the detector 38 are also provided (not shown).

The birefringent image separation crystal 34 splits the incoming beam 40 into two parallel emergent beams: a reference beam 46 that continues along the axis of the original beam 40, and a sheared measurement beam 48 that is displaced laterally from the axis of the reference beam by a shearing distance r , which depends on the material and the thickness of the crystal. The emergent beams 46,48 are linearly polarised with orthogonal polarisation axes. The analyser 36 consists of a linear polariser that is mounted at an angle of 45° with respect to the orthogonal field components of the

polarised beams 46,48. This receives the emerging beams 46,48 and allows the beams to interfere, generating an interference pattern that is detected by the CCD detector 38.

The original incoming beam 40 is usually a laser beam that is linearly polarised. The first quarter wave plate 30 is fixed with respect to the incoming beam and turns the linearly polarised light into circularly polarised light. The second quarter wave plate 32 creates linear polarisation again and ensures that the plane of polarisation is fixed with respect to the rotatable image separation crystal 34. The polarisation of the beam entering the crystal 34 is such that both emergent beams 46,48 have the same intensity. If the original incoming beam 40 is unpolarised, both quarter wave plates 30,32 can be omitted.

As in the previous embodiment, the amplitude and phase information of the modulated interference pattern detected by the array of pixels in the detector 38 is used to calculate the phase of the wavefront, using the method as described above.

The advantage of this arrangement is its compactness and robustness. Here the phase difference δ between the two emergent beams is determined by the precision of the crystal 34 and the quarter wave plates 30,32. With common manufacturing techniques it should be feasible to obtain a phase difference δ between the sheared and the unaltered beam that does not deviate by more than two degrees from the desired value of $\pi/2$.

Various modifications of the apparatus and method described above are of course possible. For example, the two interfering beams may be generated by means of an electro-optical modulator that changes its birefringent properties according to externally applied control voltages, thus enabling the direction of the shearing vector to be set by means of the control voltages without using movable optical elements. Alternatively, the two beams may be generated using a diffractive element.

Instead of using a CCD or similar two-dimensional array of photosensors, the detector can be a single light sensitive detector that can be moved in a direction perpendicular to the optical axis of the beam in order to scan the modulated intensity pattern.

The method or the apparatus can also be used in a microscope system to form image contrast.

In conclusion, the invention provides a new wavefront measurement technique that is based on circularly modulated shearing interferometry. Two embodiments have been described in detail. The first embodiment has the advantage that it is based on standard components and could be implemented in most optics labs at almost no cost. The second implementation is more compact and requires only a minimum of alignment. A general advantage of the method is the straightforward calibration. One implementation has the option to configure the sensitivity of the sensor, which would be impossible with a Shack-Hartmann configuration where the number of lenslets is fixed. A potential disadvantage of the suggested method for certain applications is speed. It is difficult to analyse a wavefront at more than approximately 1Hz because the apparatus has movable elements. An advantage is the simplicity of the algorithms needed for the extraction of the local tilt of the wavefront from the sensor data. The proposed principle may replace the currently dominant Shack-Hartmann wavefront sensor in some applications and may complement it in others.

Claims

1. Apparatus for detecting the phase of a wavefront in a beam of electromagnetic radiation, the apparatus including:
 - divider means for dividing an original beam into a reference beam and a measurement beam,
 - shearing means for displacing the measurement beam laterally according to a shearing vector,
 - rotator means for rotating the direction of the shearing vector,
 - detector means for detecting an interference pattern caused by superposition of the measurement beam and the reference beam, and
 - processor means for ascertaining the phase and magnitude of modulations in the interference pattern caused by rotation of the shearing vector.
2. Apparatus according to claim 1, in which the rotator means is constructed and arranged to provide continuous rotation of the shearing vector.
3. Apparatus according to claim 2, in which the rotator means is constructed and arranged to rotate the shearing vector at a constant angular velocity.
4. Apparatus according to claim 3, including means for selecting the angular velocity of the shearing vector.
5. Apparatus according to any one of the preceding claims, in which the shearing vector has a constant magnitude.
6. Apparatus according to claim 5, including means for selecting the magnitude of the shearing vector.
7. Apparatus according to any one of the preceding claims, in which the shearing vector lies in a plane perpendicular to the optical axis of the measurement beam.

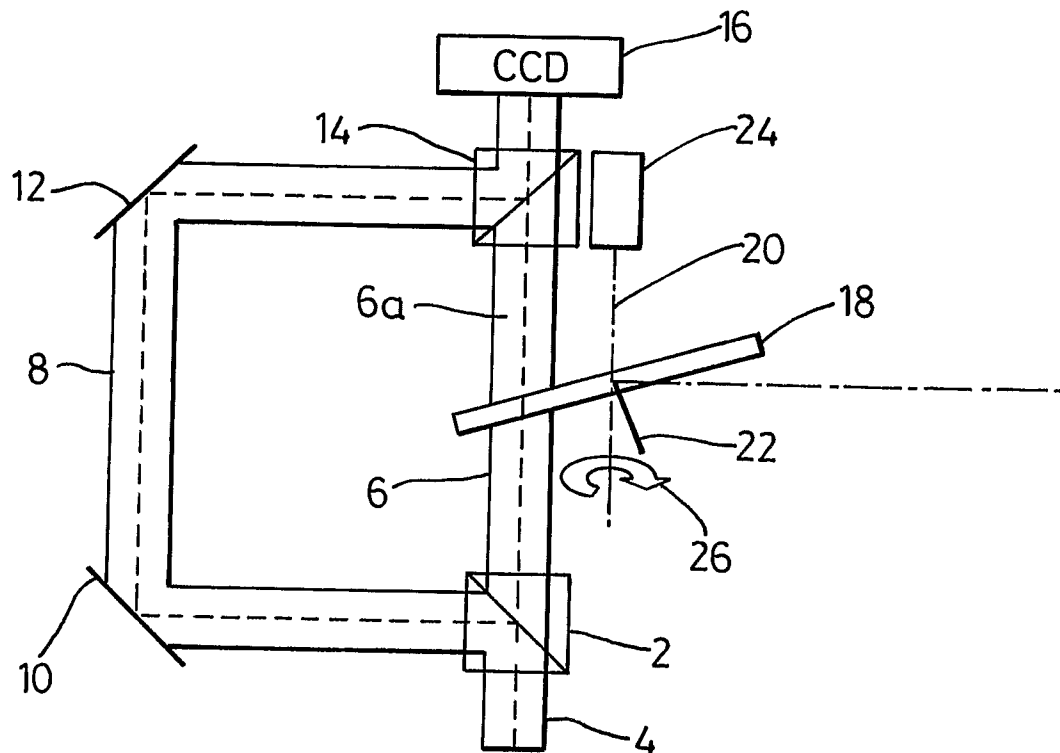
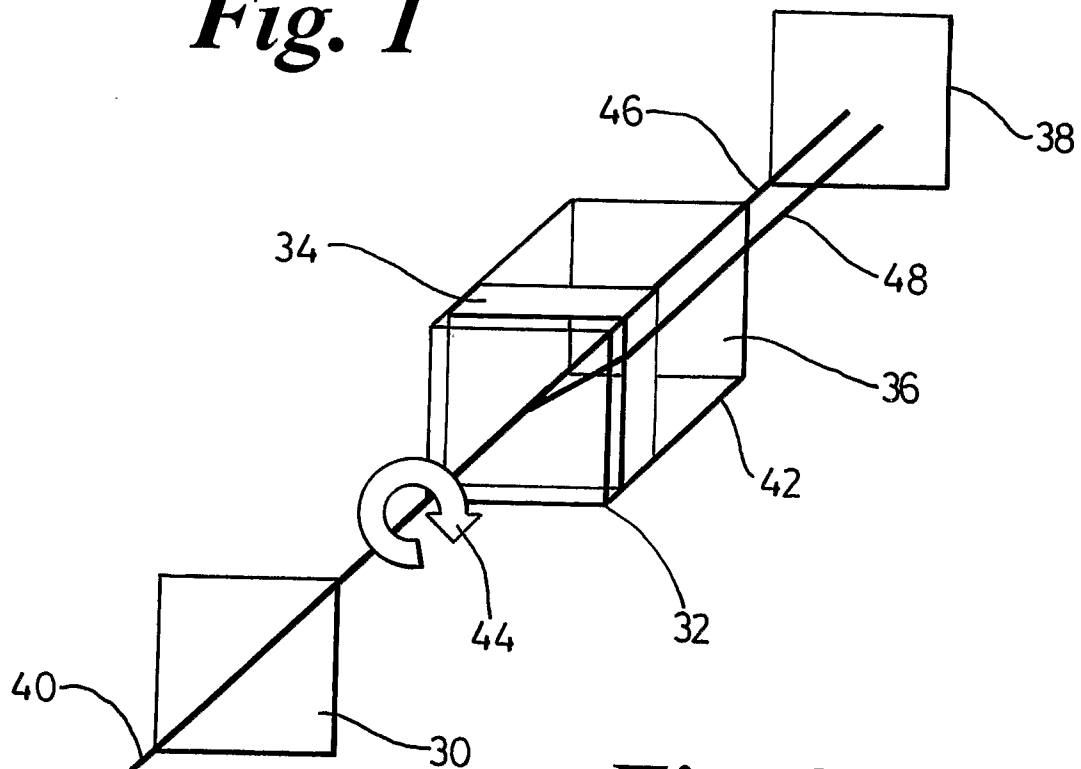
8. Apparatus according to any one of the preceding claims, in which the processor means is constructed and arranged to detect the phase difference between the modulations in the interference pattern and a reference signal.
9. Apparatus according to claim 8, in which the reference signal is related to the phase angle of the shear vector.
10. Apparatus according to any one of the preceding claims, in which the detector means includes an array of detector elements.
11. Apparatus according to any one of the preceding claims, in which the processor means is constructed and arranged to record the interference pattern at a plurality of rotational directions of the shearing vector.
12. Apparatus according to claim 11, in which the processor means is constructed and arranged to extract the local slope and the local orientation of the wavefront from the interference patterns recorded at a plurality of rotational directions of the shearing vector.
13. Apparatus according to claim 12, wherein the local slope and the local orientation of the wavefront are extracted by determining the phase and amplitude of the interference patterns recorded at a plurality of rotational directions of the shearing vector.
14. Apparatus according to claim 13, wherein the phase and amplitude of the interference patterns are determined using a Fourier technique.
15. Apparatus according to any one of claims 12 to 14, in which the processor means is constructed and arranged to reconstruct the wavefront from the local slope of the wavefront.
16. Apparatus according to any one of the preceding claims, in which the shearing means includes a parallel plate element that is positioned such that a line normal to its surface is at an acute angle relative to the optical axis of the measurement beam.

17. Apparatus according to claim 16, wherein the rotator means is constructed and arranged to rotate the parallel plate element about an axis that is substantially parallel to the optical axis of the measurement beam.
18. Apparatus according to claim 16 or claim 17, in which the divider means includes a beam splitter.
19. Apparatus according to any one of claims 1 to 15, including an optical element for dividing the original beam into a reference beam and a measurement beam and displacing the measurement beam laterally according to a shearing vector.
20. Apparatus according to claim 19, wherein the optical element includes a birefringent material.
21. Apparatus according to claim 19 or claim 20, wherein the rotator means is constructed and arranged to rotate the optical element.
22. A method of detecting the phase of a wavefront in a beam of electromagnetic radiation, the method including:
 - dividing an original beam into a reference beam and a measurement beam,
 - displacing the measurement beam laterally according to a shearing vector,
 - rotating the direction of the shearing vector,
 - detecting an interference pattern caused by superposition of the measurement beam and the reference beam, and
 - ascertaining the phase and magnitude of modulations in the interference pattern caused by rotation of the shearing vector.
23. A method according to claim 22, in which the shearing vector is rotated continuously.
24. A method according to claim 23, in which the shearing vector is rotated at a constant angular velocity.
25. A method according to any one of claims 22 to 24, in which the shearing vector has a constant magnitude.

26. A method according to any one of claims 22 to 25, in which the shearing vector lies in a plane perpendicular to the optical axis of the measurement beam.
27. A method according to any one of claims 22 to 26, in which the phase difference between the modulations in the interference pattern and a reference signal is detected.
28. A method according to claim 27, in which the reference signal is related to the phase angle of the shear vector.
29. A method according to any one of claims 22 to 28, in which the interference pattern is recorded at a plurality of rotational directions of the shearing vector.
30. A method according to claim 29, in which the local slope and the local orientation of the wavefront are extracted from the interference patterns recorded at a plurality of rotational directions of the shearing vector.
31. A method according to claim 30, wherein the local slope and the local orientation of the wavefront are extracted by determining the phase and amplitude of the interference patterns recorded at a plurality of rotational directions of the shearing vector.
32. A method according to claim 31, wherein the phase and amplitude of the interference patterns are determined using a Fourier technique.
33. A method according to any one of claims 30 to 32, in which the wavefront is reconstructed from the local slope of the wavefront.
34. A microscope system including an apparatus according to any one of claims 1 to 21, or operable according to a method as defined by any one of claims 22 to 33.
35. Apparatus for detecting the phase of a wavefront in a beam of electromagnetic radiation, the apparatus being substantially as described herein with reference to and as illustrated by the accompanying drawings.

36. A method of detecting the phase of a wavefront in a beam of electromagnetic radiation, the method being substantially as described herein with reference to and as illustrated by the accompanying drawings

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*Fig. 1**Fig. 2*

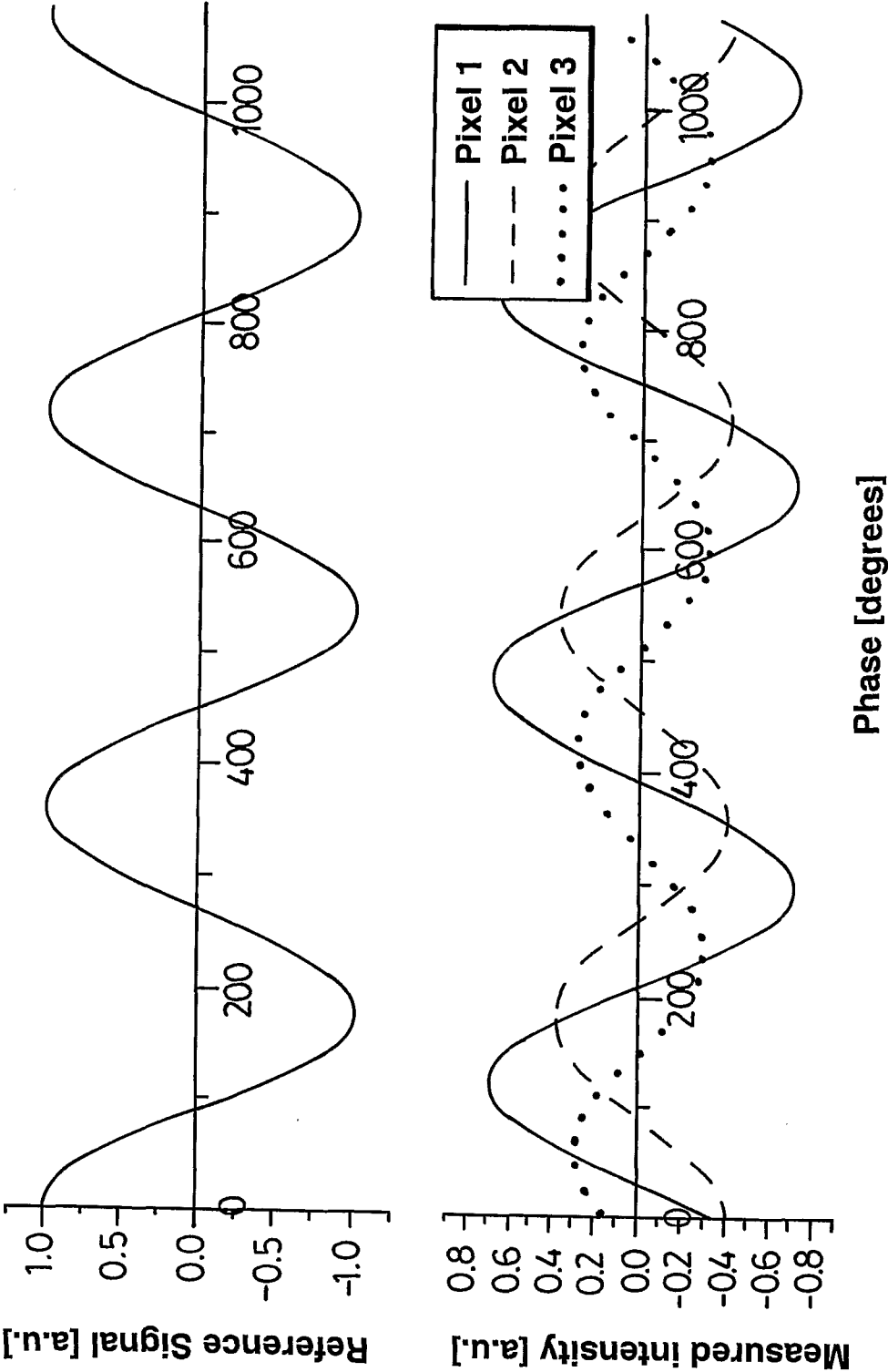


Fig. 3

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2006/004070

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01J9/02

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)

G01J G01N

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 practical, search terms used)

EPO-Internal, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SANDOVAL J ET AL: "Opto-mechanical design of a prism rotator" PROC SPIE INT SOC OPT ENG; PROCEEDINGS OF SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING 2002, vol. 4486, 1 August 2001 (2001-08-01), pages 170-180, XP002414940 page 176 - page 178 figures 7-10	1-19, 21-36
X	US 2004/145734 A1 (SHIBATA YUKIHIRO [JP] ET AL) 29 July 2004 (2004-07-29) paragraph [0077] - paragraph [0090] figures 17-19	1,8-15, 19-22, 27-36
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Date of the actual completion of the international search

16 January 2007

Date of mailing of the international search report

26/01/2007

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INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2006/004070

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 6 115 126 A (CHEN YI-CHUN [TW] ET AL) 5 September 2000 (2000-09-05) cited in the application abstract column 8, line 8 - line 31 figure 3	10-15, 29-33
A	WO 2004/068066 A (ORAXION [US]; ROSAKIS ARES J [US]; OWEN DAVID [US]; GLEDDEN STEPHEN [U] 12 August 2004 (2004-08-12) abstract paragraph [0045] figure 8	16-18

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2006/004070

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WO 2004068066 A	12-08-2004	EP 1590696 A2	02-11-2005
		JP 2006516737 T	06-07-2006