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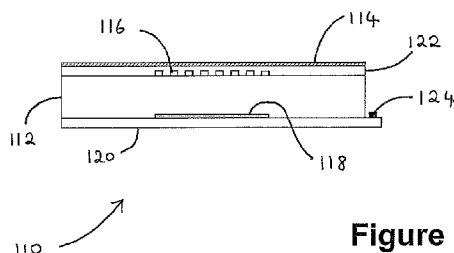


Figure 6a

(57) **Abstract:** A mirror structure is provided in which at least a portion of a wavefront sensor is integrated with a mirror. In particular, a mirror structure is provided in which a Hartmann mask or a microlens array of a Shack-Hartmann wavefront sensor is integrated with a mirror to provide a very compact wavefront detector/corrector in a single device. Such a mirror structure may be used in a laser cavity to simplify adaptive optics in the cavity. Furthermore, a Hartmann Mask may be integrated with self-deforming mirror comprising an active PZT layer bonded to a passive mirror substrate, wherein the Hartmann Mask comprises an array of apertures formed through the active PZT layer.



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MIRROR STRUCTURE

The present invention relates to mirror structures and in particular, but not exclusively, to a mirror structure in which at least a part of an optical wavefront sensor is integrated with a mirror. Such devices are particularly suited to use in adaptive laser optics.

Image sensors are used widely as diagnostic tools for lasers, for example to check laser beam quality within a test procedure before a laser system is delivered, but they may also be incorporated into a laser system to sample the laser beam with a beam splitter. Used in this way, the image sensor is limited to providing information on the intensity distribution within the laser beam. An image sensor may comprise a conventional array of charge-coupled devices (CCDs) arranged to detect the profile of light intensity across the width of the laser beam.

A more sophisticated sensor is a standard Shack-Hartmann sensor which comprises a microlens array that samples an incident wavefront over the aperture of the sensor and an image sensor that detects the position of a focussed spot of light in each microlens sub-aperture. Position data from the image sensor provides a measurement of the *average* wavefront slope across each sub-aperture as represented by the displacement of the respective focussed spot of light from the axis of the respective microlens. In order to provide an accurate representation of the total wavefront, the size of each sub-aperture is made small enough to capture the highest order aberration expected. However, the complexity of subsequent data processing increases rapidly with the number of microlenses in the array, reducing the sensor's speed. The image sensor is generally configured as a square array of individual sensors, such as a CCD array, but an array of position-sensitive detectors (PSDs) may be used alternatively.

Where the application is not photon-limited, it is possible to replace the microlens array with a Hartmann mask. A Hartmann mask is generally a mechanical mask with a square array of apertures. While the principle of

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operation is the same as for the standard Shack-Hartmann sensor, the Hartmann mask will obstruct more of the incident light than a microlens array.

It is known to use Shack-Hartmann sensors directly as diagnostic tools for deriving wavefront and intensity information for a laser, and hence the intensity profile, as one measure of the quality of a laser beam. In particular, it is
5 known to use either or both of a conventional CCD array and a Shack-Hartmann sensor in conjunction with a wavefront corrector or deformable mirror as part of an Adaptive Optics System, for example in an intra-cavity laser adaptive optics (AO) arrangement.

10 From a first aspect, the present invention resides in a mirror structure, comprising a mirror having a reflective surface arranged to allow a portion of incident light to pass therethrough and wherein the mirror has at least one component of an optical sensor integrated therewith, arranged to receive light that passes through said reflective surface.

15 In a preferred embodiment, at least a Hartmann mask of a Hartmann wavefront sensor is integrated with the mirror. If the mirror comprises a mirror substrate with the reflective surface applied thereto, then the Hartmann mask may comprise an array of apertures formed in the mirror substrate. Alternatively, if the mirror comprises a substantially transparent mirror substrate,
20 then the Hartmann mask may be formed in a distinct layer within the mirror structure, for example one applied to a surface of the mirror substrate.

Preferably, the Hartmann mask is covered by a planarisation layer to which said reflective surface is applied. A planarisation layer may provide an optically flat and polished surface on which to apply the reflective surface of the
25 mirror.

In a further preferred embodiment, the at least one component of an optical sensor is a microlens array of a Shack-Hartmann wavefront sensor integrated with the mirror. The microlens array may be covered by a planarisation layer to provide an optically flat polished surface for the reflective
30 surface.

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In a further preferred embodiment, the at least one component of an optical sensor is an optical detector. The optical detector may take one of a number of different forms according to what properties of the incident light are to be detected. For example, the optical detector may comprise a charge-coupled device (CCD) or position sensing detector (PSD). Such an optical detector may be integrated with either a plane mirror or with a deformable mirror that has an active layer of deformable material coupled to a passive substrate.

Preferably the optical detector is provided to detect the wavefront slope of the incident light at one or more points across the aperture of the mirror.

In the preferred Hartmann mask embodiments, the mirror may be a fixed profile mirror or it may be a deformable mirror. In a preferred embodiment, the mirror is a self-deforming mirror comprising an active layer of deformable material coupled to a substantially transparent passive substrate and wherein the Hartmann mask comprises an array of apertures formed in the active layer of deformable material. Of course, if the active layer is formed using a substantially transparent deformable material, such as a known form of single crystal piezo-electric material, then the Hartmann mask may be formed in another way, for example by an array of small apertures in a common electrode layer of the deformable mirror.

Preferably, the self-deforming mirror is supported by means of one or more passive flexible support elements coupled to a housing and wherein an optical detector is provided within the housing to detect the wavefront slope of the incident light at one or more points across the aperture of the mirror.

The optical sensor in preferred embodiments of the present invention may comprise a Charge Coupled Device (CCD) array, a Position Sensitive Detector (PSD) or array of PSDs, a quad detector or array of quad detectors, or a Hartmann wavefront sensor.

From a second aspect, the present invention resides in a laser mirror comprising a mirror structure according to the first aspect, above. Such a device may be used as the main component in a simplified intra-cavity adaptive optics system, removing the need for a separate sensor and wavefront corrector.

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Because the sensor is integrated behind a mirror surface, only small amounts of light will reach the sensor. While integration of the sensor behind a mirror surface will exclude photon-limited applications such as Astronomy, this type of device is ideal for use with laser systems where interrogation of the wavefront
5 or beam profile often requires some form of attenuation to ensure that excess laser power does not damage the optical sensor.

A mirror structure incorporating at least one component of a Hartmann or a Shack-Hartmann wavefront sensor may be used with a laser cavity in either a closed loop or an open loop configuration.

10 Preferred embodiments of the present invention will now be described in more detail, by way of example only, with reference to the accompanying drawings of which:

Figure 1 is a diagram representing a sectional view through a known Shack-Hartmann sensor;

15 Figure 2 is a diagram representing a simple known laser cavity;

Figure 3 is a diagram representing a known intra-cavity laser adaptive optics system;

Figure 4 provides a sectional view and a plan view of an image sensor integrated with a laser mirror, according to a preferred embodiment of the
20 present invention;

Figure 5 provides a sectional view and a plan view of an image sensor integrated with a deformable mirror, according to a preferred embodiment of the present invention;

Figure 6 provides a sectional view and a plan view of a mirror structure
25 with an integrated Hartmann mask, according to a preferred embodiment of the present invention;

Figure 7 provides a sectional view and a plan view of a mirror structure with an integrated Shack-Hartmann sensor, according to a preferred embodiment of the present invention; and

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Figure 8 provides a sectional view through a mirror structure comprising a peripherally-supported deformable mirror with an integrated Hartmann mask, according to a preferred embodiment of the present invention.

Preferred embodiments of the present invention have been devised to
5 incorporate one of several known types of optical wavefront sensor in a mirror structure giving particular advantages in simplifying adaptive optics systems, in particular for use in laser cavities. However, by way of introduction, a known type of wavefront sensor – the Shack-Hartmann sensor - suitable for use in preferred embodiments of the present invention, will firstly be described with
10 reference to Figure 1.

Referring to Figure 1, a sectional view is provided through a conventional Shack-Hartmann sensor 10 comprising an array of microlenses 12 that each sample an incident wavefront 14 over a sub-aperture of the sensor 10, and an optical sensor 16, comprising an array (typically square) of individual CCDs or
15 PSDs that each detect the position of a focussed spot of light 18 in the respective sub-aperture. Position data from the image sensor 16 provides a set of measurements of average wavefront slope 20 across each sub-aperture as represented by the displacement 22 of the respective focussed spot of light 18 from the axis 24 of the focussing microlens 12.

20 In order to provide an accurate representation of the total wavefront 14, the size of each sub-aperture, and hence of each microlens 12, is made small enough to capture the highest order aberration that needs to be corrected for. However, the complexity of subsequent data processing increases rapidly with the number of microlenses 12 in the array, reducing the overall rate of response
25 of the sensor 10 to changes in the wavefront 14.

Where the application is not photon-limited, it is known to replace the array of microlenses 12 with a so-called Hartmann mask. A Hartmann mask is generally a mechanical mask with a square array of apertures. While the principle of operation of a sensor incorporating a Hartmann mask is the same
30 as for the conventional Shack-Hartmann sensor 10, the Hartmann mask will obstruct more of the incident light than a microlens array, limiting its use to

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applications in which the light levels are going to be sufficiently high to be detectable by the image sensor 16 after passing through the Hartmann mask.

A simple known laser cavity structure will now be described briefly with reference to Figure 2 as one example of a potential application of Hartmann wavefront sensors. Features of this simple laser cavity will be referenced later
5 when discussing applications of the present invention.

Referring to Figure 2, a simple laser cavity 25 is bounded by a first laser mirror 26 and a second, partially reflective laser mirror 27. Within the cavity a laser beam 28 is generated by a lasing medium 29 and travels between the first
10 and second mirrors 26, 27 before being output from the partially reflective second mirror 27.

It is known to use Shack-Hartmann sensors 10 directly as diagnostic tools for deriving wavefront and intensity information for a laser, and hence the intensity profile, as one measure of the quality of a laser beam. In particular, it is
15 known to use either or both of a conventional CCD array and a Shack-Hartmann sensor in conjunction with a wavefront corrector or deformable mirror as part of an Adaptive Optics System, for example in an intra-cavity laser adaptive optics (AO) arrangement as will now be described in outline with reference to Figure 3.

Referring to Figure 3, a representation is provided of a laser cavity 30
20 that is bounded by a first laser mirror 32 and a second, partially reflective output mirror 34. A laser beam 36, generated within a lasing medium 38, travels between the first laser mirror 32 and the second, partially reflective output mirror 34 by way of a third, fixed mirror 40 and a deformable mirror 42. Light from the
25 laser beam 36 is sampled by a beam splitter 44 placed in the path of the laser beam 36 between the deformable mirror 42 and the output mirror 34 to direct a portion of light 46 towards a wavefront sensor 48, for example a Shack-Hartmann sensor 10 as described above with reference to Figure 1, where the wavefront profile of the laser beam 36 may be detected. The wavefront sensor
30 48 outputs data to a controller 50 which determines, on the basis of those data, an appropriate deformation profile to apply to the deformable mirror 42 so as to

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make corresponding adjustments to the laser beam wavefront as it reflects from the deformable mirror 42 within the laser cavity 30.

A Shack-Hartmann sensor 10 may be used as a wavefront sensor 48 within the laser cavity 30 in either a closed loop or an open loop configuration. The distortions induced in a laser cavity are generally thermal in nature and so there will be no instantaneous response due to modifications applied by a wavefront corrector such as the deformable mirror 42. For this reason, the controller 50 is generally arranged to implement an adaptive control system based around an iterative search algorithm. In a closed loop configuration such as that shown in Figure 3, the wavefront sensor 48 is placed after the wavefront correcting deformable mirror 42 so that it will detect any residual wavefront errors. An iterative control algorithm may be implemented by the controller 50 so that the system converges on an optimal level of correction for the laser beam 36. This provides for more accurate wavefront correction than is possible in an open loop system in which the wavefront sensor precedes the wavefront corrector and there is no feedback loop, but its response will be faster than in a closed loop system.

Preferred embodiments of the present invention will now be described which enable a simplification of the adaptive optics intra-cavity arrangement of Figure 3, amongst other advantages. A first preferred embodiment will be now be described with reference to Figure 4.

Referring initially to Figure 4a, a sectional view is provided through a mirror structure 60 comprising a fixed mirror having a reflective surface 62 that is arranged to allow a small amount of light to pass through it, and a CCD or CMOS active pixel sensor array 64 integrated within the mirror structure 60. The integrated sensor array 64 is arranged within the structure 60 such that light that passes through the reflective surface 62 may be detected by the sensor array 64. Referring additionally to Figure 4b, a plan view is provided of the same mirror structure 60 from a view point above the reflective surface 62.

Preferably, the mirror structure 60 comprises a thin layer (of the order of 300µm) of silicon 66 on which the CCD or CMOS active pixel sensor array 64 is

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fabricated using conventional fabrication techniques. The size of the sensor array 64 is chosen to be wider than the intended optical aperture 65 which, in the case of an intra-cavity laser beam, is likely to be significantly less wide than the diameter of the reflective surface 62 and most likely confined to the central region of that surface 62. A planarisation and/or passivation layer 68, preferably of silicon dioxide or silicon nitride, or one layer of each, is applied to cover the sensor array 64 to a thickness sufficient to enable an optically flat polished surface to be provided above the sensor array 64, suitable for the application of the reflective surface 62. A passivation layer, in particular, may be required to ensure that any electrically conducting tracks on the surface of the silicon layer 66 are not shorted, in particular if the reflective surface 62 is provided by a coating of gold, for example. A planarisation layer may be required for example if the sensor array fabrication process leaves behind small surface features, for example tracking or exposed circuitry, which would lead to undesirable "print-through" on the reflective surface 62. A planarisation layer would provide for a high quality, optically flat reflective surface 62.

The planarisation/passivation layers 68 are required to be at least partially transparent to light at the operating wavelength for the mirror, e.g. for a laser mirror, so that light may reach and be detectable by the sensor array 64.

Preferably the silicon layer 66 is bonded to a rigid and supportive carrier layer 70, preferably made from un-processed silicon or silicon carbide so as to have a similar expansion coefficient to the silicon layer 66 and, in the case of silicon carbide, to provide a highly thermally conductive layer to assist in the efficient removal of heat from the mirror structure 60 when applied to laser cavities. Because the silicon layer 66 is likely to be thin (e.g. 300µm), it may be beneficial during assembly of the structure 60 to bond the silicon layer 66 to the carrier layer 70 before the planarisation/passivation layer 68 is polished flat, to provide additional support.

Preferably, the electrically conducting tracks to the sensors of the array 64 extend to the periphery of the silicon layer 66 and terminate with serial output pads 72 provided around the periphery of the mirror structure 60. Interconnection to the peripheral serial output pads 72 may be achieved in a

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number of known ways, for example using a flexi-circuit of a type described in published international patent application WO 2005/124425, an elastomeric connector, wire bonding or soldering.

The level of attenuation to be introduced by the reflective surface coating
5 62 of the mirror is determined by a requirement to match, in a given application, the intensity of light transmitted to the sensor array 64 to the sensitivity of the sensors in the array 64. The reflective surface 62 preferably comprises a coating of gold, enhanced gold or a multi-layer dielectric coating.

In an alternative arrangement of the mirror structure 60, the sensor array
10 64 may be integrated/bonded to a deeper layer within the mirror structure 60, or even to the lowest surface of the mirror structure, if the intermediate layer or layers of substrate material are sufficiently transparent.

The mirror structure 60 with the integrated sensor array 64, described above, may be used in any number of known configurations. For example, in
15 the laser cavity 30 described above with reference to Figure 3, the mirror structure 60 may replace one or both of the first or second laser mirrors 32 or 40. This would simplify the laser cavity 30, removing the need for the beamsplitter 44 and separate sensor 48. If two such mirror structures 60 are incorporated in the laser cavity 30, each may contribute different measures of
20 laser beam quality to an adaptive optics control system.

The mirror structure 60 may be used in conjunction with an iterative search algorithm to control a deformable mirror for intra-cavity adaptive optics. One such algorithm is a hill-climbing algorithm which modifies the deformable mirror to maximise the optical power within a specific 'software aperture' on the
25 sensor array 64. This type of algorithm is particularly suited to intra-cavity adaptive optics where the slow response of the cavity means that, after an adjustment of the deformable mirror, the cavity needs to be left to stabilise before any further adjustments are made.

In a second preferred embodiment of the present invention, a mirror
30 structure similar to the structure 60 described above, excluding the carrier layer

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70, may form the basis of a deformable mirror structure, as will now be described with reference to Figure 5.

Referring to Figure 5, a sectional view is provided through a self-deforming mirror structure 80 comprising a thin (of the order of 300µm) passive substrate layer 82, preferably of silicon and corresponding to the silicon layer 66 in Figure 4, bonded to an active PZT layer 84. A sensor array 86 has been fabricated on the silicon layer 82 by conventional fabrication techniques, and a planarisation and/or passivation layer 88 has been applied to cover the sensor array 86 and any associated tracks to provide an optically flat surface for the application of an at least partially transmissive reflective surface 90. Sensor output connection pads 92 are provided around the periphery of the deformable mirror structure 80 for interconnection via a cable 93 with the sensor array 86.

The active PZT layer 84 is provided on one face with a thin continuous electrode layer (not shown in Figure 5), sandwiched between the silicon layer 82 and the PZT layer 84, and on the other face with a patterned array of electrodes 94 to enable selected regions of the PZT layer 84 to be energised and thus deformed. Preferably a flexi-circuit 96 of the type referenced above may be connected to the electrodes 94 and an interconnect cable 98 may be provided to enable voltages to be supplied selectively to the electrodes 94. The self-deforming parts (82 to 96 in Figure 5) of the mirror structure 80 are supported from below around their periphery by means of one or more compliant support elements 100 mounted on a rigid base 102.

Whereas, in the mirror structure 80, the silicon layer 82 is bonded to a patterned PZT layer 84 to form a deformable mirror, it may alternatively be bonded to an array of actuators, for example piezo-tubes, PZT stacks or MEMS actuators to form a zonal deformable mirror. The silicon layer 82 may alternatively be added to a true bimorph deformable mirror structure, or form the top layer of a symmetric bimorph structure.

As an alternative to PZT, the layer of active material 84 may comprise a layer of a single crystal piezo-electric material of which known examples are substantially transparent to light, or a layer of an electrostrictive material.

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The mirror structure 80 may conveniently be retro-fitted into an existing laser cavity, for example replacing the first laser mirror 26 in the simple laser cavity 25 of Figure 2 to enable adaptive optics to be added without increasing the complexity of the cavity. The usefulness of a deformable mirror in a simple
5 laser cavity 25 is dependent upon the width of the laser beam 28 within the cavity 25. If the beam width is too small then only the very lowest order distortion (e.g. spherical) would be correctable by the mirror structure 80. However, such a mirror structure 80 may still prove very useful; the main optical distortion that will be present in a cavity will be driven by thermal lensing.

10 In a third preferred embodiment of the present invention, a mirror structure will now be described with reference to Figure 6 in which a Hartmann mask is integrated with a laser mirror.

Referring initially to Figure 6a, a sectional view is provided through a mirror structure 110 comprising a transparent mirror substrate 112, made from
15 glass for example, a reflective surface 114 that is arranged to allow a small amount of light to pass through it, a Hartmann mask 116 disposed between the reflective surface 114 and the mirror substrate 112 and a sensor 118 fabricated on a layer of silicon 120 or other semi-conductor material, arranged to receive light transmitted through the reflective surface 114, the apertures of the
20 Hartmann mask 116 and the mirror substrate 112. Referring additionally to Figure 6b, a plan view is provided of the same mirror structure 110 viewed from a position above the reflective surface 114.

The Hartmann mask 116 may comprise either a pre-formed Hartmann mask that is bonded to the mirror substrate 112 or a Hartmann mask formed by
25 photolithography directly onto the surface of the mirror substrate 112.

A planarisation layer 122 is provided to cover the Hartmann mask 116 and to provide an optically flat and transparent polished surface onto which the reflective surface 114, comprising a thin deposit of gold for example, is formed. Alternatively, the Hartmann Mask 116 may be bonded between two glass
30 substrates.

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The depth of the mirror substrate 112, and hence the separation of the sensor 118 from the Hartmann mask 116, is selected according to the maximum wavefront slope that needs to be measured and the resolution of the sensor 118. The sensor 118 may comprise a conventional CCD or an array of
5 PSDs as described above, covered if necessary by a planarisation layer (not shown in Figure 6) to give a flat contact surface with the mirror substrate 112, and may be mounted on the back of the mirror substrate 112 in such a way that it may be replaced if necessary. Interconnection to the sensor is provided by means of connection pads 124 provided around the periphery of the silicon layer
10 120.

For applications that involve use of the mirror structure 110 in a harsh environment, the sensor 118 may be hermetically bonded to the back of the mirror substrate 112.

In view of the high level of optical attenuation provided by the
15 combination of a reflective surface coating 114 and a Hartmann Mask 116, the mirror structure 110 according to this third preferred embodiment is likely to be used in a high power laser system.

In a fourth preferred embodiment of the present invention, a mirror structure is provided in which a microlens array and a sensor are integrated with
20 a laser mirror to provide an integrated Shack-Hartmann sensor. The mirror structure according to this fourth preferred embodiment will now be described with reference to Figure 7.

Referring initially to Figure 7a, a sectional view is provided through a mirror structure 130 comprising a transparent mirror substrate 132, made from
25 glass for example, a reflective surface 134 that is arranged to allow a small amount of light to pass through it, a microlens array 136 disposed between the reflective surface 134 and the mirror substrate 132 and an optical sensor 138 arranged to receive light transmitted through the reflective surface 134, the microlens array 136 and the mirror substrate 132. Referring additionally to
30 Figure 7b, a plan view is provided of the same mirror structure 130 viewed from a position above the reflective surface 134.

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In common with the sensors used in preferred embodiments described above, the sensor 138 comprises an CCD or an array of PSDs fabricated on a layer of silicon 140 or other semi-conductor material, covered if necessary with a planarisation layer 142 to provide a flat surface for bonding to the mirror substrate 132. Connection pads 139 are provided, as above, for interconnection with the sensor 138. A further planarisation layer 144 is formed to cover the microlens array 136 for the purpose of providing an optically flat polished surface ready to receive a layer of gold, for example, to form the reflective surface 134. However, in order for the microlenses in the array 136 to function as lenses, the microlenses are formed using a material with a different refractive index to the material forming the planarisation layer 144.

In common with the third preferred embodiment described above, the depth of the transparent mirror substrate 132 is selected according to the maximum wavefront slope to be measured and the resolution of the sensor 138.

In a fifth preferred embodiment of the present invention, a mirror structure will now be described with reference to Figure 8 in which a Hartmann mask is integrated with a self-deforming mirror.

Referring to Figure 8, a sectional view of is provided through a mirror structure 150 in which an otherwise conventional self-deforming mirror, having an active layer 152 of deformable material such as PZT bonded to an optically transparent passive substrate 154 made from glass for example, with an intermediate common electrode layer (not shown in Figure 8), has been modified by drilling an array of apertures 156 through the non-transparent layers, in particular the active PZT layer 152, to form a Hartmann mask. However, if a transparent single crystal piezo-electric material were to be used for the active layer 152, then the Hartmann mask may be implemented in a different way and may comprise an array or apertures formed only in the common electrode layer for example.

A partially transmissive reflective surface 158, for example of gold, is carried by the passive substrate 154, if necessary formed on an optically flat polished surface of a thin, optically transparent planarisation layer (not shown in

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Figure 8) applied to cover the passive substrate 154. A partitioned electrode layer 160 is provided to enable selected regions of the active layer 152 to be energised via a flexi-circuit 162 of a type referenced above. An interconnect cable 164 connects to the flexi-circuit.

5 The deformable mirror, comprising the components 152 to 164, is supported preferably from below by means of a number of discrete passive flexible support elements 166 disposed around its periphery or, alternatively, by a continuous annular flexible support element 166. The support elements 166 are mounted on an annular section 170 of a rigid housing that comprises the
10 annular section 170 fixed to a base plate 172. The rigid housing 170, 172 encloses a cavity 174 beneath the supported deformable mirror components.

 An optical sensor 176 is provided within the rigid housing 170, 172, conveniently mounted within the cavity 174 on the base plate 172, comprising an array of discrete quad detectors or an array of CCDs fabricated on a wafer of
15 silicon 178 with each discrete detector centred below the position of a respective aperture 156 of the Hartmann mask. Connection to the detectors of the sensor array 176 is preferably by means of a flexi-circuit and a further interconnect cable 180.

 Light from an incident wavefront 155 passes through the apertures 156
20 of the Hartmann mask and through the cavity 174 to be detected by the sensor 176. The distance h separating the apertures 156 of the Hartmann mask and the sensor 176 is chosen according to the maximum wavefront slope that needs to be measured and the resolution of the sensor 176. The displacement of the centroid of a spot of light at the sensor 176 for an incident wavefront of slope θ
25 is given by

$$\Delta x = \theta h$$

 The size of the apertures 156 is chosen to be large enough to let through enough of the incident light to be detectable by the sensor 176 but to be small enough so that "print-through" due to the apertures 156 is negligible at the
30 mirror reflective surface 158. Furthermore, because the apertures 156 for the Hartmann Mask are being created in the active PZT layer 152, there will be a

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limit on the number of apertures 156 (Hartmann “windows”) and hence sensor array size that can be used. As more and more Hartmann windows are added, the amount of PZT remaining in the active layer 152 to generate the required mirror curvatures will be reduced, restricting the voltage sensitivity of the device.

- 5 The position of each aperture 156 in the active layer 152 preferably coincides with a gap between electrodes in the electrode layer 160 to minimise the number of apertures that need to be formed in the electrodes. Correspondingly positioned apertures are made in the flexi-circuit 162.

In this fifth preferred embodiment shown in Figure 8, it has been found
10 that deformation of the active PZT layer 152 does not significantly affect the displacement of the centroids of light spots at the sensor array 176.

Whereas the mirror structure 150 in this fifth preferred embodiment is shown comprising a deformable mirror with a single active PZT layer 152, a deformable mirror may be integrated with the structure 150 that uses other
15 materials or is of a different type, for example a true bimorph or a symmetrical bimorph type of deformable mirror, or one of a type that is deformed using stacked actuators, PZT tubes, or MEMS devices.

The mirror structure 150 of this fifth preferred embodiment may be used to replace the first laser mirror 26 in the simple laser cavity 25 of Figure 2. In
20 such an application, while there may be a limit on the number of individual Hartmann windows that can be added, this may not be an issue for intra-cavity wavefront correction where the main aberration that requires correction is the thermal lensing of the laser rod 28. Depending on the geometry, the main distortions requiring correction will be either spherical or astigmatic. Spherical
25 aberrations will be circularly symmetrical, and so may be determined using just one line of Hartmann windows/apertures 156 along a radius of the mirror. The astigmatic case may be determined with two orthogonal lines of Hartmann windows/apertures 156, each along a radius of the mirror.

The mirror structure 150 may be used extra-cavity but the control system
30 would be based either on an iterative search algorithm system or it would be configured for open loop control. In a further refinement, the mirror structure 150

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may be used in a distributed control configuration where the control for a particular element of the deformable mirror is calculated based only upon the outputs of sensors in the sensor array 176 that are closest to the axis of the mirror element.

5 The mirror structures in preferred embodiments of the present invention, described above, have provided different examples of both fixed and deformable mirrors each having at least a part of an optical wavefront sensor integrated with them to enable light passing through the reflective surfaces of the mirrors to be detected for the purpose of wavefront correction. Those parts
10 of a wavefront sensor have included at least a Hartmann Mask for a Hartmann sensor or the microlens array for a Shack-Hartmann sensor. Preferred positions of those parts within the mirror structures have been discussed but preferred mirror structures according to the present invention would not be limited to those positions. Furthermore, preferred sensor configurations have also been
15 discussed, but preferred mirror structures according to the present invention are not limited to those configurations and alternative configurations are included within the scope of the present invention, as would be apparent to a person of ordinary skill in this field.

Whereas laser applications have been discussed, in particular, it will be
20 clear that mirror structures according to the present invention may be applied to any field where the incident light levels are sufficient to enable wavefront measurement using those mirror structures.

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CLAIMS

1. A mirror structure, comprising a mirror having a reflective surface arranged to allow a portion of incident light to pass therethrough and wherein
5 the mirror has at least one component of an optical sensor integrated therewith, arranged to receive light that passes through said reflective surface.

2. The mirror structure according to claim 1, wherein said at least one
10 component of an optical sensor is a Hartmann mask of an optical wavefront sensor.

3. The mirror structure according to claim 2, wherein the mirror further
comprises a mirror substrate with said reflective surface applied thereto and
wherein the Hartmann mask comprises an array of apertures formed in the
15 mirror substrate.

4. The mirror structure according to claim 2, wherein the mirror further
comprises a substantially transparent mirror substrate and wherein the
Hartmann mask is formed as a distinct layer within the mirror structure.
20

5. The mirror structure according to claim 4, wherein the Hartmann mask is
formed in a layer applied to a surface of the mirror substrate.

6. The mirror structure according to any one of claim 3 to 5, wherein the
25 Hartmann mask is covered by a substantially transparent planarisation layer to
which said reflective surface is applied.

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7. The mirror structure according to claim 1, wherein said at least one component of an optical sensor is a microlens array of a Shack-Hartmann wavefront sensor.

5 8. The mirror structure according to claim 7, wherein the microlens array is covered by a substantially transparent planarisation layer and the reflective surface is applied thereto.

9. The mirror structure according to claim 1, wherein said at least one
10 component of an optical sensor is an optical detector.

10. The mirror structure according to claim 9, wherein the mirror is a self-deforming mirror having an active layer of deformable material coupled to a passive substrate.

15

11. The mirror structure according to claim 9 or claim 10, wherein said optical detector is arranged to detect the wavefront slope of said incident light at one or more points across the aperture of the mirror.

20 12. The mirror structure according to claim 2, wherein the mirror is a self-deforming mirror having an active layer of deformable material coupled to a substantially transparent passive substrate and wherein the Hartmann mask comprises an array of apertures formed in the active layer of deformable material.

25

13. The mirror structure according to claim 12, wherein the self-deforming mirror is supported by means of one or more passive flexible support elements coupled to a housing and wherein an optical detector is provided within the

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housing to detect the wavefront slope of said incident light at one or more points corresponding to the positions of said apertures.

14 A laser mirror comprising a mirror structure according to any one of
5 claims 1 to 13.

15. A mirror structure substantially as described hereinbefore with reference to and as shown in the accompanying drawings.

10 16. A laser mirror comprising a mirror structure substantially as described hereinbefore with reference to and as shown in the accompanying drawings.

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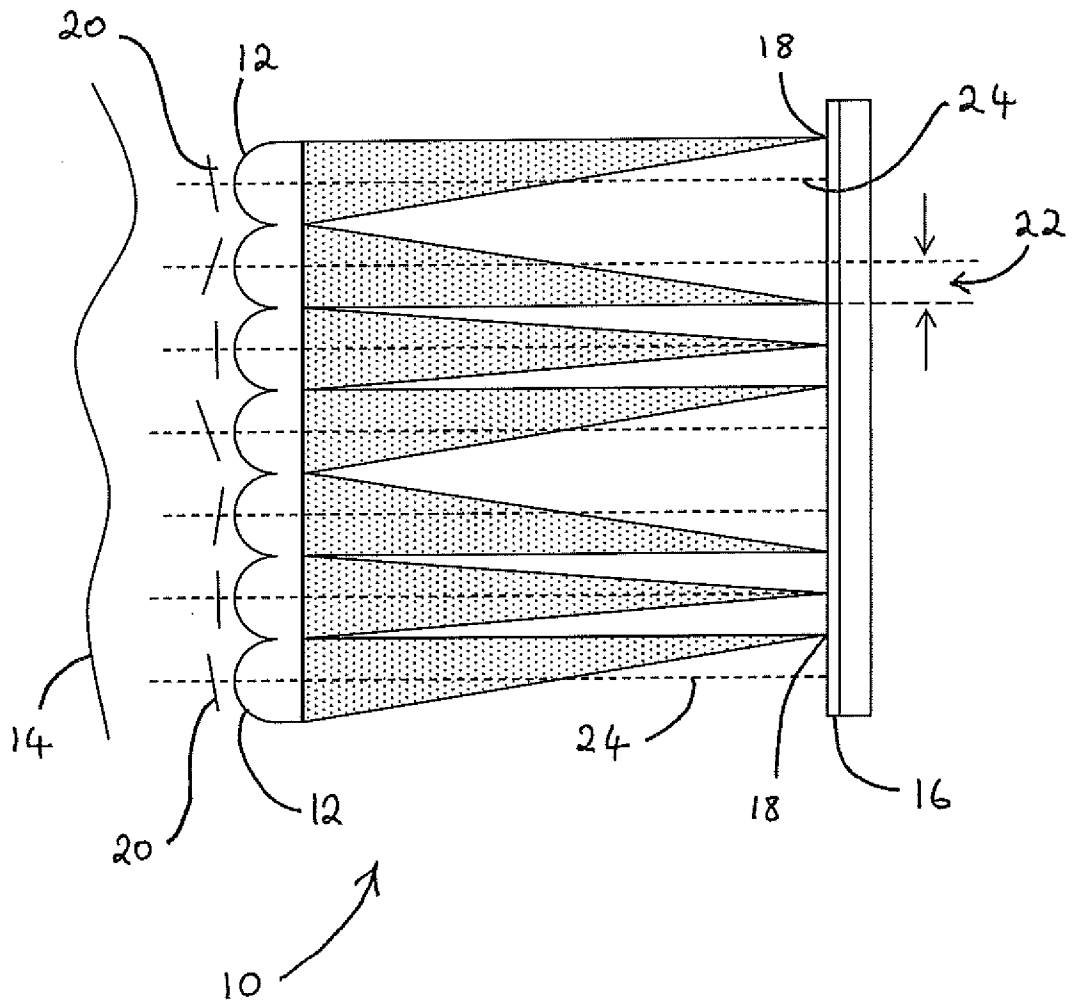


Figure 1
(Prior Art)

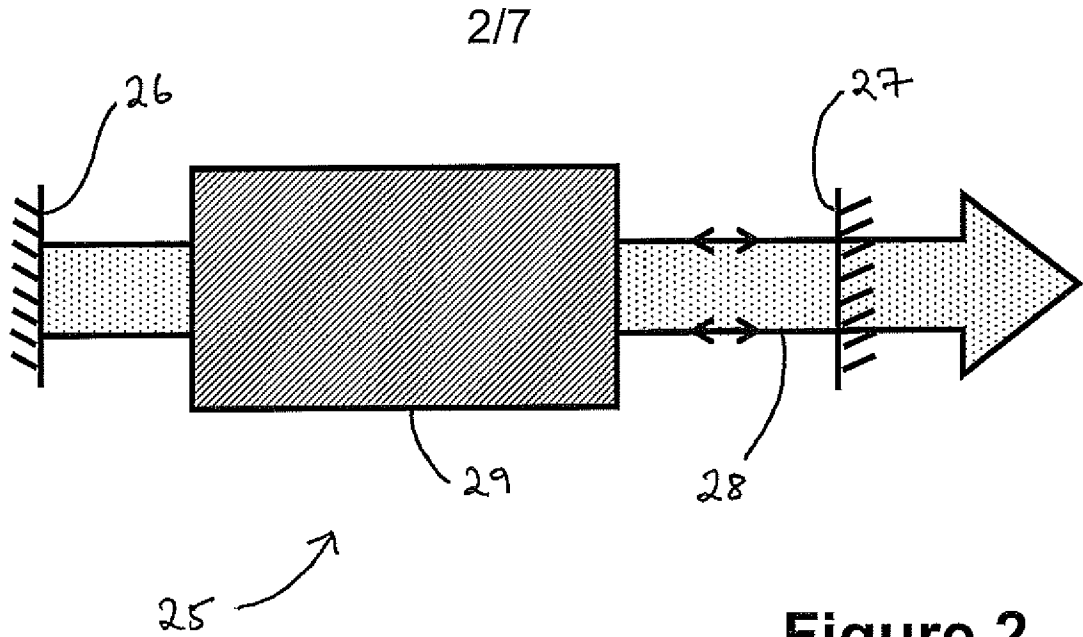


Figure 2
(Prior Art)

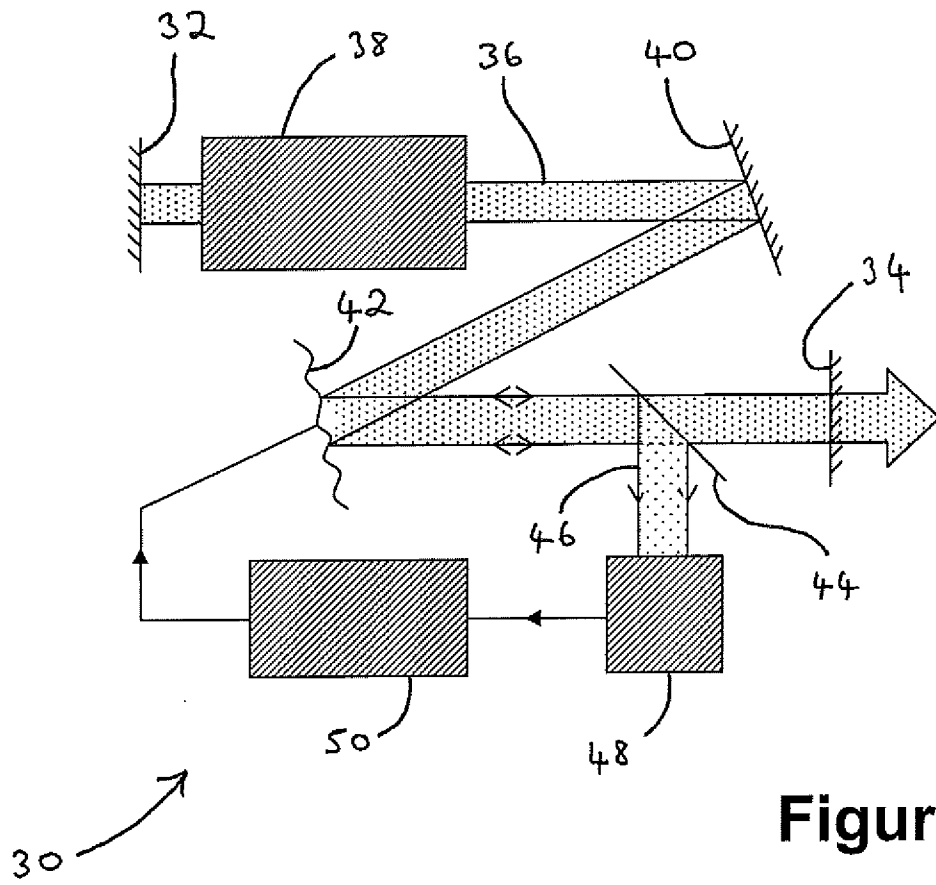


Figure 3
(Prior Art)

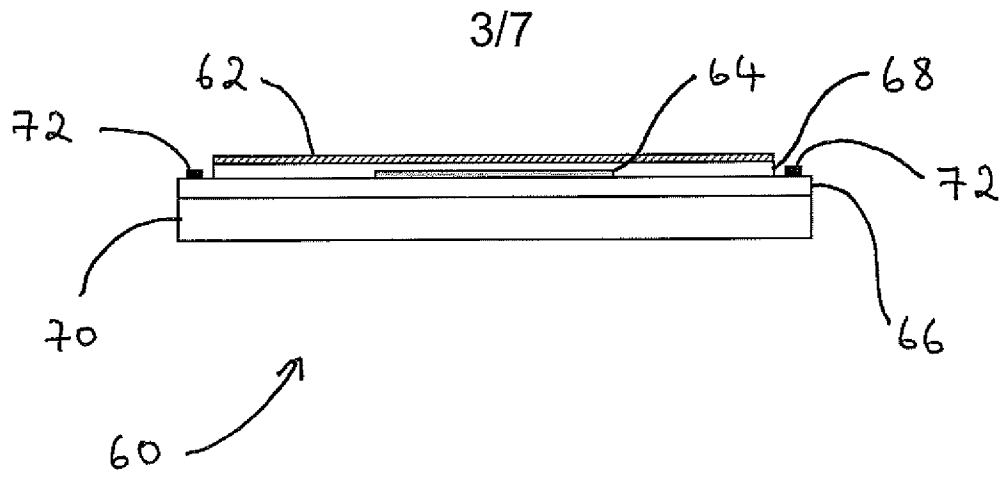


Figure 4a

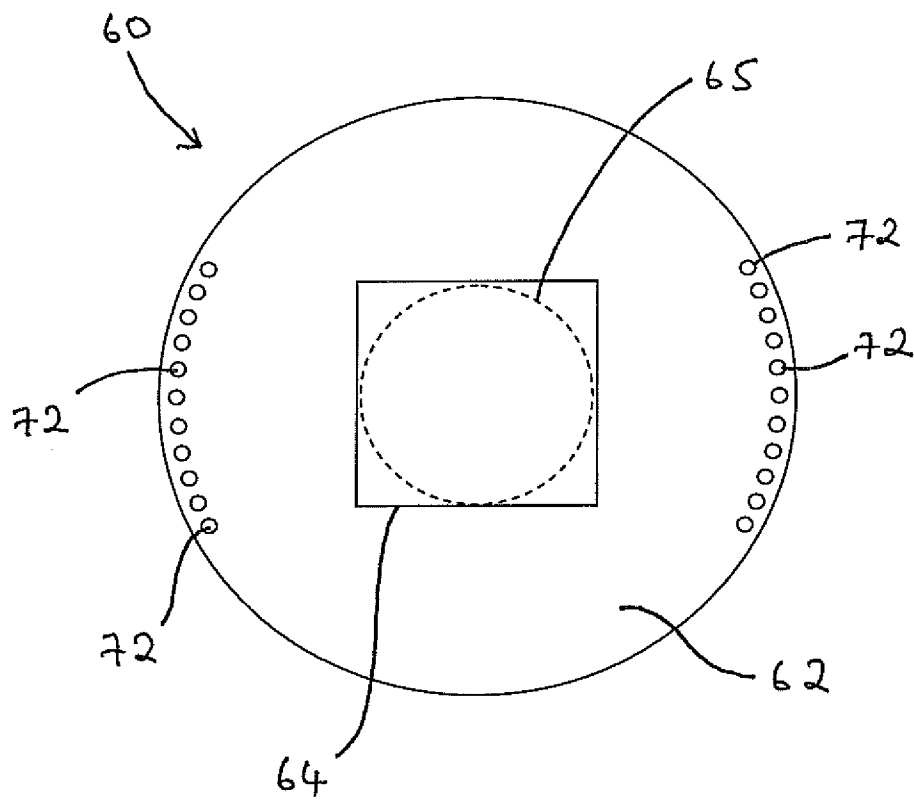


Figure 4b

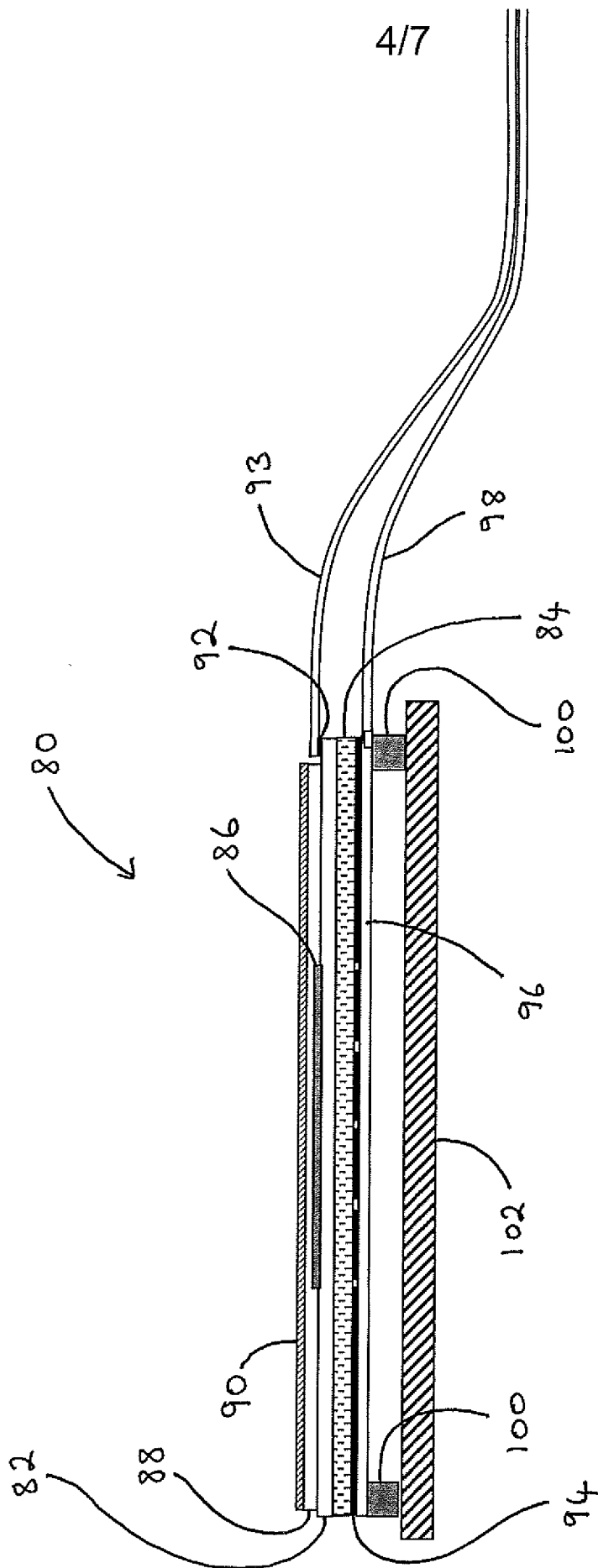


Figure 5

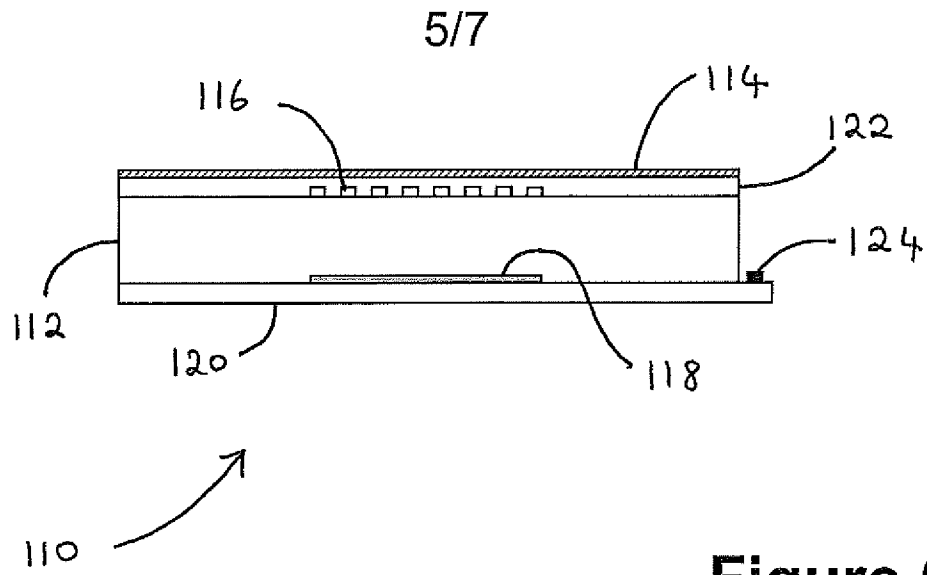


Figure 6a

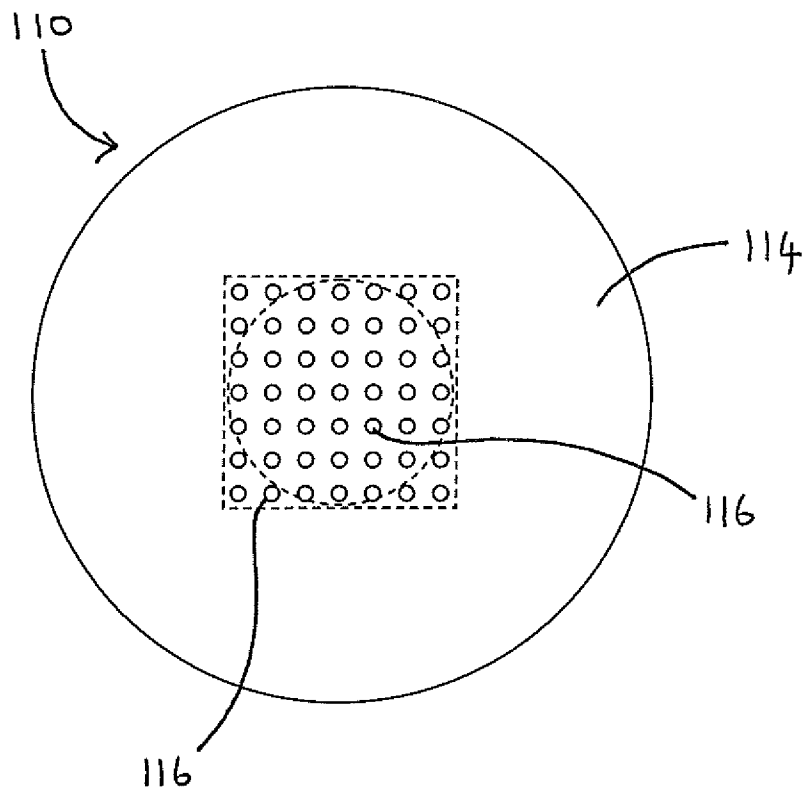


Figure 6b

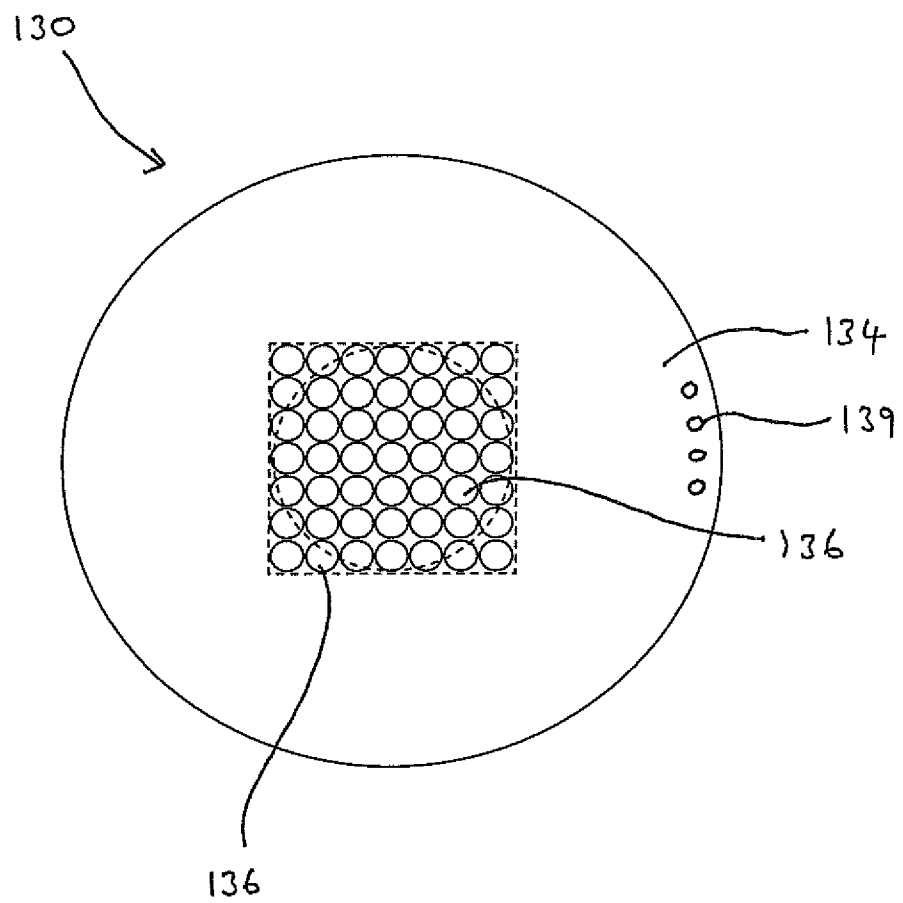
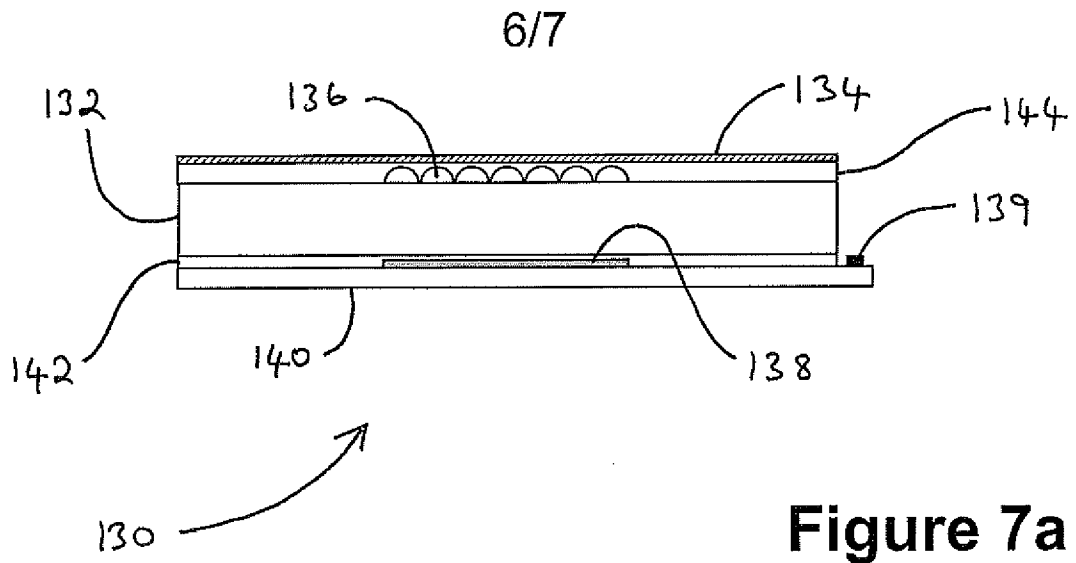


Figure 7b

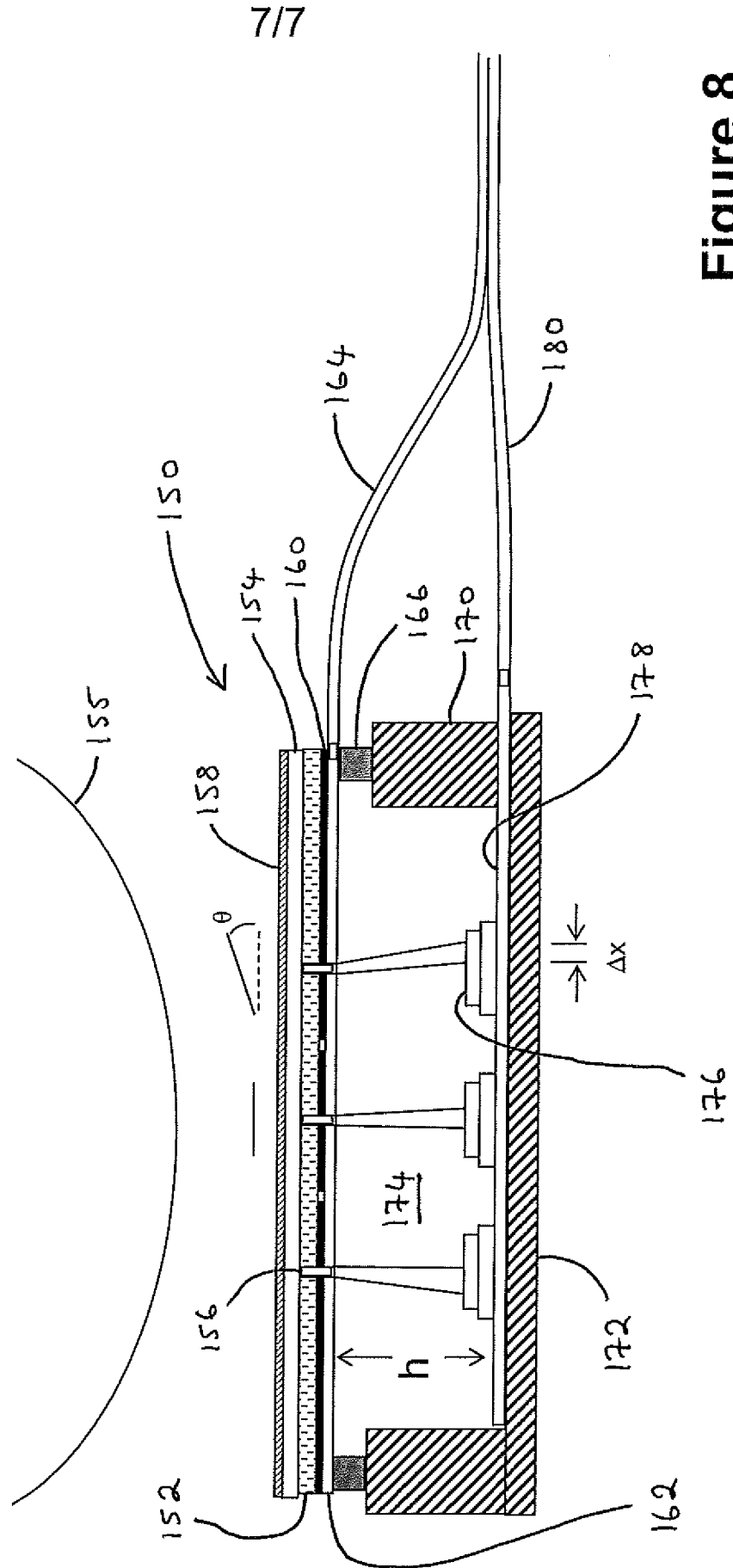


Figure 8

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2009/051539

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01J1/42 G01J9/00 G02B26/06 H01S3/139

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)

H01S G01J G02B

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 871 250 A (KOSEKI RYOJI [US]) 3 October 1989 (1989-10-03)	1, 9, 11, 14
Y	abstract column 3, line 7 - line 63 figures 2-4	2-8, 10
X	WO 2008/133648 A (RAYTHEON CO [US]) 6 November 2008 (2008-11-06)	1, 9, 11, 14
Y	abstract page 13, line 1 - line 21 figure 4	
Y	US 4 737 621 A (GONSIOROWSKI THOMAS [US] ET AL) 12 April 1988 (1988-04-12)	2-8, 10
	column 3, line 54 - column 4, line 9 figures 1, 1A, 1B	
	-/--	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search

15 January 2010

Date of mailing of the international search report

25/01/2010

Name and mailing address of the ISA/

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Authorized officer

Haller, Mirjam

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2009/051539

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 2005/006559 A1 (SMITH CAREY A [US]) 13 January 2005 (2005-01-13) the whole document -----	1-14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB2009/051539

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. Claims Nos.: 15-16
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.2

Claims Nos.: 15-16

Claims 15 and 16 contain references to the drawings. According to Rule 6.2(a) PCT, claims should not contain such references except where absolutely necessary, which is not the case here. Due to the unclear definition regarding which subject-matter is actually meant to be protected by the claims (i.e. no technical features are defined) a meaningful search of said claims is not possible.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.2), should the problems which led to the Article 17(2) declaration be overcome.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2009/051539

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 4871250	A	03-10-1989	NONE	
WO 2008133648	A	06-11-2008	EP 2137567 A2	30-12-2009
US 4737621	A	12-04-1988	NONE	
US 2005006559	A1	13-01-2005	US 2006049331 A1	09-03-2006