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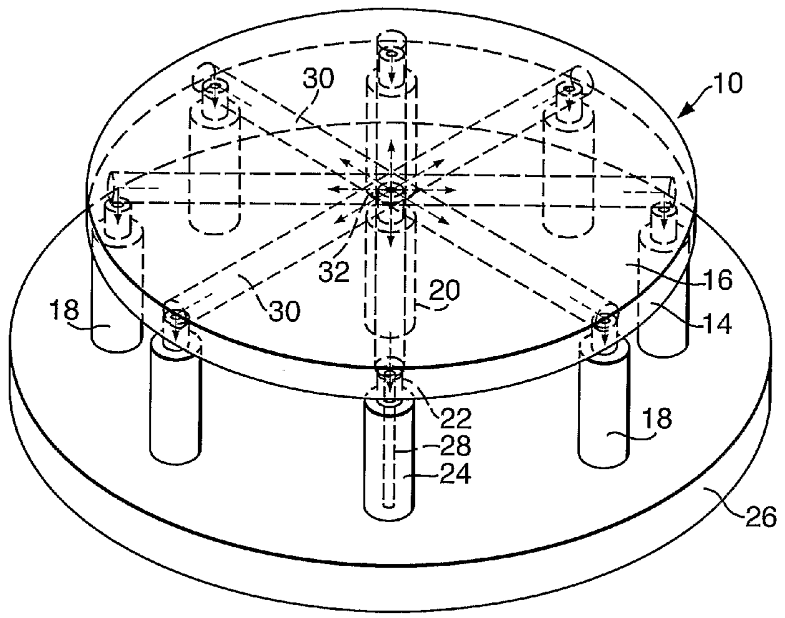
(54) **Title:** DEFORMABLE-MIRROR COOLING



(57) **Abstract:** This invention relates to a deformable mirror that is provided with cooling. A deformable mirror is provided comprising a reflective surface provided on a substrate and supported by a pair of actuators; wherein the pair of actuators are hollow thereby to define a conduit with a pair of openings for access to the conduit, the substrate has a passage with a pair of orifices for access to the passage, an opening of each of the pair of actuators being in fluid communication with one of the orifices of the substrate such that, in use, a cooling circuit is provided where fluid coolant may flow through the conduit of one actuator into the passage of the substrate and out through the conduit of the other actuator.

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DEFORMABLE-MIRROR COOLING

This invention relates to a deformable mirror that is provided with cooling. In particular, this invention relates to a cooled deformable mirror that is supported by a pair of actuators, where the actuators form part of a cooling circuit.

Deformable mirrors are often used in the field of adaptive optics. For example, phase distortions in a signal may be sensed by a wavefront sensor and these distortions may be corrected for by an adaptive mirror. Such adaptive mirrors may be employed in numerous fields, including:

- imaging, for example adaptive mirrors are used in astronomy to improve the resolution of earth-based telescopes that are otherwise affected by atmospheric distortions;
- laser sensing, where the amount of laser light that can be delivered onto a target is significantly increased by using an adaptive mirror to correct for atmospheric distortions – this enables either better information to be obtained or objects to be identified at a greater range; and
- laser generation, where an adaptive mirror can be used intracavity within a high power laser to counter the thermal blooming that can be otherwise induced by the high concentration of laser light inside the cavity.

Deformable mirrors generally comprise a reflective surface provided on a substrate. The mirror is made to deform to adopt a desired shape, for example a convex shape, and this may be effected by one or more actuators that support the mirror. Changing the relative heights of the actuators will cause the mirror to deform to the desired shape.

An alternative design is bimorph deformable mirrors that have been proposed as low cost adaptive mirrors. Bimorph (and unimorph and multilayer stacks) mirrors comprise a substrate bonded to an active element such as a piezoelectric crystal. The active element is controlled such that the mirror is made to deform to adopt a desired shape.

An important issue that needs addressing is thermal management. The two main aspects of this are heat absorbed from any incident radiation must be dissipated and the effect of temperature fluctuations on the mirror. Changes in temperature will affect the optical performance of the mirror. In lower-power mirrors, thermal management may be achieved by using a very high-reflectivity surface, so that very little of the incident radiation is absorbed. In higher-power mirrors, the very large intensity of incident radiation means that some form of active cooling of the mirror is required. Most commonly, this is water cooling due to its efficiency. In these arrangements, water is allowed to flow across the mirror in linear fashion. However, temperature gradients frequently develop across the mirror, even when large flows of water are used.

From a first aspect, the present invention resides in a deformable mirror comprising a reflective surface provided on a substrate and supported by a pair of magnetostrictive or electrostrictive actuators; wherein the pair of actuators are hollow thereby to define a conduit with a pair of openings for access to the conduit, the substrate has a passage with a pair of orifices for access to the passage, an opening of each of the pair of actuators being in fluid communication with one of the orifices of the substrate such that, in use, a cooling circuit is provided where fluid coolant may flow through the conduit of one actuator into the passage of the substrate and out through the conduit of the other actuator. This allows water or any other coolant to be circulated directly within the substrate, providing more efficient cooling, and the magnetostrictive actuators provide a convenient way of passing a coolant in and out of the substrate. Providing a conduit within the magnetostrictive or electrostrictive actuator is convenient as magnetostrictive or electrostrictive materials tend to be metallic and so lend themselves to this purpose. This is in contrast to other materials, e.g. piezoelectric crystals that tend to be porous and are hence not nearly as good a choice for providing a coolant conduit.

Preferably, the actuators are substantially cylindrical and each comprises a conduit that extends centrally through the actuator to terminate with openings at either end of the actuator. This provides a simple arrangement to fabricate and assemble.

Optionally, the deformable mirror further comprises a second pair of hollow actuators having a conduit with a pair of openings, an opening of each of the second pair of actuators being in fluid communication with an orifice of a second passage provided in the substrate thereby providing a second cooling circuit. The first and second passage may be distributed evenly around the substrate to ensure even cooling around the mirror. Preferably, the first and second passages are interconnected by a chamber. Optionally, the first and second passages intersect to form the chamber. This allows coolant passing down the passages to mix and to be forced through different passages e.g. if coolant is passed down alternative arms of a passage and exiting the mirror. Optionally, the passages extend radially to intersect at the centre of the substrate, i.e. in a hub and spoke arrangement. This design provides efficient cooling of the mirror over its entire extent, thereby achieving a near-uniform temperature profile across the mirror.

Optionally, the deformable mirror further comprises a central actuator that is hollow to define a conduit with a pair of openings, and wherein the chamber is enlarged to meet an outer surface of the substrate to form a port and one of the openings of the central actuator is in fluid communication with the port of the chamber. This allows coolant to be passed into the central chamber from the central actuator before exiting through the passage and out of the other actuator. This is advantageous as the coolant is delivered to the hottest part of the mirror before flowing out to the cooler parts of the mirror as it warms up.

In order that the invention can be more readily understood, reference will now be made, by way of example only, to the accompanying drawings in which:

Figure 1 is a perspective view of a deformable mirror according to a first embodiment of the present invention;

Figure 2 is a perspective view of a deformable mirror according to a second embodiment of the present invention;

Figures 3a and 3b are plan and perspective views respectively of an alternative embodiment of the mirror substrate;

Figure 4 is a plan view of a deformable mirror and a mount according to a third embodiment the present invention;

Figure 5 is a cross-section through line V-V of Figure 4 showing the mirror in a relaxed state;

Figure 6 corresponds to Figure 5 but with the mirror in a state of deformation;

Figure 7 is a detail from Figure 5;

Figure 8 is a perspective view of part of the mount of Figure 5;

Figure 9 corresponds to Figure 7 but for a fourth embodiment of the present invention;

Figure 10 corresponds to Figure 7 but for a fifth embodiment of the present invention;

Figure 11 is a cross-sectional view of a sixth embodiment of the present invention;

Figure 12 is a perspective view of part of the mount of Figure 11, with the mirror removed; and

Figure 13 is a further perspective view of a part of the mount of Figure 11, with the mirror in place.

A deformable mirror 10 is shown in Figure 1, including parts of its cooling system. Before describing the cooling system, the mirror 10 and its method of support will be described to allow an appreciation that the cooling system has little impact on this method of support in due course.

The mirror 10 comprises a copper substrate 14 whose outer face 16 provides a reflective surface by virtue of a series of thin dielectric coatings provided on the outer surface 16 (coatings not shown). The mirror 10 is supported around the periphery of its base by eight actuators 18 and also at the centre of its base by a further actuator 20. All actuators 18, 20 are identical and are fabricated from a cylinder of giant magnetostrictive material such as Terfenol-D. Each actuator 18, 20 has a stepped profile to form a small upper cylindrical head 22 that is attached to the base of the substrate 14 by co-operating screw threads. The larger base 24 of the actuators 18, 20 is bonded to a housing 26. Voltages can be applied to each of the actuators 18, 20 independently to cause them to expand or contract that, in turn, causes the mirror 10 to deform to a desired shape. The electrical connections to the actuators 18, 20 are not shown.

The substrate 14 is provided with three passages 30 that are arranged to extend radially and are separated by equal angles. Rather than extending the full width of the substrate 14, the passages 30 have a 90° bend at each of their ends close to the edge of the substrate 14 such that they break through the base of the substrate 14. The three passages 30 intersect at the centre of the substrate 14 to form a central chamber 32. This central chamber 32 extends downwardly, also to break through the base of the substrate 14.

Each actuator 18, 20 is hollow to form a central conduit 28 that extends the full length of each actuator 18, 20 from end to end. The conduits 28 align at their tops with the holes the passages form in the base of the substrate 14. This allows coolant to flow up or down the middle of the actuator 18, 20 either into or out of the substrate 14. In the embodiment shown in Figure 1, the coolant flows up the central actuator 20, along the passages 30 and out down the conduit 28 of each of eight peripheral actuators 28 situated close to the outside of the mirror 10 into channels provided in the housing 26 (not shown). Provision is made in the housing 26 for hose connectors to feed coolant into and out of the housing 26 (not shown).

An alternative embodiment is shown in Figure 2. This embodiment corresponds substantially to the embodiment of Figure 1 and so like parts are assigned corresponding reference numerals and will not be described again in order to avoid unnecessary repetition. The embodiment of Figure 2 differs most markedly from that of Figure 1 in the absence of a central actuator (reference 20 in Figure 1). As a result, the central chamber 32 does not extend downwardly to meet the base of the substrate 14, but instead is contained entirely within the substrate 14.

Two of the passages 30a form inlets for the coolant, i.e. coolant is passed into each passage 30a at each of its ends through the conduits 28 of the corresponding actuators 18. The coolant then meets at the central chamber 32 where it will mix before exiting down one of the two remaining passages 30b and out through the corresponding actuator 18.

Flexible O-rings can be placed between the conduits 28 of the actuators 18, 20 and the passages 30 of the substrate 14 in order to make a leak-free join therebetween. O-rings have the advantage of deforming with the mirror 10, thereby ensuring that coolant does not leak during deformation of the mirror 10.

As well as the mirror 10 being deformable by expansion and contraction of the actuators 18, 20, the mirror 10 may also be deformable via the action of piezoelectric elements. Figures 4 to 13 show such a mirror 50 that comprises at least one active piezoelectric element 80 bonded to the substrate 78 using epoxy resin 82. An array of electrodes 84 are used to activate the piezoelectric element(s) 80. Applying a potential to the electrodes 84 causes the piezoelectric element(s) 80 to deform so that, in turn, the substrate 78 deforms to create a mirror 50 with a desired shape, convex for example. In addition, each embodiment includes at least one actuator fabricated 59 from magnetostrictive or electrostrictive material. The actuators 59 are attached at one end to a base 81 of a mount 52 and, at its other end, either to the piezo-electric element 80 or to the substrate 78 itself. Applying a potential to the actuator 59 causes it to expand or contract thereby deforming the substrate 78 and hence the mirror 50.

In addition to the mirror 50 being supported from below, the mirror 50 may also be supported around its peripheral edge. It may be supported in a rigid manner or in a flexible manner. A flexible support is illustrated in Figures 4 to 13 although the hybrid mirror deformation and flexible support features are independent and need not be employed together.

The deformable bimorph mirror 50 is supported in a mount 52. The mount 52 is a unitary structure made from stainless steel. The mount 52 comprises a round body 54 that defines a central circular aperture 56. The aperture 56 is shaped and sized to receive the disc-shaped deformable bimorph mirror 50 therein. Hence, the mirror 50 is held in a protected position within the mount 52.

Whilst the outer edges of the mount's body 54 are regular, the internal edges 58 are stepped to form a series of three interconnected and concentric circular apertures 56a-c that increase in size from top to bottom. The stepped inner profile 58 of the mount 52 produces a series of three shoulders 60a-c. Twenty generally L-shaped flexible beams 62 extend downwardly in cantilever fashion from the topmost 60a of these shoulders 60a-c. The twenty beams 62 are of identical size and shape and are equispaced around the circular topmost shoulder 60a. The beams 62 are L-shaped such that they extend downwardly from the topmost shoulder 60a before turning through 90° to extend inwardly towards the centre of the middle aperture 56b. Rather than having a pure L-shape, a square-shaped support shoulder 64 extends from the internal corner of each beam 62 as best seen in Figure 7. The support shoulder 64 only extends partially up the height of the upright portion 66 of the beam 62, thereby leaving a narrow neck 68 in the portion of the beam 62 that bridges the topmost shoulder 60a of the mount body 54 and the support shoulder 64 of the beam 62. It is this neck 68 that gives the beam 62 its flexibility, i.e. this neck 68 can be deformed to allow the beam 62 to deflect and bend. The length and thickness of the neck 68 of the beams 62 are chosen to achieve the desired flexing properties. Figure 8 shows four of the beams 62 in perspective and indicates the width W of the beams 62 relative to their separation. It is the relative width of the beams 62 that gives the required degree of stiffness in the plane of the mirror 10.

The inwardly-extending portion 70 of the beam 62 extends beyond the support shoulder 64 to provide an upwardly-facing support surface 72 for receiving the mirror 50. The mount 52 and the beams 62 are sized such that the mirror 50 may be received within the beams 62 to be supported from below by the support surfaces 72 and so that the mirror's edge 74 fits snugly against the upright face 76 of the support shoulders 64. Hence, the mirror 50 is held firmly in place.

As the mirror 50 deforms, it remains firmly held in place against the support surface 72 and support shoulder 64 because the beam 62 deflects with the mirror 50 by flexing about its neck 68, as shown in Figure 6. Moreover, the beams 72 offer minimal resistance to the mirror 50 as its peripheral edge 74 rotates towards the mirror axis. This is because they have minimal stiffness radially and so require little force to deform radially towards the mirror centre. The mass and stiffness of the beams 62 are very small in comparison to that of the mirror 50 and therefore the beams 62 have minimal impact upon the mirror 50 deformation. In addition, the relatively large width W of the beams 62 provides stiffness in all directions in the plane of the mirror and torsionally about the mirror axis. The short length of the beams 62 provides stiffness in the axial direction.

Figure 6 shows that convex deformation of the mirror 50 extends to the very edge 74 of the mirror 50 and hence eliminates virtually all dead space from the mirror 50. Hence, the active area of the mirror 50 covers virtually the whole of the mirror 50. This is highly beneficial because a mirror mount 52 that prevents rotation of the mirror's peripheral edge 74 would need to be twice the diameter to obtain a similar convex active area and would have a first mode resonant frequency of half that of the simply supported mirror 50 of the present invention. Thus, the present invention allows for a mirror 50 of much smaller size to be used to obtain the same stroke/bandwidth product.

The person skilled in the art will appreciate that modifications can be made to the embodiments described hereinabove without departing from the scope of the invention.

For example, fabricating the actuators 18, 20; 59 from magnetostrictive material is but one of many choices. Other types of actuators that may be used include electrostrictive materials, electromagnetic arrangements, hydraulic arrangements, mechanical or electro-mechanical arrangements. In all instances, the actuators 18, 20; 59 need only be hollow to define a conduit through which coolant may be passed. The conduit may either directly carry the coolant or may merely define the path for a pipe or similar that carries the coolant.

Clearly, the shape of the mirror 10; 50 is not fundamental and can be varied freely. The radial configuration of passages 30 above can also be varied. For example, more complex designs combining selectively cooled regions of the substrate 14; 78 including mixing manifolds may also be devised. These may lead to an overall mass reduction. Moreover, the passages 30 could simply extend from one point on the edge of the substrate 14; 78 to another point on the edge of the substrate 14; 78 and need not meet at a central chamber 32, such that water merely flows in one end of the passage 30 and out the other.

A second embodiment of the mirror substrate 14; 78 is shown in Figure 3. Many features of this substrate 14′ are the same as for the substrate 14 shown in Figure 2 and so have been assigned like reference numerals. In common with the substrate 14 of Figure 2, the substrate 14′ of Figure 3 has eight passages 30′. However, the passages 30′ are no longer arranged radially to form a central mixing chamber 32′. Instead, a mixing chamber 32′ is created at the centre of the substrate 14′ by offsetting the passages 30′. All the inlet passages 30′ are offset one way, while all the outlet passages 30′ are offset the other way. The result is a roughly toroidal mixing chamber 32′ with turbulent circulatory flow. There will be relatively laminar flow in the inlet passages 30′, but turbulent flow is induced in the mixing chamber 32′, and the flow will remain turbulent in the outlet passages 30′. The difference in types of flow will act to minimise any temperature gradient that might otherwise develop between the input and output passages 30′ because of differences in water temperature: although the temperature of the water in the outlet passages 30′ is likely to be higher, the heat exchange efficiency will also be higher because of the turbulent flow.

Whilst flexible O-rings provide a convenient method of forming a water-tight channel between the mirror and the actuators 18, 20; 59, other seals are possible. Of course, it is highly beneficial if the seals are flexible such that they can accommodate deformation of the mirror 10; 50 without losing the integrity of the seal.

Whilst water is the preferred choice for a coolant, other types of coolant can also be used, such as, an anti-freeze solution or mercury. Alternatively, a gas could be used such as a liquefied gas (e.g. liquid nitrogen).

Use of unimorph, bimorph or multilayer piezoelectric elements 80 can be freely varied according to need in any of the embodiments. In addition, the type of actuators 18, 20; 59 used may be varied in each embodiment. Suitable types of actuators 18, 20; 59 include magnetostrictive, electrostrictive, piezoelectric, electromagnetic, hydraulic, mechanical or electromechanical. An example of an electrostrictive material is PMN (lead magnesium nitrate).

The arrangement of actuators 18, 20; 59 given herein are merely examples of preferred configurations and may be varied without departing from the scope of the invention. Moreover, many types of standard configurations of piezoelectric elements 80 can be used in order to obtain the desired deformation of the mirror 10; 50. In particular, the choice of using a monolithic piezoelectric element 80 or an array of discrete piezoelectric elements 80 can be made for each of the embodiments shown.

Details of the mirror 10; 50 and how it is arranged to deform are given as useful background in which to set the context of the present invention, but are not essential to the invention. Other mirror configurations can be equally well accommodated by the present invention.

Whilst some of the above embodiments use L-shaped beams 62, strict compliance with this shape is not necessary. For example, the support shoulders 64 may be omitted and the peripheral edge of the mirror 74 may abut against the upright face of the beam 62. This arrangement would lead to a longer neck 68 that could flex along its entire height. In addition, the beam 62 could be J-shaped rather than being L-shaped. This may be advantageous where the mirror 50 has rounded edges rather than square edges. In fact, the beam 62 may be shaped to conform to any profile the mirror 50 may have, e.g. to conform to chamfered edges.

Furthermore, the beams 62 need not necessarily extend downwardly from the mount body 54 to house the mirror 50 within the mount body 54. An alternative arrangement is shown in Figure 9, that broadly corresponds to the view shown in Figure 7 and so like reference numerals have been used for like parts but with the addition of a prime. In this embodiment, the flexible neck 68′ is L-shaped such that, in addition to the flexible upright portion 86′ that allows deflection as the mirror 50 deforms, there is a horizontal portion 88′ that connects the upright portion 86′ to the mount body 54. The horizontal portion 88′ of the beam 62′ allows vertical movement of the edges of the mirror 50, as indicated by the arrows in Figure 9. This is beneficial because the mirror 50 may be deformed to adopt shapes that require relative movement around the edge 74 of the mirror 50, e.g. to adopt radially-extending ridges and troughs thereby creating an undulating mirror edge 74.

A further alternative arrangement of the beams 62 is shown in Figure 10 where beams 62′′ extend upwardly from the mount body 54′′ (like reference numerals are used for like parts, the double prime denoting the parts that belong to the embodiment of Figure 10). Most importantly they retain the flexible neck 68′′ that allows the beam 62′′ to bend with the mirror (not shown) as it adopts a convex shape.

A yet further embodiment is shown in Figures 11 to 13. Again, like reference numerals are used for like parts, the triple prime denoting the parts that belong to the embodiment of Figures 13 to 15. In this embodiment, the mirror 50′′′ is supported at the top of the mount 52′′′. The mount 52′′′ has an outer wall 90′′′ extending from the outer edge of its top surface. Twenty flexible beams 62′′′ extend from the inner edge 60a′′′ of the mount 52′′′. The flexible beams 62′′′ comprise an L-shaped flexible neck 68′′′ that extends from the mount 52′′′ first upwardly as an upright portion 86′′′ before turning through 90° to extend inwardly as a horizontal portion 88′′′. The horizontal portion 88′′′ of each of the flexible beams 62′′′ meets a unitary L-shaped annular ring 92′′′ that is shaped and sized to receive the mirror 50′′′. The L-shape of the ring 92′′′ is such that it supports the mirror 50′′′ from the side and from below.

The advantage of this arrangement is that the shape of the flexible beams 62′′′ allows vertical movement of the mirror's edge. This provides additional enhancement by further minimising the ratio of the total diameter of the mirror 50‴ to the active diameter. This reduces the overall mirror diameter required to achieve a given stroke for a set applied voltage and bandwidth by virtually eliminating any dead space from the outside of the mirror 50‴.

As will be appreciated by the skilled person, other arrangements of the beams 62 are possible. For example, the flexible beams 62 could extend inwardly to meet a supporting end of the beam 62. Essentially, any arrangement could be used where the supporting end of the beam 62 is connected to the mount body 54 by a flexible neck 68 that allows the supporting end to bend as the mirror 10 deforms.

Whilst the mount 52 of the above embodiments is made from stainless steel, many other materials such as other metals, plastics, glasses or ceramics could be used instead.

CLAIMS

1. A deformable mirror comprising a reflective surface provided on a substrate and supported by a pair of magnetostrictive or electrostrictive actuators; wherein the pair of actuators are hollow thereby to define a conduit with a pair of openings for access to the conduit, the substrate has a passage with a pair of orifices for access to the passage, an opening of each of the pair of actuators being in fluid communication with one of the orifices of the substrate such that, in use, a cooling circuit is provided where fluid coolant may flow through the conduit of one actuator into the passage of the substrate and out through the conduit of the other actuator.

2. A deformable mirror according to claim 1, wherein the actuators are substantially cylindrical and each comprises a conduit that extends centrally through the magnetostrictive actuator to terminate with openings at either end of the actuator.

3. A deformable mirror according to claim 1 or claim 2, further comprising a second pair of hollow actuators having a conduit with a pair of openings, an opening of each of the second pair of actuators being in fluid communication with an orifice of a second passage provided in the substrate thereby providing a second cooling circuit.

4. A deformable mirror according to claim 3, wherein the first and second passages are interconnected by a chamber.

5. A deformable mirror according to claim 4, wherein the first and second passages intersect to form the chamber.

6. A deformable mirror according to claim 5, wherein the mirror is disc shaped and the first and second passages extend radially to intersect at the centre of the substrate.

7. A deformable mirror according to claim 5, wherein the first and second passages extend from a central portion of the substrate to the edge of the

mirror in an offset arrangement, thereby intersecting to form a substantially ring-shaped chamber.

8. A deformable mirror according to claim 6, further comprising a central actuator that is hollow to define a conduit with a pair of openings, and wherein the chamber is enlarged to meet an outer surface of the substrate to form a port and one of the openings of the central actuator is in fluid communication with the port of the chamber.

9. A deformable mirror according to any preceding claim, further comprising a layer of deformable material attached to the substrate that is operable to deform the mirror

10. A deformable mirror according to claim 9, wherein the actuators are arranged to be operable to correct lower order Zernike modes.

11. A deformable mirror according to claim 9 or claim 10 wherein the layer of deformable material is segmented and the segments are arranged to be operable to correct higher order Zernike modes.

12. A deformable mirror according to any of claims 9 to 11, wherein the deformable material comprises piezoelectric material.

13. A deformable mirror and deformable-mirror holder, comprising a deformable mirror according to any preceding and wherein the holder comprises a body with a central aperture for receiving the deformable mirror, the central aperture being defined by a plurality of flexible beams, with each flexible beam having an end shaped to provide a supporting surface and a flexible portion that connects the beam's end to the holder's body.

14. A deformable mirror and deformable-mirror holder according to claim 13, wherein the ends of the flexible beams are co-joined to form a unitary structure shaped to provide a supporting surface.

15. A deformable mirror and deformable-mirror holder according to claim 13 or claim 14, wherein the beams' ends lie in the plane of the holder's body such that, in use, the mirror is received within the holder's body.

16. A deformable mirror and deformable-mirror holder according to any of claims 13 to 15, wherein at least one beam is generally L-shaped such that one leg of the L-shape provides the flexible portion and the other leg of the L-shape provides the supporting surface of the beam's end.

17. A deformable mirror and deformable-mirror holder according to claim 16, wherein the internal corner of the L-shaped beam has a shoulder that extends part of the way along both legs of the L-shape.

18. A deformable mirror and deformable-mirror holder according to any of claims 13 to 17, wherein the plurality of flexible beams are arranged around the entire aperture.

19. A deformable mirror and deformable-mirror holder according to claim 18, wherein the width of the beams is larger than the separation between beams.

20. A deformable mirror and deformable-mirror holder according to claim 19, wherein the width of the beams is greater than four times the separation between beams.

21. A deformable mirror and a deformable-mirror holder according to claim 16, wherein the peripheral edge of the mirror is supported from below by one leg of the L-shaped beam and is supported from the side by the other leg of the L-shaped beam.

22. A deformable mirror and a deformable-mirror holder according to claim 17, wherein the peripheral edge of the mirror is supported from below by one leg of the L-shaped beam and is supported from the side by an inwardly-facing side of the shoulder.

23. A method of correcting phase variations in a beam of electromagnetic radiation incident upon the deformable mirror of any of claims 1 to 12, wherein the actuator or actuators are moved to correct Zernike modes at or

below a threshold order and the deformable material is moved to correct Zernike modes above the threshold order.

24. A method according to claim 23, wherein the actuator or actuators are moved to correct the first and second ordered Zernike modes and the deformable element is moved to correct third and higher order Zernike modes.

25. A deformable mirror substantially as described herein with reference to any of the accompanying Figures.

26. A deformable mirror and deformable mirror holder substantially as described herein with reference to any of the accompanying Figures.

27. A method of correcting phase variations substantially as described herein with reference to any of the accompanying Figures.

Fig.1.

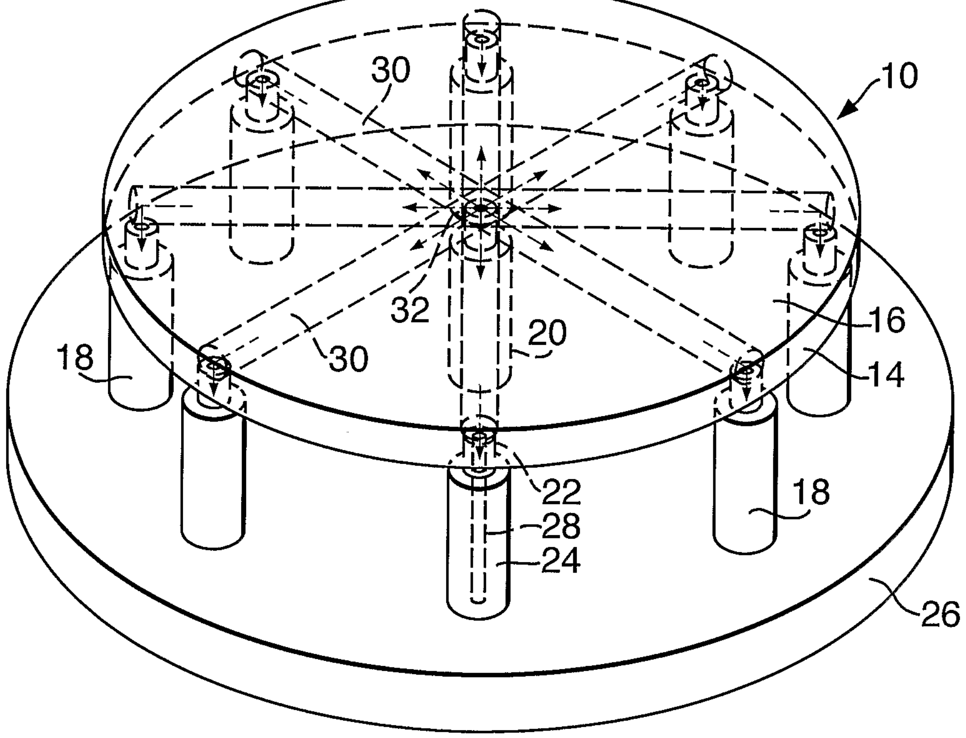
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Fig.2.

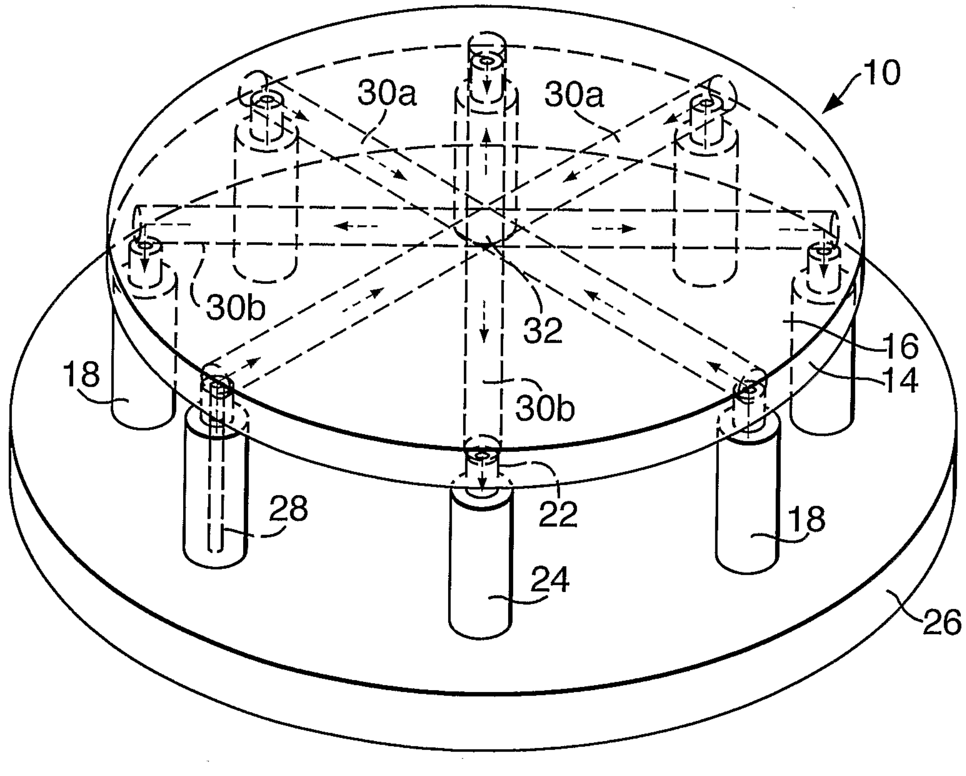
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Fig.3a.

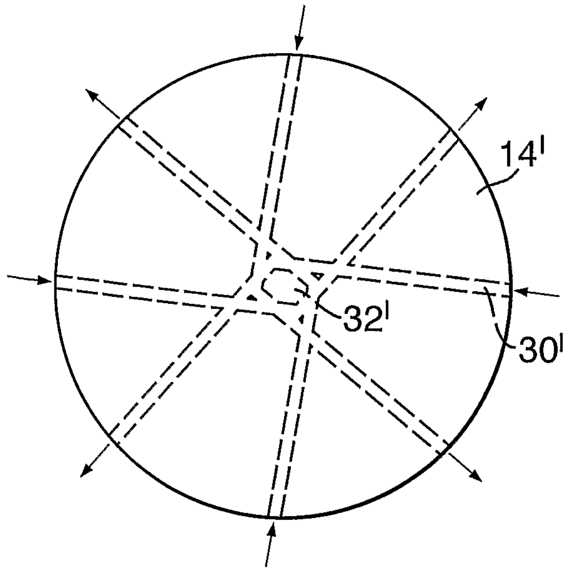


Fig.3b.

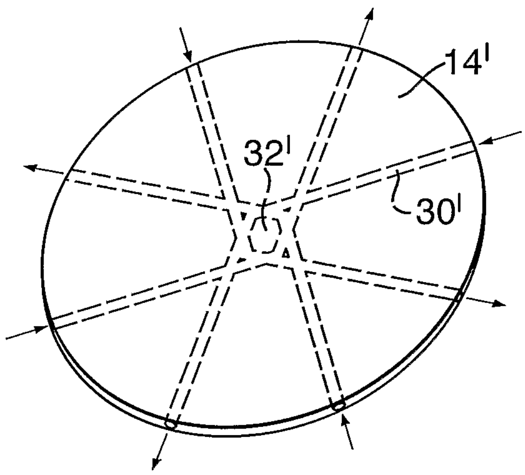


Fig.4.

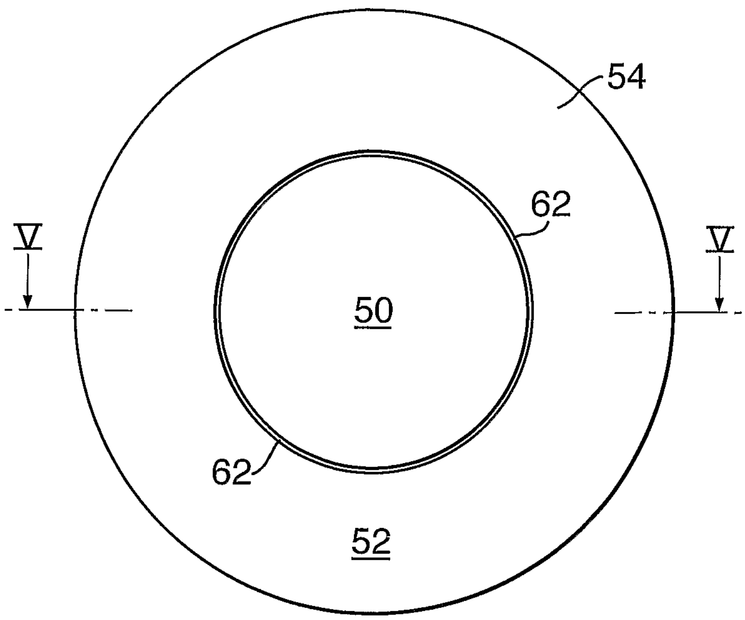


Fig.5.

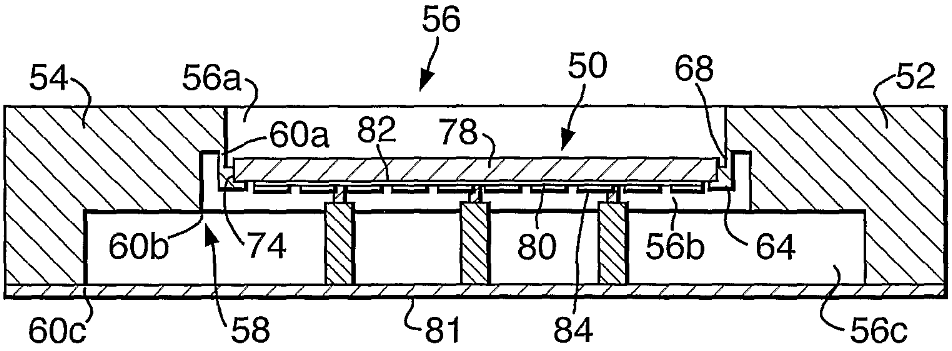


Fig.6.

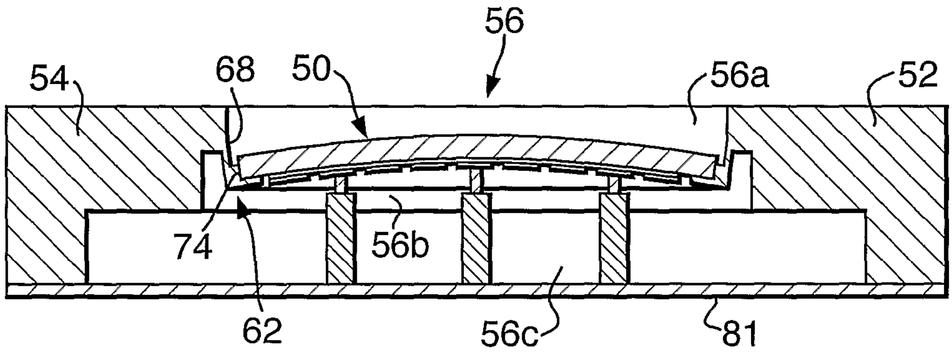


Fig.7.

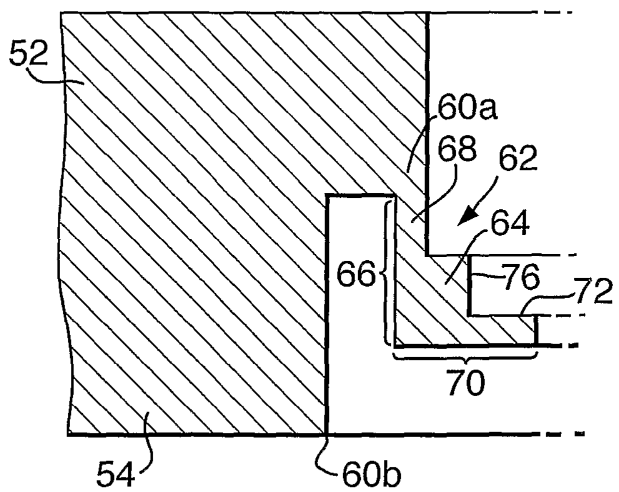


Fig.8.

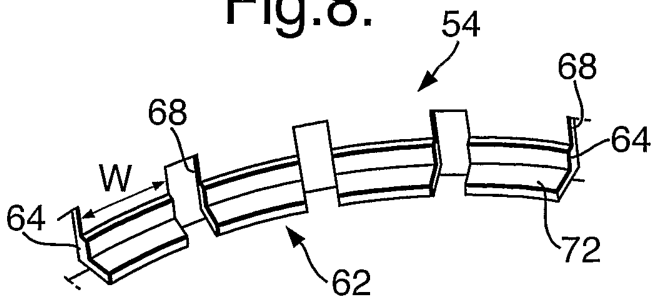


Fig.9.

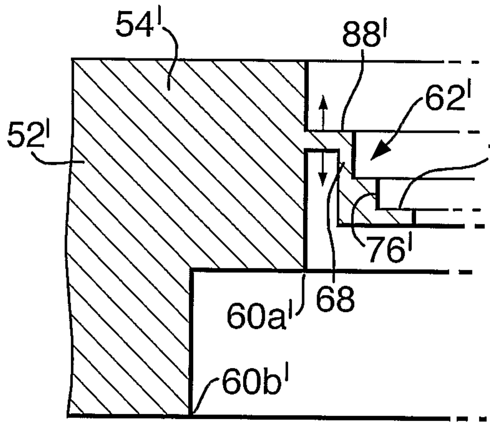


Fig.10.

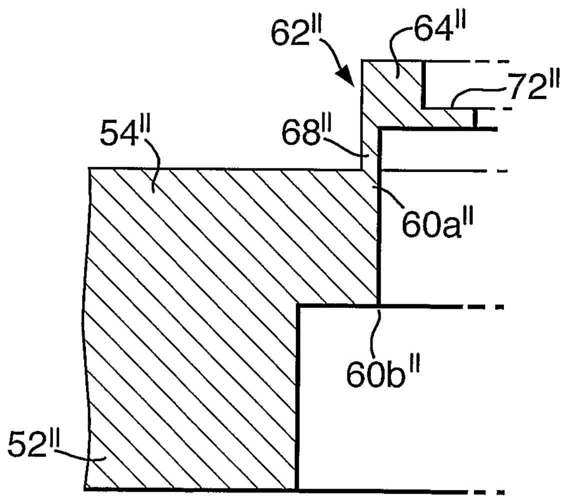


Fig.11.

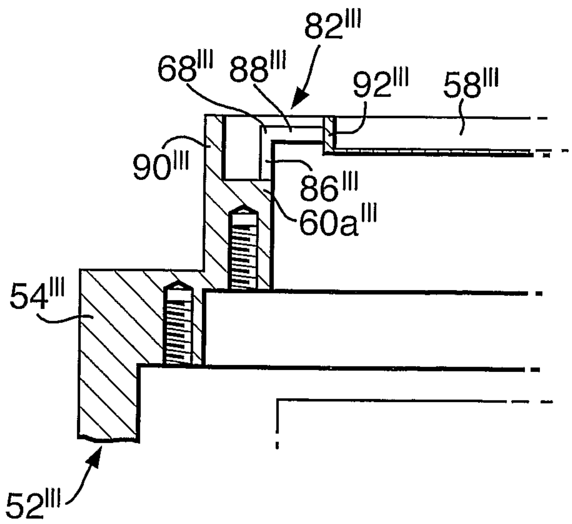
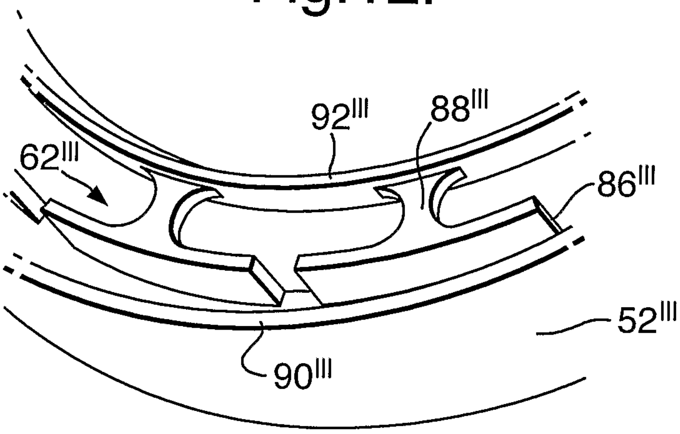


Fig.12.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86III
52III
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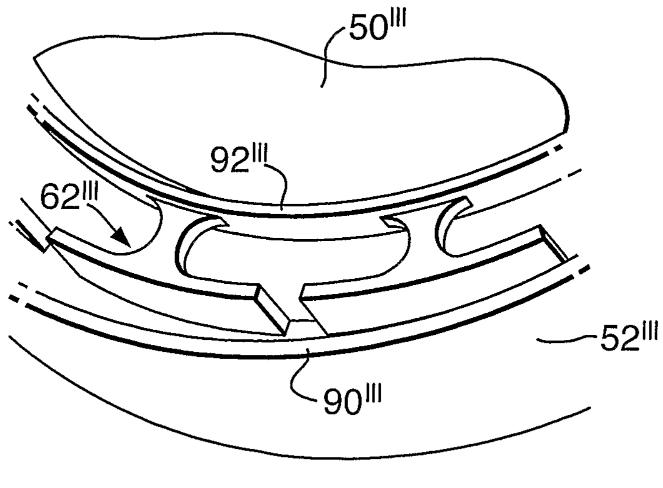
Fig.13.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