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(71)(72) Applicant and Inventor: MAYNARD, Ronald, S. [US/US]; 777 Hollenbeck #15, Sunnyvale, CA 94087 (US).

(74) Agent: CARY, Charles, C.; Wilson Sonsini Goodrich & Rosati, 650 Page Mill Road, Palo Alto, CA 94304-1050 (US).

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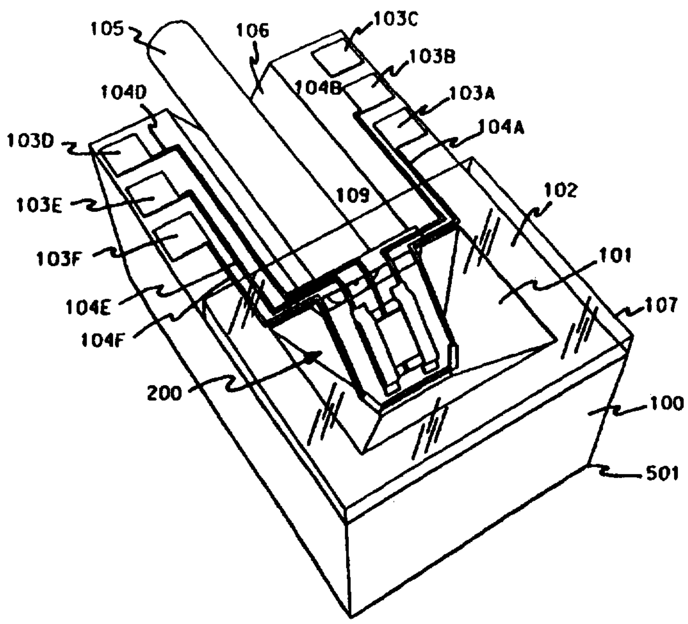

(57) Abstract

An optical beam steering apparatus has a substrate that defines one or more aligned cavities. A primary optical path means accommodates passage of a light beam. An upper cavity is provided in a portion of the substrate. The upper cavity is aligned to a predetermined degree of precision and is in direct communication with the primary optical path means. A beam steering means is provided in the upper cavity to controllably direct the beam.

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Hybrid Optical Multi-Axis Beam Steering Apparatus

Background

The field of the present invention relates, in general, to methods and devices for manipulating and steering beams of light. More specifically, the field of the invention relates to a compact, hybrid system of optical components that accept a beam of light from an optical element or fiber, steer the beam in one or more directions, and pass the deflected beam into open space or through a secondary optical element or fiber.

Investigators of optical phenomenon typically rely on massive, vibration damped optical benches to maintain precise alignment between optical elements during prototyping. Optical elements might consist of lenses, mirrors, beam splitters, piezoelectric actuators, translation tables, prisms, screens, lasers, optical fibers, gratings, etc. Quite commonly, these elements are macroscopic in size and can easily be handled and adjusted. Although suitable for most optical prototyping purposes, the use of macroscopic optical elements can have its drawbacks.

For example, to precisely steer a beam of light at a high angular rate, one might employ a conventional piezo motor, or angular galvanometer, and mirror assembly.

Using two such devices at right angles to one another in the same optical path would give two degrees of freedom for controlling the path of the beam. This arrangement is commonly used for steering laser beams in "laser show" productions. In this application, the physiological demands of human eyesight require only a 30 to 60 Hertz refresh cycle of each laser scanned frame to provide the illusion of smooth motion. Given that the reflected laser light is of adequate intensity at the maximum angular slew rate, the overall angular size and detail of a single frame will be limited by the total path length traced out to form that frame. That is to say, the angular extent of a laser image is limited by the maximum angular slew rate of each steering mirror.

One apparent solution might be to increase the torquing capability of the mirror driving motor. This is effective to a point. With increasing torque capability, the angular inertial mass of the rotor elements becomes ever larger. At some point, the mechanical dynamics of the coupled motor/mirror system will suffer. Unwanted torsional deflections will be introduced that result in beam steering errors. Stiffening the rotor might remedy the deflection problem, but would again increase the angular inertial mass. Thus, motor sizing is not a complete panacea.

A better solution would be to significantly reduce the size, and therefore, the mass and angular inertia of the moving mirror. There is no torque penalty in doing so. However, care must be taken to insure that the stiffness of the lighter mirror remains high so that dynamic distortion of the mirror itself does not compromise optical performance.

Beam steering devices and their functional equivalents, are found in a wide variety of products including laser bar scanners, heads, laser printers, optical switches, robotic vision scanners, optical choppers, optical modulators and display devices to name a few.

In the field of micromechanics, a number of recent developments in the area of spatial light modulators (SLM), light valves, and deformable mirror devices (DMD) have resulted in a significant cost reduction and a substantial increase in performance of beam steering devices.

TEXAS INSTRUMENTS holds a number of DMD patents including #5,504,614 and #5,448,546 that describe methods of fabricating electrically controllable micromirrors using an additive process. The micromirrors may operate independently or within a distributed array. The micromirrors are generally of torsion or gimbaled hinge design.

An additional patent # 5,325,116 held by TEXAS INSTRUMENTS describes a beam steering device used for writing to and reading from an optical storage media using a micromachined SLM. Although the single SLM component has the potential to greatly improve the mechanical dynamic response of the overall device, the surrounding structure within which the SLM resides remains bulky.

What is needed is a faster, more precise and compact apparatus for steering beams of light. In particular, it would be advantageous to miniaturize a complete optical system upon a single substrate, including lenses, optical fibers, optical sensors, SLMs and the like. Not only would performance be greatly enhanced due to smaller moving masses, but manufacturing costs and uniformity would also be improved.

Reducing all dimensions proportionately on a given mirror design results in a reduction of surface area by an inverse squared term and a reduction of volume and mass by an inverse cubed term. Thus, by diminishing the size of any object, the surface-area-to-mass-ratio will increase linearly. Consequently, surface force reactions such as surface tension, electrostatics and Van der Waals forces, become more significant, while gravitational and inertial forces becomes less of a factor in governing the static and dynamic equations of motion.

The angular inertia of a rectangular plate about a center line lying in the plane of the plate, is linearly proportional to the mass of the plate. It is also proportional to the square of the width of the plate which is perpendicular to that axis. Therefore, if all dimensions of a plate are reduced by a factor of two, then the final mass would be the inverse cube of two, or one eighth of the original mass. The inertial mass, sometimes referred to as the mass moment of inertia, of the smaller plate would then be one eighth times the inverse square of two or one thirty-second times the original mass.

Since the angular acceleration of a body is directly proportional to an externally applied torque and inversely proportional to its angular inertial mass, one can conclude that halving all plate dimensions will result in thirty two fold increase in angular acceleration for a given torque.

As is commonly known, electrostatic force is an effective means for moving small, micromachined components. The force produced between an electrostatically charged plate and ground is directly proportional to the plate's surface area and inversely proportional to the square of the plate-to-ground gap for a given voltage. Thus, if all dimensions are again halved, the electrostatic force generated between the plate and ground would be equal to the initial force for a given voltage.

By taking the previous dynamic and electrostatic arguments into consideration, it can be surmised that by halving all dimensions of an electrostatically driven plate, the dynamic response would be improved by a factor of thirty two for a given driving voltage. More generally, assuming that the driving voltage is such that electrostatic breakdown of air and insulators does not occur, then the dynamic response of an electrostatically driven plate will increases as the inverse forth power of size reduction.

SUMMARY

One aspect of the present invention is a method and apparatus for steering beams of light.

Another aspect of the present invention is steering a beam of light with one or more degrees of freedom.

An aspect of the invention provides a method and apparatus for precisely steering a beam of light by making use of a hybrid inter-optical alignment precision which occurs when a beam steering mechanism is micromachined with respect to a crystallographic orientation of a substrate.

Another aspect of the invention provides a micromachined mirror which is capable of steering a beam of light with multiple degrees of freedom.

Yet another aspect of the invention provides a micromirror that is precisely steered by the application of a controlled electrostatic effect, in either a current or a voltage mode.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a perspective view of a hybrid fiber optic multi-degree-of-freedom beam steering apparatus according to the present invention.

FIGURE 2 is a perspective view and close up of the multi-degree-of-freedom micro-mirror shown in FIGURE 1.

FIGURE 3 is an exploded perspective view of FIGURE 2 showing the details of the multi-degree-of-freedom micro-mirror.

FIGURE 4 is a side view cross section showing the internal detail of either a torsion or cantilever hinge.

FIGURE 5 is a top view of FIGURE 1.

FIGURE 6 is a side view cross section of FIGURE 5 indicated by the section line B-B in that view.

FIGURE 7 is a front view cross section of FIGURE 5 indicated by section line A-A in that view.

FIGURE 8 is an exploded perspective view of the hybrid fiber optic multi-degree-of-freedom beam steering apparatus shown in FIGURE 1.

FIGURE 9 is perspective view of a generalized double gimbaled micromirror.

FIGURE 10 is an exploded perspective view of FIGURE 9.

FIGURE 11 is a perspective view of an alternate embodiment

FIGURE 12 is a perspective view of another alternate embodiment

FIGURE 13 is a perspective view of an alternate embodiment with an integral optical device and cover plate

FIGURE 14 is a side view cross section of FIGURE 13

FIGURE 15 is a perspective view of FIGURE 1 showing a distal and lateral flap locking means

FIGURE 16 is a side view cross section of FIGURE 1 showing an end flap locking means

FIGURE 17 shows the functionality blocks of an embodiment of the invention

DETAILED DESCRIPTION

Referring now to FIGURES 1, 2 and 6 a first aspect of the present invention provides a precision micromachined V-groove **106** into which an optical fiber **105** is cemented or otherwise affixed. A light wave propagating through optical fiber **105** is emitted from the core in the direction of micromirror assembly **200**. The surface normal of micromirror assembly **200** is given a precise angle **508** and locked in place with the activation of solder bars **201A** and **201B**. For the configuration shown, angle **508** has a value of 45 degrees with respect to optical axis **507** as shown in FIGURE 6. Upon striking the underside of submirror **207**, the light wave is reflected downward through body **100** of the device. Electrodes **202** and **203** are in close proximity to submirror **207** and when a voltage potential is disproportionately introduced on one or the other electrode with respect to grounded submirror **207**, an unbalanced electrostatic force is generated. The net effect of this force is to rotate submirror **207** about its torsional axis defined by torsion hinges **204A** and **204B**, thereby deflecting the reflected beam parallel to the bottom surface of the device and perpendicular to the axis of optical fiber **105**.

The beam, having had its optical path **507** altered by submirror **207**, passes down through the bottom of cavity **101** and into adjoining cavity **504** as shown in FIGURE 6. In one aspect of the invention, the beam passes through the bottom of cavity **504** and into free space. In another aspect of the present invention, a circular, spherical, rectangular, cylindrical or otherwise irregularly shaped optical element **503**, may be precisely positioned within cavity **504** so as to provide optical shaping of the emitted beam. For example, if a light beam traveling along optical path **507** is made to pass through optical element **503**, it can be made to converge to a focal point somewhere below body **100** if optical element **503** is a converging lens, or diverge if optical element **503** is a diverging lens. Optical element **503** can take the form of a singlet lens, compound lens, achromatic lens, index gradient lens, micromachined lens or lens array, grating, prism, mirror, laser cavity, optical fiber, optical amplifier, optical sensor or any variety of optical elements known to those skilled in the art.

FIGURE 1 shows one embodiment of a hybrid fiber optic multi-degree-of-freedom beam steering apparatus. The device body **100**, is preferably fabricated from a conventional, double side polished silicon wafer having a normal to its surface coincident with the (100) crystallographic direction. After depositing and patterning all sacrificial SiO_2 pads, a thin film **102** and **501** of silicon nitride, silicon carbide, silicon monoxide or the like, is deposited on both surfaces of substrate **100,** primarily to provide an inert masking layer for subsequent anisotropic etchants. A detailed account of these and other fabrication steps will be described later. The thickness of films **102** and **501** is dictated by the pinhole free quality of the deposit but may typically be on the order of 1000 angstroms. Films **102** and **501** may be deposited using Chemical Vapor Deposition (CVD), Pressure Enhanced Chemical Vapor Deposition (PECVD), electron beam evaporation, plasma sputtering, or other methods known to those skilled in the art.

Optical fiber **105** is shown lying in a precision etched V-groove **106** which is connected to cavity **101**. V-groove **106**, cavity **504** and cavity **101** are all formed by a wet anisotropic etchant such as potassium hydroxide (KOH) and water, tetra-methyl ammonium hydroxide (TMAH) and water, or the like. As with all such etch profiles in silicon, the walls of groove **106** and cavity **101** are defined by the crystallographic (111) planes of silicon. This is due to the fact that there is a dramatic difference in etch rate among the different plane orientations. Specifically, for a KOH water etchant the (100):(110):(111) planes etch at a ratio of roughly 300:150:1 respectively at 85 C.

A significant aspect of utilizing the crystallographic planes of single crystal silicon to define a complex interconnection of optical fixturing is that the registration of intersecting angles from one groove or pit to the next, is governed with atomic precision. For (100) silicon, there are four (111) walls that slope down 54 degrees with respect to the top (100) surface and they intersect one another at precisely 90 degrees. Further, if a square opening of width W is made in a KOH resistant mask, such as silicon nitride, and any one side of that square opening is coincident with a (111) plane, then the resulting etched pit will have a depth of exactly 0.707 times W. Such precise control of interconnected features provides a highly reliable and relatively inexpensive method for aligning optical components with great precision.

As shown in FIGURE 6, cavity **101** is connected to cavity **504** and provides clearance for movement of micromirror assembly **200**. In one embodiment of the invention, cavity **101** may also play the role of a ground plane for the electrostatic actuation of one or more parts of micromirror assembly **200**.

In another embodiment of the invention, groove **106** and cavity **101** may be overcoated with a solderable surface such as a sputtered titanium/platinum/gold film approximately 0.5 microns thick. The titanium provides for good adhesion between the silicon and platinum, and the platinum acts as a diffusion barrier to prevent excessive alloying of the gold and titanium and is a well know technique to those skilled in the art. A gold surface in groove **106** provides for the soldering of a metal coated optical fiber; this being but one method of reliably affixing fiber **105** into groove **106**. Other methods for securing fiber **105** into groove **106** include the use of adhesives such as cyanoacrylate (3M) , epoxies (MASTER BOND, 154 Hobart St. Hackensack, NJ), photo curable adhesives (EDMUND SCIENTIFIC , 101 E. Gloucester Pike, Barrington, NJ), thermoplastics (DUPONT) and the like.

A unique aspect of the invention involves an in situ method for assembling micromachined parts, herein referred to as the self-solder technique. Referring to FIGURE 2, in one aspect of the invention, solder bars **201A** and **201B** are fabricated directly on resistive heating elements **201C** and **201D** (not shown).

Heating elements **201C** and **201D** can take the form of a meandering path, thin film conductor (1000 angstroms), such as a Ti/Au film, whose resistance is greater than the thicker (a few microns) feed lines **104A** and **104F**. As current is passed from line **104A**, through the heating elements, and out to line **104F**, intense heat is conducted from heating elements **201C** and **201D** to solder bars **201A** and **201B** respectively, thereby causing them to melt. As is the case with the present invention, if solder bars **201A** and **201B** are in close proximity or intimate contact with a wetable surface such as a gold coated wall of cavity **101**, then the molten solder will wick between wall of cavity **101** and mirror assembly **200** at the point of solder joint contact. These contact points are shown as **601** and **602** in FIGURE 7. Removing current flow from **104A** and **104F** disengages the heaters and permits the joint to solidify. The resulting solder joint is permanent and strong.

Solder bars **201A** and **201B** can be composed from a wide range of materials with a range or melting points from room temperature to 500 C, depending on the desired strength of the resulting solder joint and range of service temperatures. A higher melting point solder usually results in a stronger joint. Solder composition can be any variety of commonly known low temperature alloys such as PbSn, PbSbSn, PbSnAg, In, or higher melting point alloys composed of Sn, Ag, Au, Cu, Si etc. These materials may be obtained from companies such as the INDIUM CORPORATION OF AMERICA (34 Robinson Rd, Clinton NY) or TECHNICS (1254 Alma Ct. San Jose, CA). Solder bars **201A** and **201B** may be formed by electroplating in the case of the Pb and In alloys, or may also be sputtered and patterned in the conventional manner as is known by those skilled in the art. It can be appreciated that it may also be desirable to incorporate a layer of flux on or within solder bars **201A** and **201B** to enhance the wetability of the joined surfaces.

A low temperature self-soldering joint can be created by making solder bars **201A** and **201B** from any of a variety of low melting point thermoplastics such as polyester resins, microcrystalline wax, polyethylene and the like. A large variety of thermoplastic adhesive resins are available from DUPONT.

It is well known that gold alloys quite readily with silicon at low (400C) temperatures, forming an excellent silicide. Given sufficient heat input, it may be possible to use pure gold, or a eutectic gold/silicon solder (96.8% Au, 3.2% Si) to produce a bond directly on a bare silicon surface, thereby simplifying the self-solder technique.

In an alternate embodiment of the invention, it may be desirable to eliminate lines **104A** and **104F** and resistive heating elements **201C** and **201D** in lieu of placing the entire device on a hot plate or in an oven to directly activate solder bars **201A** and **201B**. It can be appreciated that any one of these method of self-soldering described in the preceding paragraphs, could also be used to secure fiber **105** into groove **106**, or optical element **503** into cavity **504**.

Bar **109** provides support for bond pads **103A-103F** and corresponding conducting lines **104A-104F** as they traverse the underetched void created by groove **106**. Bar **109** may be composed of a particularly thick layer of insulating material similar to that which makes up micromirror assembly **200**. Another method for fabricating bar **109** would involve the plating of a metal such as Fe, Ni, Cu, Au or Cr that is subsequently overcoated with an insulator such as Si_xN_y, SiO_2, SiC or the like.

For the embodiment shown in FIGURES 1 through 8, a light beam approaches submirror **207** from below, thus a reflective material must be provided on the lower surface if the body of submirror **207** is comprised of an opaque dielectric. If a thin or otherwise transparent dielectric such as silicon nitride is used, then the reflective surface may be encapsulated within the body or reside on the upper surface of the mirror.

A major advantage of the fabrication means disclosed herein, is that the critical reflective surface of a mirror may be sputtered directly on the surface of a freshly polished wafer, before any additive processing has been done. Because this is done first, mirrors are optically flat and smooth, and global planarization is not an issues.

Details of the hinge structure employed for both torsion and cantilever hinges is shown in FIGURE 4. Area **401** refers to the anchored or frame side of hinge **402**, while area **403** refers to the mirror or suspended side of the structure. As shown here, conductor **405** traverses hinge **402** and is made as thin as possible so as not to significantly contribute to hinge stiffness. Via pad **406** is in communication with layer **405** and built up to prevent punch through as a plasma etched via is made through layer **407**. Thicker lines may then be connected to via pad **406**. In general, via pad **406** may be on either side of a hinge structure. In the preferred embodiment, a via pad **406** resides on both sides of a hinge structure for all lines since thicker, high current carrying lines are present on the cantilevered structure side.

A general, presently preferred fabrication sequence for micromirror assembly **200** is as follows. Referring to FIGURES 3 and 4, first, a thin (400 A) layer **404** of low stress LPCVD silicon nitride is deposited over the upper surface of substrate **100**.

Next, a conducting layer **405** of Ti (100A) / Au (400A) / Ti (100A) is sputtered or evaporated onto the surface. Layer **405** is patterned with a photoresist mask and a combination of 6:1 BOE to etch the Ti, and room temperature aqua regia (3:1 HCl/HNO3) to etch the Au. All via pads **406**, may be built up by selectively electroplating these areas.

A thicker layer **407** (i.e. 2 microns for a mirror 100 microns wide) of low stress, low temperature PECVD silicon nitride is deposited over the surface. A second mask is then provided such that there are openings defining those areas that will be etched down to bare substrate **100**. Specifically, those are areas that define the edges of mirror frame **303**, submirror **207**, torsion hinges **302A** and **302B**, side wall accommodating edges **304**, the area between micromirror assembly **200** and the defining edges of cavity **101**, and cantilever hinge perforations shown as hinge group **301** in FIGURE 3. For reasons to be discussed later, a plasma etch of only 3000 A is performed at this point, and is herein refereed to as the "head start" etch.

After the old mask is removed, a third mask is provided having openings as previously described, but with additional opening over all hinge areas. A plasma etch is done such that layer **407** is removed from all areas that will see a subsequent Si anisotropic etch. This leaves a substantially thick hinge area **408**, that is approximately equal to the thickness of the "head start" etch.

A forth mask defines via openings down to all via pads **406**. A plasma etch is performed until all pads **406** are exposed.

A sacrificial material (not shown) such as polyimide, PMMA, SiO2 or the like, is deposited and patterned with a fifth mask to form a pad above and about submirror **207** and extends laterally to cover those openings that define submirror **207** while remaining within the bounds of frame **303** and not covering pads **406**. The thickness of this sacrificial pad defines the electrode spacing between submirror **207** and electrodes **202** and **203**.

A seed layer of Ti (200A), Au (1500A), Ti (500A) is deposited onto the substrate. A sixth mask is provided, with openings defining lines **104A** - F and electrodes **202** and **203**. The upper layer of Ti is removed with BOE, thereby exposing the Au. Au is then electroplated within the open mask areas. After stripping of the mask, the seed layer is removed with wet etchants as before.

A similar series of procedures may be used to define thin film heaters **201C** and **201D** and to electroplate or pattern the optional solder bars **201A** and **201B**.

After electroplating, all sacrificial materials are removed. If polyimide is used, then a three Torr oxygen plasma is used to remove it. If SiO2 is used, then an extended length BOE wet etch is employed.

The bare areas of substrate **100** are then subject to an 85 C, 25% KOH:DI etch. As cavity **101** is defined by the anisotropic etch, micromirror assembly **200** becomes fully under etched and is suspended above the cavity by hinge group **301**. Post etch debris is removed with a 10 minute immersion in 1:1:1 HCl:H_2O_2:DI followed by a DI rinse.

As previously mentioned, the cross section **408** of hinge group **301** is relatively thick. A thick cross section produces a very stiff hinge structure, thereby preventing the well know destructive force of surface tension from pulling micromirror assembly **200** into hard contact with the walls of cavity **101**, a condition that is irreversible.

An overly stiff hinge, however, is undesirable for creating large angular deflections with moderate driving voltages. Thus, all hinges require a dry etch "tuning" to a cross sectional thickness **409** before being called into service. Depending on the thickness of layers **404** and **405**, a hinge can be made arbitrarily thin and compliant. Because the final etch takes place in a dry environment, there is no danger of surface tension induced damage.

Once completed, micromirror assembly **200** is electrostatically driven down into cavity **101** by placing a potential across pads **103C** and **103D**. At a sufficient voltage, edges **304** of micromirror assembly **200** will rest against the side walls of cavity **101**. The predetermined geometry of micromirror assembly **200** and cavity **101** is such that when fully deployed to contact, micromirror assembly **200** will rest at a 45 degree angle with respect to the upper surface substrate **100**. While maintaining the voltage, current is momentarily driven through pads **104A** and **104F** to initiate the self soldering means, thereby firmly establishing micromirror assembly **200** within cavity **101**.

It can be appreciated that the fabrication sequence previously suggested, can be altered significantly while attaining the same objectives. Thus, any permutations of sequencing are considered equivalent methods. In addition, other techniques such as plasma etching of the conductive layer, replacing dry etches with wet etches, and other substitutions known to those skilled in the art, are essentially equivalent methods to those already disclosed.

Once deployed, a transparent or opaque cover plate **107**, made from glass, ceramic, plastic, silicon etc., serves as a mechanically rigid barrier to prevent inadvertent damage of the delicate micromirror assembly **200**. Cover plate **107** may be attached to body **100** with methods commonly in use today including, solder glass, glass frit, two part adhesives, thermal adhesive, UV cure adhesives, cyanoacrylate, etc. In order to reduce possible electrostatic interference with or to the environment, cover plate **107** may also have one or more surfaces coated with a conductor, or may itself, be electrically conductive. If **107** is made conductive, it is apparent that it could provide the necessary ground for rotating submirror **207** in lieu of electrodes **202** and **203**. In this configuration, two isolated conducting surfaces disposed on either side of the rotational axes defined by hinges **302A** and **302B** on submirror **207**, could produce an unbalanced electrostatic force by applying a voltage potential between one or the other of the conducting surfaces and the grounded surface of cover **107**. Similarly, torsional forces can be produced between cavity **101** and the isolated conducting surfaces of submirror **207**, as described previously, if cover **107** is made non-conductive or is electrically isolated and cavity **101** is grounded.

Cavity **504** is formed on the underside of body **100** in a five step process. First, sacrificial pad **502**, preferably composed of SiO_2, is deposited (approximately 0.5 microns thick) and patterned on the bottom surface of body **100**. Secondly, a thick (1000 A to a few microns) underside cap layer **501** of Si_xN_y, SiC or any other material that shows excellent resistance to Hydrofluoric Acid (HF) or Buffered Oxide Etch (BOE), is deposited over the bottom surface of body **100**, thereby covering sacrificial pad **502**. A hole **505** is then etched through underside cap **501** and sacrificial pad **502** down to bare silicon, preferably with a fluorinated, high frequency plasma as is typically the case for these materials. The shape of hole

505, be it round, square or irregular, is such that it will accommodate the insertion of optical element 503. Next, hole 505 is subjected to a wet BOE or HF dip until sacrificial pad 502 is completely consumed. This process can extend from minutes to hours, depending on acid concentration and the size of sacrificial pad 502. Typically, for 6:1 BOE, SiO_2 will etch at a rate of approximately 4000 A per minute. Finally, a KOH etch is performed that will form cavity 504. The lateral extent and depth of cavity 504 is defined by the initial (100) surface area exposed to the KOH etchant, which is precisely the surface area previously occupied by sacrificial pad 502.

Subsequent to the formation of cavity 504, the bare silicon walls are exposed to a high temperature oxygen or steam atmosphere, thereby forming a thermal SiO_2 layer. This step is required to prevent irregular etching in the (110) direction at the geometrically complex intersection of cavity 101 and cavity 504, identified as 509 in FIGURE 6.

Upon assembly, optical element 503 is inserted into hole 505 until its upper edges come into contact with the walls of cavity 504. The points of contact between optical element 503, cavity 504, and underside cap 501 define a mechanically over-constrained system that will, in most cases, insure alignment of optical element 503's optical axis with the surface normal of body 100. The precision with which the center of optical element 503 is aligned with the center of micromirror assembly 200 is defined by the front-to-back alignment errors of the photolithographic aligner used. With very little difficulty, this error is typically less than a few microns. Once optical element 503 is inserted, it may be externally cemented in place using the self solder technique or with more conventional adhesives such as cyanoacrylates, thermoplastics, two part epoxies, UV cure adhesives, etc.

An alternate embodiment of micromirror assembly **200** is shown in FIGURES 9 and 10. The double gimbaled configuration of micromirror **708** permits rotation about two perpendicular axes defined by gimbaled hinges **704**, and **705** on one axes and gimbaled hinges **706**, and **707** on the other axes. Electrostatic forces are produced by grounding micromirror **708** and surrounding frame **710** through bonding pad **709**, while selectively charging one or more of electrostatic pads **801A**, **801B**, **801C**, and **801D** directly below. Electrical isolation between conducting layers is maintained by insulating layer **702**. Insulator **702** provides electrical isolation from the environment. The electrostatic attractive forces acting between electrostatic pads **801A** and **801D**, and frame **710**, or between electrostatic pads **801B** and **801C**, and the edges of micromirror **708**, produce the desired rotation. Electrostatic pads **801A**, **801B**, **801C**, and **801D** are electrically connected to bonding pads **800A**, **800B**, **800C**, and **800D** respectively.

Within the rotational travel limits defined by the geometry of double gimbaled micromirror **700**, any simultaneous combination of rotations about two axes is possible. For example, if frame **710** and micromirror **708** are each geometrically constrained to plus or minus 20 degrees of rotation, double gimbaled micromirror **700** would have the capability to deflect an impinging light beam in any direction within a cone of 80 degrees.

It can be appreciated that electrostatic pads **801A**, **801B**, **801C**, and **801D** could also be disposed above and around micromirror **708** and frame **710** as in micromirror assembly **200**, provided the reflective surface of the central mirror is sufficiently unobstructed. It is apparent that a gimbaled micromirror assembly with one or more axes of rotation is essentially an extension of this general case. Micromirror assembly **200** is an example of a single degree of freedom, or single axes embodiment of this general case. Double gimbaled micromirror **700**, as shown in FIGURE 10, can also be used in a stand alone implementation.

In another embodiment, double gimbaled micromirror **700** is modified to include cantilever hinges. The resulting two axis micromirror assembly, labeled **900** in FIGURE 11, can controllably alter the path of a light beam emitted by optical fiber **105** in two directions about a vector normal to the surface of substrate **100**. In this implementation, an impinging beam strikes the upper surface of the mirror assembly. Since the reflective medium must be on the upper surface, a change in the order of fabrication steps is required as would be apparent to someone skilled in the art. It is also noted that for all mirror configurations, a multi-layer dielectric will also provide an excellent reflective surface.

Due to an extra axis of motion, the apparatus of FIGURE 11 requires two additional electric lines and pads over those present in the preferred configuration. Pads **903C** and **903E** are in communication with a self solder means. Pad **903H** is in communication with the conductive surface of micromirror assembly **900**. Pad **903D** makes an electrical contact with substrate **100**, while pads **903A**, **903B**, **903F** and **903G** are in communication with electrodes (not shown) disposed beneath the double gimbaled micromirror as with double gimbaled micromirror **700**.

If optical modification of the beam is required, then a second optical element **921** can be introduced as shown in FIGURE 13. In this embodiment, optical element **921** is bonded to a transparent cover plate **920**. Cover plate **920** serves many functions. Using solder glass, adhesives, or the like, one can hermetically seal cavity **101**, intersecting groove **106**, and the voids surrounding optical fiber **105** with cover plate **920**. Such a seal would protect the delicate beam steering means below from the harshest of environments. In addition, cover plate **920** provides a convenient means for mounting optics, and providing a positive stop for positioning optical fiber **105** along groove **106**, given a sufficiently large fiber diameter.

Yet another embodiment of a beam steering device is shown in FIGURE 12. It is functionally similar to the device in FIGURE 11 with the notable exception of employing a single axes beam steering means such as micromirror assembly **200**. The pad functions and names are identical to the preferred embodiment. This apparatus can also be sealed with a cover plate and use additional optics as with the previous embodiment.

FIGURE 14 shows a cross sectional view of the embodiments shown in FIGURES 11 and 12. Optical path **930** can be traversed in either direction. Many applications of this technology require only a forward propagating optical path, from optical fiber **105** to secondary optical element **921**. For example, any of the embodiments discussed could be used as the printing engine in a high speed laser printer, a photographic emulsions laser plotter, a laser mask writing tool, a steerable industrial laser cutting device, or a pen based, full wall laser display to name a few. By fabricating three such devices side-by-side and supplying each with a different color light, a pen based, full wall color display can be envisioned.

A bi-directional optical path can be utilized in applications such as optical switches, industrial robot vision scanners, illuminating and reading from optical drives such as a CD ROM, illuminating and scanning in an optical microscope configuration, and illuminating and reading bar codes. Of course, two devices could be fabricated together where one transmits the optical signal and the other receives it as with laser range finders or optical proximity detectors.

Although these single sided embodiments lack the convenient self alignment feature provided by lower cavity **504** and alignment means **505**, they would most likely be less costly to manufacture due to the single sided photolithographic steps.

FIGURES 14 and 15 show two more ways in which a beam steering means can be locked into position within cavity **101**. In FIGURE 15, one or more lateral flaps **940**, **942**, or distal flap **941** are fabricated in conjunction with micromirror assembly **200**, and are connected to micromirror assembly **200** via a cantilever hinge structure already discussed. The flaps may be equipped with a self solder means.

During deployment of micromirror assembly **200**, flaps **940**, **942** and **941** provide an added measure of resistance as they encounter the walls of cavity **101** on their way down. As contact is made, the cantilever flap hinges (not shown) deflect, allowing the flaps to conform to the slop of the walls within cavity **101**. The resulting drag adds stability to the deployment process so that any angle between contact and full deployment can be attained. As with the preferred embodiment, once micromirror assembly **200** is at the desired angle, the self soldering means is activated.

FIGURE 16 shows yet another method for locking a beam steering means in place. In this image, a rigid locking flap **950** is anchored to substrate **100** with a cantilever hinge **951**. Locking flap **950** is patterned to a predetermined length such that when deployed, the resulting interference with micromirror assembly **200** produces the desired deployment angle. For deployments of micromirror assembly **200** beyond

32 degrees, an additional vertical tip **952** may be required to secure the mechanical interference. Flap **950** must necessarily lie over micromirror assembly **200** during fabrication, and thus, requires an additional sacrificial and masking layer.

FIGURE 17 shows the functional blocks associated with integrating a hybrid optical multi-axis beam steering apparatus with a control means. In general, a computer **960** calculates the necessary mirror angles and rates, and transmits a request to a multi-channel voltage amplifier **965**. The amplifier converts the digital request to a series of properly scaled voltages. The voltage signals are then communicated to bond pads **103A-F**, for example. Taken together, **960** and **965** make up the electronic control means for driving any embodiment of a hybrid optical multi-axis beam steering apparatus **970**. The desired beam steering transfer function is then established between the optical input **975** and the optical output **980**. It is noted that input **975** and output **980** can have either a unidirectional or bi-directional beam path, depending on the intended application.

The invention, once completely assembled, can then be wire bonded in the usual fashion. Bond wires extend from an external control circuit to pads **103 A-F**. The entire device can then be hermetically encapsulated, taking care not to permit potting resin to enter cavity **101** or cover optical element **503**.

FABRICATION SEQUENCE

In accordance with an aspect of the invention a presently preferred fabrication sequence for the hybrid optical beam steering apparatus is set forth below.

Begin with double polished (100) silicon wafers having a low resistivity (1 ohm-cm).

Deposit one or two microns of PECVD SiO_2 on both sides of the wafer.

Define the sacrificial oxide pads with patterned photoresist and a BOE etch. Oxide isolation pads will be under bond pads 103A,B,D,E,F, oxide sacrificial pads will be under bar 109, under mirror 200, and in position 502.

Deposit LPCVD low stress silicon nitride (400 A) on both sides or just top side.

Open window through nitride over pad 103C and etch down to bare silicon.

Sputter Ti (100 A) for adhesion plus Au (300 A) and pattern to form mirror and lines across hinge areas. The Ti/Au may be patterned with a F115 plasma etch or aqua regia followed by a brief BOE etch.

Mask for lift-off or plate up of Au areas over all lines and pads except across the hinge area and the mirror area.

Remove Ti/Au seed if performing a plate-up, otherwise perform lift-off.

Deposit two microns of low stress nitride, low stress silicon carbide or anything impervious to BOE. An adhesion layer may be necessary prior to deposition for good bonding to the Au surface.

Provide a mask on the top surface which opens areas that will etch down to bare Si.

Etch 2500 A of low stress nitride or low stress silicon carbide etc., for a head start etch.

Provide a mask on the top surface which opens areas that will etch down to bare Si or Au pads, plus opens up the full hinge areas.

Plasma etch down to bare Si or Au pads leaving 2500 A thick cantilever and torsion hinges. V-groove area is now open.

Deposit a sacrificial oxide over top of wafer (1 micron).

Open hole 505 on bottom of wafer and plasma etch down to bare Si.

Protect the top side with high melting temperature wax and a carrier wafer.

Perform a BOE etch to remove sacrificial pad 502.

Place wafer in an anisotropic etchant, such as KOH, EDP, TMAH etc., until cavity 504 is fully formed.

Post-etch clean with a 1:1 solution of HCl and H_2O_2.

Remove wax and carrier wafer from top of wafer.

Form an oxide on the walls of cavity 504 using a high temperature steam or oxygen process, a wet electrochemical process, or a wet chemical process.

Wax carrier wafer to bottom of wafer

Mask and etch open holes in oxide layer for electrodes and electrode vias on top side of wafer.

Sputter a seed layer of Ti (100 A) plus Au (500 A) on top surface.

Mask and electroplate electrodes.

Mask and electroplate, or sputter and pattern solder bars.

Remove all oxide blankets and sacrificial pads with a BOE etch.

Anisotropically etch cavity 101 and v-groove 106 using KOH, EDP, TMAH etc.

Post-etch clean with a 1:1 solution of HCl and H_2O_2.

Spray on photoresist and open only over v-groove 106 and open areas around mirror 200 (optional).

Sputter a layer of Ti/Au into v-groove 106 and 101(optional).

Remove photoresist.

Remove wax and carrier wafer from bottom of wafer.

Plasma etch cantilever and torsion hinges down to a thickness of approximately 400 A.

Electrically ground pad 103C and apply a positive voltage to pad 103D thereby causing micromirror assembly 200 to fully deploy downward into cavity 101.

While maintaining this position, pass current through pads 103A and 103F, thereby causing melting of the thermal adhesive or solder.

After removal of current, micromirror assembly 200 is permanently locked into position.

Insert optical element means 503 into cavity 504 and cement or self-solder in place.

Cement or self-solder primary optical means 105 into groove 106.

Cement or self-solder cover plate 107 over cavity 101.

Wire bond all pads to electrical control means.

CLAIMS

I claim:

1. An optical beam steering apparatus comprising:

a substrate defining one or more aligned cavities;

a primary optical path means for accommodating the passage of a light beam;

an upper cavity provided in a portion of said substrate that is aligned to a predetermined degree of precision and in direct communication with said primary optical path means;

a beam steering means provided in said upper cavity for controllably directing said beam.

2. The apparatus according to Claim 1 wherein said beam steering means is placed at a predetermined orientation within said upper cavity for the purpose of controllably altering, in one or more directions, the optical path of an impinging beam emanating from or propagating towards said primary optical path means.

3. The apparatus according to Claim 1 wherein said primary optical path means comprises a waveguide.

4. The apparatus according to Claim 1 wherein said primary optical path means comprises a groove provided into said substrate for accommodating the passage of a light beam.

5. The apparatus according to Claim 4 further comprising a primary optical element means for accommodating a beam of light wherein said primary optical element means is provided within said groove.

6. The apparatus according to Claim 5 wherein said primary optical element means is selected from the group consisting of optical fibers, refractive optical elements, reflective optical elements, phase optical elements, light detectors, beam splitters, lasers, light emitting diodes, incandescent light sources, fluorescent light sources, natural light sources or plasma light sources.

7. The apparatus according to Claim 1 wherein said substrate comprises a crystal made of a material that has a differential etch rate between different crystallographic planes.

8. The apparatus according to Claim 1 wherein at least one cavity is anisotropically etched into said substrate.

9. The apparatus according to Claim 1 wherein said substrate is made of a solid material capable of having geometrically precise cavities molded within said substrate.

10. The apparatus according to Claim 1 which further comprises a cover plate means for sealing one or more said aligned cavities, wherein said cover plate is provided adjacent to a surface of said substrate.

11. The apparatus according to Claim 10 wherein said cover plate is comprised of one of an optically opaque, transparent, translucent, electrically conductive, or an electrical insulator material.

12. The apparatus according to Claim 1, further comprising:

a lower cavity provided into a bottom surface of said substrate and having a predetermined alignment with respect to said upper cavity;

a suspended bridge means for spanning said primary optical path means at a juncture between said primary optical path means and said upper cavity;

a cantilever hinge means flexibly anchoring said beam steering means to said suspended bridge means; and

wherein said beam steering means has at least a reflective lower surface and is rotated downwards into said upper cavity providing an impinging beam of light emanating from said primary optical path means is to be controllably deflected in a generally downward direction through said bottom of said upper cavity and said lower cavity, and a beam of light entering from said lower cavity is controllably deflected towards said primary optical path means.

13. The apparatus according to Claim 12 further comprising:

a secondary optical element means for accommodating a beam of light, wherein said secondary optical element means is disposed within said lower cavity; and

an alignment means for aligning said secondary optical element within said lower cavity such, wherein said secondary optical element is substantially centered in the lower cavity and the optical axis of the secondary optical element is aligned to a predetermined angle with respect to a surface normal emanating from a lower surface of said substrate.

14. The apparatus according to Claim 13 wherein said secondary optical element means is selected from the group consisting of optical fibers, refractive optical elements, reflective optical elements, phase optical elements, light detectors, beam splitters, lasers, light emitting diodes, incandescent light sources, fluorescent light sources, natural light sources or plasma light sources.

15. The apparatus according to Claim 1 further comprising:

a cantilever hinge means flexibly connecting said beam steering means with an upper edge of said upper cavity that is not coincident with said primary optical path means; and

wherein, said beam steering means has at least a reflective upper surface such that said beam steering means is disposed within said upper cavity causing an impinging beam of light emanating from said primary optical path means, to be controllably deflected in a generally upwards direction and a beam of light entering from above said upper cavity is controllably deflected towards said primary optical path means.

16. The apparatus according to Claim 15 further comprising:

a secondary optical element means for accommodating a beam of light, said secondary optical element means disposed adjacent to said upper cavity;

an alignment means for aligning said secondary optical element adjacent to said upper cavity,

such that the secondary optical element is substantially centered above the upper cavity and the optical axis of the secondary optical element is aligned to a predetermined angle with respect to a surface normal emanating from an upper surface of said substrate.

17. The apparatus according to Claim 1 wherein said beam steering means comprises:

a gimbaled micromirror nested into one or more sets of gimbaled hinge means, wherein each set of gimbaled hinge means defines an independent axes of rotation of said gimbaled micromirror with respect to a frame holding an outermost set of said gimbaled hinge means and said outer most frame is connected at one edge with an upper surface of said substrate by a cantilever hinge means such that said beam steering means is capable of deflecting downwards into said upper cavity;

a plurality of independently addressable electrodes disposed for positioning said gimbaled micromirror;

a plurality of electrical lines in direct electrical communication with said independently addressable electrodes;

an electronic control means in communication with said electrical lines,

such that said gimbaled micromirror is electrically driven to a predetermined angular orientation with respect to said outer most frame.

18. The apparatus according to Claim 17 wherein said gimbaled micromirror is provided with a conductive film adjacent to its surface and across said gimbaled hinge means such that said gimbaled micromirror is in electrical communication with said electronic control means.

19. The apparatus according to Claim 1 wherein said beam steering means comprises:

a cantilevered micromirror nested into one or more sets of cantilever hinge means, each of which, defines an independent axes of rotation of said cantilevered micromirror with respect to a frame holding the outer most cantilever hinge means;

wherein said outer most frame is connected at one edge with the surface of said substrate by a cantilever hinge means such that said beam steering means is capable of deflecting downwards into said upper cavity;

a plurality of independently addressable electrodes disposed for positioning said cantilevered micromirror;

a plurality of electrical lines in direct electrical communication with said independently addressable electrodes;

an electronic control means in communication with said electrical lines,

such that said cantilevered micromirror is electrically driven to a predetermined angular orientation with respect to said outer most frame.

20. The apparatus according to Claim 19 wherein said cantilevered micromirror is provided with a conductive film adjacent to its surface and across said cantilever hinge means such that said cantilevered micromirror is in electrical communication with said electronic control means.

21. The apparatus according to Claim 1 wherein said beam steering means comprises:

a hybrid micromirror nested in any combination of cantilever hinge means and gimbaled hinge means providing one or more independent axes of rotation with respect to a frame holding the outer most hinge structure;.

wherein said outer most frame is connected at one edge with the surface of said substrate thereby forming a cantilever hinge means such that said beam steering means is capable of deflecting downwards into said upper cavity;

a plurality of independently addressable electrodes disposed adjacent to said hybrid micromirror;

a plurality of electrical lines in direct electrical communication with said independently addressable electrodes;

an electronic control means in communication with said electrical lines,

such that said hybrid micromirror is electrically driven to a predetermined angular orientation with respect to said outer most frame.

22. The apparatus according to Claim 21 wherein said hybrid micromirror is provided with a conductive film adjacent to its

surface and across said cantilever hinge means and said gimbaled hinge means such that said hybrid micromirror is in electrical communication with said electronic control means.

23. The apparatus according to Claim 1 wherein said beam steering means is rigidly affixed in a predetermined orientation within said upper cavity.

24. The apparatus according to Claim 23 wherein a chemical bonding means for rigidly affixing said steering means is selected from the group consisting of one part or more liquid adhesives, ultraviolet radiation cured adhesives, or vapor phase applied adhesives.

25. The apparatus according to Claim 23 wherein surface forces such as surface tension, Van der Waals, residual surface charge, electrical discharge bonding, or the like, is employed to rigidly affix said steering means within said upper cavity.

26. The apparatus according to Claim 23 wherein a self soldering means is employed for rigidly affixing said beam steering means within said upper cavity.

27. The apparatus according to Claim 23 wherein a mechanical locking means for rigidly affixing said beam steering means within said upper cavity comprises one or more distal or lateral flaps extending beyond the distal or lateral edges, respectively, of said beam steering means such that when said beam steering

means is deflected into said upper cavity, said distal or lateral flaps drag against one or more walls of said upper cavity and adhere to said wall by said surface forces.

28. The apparatus according to Claim 27 wherein said self solder means is provided on said distal or lateral flaps.

29. The apparatus according to Claim 23 wherein said mechanical locking means comprises one or more lockdown flaps extending beyond the edges of said upper cavity, such that after said beam steering means is deflected to said predetermined orientation within said upper cavity, said lockdown flaps are deflected downwards into said upper cavity until they adhere to said upper cavity wall by said surface forces, thereby preventing said beam steering means from deflecting upwards due to direct mechanical interference with said lockdown flaps.

30. The apparatus according to Claim 29 wherein said self solder means is provided on said lockdown flaps.

31. The apparatus according to Claim 23 wherein said mechanical locking means includes an incomplete anisotropic etch of said upper cavity wherein the floor of said upper cavity is etched to a predetermined depth such that mechanical interference between a fully deflected said beam steering means and said floor defines said predetermined orientation.

32. The apparatus according to Claim 31 wherein said self solder means is provided on distal end of said beam steering means.

33. A method for aligning an optical element within a cavity comprising:
providing substrate and a sacrificial pad disposed on a lower surface of said substrate for delineating an approximate extent of a lower most dimensions of said lower cavity;
depositing an etch resistant film over said sacrificial pad;
forming a hole through said etch resistant film, substantially centered on said sacrificial pad, said hole having a lateral dimensions sufficient to receive at least a portion of said optical element;
removing said sacrificial pad; and
etching said lower cavity to form a rim of said etch resistant film that substantially confines said optical element inserted therein.

34. A method for aligning and fixing an optical element with respect to a cavity of a substrate, comprising:
bonding said optical element to a cover plate with a predetermined orientation;
aligning said cover plate with respect to a surface of said substrate and said cavity; and
bonding said cover plate to said surface of said substrate.

35. A method for aligning and fixing an optical element within a cavity of a substrate, comprising:
providing a cover plate;

forming a hole within said cover plate, said hole having a lateral dimensions sufficient to receive at least a portion of said optical element;

bonding said optical element at least partially withing said hole;

aligning said cover plate with respect to a surface of said substrate and said cavity; and

bonding said cover plate to said surface of said substrate.

36. A method for thermally bonding a first microfabricated component to a second microfabricated component, comprising:

providing said first microfabricated component with a first surface and said second microfabricated component with a second surface;

micro-depositing and patterning a thermal adhesive material at a juncture site of the first surface and the second surface;

exposing said first surface and said second surface to a thermal environment for a sufficient time to form a mechanical bond between said first surface to said second surface.

37. A method for electrothermally bonding a first microfabricated component to a second microfabricated, comprising:

providing said first microfabricated component with a first surface and said second microfabricated component with a second surface;

micro-depositing and patterning a thermal adhesive material at a juncture site of the first surface and the second surface;

positioning an electrically addressable heater means adjacent to and in thermal communication with said thermal adhesive material; and passing sufficient current through one or more said electrically addressable heater means to form a mechanical bond between said first surface to said second surface.

38. A method for fabricating a hinge means coupled to a suspended plate, comprising:

providing an etchable substrate having a substrate surface,

depositing a first thickness of a high fatigue strength material on said substrate surface;

depositing an etch resistant mask on said material and creatingopenings over a hinge area;

etching said hinge area to a second thickness in said material, such that subsequent to an underetch of said plate, said hinge area is sufficiently stiff to prevent surface force induced sticking of said plate to said substrate;

removing said first etch resistant mask;

depositing a second etch resistant mask on said substrate with openings over areas defining free edges of said plate;

etching said free edges of said plate down to said substrate surface;

etching said substrate to form a cavity beneath said plate; and

dry etching said substrate, plate and said hinge area until said hinge area is etched below said substrate surface to a third predetermined thickness and a hinge is formed, wherein said plate with said first predetermined thickness is freely suspended above said cavity and integrally connected to said hinge, and said hinge is coupled to said material at a perimeter of said cavity.

39. A method for fabricating a hinge means coupled to a suspended plate, comprising:

providing an etchable substrate with a substrate surface and a sacrificial pad disposed on said surface of said substrate for delineating an approximate extent of said plate;

depositing a first layer with a first thickness of a high fatigue strength material on said substrate;

depositing an etch resistant mask on said material and creating openings over a hinge area;

etching said hinge area to a second thickness, such that subsequent to an underetch of said plate, said hinge area is sufficiently stiff to prevent surface force induced sticking of said plate to said substrate;

removing said first etch resistant mask;

depositing a second etch resistant mask on said substrate with openings over areas defining free edges of said plate;

etching said free edges of said plate down to said substrate;

removing said sacrificial pad;

etching said substrate to form a cavity adjacent to said plate to produce an intermediate structure; and

etching said intermediate structure until said hinge area is etched below said substrate surface to a third predetermined thickness and forming a hinge, wherein said plate of said first thickness is freely suspended above said cavity and coupled to said hinge, said hinge being coupled to said material of said first thickness disposed about a perimeter of said cavity.

40. A method for fabricating a hinge means coupled to a suspended plate, comprising:
providing an etchable substrate;
depositing a first layer with a first thickness of a high fatigue strength material on said substrate;
patterning an electrically conductive film over the substrate;
depositing an etch resistant mask on said material and creating openings over a hinge area;
etching said hinge area to a second thickness, such that subsequent to an underetch of said plate, said hinge area is sufficiently stiff to prevent surface force induced sticking of said plate to said substrate;
removing said first etch resistant mask;
depositing a second etch resistant mask on said substrate with openings over areas defining free edges of said plate;
etching said free edges of said plate down to said substrate;
etching said hinge areas to a third predetermined thickness, such that subsequent to an underetch of said plate, said hinges are sufficiently stiff to prevent surface force induced sticking of said plate to said substrate;
removing said first etch resistant mask;
depositing a second etch resistant mask on said substrate with openings over areas defining free edges of said plate;
etching said free edges of said plate down to said substrate;
etching said substrate to form a cavity adjacent to said plate to produce an intermediate structure; and
etching said intermediate structure until said hinge area is etched below said substrate surface to a third predetermined thickness and forming a hinge, wherein said plate of said first thickness is freely suspended above said cavity and coupled to said hinge, said hinge being coupled to

said material of said first thickness disposed about a perimeter of said cavity and an electrical path is provided across said hinge.

41. A method for fabricating a hinge means for a suspended plate with integral, arbitrarily thin conductive hinges comprising the steps of:

providing an etchable substrate with a substrate surface and a sacrificial pad disposed on said surface of said substrate for delineating an approximate extent of said plate;

depositing a first layer with a first thickness of a high fatigue strength material on said substrate;

patterning an electrically conductive film over the substrate;

depositing an etch resistant mask on said material and creating openings over a hinge area;

etching said hinge area to a second thickness, such that subsequent to an underetch of said plate, said hinge area is sufficiently stiff to prevent surface force induced sticking of said plate to said substrate;

removing said first etch resistant mask;

depositing a second etch resistant mask on said substrate with openings over areas defining free edges of said plate;

etching said free edges of said plate down to said substrate;

etching said hinge areas to a third predetermined thickness, such that subsequent to an underetch of said plate, said hinges are sufficiently stiff to prevent surface force induced sticking of said plate to said substrate;

removing said first etch resistant mask;

depositing a second etch resistant mask on said substrate with openings over areas defining free edges of said plate;

etching said free edges of said plate down to said substrate;

removing said sacrificial pad;

etching said substrate to form a cavity adjacent to said plate to produce an intermediate structure; and

etching said intermediate structure until said hinge area is etched below said substrate surface to a third predetermined thickness and forming a hinge, wherein said plate of said first thickness is freely suspended above said cavity and coupled to said hinge, said hinge being coupled to said material of said first thickness disposed about a perimeter of said cavity and an electrical path is provided across said hinge.

42. A beam steering apparatus, comprising:

a reflective means;

a constraint means coupled to said reflective means to constrain movement of the reflective means in one or more degrees of freedom; and

an independently addressable electrode configured to position said reflective means.

43. The apparatus of claim 42, wherein the constraint means constrains movement of the reflective means in two degrees of freedom.

44. The apparatus of claim 42, wherein the constraint means includes one or more elastically deformable members.

45. The apparatus of claim 42, wherein the apparatus is a laser printer engine and further comprises:

a control means coupled to said addressable electrode.

46. The apparatus of claim 42, wherein the apparatus is an optical storage head and further comprises:
a control means coupled to said addressable electrode.

47. The apparatus of claim 42, wherein the apparatus is a bar rastering projector and further comprises:
a control means coupled to said addressable electrode.

48. The apparatus of claim 42, wherein the apparatus is a laser plotter and further comprises:
a control means coupled to said addressable electrode.

49. The apparatus of claim 42, wherein the apparatus is a laser marking writing tool and further comprises:
a control means coupled to said addressable electrode.

50. The apparatus of claim 42, wherein the apparatus is a laser cutting apparatus and further comprises:
a control means coupled to said addressable electrode.

51. The apparatus of claim 42, wherein the apparatus is a surgical laser knife and further comprises:
a control means coupled to said addressable electrode.

52. The apparatus of claim 42, wherein the apparatus is an optical switch and further comprises:
a control means coupled to said addressable electrode.

53. The apparatus of claim 42, further comprising:
an electronic control means coupled with said addressable electrode.

54. The apparatus of claim 53, wherein said reflective means is provided with a conductive film surface in communication with said electronic control means.

55. The apparatus of claim 42, wherein the constraint means is a gimbaled hinge means.

56. The apparatus of claim 42, wherein the constaint means is a cantilevered hinge means.

57. The apparatus of claim 42, wherein the constraint means is a gimbaled and cantilevered hinge means.

58. The apparatus of claim 42, wherein the constraint means is a compliant medium means.

59. The apparatus of claim 42, wherein said reflective means is moveably constrained in relation to said electrode.

60. The apparatus of claim 42, wherein said reflective means is deformable.

61. The apparatus of claim 42, wherein the beam steering means is at least partially micromachined.

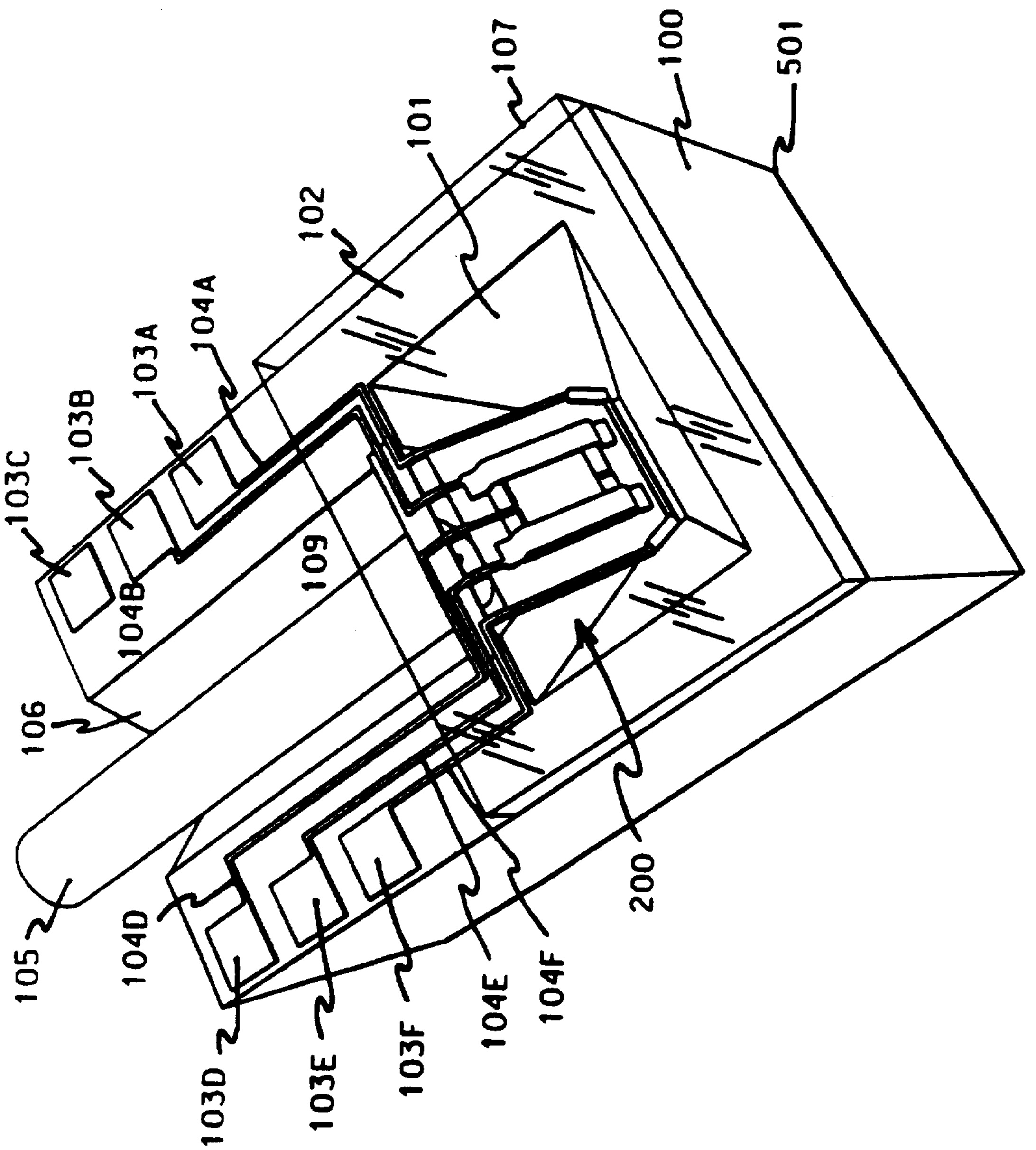

103C
103B
103A
104A
102
101
107
100
501
109
104B
106
105
104D
103D
103E
103F
104E
104F
200

FIGURE 1

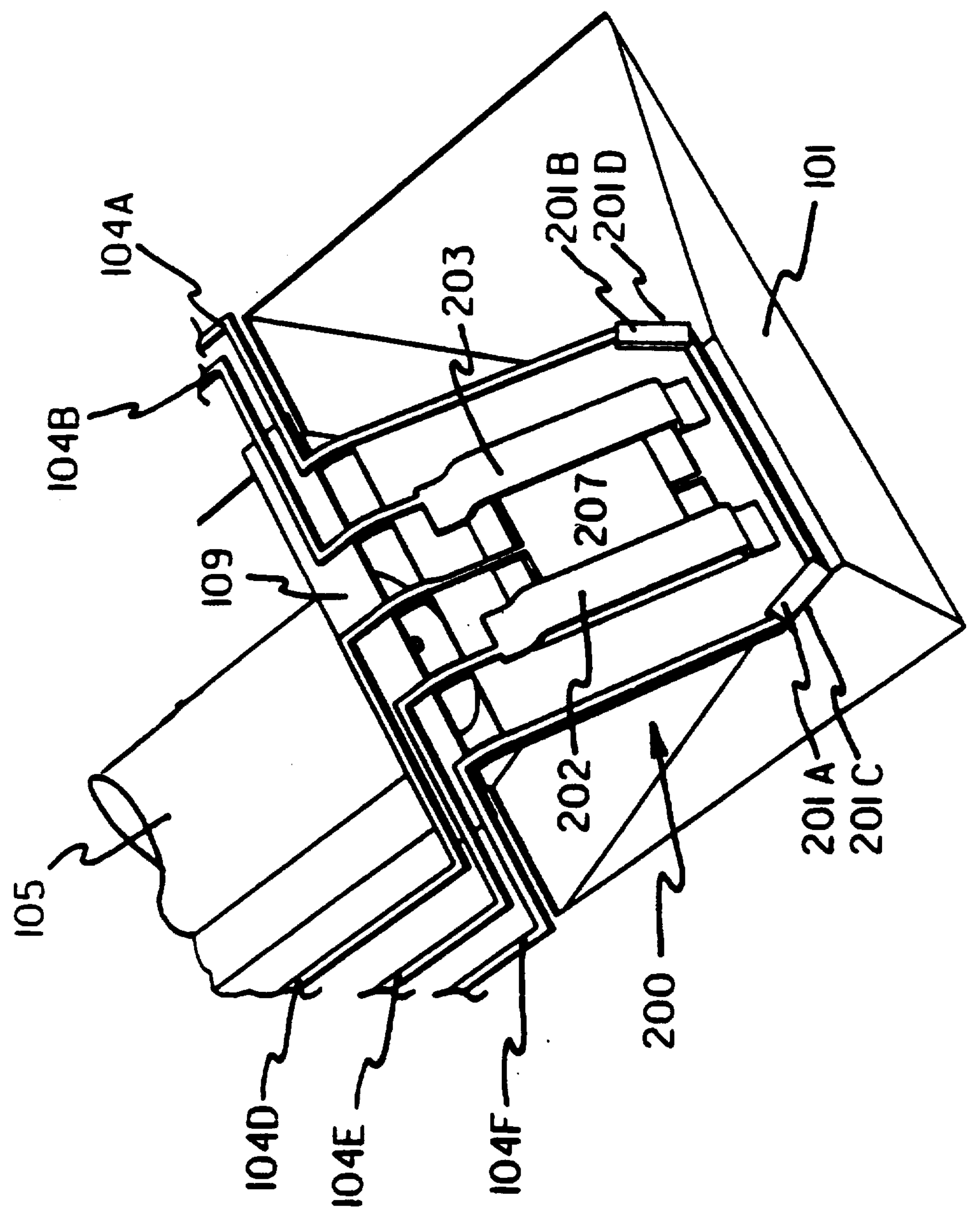
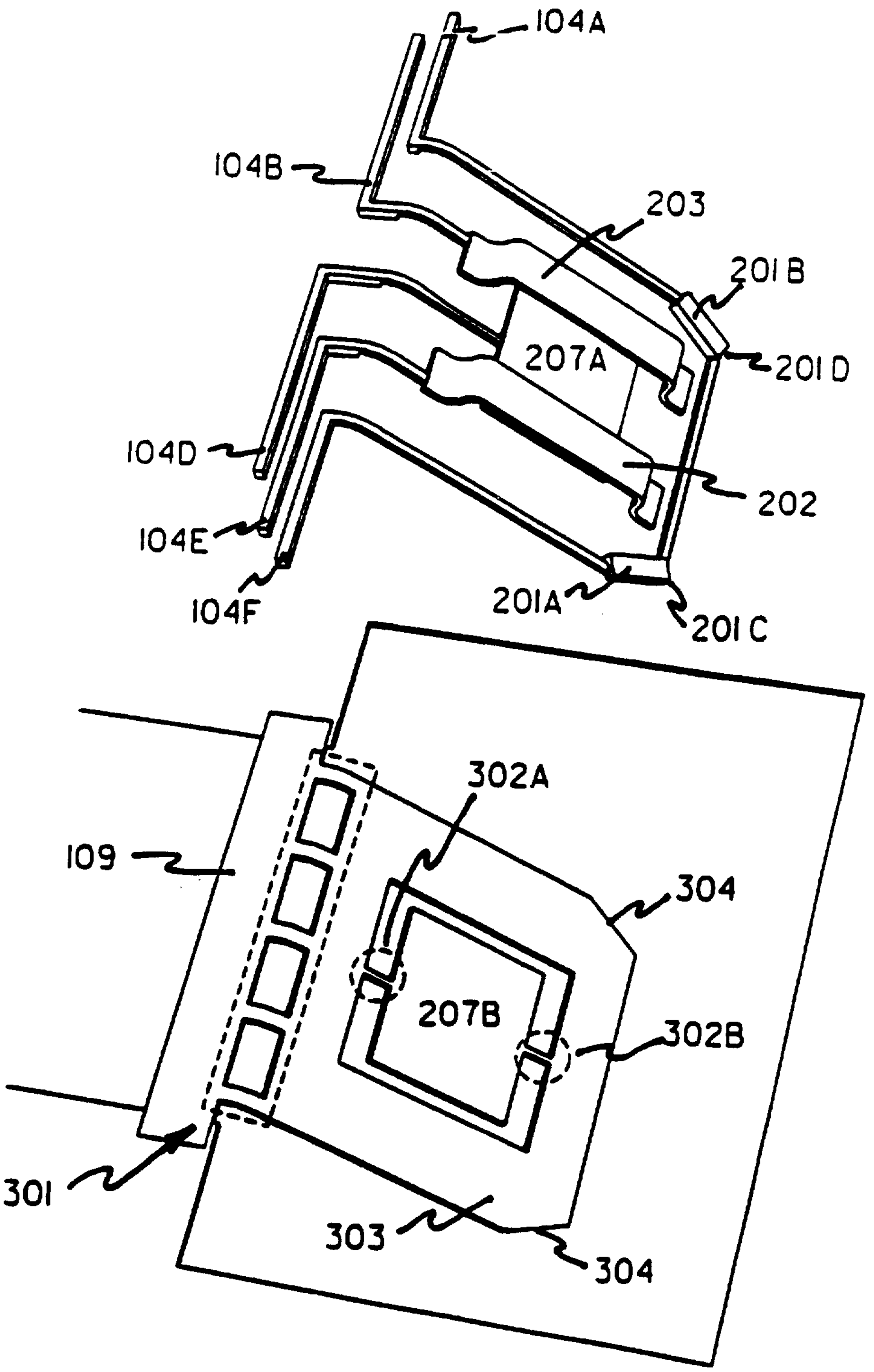

104A
104B
109
105
203
201B
201D
101
207
202
201A
201C
200
104D
104E
104F

FIGURE 2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104B
203
201B
207A
201D
104D
202
104E
104F
201A
201C
302A
109
304
207B
302B
301
303
304

FIGURE 3

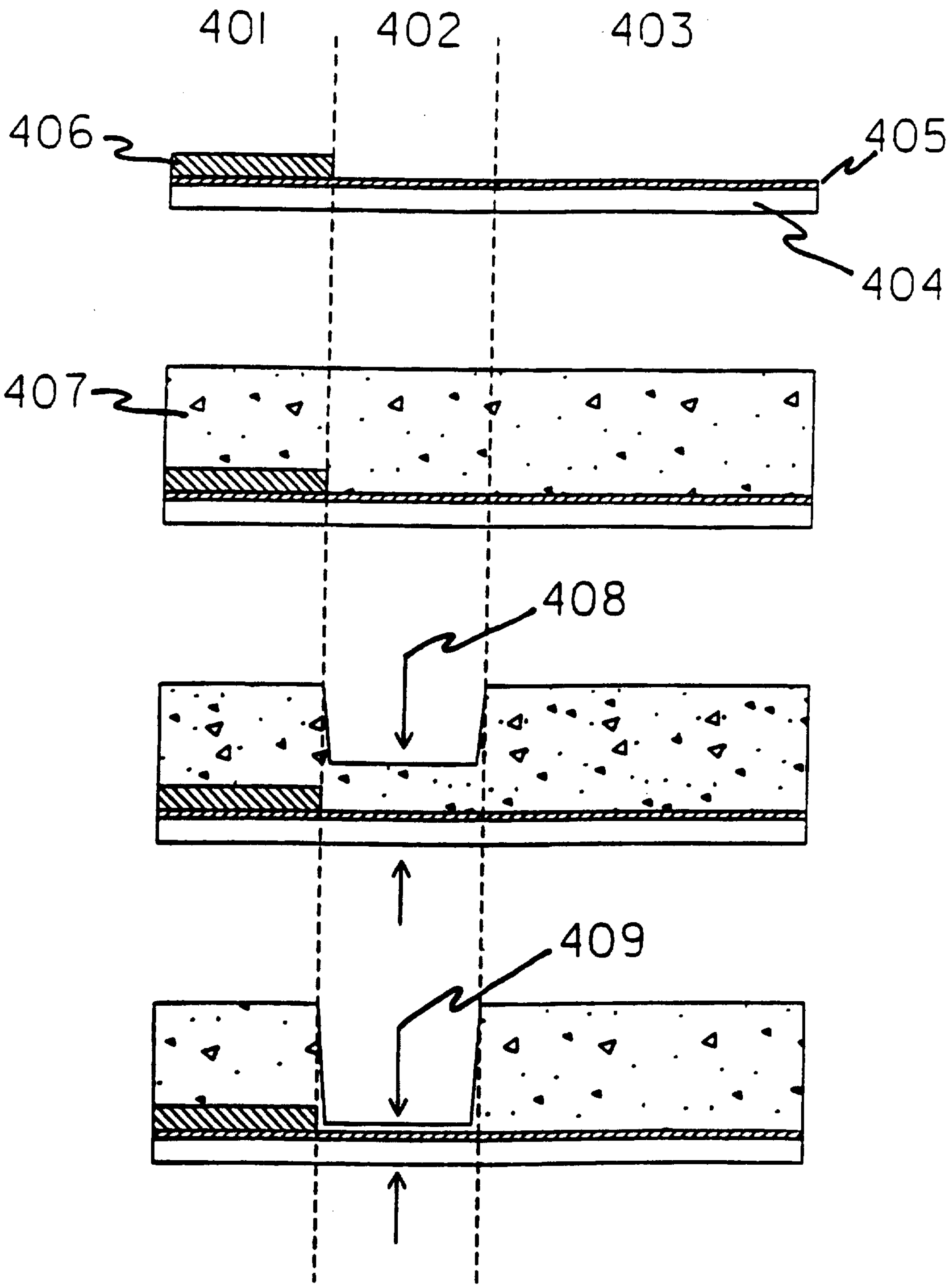

FIGURE 4

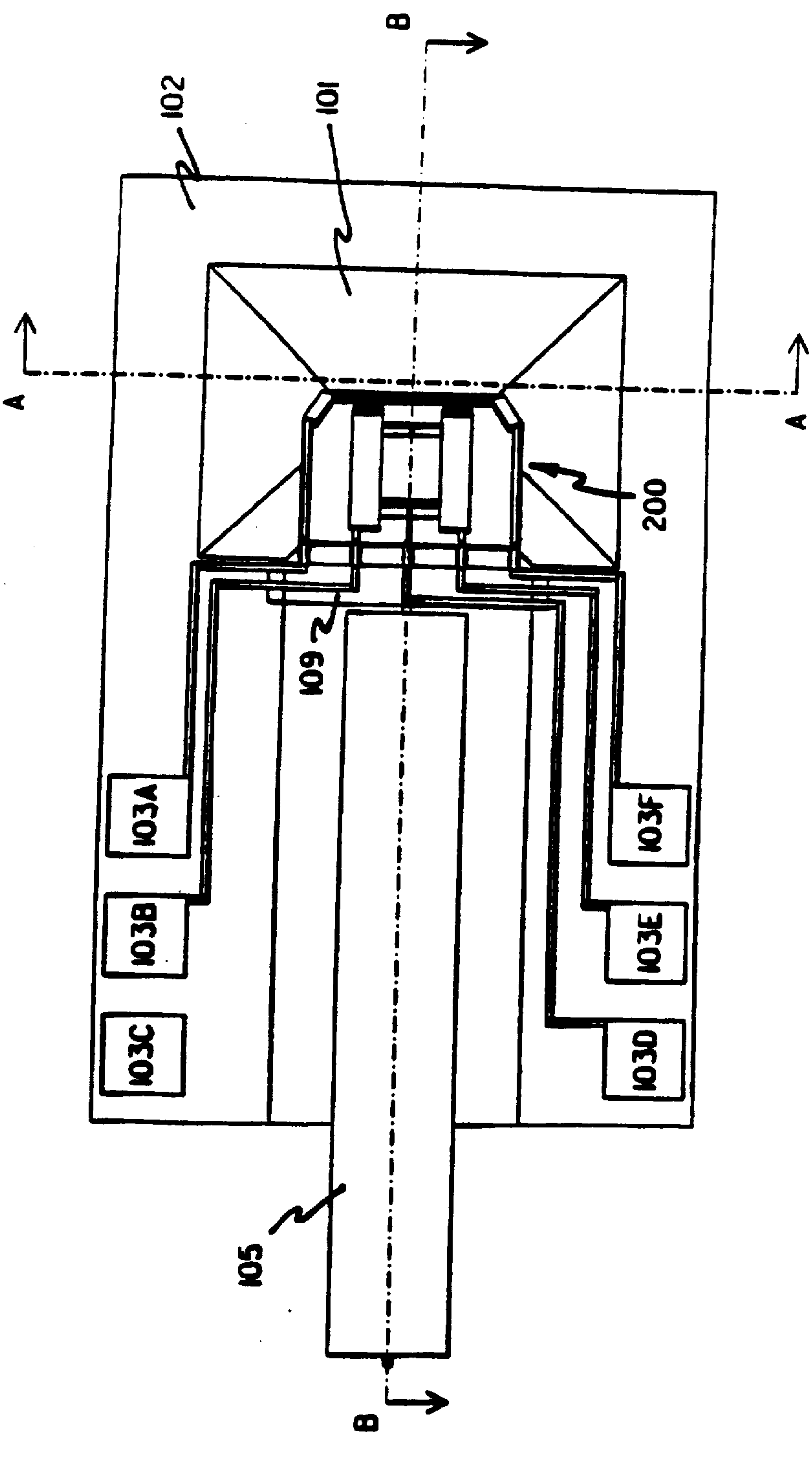

FIGURE 5

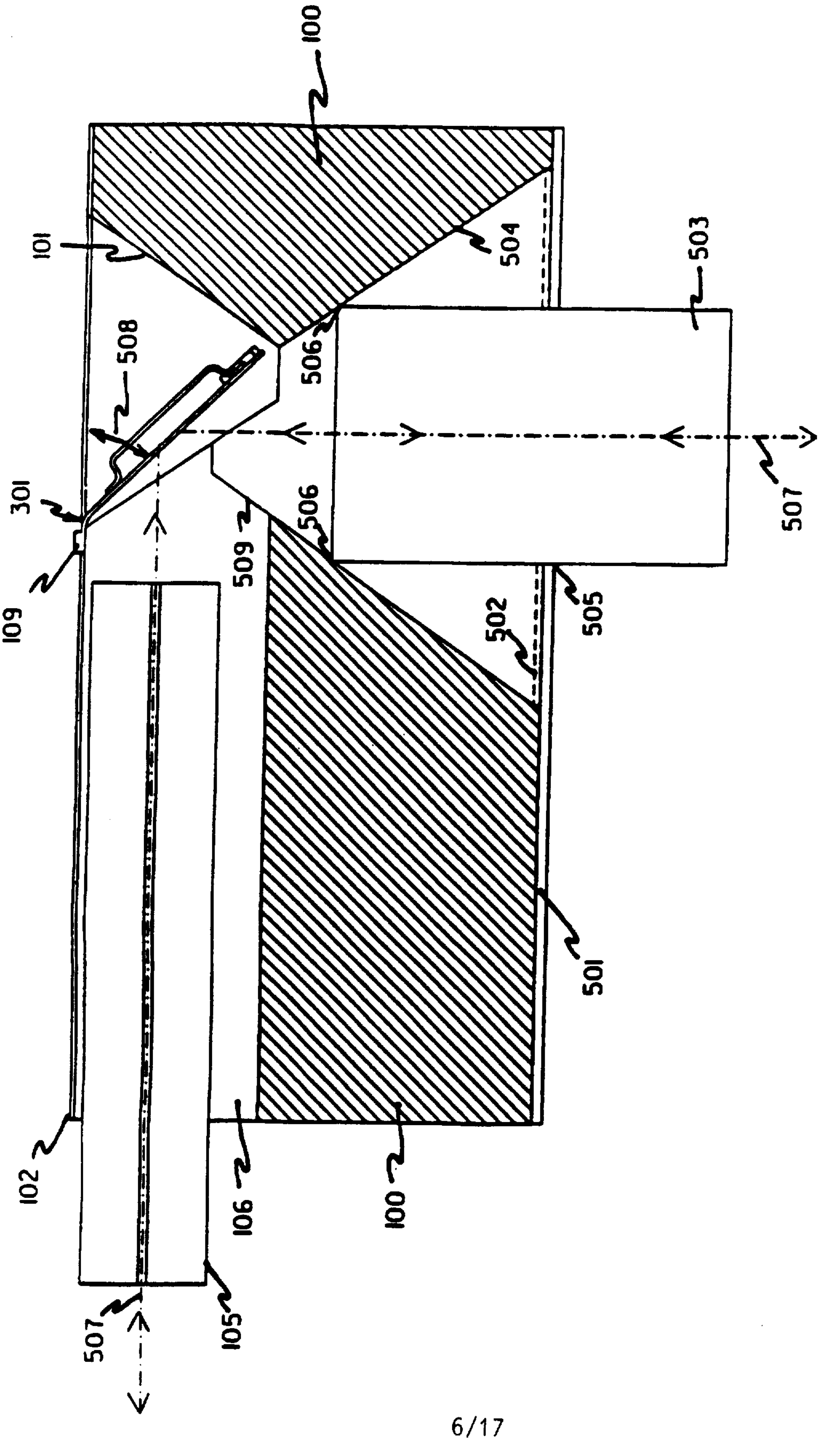

FIGURE 6

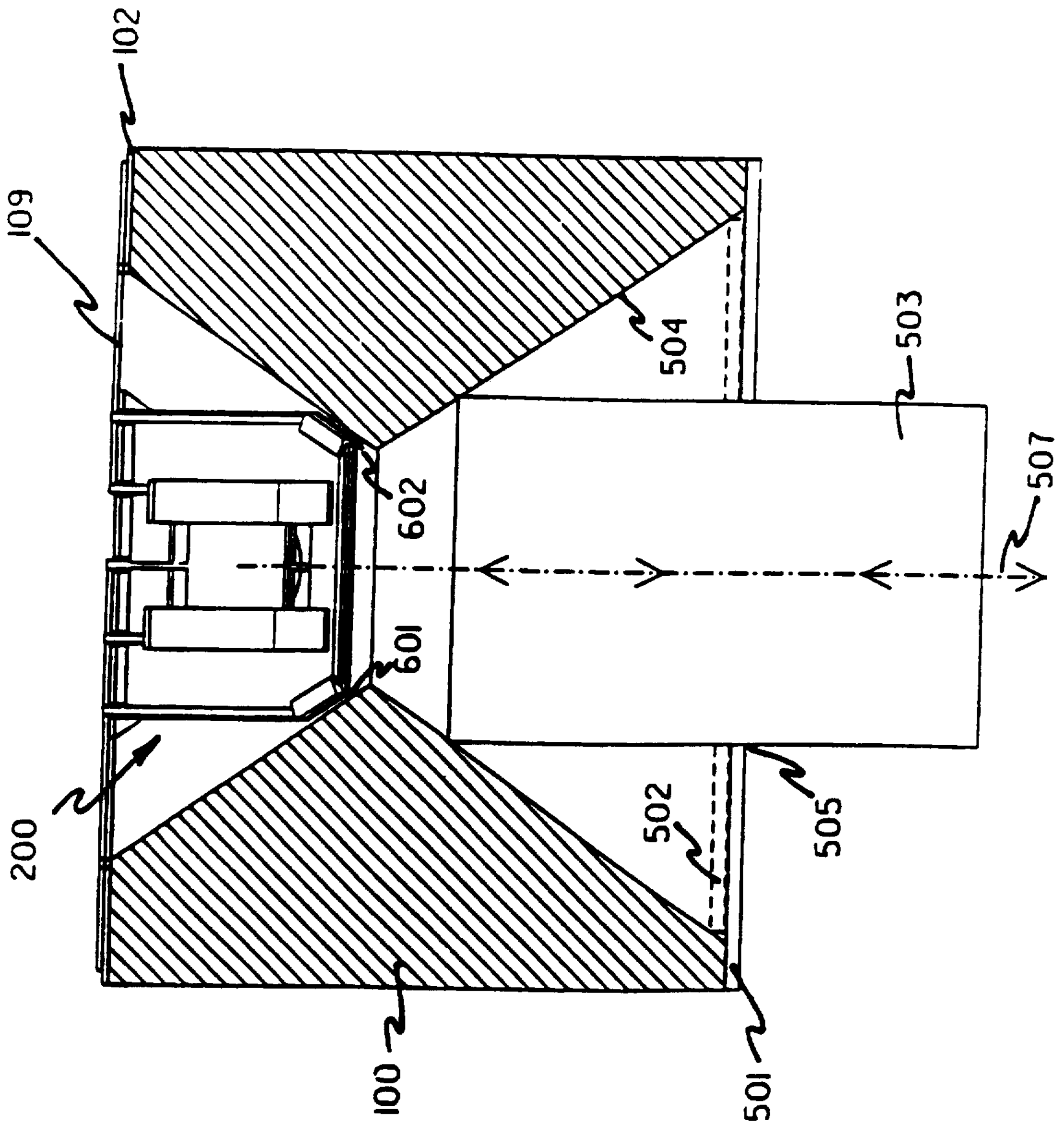

FIGURE 7

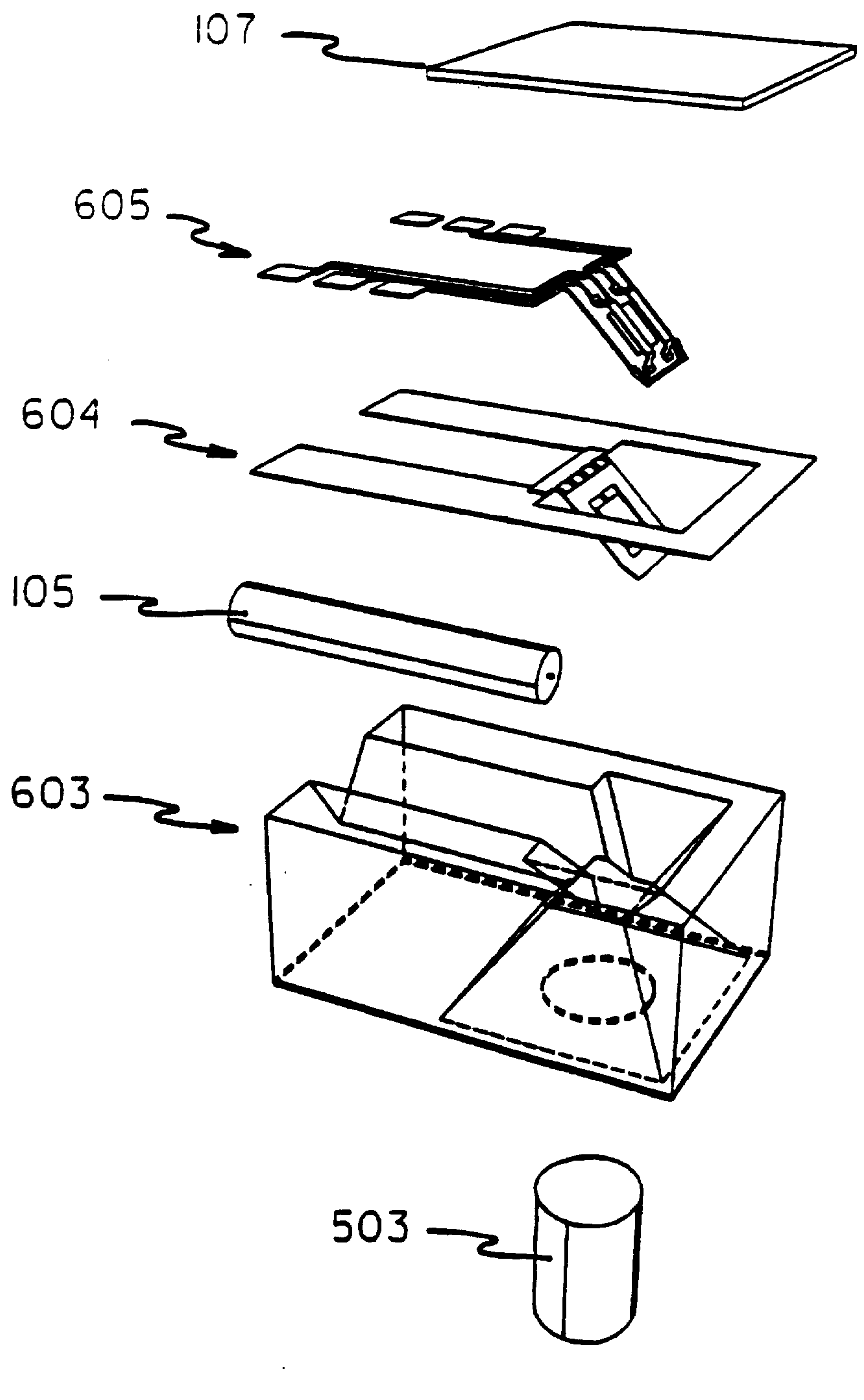

FIGURE 8

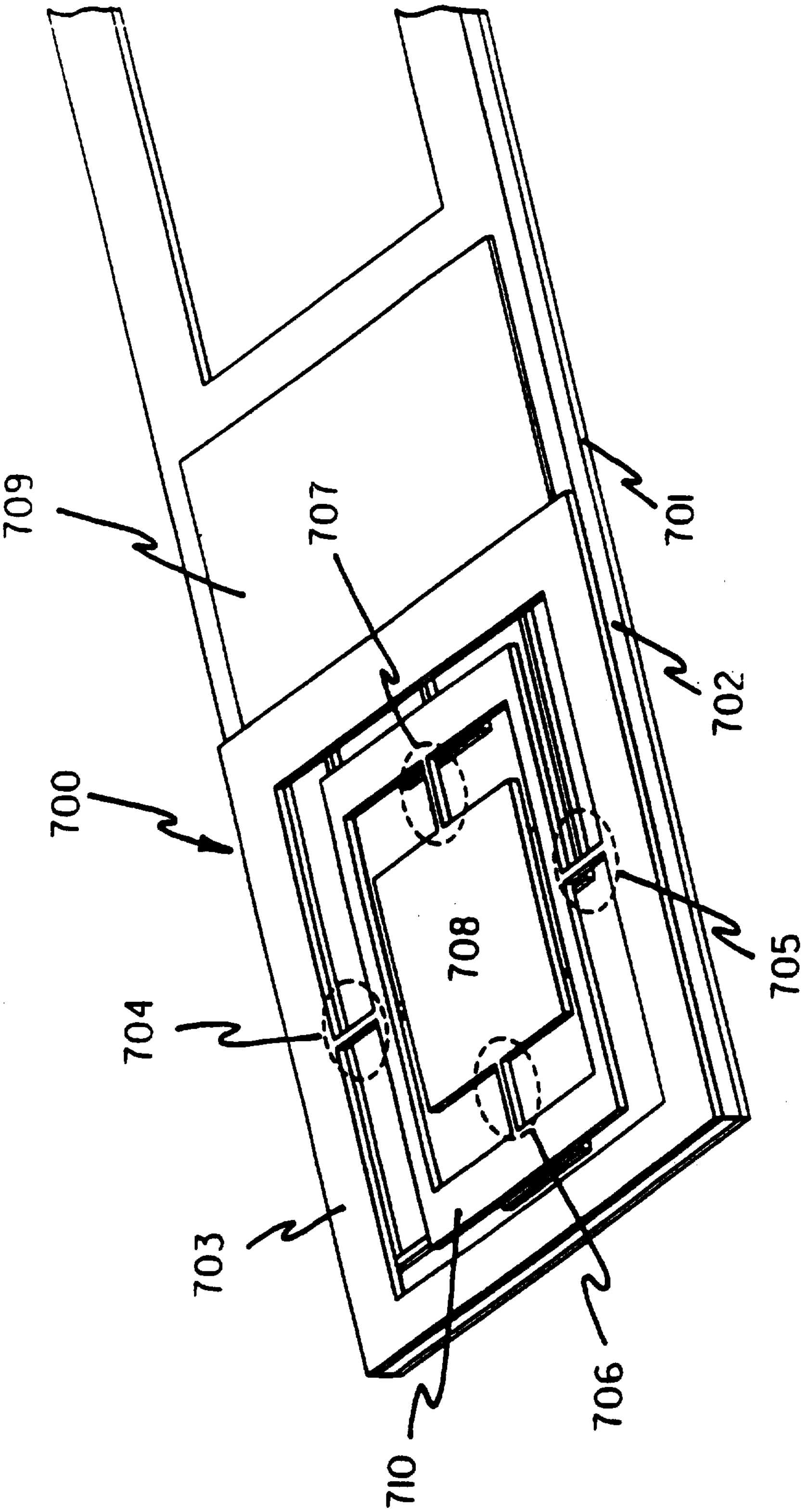

FIGURE 9

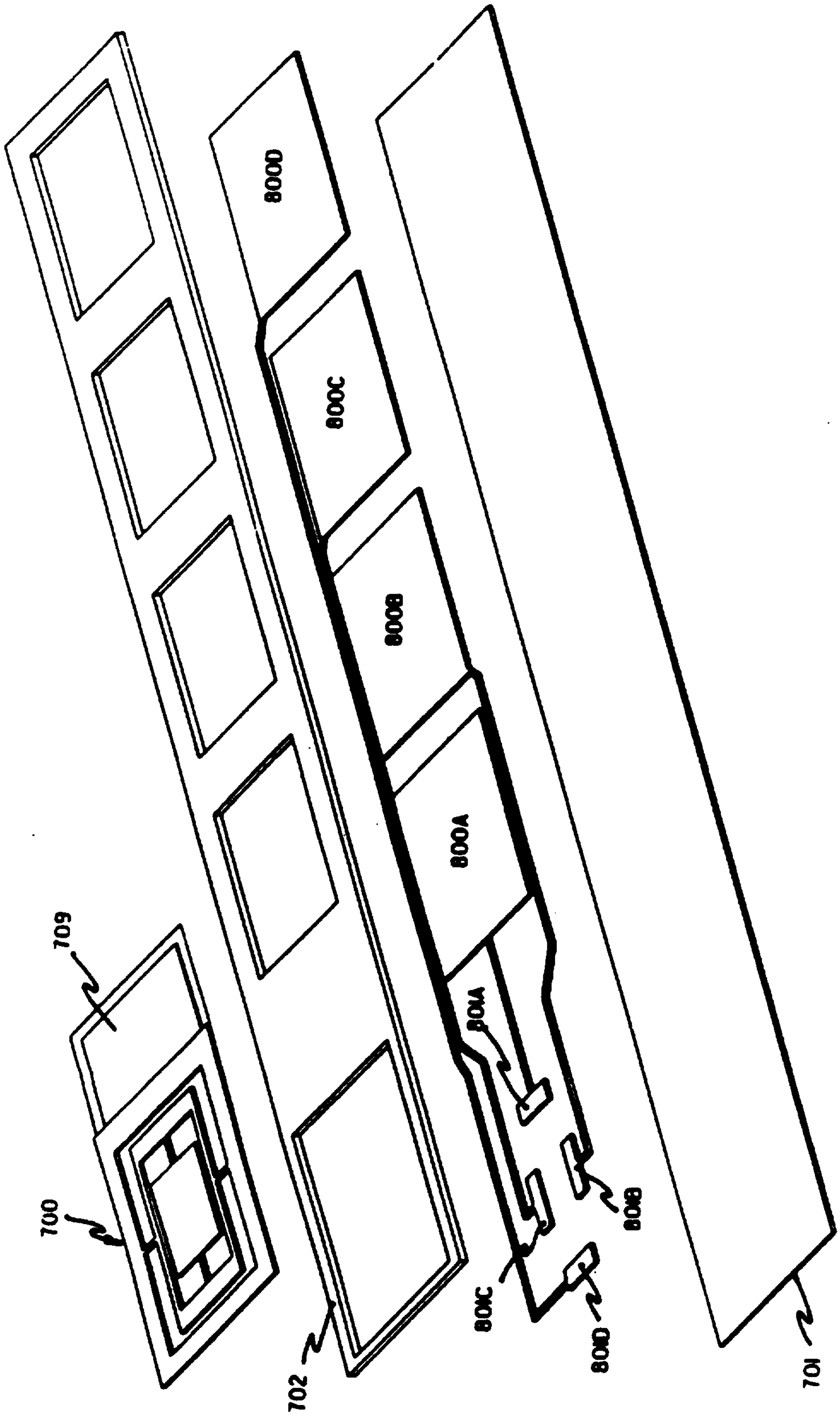

FIGURE 10

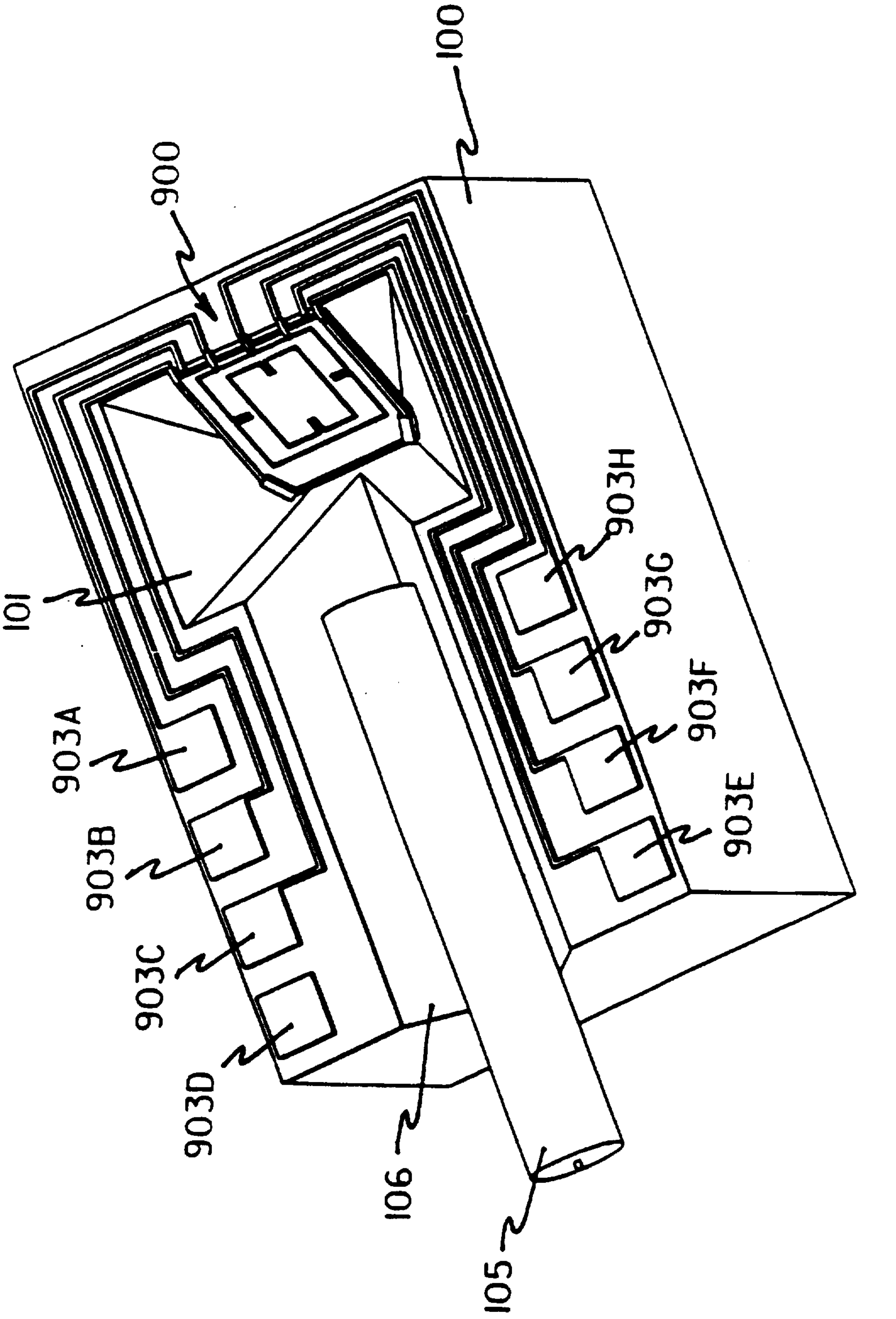

FIGURE 11

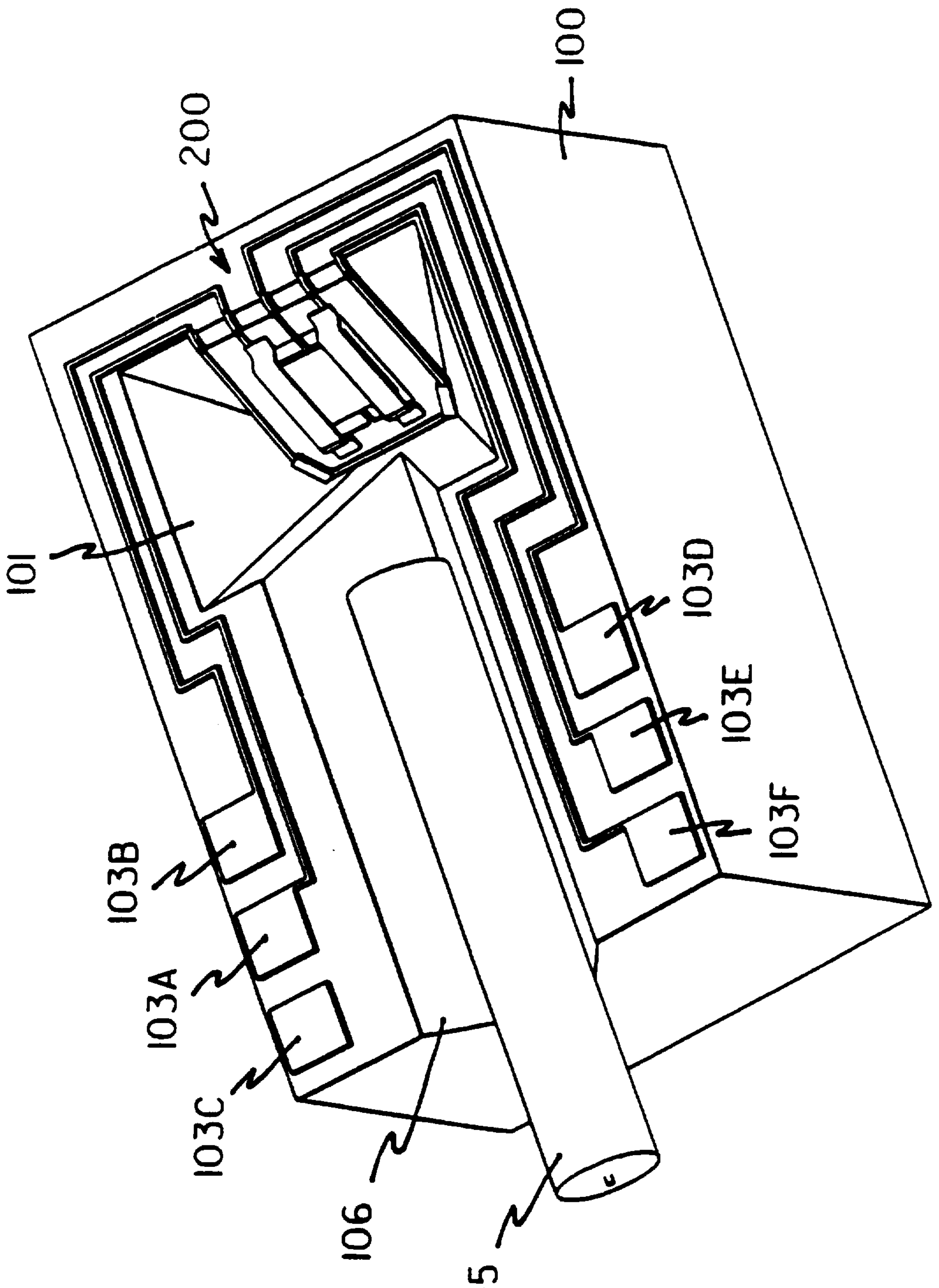

FIGURE 12

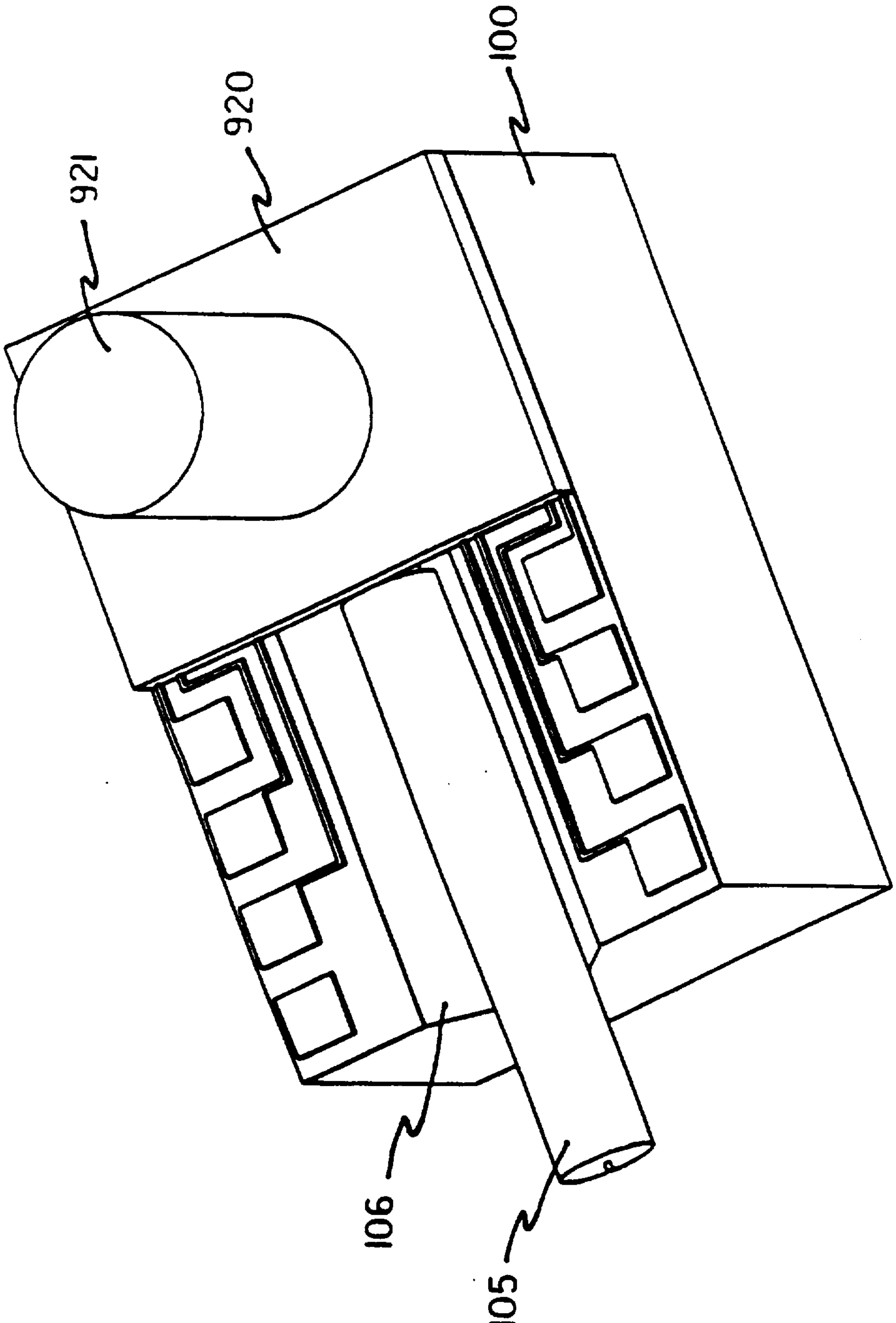

FIGURE 13

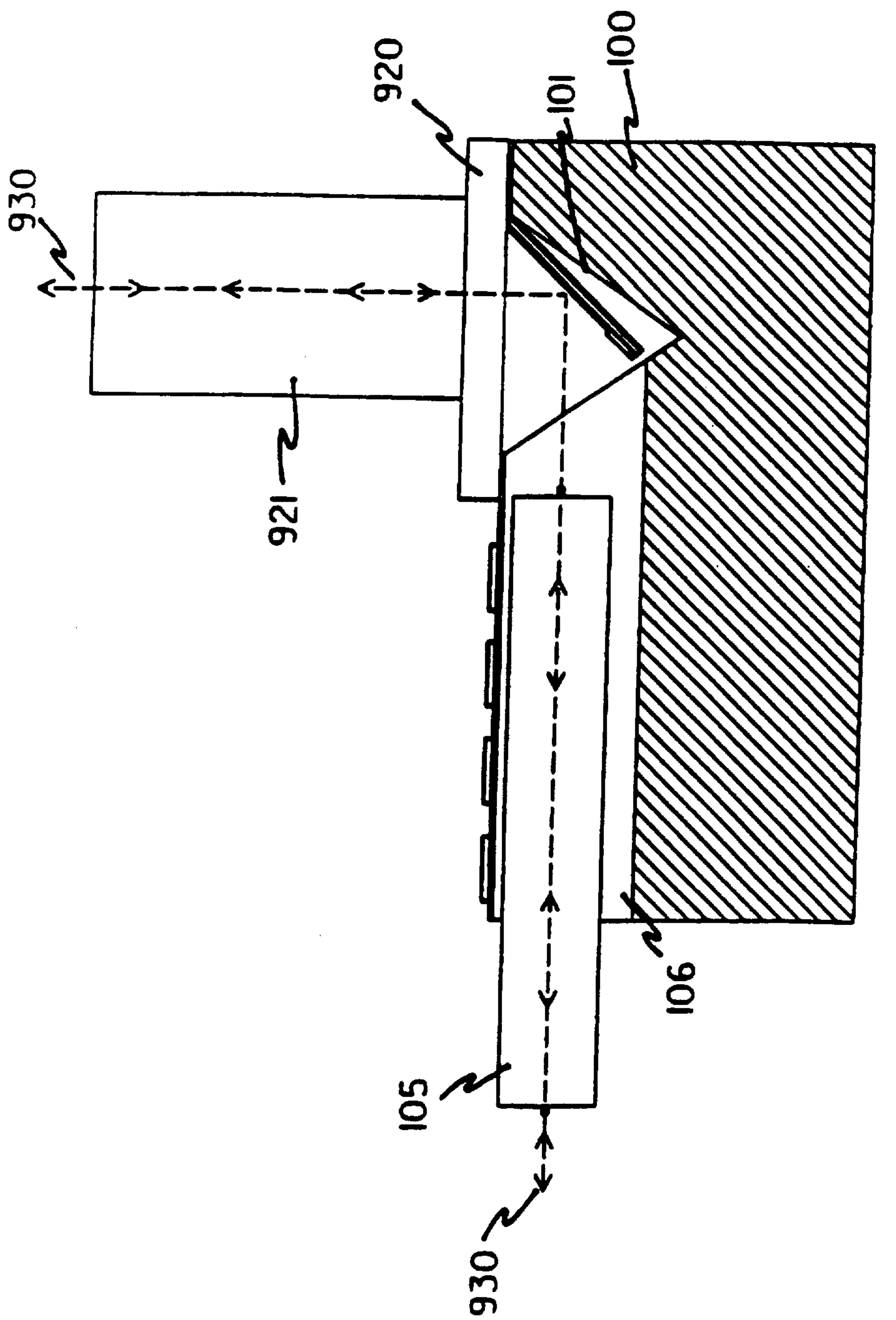

FIGURE 14

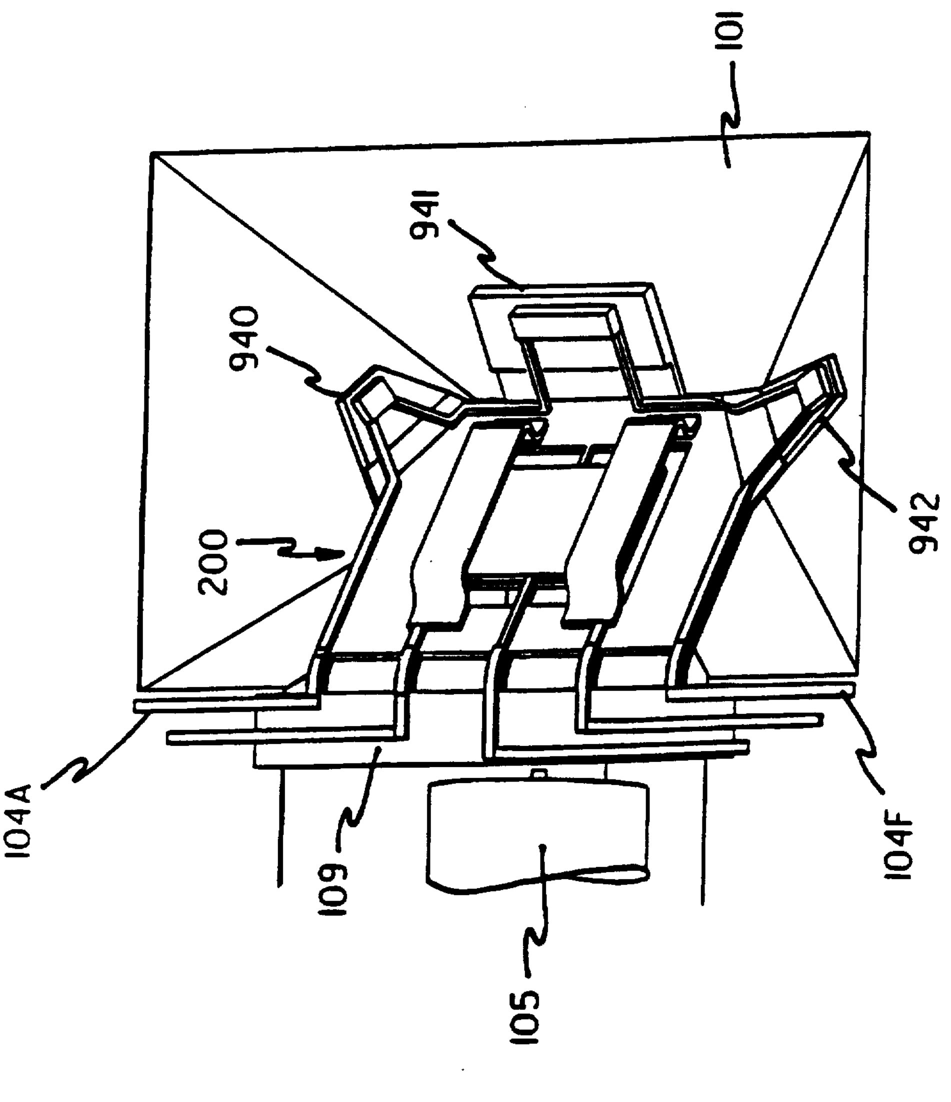

FIGURE 15

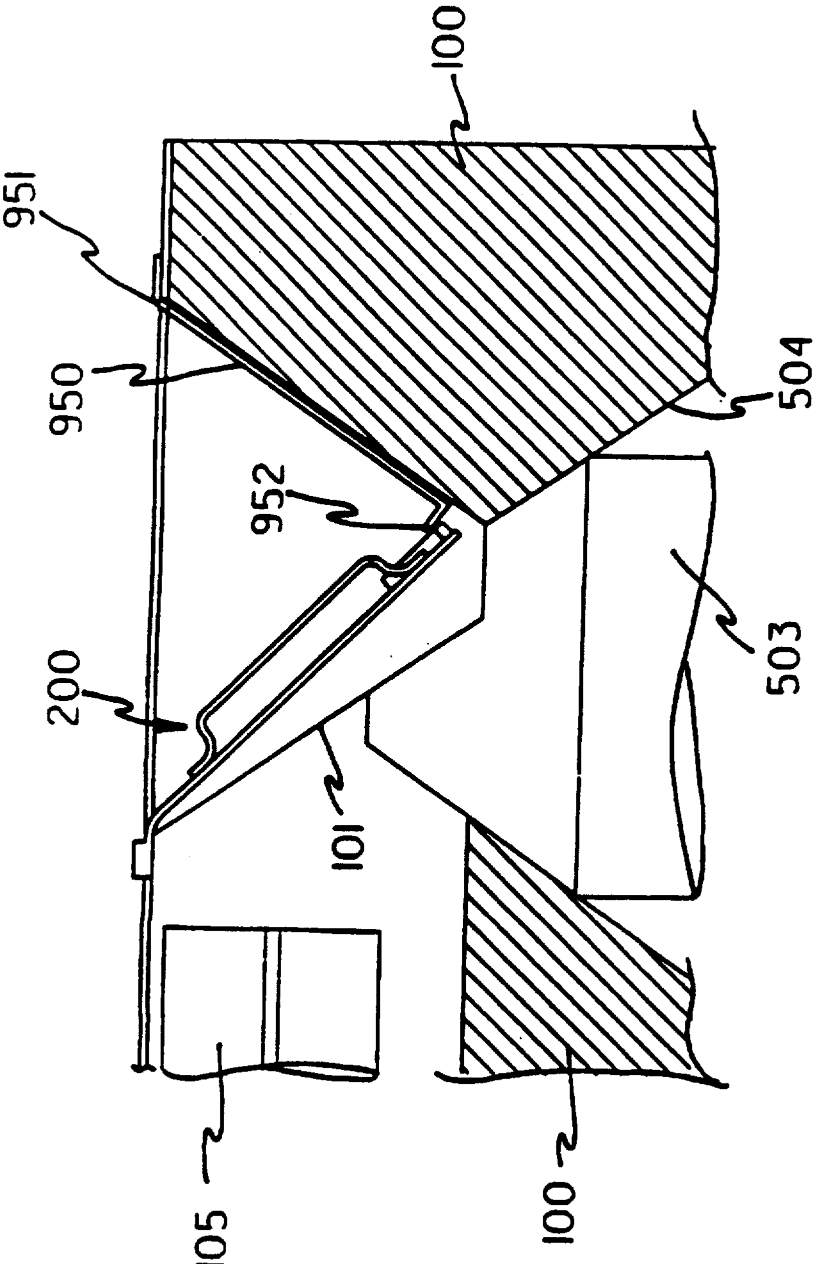

FIGURE 16

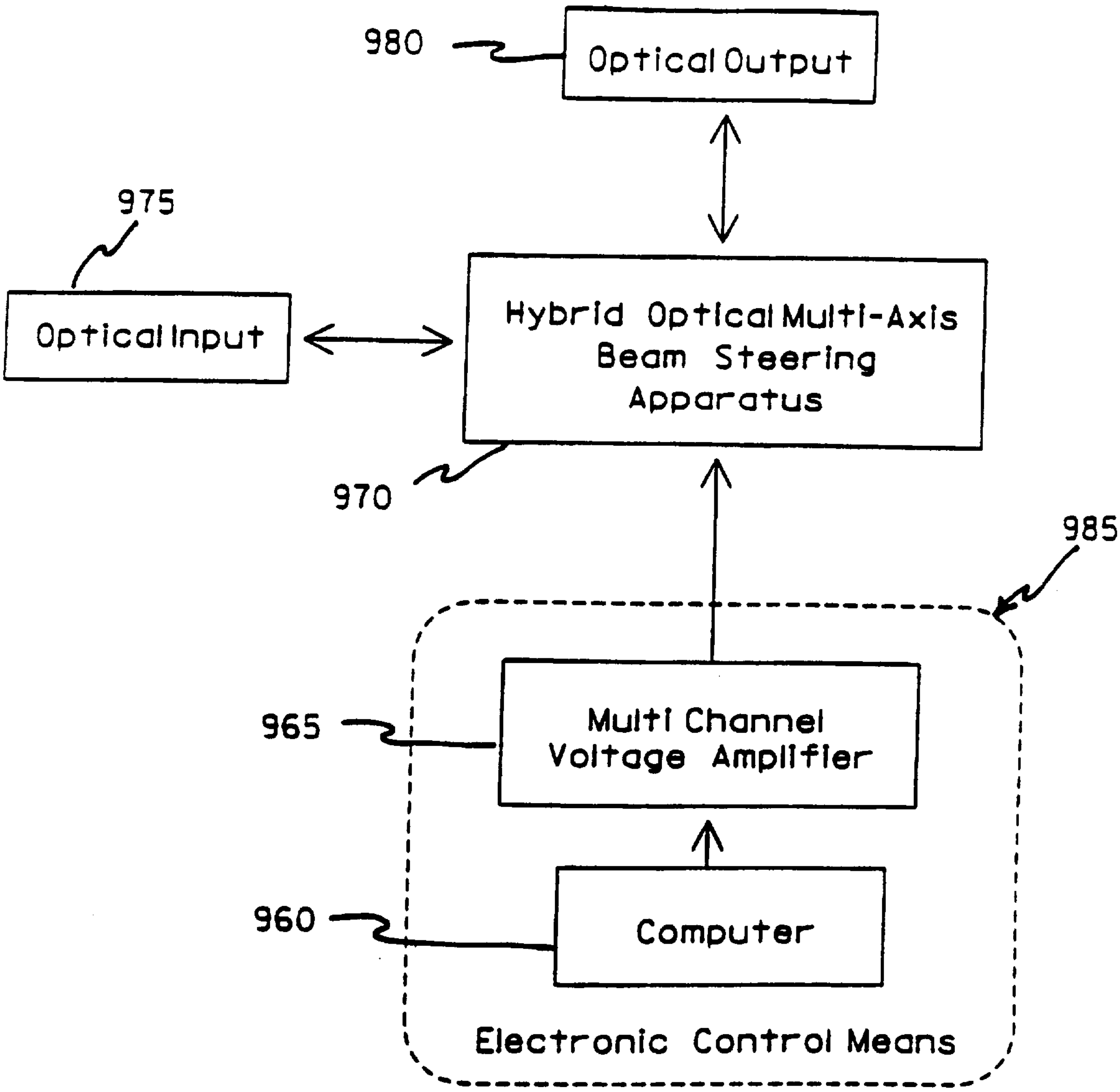
980
Optical Output
975
Optical Input
Hybrid Optical Multi-Axis
Beam Steering
Apparatus
970
985
965
Multi Channel
Voltage Amplifier
960
Computer
Electronic Control Means

FIGURE 17

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 97/11557

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B26/08

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)
IPC 6 G02B G06K H01S

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)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 650 133 A (SYMBOL TECHNOLOGIES INC) 26 April 1995	1-11,15, 16,42, 44,53, 54,56, 59-61
A	see column 2, line 46 - column 6, line 57 see column 7, line 29 - column 9, line 35; figures 1-6,8-13	12-14, 17-25, 31, 33-37, 43, 45-52, 55,57,58
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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"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

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"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
24 November 1997	09/12/1997

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	THEOPISTOU, P

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X A	WO 95 13638 A (IBM ;GERMANN ROLAND (CH); HAUSSER STEFAN (CH); VETTIGER PETER (CH)) 18 May 1995 see page 3, paragraph 4 - page 9, paragraph 3; figures 1-7	1-9,15, 16,42, 45-49, 52-54, 56,59,61 12-14, 17-23, 25,33-35
A	EP 0 331 331 A (AMERICAN TELEPHONE & TELEGRAPH) 6 September 1989 see column 2, line 13 - column 9, line 38; figures 1-11	1-24, 33-37, 42-54,61
A	US 5 325 116 A (SAMPSELL JEFFREY B) 28 June 1994 cited in the application see column 2, line 46 - column 7, line 33; figures 1-7	1-25, 33-37, 42-61
A	US 5 448 546 A (PAULI GILES A) 5 September 1995 cited in the application see column 2, line 67 - column 6, line 55; figures 1-3	1-9, 12-25, 42-61
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A	US 5 504 614 A (WEBB DOUGLAS A ET AL) 2 April 1996 cited in the application see column 4, line 3 - column 7, line 21; figures 1-4,7-9	38-48, 52-61

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International Application No
PCT/US 97/11557

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