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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification [6] :
G02B 6/42, 6/32, 6/255, 7/00, H01L 41/00

A1

(11) International Publication Number: WO 98/12587

(43) International Publication Date: 26 March 1998 (26.03.98)

(21) International Application Number: PCT/US96/15213

(22) International Filing Date: 20 September 1996 (20.09.96)

(60) Parent Applications or Grants
(63) Related by Continuation
US 08/486,242 (CIP)
Filed on 7 June 1995 (07.06.95)
US 08/473,106 (CIP)
Filed on 7 June 1995 (07.06.95)

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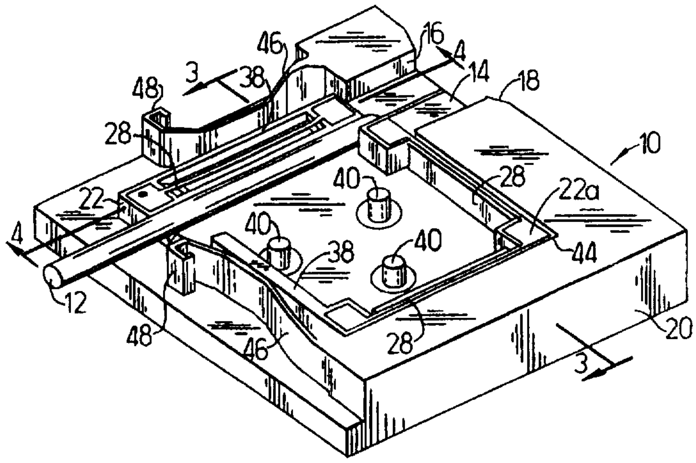
(81) Designated States: AL, AM, AT, AT (Utility model), AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CZ, CZ (Utility model), DE, DE (Utility model), DK, DK (Utility model), EE, EE (Utility model), ES, FI, FI (Utility model), GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SK (Utility model), TJ, TM, TR, TT, UA, UG, US, UZ, VN, ARIPO patent (KE, LS, MW, SD, SZ, UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

**Published**
*With international search report.*

(54) Title: AN ALIGNMENT APPARATUS FOR PRECISELY ALIGNING AN OPTICAL FIBER AND AN ASSOCIATED FABRICATION METHOD




(57) Abstract

An alignement apparatus includes a microactuator (10) for precisely aligning an optical fiber (12) with an optical device (14) includes a carrier (22) having at least one bimorphic actuator (28) which bends or deflects in response to electrical stimuli to thereby controllably position the carrier and, in turn, an optical fiber mounted on the carrier, with an optical device, such as a laser diode. The bimorphic actuator typically includes first and second layers (28a, 28b) first and second materials, respectively, which respond differently to electrical stimuli. The carrier can also be mounted on an alignment support (20) structure such that upon deflection the bimorphic actuator is urged against a portion of the alignment support structure so as to move the carrier relative to the alignment support structure. Thus, by maintaining the alignment support structure in a fixed relation to the optical device, the carrier and, in turn, the optical fiber mounted on the carrier can be positioned in precise alignment with the optical device. For example, the alignment apparatus can be a fiber optic connector that includes one or more microactuators disposed within a connector housing. The microactuators can be actuated so as to align the optical fibers with respective lens elements (86) that are at least partially disposed within respective apertures defined by the connector housing so as to collimate the optical signals transmitted via the respective optical fibers.

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# AN ALIGNMENT APPARATUS FOR PRECISELY ALIGNING AN OPTICAL FIBER AND AN ASSOCIATED FABRICATION METHOD

## Government Rights

The United States Government has rights in this invention pursuant to a contract awarded by the Department of the Army.

## Field of the Invention

The present invention relates generally to methods and apparatus for controllably positioning an optical fiber and, more particularly, to an alignment apparatus for precisely aligning an optical fiber with an optical device and an associated fabrication method.

## Background of the Invention

It is oftentimes desirable to align optical fibers with an electro-optic device, such as a laser diode. Such alignment is particularly desirable in order to maximize the percentage of light coupled from the light source or electro-optic device to the optical fiber and to thereby increase the transmission efficiency of the optical signals. However, the alignment of optical fibers is complicated by the relatively small sizes of both the optical fiber waveguide, such as a single mode optical fiber which, for example, can have a light transmitting core diameter of approximately 2-10 micrometers, and the light source which has approximately the same size.

The alignment of an optical fiber is further complicated since an optical fiber generally has six degrees of freedom, each of which must be separately aligned. In particular, an optical fiber must generally be aligned in three translational directions, i.e., the X, Y and Z directions, and three rotational directions, i.e., $\theta_x$, $\theta_y$ and $\theta_z$. Furthermore, the alignment of polarization preserving or polarization maintaining optic fibers is complicated by the need to maintain the polarization axis of the optical fibers in alignment with that of the polarized optical system.

Notwithstanding these difficulties, various methods have been proposed to align a single optical fiber with a variety of electro-optic devices. See, for example, U.S. Patent No. 4,955,683 which was issued September 11, 1992, to Nobuo Shiga, et al. and is assigned to Sumitomo Electric Industries, Ltd.; U.S. Patent No. 4,798,439 which was issued January 17, 1989, to Keith Preston and is assigned to British Telecommunications, PLC; U.S. Patent No. 4,741,796 which was issued May 3, 1988, to Hans Althaus, et al. and is assigned to Siemens Aktiengesellschaft; U.S. Patent No. 4,702,547 which was issued October 27, 1987, to R. Scott Enochs and is assigned to Tektronix, Inc.; U.K. Patent Application GB 2,128,768 which was published May 2, 1984, and is assigned to Hitachi Ltd.; and U.K. Patent Application GB 2,146,841 which was published April 24, 1985, and is assigned to Hitachi Ltd.

As illustrated by these patents and known to those skilled in the art, individual metallized optical fibers can be soldered to a support. In order to position the optical fiber, the solder bonding the metallized optical fiber to the support is generally heated to a temperature above the predetermined melting temperature of the solder. Thereafter, the optical fiber can be moved and, once the optical fiber is properly positioned, the solder can be allowed to cool and resolidify to fix the position of the optical fiber relative to the support and, more importantly, to a light source. These systems typically require, however, some means, such as solder, for retaining an optical fiber in place after the optical fiber has been positioned in a separate alignment process, distinct from the means for retaining the optical fiber in position.

In particular, U.S. Patent No. 4,798,439 to Keith Preston (hereinafter the "'439 patent") describes an optical assembly and a related method for mounting optical components, such as an optical fiber, on a substrate. According to the '439 patent, an optical fiber is lowered into a layer of solder, such as a solder preform or a solder paste, which has been applied to a submount assembly. Thereafter, a heating element is lowered into contact with the solder to locally melt the solder about the optical fiber such that the optical fiber can be mounted therein. During the mounting process, a first end of the optical fiber is positioned to receive the output of a laser, also illustratively mounted on the submount assembly. By positioning the optical fiber such that the power level of the light transmitted through the optical fiber is maximized, the optical fiber is appropriately aligned with the laser. Once aligned, the heating element is cooled to allow the solder to solidify and to fix the optical fiber to the submount assembly.

Another method of positioning an optical fiber is described in U.S. Patent No. 4,741,796 to Hans Althaus, et al. (hereinafter the "'796 patent"). In particular, the '796 patent describes a method for aligning an optical fiber with a laser diode. According to this method, an electrically conductive body having a groove defined therein is bonded to a base. An optical fiber extends through the groove and is bonded to the electrically conductive body with a bonding agent. By inducing current flow through the electrically conductive body, the temperature of the electrically conductive body is increased such that the optical fiber is positionable within the bonding agent. After properly positioning the optical fiber relative to the laser diode, the current flow is stopped to cool and solidify the bonding agent, thereby fixing the position of the optical fiber.

While the above-described alignment and bonding systems may controllably position an individual optical fiber, the heat required to allow one optical fiber to be positioned can oftentimes affect the position or alignment of adjacent optical fibers, thereby misaligning the adjacent optical fibers. In addition, these alignment and bonding systems and methods, such as the systems disclosed by the '439 patent and the '796 patent, are generally relatively laborious and time-intensive, particularly, in instances in which a number of optical fibers must be individually aligned.

Accordingly, several commercial alignment systems have been developed to automatically connect, or pigtail, an opto-electronic device, such as a laser diode, to an optical fiber. For example, Melles Griot has developed a system for precisely aligning optical fibers with other optical components. As known to those skilled in the art, however, the Melles Griot alignment system generally includes a variety of relatively complex and costly components which significantly increase the fabrication costs to produce such precisely aligned optical devices. In addition, once the optical fiber has been aligned by a Melles Griot alignment system, the optical fiber must generally be bonded with a separate bonding means, such as solder, as described in the foregoing patents.

One particular application that demands precise alignment of one or more optical fibers involves fiber optic connectors. Fiber optic connectors are commonly employed to align and to interconnect one or more optical fibers with a variety of optical devices or with other optical fibers. For example, fiber optic connectors can be mounted on end portions of a pair of fiber optic cables, each of which include a number of optical fibers. The optical fibers of the fiber optic cables can, for example, transmit data or control signals between various remote devices, such as sensors or actuators, and a central control computer, such as a flight controller of an aircraft. The fiber optic connectors can then be interconnected such that the optical fibers of a first fiber optic cable are aligned with the optical fibers of a second fiber optic cable.

In order to efficiently transmit signals between optical fibers, the fiber optic connectors must precisely align the individual optical fibers such that the optical signals transmitted therethrough are efficiently coupled from fiber to fiber. Such alignment is particularly essential in connecting single mode optical fibers which must be precisely aligned with the light-transmitting core of another single mode optical fiber of similar size in order to efficiently transmit optical signals therethrough.

In order to effectively couple optical signals from fiber to fiber, a fiber optic connector must maintain the precise alignment of the individual optical fibers in a predetermined manner such that the optical fibers will remain aligned as the fiber optic connecter is mated with another fiber optic connector or with other types of optical device. Therefore, a variety of methods as described above have been developed to align individual optical fibers prior to sealing the optical fibers within the fiber optic connector. Since fiber optic connectors typically include a plurality of optical fibers, all of which must be precisely aligned, the alignment process must generally be repeated for each optical fiber of the fiber optic connector prior to hermetically sealing the fiber optic connector. As described above, however, the heat required to allow one optical fiber to be positioned can oftentimes affect the position or alignment of adjacent optical fibers, thereby misaligning the adjacent optical fibers. In addition, these alignment and bonding systems and methods are generally relatively laborious and time-intensive, particularly, in instances in which a number of optical fibers must be individually aligned within the small volume of a single fiber optic connector.

More specifically, a fiber optic connector has been developed by AT&T Bell Laboratories and is described by R.J. Pimpinella in an article entitled "*A New Type of Fiber Optic Connector Designed for Military Optical Backplanes*", published in the Proceedings of the 42nd ECTC Conference on May 18-20, 1992, pages A-6-1 through A-6-5. This fiber optic connector includes a silicon base which defines a v-groove. An optical fiber can be positioned within the v-groove and a ball lens can be disposed adjacent an end portion of the optical fiber to form an optical fiber sub-assembly. The optical fiber sub-assembly can be mated with a second optical fiber sub-assembly, also comprised of an optical fiber and a ball lens mounted to a silicon base, such that the optical signals transmitted by a first optical fiber are collimated by the pair of ball lenses so as to be efficiently coupled to the second optical fiber. In order to prevent unnecessary exposure of the optical fiber to potentially harmful environmental influences, the optical fiber sub-assemblies can be disposed within respective self-sealing connector enclosures. In order to allow the first and second optical sub-assemblies to be mated, however, at least one of the connector assemblies has a spring-loaded cover that retracts upwardly to receive a corresponding portion of the other connector enclosure.

The fiber optic connector disclosed by R.J. Pimpinella as well as the above-described alignment methods and systems do not provide for the precise alignment of one or more optical fibers within a hermetically sealed package, such as a hermetically sealed fiber optic connector. Instead, the retraction of the spring-loaded cover of the connector enclosure of the fiber optic connector disclosed by R.J. Pimpinella can allow contaminants or moisture to enter the connector enclosure. In addition, the fiber optic connector disclosed by R.J. Pimpinella does not provide for realignment of the optical fibers without replacing the silicon bases in which respective v-grooves are defined. Further, the fiber optic connector disclosed by R. J. Pimpinella is also rèlatively difficult due to the recessed areas adjacent the ball lens.

As known to those skilled in the art, the precise alignment of an optical fiber within a hermetically sealed package is complicated since, in addition to precisely aligning the optical fiber in each of the six degrees of freedom, the alignment process must typically be performed without physically contacting or otherwise heating the optical fiber since heat, such as body heat, can cause the optical fiber to move due to thermal expansion, thereby misaligning the optical fiber. In addition, access to an optical fiber within a hermetically sealed package is generally limited since the optical device with which the optical fiber is being aligned is disposed within an internal cavity defined within the hermetic package.

## Summary of the Invention

It is therefore an object of the present invention to provide an improved method and apparatus for precisely aligning an optical fiber.

It is another object of the present invention to provide an improved fiber optic connector.

It is yet another object of the present invention to provide an improved method and apparatus for aligning an optical fiber with an optical device within a hermetically sealed package, such as a hermetically sealed fiber optic connector.

It is a further object of the present invention to provide an improved method and apparatus for aligning an optical fiber without physically contacting or otherwise heating the optical fiber.

These and other objects are provided, according to the present invention, by an alignment apparatus that includes a microactuator for precisely aligning an optical fiber with an optical device. The microactuator includes a carrier having optical fiber holding means for receiving the optical fiber and positioning means including at least one bimorphic actuator having first and second layers comprised of first and second materials, respectively, which respond differently to electrical stimuli such that the bimorphic actuator can be deflected by electrical stimuli to thereby controllably position the carrier and, in turn, the optical fiber relative to the optical device. The microactuator can also include an alignment support structure or substrate, disposed in a fixed relation to the optical device, for supporting the carrier. Thus, by controllably positioning the carrier relative to the alignment support structure, the optical fiber can be precisely aligned with the optical device.

In one advantageous embodiment, the microactuator includes first and second bimorphic actuators for controllably positioning the carrier in first and second orthogonal directions, respectively, relative to the alignment support structure. The microactuator can also include a third bimorphic actuator for positioning the carrier in a third direction, orthogonal to the first and second directions. Accordingly, the carrier and the optical fiber mounted to the carrier can be controllably positioned in three orthogonal directions relative to the alignment support structure and, in turn, to the optical device.

In one embodiment, the first and second materials from which the bimorphic actuator is formed have first and second coefficients of thermal expansion, respectively. For example, the bimorphic actuator can include a first layer of silicon and a second layer of a metallic material. The microactuator of this embodiment also includes current supply means for providing current to the bimorphic actuator such that the first and second materials differentially expand, thereby deflecting the respective bimorphic actuator. In another embodiment, the second layer of the bimorphic actuator is formed of a piezoelectric material, such as PZT or PMN. The microactuator of this embodiment also includes voltage supply means for supplying voltage to the piezoelectric bimorphic actuator such that the bimorphic actuator deflects.

In either embodiment, the carrier can also include a carrier body to which the bimorphic actuator is affixed. In particular, each bimorphic actuator can include an elongate central portion extending between opposed end portions. The opposed end portions can be affixed to the carrier body such that the elongate central portion bends in response to electrical stimuli, such as current which induces differential expansion between the first and second layers.

The alignment support structure can also include means for securing the carrier to the alignment support structure once the optical fiber is aligned with the optical device. In one embodiment, the alignment support structure includes at least one post formed, such as by a LIGA process involving a combination of lithography, electroforming and molding, so as to extend outwardly from the alignment support structure. The carrier can also define at least one aperture etched therethrough and adapted to receive a respective post therein. The aperture defined in the carrier can have a frustoconical shape to facilitate relative movement between the carrier and a respective post of the alignment support structure and can include an adhesive adapted to bond the outwardly extending post of the alignment support structure to the carrier once the optical fiber is precisely aligned with the optical device.

In addition, the alignment support structure can include a recessed portion adapted to receive and hold an optical device, such as a laser diode. Furthermore, the alignment support structure can define a reference location and can include bias means for urging a predetermined portion of the carrier toward the reference location of the alignment support structure. In one embodiment, the bias means includes a plurality of springs for contacting the carrier and for urging the predetermined portion of the carrier toward the reference location. The alignment support structure can also be comprised of a thermally conductive material for drawing heat from the optical device.

Accordingly, the microactuator of the present invention precisely aligns an optical fiber with an optical device, such as a laser diode, due to the controlled deflection of the bimorphic actuators of the microactuator. In addition, during the process of aligning and bonding an optical fiber, the microactuator of the present invention does not heat or otherwise perturb adjacent microactuators or the optical fibers maintained therein such that a plurality of adjacent optical fibers can be precisely aligned.

Moreover, since the bimorphic actuators of the microactuator do not physically contact the optical fiber, the microactuator of the present invention can precisely align an optical fiber with an optical device within a hermetically sealed package, such as a butterfly package. In addition, the microactuator of the present invention can be readily fabricated in an economical manner. Thus, the microactuator can remain within a hermetically sealed package to facilitate subsequent realignment or repositioning of the optical fiber. Alternatively, the microactuator can permanently bond an optical fiber in an aligned relationship with the optical device.

According to one advantageous embodiment, the alignment apparatus is a fiber optic connector that includes a connector housing in which the alignment support structure and at least one microactuator are disposed. By precisely aligning the optical fibers carried by the respective microactuators, such as with respective lens elements, the fiber optic connector of this embodiment can efficiently couple the aligned optical fibers, such as single mode optical fibers, with other optical devices, including other optical fibers. In addition, the microactuator can be controllably positioned relative to the alignment support structure so as to precisely align the optical fiber mounted thereto after the connector housing has been hermetically sealed so as to further enhance the precision with which the optical fibers can be aligned.

The connector housing of the fiber optic connector of this advantageous embodiment preferably defines a plurality of apertures through which the optical signals are transmitted. The fiber optic connector of this embodiment also preferably includes a plurality of optical fibers mounted to respective ones of a plurality of microactuators such that the optical fibers can be precisely aligned with respective apertures defined by the connector housing.

In one advantageous embodiment, the fiber optic connector also includes a plurality of lens elements, such as graded index lens elements, which are at least partially disposed within respective ones of the plurality of apertures defined by the connector housing. Thus, the microactuators can precisely align the plurality of optical fibers with respective ones of the plurality of lens elements such that the optical signals transmitted therethrough can be collimated. In addition, each lens element can include a metallized portion such that the lens elements can be affixed, such as by soldering, within the respective apertures.

Accordingly, the fiber optic connector of this embodiment can precisely align one or more optical fibers, such as single mode optical fibers, with respective lens elements such that the optical signals transmitted by the optical fibers can be efficiently coupled to another optical device, such as another optical fiber. In addition, the microactuators of the fiber optic connector can be disposed within the connector housing such that the optical fibers can be aligned with the respective lens elements without physically contacting the optical fiber and, in one advantageous embodiment, after the connector housing has been hermetically sealed such that the alignment of the optical fibers is further enhanced.

## Brief Description of the Drawings

Figure 1 is a perspective view illustrating a microactuator according to one embodiment of the present invention.

Figure 2 is an exploded perspective view illustrating the microactuator of Figure 1 including the alignment support structure and the carrier in greater detail.

Figure 3 is a cross-sectional view of the microactuator in one embodiment of the present invention taken along line 3-3 of Figure 1.

Figure 4 is a cross-sectional view of a microactuator according to one embodiment of the present invention taken along line 4-4 of Figure 1.

Figure 5 is a perspective view illustrating the deflection of a bimorphic actuator and the resulting movement of the carrier relative to the alignment support structure of the microactuator of one embodiment of the present invention.

Figure 6 is a schematic representation of the microactuator of one embodiment of the present invention disposed within a hermetically sealed package for aligning an optical fiber with an optical device which is also disposed within a hermetically sealed package.

Figure 7 is a front perspective view of a fiber optic connector according to one embodiment of the present invention.

Figure 8 is a rear perspective view of a fiber optic connector according to one embodiment of the present invention.

Figure 9 is a perspective view of a pair of fiber optic connectors according to our embodiment of the present invention which have been mated in an aligned relation.

Figure 10 is a fragmentary perspective view of a portion of the fiber optic connector of one embodiment of the present invention illustrating the substrate and a pair of microactuators mounted therein for aligning a pair of optical fibers with respective lens elements.

Figure 11 is a greatly enlarged perspective view of a microactuator of one embodiment of the fiber optic connector of the present invention.

Figure 12 is a schematic plan view illustrating the transmission of optical signals between the optical fibers of a pair of fiber optic connectors according to one embodiment of the present invention in which only a portion of the respective fiber optic connectors is illustrated for the sake of clarity.

Detailed Description of the Preferred Embodiments

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which a preferred embodiment of the invention is shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, this embodiment is provided so that this disclosure will be thorough and complete and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Referring now to Figure 1, an alignment apparatus of the present invention includes a microactuator **10** for precisely aligning an optical fiber **12** with an optical device **14** is illustrated. For example, the microactuator can align the optical fiber with an optical device, such as a laser diode, which is held within a corresponding recess **16** defined by the microactuator. Alternatively, the microactuator can precisely align an optical fiber with an external optical device, i.e., an optical device which is not mounted upon or otherwise held by the microactuator. In either instance, however, the microactuator is positioned in a fixed relation to the optical device. Still further, the alignment apparatus can be a fiber optic connector that includes one or more microactuators for aligning respective optical fibers, such as with the corresponding optical fibers of another fiber optic connector.

The microactuator **10** can position various types of optical fibers **12** including multi-mode, single mode, and polarization preserving optical fibers. However, the microactuator of the present invention is particularly adapted to position single mode optical fibers in an aligned position since the microactuator can readily position optical fibers with the precision required to efficiently couple single mode optical fibers. In addition, the microactuator can align an optical fiber which includes a lensed facet. However, the microactuator can, alternatively, align an optical fiber having a cleaved end facet without departing from the spirit and scope of the present invention.

The microactuator **10** typically includes an alignment support structure **20**, such as a substrate, as illustrated in Figures 1 and 2. The alignment support structure is disposed in a fixed relation to the optical device **14**. For example, the alignment support structure can include a recessed portion **16** which is adapted to receive and hold the optical device. As illustrated in Figures 1 and 2, a laser diode can be disposed within the recessed portion defined by the alignment support structure. As also shown, the alignment support structure of this embodiment can include a chamfered opening **18** so as to reduce or eliminate back reflections from the optical device.

The alignment support structure **20** is preferably comprised of a thermally conductive material to serve as a heatsink for drawing heat from the optical device **14** as described hereinafter. In addition, once the carrier **22** has been bonded to the alignment support structure, the alignment support structure also draws heat from the carrier. By drawing heat from the optical device and the carrier, the carrier and, in turn, the optical fiber **12** can be maintained at a predetermined constant temperature such that the alignment of the optical fiber is not altered or otherwise affected due to temperature fluctuations. In one exemplary embodiment, the alignment support structure is comprised of a metallic material, such as copper or nickel.

The alignment support structure **20** can be fabricated by a variety of processes as known to those skilled in the art. For example, the alignment support structure can be electroformed, such as by a LIGA process, in order to obtain relatively large height-to-width ratios. By obtaining relatively large height-to-width ratios, the alignment support structure can include vertical sidewalls having precise tolerances. As known to those skilled in the art, a LIGA process is based upon a combination of lithography, electroforming and molding. In fact, the acronym LIGA is derived from the German translation of lithography, electroforming and molding, namely, Lithografie, Galvanoformung and Abformung.

The microactuator **10** also includes a carrier **22**, movably mounted to the alignment support structure **20**, for holding the optical fiber **12** in a fixed relation thereto. As shown in Figure 2, the carrier **22** preferably includes a carrier body **24** having an optical fiber holding means, such as a groove **26** defined in the carrier body, for receiving and holding the optical fiber in a fixed relation to the carrier body. As illustrated in cross-section in Figure 3, the groove can be V-shaped and, in one embodiment, has opposed sidewalls which define an angle of 55° with respect to the surface of the carrier body. However, the groove can have a variety of other cross-sectional shapes without departing from the spirit and scope of the present invention.

In one embodiment, the carrier **22** is comprised of silicon. Thus, the V-shaped groove **26** can be formed by anisotropically wet etching the carrier body. However, the carrier can be comprised of other materials, such as metallic materials, without departing from the spirit and scope of the present invention. In addition, the carrier can be coated with a material having a relatively low coefficient of friction, such as a TEFLON® coating.

The V-shaped groove **26** preferably has a predetermined depth such that the optical fiber **12** will initially be held slightly below, such as 5μm below, the final aligned position of the optical fiber. Thus, the microactuator **10** can controllably adjust the position of the optical fiber upwardly and into alignment with the optical device **14** as described hereinafter. However, the groove can be formed so as to initially hold the optical fiber in other predetermined relationships to the final aligned position of the optical fiber without departing from the spirit and scope of the present invention.

In order to maintain the optical fiber **12** in a fixed relation to the carrier body **24**, the optical fiber is preferably bonded within the groove **26**. For example, the optical fiber can be bonded to the carrier with an optical fiber bonding agent, such as Gould GlasSolder™ bonding agent, or a high temperature fluxless solder, such as gold/tin eutectic alloy solder. As known to those skilled in the art, the optical fiber is also preferably metallized, such as with titanium, platinum and gold, in order to be securely bonded within the groove.

The microactuator **10** of the present invention also includes positioning means for controllably positioning the carrier **22** relative to the alignment support structure **20** such that the optical fiber **12** is, in turn, precisely aligned with the optical device **14**. In one embodiment, the carrier includes the positioning means which can include at least one bimorphic actuator **28**, such as a BIMORPH® element manufactured by Morgan Matroc, Inc.. For example, in the illustrated embodiment, the carrier includes three bimorphic actuators which are adapted to controllably position the carrier in three orthogonal directions relative to the alignment support structure.

As illustrated in Figures 3 and 4, each bimorphic actuator **28** is preferably comprised of first and second layers **28a** and **28b**. The first and second layers are formed of first and second materials, respectively, which respond differently to electrical stimuli. Thus, by electrically stimulating the bimorphic actuator, the bimorphic actuator will deflect in a predetermined direction by a controllable amount. Typically, the amount of the deflection of the bimorphic actuator will be proportional to the magnitude of the electrical stimulation.

Each bimorphic actuator **28** generally includes an elongate central portion **30** extending between opposed end portions **32** as shown in Figure 4. The opposed end portions can be affixed to the carrier body **24** while the elongate central portion is separated from the carrier body as shown in Figure 3. Alternatively, the opposed end portions can be disposed within slots defined by the carrier body to thereby permit limited relative movement between the opposed end portions and the carrier body. Thus, upon electrical stimulation of the bimorphic actuator, the elongate central portion of the bimorphic actuator will bend in a predetermined direction, such as downwardly as shown in Figure 5 and as indicated by arrow **34** in Figure 4. Upon bending in the predetermined direction, the bimorphic actuator is urged against the alignment support structure **20** so as to apply an oppositely directed force to the carrier **22**, thereby moving the carrier relative to the alignment support structure. Accordingly, the carrier can be controllably positioned relative to the alignment support structure such that the optical fiber **12** bonded to the carrier is precisely aligned with the optical device **14**.

As illustrated, the microactuator **10** of one advantageous embodiment includes three orthogonally positioned bimorphic actuators **28** adapted to move the carrier **22** in three orthogonal directions, namely, the x, y and z directions as designated for purposes of illustration in Figure 1, relative to the alignment support structure **20**. Thus, by electrically stimulating the respective bimorphic actuators independently, the carrier and, in turn, the optical fiber **12** bonded thereto, can be controllably positioned in each of the three orthogonal directions. In addition, the rotational alignment of the optical fiber with the optical device **14** is provided by the precise formation of the groove **26** relative to the recessed portion **18** of the alignment support structure which holds the optical device.

According to one embodiment, the first and second layers **28a** and **28b** of each of the bimorphic actuators **28** are comprised of first and second materials, respectively. The first and second materials of this embodiment are selected to have first and second coefficients of thermal expansion, respectively. For example, the first material can be silicon while the second material is a metal, such as nickel or copper, having a larger coefficient of thermal expansion than the first material. The metallic second layer can be deposited on the first layer by a variety of methods, including preferential sputtering, directed evaporation and electroplating, without departing from the spirit and scope of the present invention.

In this embodiment, the microactuator **10** also includes current supply means for providing current to the bimorphic actuator **28** to resistively heat the bimorphic actuator such that the first and second materials of the first and second layers, respectively, differentially expand, thereby deflecting the bimorphic actuator. In order to facilitate electrical stimulation of the bimorphic actuators, bonding pads, typically comprised of a conductive material, such as gold, are formed on the opposed end portions **32** of the bimorphic actuators such that an electrical current can be established therebetween.

In other words, since the end portions **32** of the bimorphic actuators **28** are affixed to the carrier body **24** and since the metallic layers expand to a greater degree than the respective silicon layers, the elongate central portions **30** of the bimorphic actuators bend downwardly and outwardly as shown in Figure 5. The elongate central portions of the first and second bimorphic actuators, i.e., the x- and z-bimorphic actuators, are therefore urged against respective sidewalls of the alignment support structure **20** such that the carrier **22** is moved in a direction away from the sidewalls in response thereto as indicated by arrows **36** in Figure 5. Likewise, the elongate central portion of the third bimorphic actuator, i.e., the y-bimorphic actuator, is urged downwardly against the alignment support structure such that the carrier is moved upwardly in response thereto as shown in Figures 4 and 5. In order to facilitate movement of the third bimorphic actuator, the elongate central portion is preferably separated from the remainder of the carrier body **24** by relief grooves **29** defined laterally alongside the elongate central portion as best shown in Figure 3 which allow the bimorphic actuator to flex. By therefore controlling the current supplied to the bimorphic actuators, the amount of the bending or deflection and, consequently, the position of the carrier relative to the alignment support structure can be controlled since the amount of bending is generally proportional to the current supplied to the individual bimorphic actuators.

A bimorphic actuator **28** having a first layer **28a** comprised of a highly doped semiconductor material, such as highly doped silicon, can also be heated by introducing current to the highly doped semiconductor material. By introducing current to a first layer comprised of a highly doped semiconductor material, the bimorphic actuator can be resistively heated such that the first and second layers differentially expand, thereby deflecting the bimorphic actuator. In addition, sufficient resistive heating can generally be provided by relatively small amounts of the current, such as 10 mA, thereby reducing the power requirements for the microactuator **10** of this embodiment.

Alternatively, in embodiments in which the metallic second layer **28b** of the bimorphic actuator **28** has a relatively low resistance, such as a second layer comprised of nickel, copper, gold or aluminum, the bimorphic actuator can include an additional layer comprised of a material having a greater resistance than that of the metallic second layer. The bimorphic actuator of this embodiment can also include an insulating layer, such as a layer of silicon dioxide, disposed between the metallic second layer and the additional layer having a greater resistance. Thus, by providing current to the additional layer of relatively high resistance, the various layers of the bimorphic actuator will be heated and will differentially expand such that the bimorphic actuator controllably bends or deflects as described above.

In another embodiment, each bimorphic actuator **28** includes a second layer **28b** of an electrostrictive or piezoelectric material which, as known to those skilled in the art, will controllably move or deflect upon the application of a voltage thereto. Thus, the microactuator **10** of this embodiment also includes voltage supply means for providing a voltage to the bimorphic actuator such that the bimorphic actuator controllably deflects. In one exemplary embodiment, the bimorphic actuator includes a first layer **28a** comprised of silicon and a second layer comprised of a piezoelectric material, such as PZT or PMN. By controlling the voltage supplied to the bimorphic actuator, the amount of deflection or bending of the bimorphic actuator and, consequently, the position of the carrier **22** relative to the alignment support structure **20** can likewise be controlled. As described above, bonding pads are preferably disposed on the opposed end portions **32** of the bimorphic actuator such that a predetermined voltage can be established therebetween.

Thus, the microactuator **10** of the present invention can align an optical fiber **12** with an optical device **14** by controllably varying the deflection of the respective bimorphic actuators **28**. As the respective bimorphic actuators are deflected, the efficiency with which the optical signals produced by the optical device are coupled to and transmitted via the optical fiber can be detected. Once the position in which the optical signals are most efficiently transmitted via the optical fiber is detected, such as by detecting the maximum output power, the optical fiber can be held in position by the bimorphic actuators while the relative positions of the carrier **22** and the alignment support structure **20** are fixed, such as by bonding the carrier to the alignment support structure.

In one embodiment, the alignment support structure **20** includes means for securing the carrier **22** thereto once the optical fiber **12** is aligned with the optical device **14**. As shown in Figures 1 and 2, the securing means can include at least one outwardly extending post **40** which is preferably formed by a LIGA process. In addition, the carrier of this embodiment preferably defines at least one aperture **42** adapted to receive a respective post therein. The apertures defined by the carrier are preferably anisotropically wet-etched or laser cut therein and, in one embodiment, are frustoconical in shape so as to facilitate movement between the carrier and the post of the alignment support structure.

As illustrated, the groove **26** and the apertures **42** are preferably anisotropically etched in the carrier **22** in two different directions or orientations, such as <110> and <100>. In order to provide such different types of etching, the carrier can be comprised of at least two different wafers, such as silicon wafers, having different orientations, such as <110> and <100> in the above example. In addition, the carrier can be coated with a material having a relatively low coefficient, such as a TEFLON® coating, in order to reduce the frictional forces between the carrier and the alignment support structure **20**.

The securing means of the alignment support structure **20** can also include an adhesive adapted to bond the outwardly extending posts **40** of the alignment support structure to the carrier **22** once the optical fiber **12** is precisely aligned with the optical device **14**. For example, a bonding agent, such as gold/tin eutectic alloy solder, a Gould GlasSolder™ bonding agent or glass frit, can be disposed on the interior surface of the aperture defined by the carrier. Once the optical fiber is precisely aligned with the optical device, the adhesive can be activated, such as by laser heating or resistive heating, to bond the carrier to the alignment support structure. Once the alignment support structure and the carrier are bonded, the alignment of the optical fiber with the optical device is maintained irrespective of further electrical stimulation of the bimorphic actuators **28**.

The microactuator **10** and, more preferably, the alignment support structure **20** can define a reference location **44** with which a predetermined portion of the carrier **22**, such as a predetermined corner **22a**, is preferably initially positioned. Thereafter, the position of the carrier can be adjusted relative to the alignment support structure such that the optical fiber **12** is precisely aligned with the optical device **14**.

Furthermore, the carrier **22** can be initially positioned relative to the alignment support structure **20** such that the optical fiber **12** is slightly misaligned, such as by 5-10 micrometers, relative to the optical device in a predetermined direction. The predetermined direction is preferably selected based upon the relative movement provided by the bimorphic actuators **28** such that the bimorphic actuators can compensate for the slight misalignment and can align the optical fiber with the optical device. In other words, the bimorphic actuators of the microactuator **10** are generally designed to move the carrier, and, in turn, the optical fiber in a predetermined direction, typically one predetermined direction, relative to the alignment support structure as illustrated by arrows **34** and **36** in Figures 4 and 5. Therefore, the carrier is preferably initially positioned so as to be slightly misaligned in a direction opposite that indicated by arrows **34** and **36** such that movement of the carrier in the predetermined direction by the bimorphic actuators compensates for the slight misalignment and, in fact, brings the optical fiber into alignment with the optical device.

In one embodiment, the alignment support structure **20** also includes bias means for urging the predetermined portion of the carrier **22** towards the reference location **44** defined by the alignment support structure. In the illustrated embodiment, the bias means includes a plurality of springs **46** for contacting the carrier, such as a sidewall **38** of the carrier, and for urging the predetermined portion of the carrier toward the reference location. In particular, the alignment support structure of the illustrated embodiment includes first and second springs for urging the carrier in first and second orthogonal directions, respectively, toward the reference location.

As illustrated in Figures 1 and 5, the first and second springs **46** preferably urge the carrier **22** in first and second directions, respectively, which are substantially opposite to the first and second directions in which the first and second bimorphic actuators **28**, i.e., the x- and z-bimorphic actuators, urge the carrier. The bias force provided by the springs is preferably less than the force provided by the bimorphic actuators upon deflection, however, such that deflection of the bimorphic actuators overcomes the bias force of the springs and frictional forces between the carrier and the alignment support structure **20** so as to move the predetermined portion of the carrier away from the reference location **44**.

The springs **46** can also be formed during a LIGA process so as to have relatively large height-to-width ratios. In addition, the springs can include a curved or hook member **48** to facilitate opening or spreading of the springs upon mounting of the carrier **22** to the alignment support structure **20**. In particular, a microprobe can engage a respective hook member so as to open or spread the spring during mounting of the carrier.

In one exemplary embodiment illustrated schematically in Figure 6, the microactuator **10** of the present invention can controllably align an optical fiber **12** with an optical device **14**, such as a laser diode, within a hermetically sealed package, such as a hermetically sealed butterfly package. According to the present invention, the microactuator can align the optical fiber with the optical device prior to or following the hermetic sealing of the package. If the optical fibers are aligned prior to hermetically sealing the package, the package can thereafter be potted, such as with a plastic material, or a lid may be affixed to the package, such as by laser welding or seam sealing, such that the package housing the aligned optical fibers is hermetically sealed.

As known to those skilled in the art, the hermetically sealed package typically includes a hermetic canister **50**, such as a gold-plated KOVAR™ canister having a plurality of KOVAR™ feed-through pins **52** which are glass-to-metal hermetically sealed to the canister. An optical device **14** and a microactuator **10** having an optical fiber **12** mounted thereto are also disposed within the hermetic canister. In order to effectively seal the hermetic canister, the optical fiber is preferably metallized and soldered to the fiber optic sealing tube **54** of the hermetic canister. As also known to those skilled in the art, the hermetically sealed package can also include means for controlling the temperature of the optical device including a thermistor **56** and a thermal electric cooler **58**. Furthermore, the hermetically sealed package can include a photodetector **60** for detecting the output of the optical device such that the excitation energy supplied to the optical device and the resulting output of the optical device can be controlled as desired, such as controlling the excitation energy supplied to the optical device such that a constant output is provided by the optical device.

The optical fiber **12** is preferably aligned with the optical device **14** with the microactuator **10** within the hermetic canister **50** as described above. In particular, the bimorphic actuators **28** of the microactuator, as well as the other electrical components disposed within the hermetic canister, are electrically stimulated, such as by leads **56** extending from respective pins **52** of the hermetically sealed package as illustrated in Figure 6. Thus, by controllably adjusting the respective deflections provided by the bimorphic actuators, the alignment of the optical fiber to the optical device can be controlled. In particular, the first, second and third bimorphic actuators can be controllably adjusted in three orthogonal directions by providing appropriate electrical stimulation via the leads identified as X, Y and Z in Figure 6. Furthermore, by detecting the efficiency with which the optical signals produced by the optical device are coupled to the optical fiber, the optical fiber can be precisely aligned with the optical device.

Thereafter, the relative positions of the optical fiber **12** and the optical device **14** can be fixed by bonding the carrier **22** to the alignment support structure **20**, such as by heating the adhesive disposed within the respective apertures **42** defined by the carrier. For example, the hermetic canister **50** can include a transparent window through which a laser can be directed so as to heat the adhesive and bond the carrier to the alignment support structure. Alternatively, the hermetically sealed package can include an additional lead which is electrically connected to the alignment support structure in the vicinity of the adhesive such that the adhesive can be resistively heated and the carrier can thereby be bonded to the alignment support structure.

Accordingly, an optical fiber **12** can be precisely aligned with an optical device **14**, such as a laser diode, within a hermetically sealed package. Once the optical fiber is precisely aligned, the respective positions of the optical fiber and the optical device can be fixed such that the precise alignment is maintained. The microactuator can thereafter remain within the hermetically sealed package following the alignment of the optical fiber with the optical device, thereby further insuring that the optical fiber maintains alignment with the optical device. For example, in embodiments in which the carrier **22** is not bonded to the alignment support structure **20** following the alignment of the optical fiber with the optical device, the microactuator can subsequently reposition or realign the optical fiber with the optical device to compensate for variations in the optical alignment which occur during use.

In addition to a hermetically sealed package which includes an optical device **14**, such as a laser diode, one or more microactuators **98** can be disposed within a fiber optic connector **70**. As described below, the microactuators can precisely align optical fibers **83** with respective lens elements **86** of the fiber optic connector in order to collimate the optical signals transmitted therethrough.

By way of example, the alignment apparatus of this embodiment is a fiber optic connector **70** as illustrated in Figure 7. The fiber optic connector generally includes a connector housing **72**. While the connector housing can be comprised of a variety of materials, the connector housing of one embodiment is comprised of a metal, such as stainless steel, and, in a more specific embodiment, is comprised of KOVAR™ brand stainless steel. As known to those skilled in the art, a KOVAR™ connector housing is comprised of a type of stainless steel which has a coefficient of thermal expansion which matches the coefficient of an optical fiber and thermal expansion of a glass lens element, an optical fiber and the glass of the glass-to-metal seals or bonds, such as between the lens elements and the front plate **74** of the fiber optic connector, as known to those skilled in the art.

As illustrated in Figure 7, the connector housing **72** can include a face plate **74** defining a plurality of apertures **76** therethrough. The face plate is mounted to the cup-shaped body portion **78** of the connector housing as shown in Figure 7 to thereby define an internal cavity within the connector housing. According to one embodiment, the face plate can be laser welded or seam sealed to the body portion such that the connector housing is hermetically sealed. In addition, the exterior surface of the front plate can be polished so as to form a relatively planar surface, including the lens elements and the front plate, such that the front plate is more readily cleanable and can be coated, such as with an anti-reflection coating. By polishing the front plate, spurious deflections from surface defects on the front plate can also be minimized. In addition, the front plate can be polished at a predetermined angle, such as 3° to 5°, to prevent light reflections from the respective front plates of a pair of mated fiber optic connectors, thereby minimizing reflected feedback.

As illustrated in Figure 8, the rear surface of the connector housing **72** can include a slot **81** through which one or more optical fibers **83** extend. For example, a fiber optic cable **84**, such as a fiber optic ribbon cable, comprised of a plurality of individual optical fibers can extend through the slot defined in the rear surface of the connector housing. As described in detail below, each of the optical fibers is preferably individually aligned with a respective aperture **76** defined in the front plate **74** of the connector housing.

In order to more efficiently couple the optical signals transmitted by the optical fibers **83**, the fiber optic connector **70** of the present invention can include one or more lens elements **86**. Preferably, a lens element is disposed within each of the apertures **76** defined in the front plate **74** of the connector housing **72** for collimating the optical signals transmitted by the respective optical fibers. At least a portion of each lens element is preferably metallized, such as with titanium, platinum and gold, such that the lens elements can be affixed, such as by soldering, within the respective apertures defined in the front plate of the connector housing. In one advantageous embodiment, an end portion **86a** of each lens element is polished, coated with an anti-reflection coating and aligned with the polished exterior surface of the front plate of the connector housing as illustrated in Figure 7. The lens elements can also include cylindrical graded index lens elements to further enhance the collimation of the optical signals.

Accordingly, the fiber optic connector **70** of the present invention can precisely align a plurality of optical fibers **83** with respective ones of a plurality of lens elements **86** disposed within the respective apertures **76** defined in the front plate **74** of the connector housing **72**. As illustrated in Figure 9, the fiber optic connector can then be mated with a second fiber optic connector, such that the optical signals transmitted via the optical fibers of the first fiber optic connector can be efficiently coupled to the optical fibers of the second fiber optic connector.

In order to mate the first and second fiber optic connectors **70** such that the respective optical fibers **83** are maintained in an aligned relationship, one of the fiber optic connectors can include a plurality of alignment pins **88** extending outwardly from the front plate **74** as shown in Figure 7. The front plate of the other fiber optic connector can define a plurality of corresponding apertures adapted to receive respective ones of the alignment pins. Once the fiber optic connectors have been aligned, the fiber optic connectors can be secured in the aligned relationship, such as by extending a connector **90** through corresponding apertures **92** defined in the laterally extending tabs **94** of the respective front plates of the fiber optic connectors as shown in Figure 9.

As shown in Figure 10, the fiber optic connector **70** of the present invention preferably includes an alignment support structure or a substrate **66**, such as a metallic, a ceramic or a silicon substrate, and at least one microactuator **98** mounted on the substrate and adapted from relative movement therewith. An optical fiber **83** is preferably affixed to each microactuator such that the relative movement of the microactuator will controllably position the respective optical fiber with respect to an aperture **76** defined in the front plate **74** of the connector housing **72** and, in one advantageous embodiment, with respect to a lens element **86** disposed within the aperture. As shown in Figure 10, the fiber optic connector of one advantageous embodiment includes a plurality of microactuators, one of which is associated with each optical fiber so as to align the respective optical fiber with a corresponding lens element **86**.

Each microactuator **98** of the fiber optic connector **70** of this embodiment operates in a similar manner to that described above. In particular, each microactuator includes positioning means, such as one or more bimorphic actuators **106**, for controllably positioning the carrier **100** relative to the substrate **96**. As shown in Figure 10, for example, the substrate can define a plurality of recessed portions in which the respective microactuators are disposed. Thus, the bimorphic actuators of the microactuators are preferably urged against the surrounding sidewalls of the substrate upon electrical stimulation of the bimorphic actuator such that the optical fibers carried by the microactuators can be controllably positioned relative to a respective lens element **86**.

The microactuator **98** of this embodiment of the present invention can thereby align an optical fiber **83** with a respective lens element **86** by controllably varying the deflection of the respective bimorphic actuators **106**. As the respective bimorphic actuators are deflected, the efficiency with which the optical signals produced by the optical device are coupled to and transmitted via the optical fiber can be detected. Once the position in which the optical signals are most efficiently transmitted via the optical fiber is detected, such as by detecting the maximum output power, the optical fiber can be held in position by the bimorphic actuators while the relative positions of the optical fibers and the lens elements are fixed.

As illustrated in Figure 10, the substrate **96** can also include one or more sets of first and second grooves **114**. The first and second grooves are sized and shaped for receiving an optical fiber **83** and a lens element **86**, respectively. As shown in Figures 10 and 11, the lens element can include a hemispherically ground surface on a first end **86b** and a polished second end **86a** to further facilitate the collimation and transmission of optical signals so as to reduce, among other things, spurious reflections. In addition, both end surfaces of the lens element, as well as the end surface of the optical fiber, can be coated with an anti-reflectant coating to further enhance optical transmission.

As shown, each optical fiber **83** received by the fiber optic connector **70** is preferably disposed within a respective groove **114** defined in the substrate **96**. A microactuator **98** and a lens element **86** are also associated with each optical fiber such that the microactuator can controllably position the respective optical fiber with the lens element. In addition to being positioned in a predetermined position, such as within an aperture **76** defined by the front plate **74** of the connector housing **72**, the lens elements collimate the optical signals.

According to the present invention, a plurality of microactuators **98** can be mounted on a substrate **96** within the internal cavity of the connector housing **72**. An optical fiber **83** is also preferably bonded to the carrier **100** of each microactuator such that the microactuators can controllably position the optical fibers with respect to respective lens elements **86** disposed within apertures **76** defined in the front plate **74** of the connector housing **72**. Since the microactuators and the optical fibers mounted thereon need not be physically contacted during the alignment process, the optical fibers can be aligned either prior to or following the hermetic sealing of the connector housing, such as by affixing the front plate thereto.

In embodiments in which the optical fibers **83** are aligned prior to sealing the connector housing **72**, the optical fibers can be aligned with respect to respective lens elements. Thereafter, the connector housing can be sealed. For example, a lid can be secured, such as by seam sealing, to the connector housing following alignment of the optical fibers. In addition, the relative positions of the optical fibers can be fixed prior to sealing the connector housing, such as by activating an adhesive between the carrier **100** and the substrate **96** as described below, thereby bonding the carrier to the substrate.

Alternatively, in embodiments in which the optical fibers **83** are aligned after hermetically sealing the connector housing **72** and as illustrated in Figure 2, the fiber optic connector **70** can also include a plurality of electrical pins **116** which can, in one embodiment, extend through the rear surface **82** of the connector housing to provide electrical access to the bimorphic actuators **106** of the plurality of microactuators **98**. In particular, electrical leads preferably interconnect the pins with respective ones of the bimorphic actuators and, more particularly, with bonding pads disposed on the opposed end portions **109** of each bimorphic actuator. Accordingly, by applying appropriate electrical stimuli to predetermined ones of the electrical pins, each optical fiber can be individually positioned in first, second and third orthogonal directions relative to the respective lens element **86** after the connector housing has been hermetically sealed.

By transmitting predetermined optical signals through the optical fibers **83** and by detecting the resulting optical signals transmitted by the respective lens elements **86**, the relative alignment of the optical fiber with a respective lens element can be determined. In particular, the position of the optical fiber at which the maximum output power is detected can be determined. In order to obtain the maximum output power, the end surface of the optical fiber is preferably aligned at the focal point of the respective lens element.

Thereafter, the relative positions of the optical fiber **83** and the lens element **86** can be fixed by bonding the carrier **100** to the substrate **96**, as described above, such as by heating the adhesive disposed within the respective apertures **112** defined by the carrier such that the position of the carrier relative to the substrate which provides the maximum output power remains fixed.

As schematically illustrated in Figure 12, the lens elements **86** preferably collimate the optical signals such that the signals can be efficiently coupled between a pair of aligned optical fibers **83**. Accordingly, optical signals which are transmitted via a plurality of first optical fibers, such as a plurality of single mode optical fibers, and can be efficiently coupled to respective ones of a plurality of second optical fibers due to the precise alignment provided by the fiber optic connector **70** of the present invention. Although not illustrated, the fiber optic connector can align and interconnect the plurality of first optical fibers with a variety of other optical devices, such as a laser diode array or an array of optical waveguides.

In the embodiment of the present invention in which the optical fibers **83** are controllably positioned relative to lens elements **86** following the hermetic sealing of the connector housing **72**, the alignment of the optical fibers is further enhanced since the optical fibers are not physically contacted or otherwise heated during the alignment process. In addition, by hermetically sealing the connector housing, the optical fibers are protected from various environmental contaminants, such as moisture and dirt.

Therefore, the microactuator **10, 98** of the various embodiments of the present invention precisely aligns an optical fiber **12, 83**, such as a single mode optical fiber, with an optical device **14, 86**, such as a laser diode, due to the controlled deflection of the bimorphic actuators **28, 106** of the microactuator. For example, one or more microactuators can be disposed within a fiber optic connector **70** as to align optical fibers with respective lens elements such that the optical signals transmitted by the optical fibers can be efficiently coupled to another optical device, such as another optical fiber. In addition, during the process of aligning and bonding an optical fiber, the microactuator of the present invention does not heat or otherwise perturb adjacent microactuators or the optical fibers maintained therein such that a plurality of adjacent optical fibers can be precisely aligned.

Since the microactuator **10, 98** does not require physical contact with the optical fiber **12, 83**, the microactuator of the present invention can precisely align an optical fiber to an optical device, such as a laser diode **14** or a lens element **86**, within a hermetically sealed package, such as a butterfly package or a connector housing **70**. In addition, the microactuator of the present invention can be readily fabricated in an economical manner such that the microactuator can remain within a hermetically sealed package following the initial alignment of the optical fiber with the optical device so as to maintain alignment or to provide subsequent realignment of the optical fiber. Alternatively, the microactuator can permanently bond an optical fiber in an aligned relationship with the optical device.

In the drawings and the specification, there has been set forth preferred embodiments of the invention and, although specific terms are employed, the terms are used in a generic and descriptive sense only and not for the purpose of limitation, the scope of the invention being set forth in the following claims.

THAT WHICH IS CLAIMED IS:

1. An alignment apparatus for precisely aligning an optical fiber with an optical device, the alignment apparatus comprising a microactuator comprising:

an alignment support structure disposed in a fixed relation to the optical device; and

a carrier, movably mounted to said alignment support structure, for holding the optical fiber in a fixed relation thereto, said carrier including at least one bimorphic actuator comprising first and second layers comprised of first and second materials, respectively, wherein the first and second materials respond differently to electrical stimuli such that said bimorphic actuator is deflected by the electrical stimuli and operably urged against a portion of said alignment structure to thereby controllably position said carrier relative to said alignment support structure such that the optical fiber is precisely aligned with the optical device.

2. An alignment apparatus according to Claim 1 wherein said carrier comprises first and second bimorphic actuators, each bimorphic actuator comprising first and second layers comprised of first and second materials, respectively, which respond differently to electrical stimuli, wherein said first and second bimorphic actuators are disposed such that said first and second bimorphic actuators deflect in first and second orthogonal directions, respectively, in response to electrical stimuli to thereby controllably position said carrier in the first and second orthogonal directions relative to said alignment support structure.

3. An alignment apparatus according to Claim 2 wherein said carrier further comprises a third

bimorphic actuator having first and second layers comprised of first and second materials, respectively, which respond differently to electrical stimuli, wherein said third bimorphic actuator is disposed so as to deflect in a third direction, orthogonal to the first and second directions, in response to electrical stimuli to thereby controllably position said carrier in the third direction relative to said alignment support structure.

4. An alignment apparatus according to Claim 1 wherein said bimorphic actuator is comprised of first and second layers comprising first and second materials, respectively, and having first and second coefficients of thermal expansion, respectively, and wherein the microactuator comprises current supply means for providing current to said bimorphic actuator such that the first and second materials differentially expand to thereby deflect said bimorphic actuator.

5. An alignment apparatus according to Claim 1 wherein the second layer of said bimorphic actuator is comprised of a piezoelectric material, and wherein the microactuator comprises voltage supply means for providing a voltage to said bimorphic actuator such that said bimorphic actuator is deflected.

6. An alignment apparatus according to Claim 1 wherein said carrier comprises a carrier body, and wherein said bimorphic actuator comprises an elongate central portion extending between opposed end portions, the opposed end portions being affixed to said carrier body such that the elongate central portion bends in response to the electrical stimuli.

7. An alignment apparatus according to Claim 1 wherein said alignment support member comprises means for securing said carrier thereto once the optical fiber is aligned with the optical device.

8. An alignment apparatus according to Claim 7 wherein said securing means of said alignment support member comprises at least one outwardly extending post, and wherein said carrier defines at least one aperture for receiving a respective post therein.

9. An alignment apparatus according to Claim 8 wherein said securing means of said alignment support structure further comprises an adhesive adapted to bond said outwardly extending post of said alignment support structure to said carrier once the optical fiber is precisely aligned with the optical device.

10. An alignment apparatus according to Claim 8 wherein said aperture defined by said carrier has a frustoconical shape to facilitate relative movement between said carrier and said outwardly extending post of said alignment support structure.

11. An alignment apparatus according to Claim 1 wherein said alignment support structure further comprises a recessed portion adapted to receive and hold the optical device therein.

12. An alignment apparatus according to Claim 1 wherein said alignment support structure defines a reference location, and wherein said alignment support structure further comprises bias means for urging a predetermined portion of said carrier toward the reference location defined by said alignment support structure.

13. An alignment apparatus according to Claim 12 wherein said bias means of said alignment structure comprises a plurality of springs for contacting said carrier and for urging the predetermined portion of said carrier toward the reference location.

14. An alignment apparatus according to Claim 1 wherein said alignment support structure is comprised of a thermally conductive material for drawing heat from said carrier.

15. An alignment apparatus according to Claim 1 wherein the alignment apparatus is a fiber optic connector comprising said microactuator and the optical device, and wherein the optical device comprises a lens element disposed in a fixed relation to said alignment support structure such that said microactuator precisely aligns the optical fiber therewith.

16. An alignment apparatus according to Claim 15 wherein the fiber optic connector further comprises a connector housing in which said microactuator is disposed, and wherein said connector housing defines at least one aperture in which said lens element is at least partially disposed.

17. An alignment apparatus according to Claim 16 wherein said lens element comprises a metallized portion adapted to be disposed within a respective aperture defined by said connector housing such that said lens element can be affixed therein.

18. An alignment apparatus according to Claim 16 wherein said connector housing further defines

a plurality of apertures, and wherein the fiber optic connector further comprises:

a plurality of lens elements disposed within respective ones of said plurality of apertures; and

a plurality of microactuators for precisely aligning the optical fibers with respective ones of said lens elements.

19. An alignment apparatus for precisely aligning an optical fiber with an optical device, the alignment apparatus comprising a microactuator comprising:

an alignment support structure disposed in a fixed relation to the optical device, wherein said alignment support structure defines a reference location;

a carrier, movably mounted to said alignment support structure, said carrier comprising:

a carrier body; and

optical fiber holding means for receiving the optical fiber and for maintaining the optical fiber in a fixed relation to said carrier body;

bias means for exerting a bias force upon said carrier to thereby urge a predetermined portion of said carrier toward the reference location defined by said alignment support structure; and

positioning means for controllably positioning said carrier in at least two orthogonal directions relative to said alignment support structure, wherein said positioning means at least partially overcomes the bias force exerted by said bias means and moves said carrier away from the reference location defined by said alignment support structure such that the optical fiber is precisely aligned with the optical device.

20. An alignment apparatus according to Claim 19 wherein said positioning means comprises first and second bimorphic actuators, each bimorphic actuator being comprised of first and second layers comprised of first and second materials, respectively, which respond differently to electrical stimuli, and wherein said first and second bimorphic actuators are disposed such that said first and second bimorphic actuators deflect in first and second orthogonal directions, respectively, in response to the electrical stimuli to thereby controllably position said carrier in the first and second orthogonal directions relative to said alignment support structure.

21. An alignment apparatus according to Claim 20 wherein said carrier further comprises a third bimorphic actuator having first and second layers comprised of first and second materials, respectively, which respond differently to electrical stimuli, wherein said third bimorphic actuator is disposed so as to deflect in a third direction, orthogonal to the first and second directions, in response to electrical stimuli to thereby controllably position said carrier in the third direction relative to said alignment support structure.

22. An alignment apparatus according to Claim 20 wherein each of said bimorphic actuators is comprised of first and second layers comprising first and second materials, respectively, and having first and second coefficients of thermal expansion, respectively, and wherein the microactuator comprises current supply means for providing current to said first and second bimorphic actuators such that the first and second materials differentially expand to thereby deflect said bimorphic actuator.

23. An alignment apparatus according to Claim 20 wherein the second layer of said bimorphic actuators is comprised of a piezoelectric material, and wherein the microactuator comprises voltage supply means for providing a voltage to said bimorphic actuators such that said bimorphic actuators are deflected.

24. An alignment apparatus according to Claim 20 wherein said bimorphic actuators comprise an elongate central portion extending between opposed end portions, and wherein the opposed end portions are affixed to said carrier body such that the elongate central portion bends in response to the electrical stimuli.

25. An alignment apparatus according to Claim 19 wherein said alignment support structure comprises a plurality of springs for contacting said carrier and for urging a predetermined portion of said carrier toward the reference location.

26. An alignment apparatus according to Claim 19 wherein the alignment apparatus is a fiber optic connector comprising:

a connector housing defining a plurality of apertures through which optical signals are transmitted; and

a plurality of microactuators disposed within said connector housing for precisely aligning the optical fibers carried by said microactuators with respective ones of the apertures defined by said connector housing.

27. An alignment apparatus according to Claim 26 wherein the fiber optic connector further comprises a plurality of lens elements disposed at

least partially within respective ones of the plurality of apertures defined by said connector housing such that said plurality of microactuators precisely align the optical fibers with respective ones of said plurality of lens elements.

28. An alignment apparatus according to Claim 27 wherein each lens element comprises a metallized portion adapted to be disposed within a respective aperture defined by said connector housing such that the respective lens element can be affixed therein.

29. A microactuator for precisely aligning an optical fiber with an optical device, the microactuator comprising:

a carrier comprising a carrier body defining a groove therein for receiving the optical fiber and for maintaining the optical fiber in a fixed relation relative to said carrier; and

at least one bimorphic actuator having first and second layers comprised of first and second materials, respectively, wherein the first and second materials respond differently to electrical stimuli such that said bimorphic actuator is controllably deflected by electrical stimuli to thereby position said carrier relative to the optical device such that the optical fiber is precisely aligned with the optical device.

30. A microactuator according to Claim 29 wherein said bimorphic actuator is comprised of first and second layers comprising first and second materials, respectively, and having first and second coefficients of thermal expansion, respectively, and wherein said microactuator further comprises current supply means for providing current to said bimorphic

actuator such that the first and second materials differentially expand to thereby deflect said bimorphic actuator.

31. A microactuator according to Claim 29 wherein the second layer of said bimorphic actuator is comprised of a piezoelectric material, and wherein the microactuator further comprises voltage supply means for providing a voltage to said bimorphic actuator such that said bimorphic actuator is deflected.

32. A microactuator according to Claim 29 wherein said bimorphic actuator comprises an elongate central portion extending between opposed end portions, and wherein the opposed end portions are affixed to said carrier body such that the elongate central portion bends in response to the electrical stimuli.

33. A microactuator according to Claim 29 further comprising an alignment support structure, disposed in a fixed relation to the optical device, for supporting said carrier.

34. A microactuator according to Claim 29 wherein said carrier further comprises first and second bimorphic actuators, each bimorphic actuator comprising first and second layers comprised of first and second materials, respectively, which respond differently to electrical stimuli, and wherein said first and second bimorphic actuators are disposed such that said first and second bimorphic actuators deflect in first and second orthogonal directions, respectively, in response to the electrical stimuli to thereby controllably position said carrier in the first and second orthogonal directions relative to said alignment support structure.

35. A microactuator according to Claim 34 wherein said carrier further comprises a third bimorphic actuator having first and second layers comprised of first and second materials, respectively, which respond differently to electrical stimuli, and wherein said third bimorphic actuator is disposed so as to deflect in a third direction, orthogonal to the first and second directions, in response to electrical stimuli to thereby controllably position said carrier in the third direction relative to said alignment support structure.

36. A microactuator according to Claim 33 wherein said alignment support structure defines a reference location, and wherein said alignment support structure further comprises bias means for urging a predetermined portion of said carrier toward the reference location defined by said alignment support structure.

37. A microactuator according to Claim 36 wherein said bias means of said alignment structure comprises a plurality of springs for contacting said carrier and for urging the predetermined portion of said carrier toward the reference location.

38. A method of precisely aligning an optical fiber with an optical device, the method comprising the steps of:

mounting a carrier on an alignment support structure, wherein the alignment support structure is disposed in a fixed relation to the optical device, and wherein the carrier includes at least one bimorphic actuator having first and second layers comprised of first and second materials, respectively, which respond differently to electrical stimuli;

disposing the optical fiber in a fixed position relative to a carrier; and

deflecting the bimorphic actuator such that the bimorphic actuator is operably urged against a portion of the alignment support structure to thereby controllably position the carrier relative to the alignment support structure such that the optical fiber is precisely aligned with the optical device.

39. A method according to Claim 38 wherein said deflecting step comprises the step of electrically stimulating the bimorphic actuator of the carrier.

40. A method according to Claim 38 further comprising the step of bonding the carrier to the alignment support structure following said deflecting step.

41. A method according to Claim 38 wherein the optical device is a lens element, and wherein the method further comprises the step of disposing the lens element in a fixed position relative to the alignment support structure prior to said deflecting step such that the optical fiber is thereafter precisely aligned with the lens element.

42. A method according to Claim 41 wherein said mounting step comprises the step of mounting a plurality of carriers on the alignment support structure, wherein said step of disposing an optical fiber in a fixed position relative to the carrier comprises the step of mounting an optical fiber on each carrier, wherein said step of disposing a lens element in a fixed position relative to the alignment support structure comprises the step of disposing a plurality of lens elements in respective fixed positions relative to the alignment support structure, and wherein said

deflecting step comprises the step of individually deflecting the bimorphic actuator of each carrier such that each carrier is controllably positioned relative to the alignment support structure and the optical fiber mounted on each carrier is precisely aligned with a respective lens element.

43. A method according to Claim 41 further comprising the steps of:

disposing the alignment support structure and the carrier within a connector housing; and

hermetically sealing the connector housing with the alignment support structure and the carrier disposed therein prior to said deflecting step.

44. A method according to Claim 43 wherein the connector housing defines at least one aperture therein, and wherein said step of disposing the lens element in a fixed position relative to the alignment support structure comprises the step of at least partially disposing the lens element in the aperture defined by the connector housing.

45. A method according to Claim 44 wherein the lens element is at least partially metallized, and wherein said step of at least partially disposing the lens element the aperture defined by the connector housing comprises the step of soldering the metallized portion of the lens element to the connector housing.

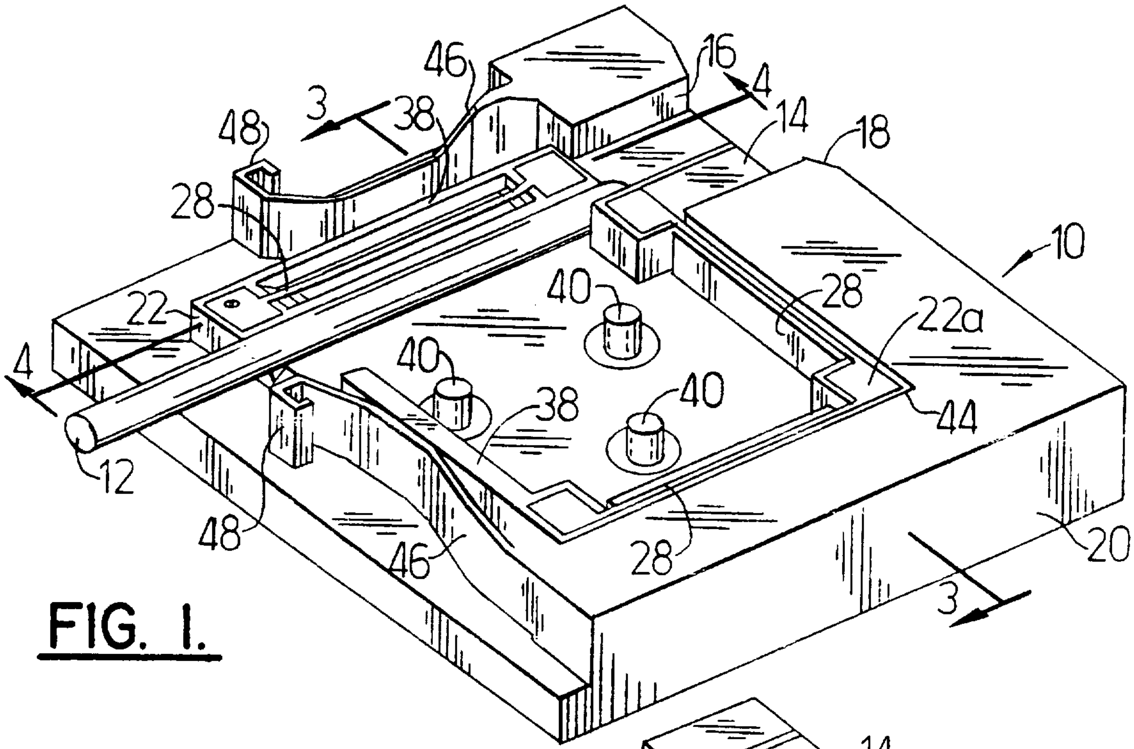
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FIG. 1.

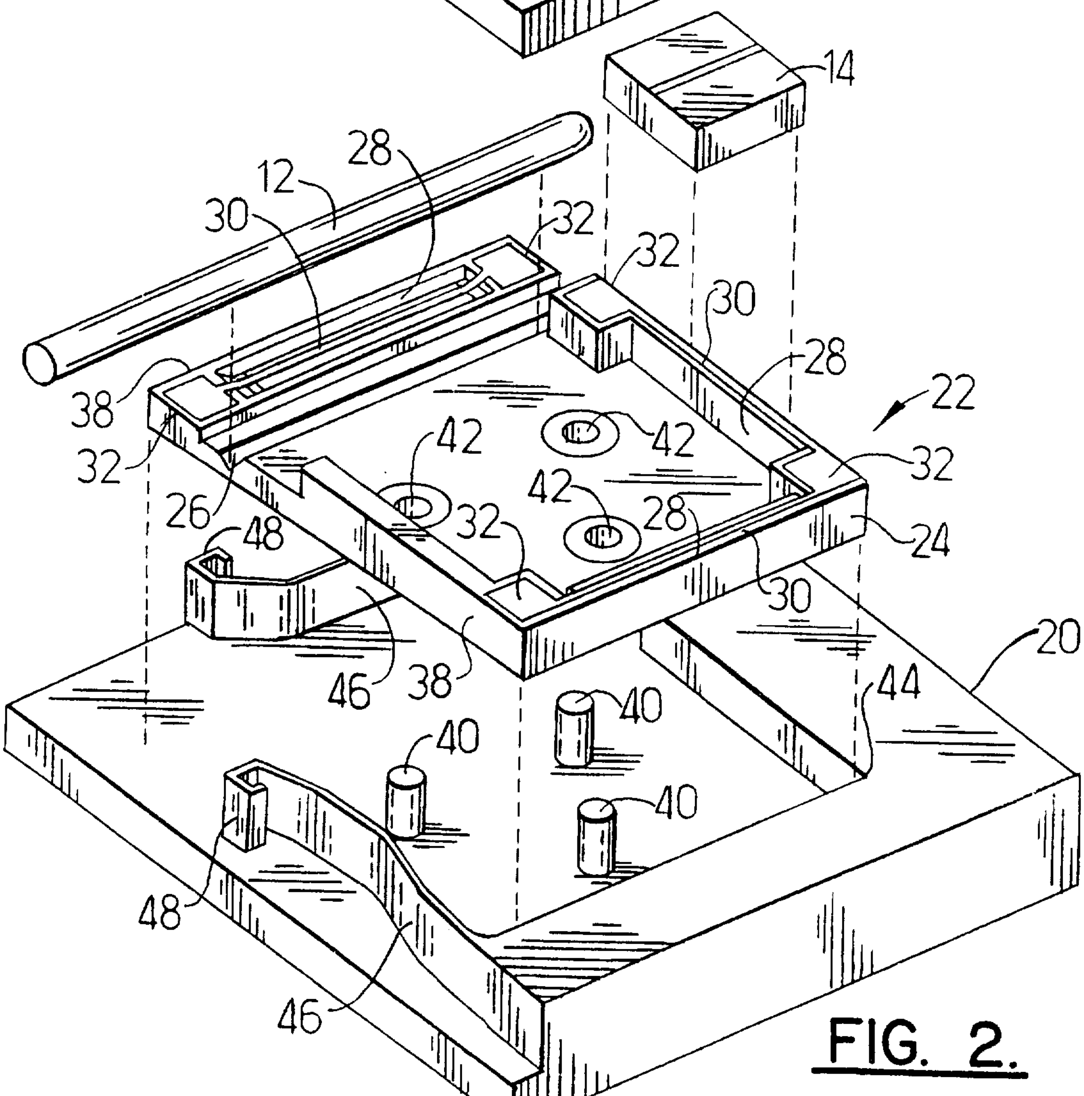
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FIG. 2.

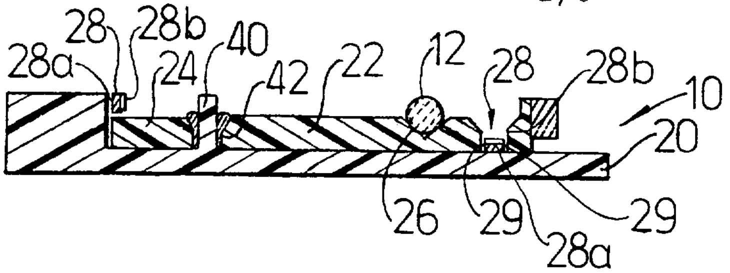


FIG. 3.

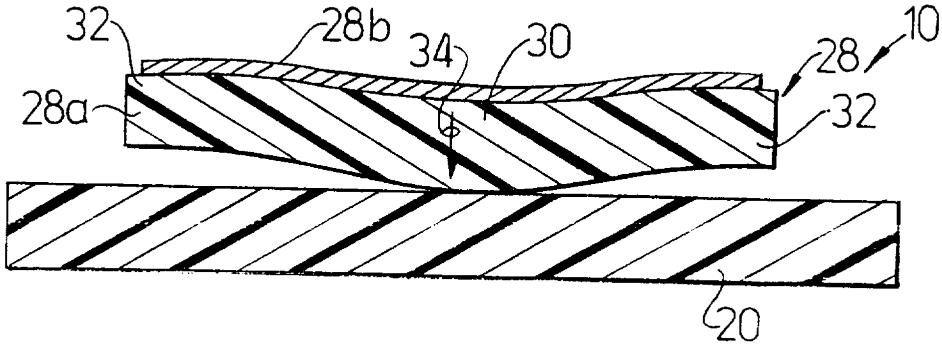


FIG. 4.

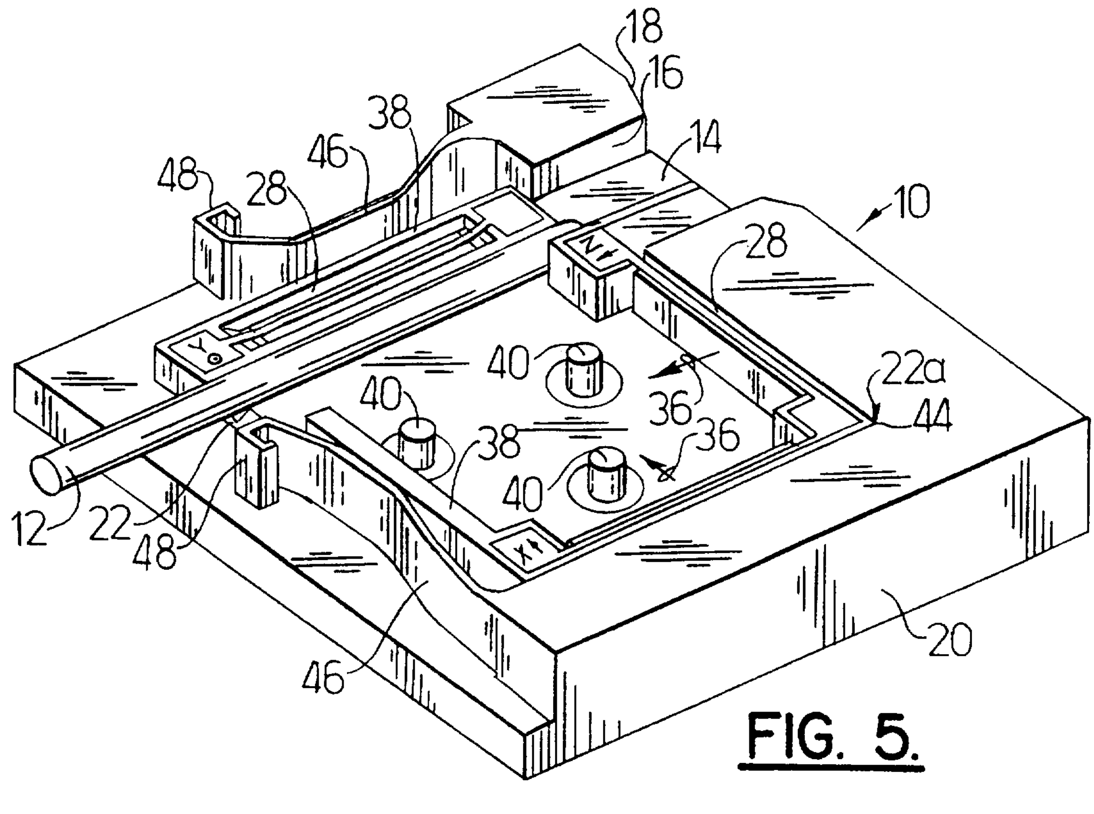


FIG. 5.

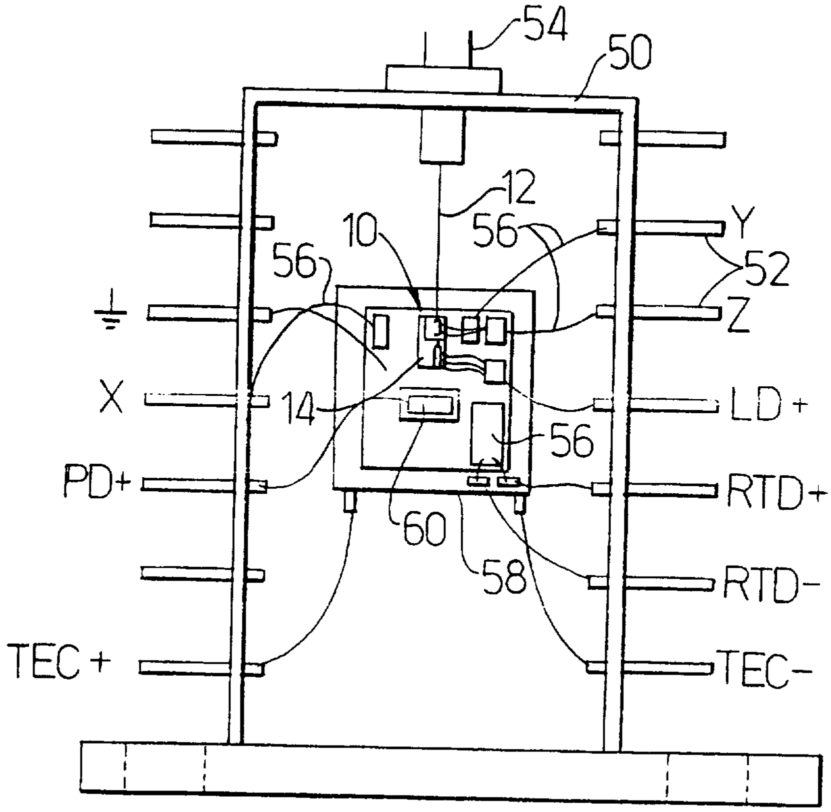


FIG. 6.

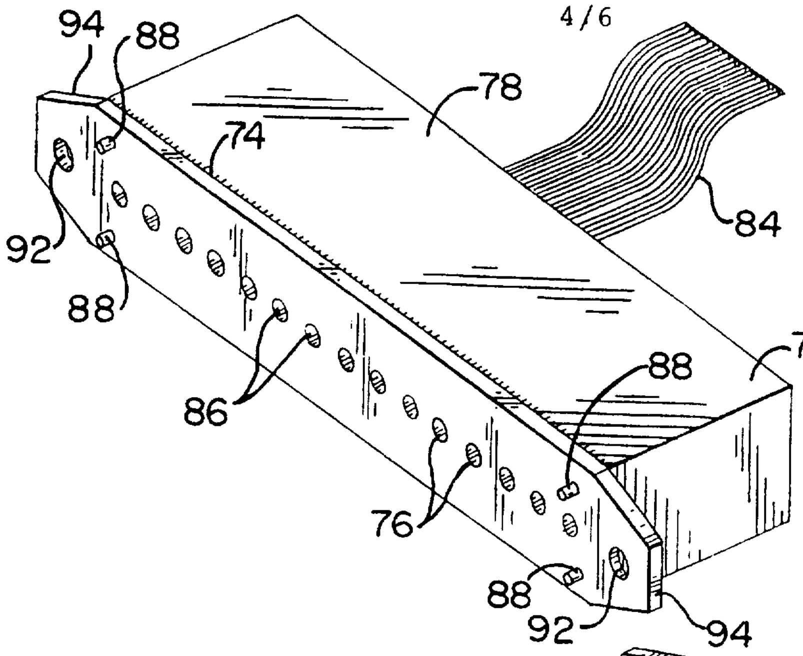


FIG. 7.

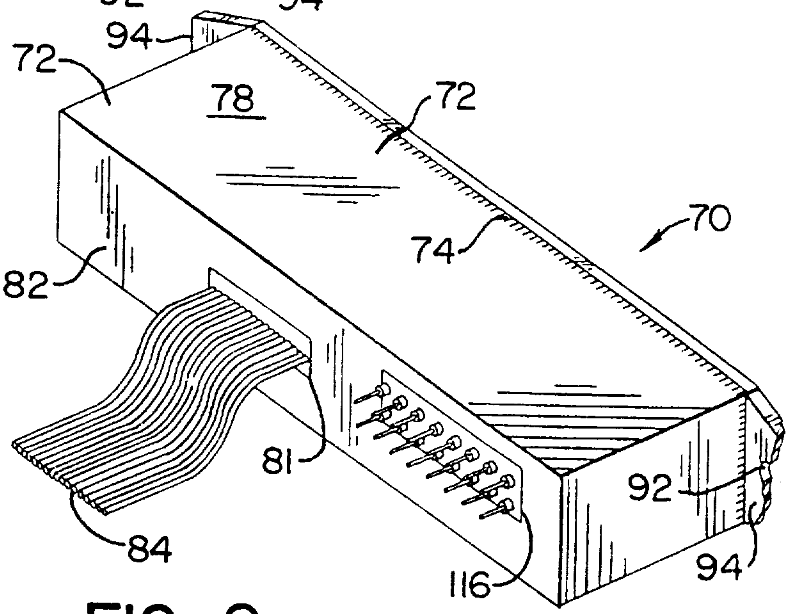


FIG. 8.

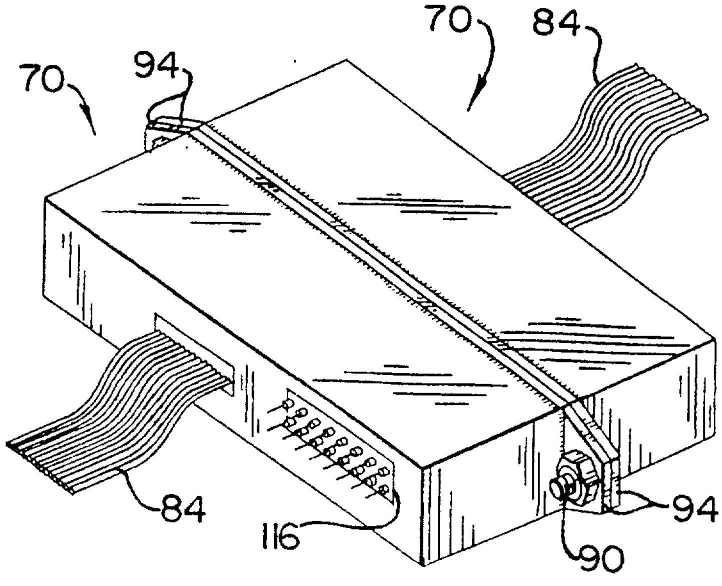


FIG. 9.

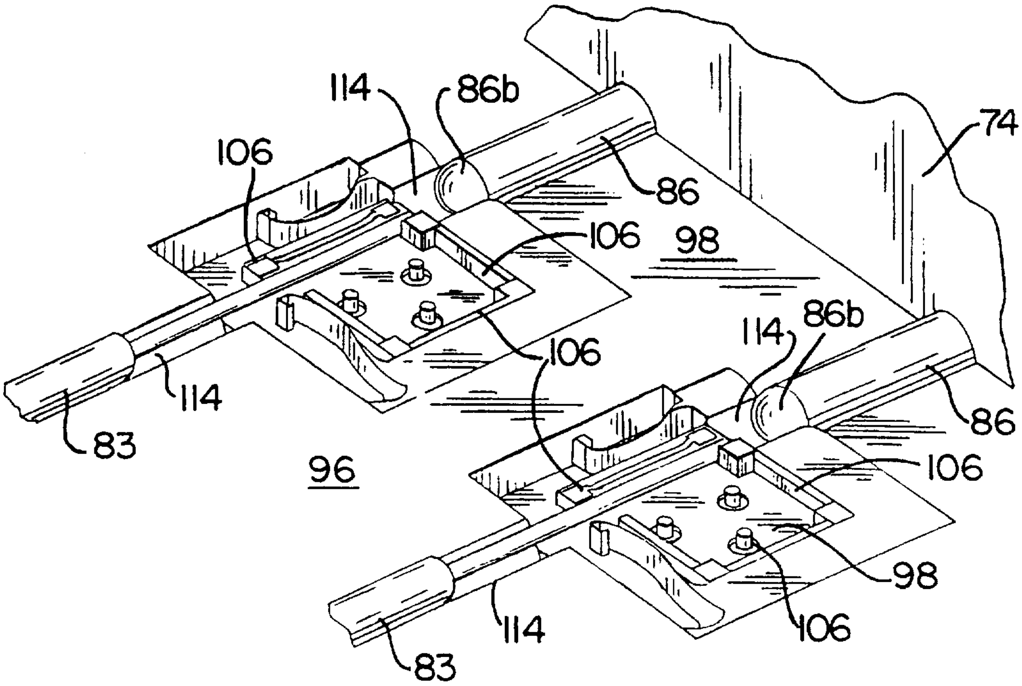
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FIG. 10.

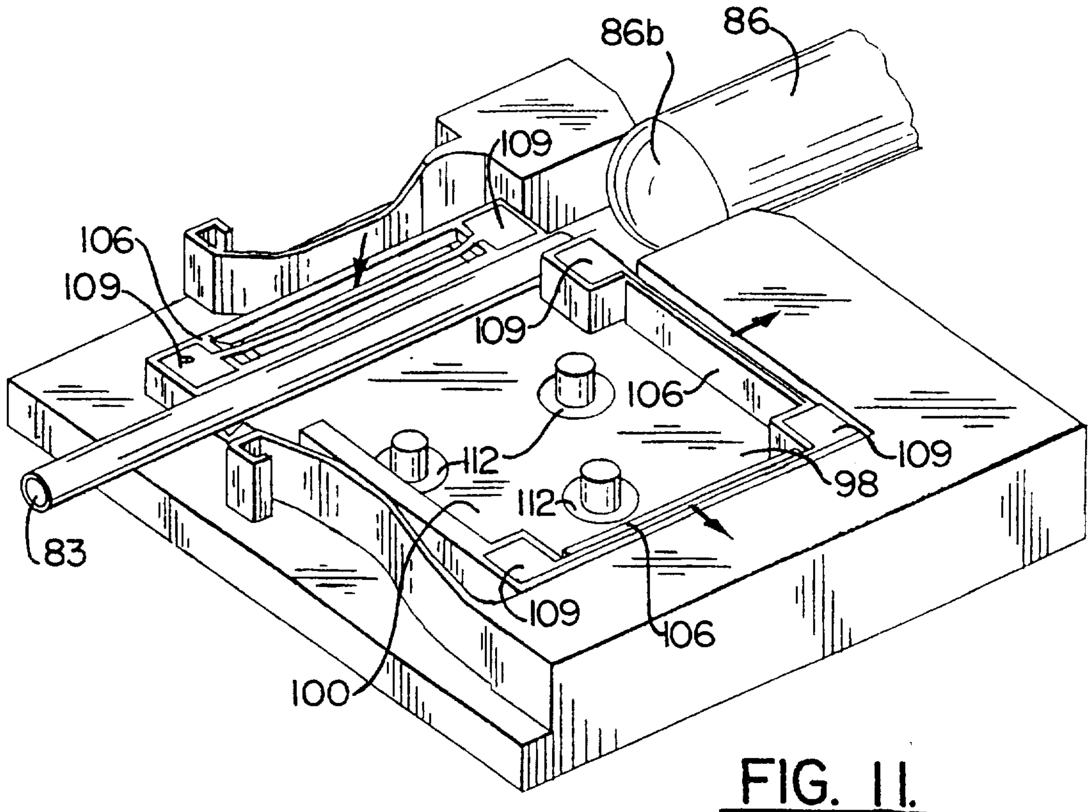
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FIG. 11.

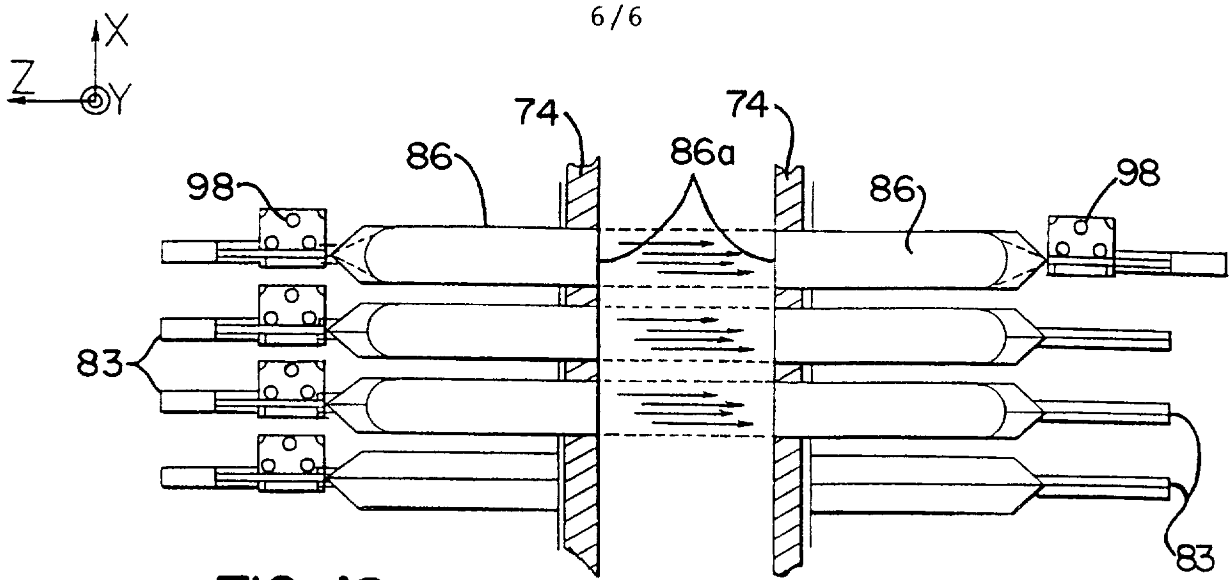


FIG. 12.

# INTERNATIONAL SEARCH REPORT

Intu ional Application No
PCT/US 96/15213

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B6/42 G02B6/32 G02B6/255 G02B7/00 H01L41/00

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

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

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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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| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 29 May 1997 | 06.06.97 |

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

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Inte[illegible]onal Application No
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