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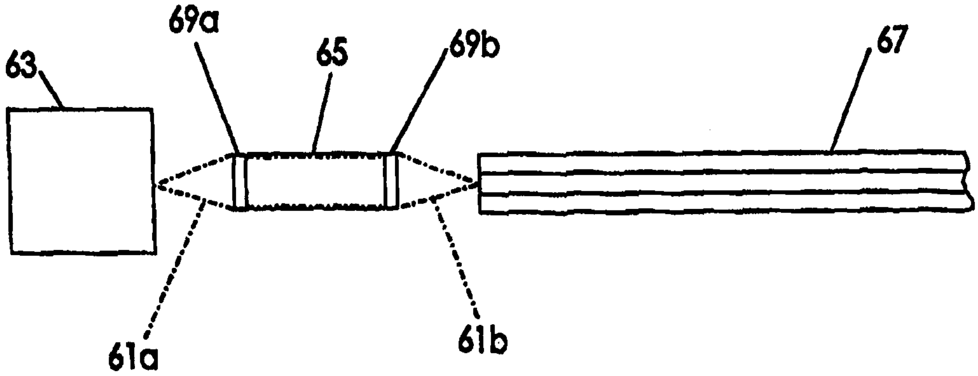

(57) Abstract

An optical transmission system includes an optical rod (65) and a radiation source (63) coupled thereto. In particular, the optical rod (65) has a length of approximately 6 millimeters or less and a width of approximately 1mm or less, and the optical rod has a three–dimensional pattern (69a or 69b) on an end thereof. The radiation source is coupled to the optical rod so that radiation generated by the optical source is transmitted through the rod along an axis thereof and through the three–dimensional pattern thereon. This optical rod can have a cylindrical shape, and the three–dimensional pattern can be a diffractive pattern so that the end of the rod has a stepped profile. Radiation (61b) out of the rod (65) is thus focused into the core of the optical fiber (67). The three dimensional patterns are preferably diffractive patterns, but refractive patterns can also be used. Moreover, the laser, the rod and the fiber can be aligned using a substrate including a V–groove, or aligned within a sleeve (or tube).

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OPTICAL TRANSMISSION SYSTEMS INCLUDING OPTICAL RODS WITH THREE-DIMENSIONAL PATTERNS THEREON AND RELATED STRUCTURES

The U.S. Government may have rights to the present invention under government contract No. N00178-97-C-3058 issued by the Naval Surface Warfare Center.

Related Applications

The present application claims priority based on Provisional Patent Application Serial No. 60/043,285, filed April 11, 1997, entitled "Wafer Processing of Multiple Glass Rods For Incorporating Optical Elements On The Ends Thereof", the disclosure of which is hereby incorporated herein in its entirety by reference. The present application is also related to U.S. Patent Application Serial No. 08/991,803 entitled "Methods of Forming Optical Rods Including Three Dimensional Patterns On End Faces Thereof" filed concurrently herewith (Attorney Docket No. 9020-3), the disclosure of which is hereby incorporated herein in its entirety by reference.

Field of the Invention

The present invention relates to the field of optics and more particularly to optical systems and structures.

Background of the Invention

Single mode fiber optic data links have been developed as alternatives to multimode fiber data links. In a single mode fiber, a single spatial mode propagates therethrough so that modal noise effects are reduced. Single mode optical systems, however, may be extremely sensitive to alignment errors. Sensitivity to alignment errors may be particularly critical when a data link is used in an extreme environment with exposure to vibrations and shock. A need thus exists to provide single mode fiber optic connections which have reduced sensitivity to shocks and vibrations. Dust and debris may also be problematic in single mode fiber connections known in the prior art.

A single mode fiber optic connection according to the prior art is illustrated in Figures 1 and 2. As shown, two single mode optical fibers **11** are inserted into ferrules **13** that are held together with a spring loaded stainless steel jacket **15**. The springs keep the ferrules in compression in an attempt to keep the ferrules in contact at all times. A ceramic sleeve **17** surrounds the ferrules to keep the ferrules and the fibers aligned in the transverse direction. This sleeve is thus precisely machined to tolerances within 1 micron on the inner diameter. Accordingly, as light is transmitted from a first one of the fibers across the junction to the second fiber, residual losses may occur.

The ferrules, however, may piston in and out of the sleeve as a result of severe shocks and/or vibrations thereby creating a gap between the two fibers **11**. This gap may increase optical losses beyond acceptable levels. Moreover, a single dust particle between the respective core portions of the two optical fibers may block a significant portion of the radiation being transmitted therebetween.

Gradient Index (GRIN) lenses have been used to collimate and focus light in fiber switching and connecting systems. GRIN lenses, however, may be quite large in comparison with the dimensions of optical fibers thus increasing overall package sizes and reducing switching densities. GRIN lenses may also be limited to simple optical focusing and collimation functions while current broadband networks may require complex functions for Wavelength Division Multiplexing (WDM).

Accordingly, there continues to exist a need in the art for improved systems and structures for collimating, focusing, and otherwise processing electromagnetic radiation such as light.

Summary of the Invention

It is therefore an object of the present invention to provide improved optical systems and structures.

It is another object of the present invention to provide improved beam shaping systems and structures.

It is still another object of the present invention to provide improved optical rods and related systems.

These and other objects are provided according to the present invention by optical systems including an optical rod having a length of approximately 6 millimeters or less and a width (or diameter) of approximately 1mm or less wherein the optical rod has a three-dimensional pattern on an end thereof. In addition, a radiation source is coupled to the optical rod so that radiation generated by the radiation source is transmitted through the rod along an axis thereof and through the three-dimensional pattern thereon. Improved micro-optical systems can thus be provided wherein light from a laser or an optical fiber is processed by the three-dimensional pattern on the end of the optical rod. In particular, the dimensions of the optical rod can be compatible with those of conventional optical fibers and/or GRIN lenses so that the optical rod can be coupled to the end of an optical fiber without significantly increasing the size of the package including the optical fiber together with the optical rod. For example, a patterned optical rod according to the present invention can be a patterned glass rod having a width (or diameter) of approximately 125 microns thus being dimensionally compatible with conventional optical fibers. Alternately, the patterned optical rod can be a patterned GRIN lens having a width (or diameter) of approximately 250 microns or 500 microns.

More particularly, the optical rod can have a cylindrical shape, and the three-dimensional pattern can be a diffractive pattern so that the end of the rod has a stepped profile. Alternately, the three-dimensional pattern can be a refractive pattern so that the end of the rod has a profile such as a rounded profile. According to another alternative, the three-dimensional pattern can be a patterned layer so that a first portion of the end of the rod is covered by the patterned layer and so that a second portion of the end of the rod is exposed by the patterned layer. Here, the patterned layer can be a patterned reflective layer such as a patterned metal layer or a patterned dielectric layer. In each of the above examples, precise three-dimensional optical patterns can be provided on the end of a micro-optical rod according to the present invention. More particularly, these three-dimensional patterns can be radially symmetric thus reducing the need for rotational alignment thereof.

A fiber can be optically coupled to the rod to receive the radiation transmitted therethrough, and/or a fiber can be optically coupled between the radiation source and the rod so that radiation is transmitted from the radiation source through the fiber to the rod. The optical rods according to the present invention can thus be incorporated into many optical systems implemented with optical fibers. The three-dimensional patterns formed on the optical rods of the present invention can be used to provide beam shaping functions, pattern generation functions, diffusion functions, collimating functions, focusing functions, and/or wavelength division multiplexing functions.

The optical rod of the present invention can have a uniform index of refraction along a cross-section thereof. Alternately, the optical rod can be a gradient index lens having a graded index of refraction along a cross-section thereof. By providing a diffractive pattern on a gradient index (GRIN) lens, shifts in the focal length of the gradient index lens due to changes in temperature can be reduced. In other words, the diffractive pattern can be used to provide athermalization of the gradient index lens. Furthermore, a second three-dimensional pattern can be provided on a second end of the rod opposite the first end. Light passing through the optical rod will thus pass through 2 three-dimensional patterns. Moreover, the transmission system can include a substrate having a groove therein, and the optical rod can be mounted in the groove adjacent the radiation source. Accordingly, the groove can be used to align the optical rod with respect to the radiation source.

The optical transmission system can also include a second optical rod having a second three-dimensional pattern on an end thereof. More particularly, the second rod is optically coupled to the first rod so that radiation is transmitted from the first rod through the second rod along an axis thereof and through the second three-dimensional pattern. In particular, the radiation source may generate divergent radiation which is collimated by the first three-dimensional pattern on the first optical rod, and which is focused by the second three-dimensional pattern on the second optical rod. The transmission system including two optical rods can thus be used to provide a coupling between two optical fibers.

Alternately, the transmission system including two optical rods can be used to provide a fiber optic sensor wherein an optically sensitive material is located along the path of the radiation between the first and second rods, and wherein a sensor is optically coupled to the second rod to receive the radiation. In particular, an optical transmission characteristic of the optically sensitive material changes in response to an environmental change, and the sensor detects changes in the transmission of the radiation through the optically sensitive material to sense the environmental change.

The transmission system including two optical rods can also be used to provide an optical isolator including a Faraday rotator and first and second polarizers. In particular, the Faraday rotator is located in a path of the radiation between the first and second rods, and the first and second polarizers are located on opposite sides of the Faraday rotator in the path of the radiation. The radiation is thus transmitted from the first optical rod through the first polarizer, through the Faraday rotator, and through the second polarizer to the second optical rod.

According to an alternate aspect of the present invention, an optical rod is provided having a length of approximately 6 millimeters or less and a diameter of approximately 1mm or less wherein the optical rod has a three-dimensional pattern on an end thereof. This optical rod can be used in many micro-optical systems as discussed above. More particularly, the patterned rod can be a patterned glass rod having a width (or diameter) of approximately 125 microns, or the patterned rod can be a patterned GRIN lens having a width or diameter of 500 microns or 250 microns, for example.

The systems and structures of the present invention can thus be used to provide improved micro-optical transmission systems. In particular, a micro-optical rod including a three-dimensional optical pattern on an end thereof can be accurately coupled with other optical elements such as laser diodes and/or optical fibers. By providing radially symmetric patterns, the need for rotational alignment can be reduced, and by providing optical rods with diameters on the order of that of a corresponding optical fiber, packaging sizes can be reduced.

Brief Description of the Drawings

Figure 1 is a cross sectional view of an fiber optic connector according to the prior art.

Figure 2 is a greatly enlarged cross sectional view of the sleeve, ferrules, and optical fibers of Figure 1.

Figure 3a is a cross sectional view of an expanded beam fiber optic connector including a glass rod according to the present invention.

Figure 3b is an enlarged cross sectional view of a glass rod of Figure 4.

Figure 4a is an photograph of a patterned end of a glass rod according to the present invention.

Figure 4b is a graph illustrating connector losses as a function of longitudinal separation for a butt coupled fiber optic connector (circles) according to the prior art and for an expanded beam fiber optic connector (squares) including glass rods according to the present invention.

Figure 5a is a cross-sectional view of an optical rod including a three-dimensional diffractive pattern on an end thereof according to the present invention.

Figure 5b is a cross-sectional view of an optical rod including a three-dimensional refractive pattern on an end thereof according to the present invention.

Figure 5c is a cross-sectional view of an optical rod including there-dimensional pattern on an end thereof according to the present invention.

Figure 6 is a block diagram illustrating a first laser-to-fiber coupler according to the present invention.

Figure 7 is a block diagram of a second laser-to-fiber coupler according to the present invention.

Figure 8 is a cross-sectional view of an optical rod providing a beam shaping function according to the present invention.

Figure 9 is a cross-sectional view of an optical rod providing a pattern generation function according to the present invention.

Figure 10 is a cross-sectional view illustrating an optical rod providing a diffusion function according to the present invention.

Figure 11 is a cross-sectional view illustrating a laser diode collimator corrector according to the present invention.

Figure 12 is a cross-sectional view of a fiber optic sensor according to the present invention.

Figure 13 is a cross-sectional view of an optical isolator according to the present invention.

Figure 14 is a cross-sectional view of an endoscope including optical rods according to the present invention.

Figure 15 is a cross-sectional view of an optical rod providing a wavelength division multiplexing function according to the present invention.

Figure 16 is a cross-sectional view of a system for reducing the coherence of a laser output including optical rods according to the present invention.

Figures 17a-17f are views of reflective patterns provided on the ends of the optical rods of Figure 16.

Figures 18 and 19 are plan views of an optical system according to Figure 16 provided on a substrate having a V-groove therein.

Detailed Description

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are 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, these embodiments are 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. In the drawings, the dimensions of elements are exaggerated for clarity. Like numbers refer to like elements throughout. It will also be understood that when an element is referred to as being "on" another element, it can be directly on the other element, or intervening elements may also be present.

An optical fiber connector including an optical rod according to the present invention is illustrated in Figures 3a and 3b. As shown, two optical fibers **21a** and **21b** are inserted into respective ferrules **23a** and **23b** which are aligned within the sleeve **25** as before. In addition, the glass rods **27a** and **27b** are provided at the ends of the respective optical fibers within the ferrules. As shown in Figure 3b, an epoxy **29** can be used to bond the glass rod **27a** to the end of the optical fiber **21a**, and a three dimensional pattern **31a** can be provided on the end of the glass rod **27a** opposite the optical fiber **21a**. In particular, the three-dimensional pattern **31a** can be used to provide a diffractive lens or a refractive lens on the end of the glass rod. Similarly, an epoxy can be used to bond the optical fiber **21b** and the glass rod **27b**, and a three-dimensional pattern **31b** can be provided on the end of the glass rod **27b** opposite the optical fiber **21b**.

The glass rods **27a** and **27b** can each be provided with a diffractive lens as discussed above to reduce optical losses for light transmitted between the two optical fibers **21a** and **21b**. The operation of the glass rods will now be discussed with reference to Figure 3a for electro-magnetic radiation such as light being transmitted from the first optical fiber **21a** to the second optical fiber **21b**. Light is generally transmitted through the central core region of an optical fiber. Accordingly, light transmitted through the first optical fiber **21a** will expand as it passes through the glass rod **27a** which has a uniform index of refraction across its diameter. The diffractive lens **31a** can thus be used to collimate the expanded beam. The diffractive lens **31b** on the second glass rod **27b** can then be used to focus the expanded and collimated beam into the core of the second optical fiber **21b**.

The end face of a glass rod with a diffractive lens patterned thereon is illustrated in the photograph of Figure 4a. In particular, the diffractive lens of Figure 4a is an eight phase-level diffractive pattern etched onto a 125 micron diameter glass rod. This micro-optical rod can thus fit snugly into a standard ferrule to provide an expanded beam optical fiber connection having coupling efficiencies with losses of less than 1 dB and having a high degree of collimation. In addition, the diffractive pattern can be radially symmetric so that radial alignment of the rod is not necessary.

The sensitivity to vibrations and shocks can thus be reduced because the expanded and collimated beam can traverse varying gaps between the glass rods with reduced optical losses. As shown in Figure 4b, the optical losses with respect to displacement are relatively invariant for expanded beam connectors. As further shown in Figure 4b, the optical losses increase rapidly with increasing displacements in conventional connectors. In other words, the performance of the conventional connector degrades rapidly as a function of separation distance. Furthermore, a single dust particle between the two optical rods may block only a small portion of the expanded beam of light transmitted therebetween thus reducing the losses due to dust.

Diffractive lenses can be used instead of the refractive ball lenses of the prior art. Diffractive lenses have the advantages of reduced birefringence and/or aberration effects because diffractive lenses can provide nearly perfect lens functions when patterned onto the rods. Methods of forming glass rods according to the present invention are discussed, for example, in copending Patent Application Serial No. 08/991,803 entitled "Methods Of Forming Optical Rods Including Three-Dimensional Patterns On End Faces Thereof" (Attorney Docket No. 9020-3) and filed concurrently herewith, the disclosure of which is hereby incorporated herein in its entirety by reference.

Figure 5a is a cross sectional side view of an optical rod **41** according to the present invention. The optical rod has a length **l** and a diameter **d** (or width), and at least one end of the optical rod has a three-dimensional pattern **43** thereon. More particularly, the optical rod can have a cylindrical shape, and the three-dimensional pattern **43** can be a diffractive pattern so that the end of the rod has a stepped profile. As shown in Figure 5b, the three dimensional pattern can be a refractive pattern **46** with the end of the rod **45** having a rounded profile. As shown in Figure 5c, the three-dimensional pattern can be a patterned layer **49** on the end of the optical rod **48**. More particularly, the patterned layer **49** can be a highly reflective dielectric layer or a metal layer.

The rod can have a length of less than approximately 6mm and a width (or diameter) of less than approximately 1mm. In particular, the optical rod can have a diameter of approximately 125 microns which can be approximately the same as that of an optical fiber to which the rod is to be coupled thus reducing the dimensions of the coupling. Furthermore, three-dimensional patterns can be provided on both ends of these optical rods. The optical rods can be glass rods having uniform indexes of refraction therethrough, or the optical rods can be gradient index (GRIN) lenses which can have widths (or diameters) of 500 microns or 250 microns, for example.

The optical rods **43** of the present invention can thus be coupled to radiation sources to provide various optical functions as will be discussed in greater detail below. For example, optical rods with diffractive patterns on ends thereof can be used to provide beam shaping functions, pattern generation functions, diffusion functions, collimating functions, and/or focusing functions.

Optical rods according to the present invention can be used to provide laser-to-fiber couplers, also known as fiber pigtails. In Figure 6, electromagnetic radiation **61** from a radiation source **63**, such as a laser, is transmitted through the optical rod **65** to the core of the optical fiber **67**. In particular, three dimensional patterns **69a** and **69b** are provided on opposing ends of the optical rod **65** so that divergent radiation **61a** generated by the source **63** is first collimated by the three-dimensional pattern **69a**, and then focused by the three-dimensional pattern **69b**. Radiation **61b** out of the rod **65** is thus focused into the core of the optical fiber **67**. The three dimensional patterns are preferable diffractive patterns, but refractive patterns can also be used. Moreover, the laser, the rod, and the fiber can be aligned using a substrate including a V-groove, or aligned within a sleeve (or tube).

An alternative coupler is illustrated in Figure 7 wherein a first three-dimensional pattern **79a** is provided on an end of a first optical rod **75a**, and a second three-dimensional pattern **79b** is provided on a second optical rod **75b**. The two optical rods **75a** and **75b** can be separated by a transparent rod **78** or a space. Divergent radiation **71a** generated by the laser **73** is thus transmitted into the first optical rod **75a** and collimated by the first three-dimensional pattern **79a**. The collimated light is then transmitted through the transparent rod **78** and focused by the second three-dimensional pattern **79b**. The focused radiation **71b** is then transmitted through the second optical rod **75b** into the core of the optical fiber **77**. Moreover, the optical rods **75a** and **75b**, the transparent rod **78**, and the optical fiber **77** can be aligned within a sleeve (or tube) **76** or using a substrate including a V-groove. Again, the three-dimensional patterns are preferably diffractive patterns, but refractive patterns can also be used.

Figures 8, 9, and 10 illustrate various optical functions that can be provided by patterned optical rods according to the present invention. Each of these figures illustrates an optical rod according to the present invention optically coupled to a fiber wherein radiation is transmitted from the optical fiber into the optical rod and an optical function performed thereon by the respective three-dimensional diffractive pattern. A laser or other radiation source can be coupled to an opposite end of the respective fiber to provide the radiation. Moreover, each of the three-dimensional patterns is preferably a diffractive optical pattern.

In Figure 8, radiation is transmitted from the core **81** of the optical fiber **83** into the optical rod **85** where the radiation diverges. A beam shaping function is then performed as the divergent radiation **87** passes through the three-dimensional pattern **89**. A desired beam shape can thus be provided on the output plane **88**. Beam shaping functions can shape the beam to different shapes without creating significant splitting or combining. In other words, each point on the three-dimensional pattern **89** is mapped to one point in the output plane **88**. Examples include circular flat-top beams, rectangular flat-top beams, elliptical beams, lines, and axicons. A focusing lens is an example of a beam shaper, but a focusing lens may produce a Gaussian beam, and a focusing lens may be provided by a refractive three-dimensional pattern. More universal beam shaping can be provided using diffractive three-dimensional patterns. When using a beam shaping function to form a circular beam, the circular beam output may include any non-uniformities that are in the input beam. Diffractive patterns used to provide beam shaping functions are discussed, for example, in copending Patent Application Serial No. 08/917,865 (Attorney Docket No. 2657-0110P) entitled "Integrated Beam Shaper And Use Thereof" and filed August 27, 1997. The disclosure of this application is hereby incorporated herein in its entirety by reference.

In Figure 9, an optical rod **95** includes a three-dimensional pattern **99** used to provide a pattern generation function. As shown, radiation is transmitted from the core **91** of the optical fiber **93** into the optical rod **95**. A pattern generation function is then performed as the divergent radiation **97** passes through the three-dimensional pattern **99**. Desired patterns such as multiple spots, a gray scale image, a grid, or multiple lines, can thus be provided.

Similar to a true hologram, radiation from each point in the three-dimensional diffractive pattern contributes to each point in the output plane **98**.

In Figure 10, an optical rod **105** includes a three-dimensional pattern **109** used to provide a diffusion function. As shown, radiation is transmitted from the core **101** of the optical fiber **103** into the optical rod **105**. A diffusion function is then performed as the divergent radiation **107** passes through the three-dimensional pattern **109**. A diffused beam is thus produced on the output plane **108**. In a diffuser, each point in the diffractive plane contributes to each spot in the output plane, and each point in the diffractive plane sends radiation to the entire output region. The output can be a circular beam. For a circular output beam, the output of the diffuser will be homogenized so that non-uniformities in the input will be reduced in the circular output beam. If the beam is coherent, however, a diffuser may generate a speckle pattern with random bright and dark spots.

An optical rod according to the present invention can also be used to provide an integrated laser diode optical structure as shown in Figure 11. As shown, the integrated structure is fabricated on a silicon substrate **111** having a V-groove **113** in a surface thereof, and the optical rod **115** is bonded or otherwise mounted in the V-groove. The V-groove **111** can be formed in the silicon substrate by isotropically etching a predetermined unmasked portion of the silicon substrate using an etchant such as a KOH solution. Moreover, the mask used to form the V-groove can be formed photolithographically thus allowing precise placement of the V-groove so that the optical rod can be positioned accurately.

A radiation source **117**, such as a laser diode, is shown mounted on the substrate adjacent the optical rod **115**, and the optical rod includes a first three-dimensional pattern **118** and a second three-dimensional pattern **119** on opposite ends thereof. Each of the three-dimensional patterns can be a diffractive pattern, a refractive pattern, or a hybrid pattern including diffractive and refractive components. Accordingly, divergent radiation **110** generated by the radiation source is collimated by the first three-dimensional pattern **118**. The collimated radiation **112** is transmitted through the optical rod **115** to the second three-dimensional pattern **119** where an optical function is performed on the collimated radiation. For example, the structure of Figure 11 can be used to provide beam shaping, pattern generation, and/or diffusion. In addition, the structure of Figure 11 can be used to circularize an elliptical beam generated by an edge emitting laser diode. Because the radiation source and the V-groove can be accurately positioned on the substrate, a high degree of alignment can be provided between the optical rod and the radiation source.

For example, a single photolithography step can be used to pattern the V-groove and to provide alignment markings for the placement of the laser. Accordingly, the laser can be precisely positioned relative to the V-groove and the optical rod in the V-groove. In addition, one end of the V-groove can be made steep and an end face of the rod can be butted against the steep end of the V-groove to control a distance from the laser to the end of the rod.

More particularly, a laser may produce an elliptical beam which is converted to a single circular beam. By including a three-dimensional pattern on each of the opposing ends, the rod and laser may be less sensitive to misalignment. Alternately, the optical rod of Figure 11 can be provided with only a single focusing three-dimensional diffractive pattern **119** opposite the radiation source **117**. The integrated structure of Figure 11 may be particularly useful for barcode scanning applications. The V-groove structure provides precise passive alignment between the radiation source and the optical rod in the x, y, and z axes. Moreover, rotational alignment of the optical rod may be unnecessary because three-dimensional diffractive and refractive patterns can be radially symmetric about the end of a cylindrical optical rod.

Optical rods according to the present invention can also be used in the fabrication of a fiber optic sensor as shown in Figure 12. In particular, radiation is transmitted from the core **121** of the optical fiber **123** into the optical rod **125** where the resulting divergent radiation **127** is collimated by the three-dimensional pattern **129** on the end of the optical rod **125**. The collimated radiation **131** is transmitted through an optically sensitive material **133** wherein a transmission characteristic of the optically sensitive material changes in response to an environmental change. For example, the transmission characteristic of the optically sensitive material can change as a function of temperature, pressure, and/or the presence or absence of a predetermined chemical.

The collimated radiation is then transmitted through the three-dimensional pattern **135** of the second optical rod **137** so that focused radiation **139** is coupled into the core **141** of the second optical fiber **143**. A third optical rod **145** is coupled to a second end of the optical fiber **143** so that divergent radiation **147** is transmitted through the three-dimensional pattern **149** and collimated radiation **151** is transmitted to the optical sensor **153**. More particularly, the optically sensitive material can be maintained in a reservoir or pocket between the optical rods **125** and **137**. As shown, radiation from a source such as a laser diode is transmitted through the fiber **123** to the optical rod **125**. Alternately, the radiation source can be coupled directly to the optical rod **125**.

As shown in Figure 13, optical rods according to the present invention can be used in the fabrication of an optical isolator. In particular, radiation is transmitted from the core **161** of the optical fiber **163** to the optical rod **165** where the resulting divergent radiation is collimated by the three-dimensional pattern **167** on the end of the optical rod **165**. The collimated radiation is then transmitted through the first polarizer **169**, the Faraday rotator **171**, and the second polarizer **173** to the three-dimensional pattern **175** on the end of the optical rod **177**. Focused radiation is then transmitted into the core **179** of the optical fiber **181**. Accordingly, the optical isolator of the present invention can be used to allow the transmission of light through the optical fibers **163** and **181** in only one direction. This structure can also reduce light loss.

Optical rods according to the present invention can also be used in the fabrication of smaller endoscopes for medical laser systems. An endoscope includes a plurality of optical elements inserted into a metal tube, and the endoscope can be used to deliver (or image) laser pulses during medical procedures. The metal tube is precisely machined to align the optical elements inserted therein. By replacing conventional optical elements with the optical rods of the present invention, the size of the endoscope can be reduced.

As shown in Figure 14, an endoscope according to the present invention includes a radiation source **191** such as a laser, a tube (or sleeve) **193**, and a plurality of optical rods **195**, **197**, **199**, **201**, and **203** wherein each of the optical rods includes a respective three-dimensional optical pattern **211**, **213**, **215**, **217**, and **219** on a respective end thereof. For example, each of the three-dimensional optical patterns **211**, **213**, **215**, and **217** can be a respective diffractive pattern, and the three-dimensional optical pattern **219** can be a refractive pattern.

A Wavelength Division Multiplexing (WDM) Device can also be provided using optical rods according to the present invention. In particular, a Wavelength Division Multiplexing Device is used to separate multiple wavelengths (λ_i) transmitted through a single optical fiber. As shown in Figure 15, radiation having at least two wavelengths is transmitted through the core **221** of the fiber **223** to the optical rod **225** where the resulting divergent radiation is transmitted through the three-dimensional pattern **229** on the end of the optical rod **225**. More particularly, the three-dimensional pattern **229** can be a grating lens etched into the end surface of the rod **225**. Accordingly, the radiation is separated into a first component having a first wavelength λ_1 and a second component having a second wavelength λ_2. Wavelength Division Multiplexing Devices according to the present invention can be used, for example, in telecommunications and fiber switching applications.

According to another aspect of the present invention, a plurality of optical rods can be used to reduce the coherence of radiation generated by a laser diode. For example, a non-coherent source of radiation may be desired for a micro-optical application, but a laser diode may be required to provide the desired level of power. Accordingly, the coherence of the radiation generated by the laser diode can be reduced using a plurality of aligned optical rods wherein a three-dimensional pattern on each rod comprises a patterned layer of a reflective material such as a highly reflective dielectric material or a metal.

As shown in Figure 16, a plurality of optical rods **231**, **233**, **235**, and **237** are coupled to a radiation source **239** such as a laser diode. Each of these optical rods has a reflective three-dimensional pattern on the opposing ends thereof. Examples of reflective patterns which can be used are illustrated in Figures 17a to 17f. The pattern **241** of Figure 17a can be provided on the end of the optical rod **231** adjacent the radiation source **239** thus allowing four laser emitters to generate radiation for transmission through the optical rods. The reflective pattern **243** of Figure 17b can be provided on the other end of the optical rod **231** and on the adjacent end of the optical rod **233**. Radiation thus passes through the central regions of the reflective patterns between the optical rods **231** and **233** as indicated by the lines and arrows through the optical rods of Figure 16.

The end of the optical rod **233** opposite the optical rod **231** can have the reflective pattern **245** of Figure 17c thereon, and the adjacent end of the rod **235** can also have the pattern **245** of Figure 17c thereon. Accordingly, radiation is transmitted between the optical rods **233** and **235** through the clear donut shaped portion of the pattern **245** of Figure 17c. The opposite end of the rod **235** can have the reflective pattern **247** of Figure 17d thereon, and the adjacent end of the rod **237** can have the reflective pattern **249** of Figure 17e thereon. As shown, the pattern of Figure 17e also includes a diffractive diffuser **251** in a central portion thereof. The end of the optical rod **237** opposite the optical rod **235** can have the reflective pattern **253** of Figure 17f. Because many different reflective transmission paths exist between the radiation source **239** and the output aperture at the far end of the optical rod **237**, the coherence of the radiation transmitted therethrough can be greatly reduced. Furthermore, losses of less than 50% may be obtained.

Each of the reflective patterns on each end surface of each optical rod can be a patterned reflective dielectric or metal layer. Because the reflective layers are etched to expose portions of the respective rod end, the reflective pattern has a three-dimensional step. An assembly of optical rods for reducing coherence is shown in Figures 18 and 19. As shown, a V-groove **259** can be formed in a surface of a silicon substrate **263**, and a radiation source **261**, such as a laser diode, can be provided on the substrate surface adjacent the V-groove. Moreover, a plurality of optical rods **265**, **267**, and **269** as discussed above with regard to Figures 16 and 17 are aligned in the V-groove **259**. In addition, a second substrate **271** having a second V-groove **273** can be bonded to the first substrate thus protecting and maintaining the alignment of the optical rods, as shown in Figure 19.

As discussed above, an optical rod according to the present invention has an end with a three-dimensional pattern thereon. For example, the rod can have a diffractive pattern on the end, a refractive pattern on the end, or a patterned layer on the end. In addition, a rod according to the present invention can be formed from glass or other optically transparent materials, and a rod can have a uniform index of refraction.

Alternately, a rod according to the present invention can have a gradient index of refraction along a cross section thereof. In other words, an optical rod according to the present invention can be a gradient index (GRIN) lens with a three-dimensional pattern formed on an end thereof. A GRIN lens uses a quadratic index profile to collimate light. This quadratic index, however, may vary with temperature so that the performance of a GRIN lens may change with temperature. In particular, a focal shift may occur with changes in temperature.

The inclusion of a three-dimensional diffractive pattern on an end of a GRIN lens can be used to reduce this temperature dependent focal shift. In particular, a diffractive pattern can be used so that a change in temperature causes a first focal shift due to the temperature dependence of the GRIN lens and a second focal shift due to the temperature dependence of the diffractive pattern wherein the two shifts are in opposite directions and thus cancel. Stated in other words, a diffractive pattern on an end of a GRIN lens can be used to provide athermalization of the GRIN lens.

In addition, the optical rods have been discussed as having a cylindrical shape with a circular cross-section. It will be understood, however, that the rods can have other shapes with other cross-sections such as rectangular cross-sections, hexagonal cross-sections, or elliptical cross-sections.

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

THAT WHICH IS CLAIMED IS:

1. An optical transmission system comprising:

an optical rod having a length of not more than approximately 6 mm or less and a width of approximately 1mm or less, wherein said optical rod has a three-dimensional pattern on an end thereof; and

a radiation source coupled to said optical rod so that radiation generated by said radiation source is transmitted through said rod along an axis thereof and through said three-dimensional pattern thereon.

2. An optical transmission system according to Claim 1 wherein said optical rod has a width of approximately 500 microns or less.

3. An optical transmission system according to Claim 1 wherein said optical rod has a cylindrical shape.

4. An optical transmission system according to Claim 1 wherein said three-dimensional pattern comprises a diffractive pattern so that said end of said rod has a stepped profile.

5. An optical transmission system according to Claim 1 wherein said three-dimensional pattern comprises a refractive pattern.

6. An optical transmission system according to Claim 1 wherein said three-dimensional pattern comprises a patterned layer on said end of said rod so that a first portion of said end of said rod is covered by said patterned layer and so that a second portion of said end of said rod is exposed by said patterned layer.

7. An optical transmission system according to Claim 6 wherein said patterned layer comprises a patterned reflective layer.

8. An optical transmission system according to Claim 6 wherein said patterned layer comprises a material chosen from the group consisting of a metal and a dielectric.

9. An optical transmission system according to Claim 1 wherein said three-dimensional pattern is radially symmetric.

10. An optical transmission system according to Claim 1 further comprising:

a fiber optically coupled to said rod to receive said radiation transmitted therethrough.

11. An optical transmission system according to Claim 1 further comprising:

a fiber optically coupled between said radiation source and said rod so that radiation is transmitted from said radiation source through said fiber to said rod.

12. An optical transmission system according to Claim 1 wherein said three-dimensional pattern performs an optical function chosen from the group consisting of a beam shaping function, a pattern generation function, a diffusion function, a collimation function, and a focusing function.

13. An optical transmission system according to Claim 1 wherein said optical rod comprises a gradient index lens.

14. An optical transmission system according to Claim 1 wherein said optical rod has a uniform index of refraction along a cross section thereof.

15. An optical transmission system according to Claim 1 wherein a second three-dimensional pattern is provided on a second end of said rod opposite said first end.

16. An optical transmission system according to Claim 1 wherein said radiation source generates divergent radiation, and wherein said three-dimensional pattern collimates said divergent radiation.

17. An optical transmission system according to Claim 1 further comprising:

a substrate having a groove therein, and wherein said optical rod is mounted in said groove adjacent said radiation source.

18. An optical transmission system according to Claim 1 further comprising:

a second optical rod having a length of not more than approximately 6 mm or less and a width of approximately 1mm or less, wherein said second rod has a second three-dimensional pattern on an end thereof, and wherein said second rod is optically coupled to said first optical rod so that said radiation is transmitted from said first rod through said second rod along an axis thereof and through said second three-dimensional pattern.

19. An optical transmission system according to Claim 18 wherein said radiation source generates divergent radiation, wherein said first three-dimensional pattern collimates said divergent radiation, and wherein said second three-dimensional pattern focuses said collimated radiation.

20. An optical transmission system according to Claim 18 further comprising:

an optically sensitive material located along a path of said radiation between said first and second rods wherein an optical transmission characteristic of said optically sensitive material changes in response to an environmental change; and

a sensor optically coupled to said second rod to receive said radiation wherein said sensor detects changes in transmission of said radiation through said optically sensitive material.

21. An optical transmission system according to Claim 18 further comprising:

a Faraday rotator in a path of said radiation between said first and second rods; and

first and second polarizers on opposite sides of said Faraday rotator in said path of said radiation so that said radiation is transmitted from said first optical rod through said first polarizer, said Faraday rotator, and said second polarizer to said second optical rod.

22. An optical transmission system according to Claim 1 wherein said radiation source generates radiation having at least two different wavelengths, and wherein radiation of a first wavelength is separated from radiation of a second wavelength upon transmission through said three-dimensional pattern.

23. An optical transmission system according to Claim 1 further comprising:

a tube surrounding said first optical rod wherein an axis of said tube is coincident with an axis of said first optical rod; and

a second optical rod having a length of approximately 6 mm or less and a width of approximately 1mm or less in said tube, wherein an axis of said second optical rod is coincident with said axis of said tube, wherein said second optical rod has a three-dimensional pattern on an end thereof so that radiation generated by said radiation source is transmitted through said first and second optical rods.

24. An optical transmission system comprising:

a radiation source that generates radiation; and

an optical rod having a three-dimensional diffractive pattern on an end thereof so that said end of said rod has a stepped profile, wherein said rod is optically coupled to said radiation source so that radiation generated by said radiation source is transmitted through said rod along an axis thereof and through said three-dimensional diffractive pattern thereon.

25. An optical transmission system according to Claim 24 wherein said optical rod has a length of approximately 6 mm or less and a width of approximately 1mm or less.

26. An optical transmission system according to Claim 25 wherein said width is approximately 500 microns or less.

27. An optical transmission system according to Claim 24 wherein said optical rod comprises a gradient index lens.

28. An optical transmission system according to Claim 24 wherein said optical rod has a uniform index of refraction along a cross section thereof.

29. An optical transmission system according to Claim 24 wherein said three-dimensional diffractive pattern performs an optical function chosen from the group consisting of a beam shaping function, a pattern generation function, a diffusion function, a collimating function, and a focusing function.

30. An optical transmission system according to Claim 24 wherein said radiation source generates radiation having at least two different wavelengths, and wherein radiation of a first wavelength is separated from radiation of a second wavelength upon transmission through said three-dimensional diffractive pattern.

31. An optical transmission system according to Claim 24 wherein said optical rod has a cylindrical shape.

32. An optical transmission system according to Claim 24 wherein said optical rod has a second three-dimensional diffractive pattern on a second end thereof opposite said first end so that said radiation is transmitted through both said first and second three-dimensional diffractive patterns.

33. An optical transmission structure comprising:

a radiation source that generates radiation;

a first optical rod having a first three-dimensional pattern provided on an end thereof wherein said first rod is optically coupled to said radiation source so that radiation generated by said radiation source is transmitted through said first rod along an axis thereof and through said first three-dimensional pattern thereon; and

a second optical rod having a second three-dimensional pattern provided on an end thereof wherein said second rod is optically coupled to said first rod so that said radiation is transmitted from said first rod through said second rod along an axis thereof and through said second three-dimensional pattern.

34. An optical transmission system according to Claim 33 wherein each of said first and second rods have a length of approximately 6 mm or less and a width of approximately 1mm or less.

35. An optical transmission system according to Claim 34 wherein said width is approximately 500 microns or less.

36. An optical transmission system according to Claim 33 further comprising:

a tube wherein said first and second optical rods are aligned within said tube.

37. An optical transmission system according to Claim 33 further comprising:

a first fiber optically coupled between said radiation source and said first optical rod so that said radiation is transmitted from said radiation source through said first optical fiber to said first optical rod; and

a second fiber optically coupled to said second optical rod so that said radiation is transmitted from said second optical rod to said second fiber.

38. An optical transmission system according to Claim 33 further comprising:

a substrate having a groove in a surface thereof wherein said first and second optical rods are aligned within said groove on said surface of said substrate.

39. An optical transmission system according to Claim 33 further comprising:

an optically sensitive material located along a path of said radiation between said first and second rods wherein an optical transmission characteristic of said optically sensitive material changes in response to an environmental change; and

a sensor optically coupled to said second rod to receive said radiation wherein said sensor detects changes in transmission of said radiation through said optically sensitive material.

40. An optical transmission system according to Claim 33 further comprising:

a Faraday rotator in a path of said radiation between said first and second rods; and

first and second polarizers on opposite sides of said Faraday rotator in said path of said radiation so that said radiation is transmitted from said first optical rod through said first polarizer, said Faraday rotator, and said second polarizer to said second optical rod.

41. An optical transmission system comprising:

a substrate having a groove in a surface thereof;

an optical rod mounted in said groove on said surface of said substrate wherein a three-dimensional pattern is provided on an end of said rod; and

a radiation source optically coupled to said rod so that radiation generated by said radiation source is transmitted through said rod along an axis thereof and through said three-dimensional pattern thereon.

42. An optical transmission system according to Claim 41 wherein said optical rod has a length of approximately 6 mm or less and a width of approximately 1 mm or less.

43. An optical transmission system according to Claim 42 wherein said width is approximately 500 microns or less.

44. An optical transmission system according to Claim 41 wherein said radiation source comprises a laser mounted on said surface of said substrate adjacent said groove.

45. An optical transmission system according to Claim 41 wherein said three-dimensional pattern comprises a diffractive pattern so that said end of said rod has a stepped profile.

46. An optical transmission system according to Claim 44 wherein said three-dimensional pattern comprises a refractive pattern so that said end of said rod has a rounded profile.

47. An optical transmission system according to Claim 41 wherein said three-dimensional pattern performs an optical function chosen from the group consisting of a beam shaping function, a pattern generation function, a diffusion function, a collimation function, and a focusing function.

48. An optical transmission system according to Claim 41 wherein said three-dimensional pattern comprises a patterned layer on said end of said rod so that a first portion of said end of said rod is covered by said patterned layer and so that a second portion of said end of said rod is exposed by said patterned layer.

49. An optical transmission system according to Claim 48 wherein said patterned layer comprises a patterned reflective layer.

50. An optical transmission system according to Claim 49 wherein said patterned layer comprises a material chosen from the group consisting of a metal and a dielectric.

51. An optical transmission system according to Claim 49 further comprising a second three-dimensional patterned reflective layer on a second end of said rod opposite said first end so that said radiation from said radiation source passes through both said first and second three-dimensional patterned reflective layers.

52. An optical transmission system according to Claim 51 further comprising:

a second optical rod in said groove on said substrate and aligned with said first optical rod so that said radiation from said radiation source is transmitted from said first optical rod to said second optical rod wherein said second optical rod has a third three-dimensional patterned reflective layer on an end of said second rod opposite said first rod.

53. An optical structure comprising:

an optical rod having a length of approximately 6 mm or less and a width of approximately 1mm or less, wherein said optical rod has a three-dimensional pattern on an end thereof.

54. An optical structure according to Claim 53 wherein said width is approximately 500 microns or less.

55. An optical structure according to Claim 53 wherein said three-dimensional pattern comprises a diffractive pattern so that said end of said rod has a stepped profile.

56. An optical structure according to Claim 53 wherein said three-dimensional pattern comprises a refractive pattern.

57. An optical structure according to Claim 53 wherein said three-dimensional pattern comprises a patterned layer on said end of said rod so that a first portion of said end of said rod is covered by said patterned layer and so that a second portion of said end of said rod is exposed by said patterned layer.

58. An optical structure according to Claim 57 wherein said patterned layer comprises a patterned reflective layer.

59. An optical structure according to Claim 53 wherein said three-dimensional pattern is radially symmetric.

60. An optical structure according to Claim 53 wherein said optical rod has a cylindrical shape.

61. An optical structure according to Claim 53 wherein said optical rod comprises a gradient index lens.

62. An optical structure according to Claim 53 wherein said optical rod has a uniform index of refraction along a cross section thereof.

63. An optical structure according to Claim 53 further comprising:

a radiation source optically coupled to said rod to transmit radiation through said rod along an axis thereof and through said three-dimensional pattern thereon.

64. An optical structure according to Claim 63 wherein said radiation source comprises a laser.

65. An optical structure according to Claim 63 further comprising:

a fiber optically coupled to said rod to receive said radiation transmitted through said rod and said three-dimensional pattern thereon.

66. An optical structure according to Claim 63 further comprising:

a fiber optically coupled between said radiation source and said rod so that radiation is transmitted from said radiation source through said fiber to said rod.

67. An optical structure according to Claim 53 wherein a second three-dimensional pattern is provided on a second end of said rod opposite said first end.

FIG. 1
PRIOR ART

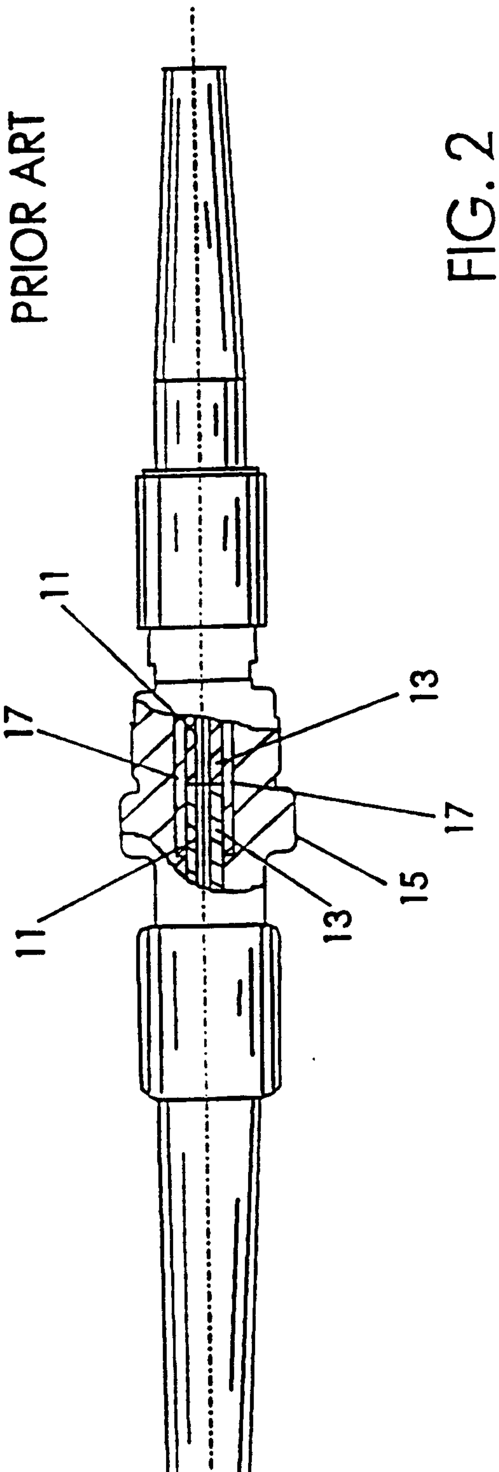


FIG. 2
PRIOR ART

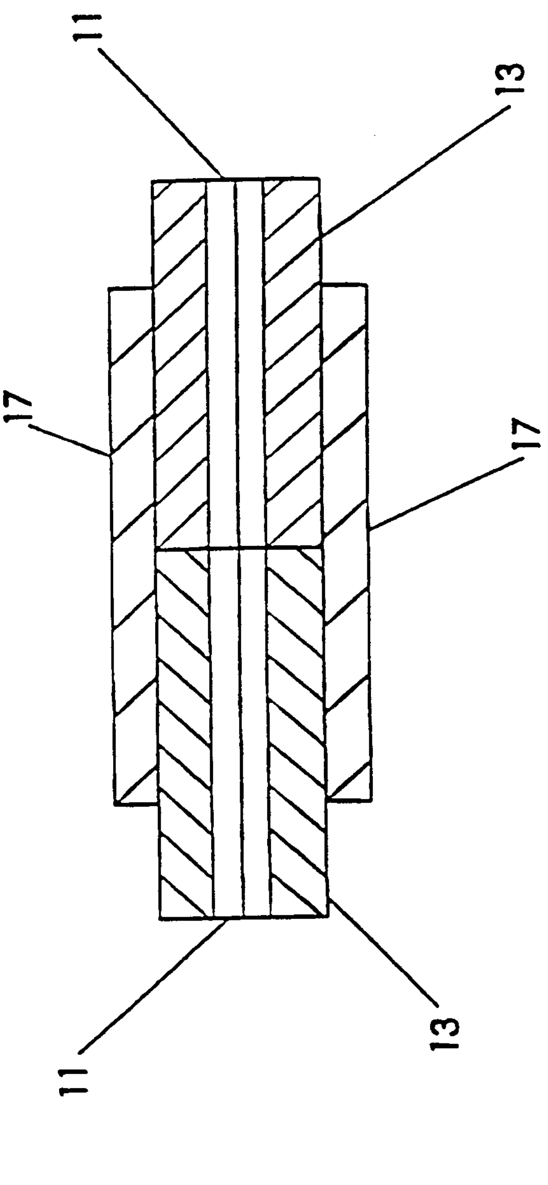


FIG. 3a

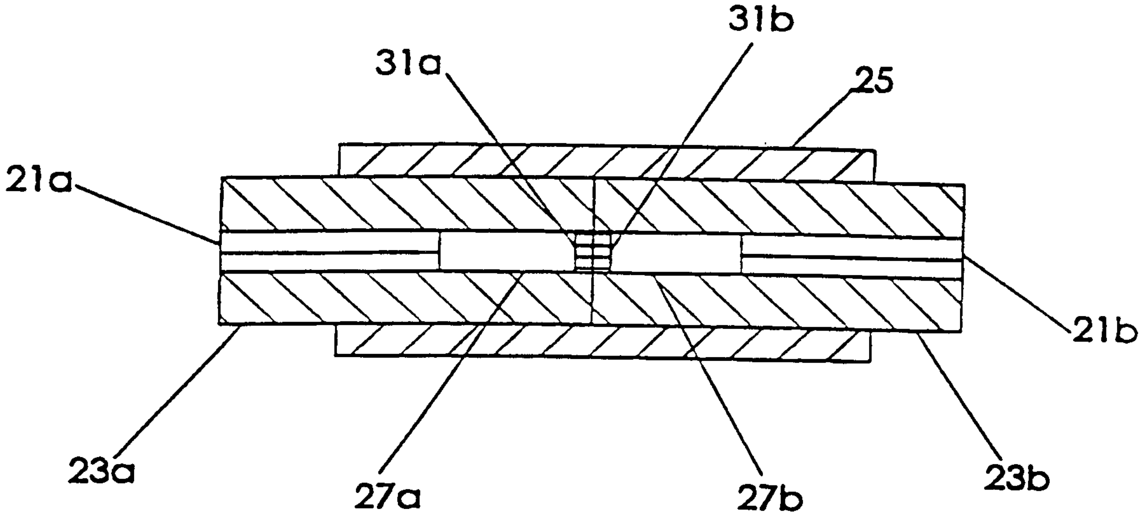


FIG. 3b

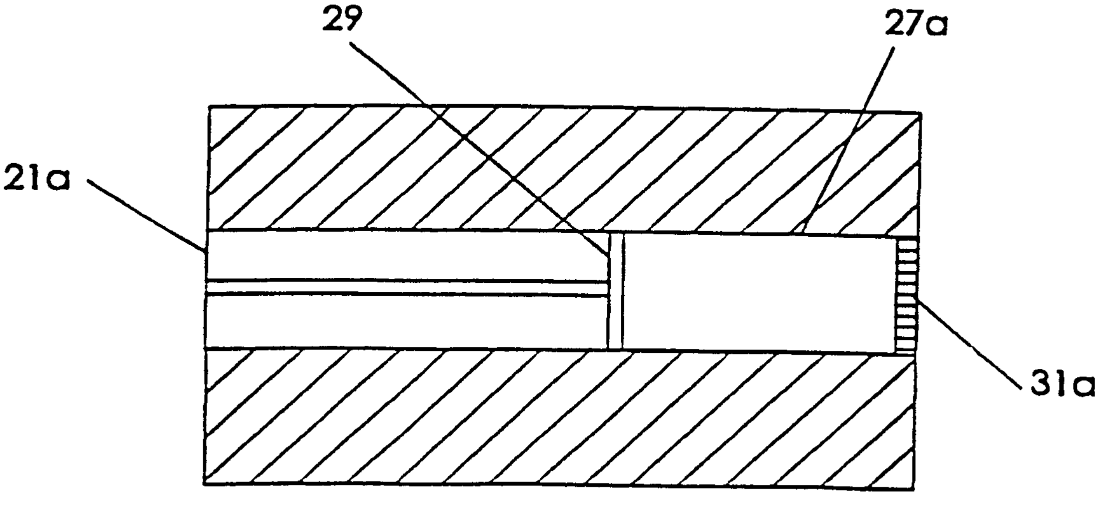


FIG. 4a

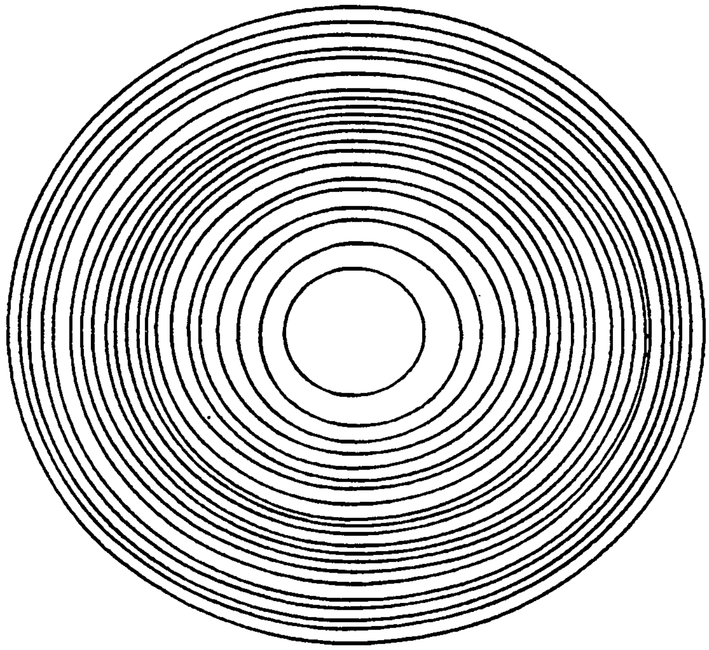
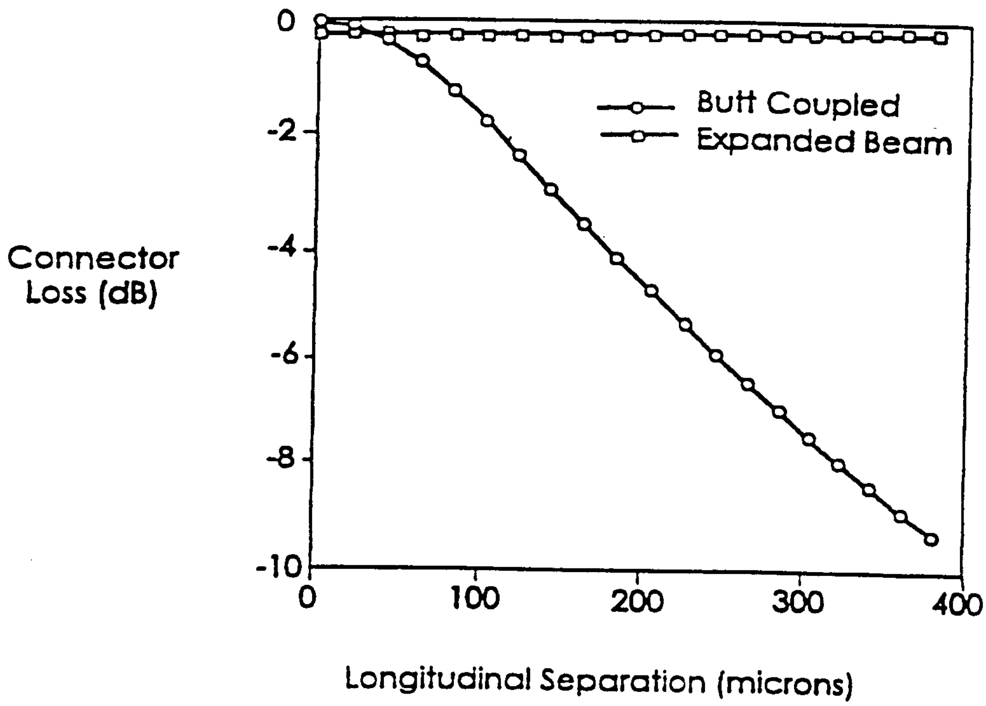


FIG. 4b


0
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-4
-6
-8
-10
Connector Loss (dB)
Butt Coupled
Expanded Beam
0
100
200
300
400
Longitudinal Separation (microns)

FIG. 5a

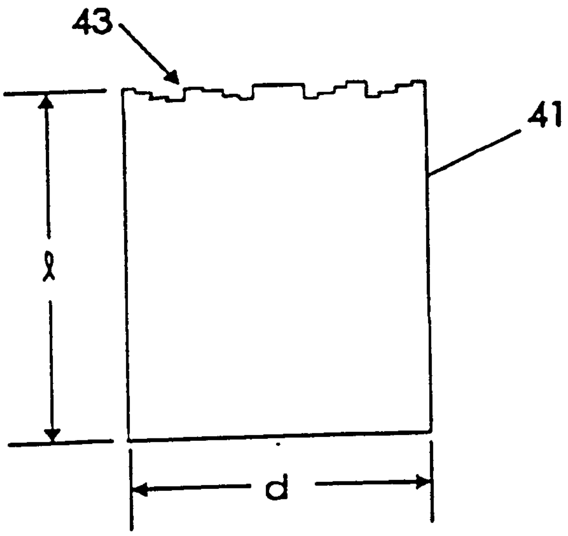

FIG. 5b

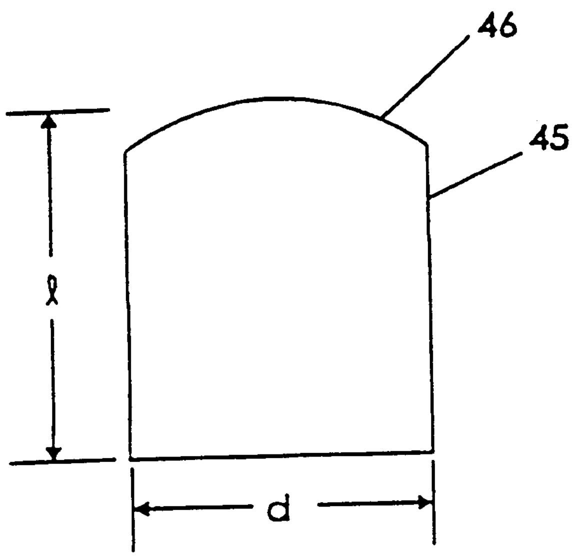

FIG. 5c

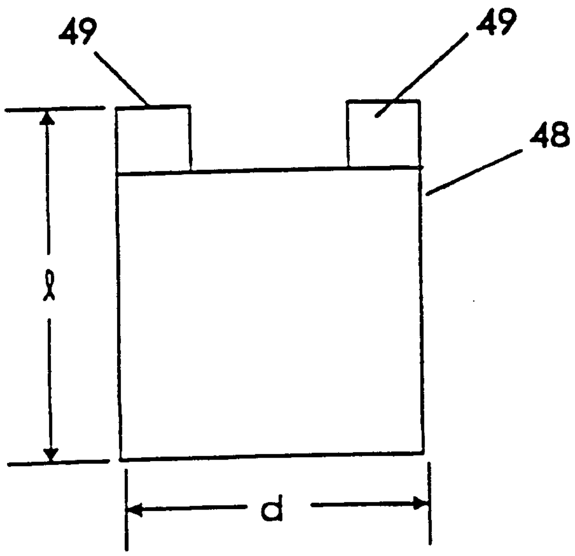

FIG. 15

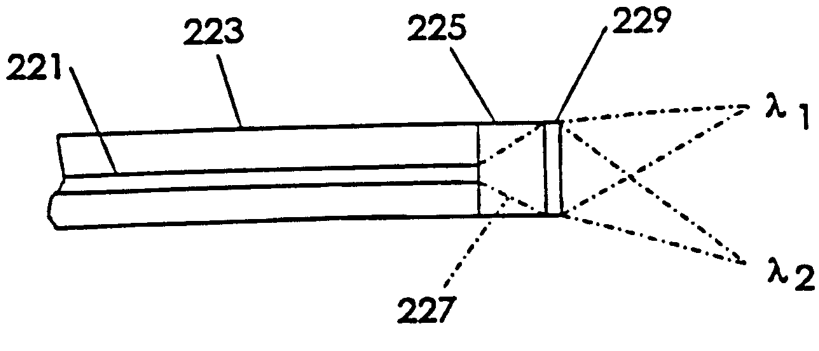

FIG. 6

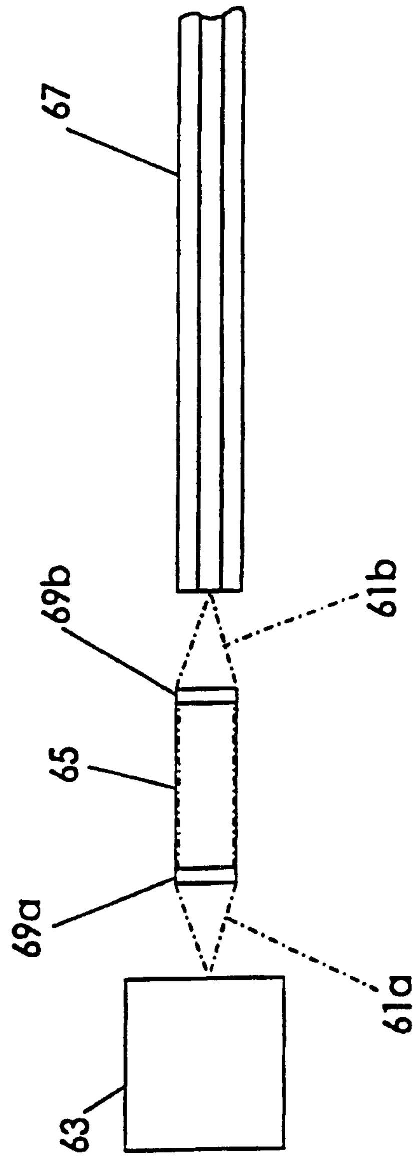

FIG. 7

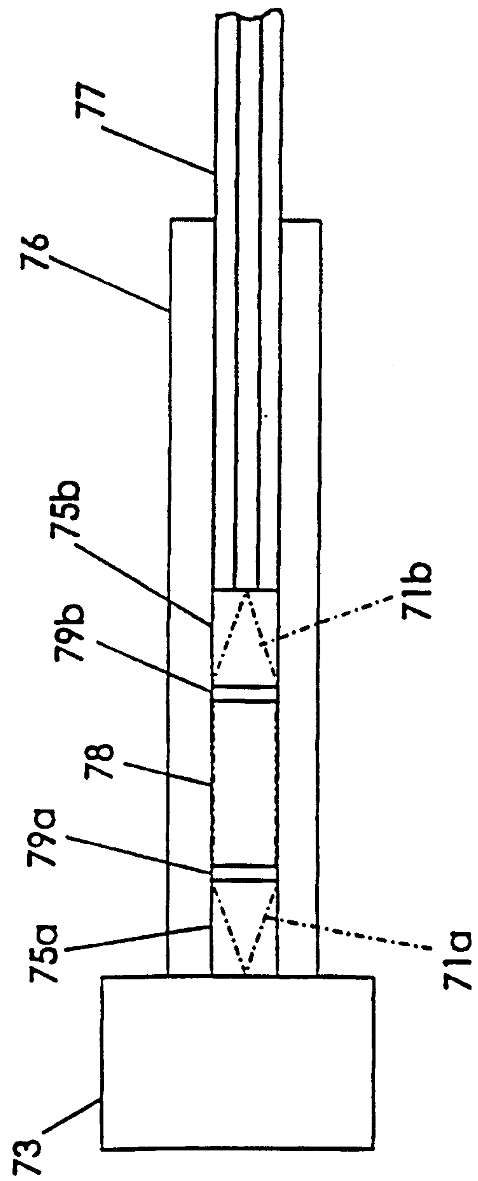

FIG. 8

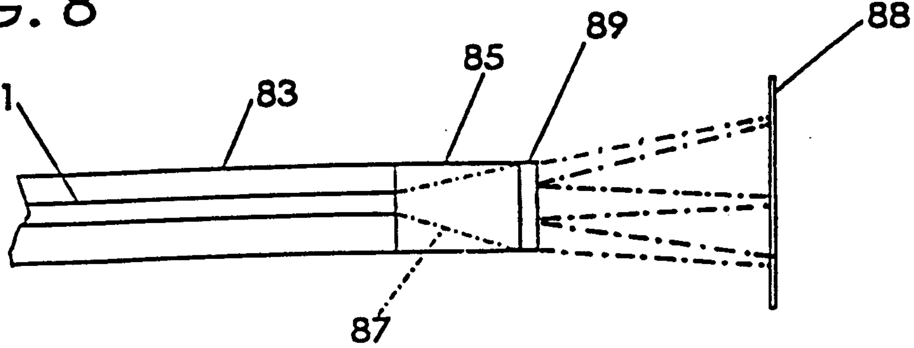

FIG. 9

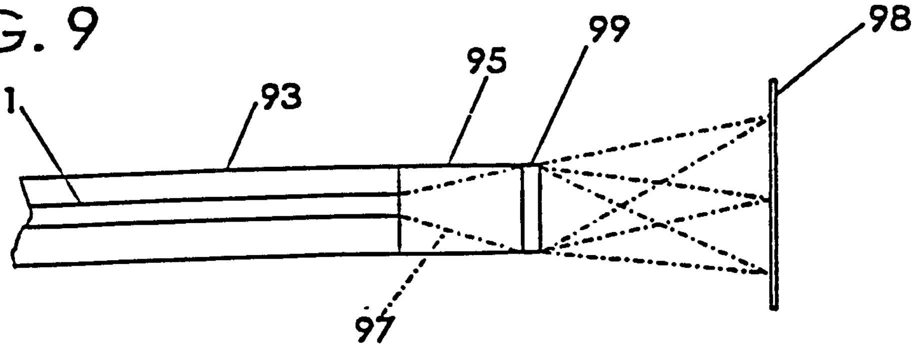

FIG. 10

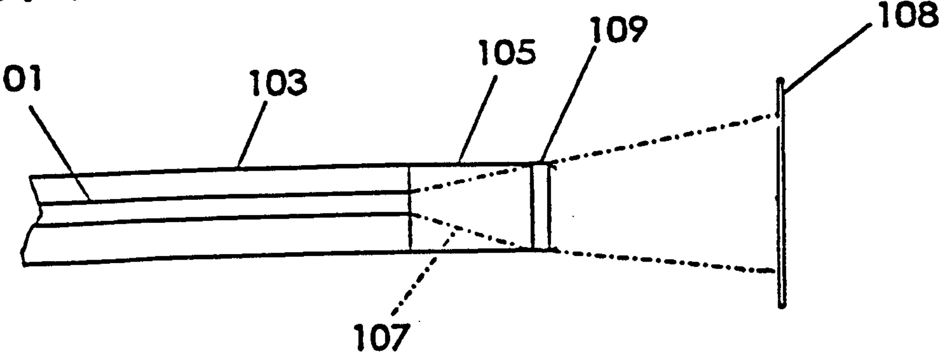

FIG. 11

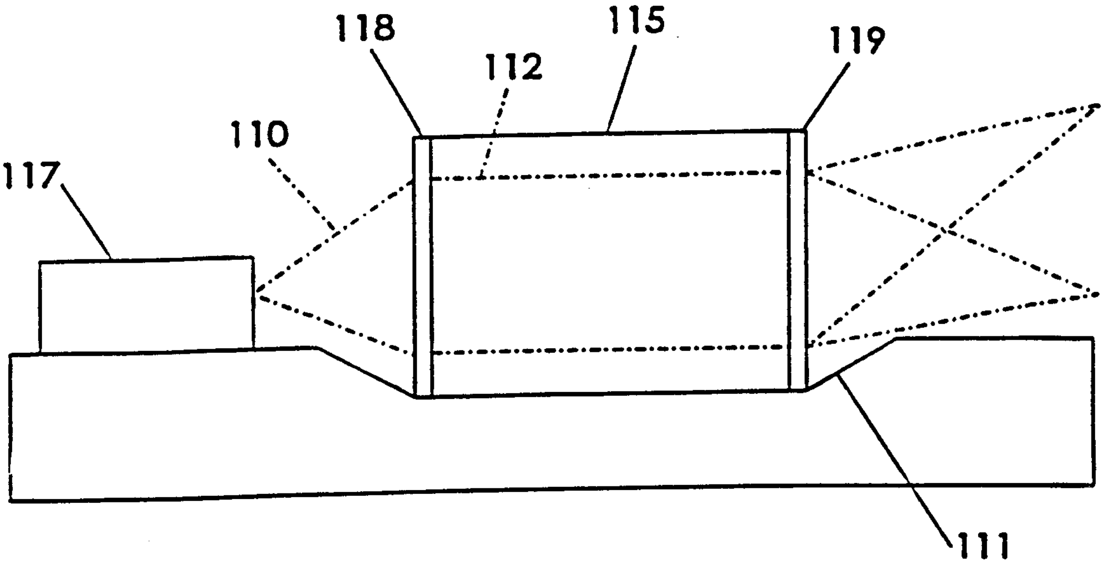
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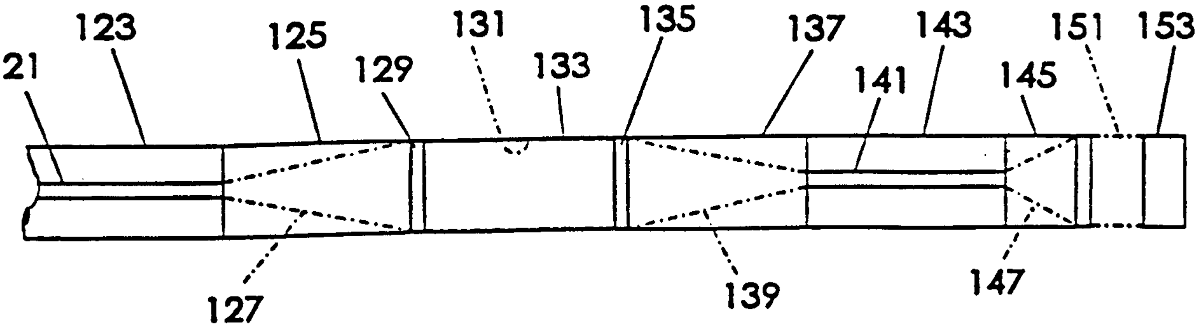
FIG. 12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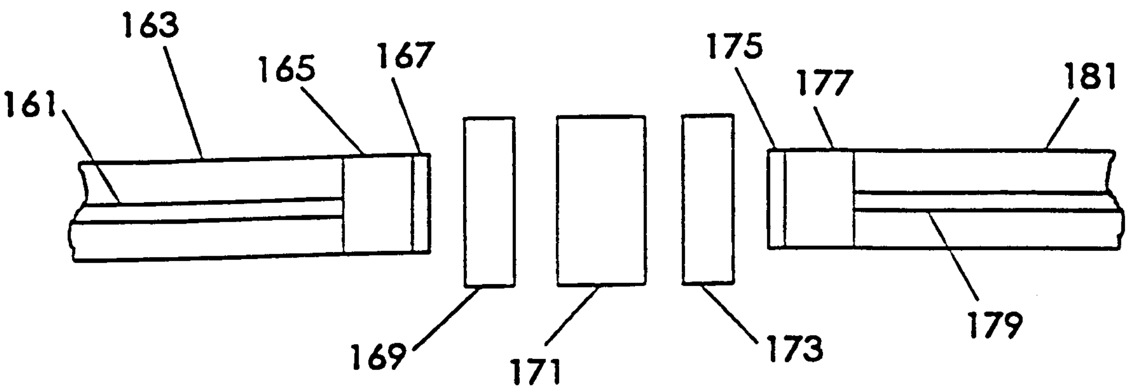
147

FIG. 13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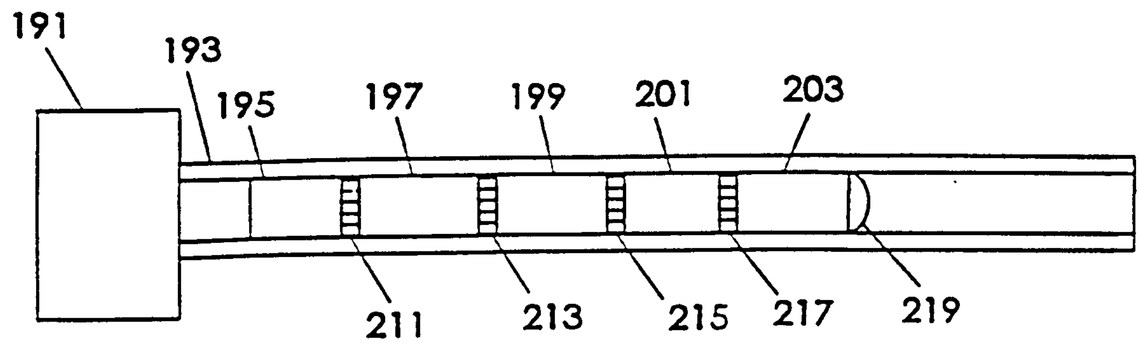
179

FIG. 14


191
193
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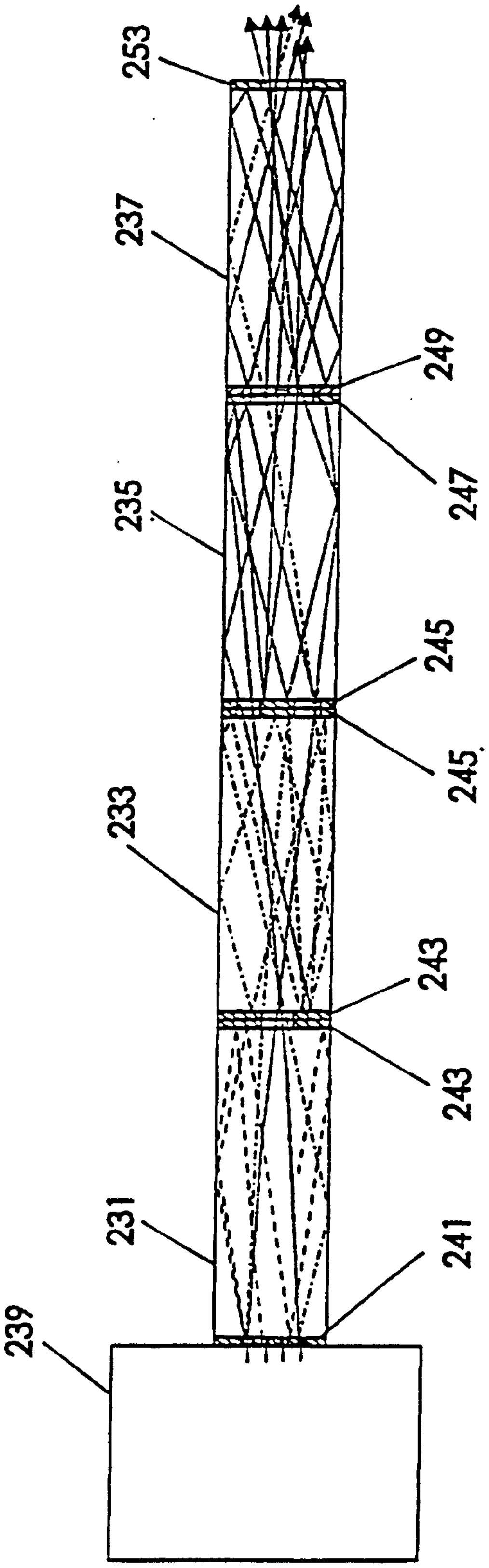
219

FIG. 16



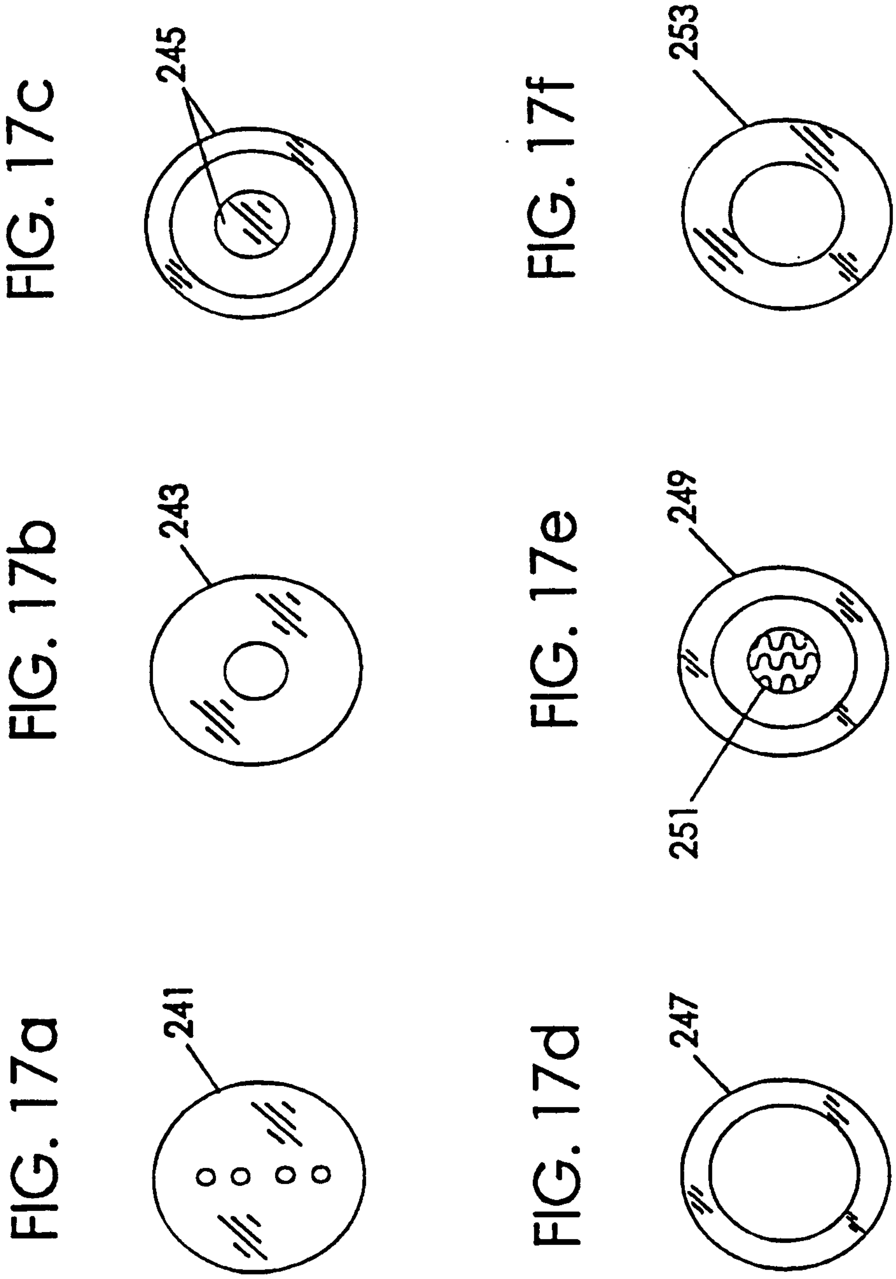


FIG. 17a

FIG. 17b

FIG. 17c

FIG. 17d

FIG. 17e

FIG. 17f

FIG. 18

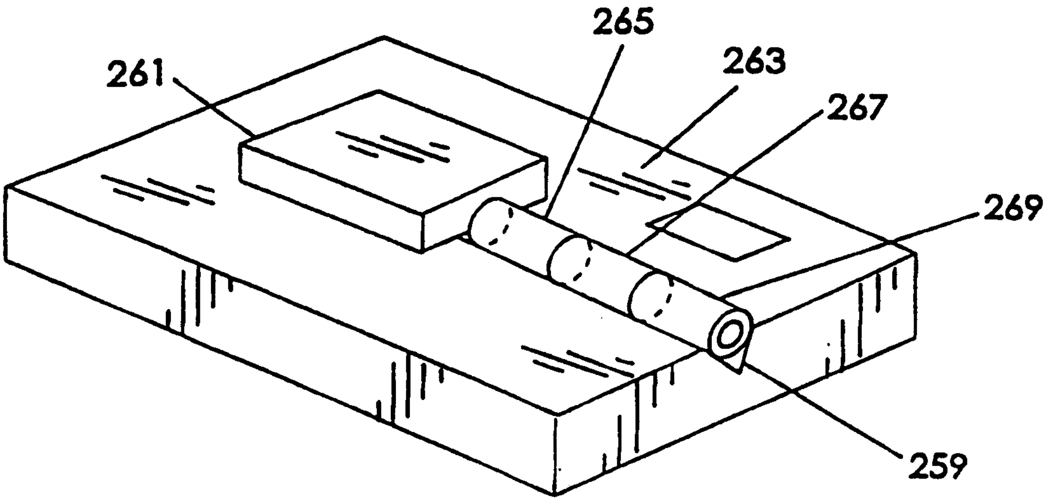


FIG. 19