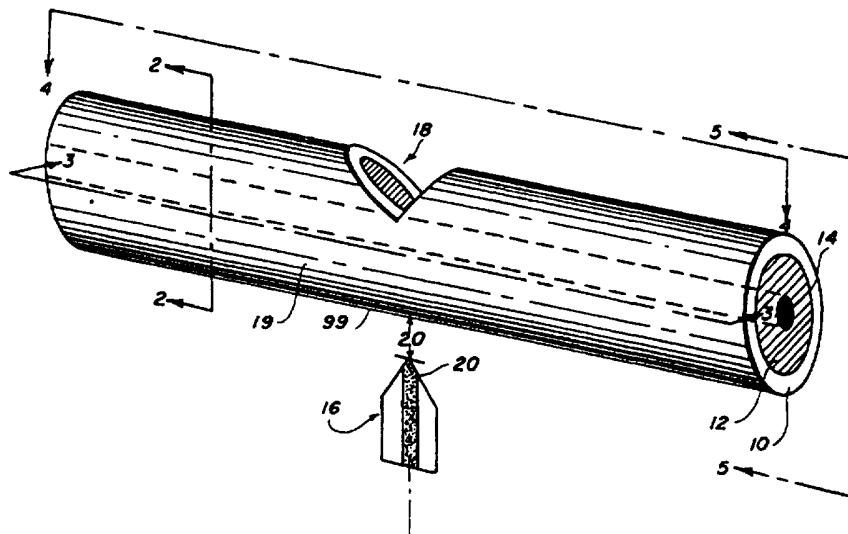


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(54) Title: METHOD AND APPARATUS FOR SIDE PUMPING AN OPTICAL FIBER



(57) Abstract

A technique for the efficient coupling of pump light into a fiber (19) by injecting the light through the side of a fiber leaving the fiber ends accessible to input and output coupling. This technique relies on the fabrication of a groove (18) or a microprism into the side of the fiber. The groove shape is adapted effective to the variables of light wavelength, orientation of the source and visible relating to fiber construction so as to allow the efficient injection of pump light. Light emerging from a laser diode or other suitable means (16) for launching light placed on the opposite side of the fiber, and in proximity to the fiber wall, propagates laterally through the fiber and impinges on the sides of the groove (18). The vertical rays impinging on the groove facets are specularly reflected and directed along the horizontal fiber axis of the outer core. By employing a reflective coating on the groove (18), the reflectivity of the groove facets approach 100 % for a wide range of incidence angle. In this manner one can launch external optical signals into an optical fiber (19).

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METHOD AND APPARATUS FOR SIDE PUMPING AN OPTICAL FIBER**BACKGROUND OF THE INVENTION*****Field of the Invention***

5 The present invention relates generally to a technique of coupling pump light into a fiber waveguide through the side of the fiber cladding and to fiber optic amplifiers and lasers particularly.

Description of the Related Art

10 Launching an optical signal into an optical fiber is one of the most basic problems confronting scientist and engineers who design, build, and employ fiber optic systems. The manipulation of optical signals once propagating in an optical fiber represents an equally challenging problem to those attempting to use optical fibers to transmit information or other signals. It is generally accepted that an optical signal propagating in an optical fiber may be manipulated by launching or

15 coupling light of differing wavelengths into the same fiber.

These fibers are often coupled to laser light sources which act as pumps for the information coded therein. Of the methods used to couple pump light to optical fibers, pigtailing is a preferred method. Typically single spatial mode, diffraction limited laser diodes with an emission aperture of approximately $1 \times 3 \mu\text{m}$ are used to achieve efficient diode to fiber coupling. Pump light is injected into the fiber core by proximity coupling into the polished face of the fiber, or by using small lenses between the laser aperture and the input face of the fiber. This fiber pigtailing process is expensive because of the sub- μm alignment and mechanical stability required to achieve efficient and stable laser to fiber coupling.

20 The use of optical fibers with doped cores has become an indispensable tool in building optical systems for the transmission and amplification of optical information signals. Doping these fibers with different ions produces optical gain for light propagating in the fiber core at various wavelength ranges.

25 Optical gain for a signal propagating in the doped fiber core occurs when population inversion in the inner core material is induced by the absorption of pump light. For the majority of systems, pump light is coupled directly into the inner core via a wavelength selected fused fiber coupler. However, these fused fiber couplers, which allow the pump light coupling and constitute wavelength division multiplexers, add complexity and expense.

A current development in the art is the use of an active fiber configuration with a double cladded structure. The double cladded structure consists of a single mode fiber inner core, an outer core and an outer cladding. The refractive index is highest in the inner core and lowest in the outer cladding, so that both the fiber 5 inner core and the outer core function as optical waveguides. The important feature of the double cladded structure is that light can be injected into the outer core where it propagates until it is absorbed by the active dopant in the fiber inner core.

The index difference between the outer core and the outer cladding is made 10 relatively large, so that the effective numerical aperture (critical angle) of the outer core waveguide is very large, typically above 0.3. The large diameter and numerical aperture of the outer core waveguide make it possible to efficiently couple spatially incoherent emission from high power, large aperture, broad area laser diodes or laser diode arrays. These pump lasers typically generate 1-2 W 15 from an emission area of $1\mu\text{m}$ by $100\mu\text{m}$, or a factor of ten greater power than is available from single mode laser diodes pigttailed into a single mode fiber. An important advantage of the broad area laser diodes is that their cost is approximately ten times smaller than of pigtailed single mode laser diodes.

High power, double core fiber amplifiers and lasers can be constructed by end- 20 pumping using multiple large active area diodes. However, this configuration does not provide access to both ends of the fiber, thus diminishing flexibility in source placement. The double core design fibers can also in principle be pumped at multiple points by using special types of fused fiber couplers which allow pump 25 light transfer from a multimode fiber into the outer core but do not disturb the signal propagating in the fiber inner core. This however, is accomplished at the expense of efficiency, complexity and cost.

SUMMARY OF THE INVENTION

30 It is an object of this invention to efficiently couple pump light from a pump laser into an optical fiber waveguide.

Another object of the present invention is to provide a means for coupling light from multiple pump lasers into a single fiber to achieve high output in optical fiber amplifiers, and fiber lasers.

Yet another object of the present invention is to provide a means for efficient coupling of pump light from spatially incoherent, large active area, high power laser diode arrays or broad stripe diode lasers into the fiber.

5 A further object of this invention is to eliminate the need for wavelength division multiplexing fiber couplers.

Yet a further object of the present invention is to provide a means for injecting pump light through the side of the fiber leaving the fiber ends accessible for input and output coupling of the signal light.

10 Yet another objective is to reduce the cost of the overall system by permitting efficient coupling with less expensive lasers.

Yet a further object of the present invention is to provide a means for injecting pump light from multiple lasers through the side of the fiber leaving the fiber ends accessible for input and output coupling of the signal light.

15 In accordance with these and other objects made apparent hereafter, the invention concerns a technique for the efficient coupling of pump light into a fiber by injecting the light through the side of a fiber leaving the fiber ends accessible to input and output coupling. This technique relies on the fabrication of a groove or a micro-prism into the side of the fiber. The groove shape is adapted effective to the variables of light wavelength, orientation of the source and variables relating to 20 fiber construction so as to allow the efficient injection of pump light. Light emerging from a laser diode or other suitable means for launching light placed on the opposite side of the fiber, and in proximity to the fiber wall, propagates laterally through the fiber and impinges on the sides of the groove. The vertical rays impinging on the groove facets are reflected and directed along the horizontal fiber axis of the outer core. By employing a reflective coating on the groove, the 25 reflectivity of the groove facets approach 100% for a wide range of incidence angles. In this manner one can launch external optical signals into an optical fiber.

30 These and other objects, features and advantages of the invention will become better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein like reference numerals and symbols designate identical or corresponding parts throughout the several views, while equivalent elements bear a prime designation.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG 1. is an elevational view of an optical fiber according to the invention.

FIG 2. is a cross sectional view in the direction of 2-2 of FIG 1.

FIG 3. is a side elevational view in the direction indicated as 3-3 in FIG 1.

5 FIG 4. is a top elevational view in the direction indicated as 4-4 in FIG 1.

FIG 5. is a front end view the fiber in the direction of lines 5-5 in FIG 1.

FIG 6. is a schematic view of one configuration for pumping light from multiple lasers.

10 FIG 7. is a schematic illustration of one configuration for coupling multiple sources into a cladded fiber.

DETAILED DESCRIPTION

Referring now to the drawings, and in particular to FIGs 1-2, which shows an optical fiber **19** and laser light source **16**. Fiber **19** has an inner core **14**, an outer core **12** disposed about the inner core, and an outer cladding **10** disposed about the outer core **12**. The outer core and outer claddings **10**, **12** have groove **18** and facets **22** disposed thereon. Laser light source **16** is disposed opposite groove **18** and facets **22** to direct light **30** across interface **20** into the fiber **19**, and transverse to inner core **14** and outer core **12** and outer cladding **10**. Groove **18** and facets **22** are selected so that light incident thereon from laser **16** will undergo specular reflection, for reasons discussed below.

FIG 2 is a cross sectional view of the optical fiber. The refraction index is usually lowest in outer cladding **10**, with the highest index of refraction located in inner core **14**. A lower index of refraction in outer cladding **10**, allows outer core **12** and inner core **14** to function as optical waveguides, efficiently propagating light within the fiber **19**, minimizing energy loss through the outer cladding **10**.

With reference to FIG 3, groove **18** is fabricated into fiber outer core **12** and outer cladding **10**. Groove **18** extends through outer cladding **10**, and into outer core **12**. A broad area laser diode **16** is the laser light source **16**; however other light sources which launch light **30** at useful wavelengths and intensities are suitable.

In operation laser light diode **16** launches light **30** through fiber outer cladding **10**, and outer core **12** and onto faceted surface **22** of groove **18**. The light **30**, emitted by diode **16**, impinges on faceted surface **22** of groove **18** and is specularly

reflected into fiber 19. Specular reflection, ensures maximum reflection into outer core 12, because this minimizes further divergence of the incident light 30. The light 30 is reflected by faceted surface 22 of groove 18 and injected into outer core 12 of the fiber 19. In this manner, one can inject any optical signal into an optical fiber 19 having a groove such as 18. In an embodiment employing a cladded fiber 19, inner core 14, may contain an active medium, such as an Er or other dopant, which at a selected wavelength absorbs the light 30 propagating in the inner core 14, activating the Er and permitting it to function as an amplifier for any other optical signal propagating in inner core 14.

For example, assume a typical outer core 12 diameter of $125\mu\text{m}$ and inner core 14 diameter of $10\mu\text{m}$. Further assuming the angle ϕ of groove 18 is 90° , a maximum groove 18 depth and width of $52.5\mu\text{m}$ and $105\mu\text{m}$, respectively is suggested. This provides for $5\mu\text{m}$ clearance between groove 18 and inner core 14, disposing groove 18's apex slightly above inner core 14, allowing unobstructed propagation of an optical signal in inner core 14. Light 30 emerging from laser diode 16 or other type pump laser, placed on the opposite side of the fiber 19, and in proximity to fiber outer cladding 10, propagates laterally through fiber 16, impinges on the sides of groove 18, undergoes specular reflection, and is injected into outer core 12.

If the above exemplified embodiment employs a glass fiber with a refractive index of 1.5, the critical angle required for total internal reflection is 41° relative to the surface normal, and vertical rays impinging at 45° on air-to-glass groove facets 24 are totally reflected and directed along the horizontal fiber axis. For a typical broad area laser diode 16, the emission divergence angle in the junction plane is 10° FWHM in air or 6.6° inside fiber 19, so that substantially all of the pump emission would undergo total internal reflection at groove facets 22 thus launching light 30 in outer core 12 with very high efficiency. For an outer core 12 numerical aperture of 0.3 outer core waveguide 12 acceptance angle is 17.5° , thus virtually all of the laser's emission would be captured by outer core waveguide 12. The reflectivity of groove facets 22 can approach 100% for a wide range of incidence angels when thin film reflective coating 55 is placed on groove surface 24.

Although the foregoing dimensions are merely exemplary, the dimensions involved are not atypical of commonly used optical fibers. Thus, one can see that, a groove such as 18 permits injection of light from broad area laser diodes (i.e.

inexpensive laser diodes) with high efficiency. This is equally so for the examples given below.

Referring to FIG 4, and once again to FIG 3, and assuming, for example, a typical emission aperture of $100\mu\text{m}$ for a 1.0-2.0w broad area laser diode 16, the 5 output light cone in the junction plane diverges to a width of $112\mu\text{m}$ at the opposite side of fiber 19 cross section. For a $105\mu\text{m}$ wide groove 18, substantially all of pump light 30 would therefore be intercepted and coupled into fiber 19. Fibers with large outer core diameters can be used to allow larger groove width. Of course, lenses could be placed, if one desired, in between laser diode 16 and 10 fiber 19 to decrease the beam divergence or to project a reduced image of the laser emission aperture on the groove. Laser 16 can also be oriented as shown in FIG 3, or rotated by 90° , so that the emitting area is parallel to the apex of groove 18.

Referring now to FIG. 5, similar considerations to those of the above example apply in the plane perpendicular to the junction 20 (i.e. the plane perpendicular to 15 the page containing FIG 5), where the laser diode emission area 21 is approximately $1\mu\text{m}$, and the pump light 30 diverges much faster than in FIG 3, with a typical divergence angle of 40° in air or 25° in glass. With laser diode 16 placed in proximity to fiber wall 10, the emission spreads out to approximately 50 μm after propagation of a distance of one fiber diameter. Since the total length 20 of groove 18 would typically be $100\mu\text{m}$ at the apex, the beam spread in this plane is sufficiently small so that substantially all of pump light 30 is intercepted by groove facets 22.

The cylindrical fiber to air interface 99 provides a lensing effect which can be used to collimate or focus light 30 propagating in the plane perpendicular to the 25 laser diode function. For example, for a glass fiber with a refractive index of 1.5, the effective cylindrical lens focal length is given by $1/3R$, where R is the fiber radius. For a $125\mu\text{m}$ fiber OD, this corresponds to a focal length of $21\mu\text{m}$. Collimation is achieved with the laser diode facet placed approximately $21\mu\text{m}$ from the fiber side-wall 10, whereas greater distances result in a converging beam.

30 In an embodiment which employs a doped fiber inner core pump light 30 is injected into outer core 12 where it propagates until it is absorbed by the dopant in fiber inner core 14. More efficient absorption of pump light 30 is made possible via the use of special outer core 12 shapes and off center inner core 14 placement which assure that light injected into the outer core waveguide 12 will spatially

overlap with fiber inner core **14** and insure absorption of the pump light **30** by the inner core **14**. One skilled in the art knows how to accomplish this once instructed on the reasons for so doing in the text of this specification. An example of such is fiber with a rectangular shaped outer core **12** with a centrally disposed inner core. 5 Of course, if one has a fiber geometry which gives rise to modes disposed about the fiber's periphery (as is frequently the case with cylindrical fibers), one could effect spacial overlap by simply placing the inner core nearer the fiber's periphery.

With reference to FIG 6, a pair of lasers **16**, **16'** are disposed on opposite sides of fiber **19** so as to direct light beams **30**, **30'** to groove **18** from opposite 10 directions along the length of fiber **19**. To accomplish this face **60** is preferably disposed at about 45° to each of beams **30**, **30'**. Face **62** is preferably disposed at about 45° to face **60** (90° to direction **64**) so that the angle at which beam **30'** is incident on face **62** is as close to 90° as possible, to ensure that little of beam **30** is reflected from face **62**.

15 Referring now to FIG 7, which illustrates one embodiment in which multiple grooves **18** are appropriately spaced along fiber **19** to couple light from multiple lasers **16** into fiber outer core **12**. This embodiment of the side pumping technique can be used to increase the total pump power in fiber **19** and scale up the fiber laser output or fiber amplifier saturation power. For a 4-level atomic 20 transition, the spacing L of grooves **18** is such that almost all of the pump light injected from one groove **18** is absorbed by the gain medium before it reaches the adjacent groove **18'**. For exponentially decaying pump light intensity, characterized by an absorption coefficient α , this corresponds to a spacing of approximately $2/\alpha$.

25 For example, in a typical Nd doped or a 3-level Er/Yb co-doped fiber, the absorption lengths are in the range of 1-10 m, while passive transmission losses for the single mode guided light are few dB/km. Multiple pump diodes **16** are multiplexed along fiber **19** with active fiber lengths of 10-100 m. In the case of a 30 3-level atomic transition, such as that occurring in the Er /Yb doped fiber, the pump intensity must be of sufficient magnitude to achieve gain or transparency everywhere, including regions of low pump power. Incomplete absorption of the pump power injected by one groove **18** results in coupling a portion of the residual pump out of fiber **19** by adjacent groove **18'**, causing a small drop in overall laser efficiency. This effect is somewhat reduced by the fact that pump

intensities from two grooves overlap, resulting in a more uniform pump distribution than would be the case for end-fire pumping from a single fiber facet.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that
5 within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

We Claim:

1. An optical fiber, comprising:
 - a cladding;
 - 5 a core disposed within said cladding; said core comprising an outer core and an inner core, said inner core being disposed within said outer core, said inner core being doped with a preselected gain material;
 - 10 a groove extending through said cladding into said outer core said groove having a surface disposed effective to specularly reflect light from a preselected direction and of a preselected frequency, into said outer core facilitating absorption into said inner core.
2. The fiber of claim 1, wherein said groove comprises a pair of faces disposed generally opposite of one another along the length of said fiber, said faces intersecting one another at about a 45° angle.
- 15 3. The fiber of claim 2, wherein one of said faces is disposed at about 45° to said length of said fiber, and the other of said faces is disposed at about 90° to said length.
- 20 4. The fiber of claim 3, wherein said fiber further comprises a reflective coating disposed on said one of said faces.
- 25 5. The fiber of claim 1, wherein said groove comprises a pair of faces disposed generally opposite of one another along the length of said fiber, said faces intersecting one another at about a 45° angle.
- 30 6. The fiber of claim 5, wherein one of said faces is disposed at about 45° to said length of said fiber, and the other of said faces is disposed at about 90° to said length.
7. The fiber of claim 6, wherein said fiber further comprises a reflective coating disposed on said one of said faces.

8. The fiber of claim 1, wherein said fiber comprises at least one additional groove, said at least one additional groove having a surface disposed effective to specularly reflect light from a preselected direction and of a preselected frequency into said core.

5

9. A method of injecting light of a preselected frequency into an optical fiber, said method comprising:

providing a groove in said fiber, said groove extending through said cladding into said core, said groove having a surface disposed effective to specularly reflect

10 light from a preselected direction and of a preselected frequency, into said core;

directing light of said preselected frequency onto said groove from said preselected direction.

11. The method of claim 10, wherein:

15 said core is an outer core, said fiber comprises an inner core disposed within said outer core, said groove extends into said outer core, and said inner core comprises an optically active preselected gain material, and

wherein said directing of said light is effective to excite said dopant by optical coupling of said light between said inner and said outer core.

1/4

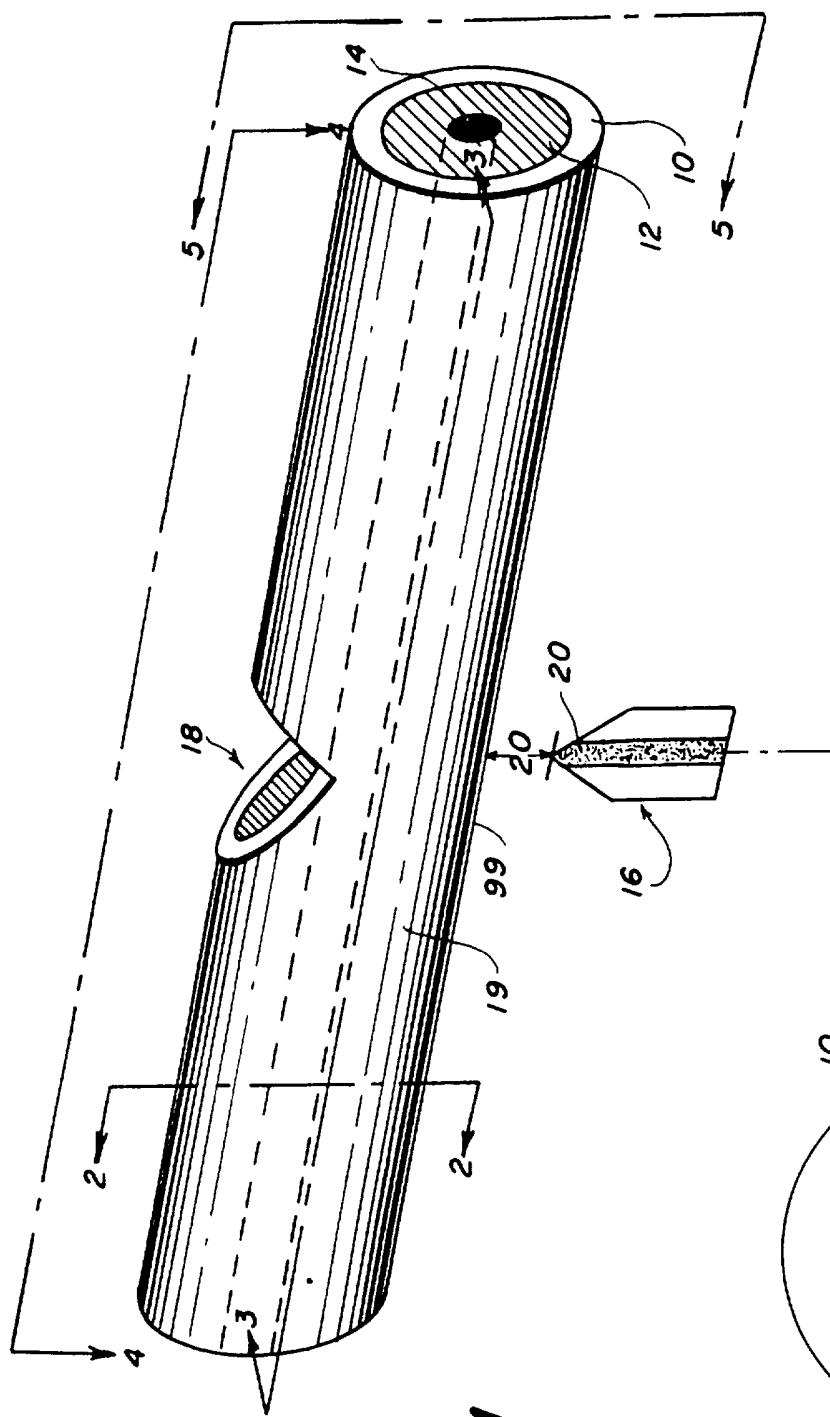
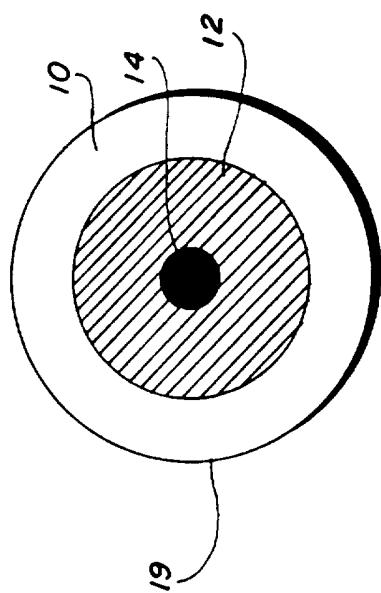


FIG. 2



2/4

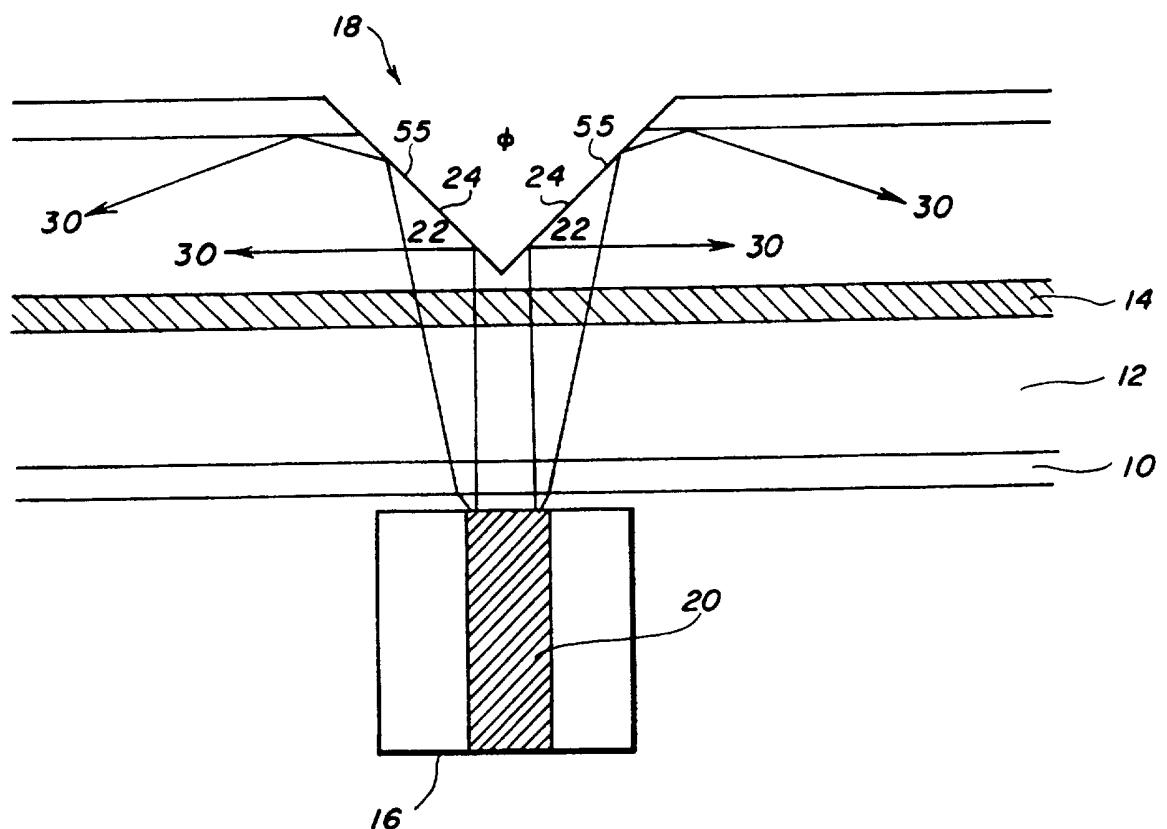


FIG. 3

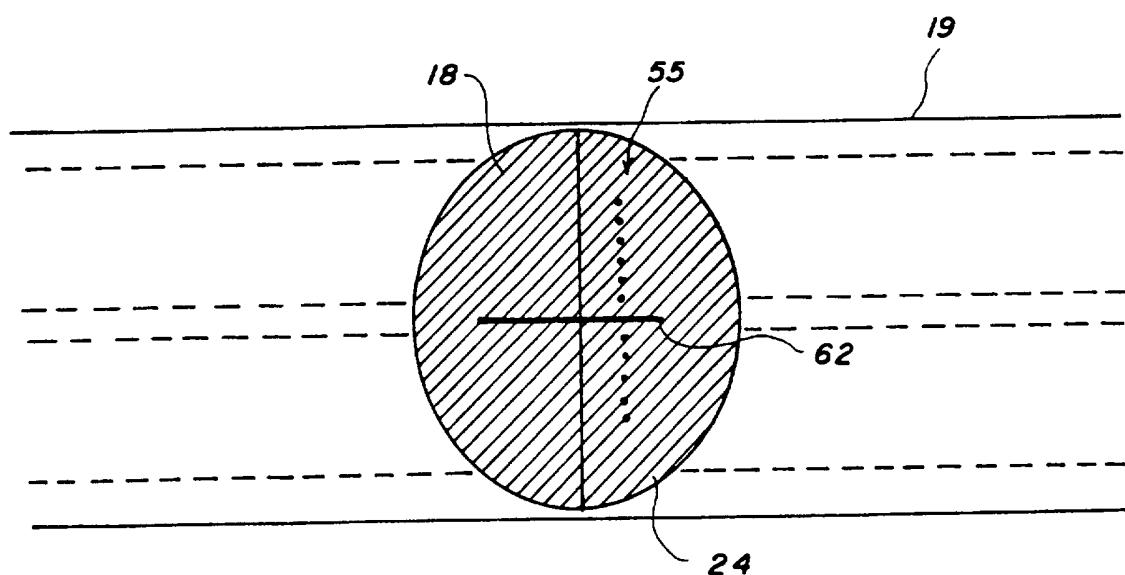


FIG. 4

3 / 4

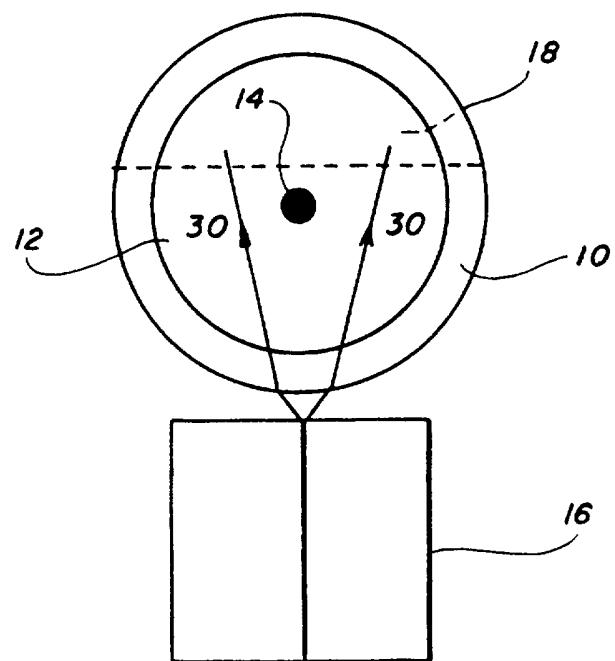


FIG. 5

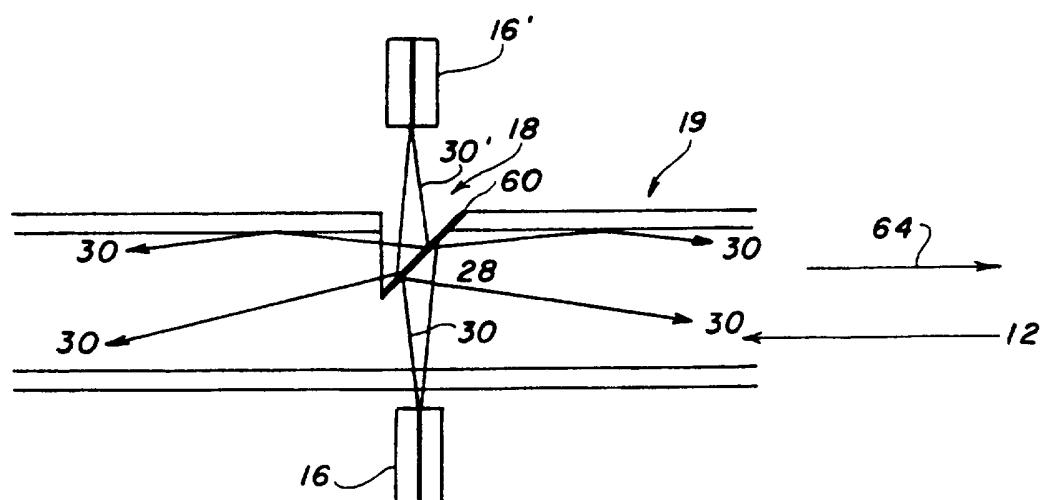


FIG. 6

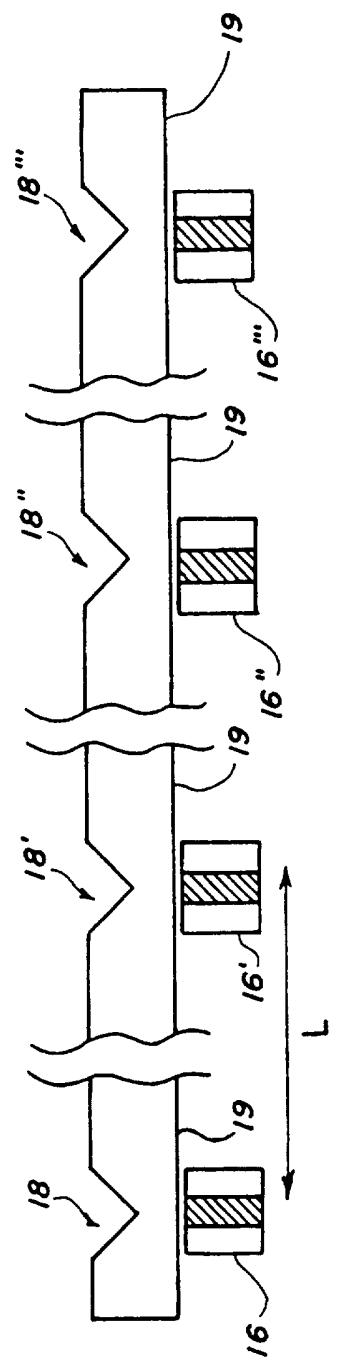


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US96/19452

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G02B 6/26; HO1S 3/30

US CL : 385/31, 49, 88; 372/6

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)

U.S. : 385/31, 32, 49, 88; 372/6

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 practicable, search terms used)

APS

search terms: (fiber# or fibre#), groove#, pump##

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,037,172 A (HEKMAN et al) 06 August 1991, column 5, lines 37-40 of column 6, lines 19-22 of column 9, lines 24-27 of column 17.	1-9, 11
A	US 5,278,850 A (AINSLIE et al) 11 January 1994, see Abstract.	1-9, 11

Further documents are listed in the continuation of Box C. See patent family annex.

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