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Apparatus and Method of Fabricating Directional Fiber Optic Taps, Sensors and Other Devices with Variable Angle Output

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[54] **APPARATUS AND METHOD OF FABRICATING DIRECTIONAL FIBER OPTIC TAPS, SENSORS AND OTHER DEVICES WITH VARIABLE ANGLE OUTPUT**

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[52] **U.S. Cl.** **385/48**; 385/15; 385/27; 385/31; 385/39; 385/42; 219/121.6; 219/121.61; 219/121.67; 219/121.68; 219/121.69

[58] **Field of Search** 385/12, 13, 15, 385/24, 25, 27, 28, 29, 30, 31, 32, 33, 34, 35, 39, 42, 43, 44, 46, 48, 51; 219/121.6, 121.61, 121.65, 121.66, 121.67, 121.68, 121.69, 121.78, 121.8, 121.81, 121.83

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*Attorney, Agent, or Firm*—Mark L. Fleshner

[57] **ABSTRACT**

An apparatus and method for fabricating directional fiber optic taps having a variety of output angles. The taps can be used to monitor losses due to misalignment of the fiber or losses due to bending and straining of the fiber. The apparatus and method can also be used to fabricate taps which filter out higher order modes in a fiber. The apparatus and method can also be used to produce taps which can be used in a position or refractive index measuring system.

48 Claims, 32 Drawing Sheets
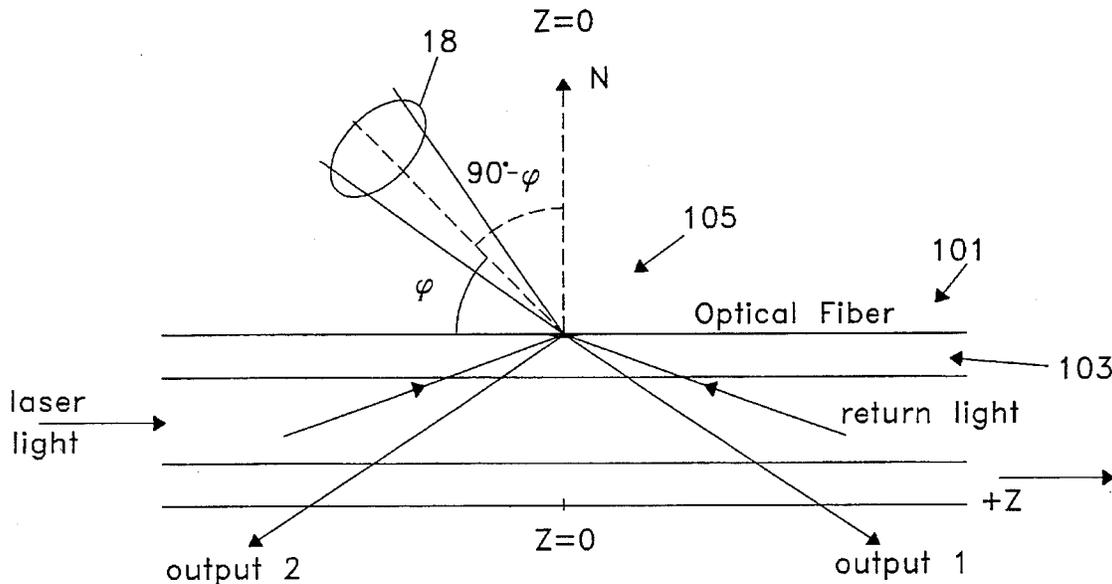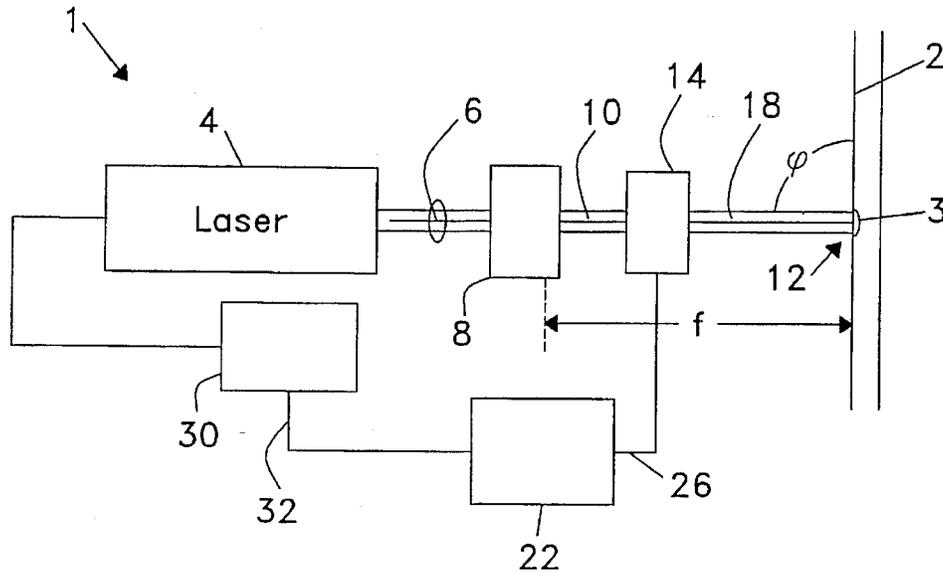
Figure 1A

Figure 1B

Figure 1C

output A1

β(A1)

2

α

21

detch

200 um

2a

2b

Z

β(A2)

output A2

Figure 2A

output A1

β(A1)

25

detch

200 um

2a

α

2b

Z

β(A2)

2

output A2
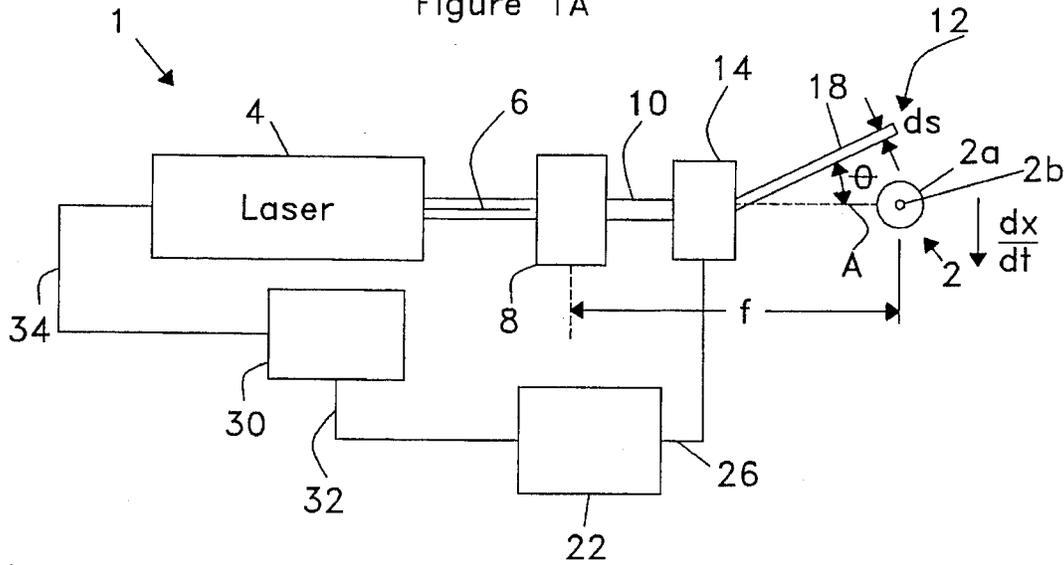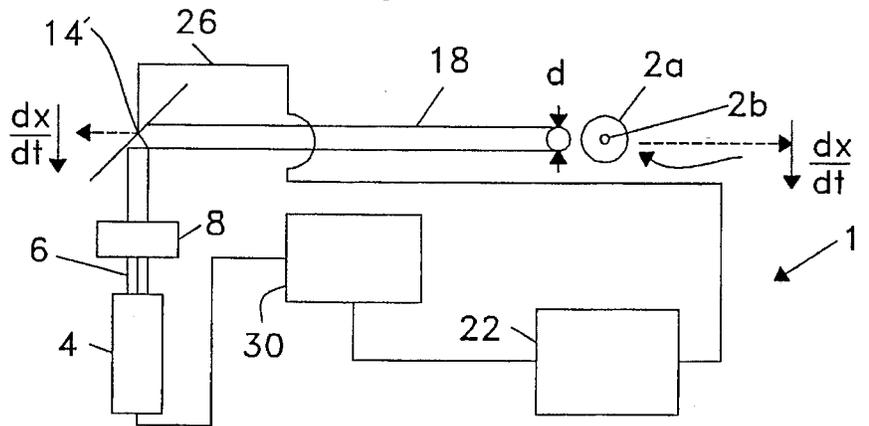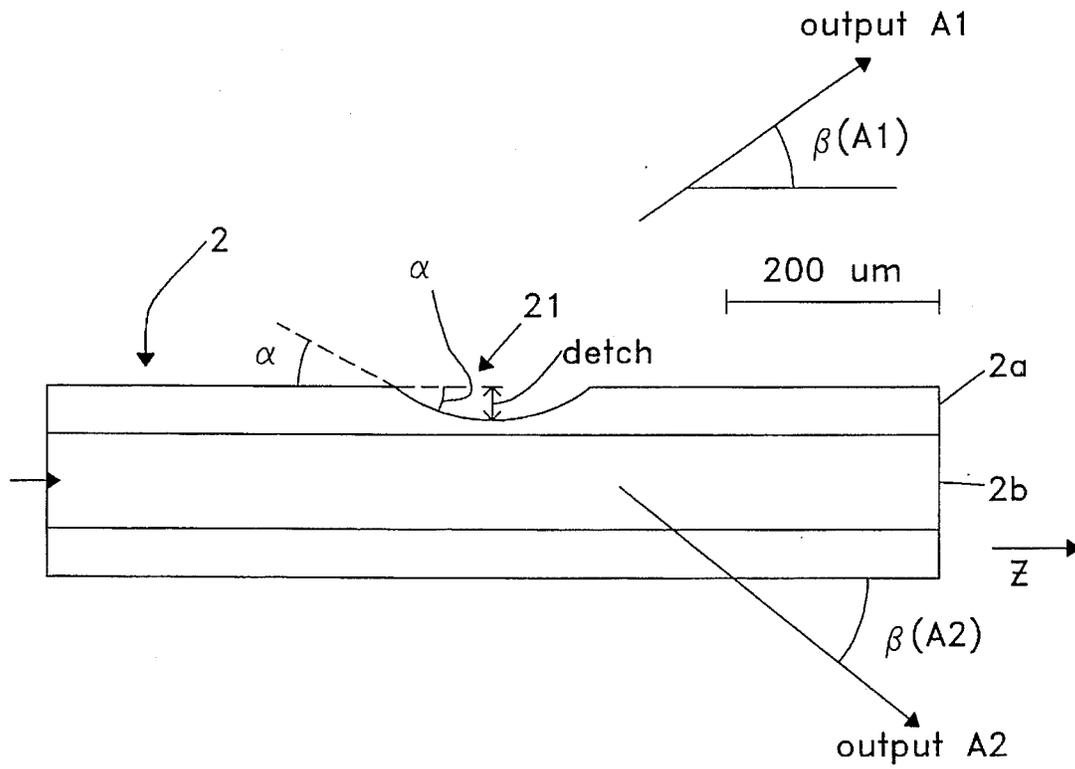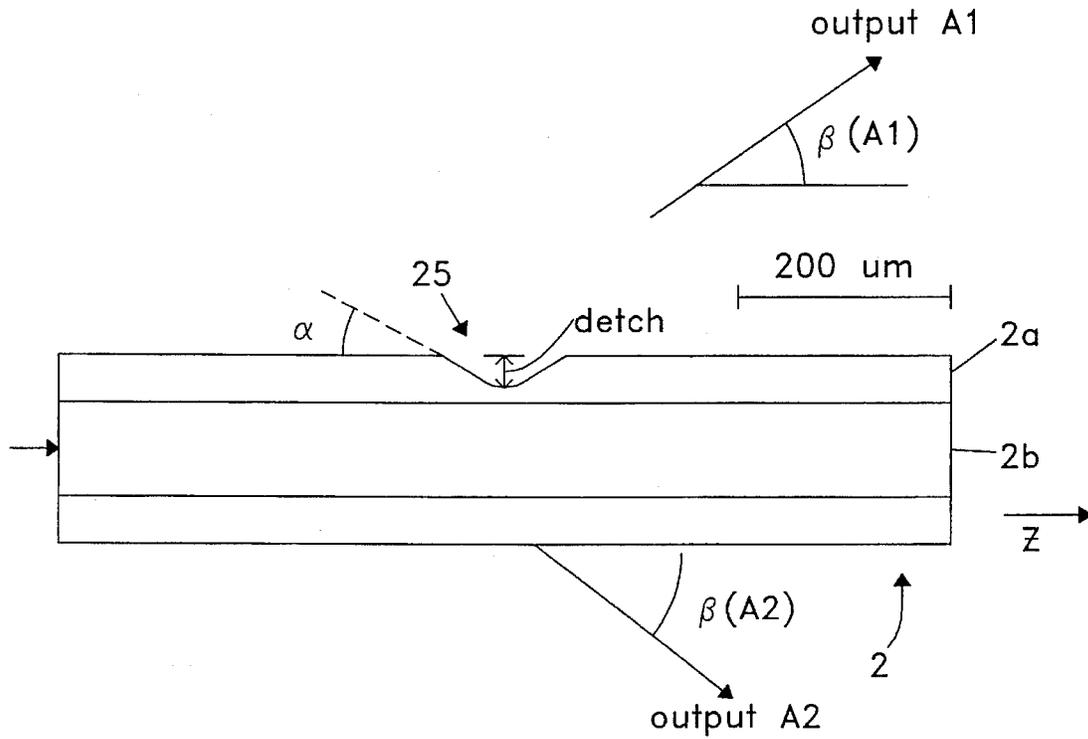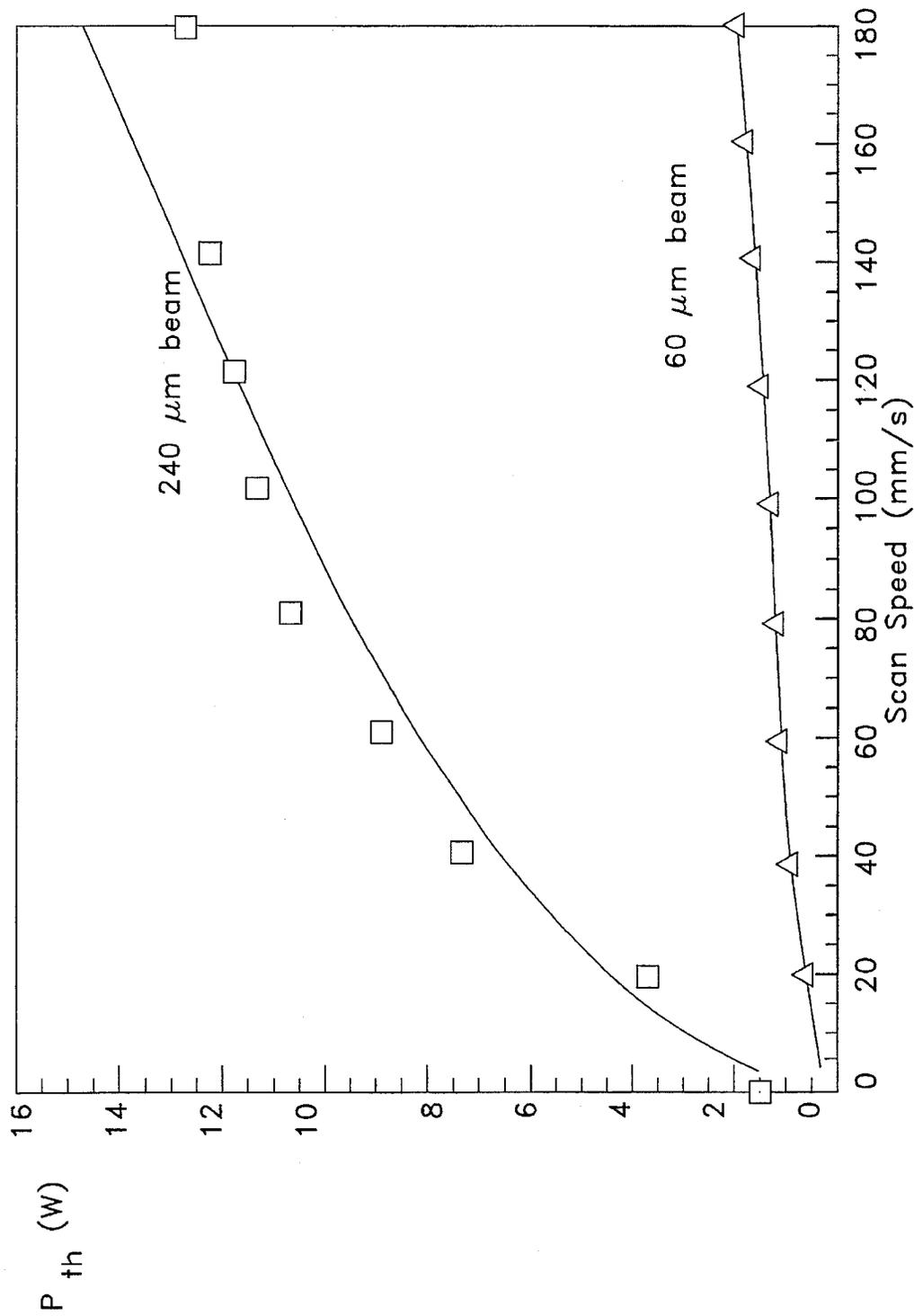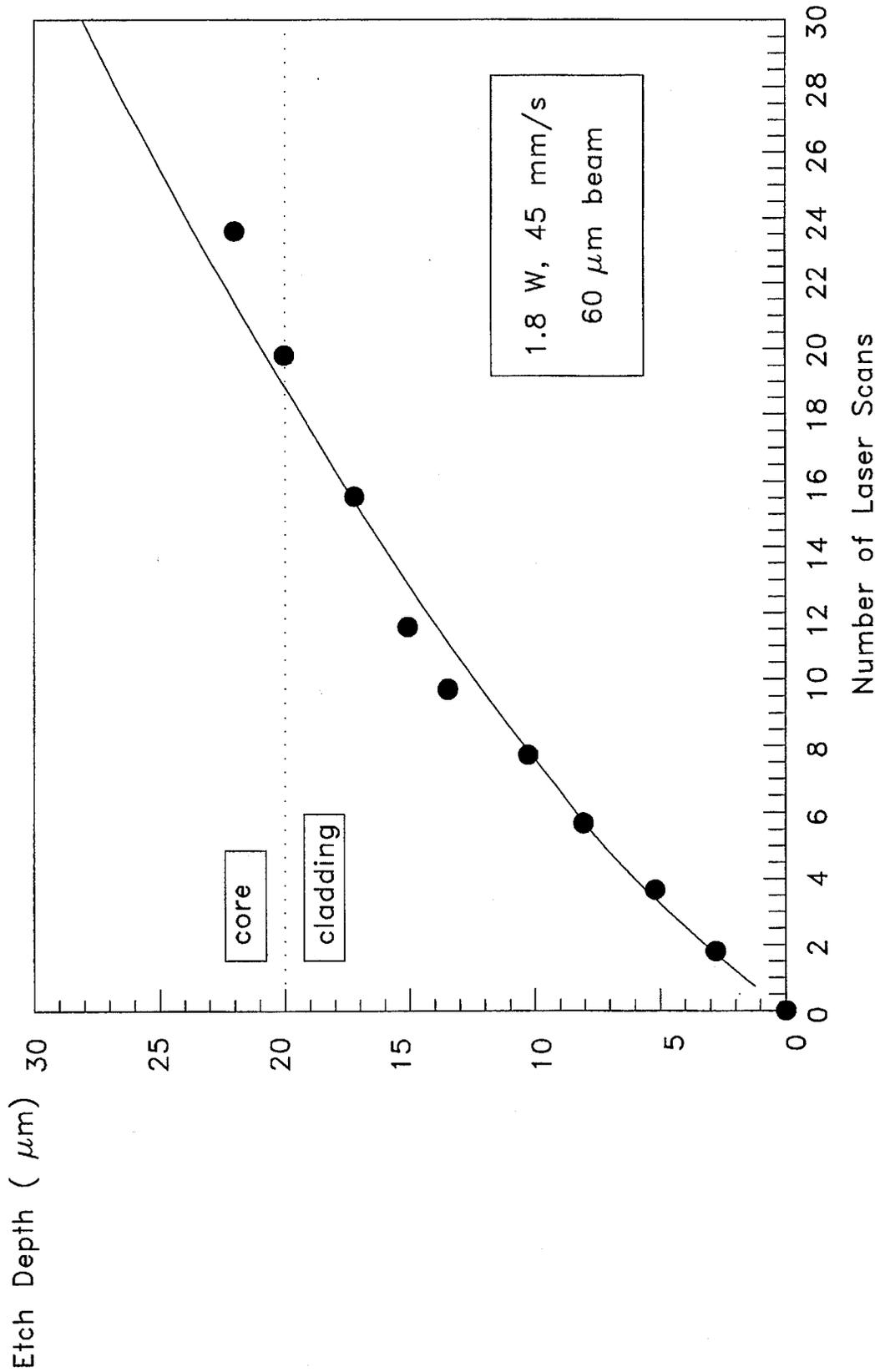
Figure 2B

Figure 2C

Figure 2D
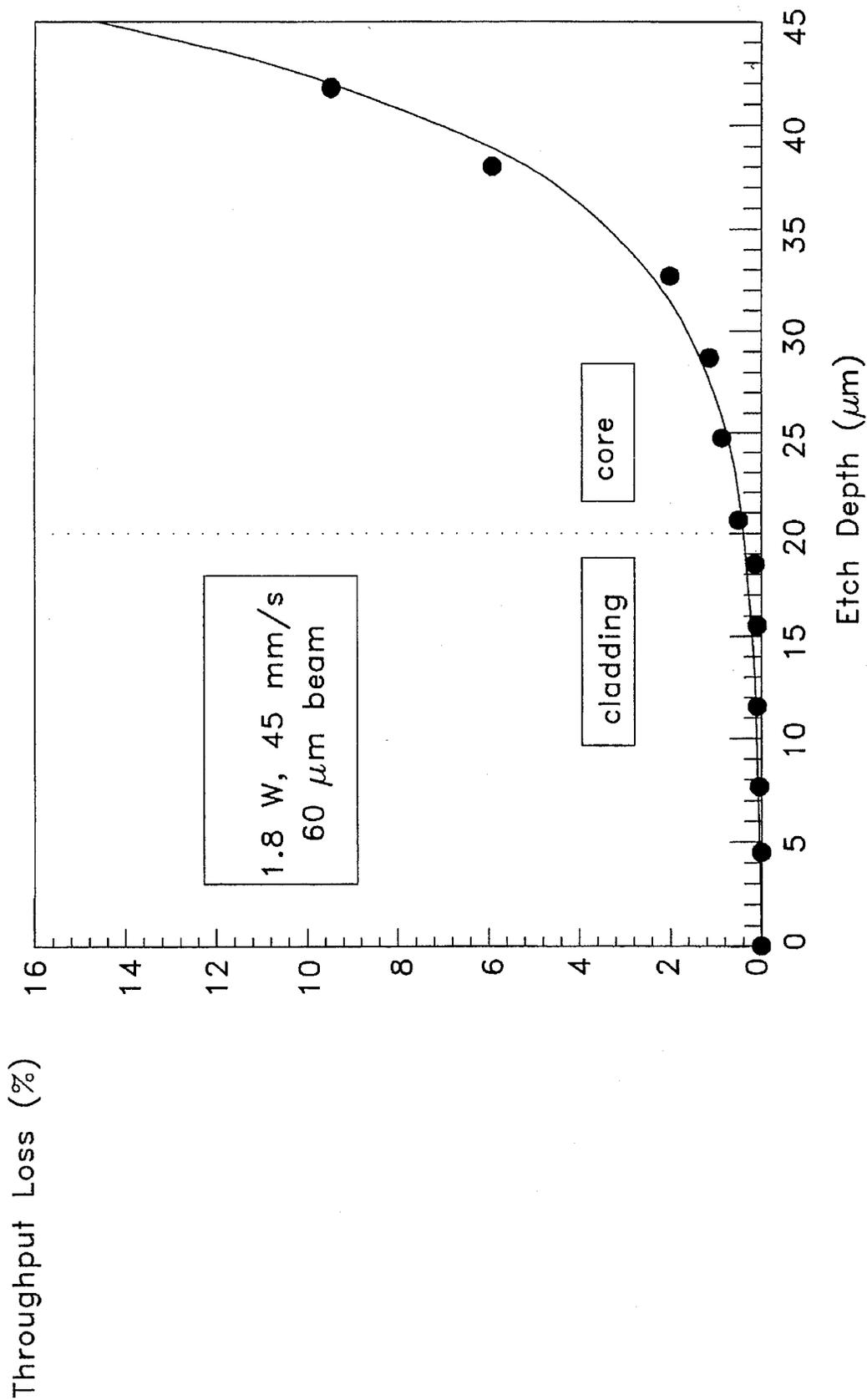
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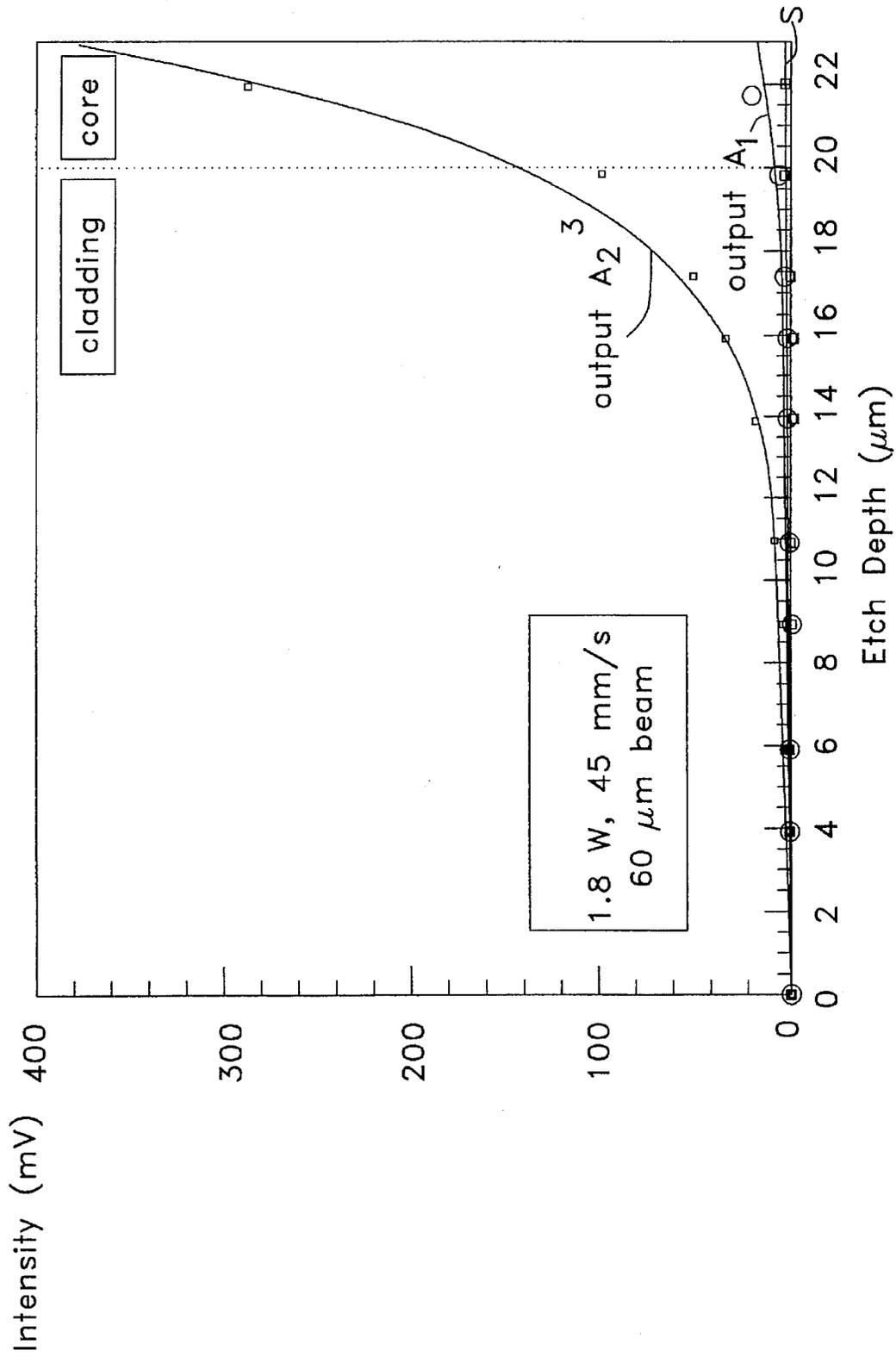
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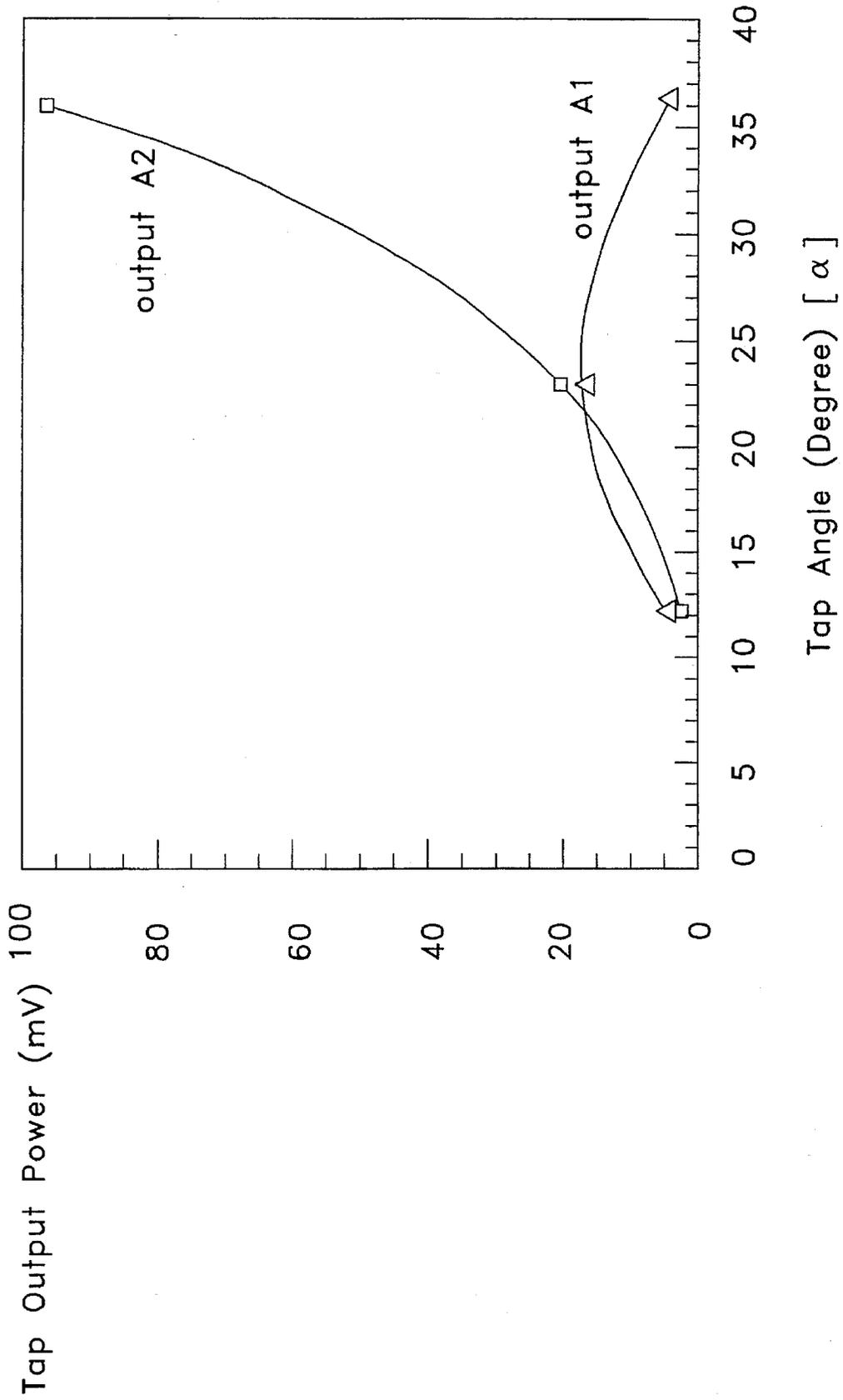
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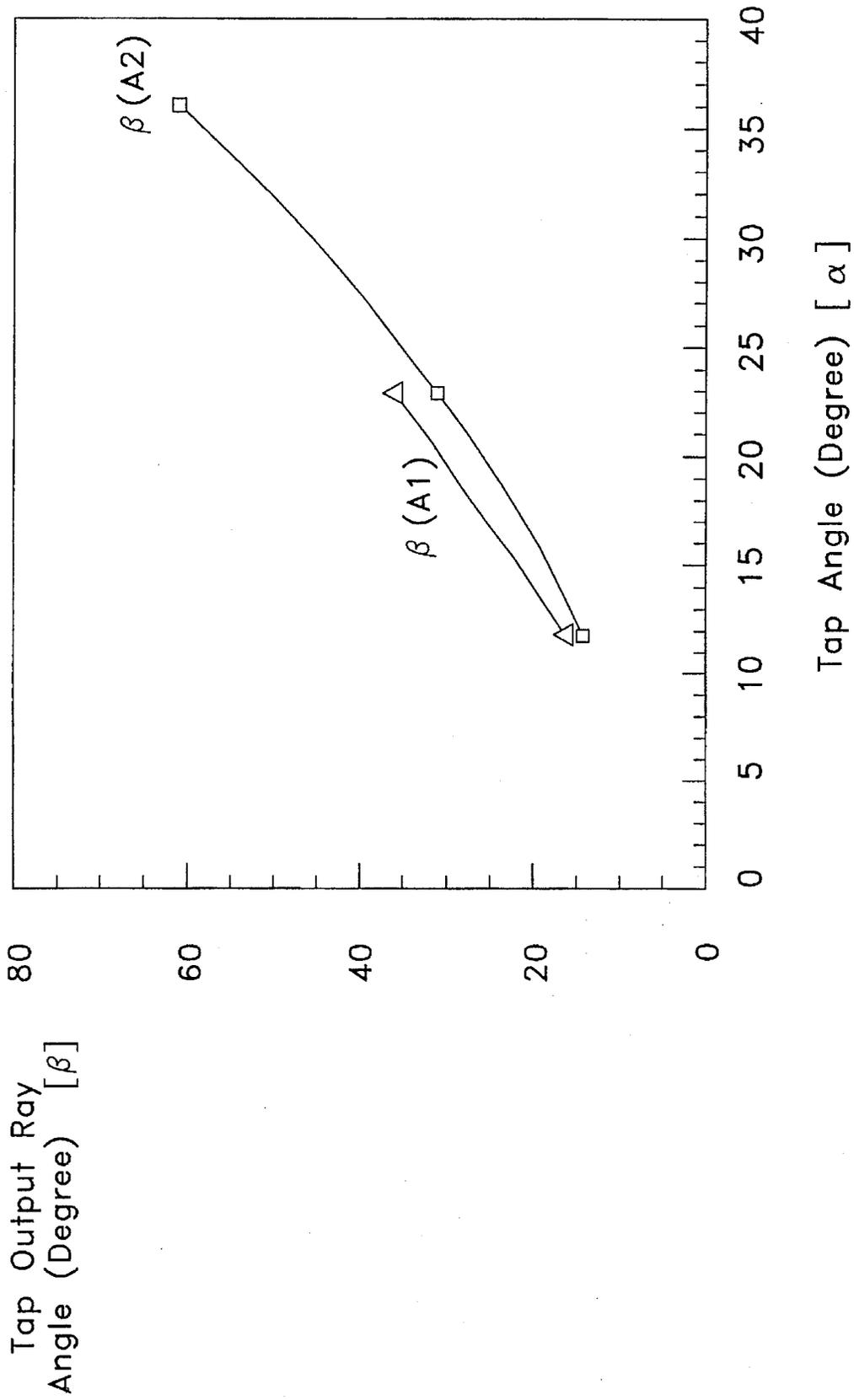
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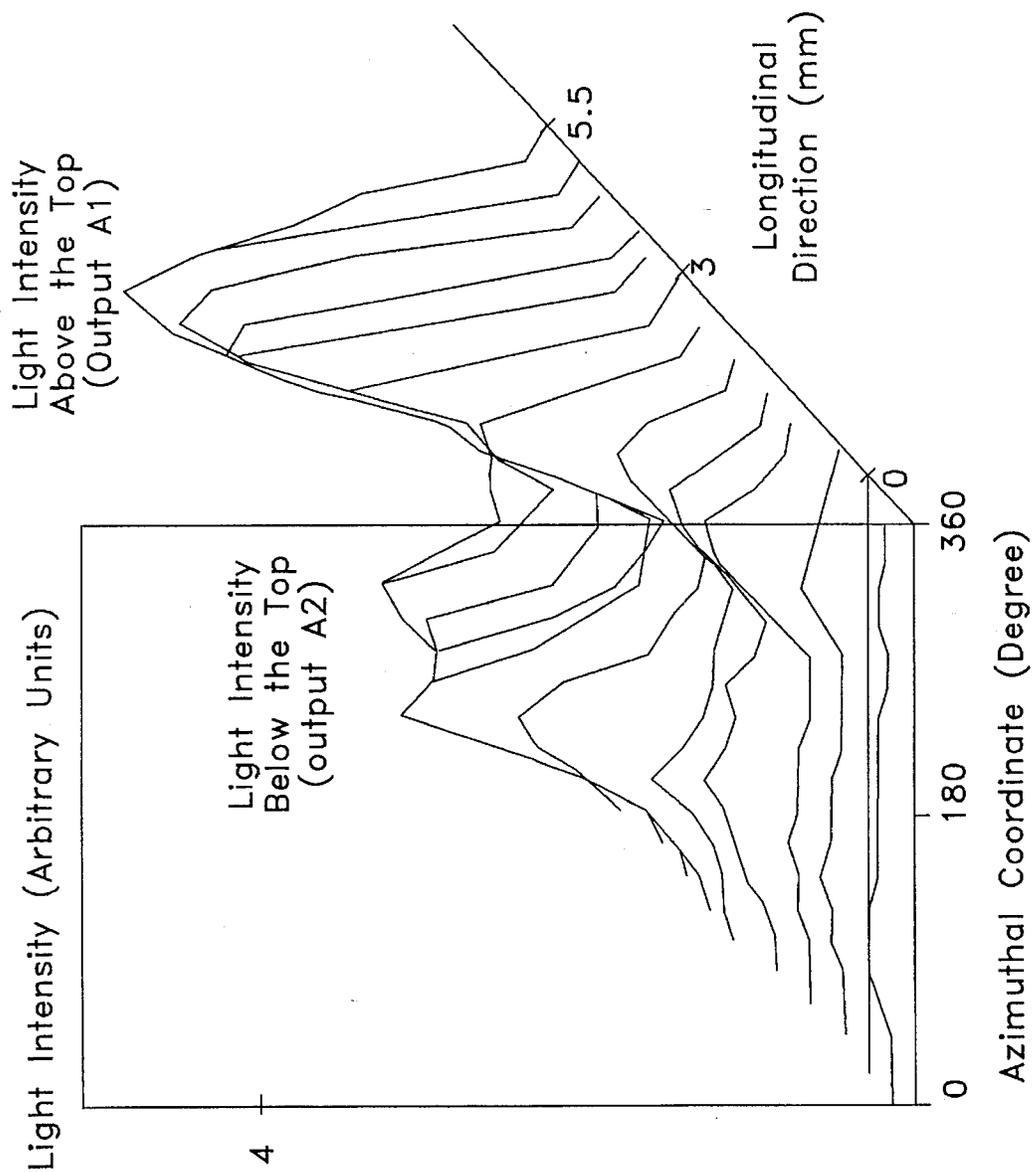
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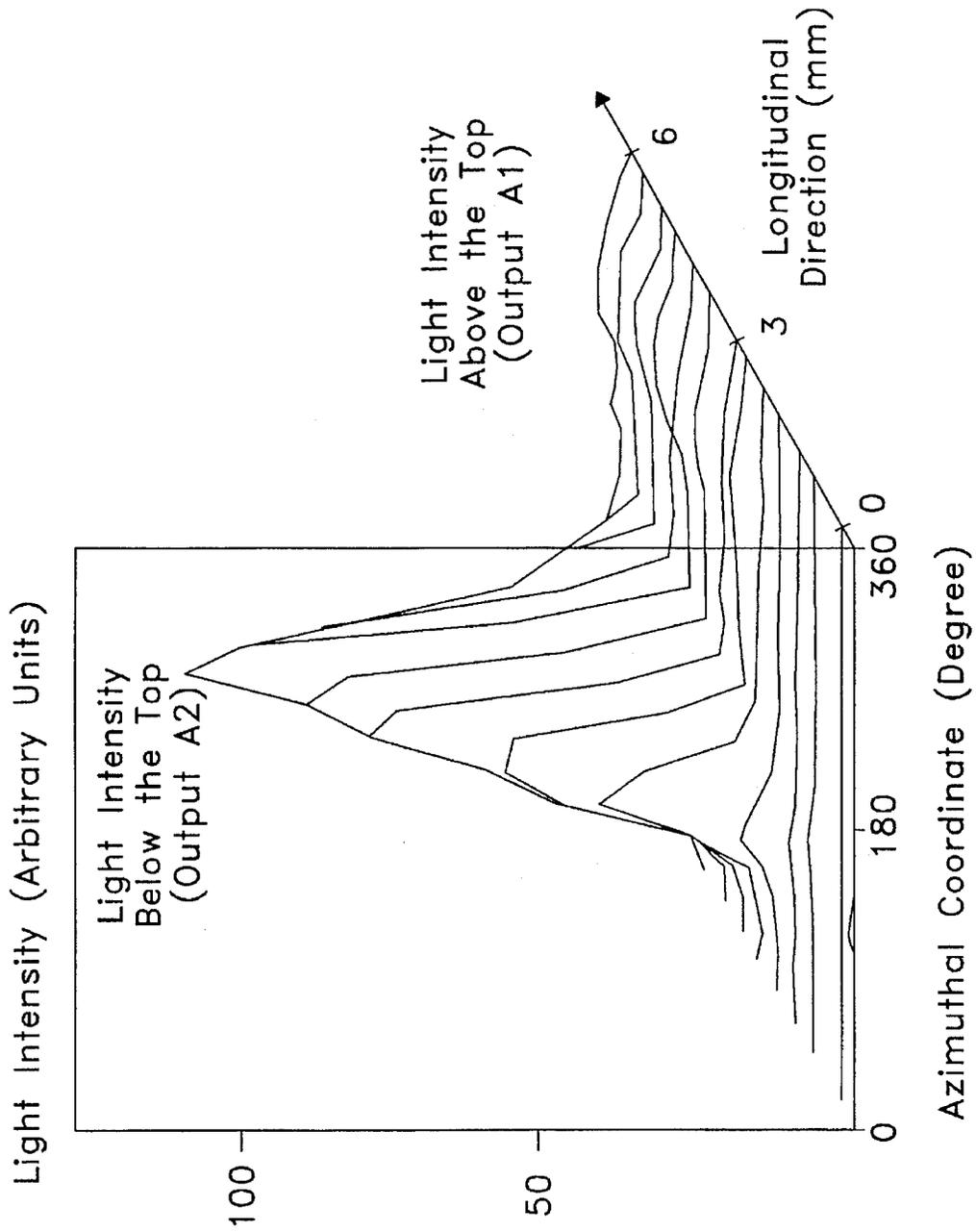
Figure 3B

$$\alpha = 10°$$

Figure 3C

$$\alpha = 23°$$

Figure 3D

$$\alpha = 35°$$

Output A2

Intensity

Light Intensity
Below the Top

100

Output A1

Light Intensity
Above the Top

6

3 Longitudinal
Direction (mm)

0 (Top Position)

0   180   360

Azimuthal Coordinates (Degree)
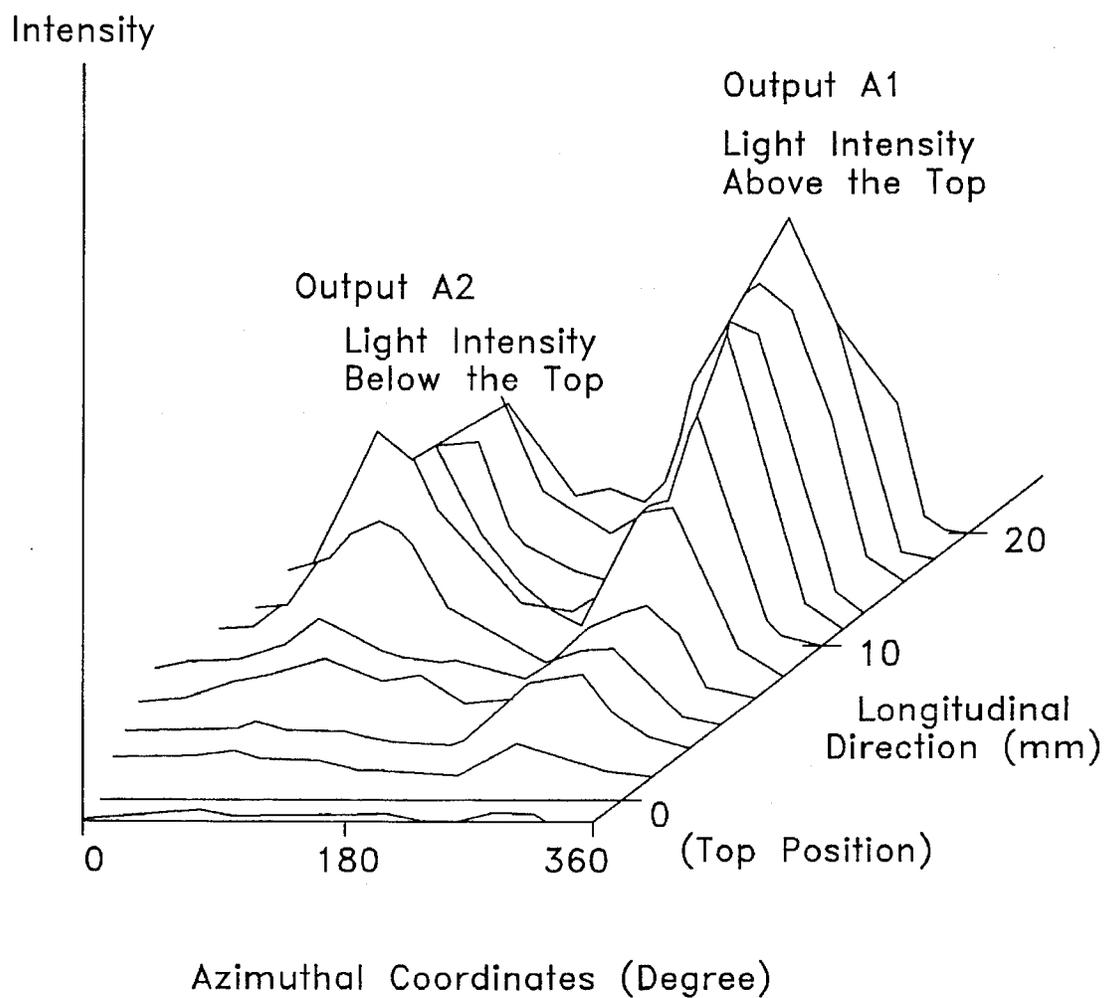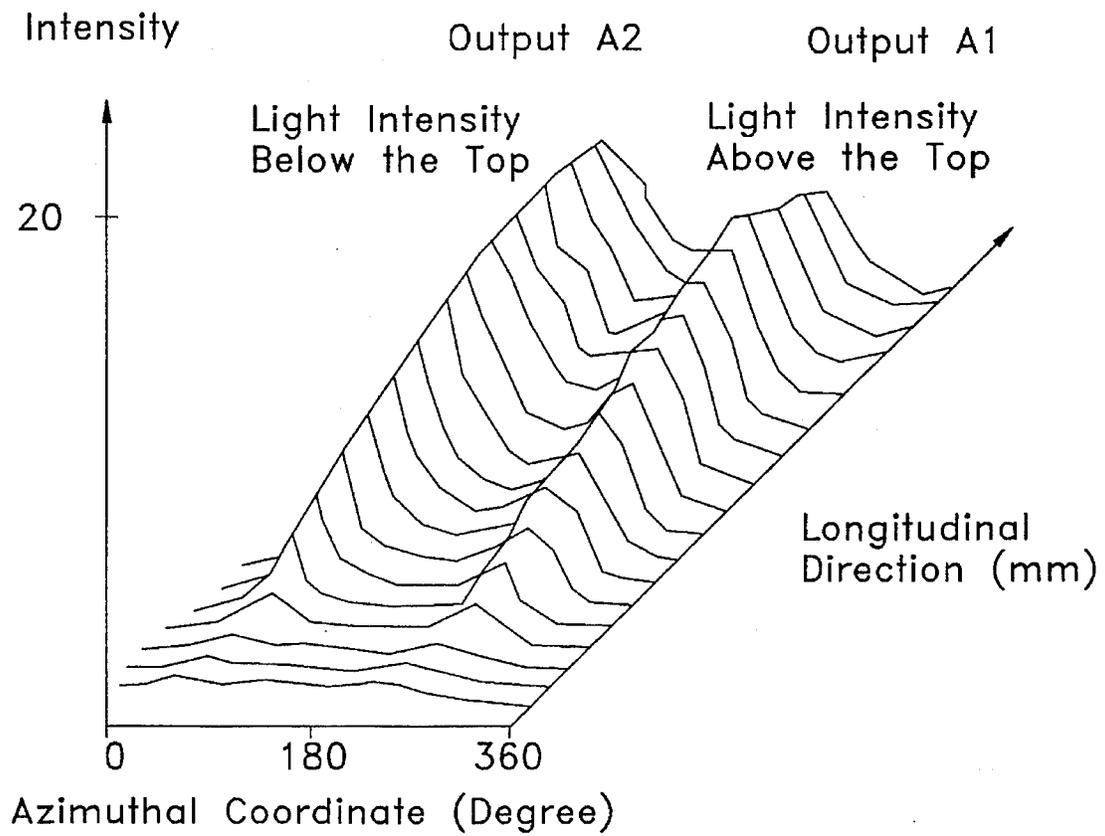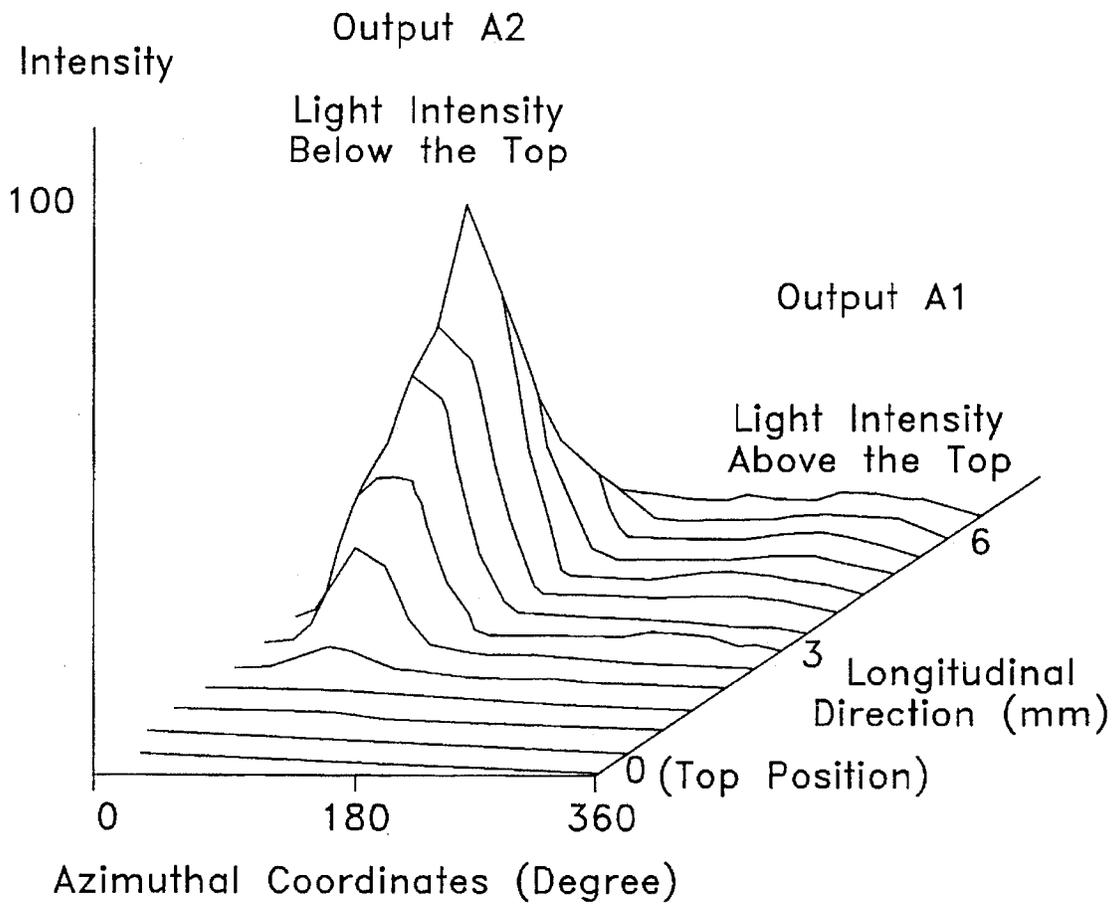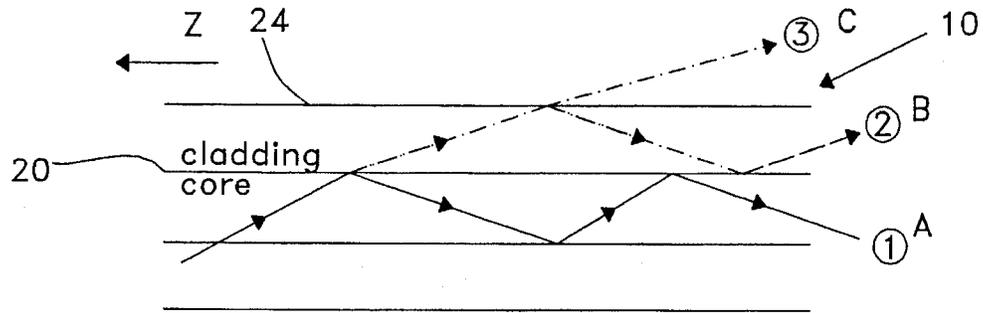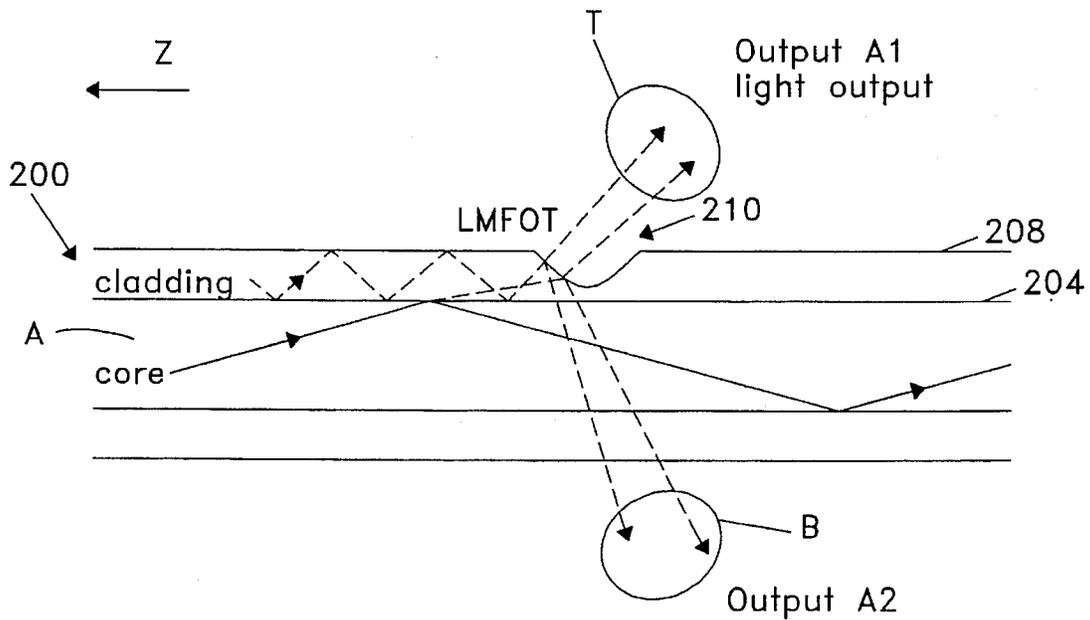
Figure 3E

Figure 4

Figure 5

Figure 6A

Figure 6B

Output A1

210

200

204

208

Output A2

300

304

308

P_I

A

Z

Figure 6C

200

208

204

Output A1

210

Output A2

A
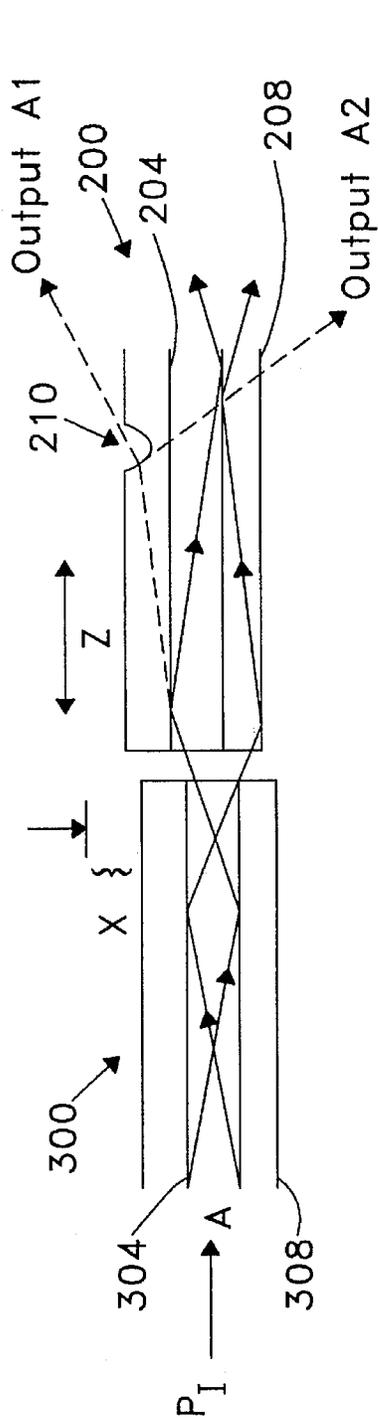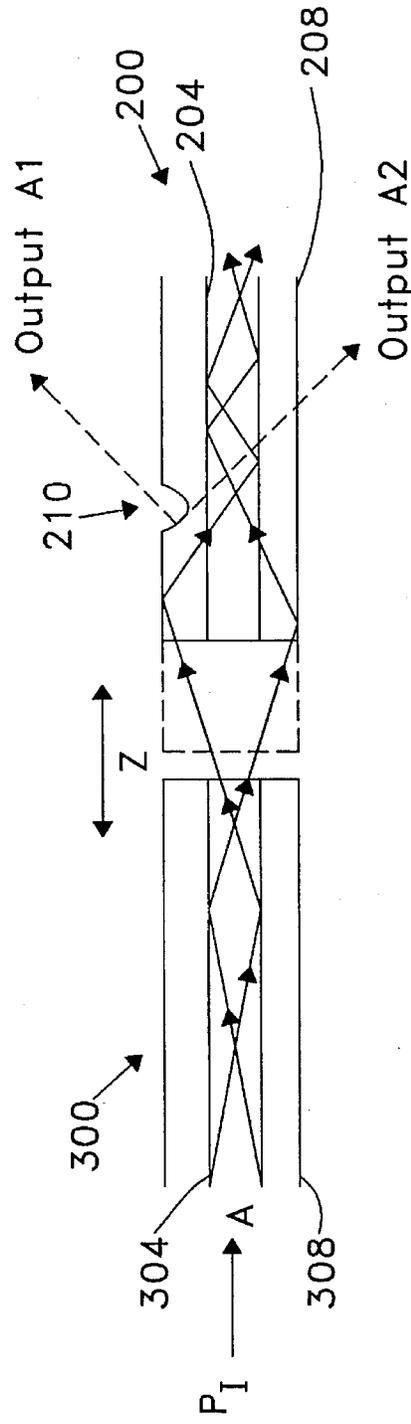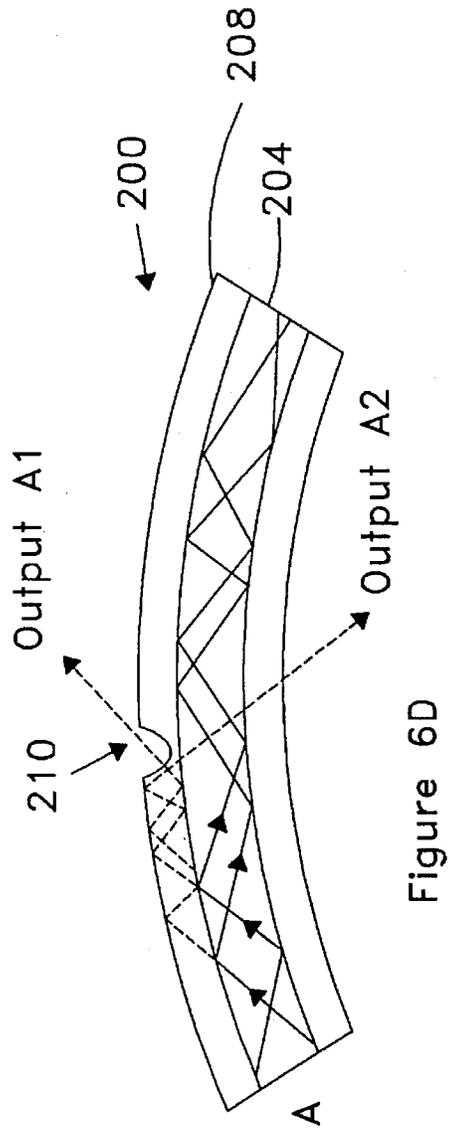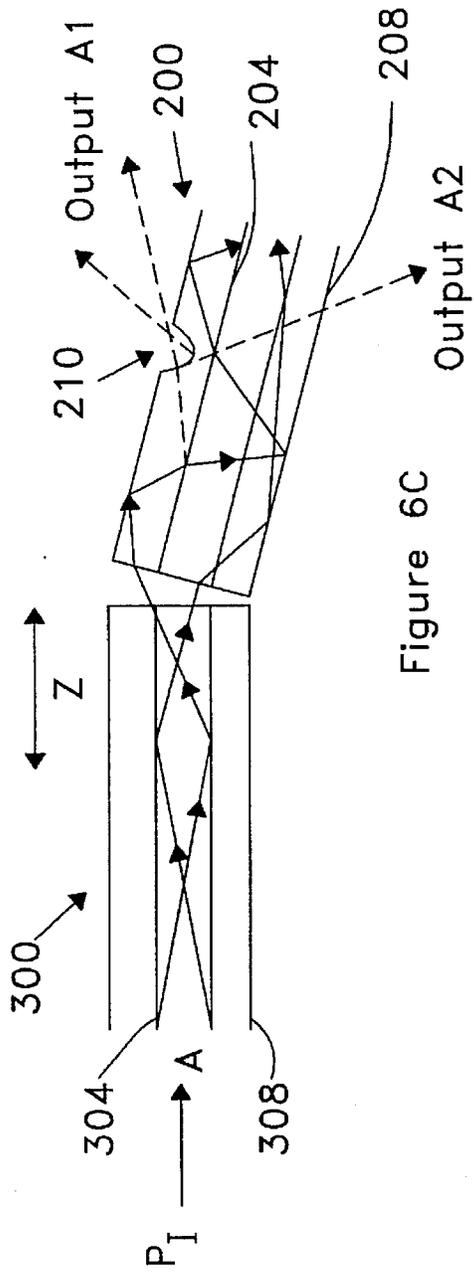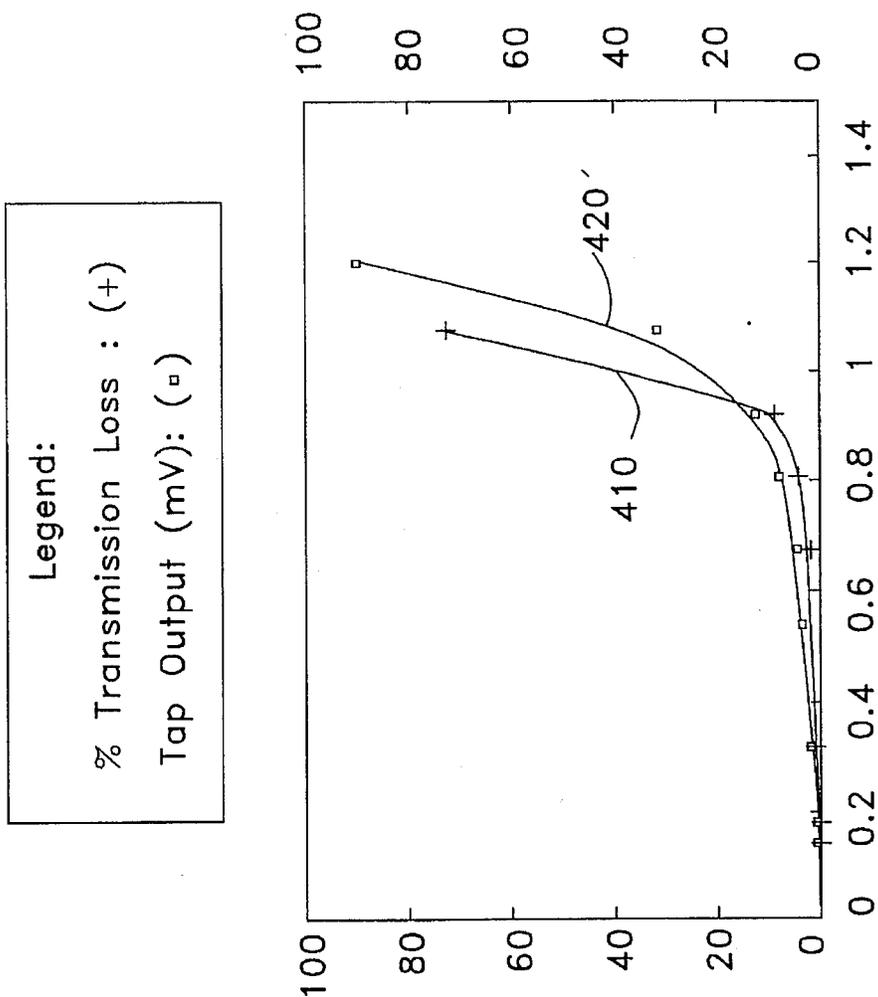
Figure 6D

Figure 7

Figure 8

Figure 9A

646

642

647

634

630

620

650'

624

638 650

650

600

604

light

polymer jacket

cladding

core
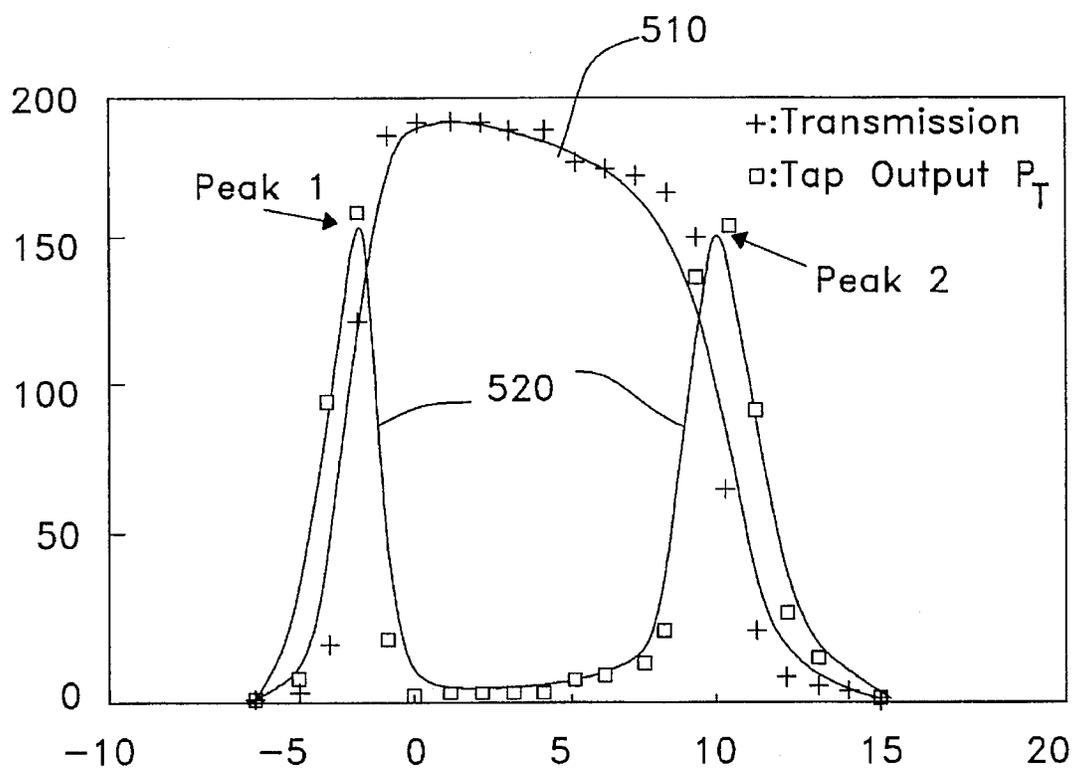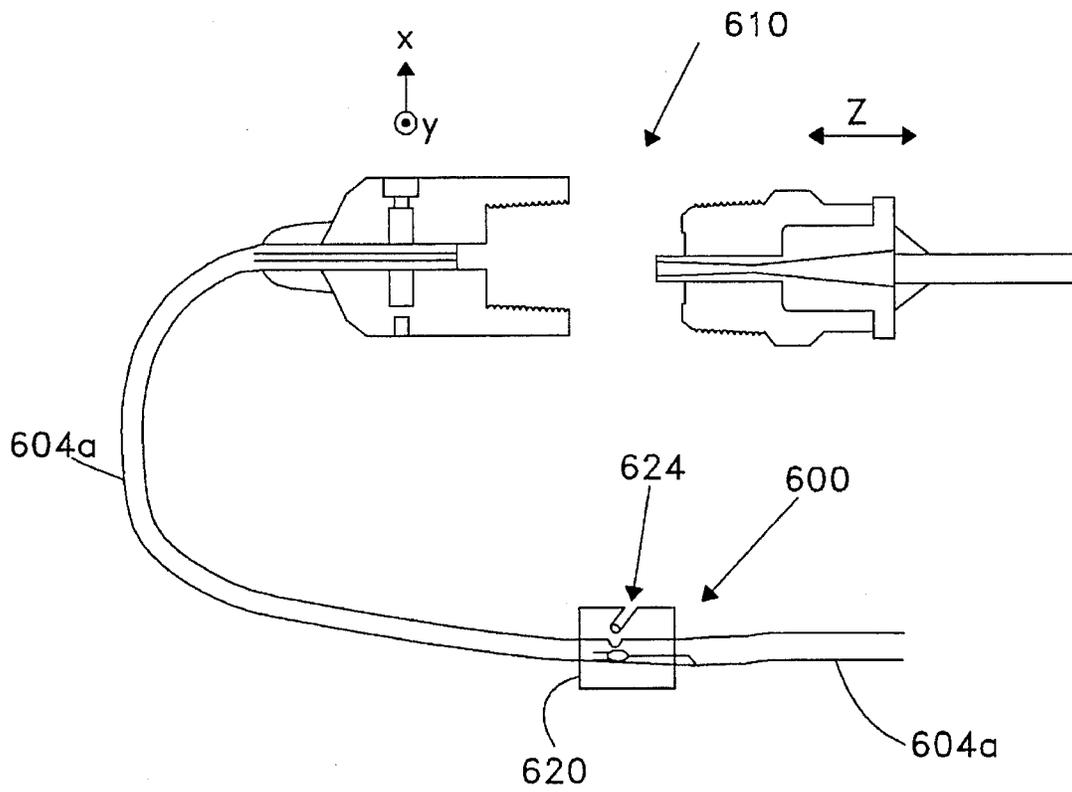
604a
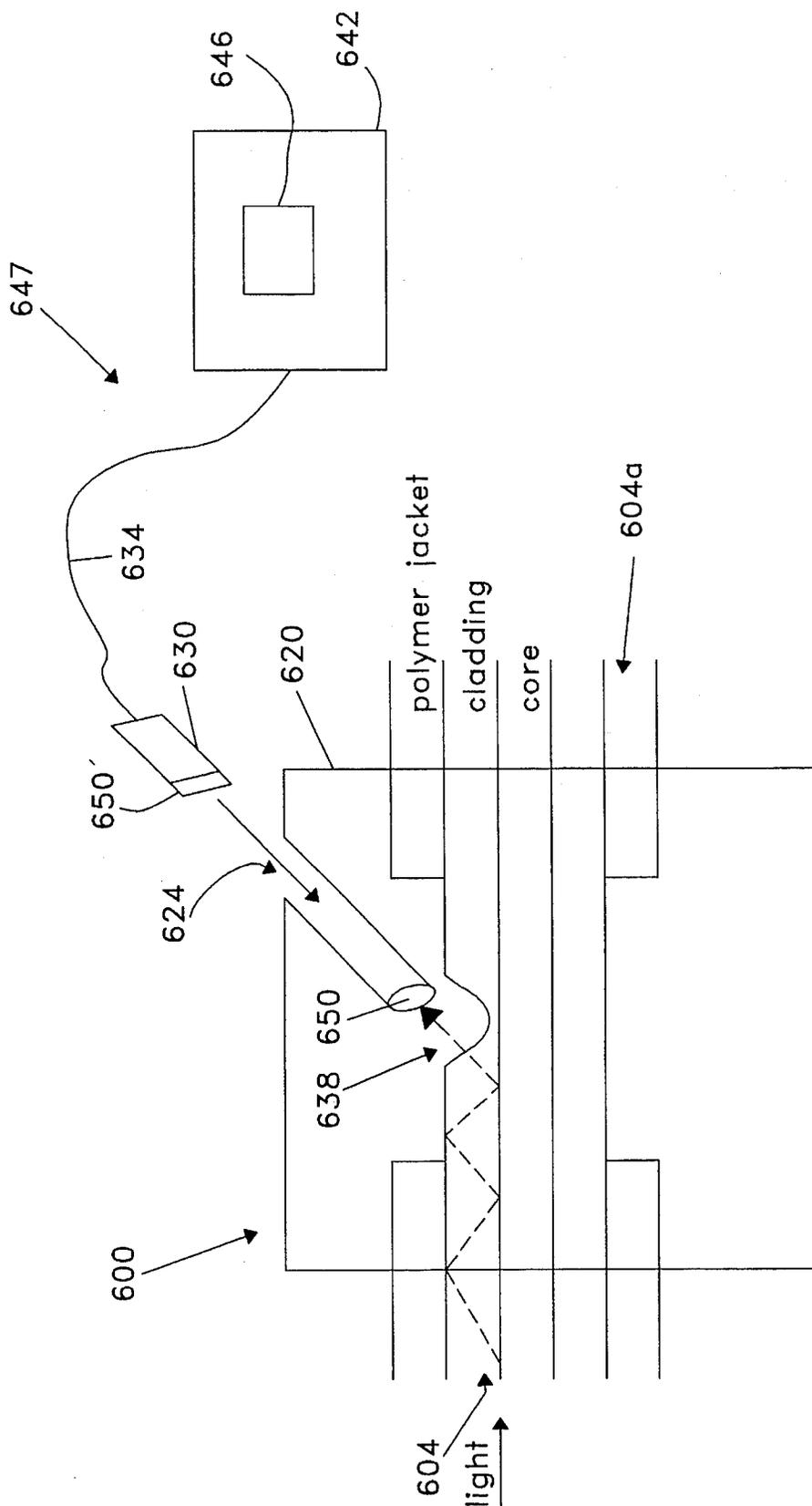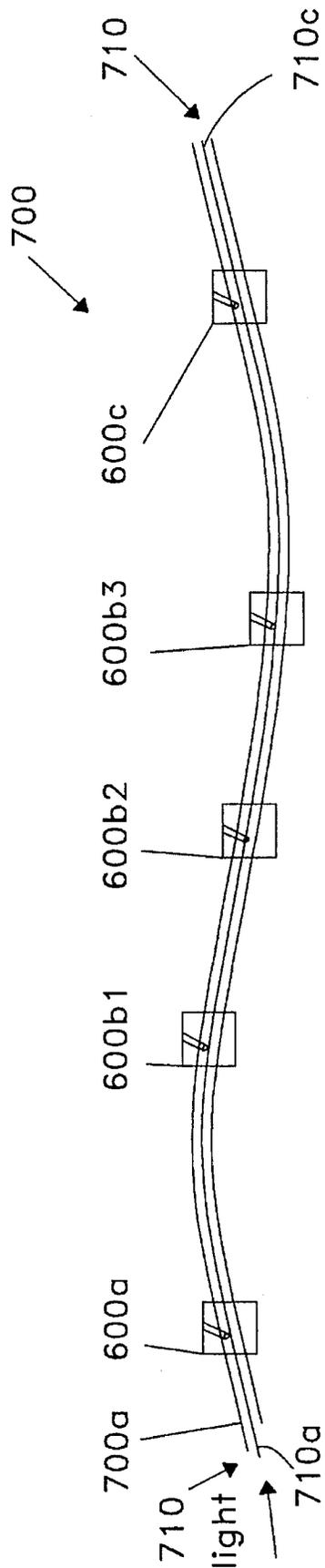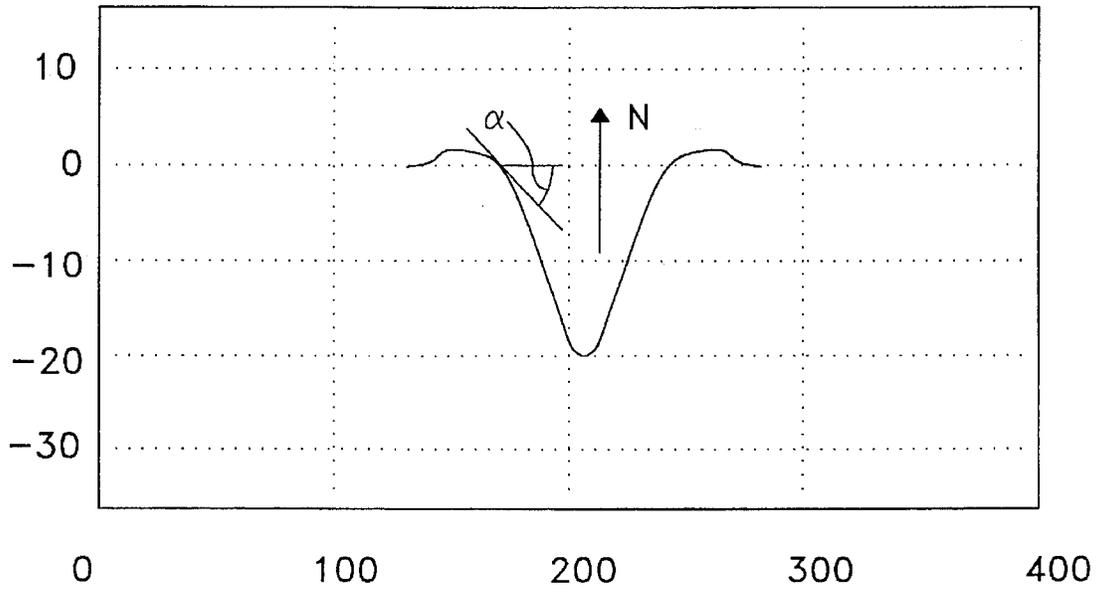
Figure 9B

Figure 10

Figure 11

Figure 12a

φ=45˚

α2

105´

N

α1

Z

101
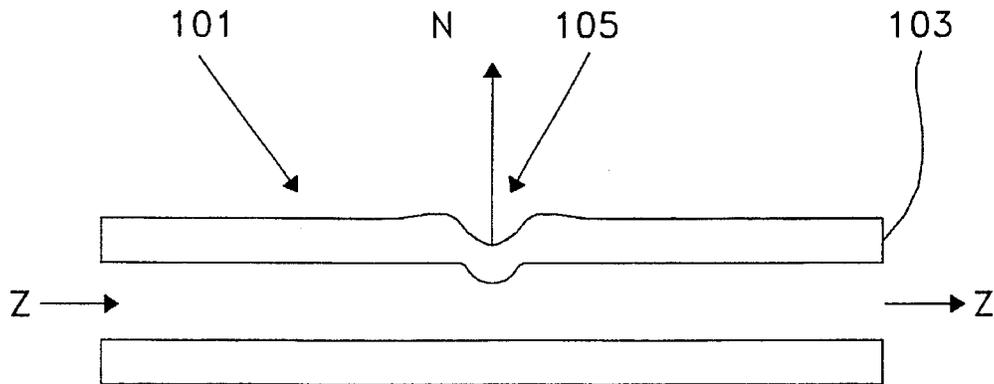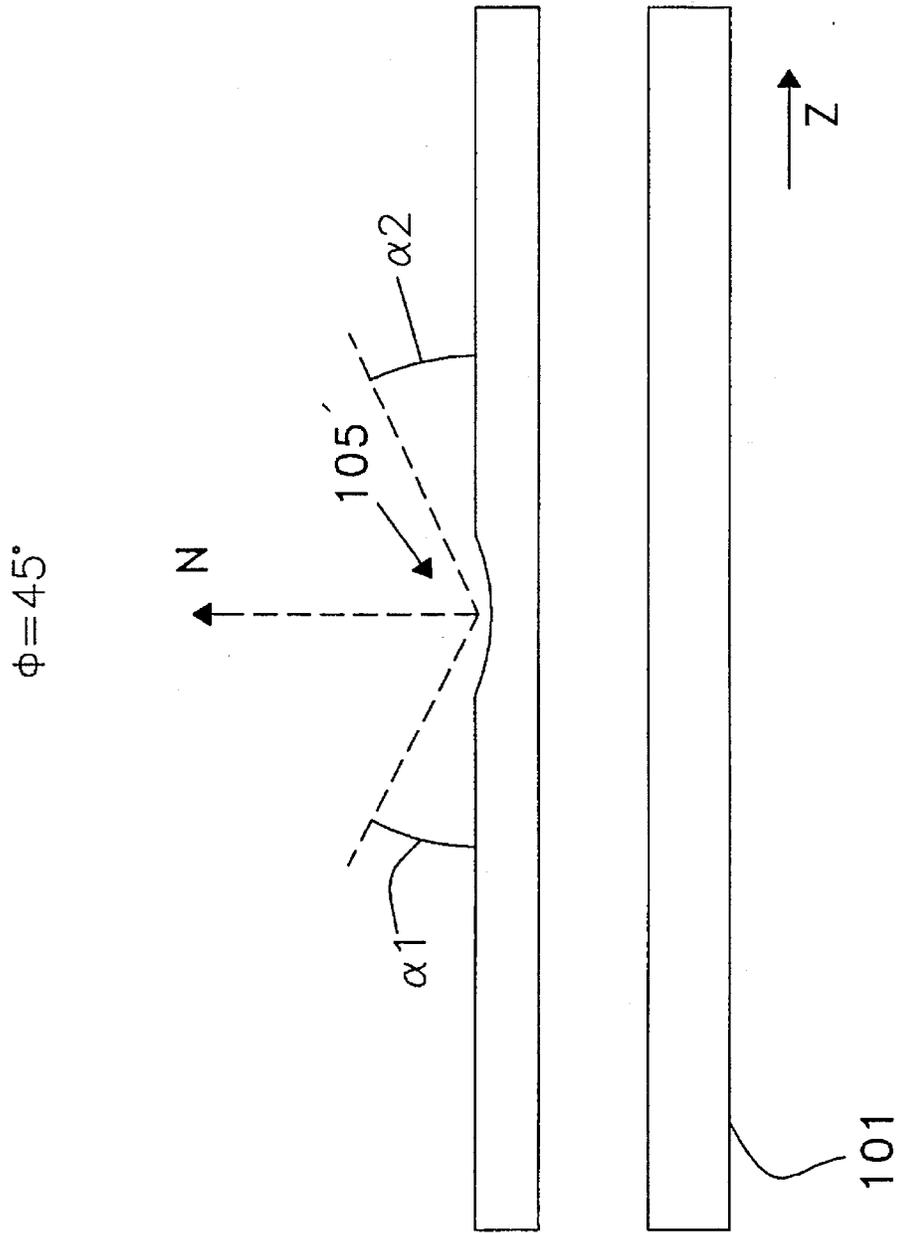
* 10 W, 70 mm/s

Figure 12B
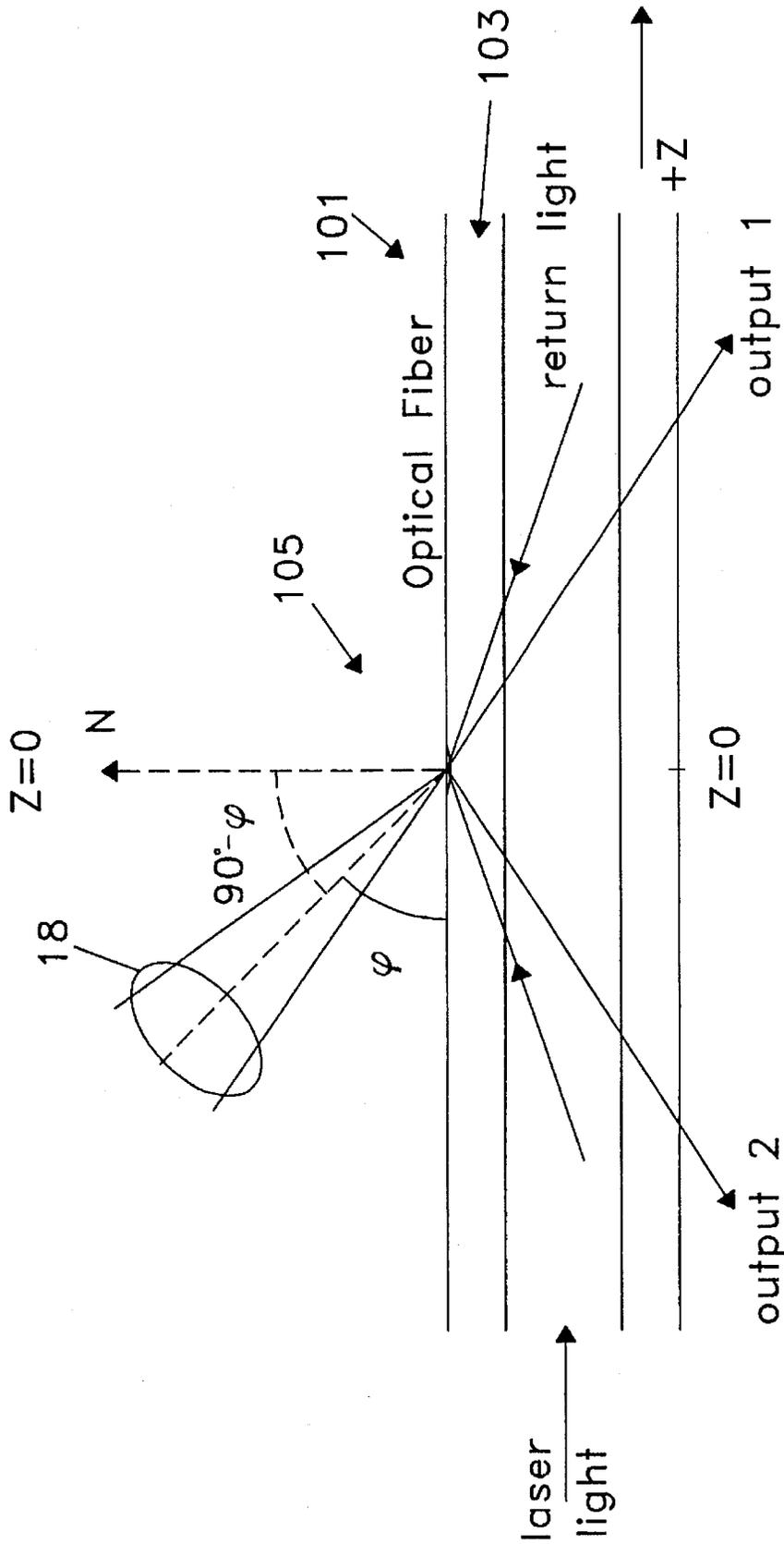
Figure 13
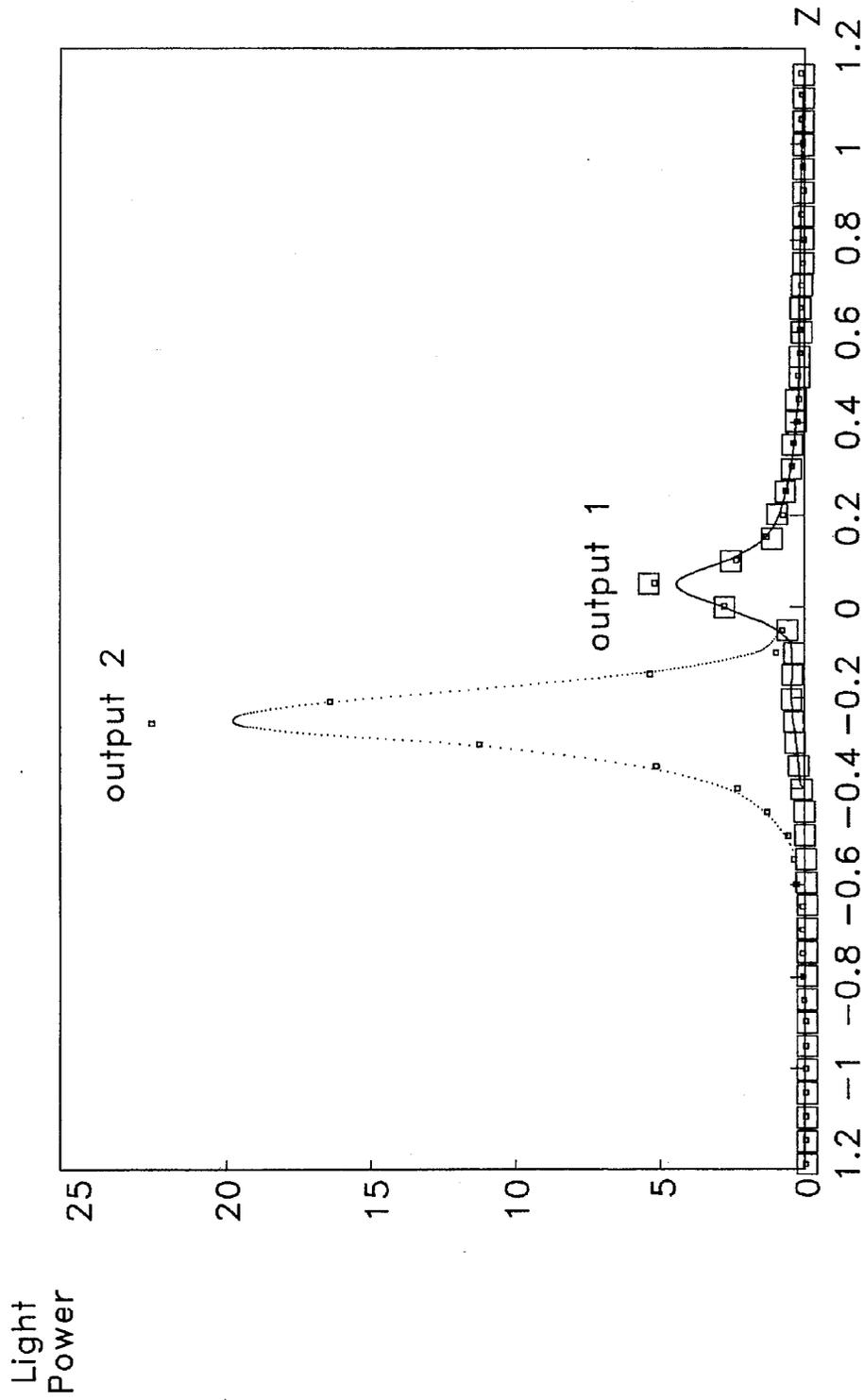
Figure 14

Figure 15

Figure 16A

538

634´

634

522

534

from
laser
510

542

546

A/D

548
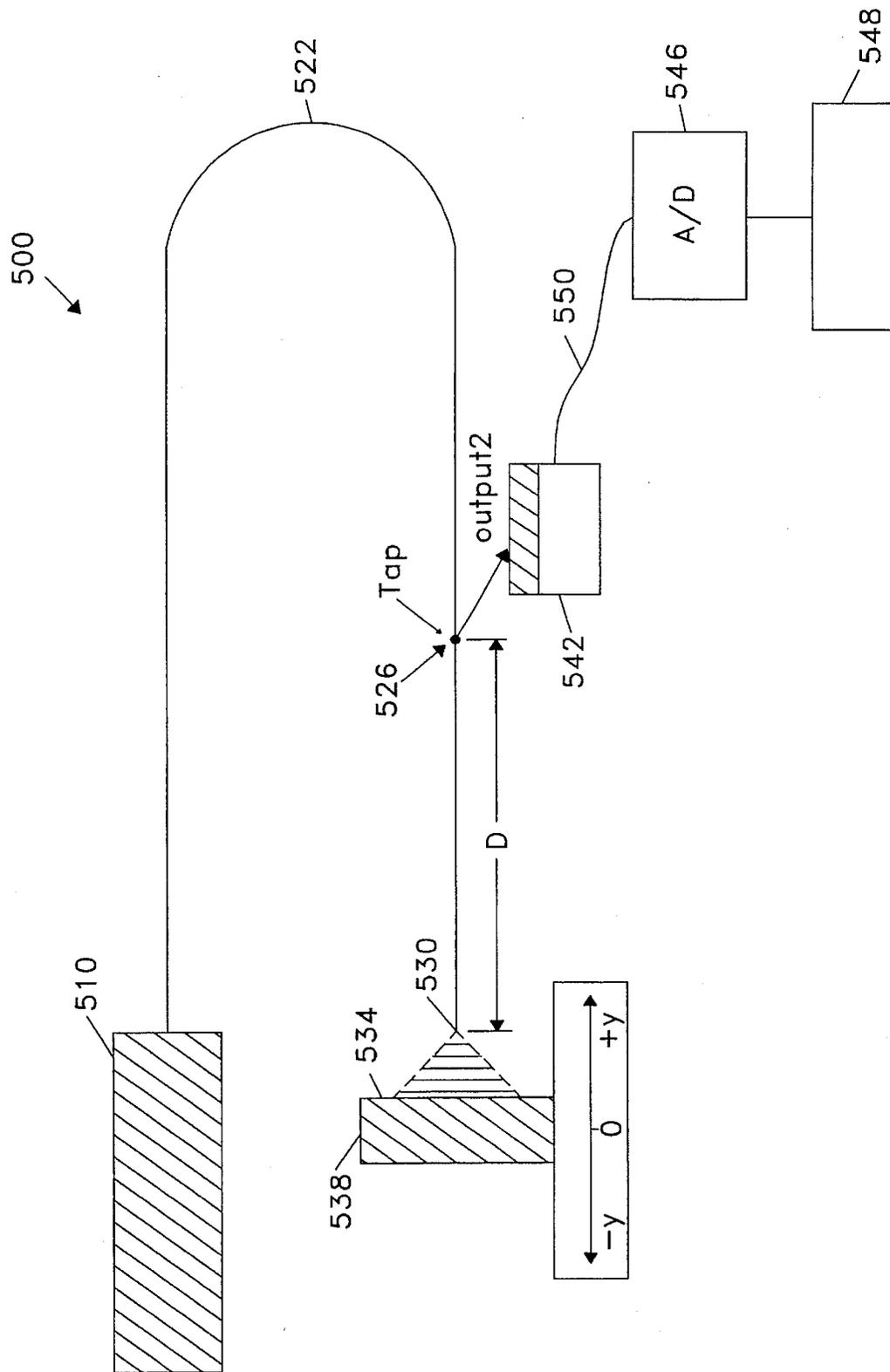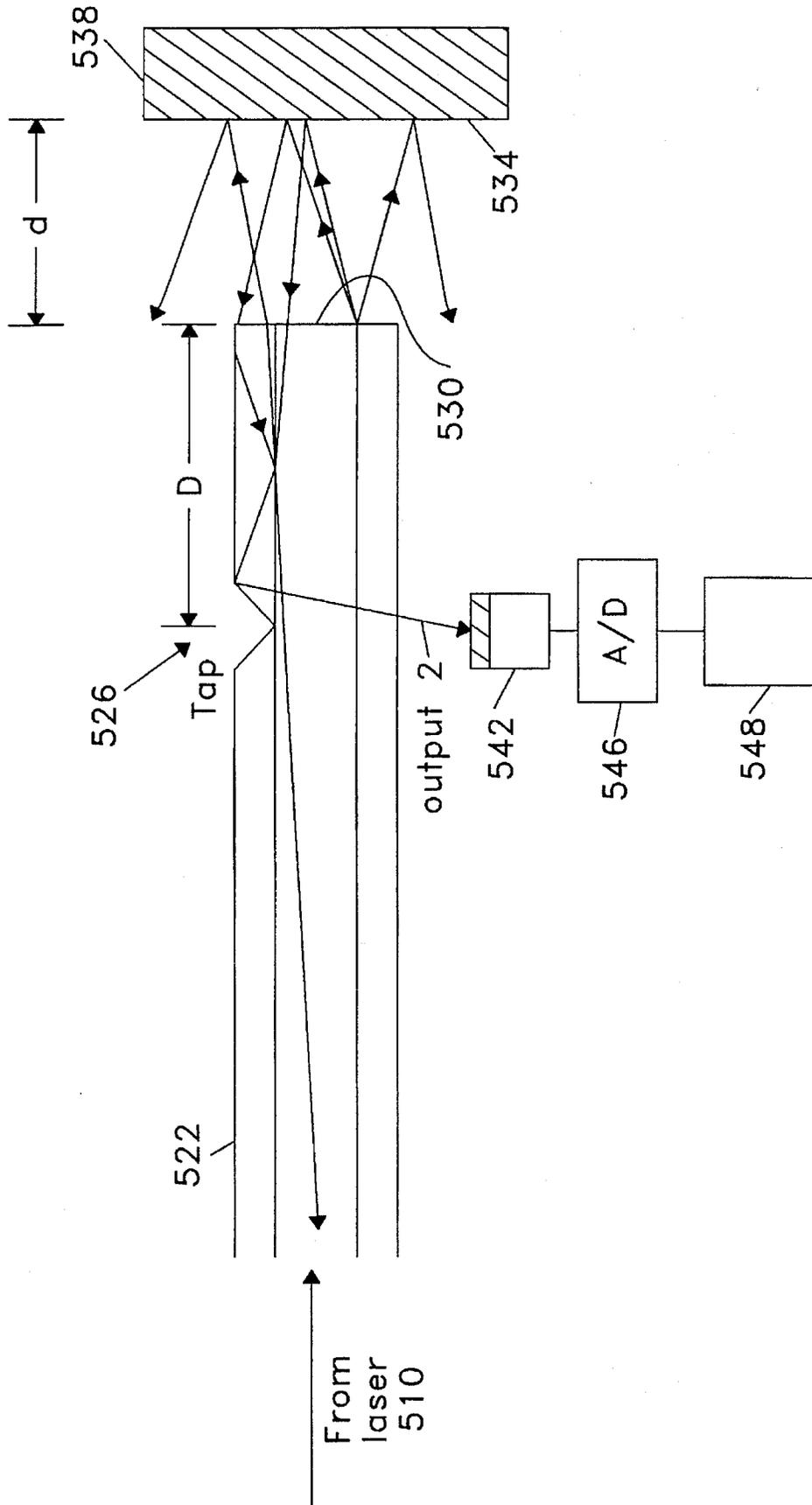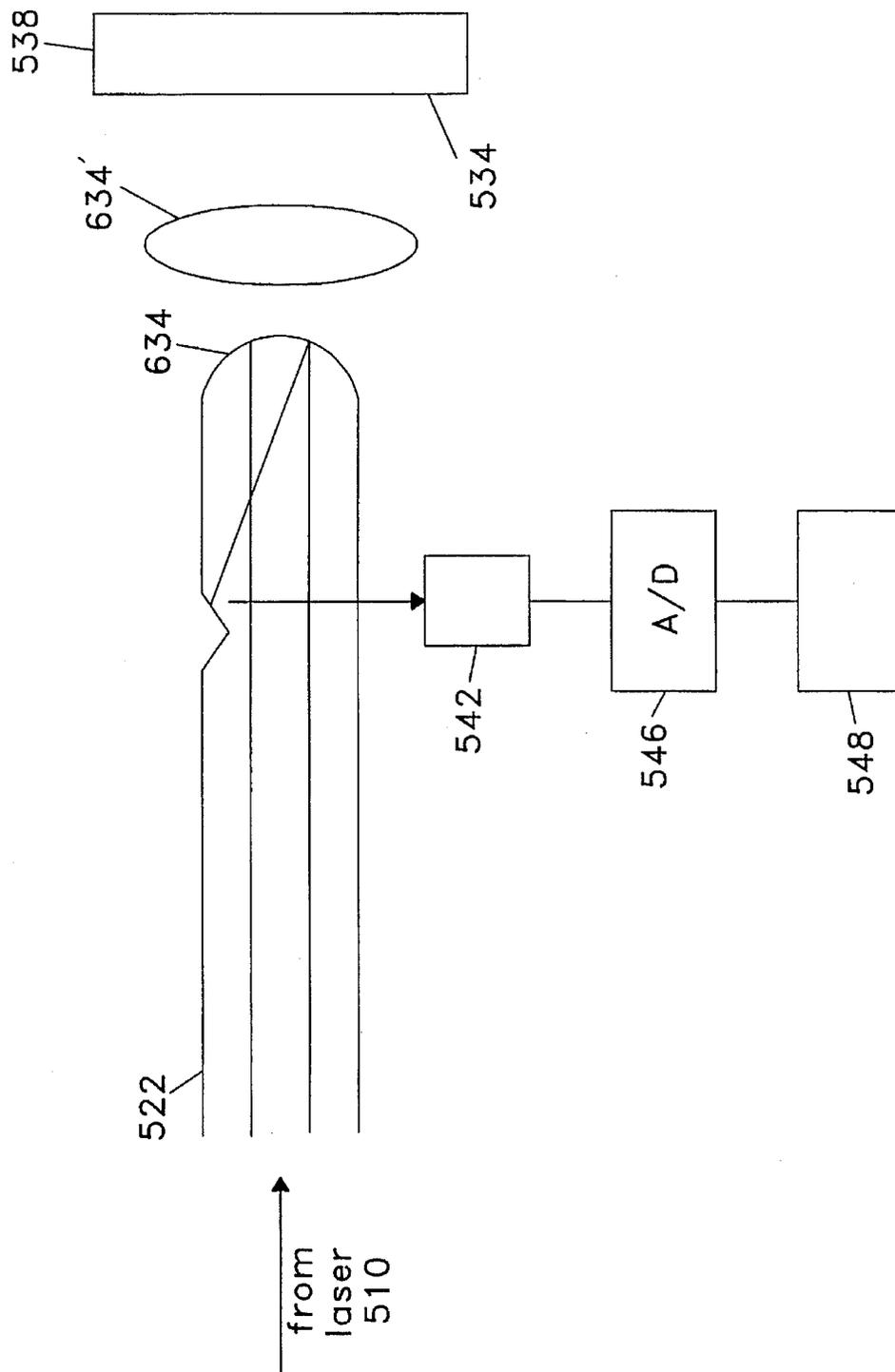
Figure 16B

Figure 17

Figure 18

500

548

546

A/D

542

Detector

output 2

700

n_{fiber}

n_{medium}

530

522

LMFOT

526
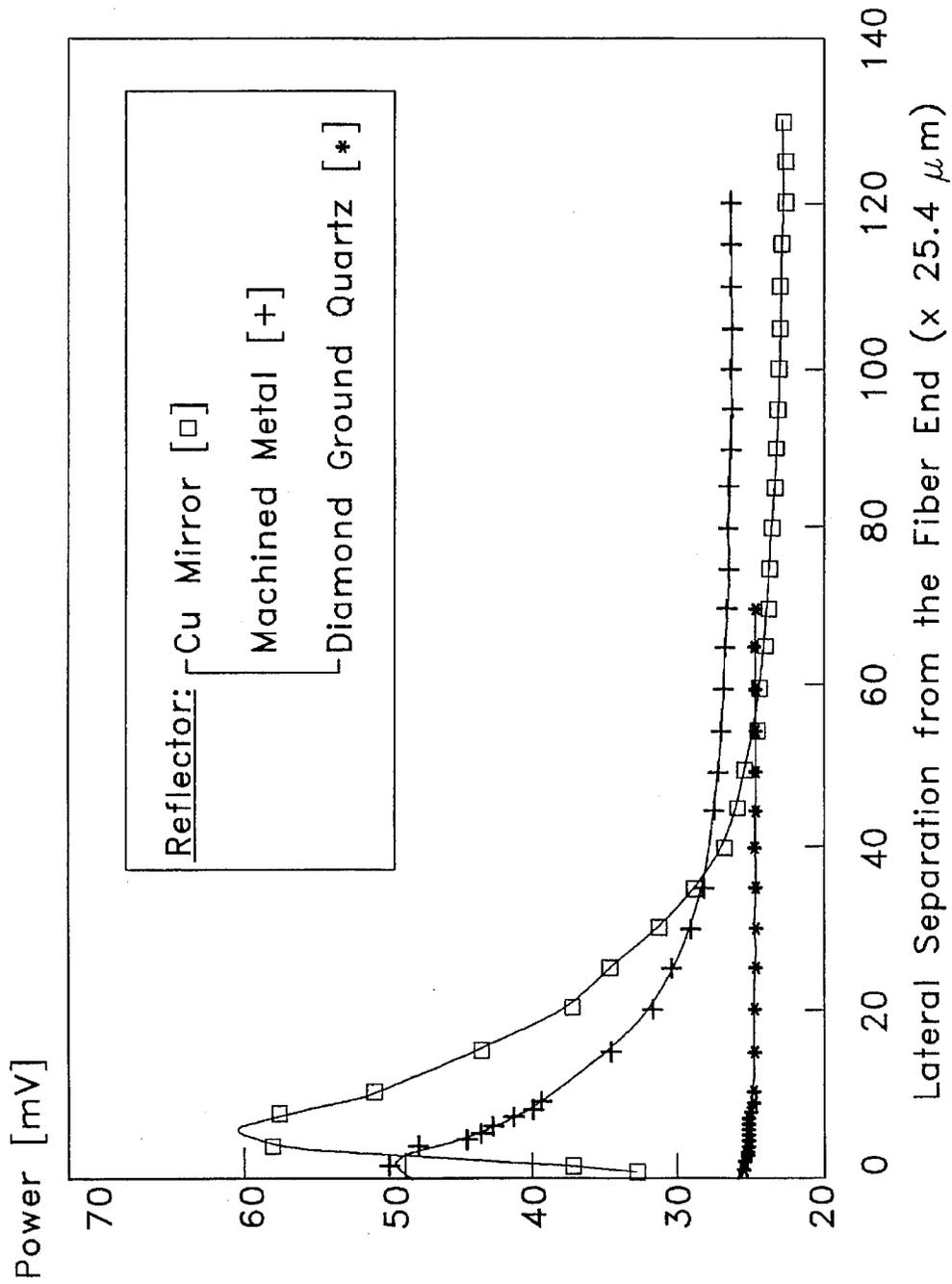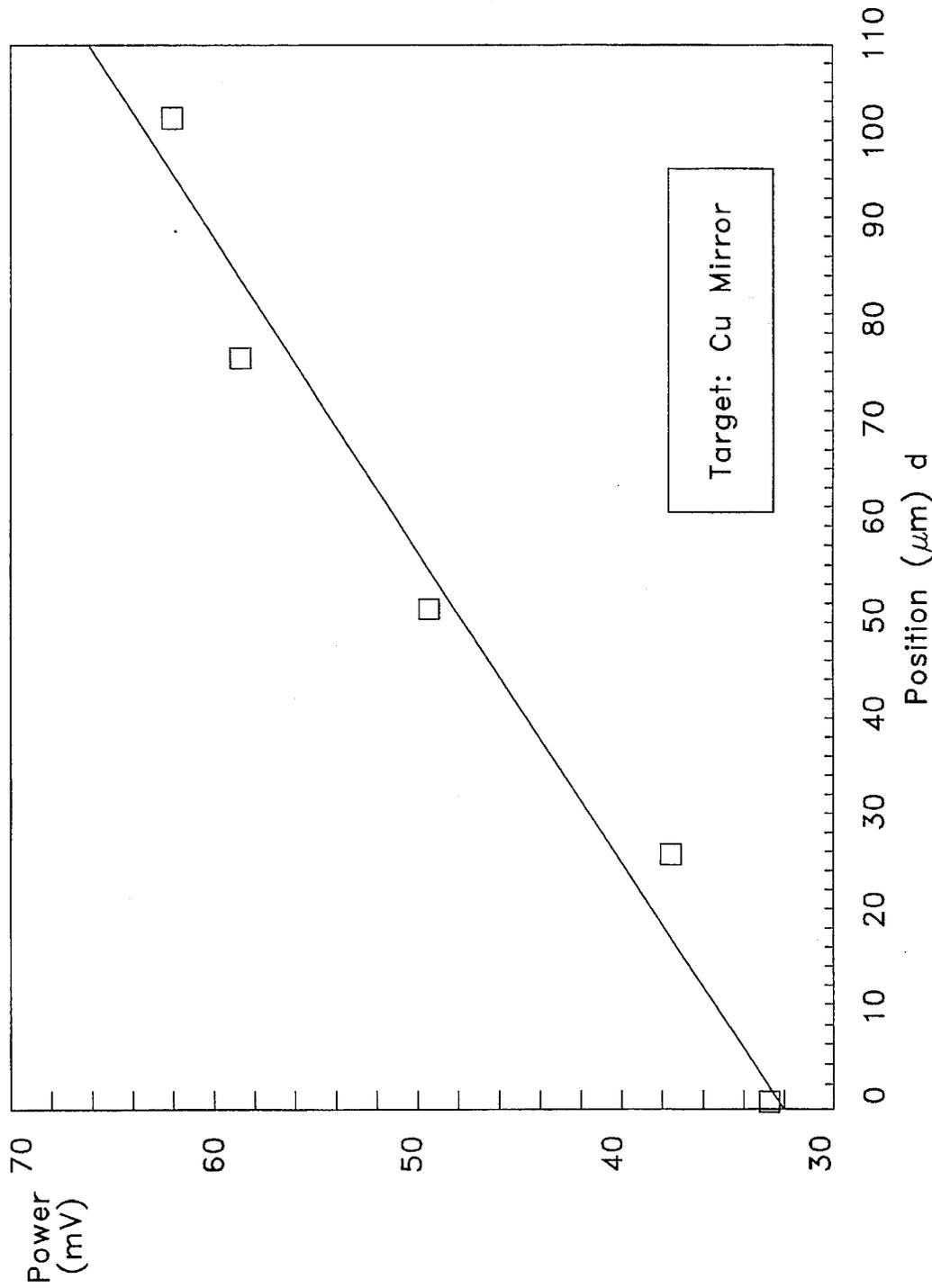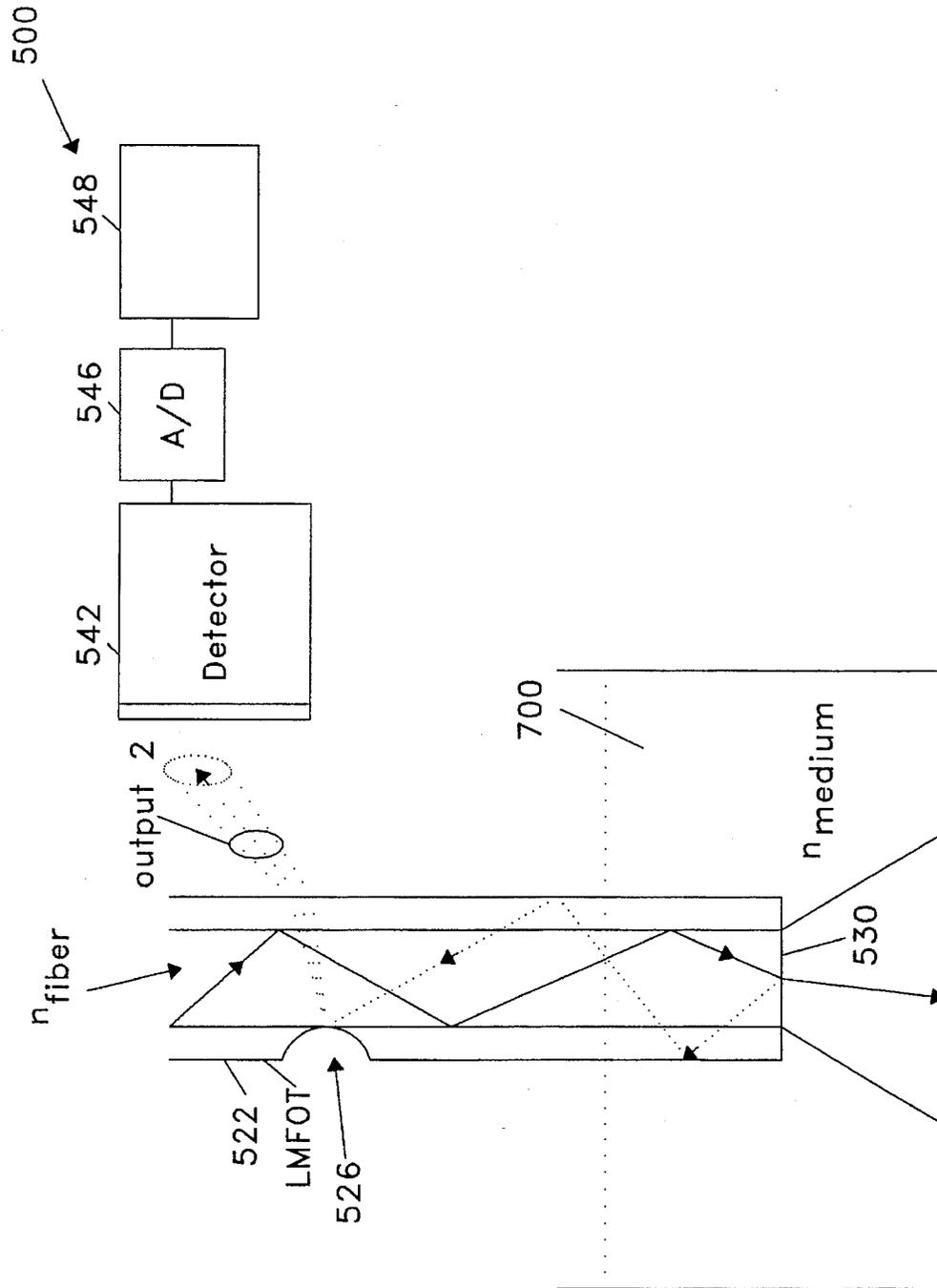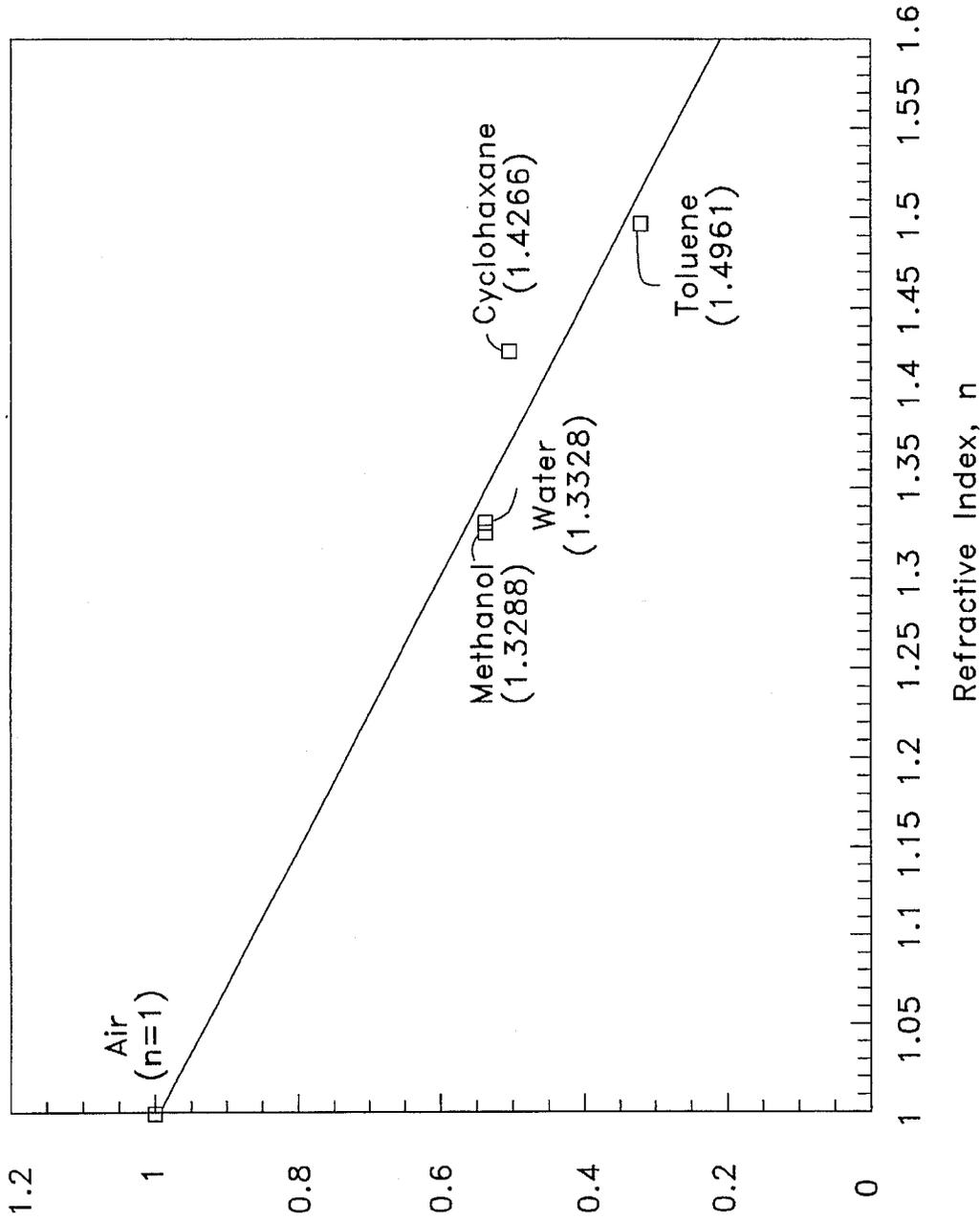
Figure 19A

Figure 19B

APPARATUS AND METHOD OF FABRICATING DIRECTIONAL FIBER OPTIC TAPS, SENSORS AND OTHER DEVICES WITH VARIABLE ANGLE OUTPUT

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to an apparatus and method for fabricating directional optical taps, sensors and other devices with variable angle tap outputs into optical fibers and to the optical taps themselves. This invention also relates to a method and apparatus for making optical sensors, for example, sensors for determining optical fiber misalignment losses with other optical devices, strain losses in optical fibers and optical mode filters. This invention also relates to a method and apparatus for measuring position of an object and refractive index of liquids.

2. Background of the Related Art

Optical fibers are replacing wires in telecommunication systems, data link systems such as local area networks (LANs) and sensor systems such as "fly-by-light" systems in aircraft. Optical fibers are advantageous in these systems because fibers can carry significantly more information than electrical wires. For example, an optical fiber can carry up to 5 billion bits per second whereas a wire can carry a maximum of 150 million bps. In addition, optical fibers are reliable and more compact than the electrical wires they replace. Also, optical fibers do not produce electro-magnetic interferences nor are the signals they transmit effected by electro-magnetic disturbances.

Losses are encountered in any couplings between an optical device (e.g. a laser, an optical modulator, an optical waveguide etc . . . ) and a fiber or between two fibers. Installation and upkeep of these couplings represents a costly aspect of fiber optic telecommunication systems, fiber optic LANs and fiber optic sensor systems. One reason for this is that installation of optical devices must be done by hand using specially trained and expensive technicians. It is therefore desirable to be able to conveniently and inexpensively couple information from an optical device or fiber to another optical fiber.

Another problem with current optical couplings is that they can produce significant signal losses. One reason for this is that optical fibers have very small fiber cores, (the diameter of fiber core is typically between a few micrometers to a several hundred micrometers) making it difficult to align and maintain alignment between optical devices and fibers or between two fibers. It is even more difficult to couple a bundle of optical fibers contained in optical cables with other optical devices or another bundle of fibers. It is therefore desirable to be able to conveniently and non-intrusively determine whether the coupling is producing losses insuring minimal signal loss at the connector.

In addition to coupling losses which occur at couplings between optical devices and fibers, additional losses can occur due to bending or straining optical fibers. In such situations, a significant amount of radiation is lost due to guided cladding modes and radiation (leaky) modes.

Optical time domain reflectometry (OTDR) has been used as a distributed reflective loss monitor in such optical data link systems. OTDR systems involve sending a pulse of monochromatic light of a known power level into one end of a particular fiber link in the fiber optic system and measuring the reflected power level due to discontinuities such as splices, connectors or fiber breaks. This approach does not however locate the strain or misalignment in short distances or in complicated local area networks. Also, this type of OTDR requires significant additional complicated components as well as access to the end of the fiber in order to launch the laser pulses into the fiber.

Another technique for status monitoring in optical fibers involves using clip-on optical components or sandwiching optical fiber between a grating and a lens. These clip-on optical components couple a small amount of laser light out of the fiber core. However, such clip-on components are not suitable for long-term installation because they place a high stress on the optical fiber which can generate microcracks. Consequently, it is advantageous to have a simple, non-intrusive, long-term technique to determine whether strains and misalignment are being placed on optical fibers in any type of fiber system without disconnecting any fibers in the system.

In addition to providing a convenient and inexpensive approach to minimizing losses due to couplings, it is desirable to replace electrical sensing systems such as electrical position sensing systems with optical sensing systems such as optical position sensor systems. Fiber optic sensing systems offer numerous advantages over conventional electrical sensing systems because they are small and light weight. It is even more advantageous if sensors in the sensing system are completely passive optical components, i.e., they have no active electro-optic components such as semiconductor lasers or light emitting diodes. Passive sensors are desirable because they would be immune from electromagnetic interference (EMI) which occurs near power lines and they would also be immune from electro-magnetic pulses (EMP) which can occur in the event of a nuclear explosion. EMI/EMP immunity is especially important advantage for new generation aircraft which have skins made of composite materials.

Smart skin technology relies on embedding a plurality of passive optical sensors in a structure such as an aircraft wing. Smart skin technology can be used to passively measure strain or other local deviations of parameters such as strains or temperatures with a particular spacial resolution, wherein a large number of optical sensors produces a high spacial resolution. Consequently, it is desirable to be able to fabricate optical fiber with a large number of optical sensors, which can be used in smart screen structures.

SUMMARY OF THE INVENTION

It is therefore an object of the invention to provide a method and apparatus for fabricating directional optical taps.

Another object is to be able to fabricate optical taps with known geometry.

Another object of the invention is to provide an optical fiber having at least one optical tap which filters higher order optical modes from an optical fiber.

Another object of the invention is to provide a long-term, non-intrusive apparatus and method for monitoring strain on optical fibers.

Another object of the invention is to provide a non-intrusive apparatus and method for monitoring alignment between optical fibers and optical devices.

Another object of the invention is to provide a method and apparatus for determining position of an object.

Another object of the invention is to provide a method and apparatus for determining refractive index of a material.

One advantage of the invention is that it can be used to precisely fabricate a variety of optical taps for a variety of applications.

Another advantage of the invention is that it can be used to fabricate optical taps with a known geometry.

Another advantage of the invention is that it simplifies monitoring optical couplers.

Another advantage of the invention is that it is non-destructive.

Another advantage of the invention is that it enables fiber strain losses to be monitored.

Another advantage of the invention is that it enables connector losses to be monitored.

Another advantage of the invention is that it can measure position of an object using passive optical components near the object.

Another advantage of the invention is that it can measure position of an object without high frequency modulation of a light source.

One feature of the invention is that it uses laser ablative chemical etching to fabricate directional optical taps.

Another feature of the invention is that it can be programmed to fabricate taps having specific geometric features.

Another feature of the invention is that it scans an appropriately focussed energy source across a fiber.

An alternative feature of the invention is that it uses a pulsed laser to ablate fiber cladding.

Another feature of the invention is that it focusses a beam of light on a fiber in a known manner to ablate fiber cladding.

Another feature of the invention is that it uses a mount having a receptor for receiving a portable power testing insert.

These and other objects, advantages and features are accomplished by the provision of an apparatus for fabricating a tap in an optical fiber having an optical axis, including: an energy source for outputting a beam of energy at a threshold power; beam directing means for the beam of energy toward the fiber at an angle ϕ from the optical axis of the fiber, thereby fabricating the tap in the fiber.

These and other objects, advantages and features are also accomplished by the provision of a fiber having a tap fabricated using the above apparatus.

These and other objects, advantages and features are further accomplished by the provision of a method for fabricating a tap in an optical fiber having an optical axis, including the steps of: outputting a beam of energy at a threshold power; directing the beam of energy across the fiber at an angle ϕ from the optical axis of the fiber, thereby fabricating the tap in the fiber.

These and other objects, advantages and features are also accomplished by the provision of a fiber having a tap fabricated using the above method.

These and other objects, advantages and features are also accomplished by the provision of a sensing system including: a light source for outputting an optical signal; a fiber having a first end, a second end and a tap, the fiber receiving the optical signal at the first end, guiding the optical signal to the second end and guiding a portion of the optical signal as a return signal traveling toward the first end, wherein the tap couples a portion of the return signal out of the fiber as a tap signal; and a detector for detecting the tap signal.

These and other objects, advantages and features are also accomplished by the provision of a method for sensing a

parameter, comprising the steps of: outputting an optical signal; receiving the optical signal at a first end of a fiber; guiding the optical signal to a second end of the fiber; guiding a portion of the optical signal as a return signal traveling toward the first end; coupling a portion of the return signal out of the fiber as a tap signal; and detecting the tap signal.

The above and other objects, effects, features and advantages of the present invention will become more apparent from the following description of embodiments thereof taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A and 1B show a side and top view, respectively, of a tap fabricating system 1 according to one embodiment of the invention and FIG. 1C shows a top view of a tap fabricating system 1' according to an alternative embodiment of the invention.

FIGS. 2A and 2B show two types of taps, a large Gaussian shaped tap and a small triangular shaped tap, respectively, FIG. 2C shows a plot of laser power threshold versus scanning speed for a beam spots having diameters of 60 micrometers and 240 micrometers, FIG. 2D shows etch depth d_{etch} versus number of scans for a 1.8W CO_2 laser with scanning rate $dx/dt=45$ mm/s. FIG. 2E shows a plot of power lost at the far tip of fiber 2 (which is the right tip in FIGS. 2A or 2B) versus etch depth d_{etch}, FIG. 2F shows power in output A1, A2 and scattered (non-localized output) S versus etch depth d_{etch}, FIG. 2G shows power in outputs A1 and A2 as a function of angle α, FIG. 2H shows output angles $\beta(A1)$ and $\beta(A2)$ as a function of tap angle α.

FIG. 3A is a three dimensional plot of intensity (arbitrary units) above and below a large Gaussian tap, FIG. 3B is a three dimensional plot of intensity (arbitrary units) above and below a small triangular tap and FIGS. 3C, 3D and 3E show three dimensional plots of intensity (arbitrary units) above and below taps with α equal to 10, 23 and 35 degrees, respectively.

FIG. 4 shows three types of optical radiation modes which can occur when optical radiation is launched into an optical fiber.

FIG. 5 shows an optical fiber with a laser micro-machined fiber optic tap (LMFOT) according to another embodiment of the invention.

FIGS. 6A–6D show four different situations which can change the intensity at outputs A1 and A2 and consequently also cause a loss in intensity of core modes.

FIG. 7 shows a plot of the percentage of power lost due to lateral misalignments.

FIG. 8 shows a plot 510 of power P_{out} output from fiber core 200a and another plot 520 of power P_{A1} output from tap 210 due to lateral misalignment of fibers.

FIGS. 9A and 9B show a far and close view, respectively, of a fiber monitoring attachment on a fiber polymer jacket for monitoring the integrity of an optical coupler 610 according to another embodiment of the invention.

FIG. 10 shows an example of a tapped fiber having various fiber monitoring attachments.

FIG. 11 shows a profile of a bi-directional optical fiber tap according to another embodiment of the invention.

FIG. 12A and 12B shows an optical micrograph of a symmetric, bi-directional tap 105 and asymmetric tap 105', respectively.

FIG. **13** shows the orientation for fabricating an asymmetrical tap.

FIG. **14** shows actual radiation power (in units of mV as detected by a detector) at output **1** and output **2** from bi- the directional tap in FIG. **11**.

FIG. **15** shows how the above observation can be used in a sensing system according to another embodiment of the invention.

FIG. **16A** shows an enlarged view at a fiber tip of a fiber in the sensing system of FIG. **15**, and FIG. **16B** shows an enlarged view of an alternative fiber tip.

FIG. **17** shows a plot of a digital output signal in the sensing system of FIG. **15** using three different target surfaces versus distance d for a position sensing system **500** with the fiber tip in FIG. **16A**.

FIG. **18** shows output power at output **2** versus position of a target having a copper surface.

FIGS. **19A** and **19B** show the sensing system **500** being used to measure refractive index of various mediums **700** and results of those measurements, respectively.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIGS. **1A** and **1B** show a side and top view, respectively, of a tap fabricating system **1** according to one embodiment of the invention and FIG. **1C** shows a top view of a tap fabricating system **1'** for fabricating a tap **3** into a fiber **2** (multi-mode or single mode) having cladding **2a** and core **2b** using laser ablative chemical etching (LACE) process according to another embodiment of the invention. In particular, a laser **4** outputs a laser beam **6** which is focussed by a focussing system **8**. Focussing system **8** can be a single converging lens having a focal length f or a plurality of lenses having a net or resultant focal length f. Focussing system **8** focusses laser beam **6** into a converging beam **10** which eventually converges into a laser spot **12** with a diameter d_s (see FIG. **1B**). Converging beam **10** is directed toward and passes through a scanner **14** as a scanning beam **18** toward fiber **2**. Scanner **14** controls the angle Θ that scanning beam **18** forms with an imaginary line (dashed line A in FIG. **1B**). Scan rate dx/dt is defined here to be the rate that spot **12** passes across fiber **2** when Θ is approximately zero.

A processor **22** is connected to scanner **14** by a cable **26** and controls the angular scanning rate $d(\theta)/dt$ and consequently the scan rate dx/dt defined above as the rate at which spot **12** passes across fiber **2** when θ is 0. Processor **22** is also connected to a pulse controller **30** via cable **32**. Pulse controller **30** in turn is connected to laser **4** via cable **34**. In addition, pulse controller **30** can be used to pulse laser **4** in accordance with a timing signal periodically output by processor **22**, thereby producing a pulsed laser beam **6**.

Fiber **2** makes an angle ϕ with converging beam **18** where ϕ ranges from over 0 to 90 degrees. Tap **3** is symmetric if ϕ is 90 degrees but becomes asymmetric as ϕ deviates farther from 90 degrees.

FIG. **1C** shows tap fabricating system **1'** according to another embodiment of the invention. Here, the same reference numerals are used for those components in system **1'** which are the same as in system **1**. As can be seen, scanner **14** has been replaced by a linear translation scanner **14'**. Linear translation scanner **14'** linearly shifts position x of spot **12** by linearly shifting converging beam **18** in response to commands from processor **22**.

Laser **4** should be selected to output laser radiation at wavelengths which are absorbed by fiber **2** and in particular by fiber cladding **2a**. Alternatively, laser **4** can be replaced by any other energy source such as particle beam sources (e.g., ion beam or electron beam sources) provided that spot size d_s is sufficiently small and the power output by these sources sufficiently large to ablate fiber **2** in accordance with "Laser fabricated fiber optical taps for interconnects and optical data processing devices" by K. Imen et al. SPIE Vol. 1365 *Components for Fiber Optic Applications V,* pp. 60–64 (1990), and "Laser-fabricated fiber-optic taps", by K. Imen, et al. OPTICS LETTERS Vol. 15, No. 17, pp. 950–952, Sep. 1, 1990 the contents of which are incorporated herein by reference.

For standard silica based optical fibers, a CO_2 laser operating in a 9–11 micrometer range of wavelengths and typically at 10.6 micrometers can serve as laser **4**. It should be noted however, that any energy source can be used to ablate fiber **2** provided that the energy source is absorbed by cladding **2a** of fiber **2** and that the energy source can be focussed sufficiently tight (i.e., spot **12** is sufficiently small) that an energy threshold power P_{th} is exceeded. Once P_{th} is exceeded, each scan across fiber **2** increases the etch depth d_{etch}.

FIGS. **2A** and **2B** show two symmetric taps, a large Gaussian shaped tap **21** and a small triangular shaped tap **25**, respectively, which can be fabricated into fiber **2** using tap fabricating system **1** or **1'**. Since taps **21** and **25** are symmetric, they can be characterized by a single angle α as shown. Here $\alpha=10$ degrees for tap **21** in FIG. **2A** and $\alpha=35$ degrees for tap **25** in FIG. **2B**. Radiation from laser **4** travels left to right as shown. Large Gaussian shaped tap **21** couples radiation out of fiber **2** above tap **21** (output A1) at an angle $\beta(A1)$ with respect to fiber **2** and below tap **21** (output A2) at an angle $\beta(A2)$ with respect to fiber **2**. Similarly, small triangular shaped tap **25** couples radiation out of fiber **2** above tap **25** (output A1) and below tap **25** (output A2).

Large Gaussian shaped tap **21** was fabricated using a 10 Watt, CO_2 laser and 40 laser scans at a scan rate dx/dt of 70 mm/s. Focussing system **8** produced a spot **12** with a diameter d_s of 240 micrometers. The diameter of fiber cladding **2a** in FIG. **2A** is about 140 micrometers.

Small triangular shaped tap **25** was fabricated using a 1.8 Watt CO_2 laser and 8 laser scans at a scan rate dx/dt of 45 mm/s. Focussing system **8** produced a spot **12** with a diameter d_s of 60 micrometers. The diameter of fiber cladding **2a** in FIG. **2B** is also about 140 micrometers.

FIG. **2C** shows a plot of laser power threshold P_{th} in watts versus scanning speed for a beam spot of 60 micrometers and 240 micrometers. As mentioned above, once P_{th} is exceeded, each scan across fiber **2** increases the etch depth d_{etch}.

FIG. **2D** shows etch depth d_{etch} versus number of scans for a 1.8W CO_2 laser with scanning rate dx/dt=45 mm/s and the spot **12** has a 60 micrometer diameter. FIG. **2E** shows a plot of power lost at the far tip (right tip in FIGS. **2A** or **2B**) versus etch depth d_{etch}. FIG. **2F** shows power in output A1, A2 and scattered (non-localized output) S versus etch depth d_{etch} for a 1.8W CO_2 laser with spot diameter $d_s=60$ micrometers, and scanning rate dx/dt=45 mm/s. Here, scattered output S corresponds to radiation output at the sides (not top or bottom) of fiber **2**.

It was found that varying tap angle α, varies power in outputs A1 and A2. FIG. **2G** shows power in outputs A1 and A2 as a function of angle α. It was also found that varying tap angle α, varies power in output angles $\beta(A1)$ and $\beta(A2)$.

FIG. 2H shows output angles β(A1) and β(A2) as a function of tap angle α for multimode fiber.

FIG. 3A is a three dimensional plot of intensity (arbitrary units) above large Gaussian tap **21** (output A1) and below tap **21** (output A2). As can be seen, tap **21** couples light out of fiber **2** above fiber **2** (output A1) as well as below fiber **2** (output A2) and consequently, tap **21** is a dual output tap.

FIG. 3B is a three dimensional plot of intensity (arbitrary units) above small triangular tap **25** (output A1) and below tap **25** (output A2). As can be seen, tap **25** only couples light out of fiber **2** below fiber **2** (output A2) and consequently tap **25** is a single output tap.

FIGS. 3C, 3D and 3E show three dimensional plots of intensity (arbitrary units) above and below taps with α equal to 10, 23 and 35 degrees, respectively.

FIG. 4 shows three types of optical radiation modes which can occur when optical radiation is launched into an optical fiber **10**. In particular, FIG. 4 shows optical fiber **10** with a core **20** and a cladding **24**. Optical radiation launched into optical fiber **10** can be transmitted via core modes (A) and cladding modes (B). A certain portion of core modes (A) and cladding modes (B) escapes as radiation modes (C). Moreover, it was found that the amount of loss of this radiation increases depending on the amount of misalignment or bending present upstream (direction z) which occurs for fiber **200**. Such losses are typically spread over the entire length of fiber **10**. In addition, radiation modes can be output in any transverse direction.

FIG. 5 shows an optical fiber **200** having a core **204** and a cladding **208** with a laser micro-machined fiber optic tap (LMFOT) **210** according to another embodiment of the invention. LMFOT **210** was etched into cladding **208** using tap fabricating system **1'**. As can be seen, LMFOT **210** has two outputs, output A1 and output A2. Both output A1 and output A2 are stronger and more localized than non-localized radiation C from FIG. 4. That is, both top and bottom outputs A1 and A2 are not uniformly distributed in all transverse directions. Instead, outputs A1 and A2 are concentrated in regions T and B, respectively. That is, outputs A1 and A2 are actually beams of radiation whose shape and orientation is determined by the geometry of LMFOT **210**.

FIGS. 6A–6D show four different situations which can change the intensity at outputs A1 and A2 and consequently can also cause a loss in intensity of core modes A. FIGS. 6A, 6B and 6C show a lateral, axial and angular misalignment of fibers **300** and **200**, respectively. Here a fiber **300** having a core **304** and a cladding **308** is demonstrated, it being understood that fiber **300** could be any optical device such as a laser, optical waveguide, etc . . . . In all three cases the intensity at output A1 and at output A2 is increased as the misalignment is increased. FIG. 6D shows fiber **200** under a strain or bending force. Again, the larger the strain the more radiation appears at outputs A1 and A2, respectively.

FIG. 7 shows a plot of the percentage of power lost due to lateral misalignment of a fiber **200** and a coupling lens simulating fiber **300**, where lateral misalignment is defined as X/a, a is the diameter of core **204** and X is the lateral misalignment. The power at output A2 of LMFOT **210** is graph **410** of (+) in FIG. 7. The percentage of the power lost due to lateral misalignment of fibers **200** and **300**, is graph **420** (dots) in FIG. 7. As can be seen, as X approaches a (the diameter of core **204** and **304**) and consequently X/a approaches 1, the power output at output A2 of LMFOT **210** becomes large. It was also found that the power in output A2 was linearly proportional to power lost at the end of fiber **2**.

FIG. 8 shows a plot **510** of power P_{out} output from fiber core **204** and another plot **520** of power in output A2 due to

lateral misalignment of fiber **200** and some other optical device such as a lens. Again, the other device will be referred to as fiber **300**, it being understood that fiber **300** is just one type of an optical component to be aligned with fiber **200**. Here, lateral misalignment is actual lateral misalignment in units of 6.66 micrometers and power is proportional to a voltage in units of millivolts (as detected by a light detector). Also, negative lateral misalignments means that fiber **300** (simulated by a lens as discussed above) is below fiber **200**. Consequently, a lateral misalignment of −5 means fiber **300** is 5×6.66=33.33 micrometers below fiber **200**. As can be seen, output power P_{out} has a maximum between two peaks, peak1 and peak2 of tap output power P_T.

As was the case with lateral displacement, an axial displacement and/or an angular displacement (see FIGS. 6B and 6C, respectively) also causes radiation to be coupled out of fiber **200** into outputs A1 and A2. Consequently, the power in output A1, output A2 or their sum P_T (the total power output from tap **210**), can be used to determine the integrity of couplings up stream from tap **210**.

FIGS. 9A and 9B show a far and close view, respectively, of a fiber monitoring attachment **600** on a fiber polymer jacket **604a** for monitoring the integrity of an optical coupler **610** according to another embodiment of the invention. Attachment **600** includes a mount **620** having a receptor **624** for receiving a portable power testing insert **630**. A single fiber **604** (rather than two fibers with an optical connector) is on both sides of attachment **600** and is not divided or severed any way. Mount **620** of attachment **600** can be made of plastic and secured to polymer jacket **604a**. Portable insert **630** is connected to a testing fiber **634** which guides the radiation output from tap **638** to a detector **642** which has a display **646** for displaying the power received by insert **630**. Insert **630** with fiber **634** and detector **642** comprise a testing apparatus **647**. Attachment **600** can have a lens **650** to help guide radiation output from tap **638** into insert **630**. Alternatively, portable insert **630** itself can have a lens **650'** which helps couple light into fiber **634**.

FIG. 10 shows an example of a tapped fiber **700** having a polymer jacket **700a** and fiber monitoring attachments **600a** and **600c** near ends **710a** and **710c**, respectively. Fiber **700** can also have attachments **600b1**, **600b2** and **600b3** between attachments **600a** and **600c**. Here, light travels from left to right so attachment **600a** is upstream from attachment **600b1**, attachment **600b1** is upstream from attachment **600b2**, etc, ... Since attachment **600a** is near end **710a** of optical fiber **700** (for example a few centimeters to a few meters from end **710a**), it primarily monitors the integrity (e.g., occurrence of a misalignment) of a coupling at end **710a**. The coupling at end **710a** can be from another fiber (not shown) or from an optical source such as a laser (not shown). In either case, since attachment **600a** is relatively close to fiber end **710a**, it monitors the coupling of light into fiber end **710a**.

Attachments **600a** together with attachments **600b1**–**600b3** can be used to monitor bends and strains in fiber **700** itself. For example, if a worker using testing apparatus **647** detects no optical signal at **600a** but detects an optical signal at attachment **600b1**, that worker would know that fiber **700** must be strained or bent between attachments **600a** and **600b1**. Alternatively, if no signal is detected at attachments **600a** or **600b1**–**600b3**, but a signal is detected at attachment **600c**, the worker would know that fiber **700** must be strained or bent between attachments **600b3** and **600c**. Taps in attachments **600a**, **600b1**–**600b3** and **600c** can also serve to couple all higher order optical modes traveling in fiber **700**.

Attachments **600a**, **600b1–600b3** and **600c** can be differentiated by shape, and or color or color coding. They can also have a cone shape or have an arrow which indicates direction of light flow.

FIG. **11** shows a profile of a bi-directional optical fiber tap **105** according to another embodiment of the invention. In particular, FIG. **11** shows a profile of a multi-mode optical fiber **101** having a cladding **103** with a diameter of 140 micrometer. Bi-directional tap **105** was produced using system **1** in FIG. **1A** with laser **4** operating in a continuous mode at 1.8W and having a scan rate dx/dt of 45 ram/s.

FIG. **12A** shows an optical micrograph of a symmetric and consequently bi-directional tap **105**. As can be seen, bi-directional tap **105** has an approximately Gaussian profile and consequently is symmetric to an imaginary line N which is perpendicular to the longitudinal axis z of fiber **101**.

FIG. **12B** shows a profile of an optical micrograph of an asymmetric tap **105'** fabricated using ϕ=45 degrees (see FIG. **1A**). As can be seen, tap **105'** is asymmetric to imaginary line N which is perpendicular to the longitudinal axis z of fiber **101**.

FIG. **13** shows a tap **105** with laser light traveling along the z direction. Tap **105** outputs laser radiation in two directions corresponding to output **1** and output **2** provided ϕ is 45 degrees.

FIG. **14** shows actual radiation power (in units of mV as detected by a detector) at output **1** and output **2** from bi-directional tap **105** in FIG. **11**. In particular, FIG. **14** shows intensity at outputs **1** and **2** with (large boxes) and without (small solid boxes) index matching material (not shown) at an end (down stream) of fiber **101**. When index matching material is present at the down stream end of fiber **101**, essentially no optical radiation is reflected back in the negative z direction. As can be seen, in this situation the intensity at output **2** is essentially zero. On the other hand, if no index matching material is used at the down stream end of fiber **101**, the air-core interface that end makes with its surrounding atmosphere causes radiation to reflect back up fiber **101** in the -z direction. A portion of this reflected radiation was then coupled out of fiber **101** at output **2** due to bi-directional fiber optic tap **105**. This shows that radiation which appeared at output **2** was radiation coupled out of fiber **101** which was traveling upstream (-z direction). Hence, since the magnitude of output **2** changes as the difference between the index of refraction of the core and the surrounding medium, output **2** can be used to sense the difference between the index of refraction of the optical core and the surrounding medium.

FIG. **15** shows how the above observation can be used to make a sensing system **500** according to another embodiment of the invention. In particular, FIG. **15** shows a laser **510** coupled to a tapped fiber **522**. Tapped fiber **522** has bi-directional optical tap **526** located a distance D from fiber end **530** of tapped fiber **522**. D can range from less than a centimeter to over several meters. Fiber tip **530** outputs optical radiation from laser **510** toward a surface **534** of a target **538** whose distance d from fiber tip **530** is to be determined.

A detector **542** located near bi-directional tap **526** measures the intensity of radiation in output **2** (recall FIGS. **13** and **14**). Detector **542** outputs an analog signal on wire **550**, whose voltage is proportional to the intensity of light at output **2** of tap **526**. This analog output signal can be used directly or it can be analog-to-digital (A/D) converted to a digital output signal using an A/D converter **546**. A/D converter **546** can then send the digital output signal to a

processor **548** to be used to calculate other parameters or to be displayed. Modulating laser **510** increases the signal to noise ratio of the signal output by detector **542** . Also, fluctuations in output power of laser **10** cancel out if the ratio of output **2** and output **1** is determined.

FIG. **16A** shows an enlarged view at fiber tip **530** of fiber **522** a sensing system **520**. Target surface **534** can be rough or smooth and preferably a retro-reflective surface such as retro-reflective paint or one or more (such as an array of) corner cubes. Target **538** can be a separate piece secured to an object whose position is to be determined. Alternatively, target **538** can be the object itself in which case surface **534** can be modified e.g., painted with retro-reflective paint, or covered with a material which is highly reflective at the wavelength of laser **510**. Note that since the position of target **538** is fixed, sensing system **520** can be used as a surface measuring system.

FIG. **16B** shows an enlarged view of fiber **522** according to an alternative embodiment of the invention. Here fiber tip **530** is replaced by a semi-spherical fiber lens **634**. Alternatively or additionally, a separate lens **634'** can be arranged between fiber tip **530** and surface **534**. These approaches would increase the amount of light scattered off of surface **534** which is collected and transmitted back through fiber **522**. Laser **510** can be modulated to increase signal-to-noise of position or refractive index measurements.

FIG. **17** shows a plot of the digital output signal using three different surfaces **534** versus distance d for a position sensing system **500** with fiber tip **530** in FIG. **16A**. In particular, FIG. **17** shows the voltage in millivolts, where laser **510** was a Helium Neon (HeNe) laser, distance D was 50 cm, tapped fiber **522** was multimode fiber with a core diameter of 100 micrometers fiber tip **530** had a numerical aperture (NA) of 0.29 and surface **534** was copper (solid box), machined metal (+) and diamond ground quartz (*). The digital output signal was found to be linearly proportional to the distance d with an accuracy of a few micrometers as d varied from a few micrometers to over a 100 micrometers. Smooth and highly reflective target surfaces **534** seem to provide the longest linear range and the highest accuracies. The range of distances d can be improved if surface **534** is retro-reflective type material and/or if fiber tip **534** is replaced with fiber lens **634** and/or lens **634'**.

FIG. **18** shows output power at output **2** (proportional to voltage in mV output from detector **542** in position sensing system **500** of FIG. **15**) versus position of target **538** having a copper surface as surface **534**. As can be seen, the output **2** varied approximately linearly as distance d varied from about 0 micrometers to about 110 micrometers. The range and sensitivity of sensing system **520** can be by varying core/cladding diameter ratio, the wavelength of laser **510** and light collection optics at fiber end **530**. Also, multiple fibers **522** can be used in parallel to further extend the range of positions which can be sensed by system **500**.

FIG. **19A** shows how sensing system **500** can measure refractive index n of a medium **700**. As can be seen, fiber end **530** is inserted into a medium **700** with refractive index n to be measured.

FIG. **19B** shows results of measuring four different solutions. In particular, FIG. **19B** shows methanol (n=1.3288), water (n=1.3288), cyclohaxane (n=1.4266) and toluene (n=1.4961).

Numerous and additional modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically claimed.

What is claimed is:

1. An apparatus for fabricating a tap in an optical fiber having an optical axis, comprising:

an energy source for outputting a beam of energy equal to or greater than a threshold power;

beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical axis of the fiber, wherein said angle φ is not equal to approximately 90 degrees.

2. An optical fiber having a tap fabricated using compris- ing: an energy source for outputting a beam of energy equal to or greater than a threshold power and beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical axis of the fiber, wherein said angle φ is not equal to approximately 90 degrees.

3. A method for fabricating a tap in an optical fiber having an optical axis, comprising the steps of:

outputting a beam of energy at a threshold power;

directing said beam of energy toward said fiber at an angle φ from the optical axis of the fiber, wherein said angle φ is not equal to approximately 90 degrees.

4. An optical fiber having an optical axis and having a tap fabricated according to a method comprising the steps of: outputting a beam of energy at a threshold power and directing said beam of energy toward said fiber at an angle φ from the optical axis of the fiber, wherein said angle φ is not equal to approximately 90 degrees.

5. An apparatus, comprising:

an optical fiber having an optical axis.;

an energy source for outputting a beam of energy equal to or greater than a threshold power;

beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical axis of the fiber, wherein said beam directing means directs said beam of energy at an angle φ not equal to approximately 90 degrees, thereby fabricating an asymmetric tap in said optical fiber.

6. An apparatus, comprising:

an optical fiber having an optical axis;

an energy source for outputting a beam of energy equal to or greater than a threshold power;

beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical axis of the fiber, wherein said beam directing means directs said beam of energy at an angle φ approximately equal to 45 degrees, thereby fabricating an asymmetric tap in said optical fiber.

7. The apparatus as claimed in claim 1, wherein said energy source is a carbon dioxide laser.

8. An apparatus, comprising:

an optical fiber having an optical axis;

an energy source for outputting a beam of energy equal to or greater than a threshold power;

beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical axis of the fiber, wherein said beam directing means comprises scanning means for scanning said beam of energy across the fiber at a scanning rate which main-tains said threshold power.

9. An apparatus, comprising:

an optical fiber having an optical axis;

an energy source for outputting a beam of energy equal to or greater than a threshold power;

beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical

axis of the fiber, wherein said beam directing means comprises focussing means for focussing said beam of energy into a spot having about a 240 micrometer diameter and said beam directing means directs said beam of energy at an angle φ of about 90 degrees, said tap thereby being a symmetrical Gaussian shaped tap.

10. An apparatus, comprising:

an optical fiber having an optical axis;

an energy source for outputting a beam of energy equal to or greater than a threshold power;

beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical axis of the fiber, wherein said beam directing means comprises focussing means for focussing said beam of energy into a spot having about a 60 micrometer diameter, said tap thereby being a symmetrical trian-gular shaped tap having a single output.

11. The apparatus as claimed in claim 10, wherein said scanning means scans across said fiber at a rate of about 45 millimeters per second.

12. The apparatus as claimed in claim 11, wherein said scanning means scans across said fiber at least twice yield-ing a symmetrical triangular shaped tap with an etch depth of at least about 4 micrometers.

13. An optical fiber having a variety of taps, each of said taps fabricated using an apparatus comprising: an energy source for outputting a beam of energy equal to or greater than a threshold power and beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical axis of the fiber, wherein said angle φ is not equal to approximately 90 degrees.

14. The optical fiber as claimed in claim 13, wherein each of said plurality of taps has an associated mount.

15. The optical fiber as claimed in claim 14, wherein each of said associated mounts has a receptor.

16. An optical fiber having an optical axis and having a tap fabricated using an energy source for outputting a beam of energy equal to or greater than a threshold power and beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical axis of the fiber, wherein said angle φ is not equal to approximately 90 degrees and wherein said tap is a symmetric triangular shaped tap.

17. An optical fiber having a tap fabricated using an apparatus for fabricating a tap in an optical fiber having an optical axis, comprising:

an energy source for outputting a beam of energy equal to or greater than at a threshold power;

beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical axis of the fiber, thereby fabricating said tap in the fiber, wherein said tap is a symmetric triangular shaped tap at least 4 micrometers deep.

18. An optical fiber having a tap fabricated using an apparatus for fabricating a tap in an optical fiber having an optical axis, comprising:

an energy source for outputting a beam of energy equal to or greater than at a threshold power;

beam directing means for directing said beam of energy toward said optical fiber at an angle φ from the optical axis of the fiber, thereby fabricating said tap in the fiber, wherein said tap has a tap angle between about 12 degrees and 35 degrees, thereby yielding an upper optical output above said tap, said upper optical output forming a corresponding angle between about 20 degrees and 60 degrees with respect to the optical axis of the optical fiber.

19. A method for fabricating a tap in an optical fiber having an optical axis, comprising the steps of:

    outputting a beam of energy equal to or greater than a threshold power;

    directing said beam of energy toward said fiber at an angle ϕ from the optical axis of the fiber, thereby fabricating said tap in the fiber, wherein said directing step comprises directing the beam of energy at an angle not equal to 90 degrees, thereby fabricating an asymmetric tap.

20. A method for fabricating a tap in an optical fiber having an optical axis, comprising the steps of:

    outputting a beam of energy equal to or greater than a threshold power;

    directing said beam of energy toward said fiber at an angle ϕ from the optical axis of the fiber, thereby fabricating said tap in the fiber, wherein said directing step comprises the step of scanning the beam of energy across the fiber at a scanning rate which maintains the threshold power.

21. The method as claimed in claim **3**, wherein said outputting step comprises outputting a beam of carbon dioxide laser radiation.

22. A method for fabricating a tap in an optical fiber having an optical axis, comprising the steps of:

    outputting a beam of carbon dioxide laser radiation energy equal to or greater than a threshold power; and

    directing said beam of carbon dioxide laser energy toward said fiber at an angle ϕ from the optical axis of the fiber, thereby fabricating said tap in the fiber, wherein said directing step further includes focussing the beam of carbon dioxide laser radiation into a spot having about a 240 micrometer diameter, the tap thereby being a symmetrical Gaussian shaped tap.

23. A method for fabricating a tap in an optical fiber having an optical axis, comprising the steps of:

    outputting a beam of carbon dioxide laser radiation energy equal to or greater than a threshold power; and

    directing said beam of carbon dioxide laser energy toward said fiber at an angle ϕ from the optical axis of the fiber, thereby fabricating said tap in the fiber, wherein said directing step further includes focussing the beam of carbon dioxide laser radiation into a spot having about a 60 micrometer diameter, the tap thereby being a symmetrical

24. The method as claimed in claim **23**, wherein said scanning step comprises scanning the beam of energy across the fiber at a rate of about 45 millimeters per second.

25. An optical fiber having an optical axis with a tap fabricated according to a method, comprising the steps of:

    outputting a beam of energy equal to or greater than a threshold power;

    directing said beam of energy toward said fiber at an angle ϕ from the optical axis of the fiber, thereby fabricating said tap in the fiber, wherein said tap is a symmetric triangular shaped tap.

26. An optical fiber having an optical axis with a tap fabricated according to a method, comprising the steps of:

    outputting a beam of energy equal to or greater than a threshold power;

    directing said beam of energy toward said fiber at an angle ϕ from the optical axis of the fiber, thereby fabricating said tap in the fiber, wherein said tap is a symmetric triangular shaped tap at least 4 micrometers deep.

27. An optical fiber having an .optical axis with a tap fabricated according to a method, comprising the steps of:

outputting a beam of energy equal to or greater than a threshold power;

directing said beam of energy toward said fiber at an angle ϕ from the optical axis of the fiber, thereby fabricating said tap in the fiber, wherein said tap has a tap angle between about 12 degrees and 35 degrees, thereby yielding an upper optical output above said tap, said upper optical output forming a corresponding angle between about 20 degrees and 60 degrees with respect to the optical axis of the optical fiber. triangular shaped tap.

28. An optical fiber comprising a variety of taps each fabricated according to a method comprising the steps of: outputting a beam of energy at a threshold power and directing said beam of energy toward said fiber at an angle ϕ from the optical axis of the fiber, wherein said angle ϕ is not equal to approximately 90 degrees.

29. The optical fiber as claimed in claim **28**, wherein each of said plurality of taps has an associated mount.

30. The optical fiber as claimed in claim **29**, wherein each of said associated mounts has a receptor.

31. The apparatus as claimed in claim **1**, wherein said beam directing means directs said beam of energy at an angle ϕ not equal to approximately 90 degrees, thereby fabricating an asymmetric tap.

32. An apparatus, comprising:

an optical fiber having an optical axis;

an energy source for outputting a beam of energy equal to or greater than a threshold power;

beam directing means for directing said beam of energy toward said optical fiber at an angle ϕ from the optical axis of the fiber, wherein said beam directing means directs said beam of energy at an angle ϕ approximately equal to 45 degrees, thereby fabricating an asymmetric tap in said optical fiber.

33. An apparatus for fabricating a tap in an optical fiber having an optical axis, comprising:

an energy source for outputting a beam of energy equal to or greater than a threshold power; and

beam directing means for directing said beam of energy toward said optical fiber at an angle ϕ from the optical axis of the fiber, wherein said angle ϕ is not equal to 90 degrees, and wherein said beam directing means comprises scanning means for scanning said beam of energy across the fiber at a scanning rate which maintains said threshold power.

34. An apparatus for fabricating a tap in an optical fiber having an optical axis, comprising:

an energy source for outputting a beam of energy equal to or greater than a threshold power; and

beam directing means for directing said beam of energy toward said optical fiber at an angle ϕ from the optical axis of the fiber, wherein said energy source is a carbon dioxide laser and wherein said beam directing means comprises focussing means for focussing said beam of energy into a spot having about a 240 micrometer diameter and said beam directing means directs said beam of energy at an angle ϕ of about 90 degrees, said tap thereby being a symmetrical Gaussian shaped tap.

35. An apparatus for fabricating a tap in an optical fiber having an optical axis, comprising:

an energy source for outputting a beam of energy equal to or greater than a threshold power; and

beam directing means for directing said beam of energy toward said optical fiber at an angle ϕ from the optical

axis of the fiber, wherein said angle ϕ is not equal to 90 degrees, said energy source is a carbon dioxide laser, and said beam directing means comprises focussing means for focussing said beam of energy into a spot having about a 60 micrometer diameter, said tap thereby being a symmetrical triangular shaped tap having a single output.

36. An apparatus for fabricating a tap in an optical fiber having an..optical axis, comprising:

an energy source for outputting a beam of energy equal to or greater than a threshold power; and

beam directing means for directing said beam of energy toward said optical fiber at an angle ϕ from the optical axis of the fiber, wherein said angle ϕ is not equal to 90 degrees, said energy source is a carbon dioxide laser, said beam directing means comprises focussing means for focussing said beam of energy into a spot having about a 60 micrometer diameter, said tap thereby being a symmetrical triangular shaped tap having a single output, and said scanning means scans across said fiber at a rate of about 45 millimeters per second.

37. An apparatus for fabricating a tap in an optical fiber having an optical axis, comprising:

an energy source for outputting a beam of energy equal to or greater than a threshold power; and

beam directing means for directing said beam of energy toward said optical fiber at an angle ϕ from the optical axis of the fiber, wherein said angle ϕ is not equal to 90 degrees, said energy source is a carbon dioxide laser, said beam directing means comprises focussing means for focussing said beam of energy into a spot having about a 60 micrometer diameter, said tap thereby being a symmetrical triangular shaped tap having a single output, said scanning means scans across said fiber at a rate of about 45 millimeters per second, and said scanning means scans across said fiber at least twice yielding a symmetrical triangular shaped tap with an etch depth of at least about 4 micrometers.

38. The optical fiber as claimed in claim 2, wherein said tap is a symmetric triangular shaped tap.

39. The optical fiber as claimed in claim 2, wherein said tap is a symmetric triangular shaped tap at least 4 micrometers deep.

40. An optical fiber having an optical axis and having a tap fabricated using an energy source for outputting a beam of energy equal to or greater than a threshold power and beam directing means for directing said beam of energy toward said optical fiber at an angle ϕ from the optical axis of the fiber, wherein said angle ϕ is not equal to 90 degrees, and wherein said tap has a tap angle between about 12 degrees and 35 degrees, thereby yielding an upper optical output above said tap, said upper optical output forming a corresponding angle between about 20 degrees and 60 degrees with respect to the optical axis of the optical fiber.

41. The method as claimed in claim 3, wherein said directing step comprises directing the beam of energy at an angle ϕ not equal to approximately 90 degrees, thereby fabricating an asymmetric tap.

42. A method for fabricating a tap in an optical fiber having an optical axis, comprising the steps of:

outputting a beam of energy at a threshold power; and

directing said beam of energy toward said optical fiber at an angle ϕ from the optical axis of the fiber, wherein said angle ϕ is not equal to 90 degrees, and wherein said directing step comprises the step of scanning the beam of energy across the fiber at a scanning rate which maintains the threshold power.

43. A method for fabricating a tap in an optical fiber having an optical axis, comprising the steps of:

outputting a beam of energy at a threshold power; and

directing said beam of energy toward said optical fiber at an angle ϕ from the optical axis of the fiber, wherein said angle ϕ is not equal to 90 degrees, wherein said outputting step comprises outputting a beam of carbon dioxide laser radiation, and wherein said directing step further includes focussing the beam of carbon dioxide laser radiation into a spot having about a 240 micrometer diameter, the tap thereby being a symmetrical Gaussian shaped tap.

44. A method for fabricating a tap in an optical fiber having an optical axis, comprising the steps of:

outputting a beam of energy at a threshold power; and

directing said beam of energy toward said optical fiber at an angle ϕ from the optical axis of the fiber, wherein said angle ϕ is not equal to 90 degrees, wherein said outputting step comprises outputting a beam of carbon dioxide laser radiation, and wherein said directing step further includes focussing the beam of carbon dioxide laser radiation into a spot having about a 60 micrometer diameter, the tap thereby being a symmetrical triangular shaped tap.

45. A method for fabricating a tap in an optical fiber having an optical axis, comprising the steps of:

outputting a beam of energy at a threshold power;

directing said beam of energy toward said optical fiber at an angle ϕ from the optical axis of the fiber, wherein said angle ϕ is not equal to 90 degrees, wherein said outputting step comprises outputting a beam of carbon dioxide laser radiation, wherein said directing step further includes focussing the beam of carbon dioxide laser radiation into a spot having about a 60 micrometer diameter, and

scanning the beam of energy across the fiber at a rate of about 45 millimeters per second, the tap thereby being a symmetrical triangular shaped tap.

46. The optical fiber as claimed in claim 4, wherein said tap is a symmetric triangular shaped tap.

47. The optical fiber as claimed in claim 4, wherein said tap is a symmetric triangular shaped tap at least 4 micrometers deep.

48. An optical fiber having an optical axis with a tap fabricated by outputting a beam of energy at a threshold power and directing said beam of energy toward said fiber at an angle ϕ from the optical axis of the fiber, wherein said angle ϕ is not equal to 90 degrees, and wherein said tap has a tap angle between about 12 degrees and 35 degrees, thereby yielding an upper optical output above said tap, said upper optical output forming a corresponding angle between about 20 degrees and 60 degrees with respect to the optical axis of the optical fiber.

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