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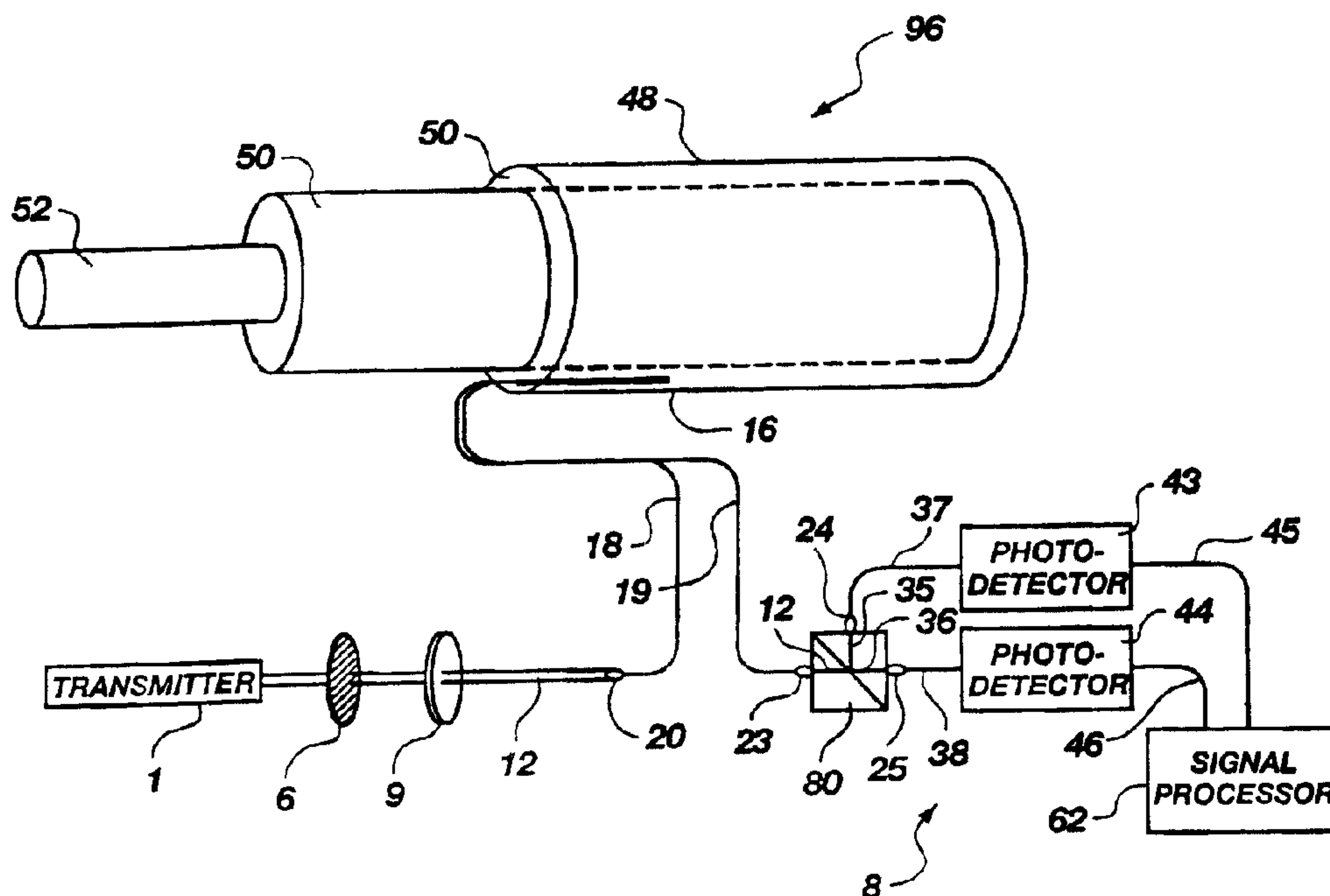
(72) Inventeurs/Inventors:
WOODS, GREGORY K., US;
RENAK, TODD W., US

(73) Propriétaire/Owner:
LOCKHEED IDAHO TECHNOLOGIES COMPANY, US

(74) Agent: SMART & BIGGAR

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(54) Title: ELECTRO-OPTIC VOLTAGE SENSOR



(57) Abrégé/Abstract:

An electro-optic voltage sensor for achieving voltage measurement without significant error contributions from neighboring conductors or environmental perturbations. The voltage sensor includes a transmitter (1), a sensor (4), a detector (43, 44) and a processor (62). The transmitter (1) produces a beam of electromagnetic radiation which is routed into a sensor (4). Within the sensor (4), the beam undergoes the Pockels electro-optic effect. The electro-optic effect produces a modulation of the beam's polarization, which is in turn converted to a pair of independent conversely-amplitude-modulated signals, from which the voltage of the E-field is determined by the processor (62). The use of converse AM signals enables the signal processor (62) to better distinguish signal from noises. The sensor (4) converts, the beam by splitting the beam in accordance with the axes of the beam's polarization state (an ellipse whose ellipticity varies between -1 and +1 in proportion to voltage) into at least two AM signals. These AM signals are fed into a signal processor (62) and processed to determine the voltage between ground conductor and the conductor (2) on which voltage is being measured.

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Abstract

An electro-optic voltage sensor for achieving voltage measurement without significant error contributions from neighboring conductors or environmental perturbations.

5 The voltage sensor includes a transmitter (1), a sensor (4), a detector (43, 44) and a processor (62). The transmitter (1) produces a beam of electromagnetic radiation which is routed into a sensor (4). Within the sensor (4), the beam undergoes the Pockels electro-optic effect. The electro-

10 optic effect produces a modulation of the beam's polarization, which is in turn converted to a pair of independent conversely-amplitude-modulated signals, from which the voltage of the E-field is determined by the processor (62). The use of converse AM signals enables the

15 signal processor (62) to better distinguish signal from noises. The sensor (4) converts the beam by splitting the beam in accordance with the axes of the beam's polarization state (an ellipse whose ellipticity varies between -1 and +1 in proportion to voltage) into at least two AM signals.

20 These AM signals are fed into a signal processor (62) and processed to determine the voltage between ground conductor and the conductor (2) on which voltage is being measured.

ELECTRO-OPTIC VOLTAGE SENSOR

BACKGROUND OF THE INVENTION

1. The Field of the Invention.

5 The present invention pertains generally to the field of voltage sensors and more particularly to a voltage sensor system which utilizes the Pockels electro-optic effect to measure voltage.

10 2. The Background Art.

 High-accuracy measurement of high voltage has traditionally been accomplished using iron-core ferro-magnetic potential transformers. These devices have substantially limited dynamic range, bandwidth,
15 linearity, and electrical isolation. During electrical fault conditions these transformers can conduct dangerous levels of fault energy to downstream instrumentation and personnel, posing an additional liability.

20 A variety of optic sensors for measuring voltage have been developed in attempts to offer the power industry an alternative to the conventional transformer technology. Generally, these voltage sensor systems require that direct electrical contact
25 be made with the energized conductor. This contact is made necessary by the use of a voltage divider which is utilized to connect the sensing element with the energized conductor on which a measurement is to be made. Direct electrical contact with the conductor

may alter or interrupt the operation of the power system by presenting a burden or load.

In addition to the disadvantages associated with direct electrical contact with the energized conductor, prior art voltage sensor systems are typically bulky, particularly in extremely high voltage applications. This is true because the size of the voltage divider required is proportional to the voltage being measured. The size of such systems can make them difficult and expensive to install and house in substations.

Many prior art sensors are based upon the electrostrictive principle which utilize interferometric modulation principles. Unfortunately, interferometric modulation is extremely temperature sensitive. This temperature sensitivity requires controlled conditions in order to obtain accurate voltage measurements. The requirement of controlled conditions limits the usefulness of such systems and makes them unsuited for outdoor or uncontrolled applications. In addition, interferometric modulation requires a highly coherent source of electromagnetic radiation, which is relatively expensive.

Open-air E-field based sensors have also been developed, but lack accuracy when used for measuring voltage because the open-air E-field used varies with many noisy parameters including ambient dielectric constant, adjacent conductor voltages, moving conductive structures such as passing vehicles, and other electromagnetic noise contributions.

Systems which utilize mechanical modulation of the optical reflection within an optic fiber have also been developed. Among other drawbacks, the reliance of such systems on moving parts is a significant deterrent to widespread use.

It would therefore be an advantage in the art to provide a system which does not require direct

electrical contact with the energized conductor, is compact, operates in a variety of temperatures and conditions, is reliable, and is cost effective.

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OBJECTS AND SUMMARY OF THE INVENTION

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It is therefore an object of the present invention to provide an electro-optic voltage sensor system which does not require contact with a conductor.

It is a further object of the present invention to provide such an electro-optic voltage sensor system which is capable of use in a variety of environmental conditions.

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It is a still further object of the present invention to provide such an electro-optic voltage sensor system which can be employed to accurately measure high voltages without use of dedicated voltage division hardware.

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It is an additional object of the present invention to provide such an electro-optic voltage sensor system which minimizes the electronics needed for implementation.

25

It is a further object of the present invention to provide a sensor system capable of being integrated with existing types of high voltage power transmission and distribution equipment so as to reduce or eliminate the need for large stand-alone voltage measurement apparatus.

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It is yet another object of the present invention to provide a sensor system capable of being integrated with existing types of power transmission and distribution equipment.

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These and other objects of the present invention will become more fully apparent from the following description and appended claims or may be learned by the practice of the invention as set forth herein.

While the present invention is described in terms of a sensor system, it is to be understood that the subject apparatus and method may be used in any field of electrical or optical application. Those having
5 ordinary skill in the field of this invention will appreciate the advantages of the invention, and its application to a wide variety of electrical uses.

The above objects and others not specifically recited are realized in a specific illustrative
10 embodiment of an Electro-Optical Voltage Sensor System whereby one may measure the voltage difference (or electrical potential difference) between objects or positions. Voltage is a function of the electric field (hereinafter "electric field" shall be indicated
15 "E-field") and the geometries, compositions and distances of the conductive and insulating matter. Where, as in the present invention, the effects of an E-field can be observed, a voltage measurement can be calculated.

The invention employs a transmitter, a sensor, a detector, and a signal processor. The transmitter produces a beam of electromagnetic radiation which is routed into the sensor. Although this electromagnetic radiation used in the present invention can comprise
25 any wavelengths beyond the visible spectrum, the term "light" will be used hereinafter to denote electromagnetic radiation for the purpose of brevity. The beam undergoes polarization before it undergoes an electro-optic effect in transducer material which is included in the sensor. In the polarized beam, the
30 light has at least two components which propagate along at least two orthogonal axes, thus forming at least two orthogonal planes within the beam. The electro-optic effect occurs when the sensor, and in particular the transducer material, is placed in an E-field, and is observable as a differential phase shift of the orthogonal beam components (the two components

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are shifted in opposite directions). The planes of propagation are the object of the differential phase shift, also called phase modulation. The differential phase shift causes a corresponding change in the beam's polarization.

5 The polarization change is in turn converted into a set of amplitude modulated (AM) signals of opposing polarity that are transmitted out of the sensor. The detector converts the set of optical AM signals into electrical signals from which the voltage is determined by the signal processor.

10 The sensor processes the beam by splitting the beam in accordance with the components of the orthogonal polarization planes into at least two AM signals. In the preferred embodiment, these AM signals are then converted into digital signals, fed into a digital signal processor
15 and mathematically processed into a signal proportional to the voltage which produced the E-field.

In a preferred embodiment of the sensor, the beam is routed through the transducer material along an initial axis and then reflected by a retroreflector back along a
20 second axis generally parallel to the initial axis.

In accordance with an aspect of the present invention, there is provided a sensor head for use in combination with at least one beam of electromagnetic radiation for detecting presence and magnitude of electric
25 field and voltage, said sensor head comprising: polarizing means for polarizing said at least one beam such that said at least one beam comprises at least two beam components in at least two orthogonal planes; transducing means configured for disposition in an electric field, but out of contact
30 with electrical conductors generating said electric field, and for receiving said at least one beam from said

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polarizing means and inducing a first differential phase shift of the beam components which varies in magnitude in response to the magnitude of an electric field; and first reflecting means for receiving said at least one beam from
5 said transducing means and reflecting said beam back into said transducing means.

In accordance with another aspect of the present invention, there is further provided a sensor head for use in combination with at least one beam of electromagnetic
10 radiation for detecting magnitude of an electric field, said sensor head comprising: polarizing means for polarizing said at least one beam such that said at least one beam comprises at least two beam components in at least two orthogonal planes; transducing means configured for disposition in an
15 electric field, but out of contact with electrical conductors generating said electric field, and for receiving said at least one beam from said polarizing means and inducing a differential phase shift of the beam components which varies in magnitude in response to the magnitude of an
20 electric field; and first reflecting means for receiving said at least one beam from said polarizing means and reflecting said beam into said transducing means.

In accordance with another aspect of the present invention, there is further provided a sensor head for use
25 in combination with at least one beam of electromagnetic radiation for detecting magnitude of an electric field, said sensor head comprising: polarizing means for polarizing said at least one beam such that said at least one beam comprises at least two beam components in at least two orthogonal
30 planes; transducing means configured for disposition in an electric field, but out of contact with electrical conductors generating said electric field, and for receiving said at least one beam from said polarizing means and

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inducing a differential phase shift of the beam components which varies in magnitude in response to the magnitude of an electric field; beam separation means for receiving said at least one beam and separating the beam components and forming at least two signals therefrom; and first reflecting means for receiving said at least one beam from said transducing means and reflecting said beam into said beam separation means.

In accordance with another aspect of the present invention, there is further provided a method for detecting magnitude of an electric field using at least one beam of polarized electromagnetic radiation having at least two beam components propagating in at least two orthogonal planes, comprising the steps of: (a) imposing an electric field upon at least one transducing means by disposing said at least one transducing means into an apparatus containing electric flux proportional to voltage, wherein said at least one transducing means is out of contact with electrical conductors generating said electric field; (b) passing said beam through said at least one transducing means; (c) inducing a differential phase shift between the beam components when said beam passes through said transducing means in said electric field, said differential phase shift indicating a presence and a magnitude of said E-field; (d) reflecting said beam after said beam has passed through the transducing means with a reflective means, so that said beam is directed back into the transducing means, thereby causing said beam to reenter the transducing means; (e) separating beam components into at least one pair of converse amplitude modulated (AM) signals, said AM signals corresponding to a major axis and a minor axis of said beam's polarization ellipse, whose ellipticity modulates between -1 and +1 in proportion to voltage, wherein an intensity along the minor

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axis modulates conversely to an intensity along the major axis; (f) transmitting said AM signals, whereby the electric field magnitude (and hence voltage) can be ascertained.

BRIEF DESCRIPTION OF THE DRAWINGS

5 The above and other objects, features and advantages of the invention will become apparent from a consideration of the subsequent detailed description presented in connection with the accompanying drawings in which:

10 FIG. 1 is a diagram of the electro-optical voltage sensor system shown in a generalized high voltage application scenario. The diagram was made in accordance with the principles of the present invention.

15 FIG. 2 is a diagram of an alternative embodiment of the electro-optical voltage sensor system (in the same generalized application scenario) made in

accordance with the principles of the present invention.

FIG. 3 is a diagram of the light polarizing beam splitter of FIGS. 1 and 2.

FIG. 4 shows a partially sectioned side view of a collimator of FIG. 2 and also FIGS. 7 and 8, below.

FIG. 5 is a diagram of one embodiment of the transducer of FIGS. 1 and 2, wherein transducing material in only one orientation is shown.

FIG. 6 is a diagram of one embodiment of the transducer in FIGS. 1 and 2, wherein transducing material in two orientations is shown.

FIG. 7a is a top-down schematic view of one embodiment of the sensor head of FIG. 2.

FIG. 7b is a top-down schematic view of one embodiment of the sensor head of FIG. 2.

FIG. 7c is a top-down schematic view of one embodiment of the sensor head of FIG. 2.

FIG. 8 is a top-down schematic view of one embodiment of the sensor head of FIG. 1.

FIG. 9 is a cross-sectional, schematic view of one embodiment of the E-field originator of FIGS. 1 and 2, as a shielded joint.

FIG. 10 is a top perspective, partially schematic view of one embodiment of the E-field originator of FIGS. 1 and 2, as a terminator.

FIG. 11 is a cross-sectional side view of one embodiment of the E-field originator of FIGS. 1 and 2, as a bushing.

FIG. 12 is a sectional, partially schematic, side view of one embodiment of the E-field originator of FIGS. 1 and 2, as a shielded bus or shielded cable.

FIG. 13 is a sectional, partially schematic, side view of one embodiment of the E-field originator of FIGS. 1 and 2, as a gas or oil-insulated switchgear.

FIG. 14 is a sectional, partially schematic, side view of one embodiment of the E-field originator of FIGS. 1 and 2, as a duct-enclosed bus.

FIG. 15 is a side view of one embodiment of the E-field originator of FIGS. 1 and 2, as a clamp-on apparatus.

FIG. 16 is an alternative embodiment of the electro-optical voltage sensor of FIG. 1 having a current detector.

DETAILED DESCRIPTION

A preferred embodiment in accordance with the present invention is illustrated in FIG. 1, which is a diagram of the electro-optical voltage sensor system. There is shown a transmitter 1, which is a transmitting means that transmits a beam of electromagnetic radiation (the beam is not shown in FIG. 1 but generally designated as 12 elsewhere) and a sensing means, shown in FIG. 1 as a sensor head 4. In the preferred embodiment the beam is routed from the transmitter 1 to the sensor head 4 by a polarization maintaining (PM) fiber 18. In an alternative embodiment the PM fiber 18 is replaced by low-birefringence fiber. Another alternative embodiment whose cost/performance characteristic may be quite different and better suited to certain applications, entails replacement of the PM fiber 18 by single-mode or multi-mode optic fiber. The PM fiber 18 directs the beam from the transmitter 1 into the sensor head 4. Optical signals are routed from the sensor head 4 by a pair of either single-mode or multi-mode optical fibers, shown as 37 and 38. The optical fibers 18, 37, and 38 electrically isolate the sensor head 4 from the transmitter 1 and the rest of the detection system, providing further protection to personnel and equipment from the dangers of high voltage systems.

The sensor head of the preferred embodiment of FIG. 1 is shown in greater detail in the top-down schematic view of FIG. 8, where the preferred embodiment of the sensor head is generally depicted at 4. The sensor head 4 comprises a polarizer 6, a translucent medium 13, a transducer 5, a retro-reflector generally depicted at 10, a polarizing beam splitter 80 and beam reflector 14. A collimator 26 is connected to the PM fiber 18 and transmits the beam 12 from the PM fiber 18 into the polarizer 6. The polarizer 6 polarizes the beam 12 when the beam 12 is transmitted from the collimator 26; thus, the polarizer 6 polarizes the beam 12 if the beam 12 is not polarized when it is transmitted from the collimator 26, or re-polarizes the beam 12 if the beam 12 is polarized when it is transmitted from the collimator 26. As a practical matter, the polarizer 6 could be eliminated or placed anywhere between the transducer 5 and the transmitter of the beam 12, including anywhere along the PM fiber 18. In an alternative embodiment the PM fiber 18 can be aligned with sufficient precision with respect to the optical axes of the transducing medium, to perform the function of (and eliminate the need for) the polarizer 6. The beam 12 passes from the polarizer 6 through the translucent medium 13 and into the transducer 5. The translucent medium 13 comprises a non-conductive, non-birefringent material, such as fused quartz or a similar substance, which provides a pathway for the beam from the polarizer 6, which is preferably situated outside the E-field, to the transducer 5, which must reside within the E-field. The source of this E-field will be discussed shortly.

When the transducer 5 (also called the transducing medium) is in a non-zero E-field (not shown) it induces a "differential phase shift" to orthogonal beam components of the beam 12 through the

Pockels electro-optic effect, which will now be explained. In the polarized beam 12 the light has at least two components which propagate along at least two orthogonal planes, respectively, thus forming at least two orthogonal planes within the beam 12. The phase of the components in each plane of propagation are the object of a shift, relative to the phase of the component in the other plane, in the transducer 5. The Pockels electro-optic effect, which takes place in transducer 5, changes the relative phases of the beam components by altering their respective velocities, and is observed in Pockels transducing crystals and similar media. The magnitude of the phase shift, called the "differential phase shift", is proportional to the magnitude of the E-field. Thus, the Pockels electro-optic effect is observed as a "phase differential shift" of the orthogonal beam components which is proportional to the magnitude of the E-field. Due to the fixed coaxial structure of the devices in which the sensor head is to be installed, the magnitude of the E-field is proportional to the voltage. Therefore, the differential phase shift is proportional to (and can be used to measure) the voltage of the E-field between energized conductor and ground conductor.

In the preferred embodiment, the transducer 5, or transducing medium, comprises a material which exhibits the Pockels electro-optical effect. In the present invention the transducer 5 is preferably Lithium Niobate (LiNbO_3) Pockels, although other materials, such as Ammonium Dihydrogen Phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$), Ammonium Dideuterium Phosphate ($\text{NH}_4\text{D}_2\text{PO}_4$), Potassium Dideuterium Phosphate (KD_2PO_4), MgO-doped Lithium Niobate (MgO-LiNbO_3), electro-optic polymers, organic materials, and others may be used.

The phase shift between orthogonal components further manifests itself as an alteration of the

beam's polarization. Therefore, the beam may be considered either to be a differential phase shifted signal or an optical polarization modulation signal. The polarization modulation signal is used in the present invention because it can be detected using low-cost, components that are less susceptible to temperature, mechanical perturbations, and optical incoherence than those components that would be required to sense the differential phase shift directly.

In the practice of the present invention, the sensor head 4 or the transducer 5 may be encased in a dielectric buffering material, not shown, to smooth the transition geometry between the permittivity of the transducer 5 and the permittivity of the surrounding media, which in most cases will be an insulator. The dielectric buffering material promotes uniformity in the E-field, particularly around the edges of the transducer 5. This enhances uniform phase shift in the beam 12 passing through the transducer 5, and minimizes voltage stress on the materials in and surrounding the sensor head 4 as well, thereby increasing the probable maximum operating lifetime of the entire system.

After the beam 12 has passed sequentially through the polarizer 6 (FIG. 8), translucent medium 13 and transducer 5, it enters into the retro-reflector 10. The retro-reflector 10 comprises a reflector material 9 which induces the beam to reflect and causes a quarter-wave retarding of the beam 12. The quarter-wave retarding property of the reflector material 9 induces a $1/4$ wavelength shift in the orthogonal planes of the beam 12. The $1/4$ wavelength shift can be achieved by reflection of the beam 12 alone, if the material 9 is non-birefringent; alternatively, the material 9 can comprise birefringent reflector

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material wherein the properties of the material help achieve the shift.

If a reflector material 9 having birefringence is used, the phase shifting occurs when orthogonal components of the electromagnetic waves of the beam are shifted (here by 1/4 a wave length) with respect to one another. This birefringence, which is inherent in some materials, is not dependant upon the E-field. In the preferred embodiment, a reflector material 9 is used which exhibits a reflection-induced retardation to differentially shift the relative phases of the beam components in orthogonal planes in the beam 12 by $\pi/2$ radians. The polarization of the beam 12 incident upon the retro-reflector 10 depends upon the E-field present when the beam 12 makes a first pass through the transducer 5. If there is an E-field present then there will be some differential phase shift already present in the beam 12.

In some embodiments, the $\pi/2$ retardation within the retro-reflector 10 may be used to bias the sensor's overall resultant polarization such that zero E-field (and hence zero voltage) corresponds to circular-polarized light, as no differential phase shift is induced upon the beam 12 by the transducer 5. However, due to the location of the retro-reflector 10 in the sensor head 4, if the transducer 5 is in a non-zero E-field and induces a differential phase shift in the beam 12, then the retro-reflector 10 will not convert light from linear to circular-polarization, rather it will induce elliptical-polarization upon the beam 12, whose ellipticity will vary in proportion to the voltage. While laser light is used in the preferred embodiment, other forms of electromagnetic radiation could also be used in the practice of the invention.

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The reflection of the beam 12 in the retro-reflector 10 is in accordance with the principle of the angle of incidence being the same as the angle of

reflection. In the practice of the preferred embodiment of the present invention, the retro-reflector 10 is configured to cause a 180° change in the direction of the beam 12, thereby sending the beam back into the transducer 5. Upon each reflection, a beam 12 may be induced to undergo a $1/8$ wave length phase shift to produce a total of $1/4$ wave phase shift, as in the preferred embodiment. One skilled in the art could further induce a $1/4$ wave length shift in beam 12 by combining reflection and birefringence.

When the beam 12 reenters the transducer 5, it undergoes further phase shift from the Pockels electro-optic effect. As shown in FIG. 8, the beam 12 then passes through the translucent medium 13 and enters into the polarizing beam splitter 80.

In the polarizing beam splitter 80, (also called an analyzer in the art), the beam 12 is separated in accordance with the respective axes of its polarization ellipse into AM signals 35 and 36. The said polarization ellipse will exhibit an ellipticity ranging between -1 and +1, in proportion to voltage at any given time. Those skilled in the art will note that an elliptic polarization whose ellipticity ranges between -1 and +1 can be described as ranging from a linear polarization along one axis to a linear polarization along a second axis perpendicular to the first axis, wherein the point at which ellipticity equals 0 corresponds to circular polarization. As shown in FIG. 3, the major and minor axes of the polarization ellipse of beam 12 can be represented by two orthogonal components, indicated generally at 83. The beam splitter 80 then separates the beam 12 into two components 84 and 85 which comprise the intensities along each of the two axes of the polarization ellipse shown as orthogonal components 83. The intensity of beam components 84 and 85 will modulate conversely to one another in response to

modulations in the ellipticity of the beam's polarization. The beam components 84 and 85 are two AM signals shown as 35 and 36, respectively, which are routed as shown in FIG. 1 into photo-detectors 43 and 44, respectively.

The AM signals 35 and 36 are then passed by collimators 27 and 28, shown in FIG. 8, and routed through multi-mode or single-mode optic fibers 37, 38. A beam reflector 14 may be used to aid in routing the AM signals 35 and 36.

As shown in FIG. 1, first and second routing means, shown as optic fibers 37 and 38, are used to route the AM signals 35 and 36 from the sensing means into the detecting means. First the AM signals 35 and 36 are routed into the photodetectors 43 and 44 through the first and second routing means, shown as the first and second translucent fibers 37 and 38, respectively. In the preferred embodiment the first and second translucent fibers 37 and 38 comprise at least one optic fiber, wherein the optic fiber is selected from the group consisting of: a single-mode optic fiber, and a multi-mode optic fiber. In the photodetectors 43 and 44 the AM signals 35 and 36 become electrical signals 45 and 46. The electrical signals 45 and 46 are routed into a signal processor 62, the final component of the detecting means, wherein a desired E-field characteristic is determined, particularly that of voltage.

To determine the voltage in the practice of the preferred embodiment of the present invention the signal processor 62 is designed to sample each AM signal at substantially regular intervals and substantially simultaneous times, process the signals to produce a display signal (not shown) which is then displayed on a readable display such as: digital, hardcopy, video, software, computer memory displays or an audible indicator.

While it is possible to actually measure the relative phases of the orthogonal components of the beam 12 after exiting the transducer, the relative phase shift can also be derived from the intensities of the AM signals 35 and 36 shown in FIG. 8 without using complex and costly approaches as involved in direct phase measurements. Therefore, in the present invention, when the two AM signals 35 and 36 are separated from a single differential phase shifted signal using a properly oriented polarizing beam splitter 80, the beam's polarization state is analyzed to obtain AM intensity signals. The AM signals 35 and 36 extracted from the beam's polarization state by the splitter 80 are transmitted to and used in the signal processor 62 where their complementary nature facilitates rejection of common mode noise and minimizes effects of temperature dependent intrinsic birefringence that may reside in the transducing medium or other optical components within the system. This feature of the present invention substantially enhances accuracy and practicality of the system and represents an additional advancement over much of the prior art. The signal processor 62 performs these functions while converting the received AM signals 35 and 36 into a single, highly accurate voltage measurement. In addition to measuring the voltage of a device, the invention may be used in conjunction with a device for measuring current to provide information regarding power, power factor angle, and energy on the conductor of interest.

As mentioned, each AM signal, 35 and 36 (FIG. 8) is converted by a photo-detector 43 and 44 (FIG. 1) into a electrical signal 45 and 46 (FIG. 1) which can be processed by the signal processor 62. The photo-detector comprises an optic-to-electronic conversion means for converting said AM signals into analog electronic signals. Preferably, the analog electronic

signals comprise low-level analog voltage signals or current signals.

5 In the preferred embodiment of the present invention the electrical signals 45 and 46 are electronic signals transmitted to the signal processor 62 which correspond to the intensity of the AM signals 35 and 36. Thus, in the practice of the present invention, a series of AM signals are manipulated by the signal processor 62, as each of the electrical
10 signals 45 and 46 corresponds to intensity of each AM signal 35 and 36. The electrical signals 45 and 46 are sampled by the signal processor 62 at regular intervals and substantially simultaneously with one another. The sampled signals are the instantaneous
15 intensity for each AM signal, 35 and 36. These intensity signals will be discussed below as (A) and (B), respectively.

In the signal processor 62 (FIG. 1) the instantaneous intensity signal for each beam component
20 is sampled sequentially and stored, thereby forming a data base of stored signals which represents each AM signal over time. The stored signals are then converted into a displayable signal regarding the voltage of E-field at the transducer 5 (FIG. 8).

25 In the preferred embodiment signals are manipulated in the following manner. First, an average intensity for each independent amplitude modulated signal is calculated. This is done by summing the instantaneous intensities of the signals
30 which have been sampled over a pre-determined time interval and dividing by the number of samples taken in the interval. In the preferred invention this is accomplished by taking the average of the signals over time for each beam component by summing the signals of
35 each beam component and dividing the sum by the number of signal samples taken.

Mathematically, the average intensity for the AM signal (A) is expressed as follows:

$$\bar{A} = (1/L) \sum_{i=n-L}^n A_i$$

where the average intensity is ($\bar{A}$), the instantaneous AM signal is (A_i), the number of samples is (L), the samples are taken and stored at uniform time intervals (i), and the average is calculated using samples between present time index n and past time index ($n-L$). Similarly, the average intensity for the AM signal (B) is expressed as follows:

$$\bar{B} = (1/L) \sum_{i=n-L}^n B_i$$

where the average intensity is ($\bar{B}$), the instantaneous AM signal is (B_i), with the other values being as above.

Next, an adjusted instantaneous intensity for each signal is found by comparing the most recent instantaneous signal intensity with the average signal intensity of the corresponding AM signal. Thus, for the beam component corresponding to AM signal (A), the adjusted instantaneous intensity (I_n) is:

$$I_n = \bar{A} - A_n$$

Where at (A_n) is the instantaneous intensity of AM signal (A) at the present time index. Similarly, for AM signal (B), the adjusted instantaneous intensity (J_n) is:

$$J_n = \bar{B} - B_n$$

Where (B_n) is the instantaneous intensity of signal (B) at the present time. It will be recognized by those

skilled in the art that because signals (A) and (B) each represents a different axis on the polarization ellipse, their amplitudes will change in opposite directions from one another for a given change in polarization. Thus where the intensity of one signal increases there will be a decrease of intensity of equal magnitude in the other signal. Therefore, the adjusted instantaneous intensity signals (I_n) and (J_n) must be computed as indicated above in order to preserve sign.

The adjusted average instantaneous intensity signal for both signals (A) and (B) compensates for any temperature induced birefringence that may exist within the transducer. Temperature induced birefringence causes a change in the intensity of the AM signals over time, as the transducer heat or cools. The variation in the intensity due to temperature-dependant intrinsic birefringence of the transducer appears as a modulation or variation in the average intensity. Thus, by comparing the instantaneous intensity with the average intensity of the signals, and deducting the average intensity from the instantaneous intensity, temperature induced variations of the signal due to the birefringence in the transducer are compensated for in the adjusted instantaneous intensity signals (I_n) and (J_n).

An additional manipulation of the adjusted instantaneous intensity signals (I_n) and (J_n) compensates for intensity fluctuations and other common mode noise. This is accomplished by comparing the average of the adjusted instantaneous intensity signals (I_i) and (J_i) for the signals (A) and (B). This comparison entails calculating the average between (I_n) and the sign-reversed value of (J_n).

$$K_n = \frac{(I_n - J_n)}{2}$$

This average (K_n) is directly proportional to the voltage. This is so because the Pockels electro-optic

effect induces a differential phase shift in the orthogonal planes of the beam 12 (FIG. 8) which is directly proportional to the E-field, and the E-field is directly proportional to voltage. Thus, for a sampling of interest (n), the average instantaneous intensity signal (K_n) for the signals (A) and (B) is directly proportional to the actual instantaneous voltage (V_n) between energized conductor and ground, varying only by a scaling constant (k).

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$$V_n = kK_n = k \frac{(I_n - J_n)}{2}$$

The scaling constant (k) is determined by applying a precisely known voltage to the device of interest and adjusting the scaling constant (k) until the value measured as the actual instantaneous voltage (V_n) is equivalent to the precisely known voltage being applied. In a typical general application of the present invention, shown in FIG. 1, the sensor head 4 is placed in an insulator 50 between a conductor 52 and a grounded conductor 48. When voltage is applied to the conductor 52 an E-field is created between the conductor 52 and the grounded conductor 48, in the insulator 50. Determination of the scaling constant (k) is accomplished by applying a precisely known voltage to the conductor 52. Once the scaling constant (k) is known the electro-optical voltage sensor system may be operated to determine additional actual instantaneous voltages applied to conductor 52.

An alternative embodiment in accordance with the present invention is illustrated in FIG. 2, which is a diagram of the electro-optical voltage sensor system. Wherever practicable, components in the alternative embodiment which are equivalent those discussed above have the same reference numbers. In this embodiment there is shown a transmitter 1, which comprises a laser (not shown), a polarizer 6, and a wave plate 9. The laser emits an electromagnetic radiation beam 12. The electromagnetic radiation beam 12 passes first

through a polarizer 6 and then a wave plate 9, producing a polarized beam 12 which may be circular-polarized. The beam 12 enters into a PM optic fiber 18 through a collimator 20. The PM optic fiber 18 may further comprise a low-birefringence optic fiber. The optic fiber 18 routes the beam 12 to a sensor head generally designated at 16. It is important to note that the sensor head 16 in this alternative embodiment shown in FIG. 2 differs from the sensor head 4 of the preferred embodiment shown in FIG. 1.

The detector generally depicted at 8, as shown in FIG. 2, comprises a polarizing beam splitter 80, at least two photo-detectors 43, 44, a signal processor 62. The beam 12 is routed from the sensor head 16 through another PM optic fiber 19 through a collimator 23 and into the polarizing beam splitter 80. Again, as shown in FIG. 3, the polarizing beam splitter 80 separates the polarized beam 12 in accordance with the respective separate wave components propagating in the orthogonal axes of the polarization ellipse into AM signals 35, 36. In the embodiment shown in FIG. 2, the AM signals 35, 36 which are analog optic signals, are routed through multi-mode or single-mode optic fibers 37, 38 to the photo-detectors 43, 44.

The photo-detectors convert the AM signals 35, 36 into electrical signals 45, 46 which can be analyzed in the signal processor 62.

Prior to discussing the sensor head 16, consider the collimators 20, 21, 22, 23, 24, 25 in FIGS. 2, 7a, 7b, and 7c and collimators 26, 27 and 28 in FIG. 8, which each are generally represented by the collimator 29, shown in FIG. 4. Generally, a collimator 29 comprises a lens 30 and a transparent end 31 which can pass a beam 12 into or out of the core 32 of an optic fiber 40. A collimator used to couple light into the core of an optic fiber is sometimes also referred to as a "coupler" in the art, but the term "collimator"

is used herein for simplicity. In the preferred embodiment, the optic fiber 40 is a PM optic fiber 18, which may also take the form of low-birefringence fiber.

5 Referring to FIGS. 7a, 7b, and 7c, these alternative embodiments of the sensor head 16 comprise a transducer 5 and a reflector 17. In FIG. 7a the beam 12 enters into the sensor head 16, through a collimator 21 which is attached to a PM fiber 18. The
10 beam 12 then passes through the transducer 5 and upon being reflected by a beam reflector 17 enters into a second collimator 22. The second collimator 22 is connected to an optical fiber 19 by which the beam 12 is routed away from the sensor head 16. In this
15 embodiment (and that in FIG. 7b), the beam only passes through the transducer once.

Similarly, in the practice of the alternative embodiment of FIG. 7b, the beam 12 enters into the sensor head 16, through a collimator 21 which is
20 attached to a PM fiber 18, following which it is reflected by the beam reflector 17 into the transducer 5. The beam 12, after passing through the transducer 5 would enter into a second collimator 22 connected to an optical fiber 19 and be routed away from the sensor
25 head 16.

Likewise, in the practice of the alternative embodiment of FIG. 7c, the beam 12 enters into the sensor head 16, following which it travels through the transducer 5. The beam 12 is then reflected by the
30 beam reflector 17 back through the transducer 5, and into a second collimator 22 connected to an optical fiber 19. The beam 12 is then routed away from the sensor head 16.

35 In the embodiments of FIGS. 1 and 2, the sensor heads 4 and 16 each have a cross-sectional area of only approximately fifty millimeters squared (50 mm²) or less, and a length of approximately twenty five

centimeters (25 cm) or less, depending upon the particular apparatus in which the sensor head is embedded.

There are two alternative embodiments of the transducer 5 which vary according to intrinsic birefringence. The first embodiment of the transducer 5, as shown in FIG. 5, is particularly appropriate where the transducer material 5 does not exhibit intrinsic birefringence along the propagation axis, shown as z . The beam 12 propagates along axis z . The transducer 5 in the presence of the E-field 90 causes differential phase modulation in the orthogonal planes of the beam 12. The embodiment shown in FIG. 5 is preferred where the transducer 5 exhibits no intrinsic birefringence. It is desirable to avoid intrinsic birefringence, as it is typically temperature dependant.

The second embodiment for the transducer 5 which exhibits intrinsic birefringence is shown in FIG 6. Here, the transducer 5 and a second transducer 11, have matched intrinsic birefringence to one another along the propagation axes, shown as y' . The transducer 5 is aligned with the second transducer 11 such that the optic axes y' are rotated ninety degrees (180°) with respect to one another. The E-field 90, aligned along the z axes, achieves a reverse polarity in the second transducer 11. The orientation of the beam 12 with respect to the optic axes y' is preserved by the rotation of the beam 12 by ninety degrees (90°). This rotation of the orientation is achieved by placement of a 90° polarization rotator 7 between the first transducer 5 and the second transducer 11. This configuration achieves cancellation of the effects of intrinsic temperature dependant birefringence, while yielding a differential phase shift in each transducer 5, 11. Thus, in this embodiment, the beam 12 goes through the transducer 5 to the 90° polarization

rotator 7, and thence through the second transducer 11.

There are a number of expressions of the E-field originator 96 which will now be discussed. The first, shown in FIG. 9, is a shielded joint 100. A shielded joint 100 is used to connect shielded conductors 52 to one another, and may take the form of either a splice or pre-molded connector. In the preferred embodiment the two conductors 52 connected to one another are each enclosed within insulation 50, around which is a semi-conducting jacket 109 and a cable ground shield 111. Around the conductor connecting means 104 is a layer of shielded joint insulation 108 and a joint ground shield 102. The joint ground shield 102 is supported in place by the end caps 115. A ground shield connector 113 can be used to maintain a common ground potential upon the cable ground shields 111 and the joint ground shield 102. The cable ground shields 111 are electrically connected by conductive wire 106 attached to ground shield connector 113. Alternatively, the cable ground shields 111 can be physically connected to the joint ground shield 102 at the intersection points without use of a ground shield connector 113 or conductive wire 106. The sensor head 4 is disposed between the joint ground shield 102 and the conductor connecting means 104. The optical fibers 18, 37, 38, route the beam to and from the sensor head 4. The E-field of interest, and into which the sensor head 4 is introduced, arises between the joint ground shield 102 and conductor connecting means 104 when an electric voltage is present upon the conductor connecting means 104.

Another expression of the E-field originator 96 is the terminator 118 shown in FIG. 10. In the preferred embodiment showing a terminator 118, a conductor 52 is enclosed within insulation 50 forming a transition span. The insulation 50 is enclosed

within a voltage gradient control means 120. A cable ground shield 111 may partially enclose the voltage gradient control means 120. The sensor head 4 is disposed between the conductor 52 and the voltage gradient control means 120. Optical fibers 18, 37, 38 route the beam to and from the sensor head 4. The E-field of interest, and into which the sensor head 4 is introduced, arises between conductor 52 and the voltage gradient control means 120 when a voltage is present upon the conductor 52.

Another expression of the E-field originator 96 of FIGS. 1 and 2 is the through-hole insulator 124, here shown as a transformer bushing in FIG. 11. In the preferred embodiment showing a through-hole insulator 124, a conductor 52 is enclosed within insulation 50, which is enclosed within a grounded conductor 48. The through-hole insulator shown here as a transformer bushing has a mounting flange 126 for mounting the bushing and creepage distance skirts 128 which extend from the grounded conductor 48. The sensor head 4 is disposed between the conductor 52 and the grounded conductor 48. Optical fibers 18, 37, 38 route the beam to and from the sensor head 4. The E-field of interest, and into which the sensor head 4 is introduced, arises between the conductor 52 and the grounded conductor 48 when a voltage is present upon the conductor 52.

Another expression of the E-field originator 96 of FIGS. 1 and 2 is the shielded cable or bus 129, shown in FIG. 12. In the preferred embodiment of a shielded cable or bus 129, a conductor 52 is enclosed within insulation 50, which is enclosed within a grounded conductor 48. The sensor head 4 is disposed between the conductor 52 and the grounded conductor 48. Optical fibers 18, 37, 38 route the beam to and from the sensor head 4. The E-field of interest, and into which the sensor head 4 is introduced, arises

between the conductor 52 and the grounded conductor 48 when a voltage is present upon the conductor 52.

Whereas FIG. 12 shows a bus having a round cross-section, an alternative and equivalent embodiment comprises a rectangular (or square) cross-section.

Another expression of the E-field originator 96 shown in FIGS. 1 and 2 is the gas or oil-insulated switchgear 132, shown in FIG. 13. In the preferred embodiment showing a gas or oil-insulated switchgear 132, a conductor 52 is enclosed within gas or oil insulation 134, by a grounded conductive or semi-conductive containment means 140 for containing the gas or oil insulation. The sensor head 4 is disposed between the conductor 52 and the grounded containment means 140. Optical fibers 18, 37, 38 route the beam to and from the sensor head 4. The E-field of interest, and into which the sensor head 4 is introduced, arises between the conductor 52 and the grounded containment means 140 when a voltage is present upon the conductor 52.

Another expression of the E-field originator 96 is the duct-enclosed bus 142, shown in FIG. 14. In the preferred embodiment of a duct-enclosed bus 142, a conductor 52 is enclosed within insulation 50 of sufficient thickness to minimize possibility of flash-over. The insulated bus is enclosed within a grounded duct or other grounded at least semi-conducting means 144. Those skilled in the art will appreciate that by the term "at least semi-conducting", it is meant all semi-conducting and conducting means, by which the bus can be grounded. The sensor head 4 is disposed between the conductor 52 and the grounded semi-conducting means 144. Optical fibers 18, 37, 38 route the beam to and from the sensor head 4. The E-field of interest, and into which the sensor head 4 is introduced, arises between the conductor 52 and the

grounded semi-conducting means 144 when a voltage is present upon the conductor 52.

Another expression of the E-field originator 96 is the clamp-on apparatus 147, shown in FIG. 15. In the preferred embodiment of the clamp-on apparatus, a conductor 52 is enclosed within a coaxial conductive grounded surrounding means 149. In the practice of the invention, the conductor 52 is preferably a nonshielded transmission line, a nonshielded cable, or a nonshielded bus. The conductor 52 is separated from the conductive grounded surrounding means 149 by insulated standoff means 151. The sensor head 4 is disposed between the conductor 52 and the coaxial conductive grounded surrounding means 149. Optical fibers 18, 37, 38 route the beam to and from the sensor head 4. The E-field of interest, and into which the sensor head 4 is introduced, arises between the conductor 52 and the coaxial conductive grounded surrounding means 149 when a voltage is present upon the conductor 52.

FIG. 16 is an alternative embodiment of the electro-optical voltage sensor of FIG. 1, having a current detector 153 disposed substantially in common with the sensor head. The current detector 153 detects the current, not shown, passing through the conductor 52 by detecting the magnetic field, not shown, associated with the current. The current detector provides a current signal, not shown, which is routed through a current signal routing member 156 to the signal processor 62. In one embodiment the optical current signal routing member 156 consists of optic fiber, photodetection means, and electrical connecting means, none of which are shown. Where voltage (V) and current (I) are known, the power (P) can be determined by the signal processor by multiplying the current (I) by the voltage (V) as follows:

A combination of at least two sensors of the present invention may be used to achieve a line-to-ground voltage measurement on separate conductors of a multi-source system. "Multi-source system" is meant to include both a multi-phase as well as a multi-line system. In such a system, line-to-ground measurements may also be used to calculate line-to-line voltages through simple subtraction of line-to-ground values.

The present invention represents a significant advance over the prior apparatus, methods and art of voltage measurement. The present invention does not require any additional electronics to bias the transducing material to determine voltage, such as a voltage divider. Voltage is determined in the present invention by utilizing the E-field that exists within many types of devices to transmit and distribute power, often these power distribution devices are coaxial, which simplifies the application of the present invention. The E-field, which is proportional to voltage, is used to bias a transducing element in order to induce a differential phase shift in the orthogonal planes of the beam, which as modulated optic signals, is proportional to voltage.

It is noted that many of the advantages of the present invention accrue due to the simplified structure of the sensor head, which is sufficiently small so as to be conveniently installed in devices in which E-fields arise, or built in as part of a sensor.

Although the prior art apparatus and methods for voltage measurement have attempted to use the electro-optical effect in materials having either a Pockels or Kerr coefficient, they have typically required a separate compensator crystal with a known reference voltage or a separate voltage divider directly connected to the energized conductor in order to make

a voltage measurements. The result has been devices which were bulky and required additional electronics for measuring the known reference, or required extra hardware presenting size, weight, expense, reliability, and other problems.

By using the sensor head of the present invention, which may be installed or built into the described voltage transmission and distribution apparatus, voltage measurement is achieved without the use of a large, dedicated, stand-alone voltage division device. Real estate within Power substations is at a premium, thus this sensor system offers a substantial economic advantage due to space savings. In addition, contact with the energized conductor is substantially reduced and in most cases altogether eliminated with the practice of the present invention. This is advantageous, as an energized conductor can present significant life and health risks among other hazards where high voltages are involved. Further, the practice of the present invention does not interfere with the apparatus being measured, and avoids various other problems associated with the use of the voltage dividers in the prior art.

Those skilled in the art will appreciate from the preceding disclosure that the objectives stated above are advantageously achieved by the present invention.

It is to be understood that the above-described arrangements are only illustrative of the application of the principles of the invention. Numerous modifications and alternative arrangements may be devised by those skilled in the art without departing from the spirit and scope of the present invention and the appended claims are intended to cover such modifications and arrangements.

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CLAIMS:

1. A sensor head for use in combination with at least one beam of electromagnetic radiation for detecting presence and magnitude of electric field and voltage, said sensor

5 head comprising:

polarizing means for polarizing said at least one beam such that said at least one beam comprises at least two beam components in at least two orthogonal planes;

transducing means configured for disposition in an
10 electric field, but out of contact with electrical conductors generating said electric field, and for receiving said at least one beam from said polarizing means and inducing a first differential phase shift of the beam components which varies in magnitude in response to the
15 magnitude of an electric field; and

first reflecting means for receiving said at least one beam from said transducing means and reflecting said beam back into said transducing means.

2. The sensor head as in claim 1, wherein the sensor
20 head further comprises: quarter wave retarding means for biasing the beam's polarization such that zero electric field magnitude on the transducer corresponds to a circular polarization state.

3. The sensor head as in claim 1, wherein said first
25 reflecting means comprises a material having at least one surface, a reflective coating disposed on at least one surface of said reflecting means wherein said reflective coating accomplishes reflection of said beam.

4. The sensor head as in claim 2, wherein said
30 quarter wave retarding means resides within said first

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reflecting means, said first reflecting means further comprising:

phase shifting means for shifting the phase of at least one of said beam components to thereby achieve a second differential phase shift between said beam components of one-quarter of a wavelength, said quarter wavelength shift comprising at least a single order shift.

5. The sensor head as in claim 2, wherein said quarter wave retarding means comprises:

10 a quarter wave plate disposed at a point within a path of said beam following said polarizing means for shifting the phase of at least one of said beam components one-quarter of a wavelength, said quarter wavelength shift comprising at least a single order shift.

15 6. The sensor head as in claim 1, wherein said transducing means further comprises a Pockels transducing material.

7. The sensor head as in claim 6, wherein said Pockels transducing material is a material selected from a group consisting of:

Lithium Niobate (LiNbO_3),
Ammonium Dihydrogen Phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$),
Ammonium Dideuterium Phosphate ($\text{NH}_4\text{D}_2\text{PO}_4$),
Potassium Dideuterium Phosphate (KD_2PO_4),
25 MgO-doped Lithium Niobate (MgO-LiNbO_3),
Lithium Tantalate (LiTaO_3),
Electro-optic polymers, and
Organic material.

8. The sensor head as in claim 1, wherein said sensor head further comprises:

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translucent means disposed between the polarizing means and the transducing means for receiving said at least one beam from said polarizing means and transmitting said beam to said transducing means.

5 9. The sensor head as in claim 8, wherein said translucent medium further comprises a material that is substantially non-birefringent and nonconductive.

10. The sensor head as in claim 1, wherein said sensor head further comprises:

10 beam separation means for separating the beam components corresponding to a major axis and a minor axis of a polarization ellipse of said at least one beam, forming at least two signals therefrom.

11. The sensor head as in claim 10, wherein said
15 sensor head further comprises:

translucent means disposed between the transducing means and the separation means for receiving said at least one beam from said transducing means and transmitting said beam to said separation means.

20 12. The sensor head as in claim 10 wherein said at least two signals comprise independent converse amplitude-modulated signals.

13. The sensor head as in claim 9 wherein said translucent means comprises at least one material selected
25 from a group consisting of: fused quartz, fused silica, and nonconductive translucent media.

14. The sensor head as in claim 9 wherein said translucent means comprises at least one fiber selected from

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a group consisting of: collimator-coupled low-birefringence fiber and polarization-maintaining optic fiber.

15. A sensor head for use in combination with at least one beam of electromagnetic radiation for detecting
5 magnitude of an electric field, said sensor head comprising:

polarizing means for polarizing said at least one beam such that said at least one beam comprises at least two beam components in at least two orthogonal planes;

transducing means configured for disposition in an
10 electric field, but out of contact with electrical conductors generating said electric field, and for receiving said at least one beam from said polarizing means and inducing a differential phase shift of the beam components which varies in magnitude in response to the magnitude of an
15 electric field; and

first reflecting means for receiving said at least one beam from said polarizing means and reflecting said beam into said transducing means.

16. The sensor head as in claim 15, wherein the sensor
20 head further comprises:

quarter wave retarding means for biasing the beam's polarization such that zero electric field magnitude on the transducing means corresponds to a circular polarization state.

25 17. A sensor head for use in combination with at least one beam of electromagnetic radiation for detecting magnitude of an electric field, said sensor head comprising:

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polarizing means for polarizing said at least one beam such that said at least one beam comprises at least two beam components in at least two orthogonal planes;

transducing means configured for disposition in an electric field, but out of contact with electrical conductors generating said electric field, and for receiving said at least one beam from said polarizing means and inducing a differential phase shift of the beam components which varies in magnitude in response to the magnitude of an electric field;

beam separation means for receiving said at least one beam and separating the beam components and forming at least two signals therefrom; and

first reflecting means for receiving said at least one beam from said transducing means and reflecting said beam into said beam separation means.

18. The sensor head as in claim 17, wherein the sensor head further comprises:

quarter wave retarding means for biasing the beam's polarization such that zero electric field magnitude on the transducing means corresponds to a circular polarization state.

19. A method for detecting magnitude of an electric field using at least one beam of polarized electromagnetic radiation having at least two beam components propagating in at least two orthogonal planes, comprising the steps of:

(a) imposing an electric field upon at least one transducing means by disposing said at least one transducing means into an apparatus containing electric flux proportional to voltage, wherein said at least one

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transducing means is out of contact with electrical conductors generating said electric field;

(b) passing said beam through said at least one transducing means;

5 (c) inducing a differential phase shift between the beam components when said beam passes through said transducing means in said electric field, said differential phase shift indicating a presence and a magnitude of said E-field;

10 (d) reflecting said beam after said beam has passed through the transducing means with a reflective means, so that said beam is directed back into the transducing means, thereby causing said beam to reenter the transducing means;

15 (e) separating beam components into at least one pair of converse amplitude modulated (AM) signals, said AM signals corresponding to a major axis and a minor axis of said beam's polarization ellipse, whose ellipticity modulates between -1 and +1 in proportion to voltage,
20 wherein an intensity along the minor axis modulates conversely to an intensity along the major axis;

(f) transmitting said AM signals, whereby the electric field magnitude (and hence voltage) can be ascertained.

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OTTAWA, CANADA

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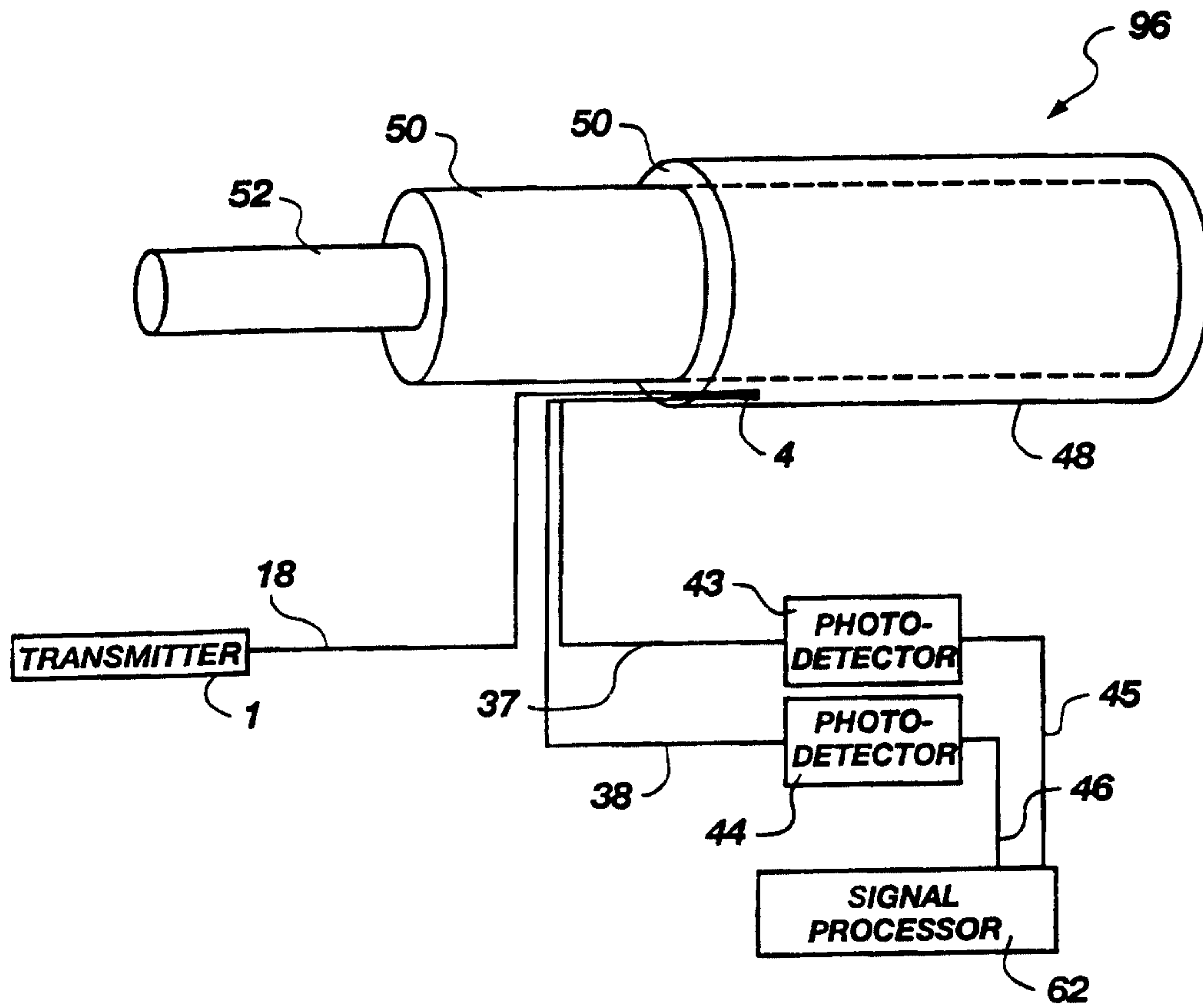


Fig. 1

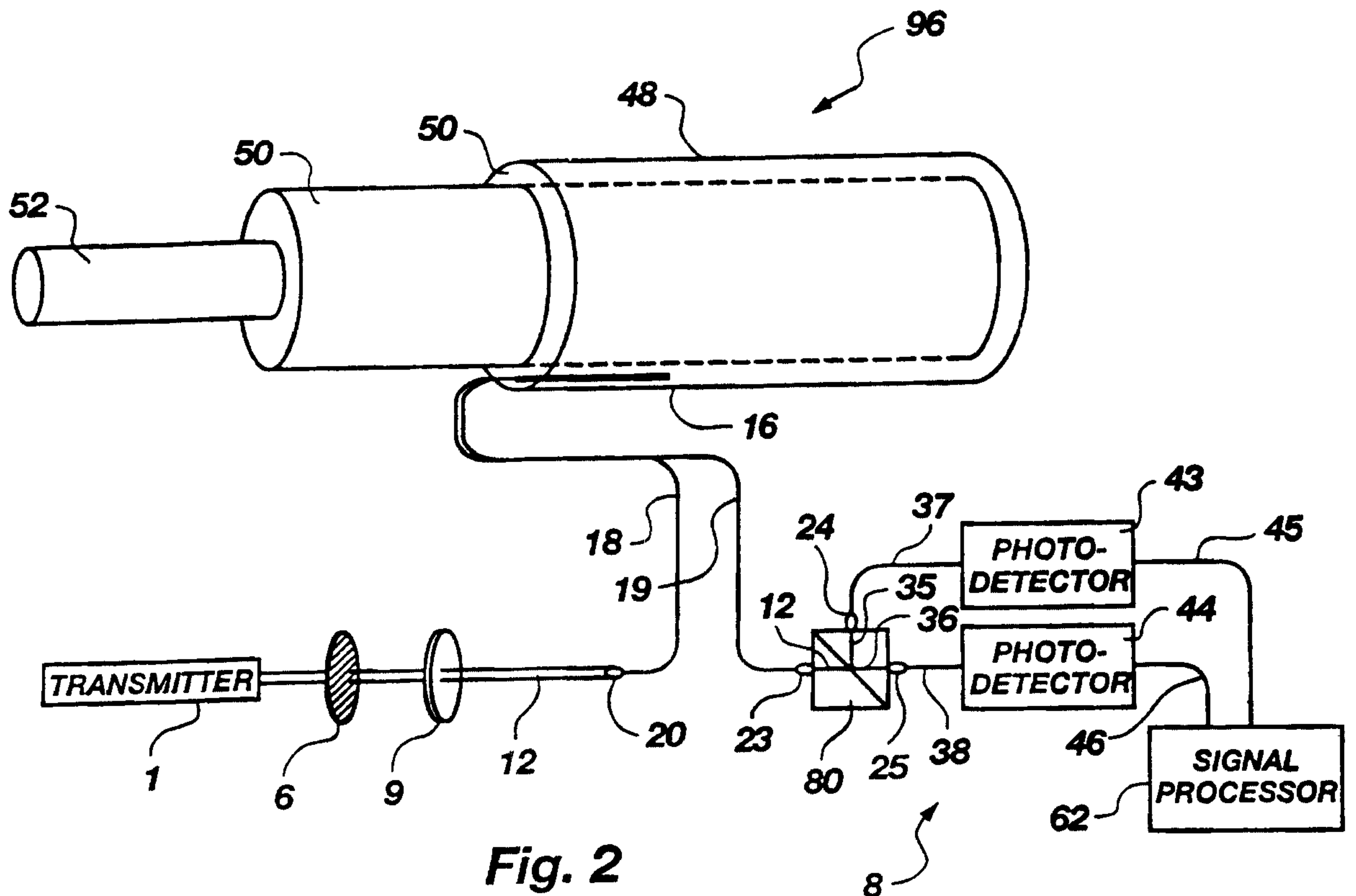
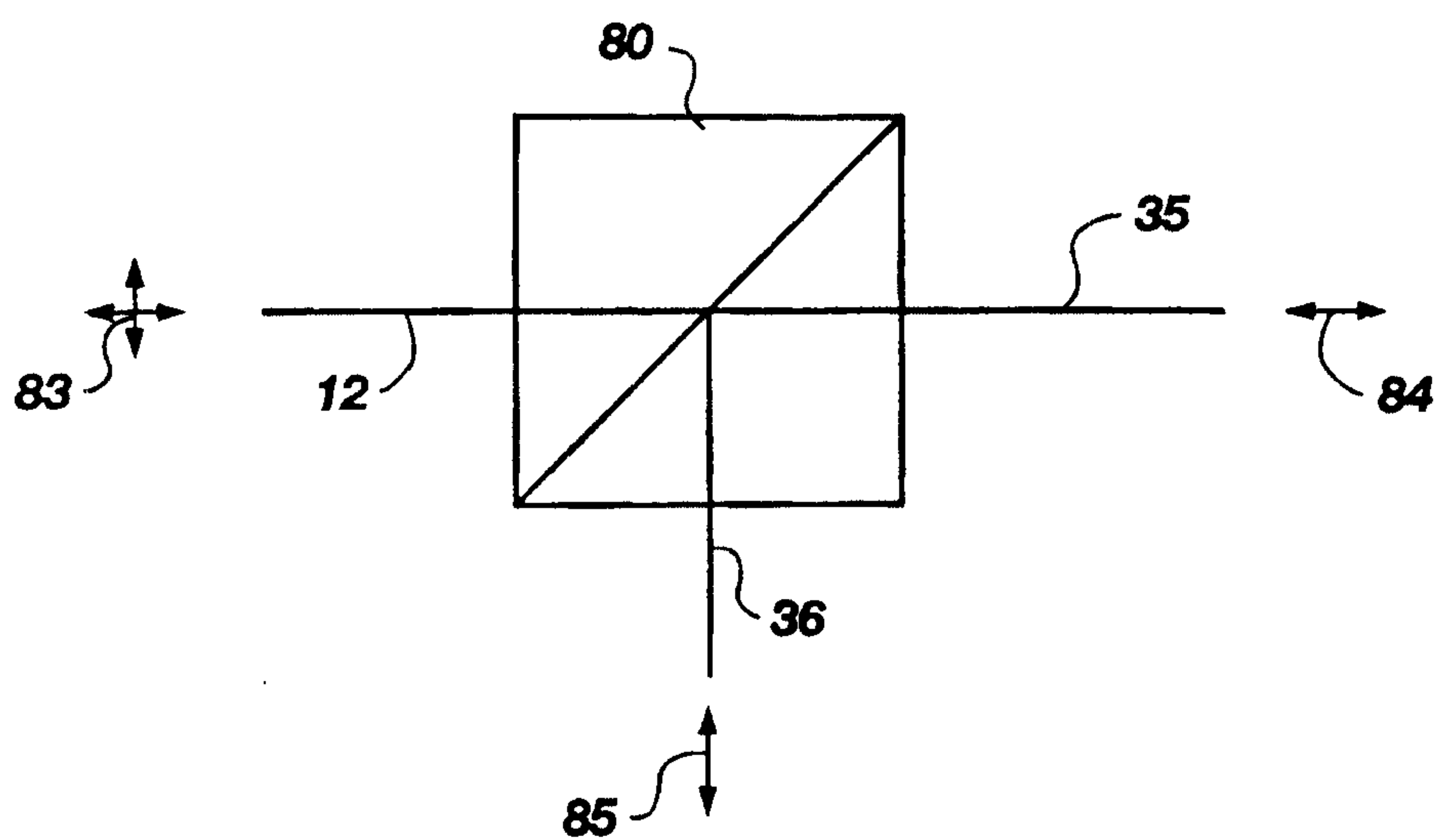
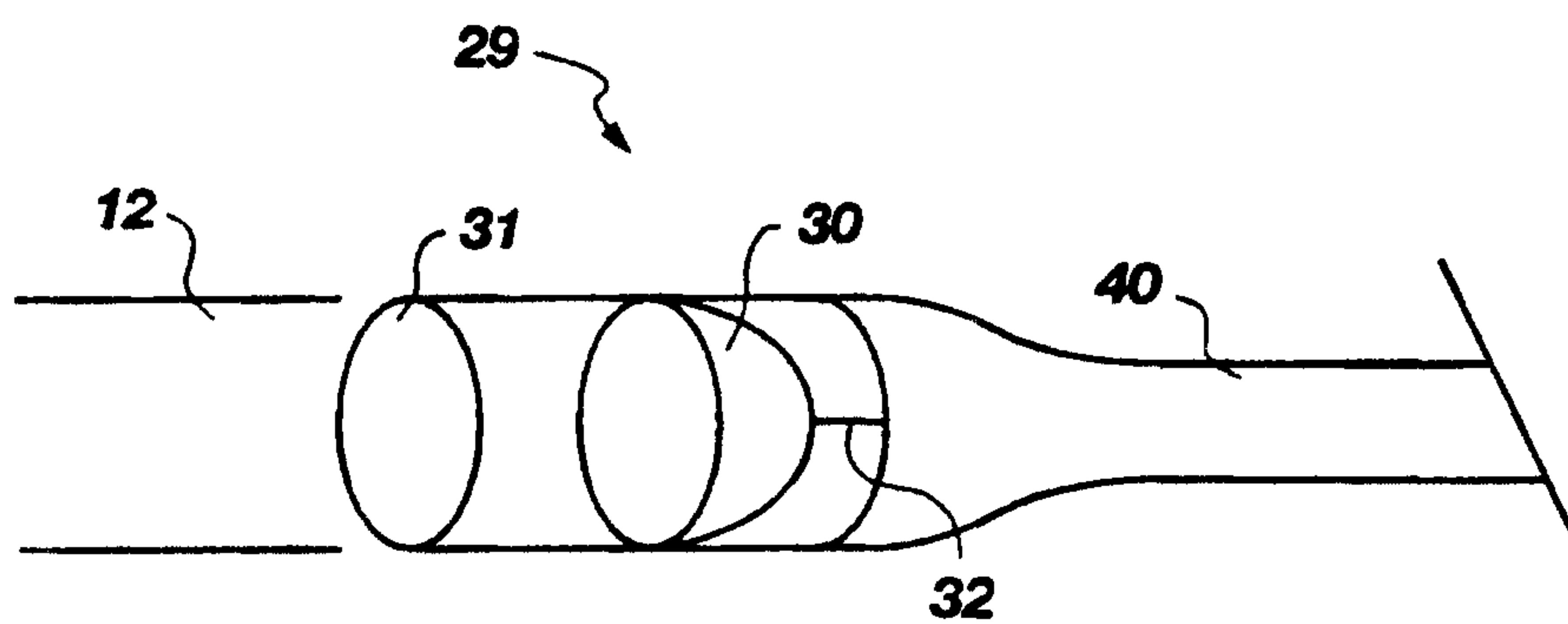
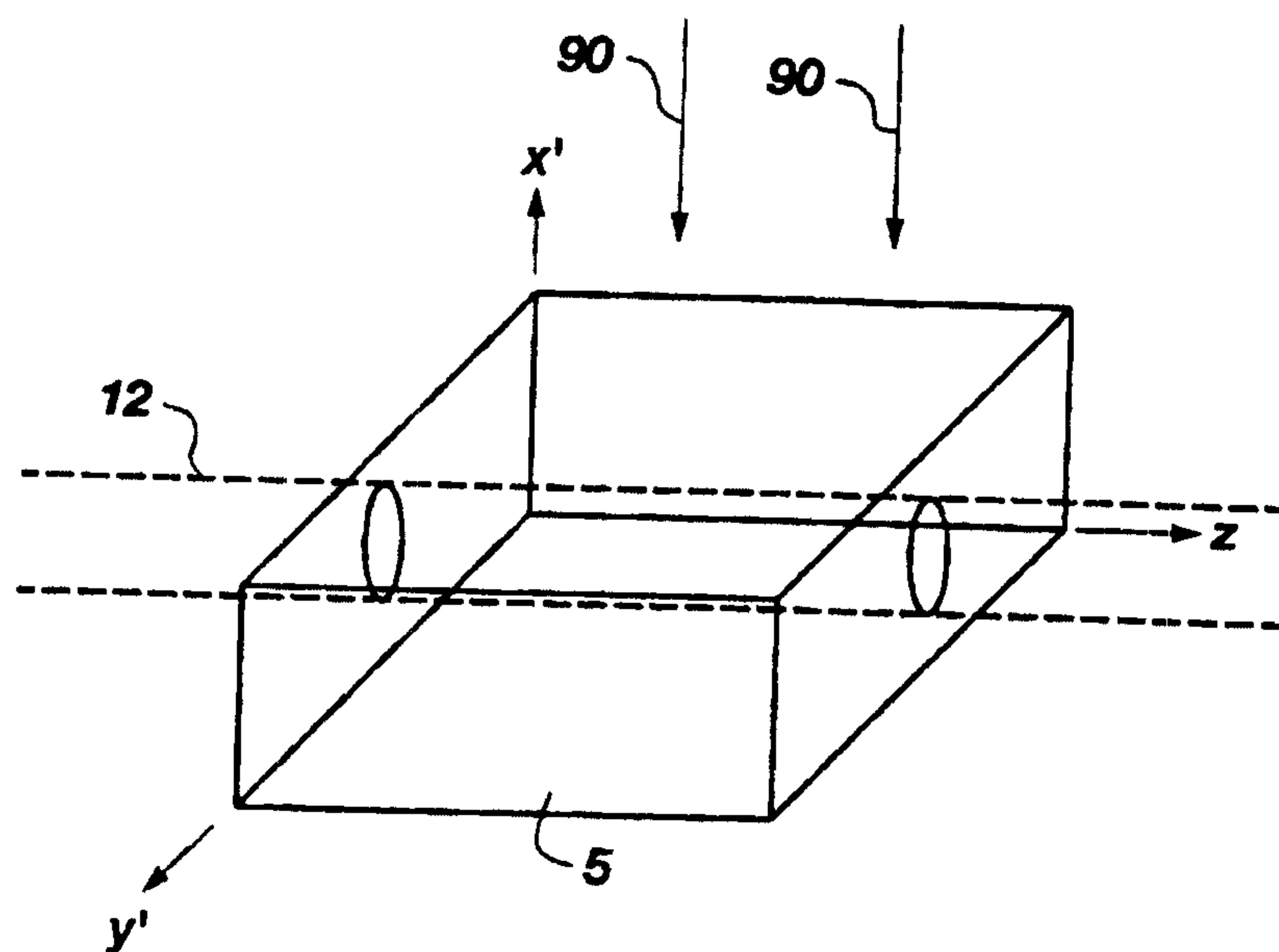
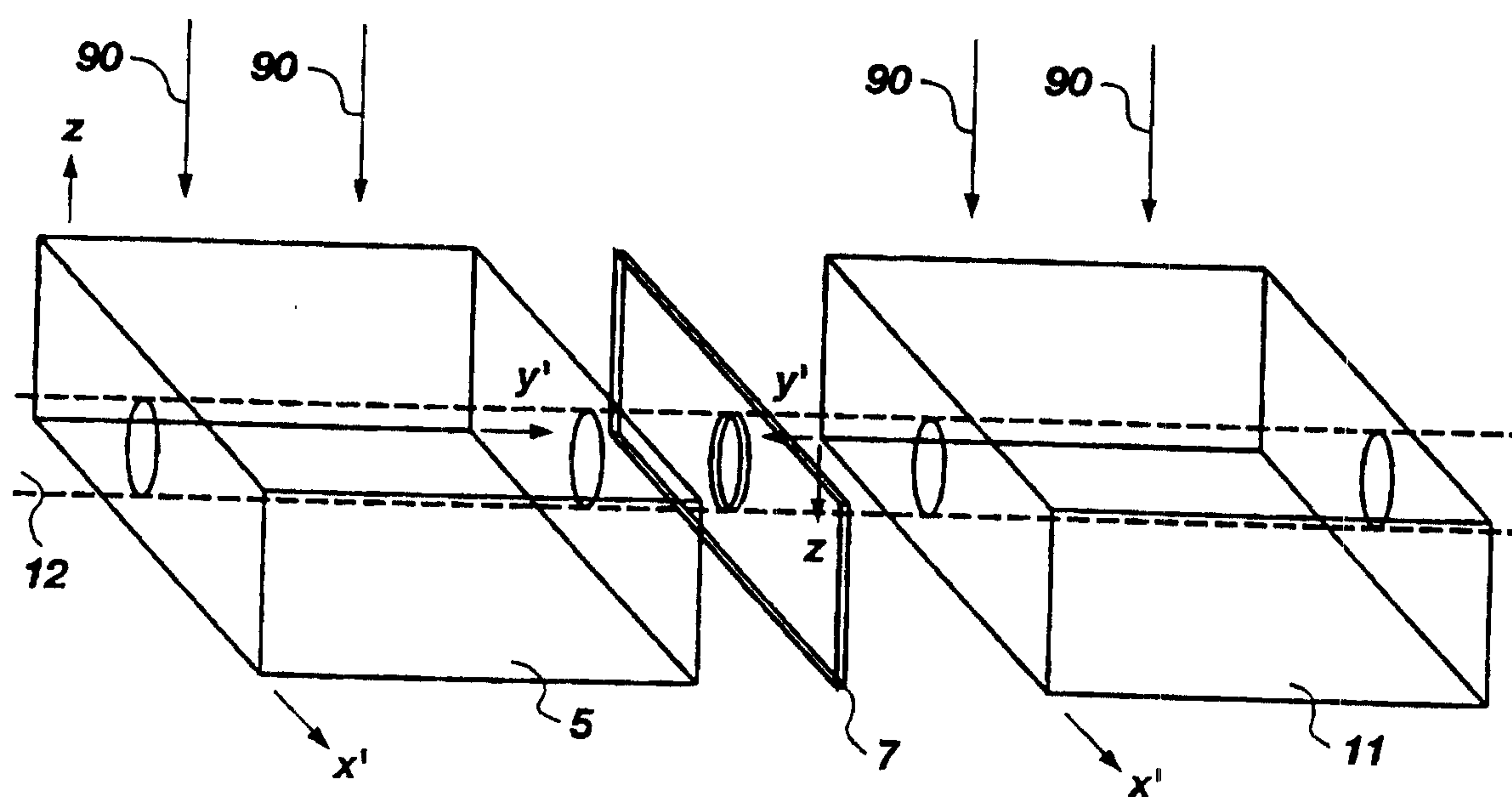


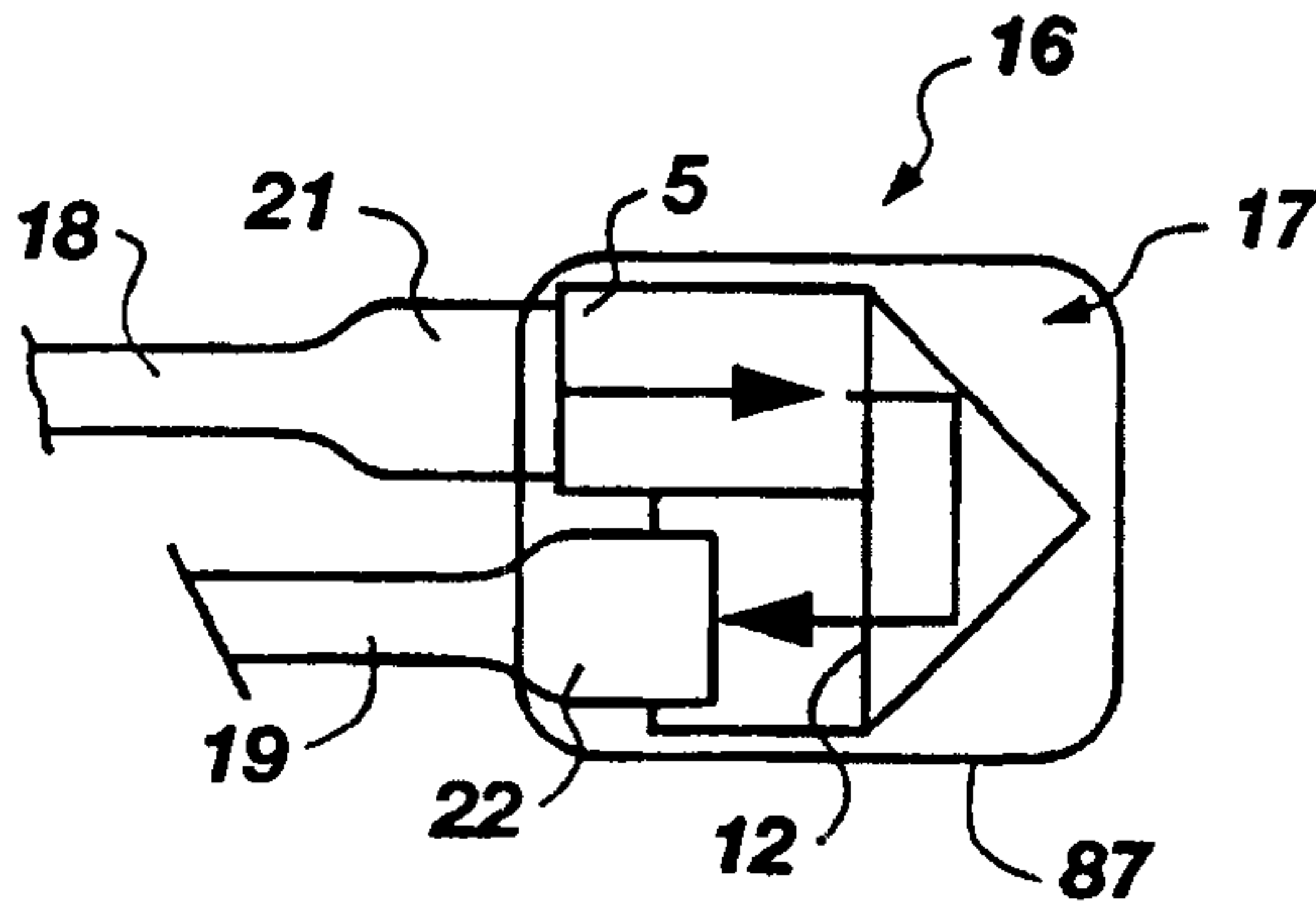
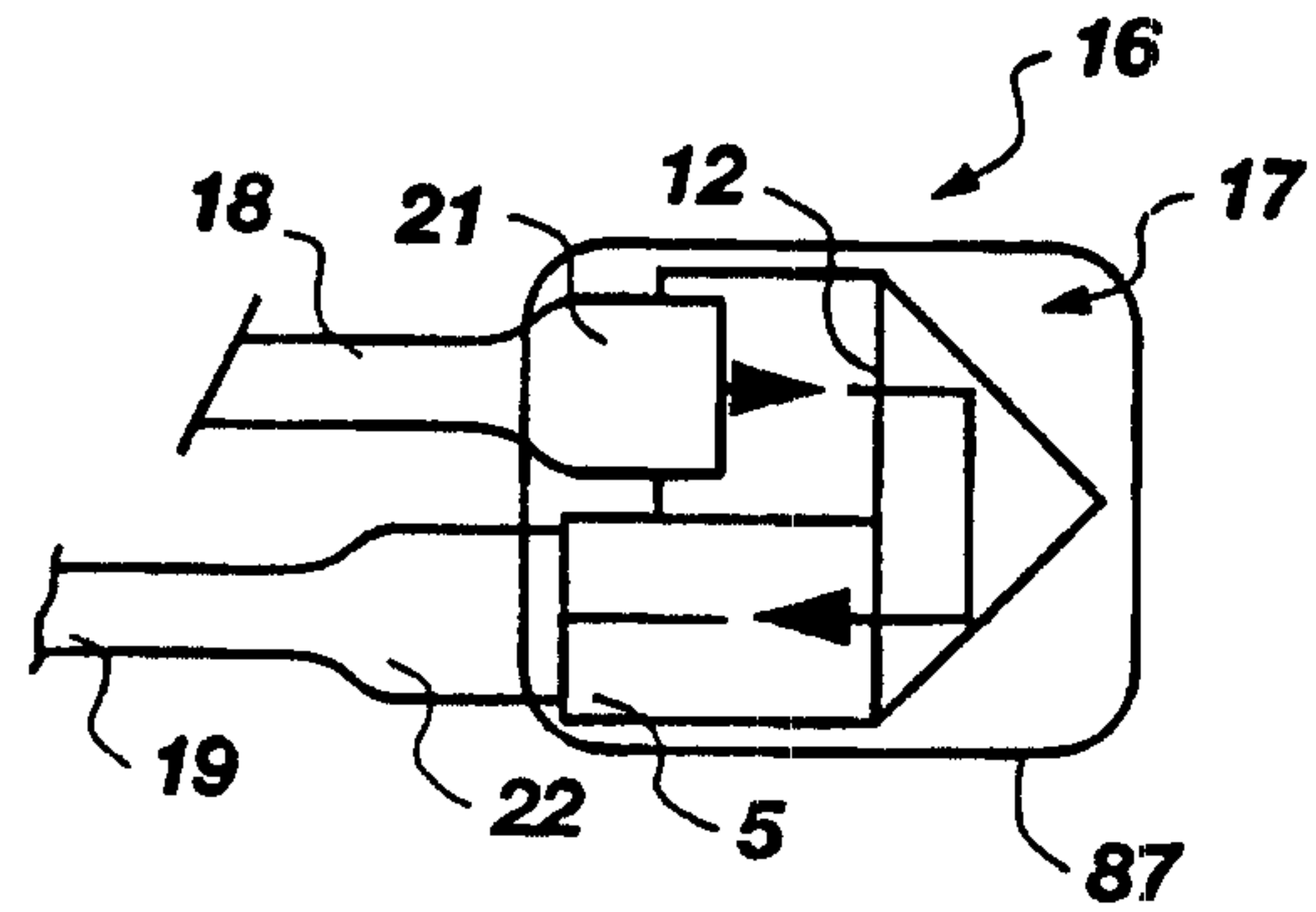
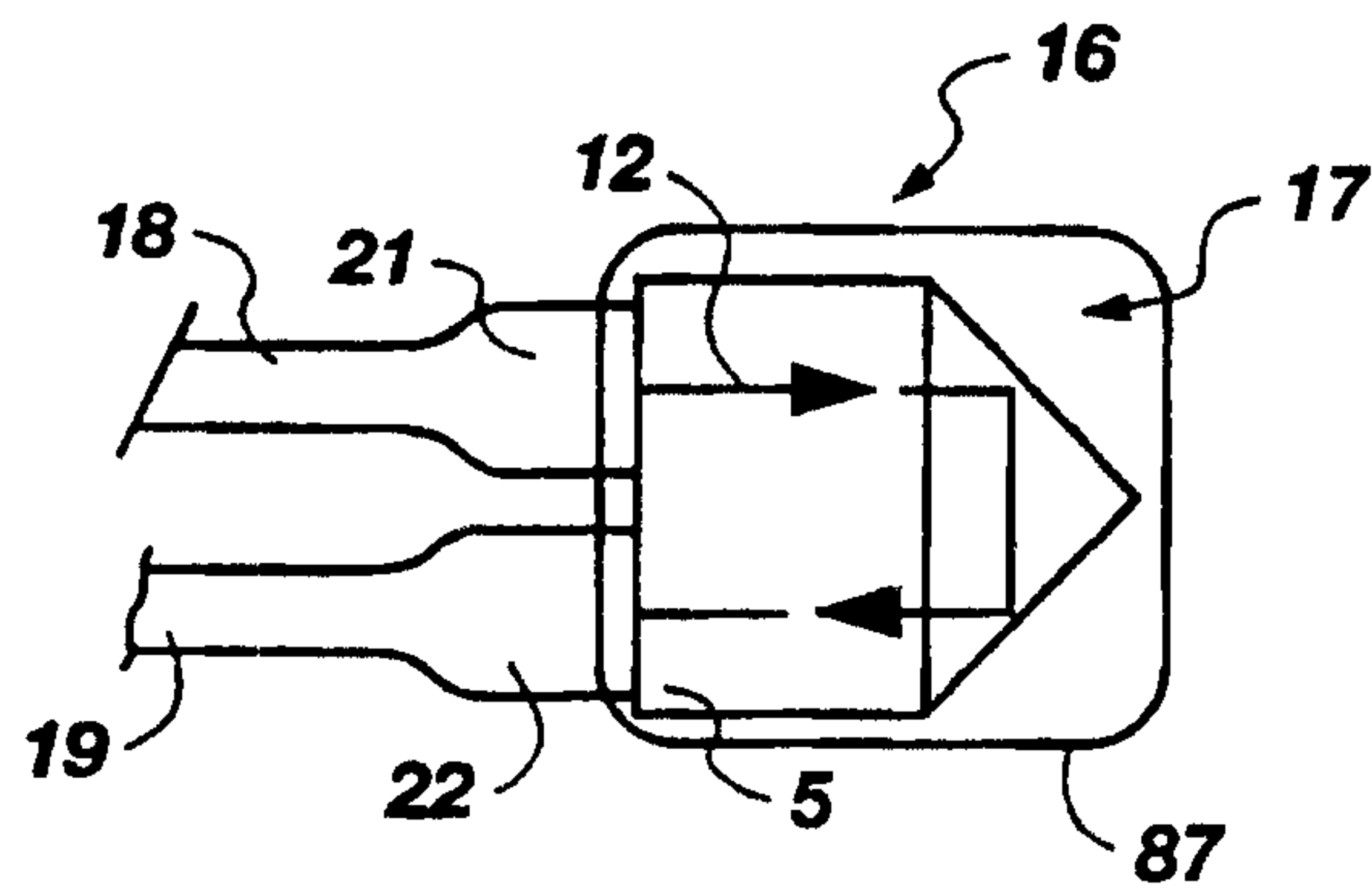
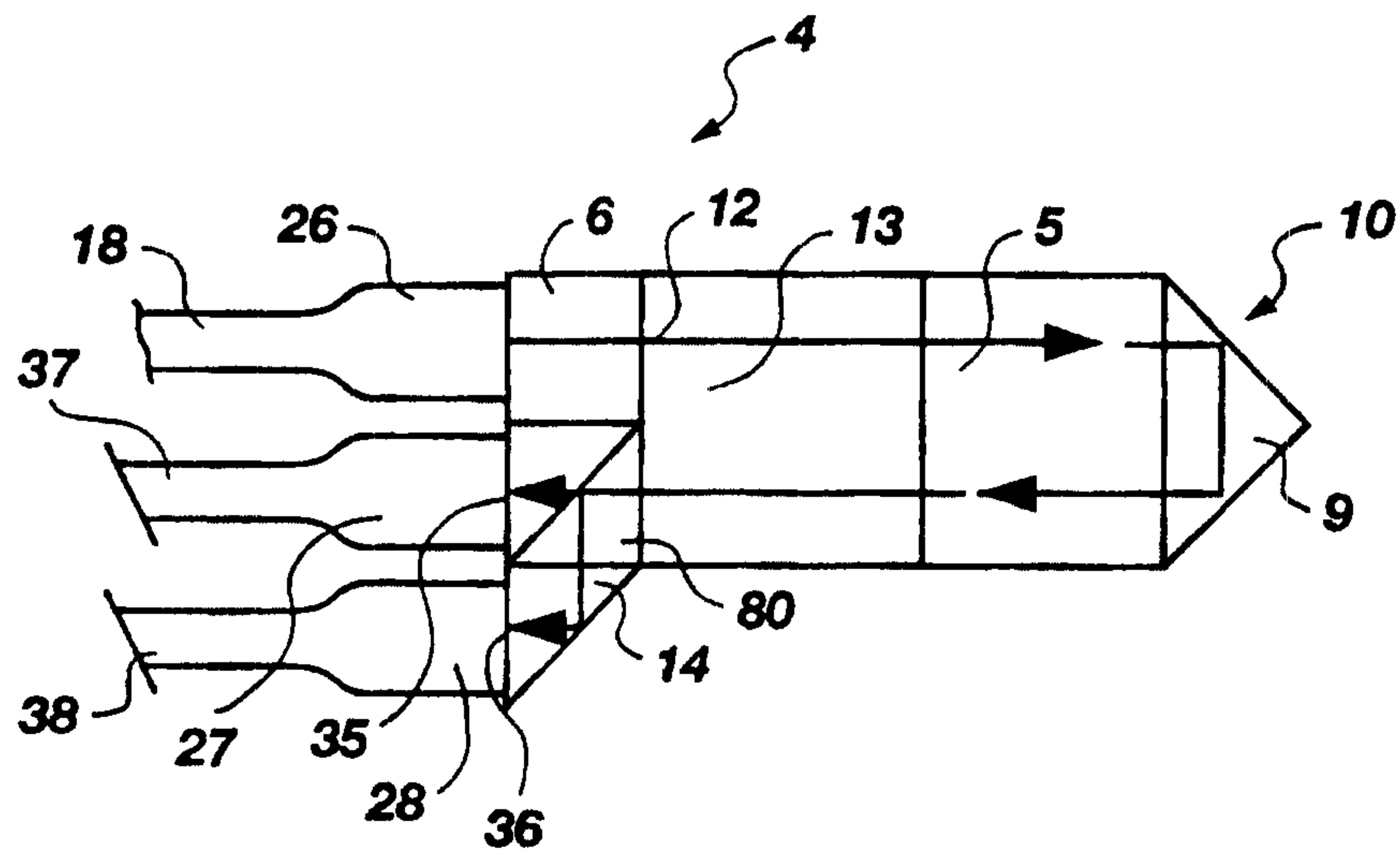
Fig. 2

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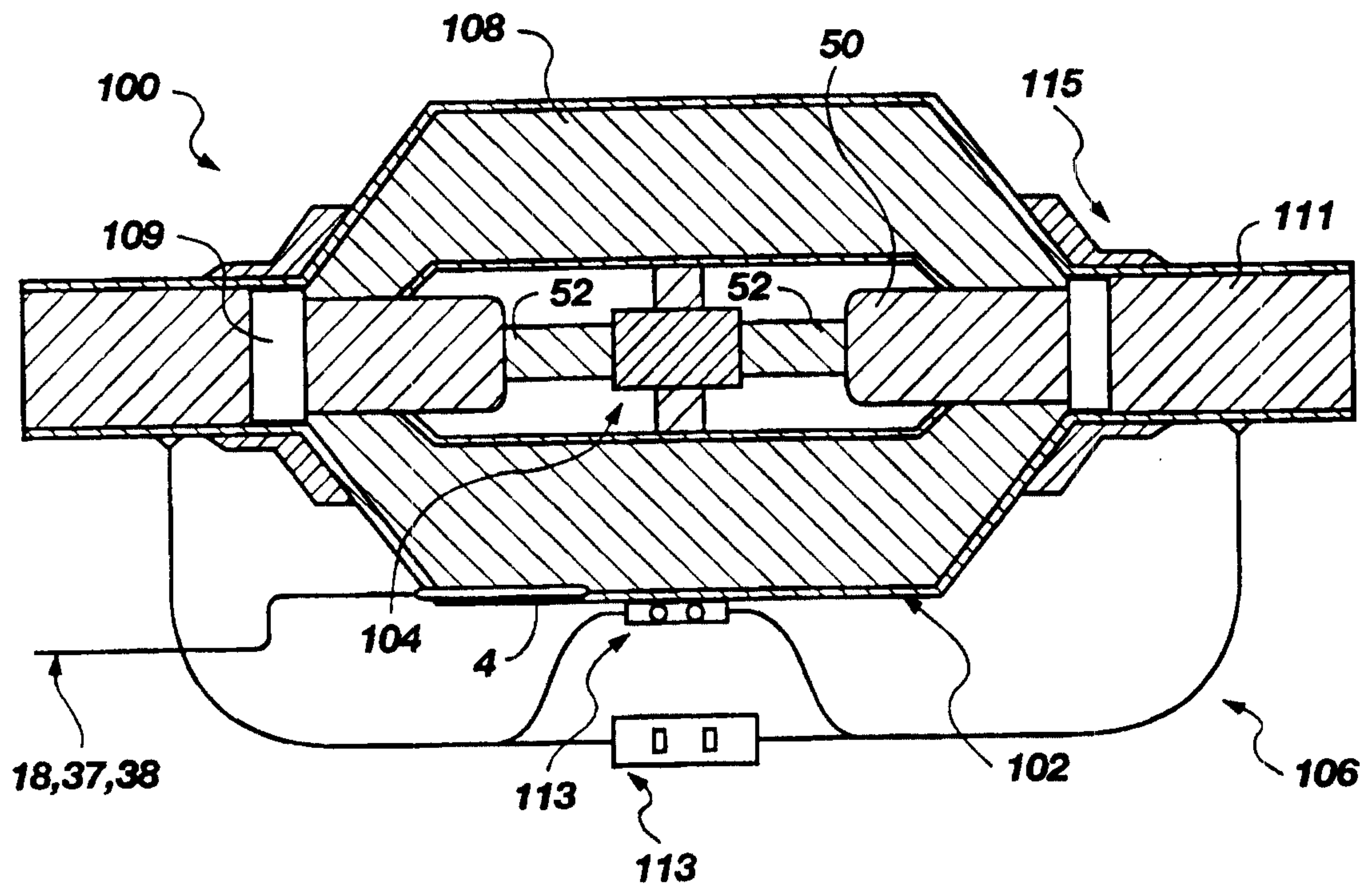
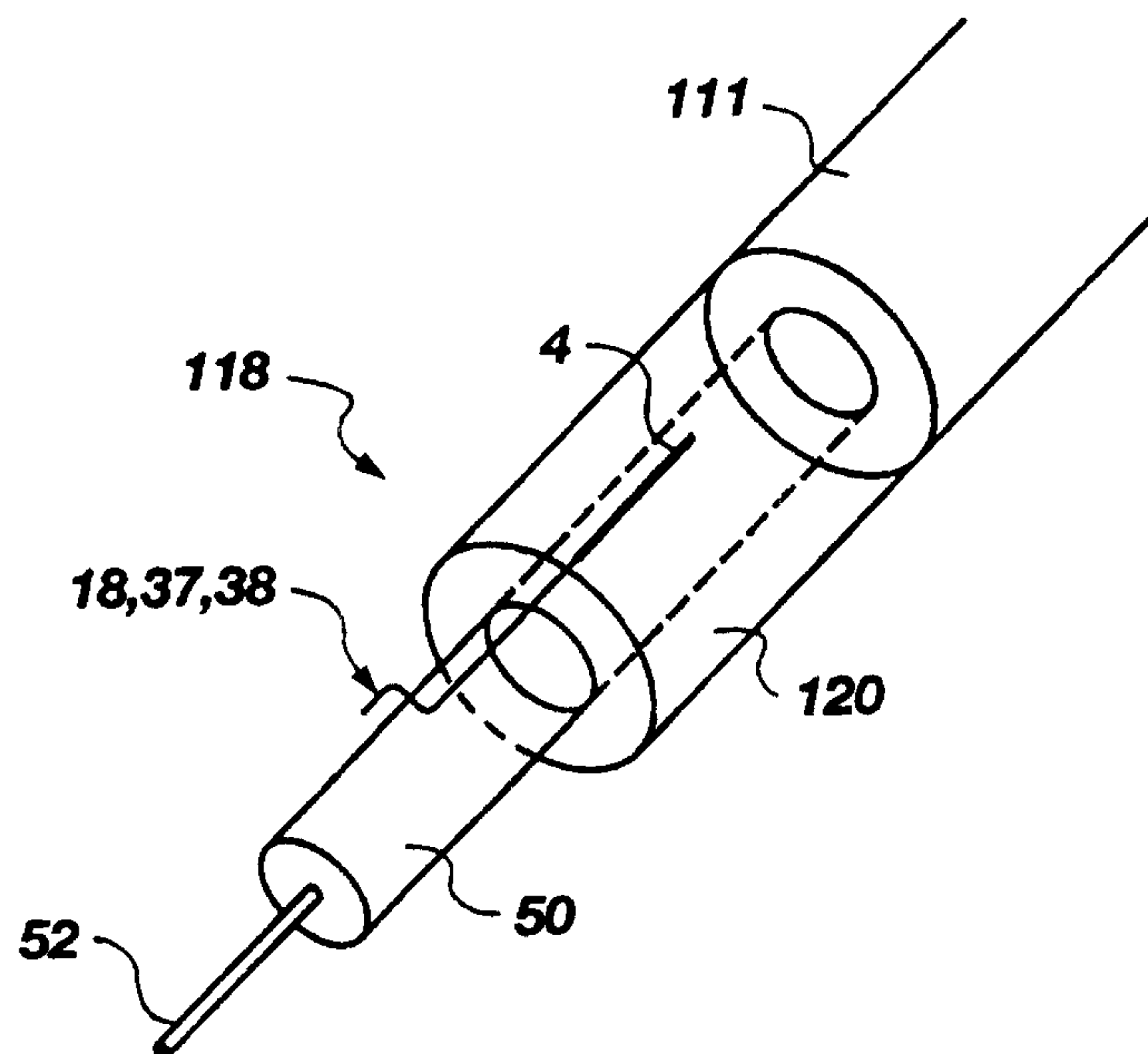
**Fig. 5****Fig. 6**

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**Fig. 7a****Fig. 7b****Fig. 7c****Fig. 8**

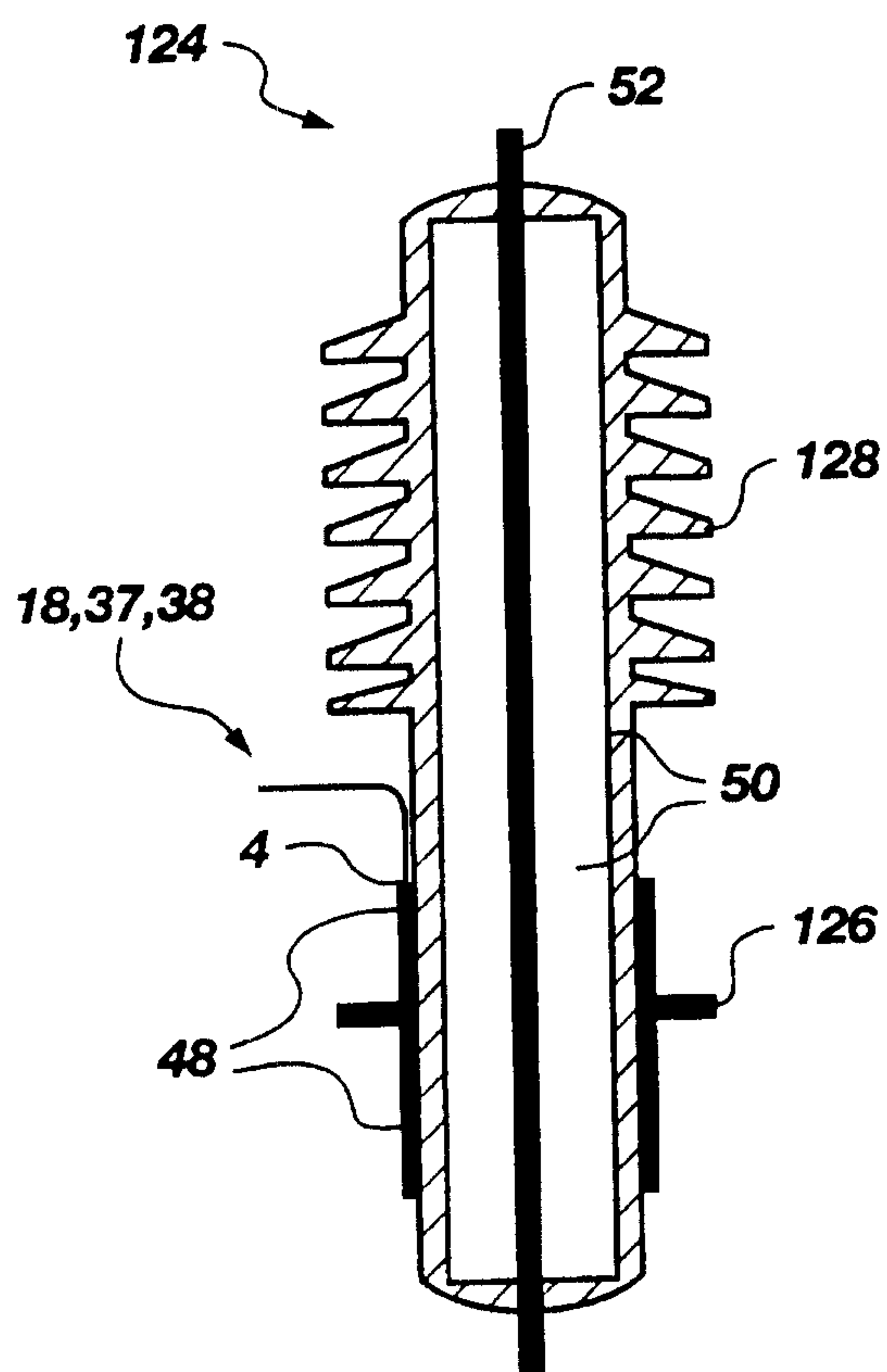
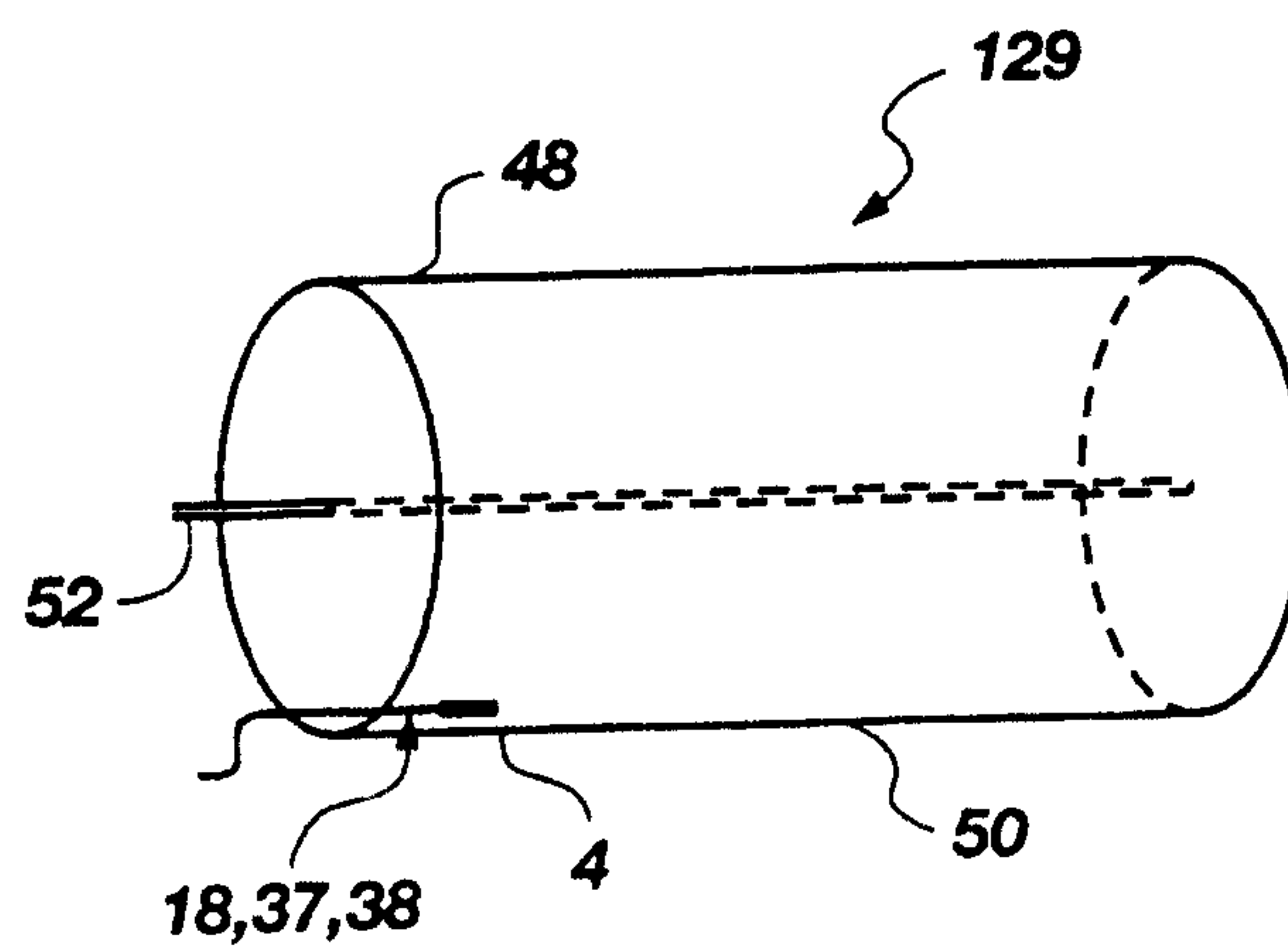
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**Fig. 9****Fig. 10**

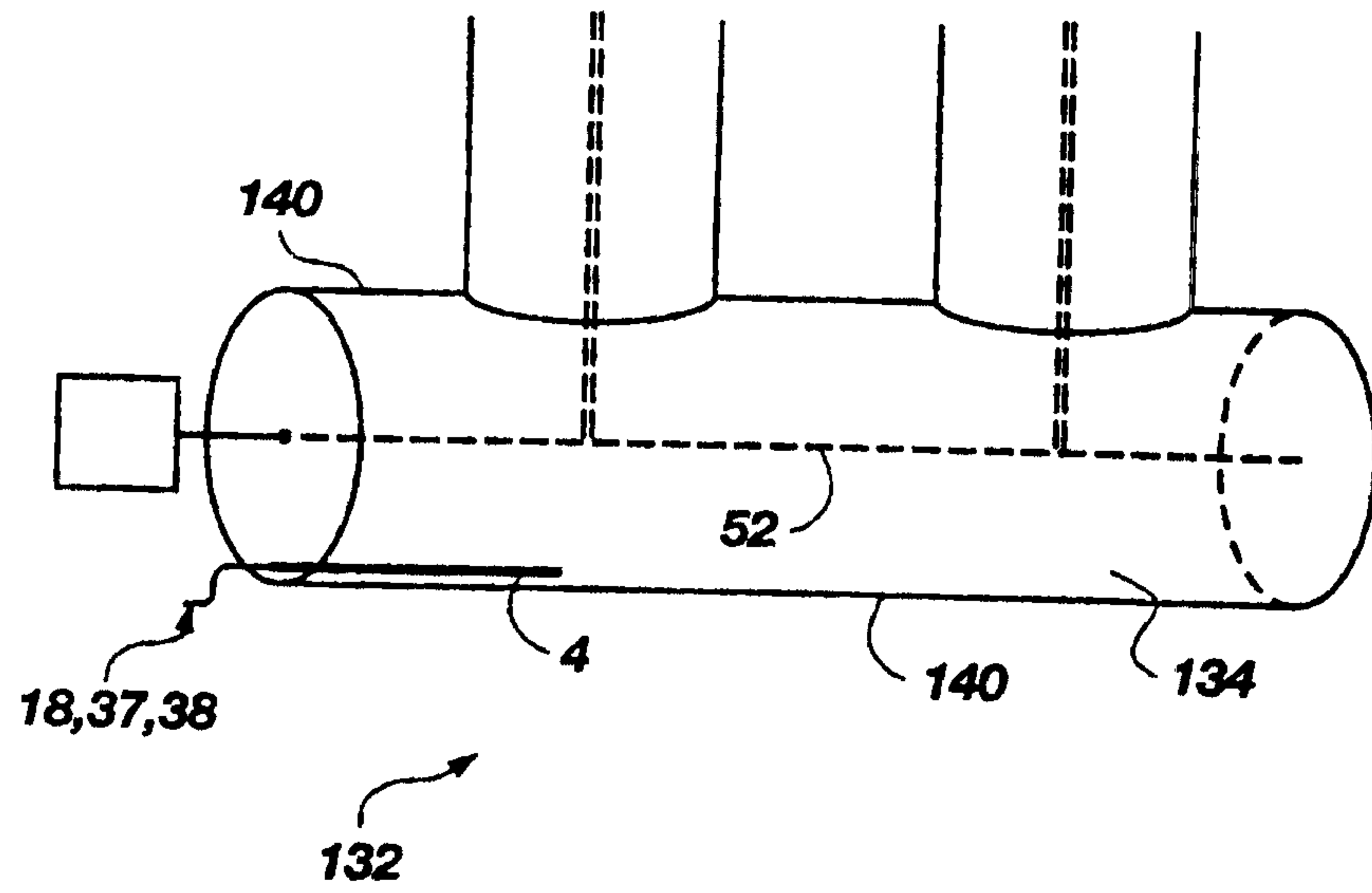
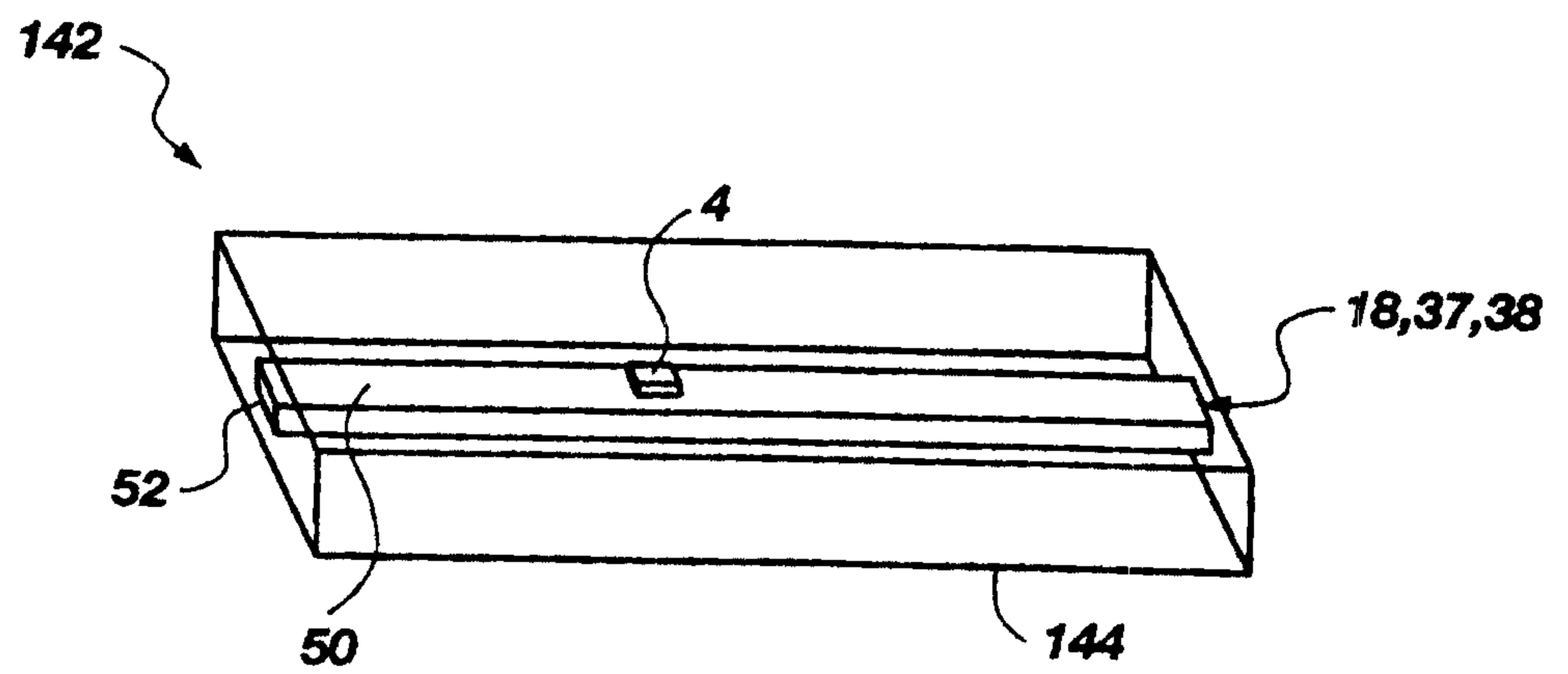
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**Fig. 11****Fig. 12**

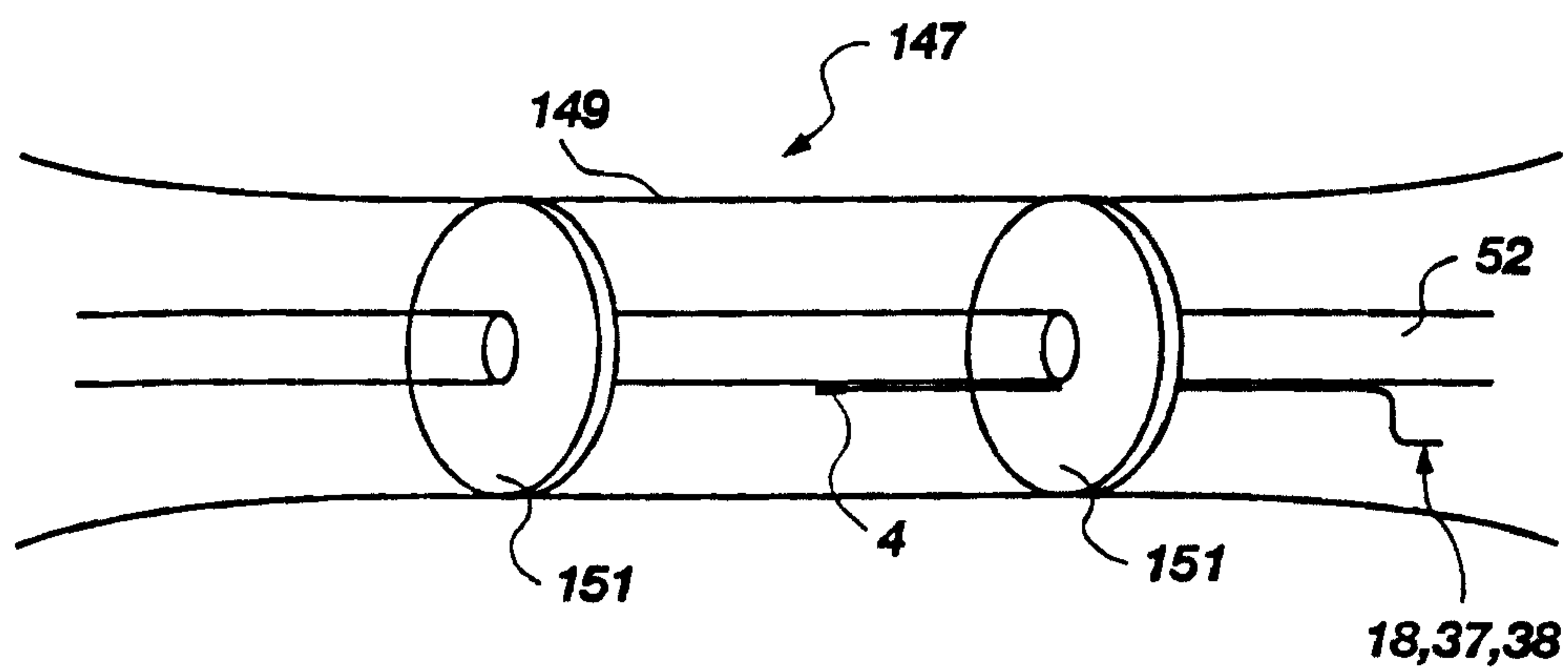
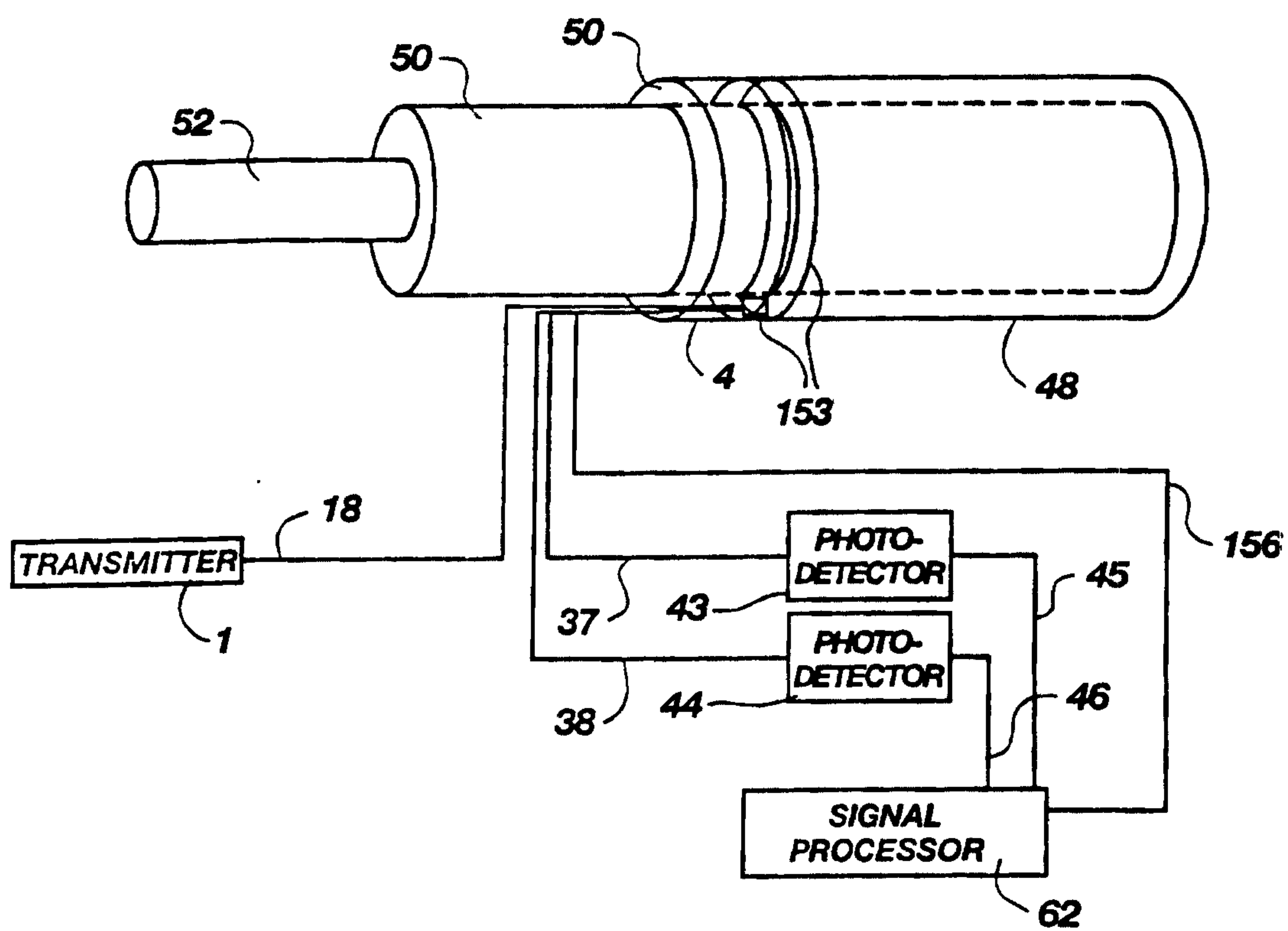
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**Fig. 13****Fig. 14**

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**Fig. 15****Fig. 16**

