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(54) **Titre : TRANSDUCTEURS ACOUSTIQUES OPTIQUES DE FOND DE TROU**
(54) **Title: DOWNHOLE OPTICAL ACOUSTIC TRANSDUCERS**

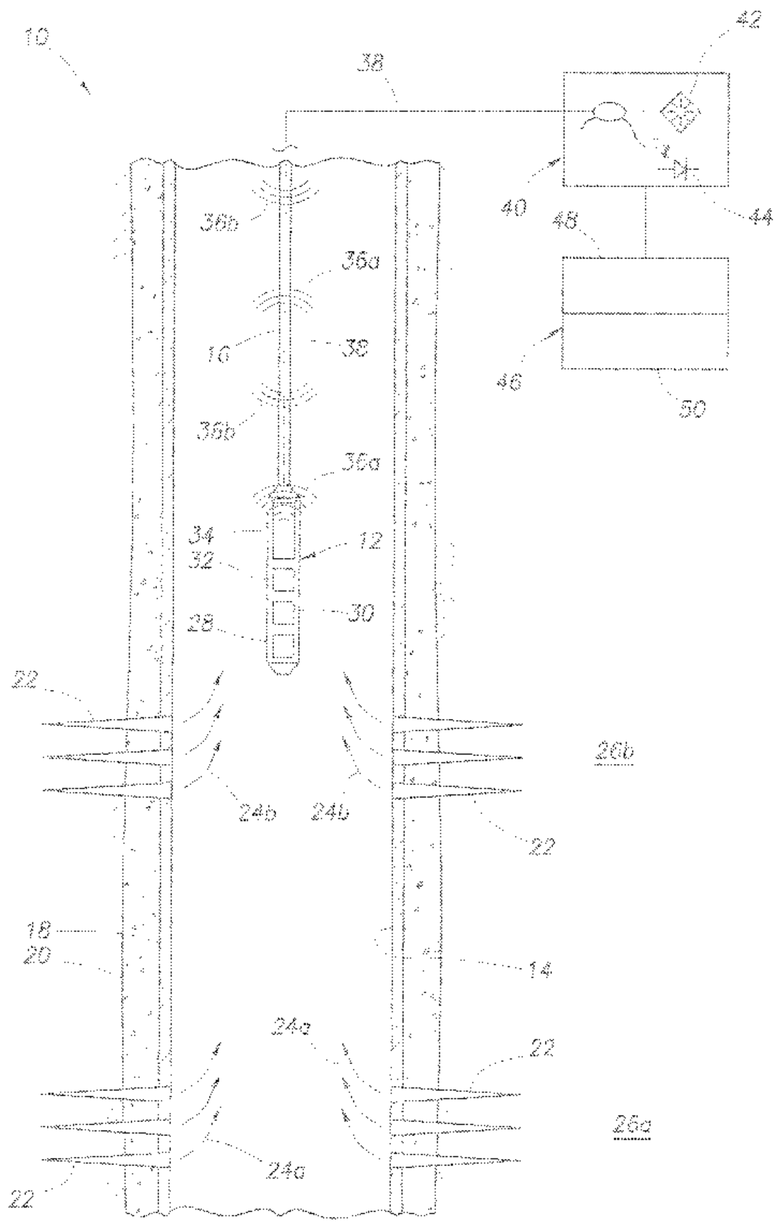


FIG. 1

(57) **Abrégé/Abstract:**
A method of generating an acoustic signal in a subterranean well can include converting optical energy to acoustic energy downhole, thereby transmitting the acoustic signal through a downhole environment. A well system can include an optical acoustic

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(57) **Abrégé(suite)/Abstract(continued):**
transducer disposed in the well and coupled to an optical waveguide in the well, whereby the transducer converts optical energy transmitted via the optical waveguide to acoustic energy. An optical acoustic transducer for use in a subterranean well can include various means for converting optical energy transmitted via an optical waveguide to acoustic energy in the well.

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[Continued on next page]

(54) Title: DOWNHOLE OPTICAL ACOUSTIC TRANSDUCERS

(57) Abstract: A method of generating an acoustic signal in a subterranean well can include converting optical energy to acoustic energy downhole, thereby transmitting the acoustic signal through a downhole environment. A well system can include an optical acoustic transducer disposed in the well and coupled to an optical waveguide in the well, whereby the transducer converts optical energy transmitted via the optical waveguide to acoustic energy. An optical acoustic transducer for use in a subterranean well can include various means for converting optical energy transmitted via an optical waveguide to acoustic energy in the well.

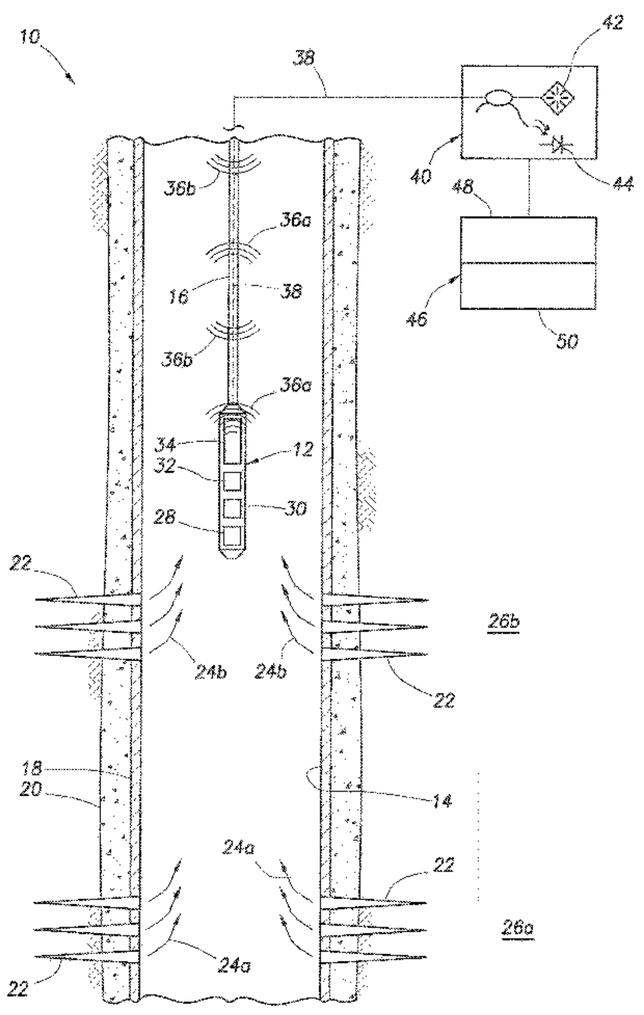


FIG. 1

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DOWNHOLE OPTICAL ACOUSTIC TRANSDUCERS

TECHNICAL FIELD

This disclosure relates generally to equipment utilized and operations performed in conjunction with a subterranean well and, in examples described below, more particularly provides downhole optical acoustic transducers and associated methods.

BACKGROUND

Acoustic energy may be used for various purposes in a well. In some well systems, a distributed acoustic sensing (DAS) system can be used to "listen" to acoustic signals in a well.

Therefore, it will be appreciated that improvements are continuously needed in the art of generating acoustic signals in a well.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a representative partially cross-sectional view of a well system and associated method which can embody principles of this disclosure.

FIG. 2 is a representative partially cross-sectional view of the system and method, wherein a well logging assembly is displaced in a wellbore by a conveyance.

FIGS. 3-11 are representative schematic views of an optical acoustic transducer which may be used in the system and method of FIGS. 1 & 2, and which can embody the principles of this disclosure.

FIG. 12 is a representative partially cross-sectional view of another example of the system and method.

FIG. 13 is a representative schematic view of another optical acoustic transducer which may be used in the system and method, and which can embody the principles of this disclosure.

FIGS. 14 & 15 are representative view of photodiode arrangements which may be used in the system and method.

DETAILED DESCRIPTION

Representatively illustrated in FIG. 1 is a system 10 for use with a well, and an associated method, which system and method can embody principles of this disclosure. However, it should be clearly understood that the system 10 and method are merely one example of an application of the principles of this disclosure in practice, and a wide variety of other examples are possible. Therefore, the scope of this disclosure is not limited at all to the details of the system 10 and method described herein and/or depicted in the drawings.

In the FIG. 1 example, a well logging assembly 12 is conveyed into a wellbore 14 by a conveyance 16. The wellbore 14 is lined with casing 18 and cement 20. Perforations 22 formed through the casing 18 and cement 20 allow fluid 24a,b

to flow into the wellbore 14 from respective formation zones 26a,b penetrated by the wellbore.

In this example, it is desired to determine a flow rate of each of the fluids 24a,b into the wellbore 14 from each of the zones 26a,b. However, in other examples it might be desired to determine a flow rate of injection fluid from the wellbore 14 into each of the zones 26a,b. Thus, the scope of this disclosure is not limited to any particular purpose for a well operation.

Instead, the principles described herein may be used for a variety of different purposes, whether or not the wellbore 14 is lined with casing 18 and cement 20, whether or not perforations 22 are used to flow fluids 24a,b between the wellbore and respective zones 26a,b, etc. These details and others are provided in the FIG. 1 example for purposes of illustration, but the scope of this disclosure is not limited to any of the FIG. 1 details.

The well logging assembly 12 may include conventional logging tools, such as, a casing collar locator 28, a gamma ray tool 30 and sensors 32 (for example, a pressure sensor and a temperature sensor). In addition, the well logging assembly 12 includes a signal generator 34 for generating one or more acoustic signals 36a in the well.

In some examples, the signals 36a could be generated by striking the conveyance 16, casing 18 or other structure. A mechanism could, for example, deliver a hammer impact driven by differential pressure, an electromagnetic solenoid, or other mechanical actuator.

In other examples, the signals 36a could be generated by detonating a series of explosive or other exothermic devices in the well. Thus, the scope of this disclosure is

not limited to any particular manner of generating the signals 36a.

The signals 36a are preferably reflected in the well, for example, at a fluid/air or fluid/metal interface or any interface in the well with an abrupt change in acoustic impedance. Reflected signals 36b travel in the wellbore 14 in a direction opposite to that of the signals 36a generated by the signal generator 34.

For simplicity of illustration and explanation, FIG. 1 depicts the signals 36a travelling upwardly from the signal generator 34, and the reflected signals 36b travelling downwardly in the wellbore 14. However, in practice, the signals 36a would travel in both directions through the wellbore 14 from the signal generator 34, and the reflected signals 36b also travel in both directions, and can be reflected from any surface or other impedance change.

Acoustic signals 36a can be generated, for example, by impacting one component against another, by energizing one or more piezoelectric elements, etc. The scope of this disclosure is not limited to any particular way of generating the signals 36a.

As mentioned above, the conveyance 16 is used to convey the well logging assembly 12 into the well. However, the conveyance 16 also includes a component of the assembly 12, in the form of an optical waveguide 38 (such as, a single and/or multi-mode optical fiber or optical ribbon).

Although only one optical waveguide 38 is depicted in FIG. 1, any number of optical waveguides may be used, as desired. In addition, the conveyance 16 could include various other types of lines, such as, electrical conductors and fluid conduits. The scope of this disclosure is not

limited to any particular number, combination, configuration or arrangement of lines in the conveyance 16.

The conveyance 16 may be in the form of a cable with suitable strength, temperature resistance, chemical resistance and protection for the optical waveguide 38. The cable could comprise stranded cable or cable made from small diameter (e.g., ¼ in. diameter) metal tubing or control line, with the optical waveguide 38 inside the line.

In some examples, the conveyance 16 could be in the form of a coiled tubing (e.g., a substantially continuous tubular string, typically stored on a reel), with the optical waveguide 38 positioned inside, in a wall of, and/or exterior to, the coiled tubing. The scope of this disclosure is not limited to any particular form of the conveyance 16, or to any particular position of the optical waveguide 38 with respect to the conveyance.

An optical interrogator 40 is coupled to the optical waveguide 38. The interrogator 40 includes a light source 42 (such as, an infrared laser) and an optical detector 44 (such as, a photodiode or other photo-detector).

The interrogator 40 is used to determine at least one parameter as distributed along the optical waveguide 38. This is accomplished by launching light from the source 42 into the optical waveguide 38 and detecting light backscattered in the optical waveguide.

In one technique known to those skilled in the art as distributed acoustic sensing (DAS), acoustic energy distributed along the optical waveguide 38 can be measured by detecting coherent Rayleigh backscattering in the waveguide. In this manner, the signals 36a and their reflections 36b can be effectively tracked as they travel along the waveguide 38 in the well.

In another technique, an array of weak fiber Bragg gratings or other artificially introduced reflectors can be used with the optical waveguide 38 to detect acoustic signals along the waveguide.

Velocities of the signals 36a and their reflections 36b can be readily determined using the DAS interrogator 40, for example, by dividing displacement of the signals by elapsed time. Using this information, with the system 10 configured as depicted in FIG. 1, an acoustic velocity in the commingled fluids 24a,b can be determined, as well as a velocity of the commingled fluids through the wellbore 14.

$$V_w = V_a + V_f \quad (1)$$

and:

$$V_o = V_a - V_f \quad (2)$$

where V_w is the velocity of a signal traveling with the flow of fluid (in the FIG. 1 example, the generated signal 36a), V_o is the velocity of a signal traveling opposite the flow of fluid (in the FIG. 1 example, the reflected signal 36b), V_a is the acoustic velocity in the commingled fluids 24a,b, and V_f is the velocity of the fluids through the wellbore 14. Solving the above linear equations yields:

$$V_a = (V_w + V_o)/2 \quad (3)$$

and, thus, the acoustic velocity V_a is simply the average of the velocities of the generated signal 36a and the reflected signal 36b in the FIG. 1 example. In addition:

$$V_f = (V_w + V_o)/2 - V_o = V_w - (V_w + V_o)/2 \quad (4)$$

gives the velocity V_f of the fluids 24a,b through the wellbore 14. Volumetric flow rate equals fluid velocity times cross-sectional area, so the flow rate of the fluids 24a,b can also be readily determined.

If Equation 4 yields a negative number for the velocity V_f, this is an indication that the fluid is flowing in an opposite direction to that assumed when applying values to the variables in Equations 1-4. The principles of this disclosure are applicable no matter whether a fluid flows with or in an opposite direction to a signal 36a generated by the signal generator 34, and no matter whether a fluid flows with or in an opposite direction to a reflected signal 36b.

The interrogator 40 can be connected to a control system 46 (including, for example, a processor 48, memory 50, software, etc.) for controlling operation of the interrogator, recording measurements, calculating acoustic velocities and fluid velocities, displaying results, etc.

In the configuration depicted in FIG. 1, the system 10 can be used to determine the flow rate of the commingled fluids 24a,b, as well as characteristics (e.g., pressure, temperature, acoustic velocity, etc.) of the commingled fluids in the wellbore 14. However, by positioning the assembly 12 below the lower set of perforations 22, as depicted in FIG. 2, flow rates of each of the fluids 24a,b can be readily determined. This is so, because the system 10 is capable of detecting the velocities of the signals 36a and their reflections 36b as distributed along the optical waveguide 38 in the wellbore 14.

Thus, in a section of the wellbore 14 below the lower set of perforations 22 (where there is substantially no flow), the velocities of the signals 36a and their reflections 36b will be the same and, according to Equation (3) above, will equal the acoustic velocity V_a in the fluid present in that section of the wellbore. In a section of the wellbore 14 between the lower and upper sets of perforations

22 (where only the fluid 24a flows), the velocity of the fluid 24a and the acoustic velocity in that fluid can be readily determined. In a section of the wellbore 14 above the upper set of perforations 22 (where the commingled fluids 24a,b flow), the velocity of the commingled fluids and the acoustic velocity in those fluids can be readily determined, as described above. Knowing the volumetric flow rate from the lower set of perforations 22, and the combined flow rate of the fluids 24a,b, one can readily determine a contribution to flow from the upper set of perforations via subtraction.

Therefore, it will be appreciated that, with the well logging assembly 12 positioned as depicted in FIG. 2, acoustic velocities and fluid velocities at each location in the wellbore 14 traversed by the optical waveguide 38 can be readily determined. This makes it unnecessary to relocate the assembly 12 to each position in which it is desired to determine a flow rate (e.g., as is the case with conventional flowmeters).

Instead, the assembly 12 can simply be positioned so that the optical waveguide 38 traverses all of the sections of the wellbore 14 of interest, the signal generator 34 can be operated to produce the signals 36a (and, consequently, their reflections 36b), and the interrogator 40 can quickly be used to measure acoustic energy along the optical waveguide. This consumes much less time as compared to conventional well logging techniques and, thus, is much more economical in practice.

The acoustic velocity V_a in a fluid composition depends on the fluids in the composition and the compliance of the pipe *walls* or conduit *walls* containing the fluid. Because the pipe walls or conduit walls are not infinitely stiff,

the speed of sound in the system is reduced in a quantifiable way. (see Robert McKee and Eugene "Buddy" Broerman, "Acoustics in Pumping Systems", 25th International Pump User Symposium (2009)).

If one knows the acoustic velocity of the fluid composition and the pipe wall compliance(s) (readily calculated from pipe parameters such as the elasticity modulus of the steel pipe, the inside pipe diameter and the pipe wall thickness), the fluids in the composition (for example, an oil/water ratio) can be readily estimated.

In order to infer the composition of the fluid (oil, water, or the fractions of oil and water), the pipe compliance is very important. Pipe compliance can reduce the speed of sound in the pipe by as little as few percent all the way up to 50 percent or more.

Pipe compliance of a steel pipe is caused by not having infinitely stiff walls. It causes the acoustic wave traveling down the pipe to move slower than it would in a pipe with infinitely stiff walls.

FIGS. 3-8 illustrate various examples of how, in a downhole environment (e.g., in the well of FIG. 1, in another wellbore, etc.), optical energy can be converted to electrical energy, which can be stored and controllably released, to generate the acoustic signals 36a. However, it should be clearly understood that it is not necessary for the optical energy to be first converted to electrical energy, and then converted to acoustic energy in the transducer 34. In other examples, the optical energy could be converted to thermal energy (e.g., by directing light transmitted via the optical waveguide 34 onto a black body, which is thereby heated, etc.), and the thermal energy could be used to generate the acoustic signals 36a (e.g., using a

heat engine, such as a Stirling engine). Thus, the scope of this disclosure is not limited to any particular series of energy conversion steps in the transducer 34.

FIG. 3 depicts a representative circuit diagram for the transducer 34. A photodiode 52 is connected to a step up transformer 54. The photodiode 52 is illuminated with pulsed light 56 carried downhole over the optical waveguide 38.

Voltage generated in the photodiode 52 from the incident light 56 is input into the transformer 54, where it may be stepped up or merely isolated from the photodiode. *C1*, *C2*, *D1* and *D2* make up a well-known alternating current to direct current (AC to DC) voltage doubler 58. DC voltage *Vout* across at an output of the voltage doubler 58 will be roughly twice an AC amplitude output from the transformer 54. If higher voltage is required, the turns-ratio of the transformer 54 can be altered and/or additional stages of voltage doublers 58 may be used.

An oscillator 60 is connected to the voltage doubler 58. The oscillator 60 is used to produce a desired acoustic wave form (amplitude, frequency, etc.) from an electrical to acoustic transducer 62. The acoustic signals 36 are propagated from the electrical to acoustic transducer 62 in the FIG. 3 example.

A suitable electrical to acoustic transducer could comprise one or more piezoelectric elements, a solenoid which drives a mass to strike another structure, etc. The scope of this disclosure is not limited to use of any particular type of electrical to acoustic transducer.

In FIG. 4, another example of the optical to acoustic transducer 34 is depicted. In this example, two voltage doublers 58 (effectively a voltage quadrupler) are used.

Note that, if a sufficient number of voltage doublers 58 is used, the step up transformer 54 may not be required.

Indeed, the transformer 54 and the voltage doubler 58 are only two examples of voltage increasers 64 (see FIGS. 6-9) which may be used to increase a voltage output by the photodiode 52. The scope of this disclosure is not limited to use of any particular type of voltage increaser.

There may be circumstances where one would want to limit the optical signals transmitted via the waveguide 38 that cause the circuit of FIG. 4 to generate *Vout*. For example, multiple circuits may be illuminated by a single optical waveguide 38, and it may be desired to multiplex the circuits so that one or more selected circuits produce *Vout* without the others doing so. FIG. 5 depicts an example of the transducer 34 which provides security against accidental operation, and/or allows for multiplexing.

In the FIG. 5 example, an optical filter 66 is positioned between the light 56 and the photodiode 52. The filter 66 passes only a narrow range of wavelengths. Only when the specific range of wavelengths that match the pass band of the filter 66 are transmitted from the light source 42 will the circuit produce *Vout*.

In other examples, the photodiode 52 may be selected so that it generates current only in response to a certain range of wavelengths. Thus, the scope of this disclosure is not limited to any particular way of preventing the circuit from producing *Vout* when certain preselected wavelengths of light 56 are not transmitted.

FIG. 5 also depicts an additional capacitor, *Cf* in series with a primary winding of the transformer 54, forming an LC filter with resonance frequency equal to $\omega = 1/\sqrt{LC_f}$

radians/second where L is the effective inductance of the transformer. This filter prevents the flow of current into the transformer 54 when the pulses illuminating the photodiode 52 are not at the resonant frequency. Other types of electric filters and filter topologies may be used to determine a light 56 pulse repetition rate required to activate a particular electrical power converter. Thus, wavelength division multiplexing and/or pulse frequency multiplexing can be added with only minor changes to the circuit.

In addition to providing the ability to multiplex multiple circuits on an optical waveguide and selectively operate one or more desired circuits independently, the wavelength or pulse frequency selective circuits described here may serve as a safety feature. For example, if one desired to use optical power to trigger an explosive device in a well (such as, a perforating gun, a seismic charge, etc.), one could combine features described here, so that the device would not be detonated, unless light with a specified wavelength is modulated with a specified frequency for a specified time period via an optical fiber in the well.

In the above examples, pulsed optical power is converted into DC voltage, however, the electrical to acoustic transducer 62 could instead be operated with short, high power electrical pulses. In order to generate electrical pulses, the circuit can be modified as shown in FIG. 6.

In FIG. 6, a voltage increaser 64 is depicted as representing any type of voltage increaser. For example, the voltage doubler 58, the step up transformer 54, any number

or combination of these and/or other types of voltage increasers.

Cout is shown to the right of the voltage increaser 64. The total energy stored in the output capacitor *Cout* is $\frac{1}{2} Cout\, Vout^2$ Joules. Where *Vout* is the voltage across *Cout*, controlled by the output voltage of the photodiode 52, and the configuration of the voltage increaser 64.

The transducer 62 to be supplied with electrical power is connected across *Cout* through a gas discharge tube (GDT) 68, a device that acts as an open switch until it reaches a threshold voltage differential, at which time it acts as a closed switch, dumping the electrical energy stored in *Cout* to the transducer 62 (and optionally via the oscillator 60, as in the FIGS. 3-5 examples). The circuit depicted in FIG. 6 will rapidly deliver the electrical power stored in *Cout* to the transducer 62 whenever the voltage across the GDT 68 reaches its threshold. The time to buildup a given threshold voltage across the GDT 68 will depend on the amplitude and frequency of the incident pulses of light 56, the size of capacitor *Cout* and internal leakage and efficiency of the circuit components. This can make timing of the delivery of electrical power through the GDT 68 to the transducer 62 difficult to predict.

This limitation is mitigated by altering the circuit further as shown in FIG. 7. In this example, the GDC 68 is replaced by, for example, a thyristor or SCR which are semiconductor devices which can be thought of as a switchable diode 70. An SCR is a diode with an additional gate. When the current flows into the gate, the diode acts normally, conducting only in the forward biased direction, however, when current is not injected into the gate, the diode does not conduct in either direction.

In order to trigger the circuit shown in FIG. 7 to supply electrical power to the transducer 62 at a desired, controllable instant, a brief pulse of triggering light 72 illuminates a trigger photodiode 74. The trigger photodiode 74 generates a brief pulse of current that causes the SCR (or switchable diode 70) to dump the energy stored in *Cout* to the transducer 62. The operating characteristics of an SCR are such that, even if the trigger pulse light 72 is turned off, the SCR will conduct until all the energy stored in *Cout* is dumped to the transducer 62 (and optionally via the oscillator 60, as in the FIGS. 3-5 examples).

Other techniques may be used to control how the circuit is triggered by the triggering light 72. For example, the triggering light 72 can be controlled or filtered via similar optical and/or electrical filtering techniques described above for controlling when voltage is supplied to the transformer 54 from the photodiode 52. The scope of this disclosure is not limited to any particular way of controlling and/or multiplexing the triggering of the circuit in response to the triggering light 72.

In yet another example depicted in FIG. 8, the SCR is replaced by a three lead neon tube 76 which can be considered as a trigger-able GDT. The triggering photodiode 74 is connected such that its output is used to trigger a gas discharge through the neon tube 76, whereby electrical power is provided to the transducer 62 (and optionally via the oscillator 60, as in the FIGS. 3-5 examples).

Referring additionally now to FIG. 9, another example of the optical acoustic transducer 34 is representatively illustrated. In this example, the light 56 illuminates an optical to electrical transducer 78. Voltage produced by the transducer 78 is input to the voltage increaser 64.

Increased voltage from the voltage increaser 64 is input to the electrical to acoustic transducer 62 via the oscillator 60. Optionally, any of the trigger circuits depicted in FIGS. 6-8 may be used to control when energy stored in *Cout* is dumped to the transducer 62.

The optical to electrical transducer 78 may be any type of transducer capable of converting optical energy to electrical energy. The photodiode 52 is one example of a suitable optical to electrical transducer 78.

Referring additionally now to FIG. 10, the optical to electrical transducer 78 of FIG. 9 is replaced by an optical to heat transducer 80 and a thermal to electrical transducer 82. Voltage output by the transducer 82 is input to the voltage increaser 64.

The optical to thermal transducer 80 may be any type of transducer capable of converting optical energy to thermal energy. For example, the light 56 could illuminate a black body, thereby generating thermal energy.

The thermal to electrical transducer 82 may be any type of transducer capable of converting heat energy to electrical energy. For example, a thermopile, thermocouple or other heat to electrical transducer 82 can receive the heat generated by the transducer 80 and convert that heat to electrical energy for input to the voltage increaser 64.

Referring additionally now to FIG. 11, another example of the optical to acoustic transducer 34 is representatively illustrated. In this example, heat generated by the optical to thermal transducer 80 is input to a thermal to mechanical transducer 84. Mechanical energy is input to a mechanical to acoustic transducer 86 to generate the signals 36.

The thermal to mechanical transducer 84 may be any type of transducer capable of converting heat energy to mechanical energy. For example, a suitably configured Stirling engine could be used for the transducer 84.

The mechanical to acoustic transducer 86 may be any type of transducer capable of utilizing mechanical energy to generate the acoustic signals 36. For example, mechanical energy could be used to strike one component against another component and thereby generate stress waves in structures in the well, pressure pulses could be generated with pistons or membranes displaced via mechanical energy, etc.

The acoustic signals 36 could be generated by detonating small explosive charges. The charges could be detonated electrically, for example, or they could be detonated by direct heating as a result of focusing laser energy from the optical waveguide onto an explosive, such as a detonator in close proximity to a main charge, etc.

The acoustic signals 36 could be generated by releasing compressed fluid, or by opening a series of low pressure chambers downhole.

It will, thus, be appreciated that the optical to acoustic transducer 34 can be constructed in a variety of different configurations, and those configurations are not limited to the examples depicted in FIGS. 3-11. It should also be appreciated that a wide variety of different applications for the principles described herein are not limited to the FIGS. 1 & 2 example of the system 10.

In FIG. 12, another example of the system 10 is representatively illustrated, in which the optical to acoustic transducer 34 is positioned in the well external to a tubular string 88. The tubular string 88 could be, for example, a production tubing string, a coiled tubing string,

a completion string, a stimulation string, an injection string, a work string, a liner, etc.

In other examples, the transducer 34 and/or waveguide 38 could be internal to, or positioned in a wall of, the tubular string 88. The transducer 34 and/or waveguide 38 could be internal to, external to, or positioned in a wall of the casing 18, or in the cement 20, etc. The scope of this disclosure is not limited to any particular location of the transducer 34 and/or waveguide 38.

The transducer 34 generates the signals 36, which propagate in opposite directions away from the transducer. The signals 36 can travel through various structures and fluids in the well.

The optical waveguide 38 can be used, as described above, to track the signals 36, and thereby determine properties of fluid 24 in the well. However, the scope of this disclosure is not limited to use of the optical acoustic transducer 34 for determining properties of fluids.

Note that the transducer 34 may be located in any position with respect to the conveyance 16 or tubular string 88 in the above examples. The transducer 34 could be at any location along the conveyance 16 or tubular string 88, and multiple transducers can be spaced apart along the conveyance or tubular string.

Referring additionally now to FIG. 13, another example of the optical to acoustic transducer 34 is representatively illustrated. In this example, the photodiode 52 is part of a photovoltaic converter 90. A suitable photovoltaic converter is available from JDSU (e.g., model PPC-XE) of Milpitas, California USA.

The voltage increaser 64 in this example can comprise a DC to DC converter. A suitable DC to DC converter is available from PICO Electronics, Inc. (e.g., model XA200, with 200v output) of Pelham, New York USA.

The electrical acoustic transducer 62 in this example can comprise a piezoelectric actuator. A suitable piezoelectric actuator is available from MIDE Engineering (e.g., model QP20W) of Medford, Massachusetts USA.

A spark gap 92 may be used to control voltage across the transducer 62. For example, a 150v spark gap is available from Bourns, Inc. (e.g., model 652-2027-1S-SN-LF) of Riverside, California USA.

Referring additionally now to FIGS. 14 & 15, techniques for increasing a voltage or current output of the photodiode 52 in the transducer 34 are representatively illustrated. In FIG. 14 multiple photodiodes 52 are connected in series, in order to increase a voltage output, and in FIG. 15 multiple photodiodes are connected in parallel, in order to increase a current output, to the voltage increaser 64.

An optical coupler 94 can be used to direct the light 56 to each of the photodiodes 52 in the FIGS. 14 & 15 examples. Any number or arrangement of photodiodes 52 may be used (e.g., singles, multiples, in series and/or in parallel), in keeping with the principles of this disclosure.

It may now be fully appreciated that the above disclosure provides significant advancements to the art of generating acoustic signals in wells. In some examples described above, an optical acoustic transducer 34 is used to convert optical energy to acoustic energy, for generating acoustic signals 36 in a well.

A method of generating an acoustic signal 36 in a subterranean well is provided to the art by the above disclosure. In one example, the method can comprise: converting optical energy to acoustic energy downhole, thereby transmitting the acoustic signal 36 through a downhole environment. The downhole environment may include structures (such as casing 18, cement 20, tubular string 88, etc.) and/or fluids 24 in the well.

The converting step can include converting the optical energy to electrical energy downhole. The converting step can further include illuminating an optical to electrical transducer 78 with light transmitted via an optical waveguide 38 downhole.

The converting step can further include converting the electrical energy to the acoustic energy downhole. The converting can also comprise converting the electrical energy to mechanical energy downhole (for example, a solenoid striker or a motor could convert electrical to mechanical energy downhole).

The method may include storing the electrical energy downhole. The method can further include triggering a release of the electrical energy downhole.

The converting step can include converting the optical energy to thermal energy downhole. The converting step can further include converting the thermal energy to the acoustic energy downhole.

The converting can include converting the thermal energy to mechanical energy downhole. The converting step can further include converting the mechanical energy to the acoustic energy downhole.

A well system 10 is also described above. In one example, the system 10 can include an optical acoustic transducer 34 disposed in the well and coupled to an optical waveguide 38 in the well. The transducer 34 converts optical energy transmitted via the optical waveguide 38 to acoustic energy.

The optical acoustic transducer 34 may comprise an optical electrical transducer 78 which converts the optical energy to electrical energy in the well. The optical electrical transducer 78 can be illuminated with light 56 transmitted via the optical waveguide 38 in the well.

The optical acoustic transducer 34 may comprise an electrical acoustic transducer 62 which converts the electrical energy to the acoustic energy in the well.

The electrical energy generated by the optical electrical transducer 78 may be stored in the well. The optical acoustic transducer 34 can release the stored electrical energy in the well.

The optical acoustic transducer 34 may comprise an optical thermal transducer 80 which converts the optical energy to thermal energy in the well. The optical acoustic transducer 34 may further comprise a thermal acoustic transducer which converts the thermal energy to the acoustic energy in the well.

The optical acoustic transducer 34 may comprise a thermal mechanical transducer 84 which converts the thermal energy to mechanical energy in the well. The optical acoustic transducer 34 may comprise a mechanical acoustic transducer 86 which converts the mechanical energy to the acoustic energy in the well. The combined thermal mechanical transducer 84 and mechanical acoustic transducer 86 may be considered a thermal acoustic transducer.

An optical acoustic transducer 34 for use in a subterranean well is also described above. In one example, the optical acoustic transducer 34 includes a means for converting optical energy transmitted via an optical waveguide 38 to acoustic energy in the well.

The converting means may comprise an optical electrical transducer 78 which converts the optical energy to electrical energy in the well. The optical electrical transducer 78 can be illuminated with light 56 transmitted via the optical waveguide 38 in the well.

The converting means may comprise an electrical acoustic transducer 62 which converts the electrical energy to the acoustic energy in the well.

The electrical energy generated by the optical electrical transducer 78 may be stored in the well. The converting means can release the stored electrical energy in the well.

The converting means may comprise an optical thermal transducer 80 which converts the optical energy to thermal energy in the well. The converting means may further comprise a thermal acoustic transducer which converts the thermal energy to the acoustic energy in the well.

The converting means may comprise a thermal mechanical transducer 84 which converts the thermal energy to mechanical energy in the well. The converting means may comprise a mechanical acoustic transducer 86 which converts the mechanical energy to the acoustic energy in the well.

Although various examples have been described above, with each example having certain features, it should be understood that it is not necessary for a particular feature of one example to be used exclusively with that example.

Instead, any of the features described above and/or depicted in the drawings can be combined with any of the examples, in addition to or in substitution for any of the other features of those examples. One example's features are not mutually exclusive to another example's features. Instead, the scope of this disclosure encompasses any combination of any of the features.

Although each example described above includes a certain combination of features, it should be understood that it is not necessary for all features of an example to be used. Instead, any of the features described above can be used, without any other particular feature or features also being used.

It should be understood that the various embodiments described herein may be utilized in various orientations, such as inclined, inverted, horizontal, vertical, etc., and in various configurations, without departing from the principles of this disclosure. The embodiments are described merely as examples of useful applications of the principles of the disclosure, which is not limited to any specific details of these embodiments.

In the above description of the representative examples, directional terms (such as "above," "below," "upper," "lower," etc.) are used for convenience in referring to the accompanying drawings. However, it should be clearly understood that the scope of this disclosure is not limited to any particular directions described herein.

The terms "including," "includes," "comprising," "comprises," and similar terms are used in a non-limiting sense in this specification. For example, if a system, method, apparatus, device, etc., is described as "including" a certain feature or element, the system, method, apparatus,

device, etc., can include that feature or element, and can also include other features or elements. Similarly, the term "comprises" is considered to mean "comprises, but is not limited to."

Of course, a person skilled in the art would, upon a careful consideration of the above description of representative embodiments of the disclosure, readily appreciate that many modifications, additions, substitutions, deletions, and other changes may be made to the specific embodiments, and such changes are contemplated by the principles of this disclosure. For example, structures disclosed as being separately formed can, in other examples, be integrally formed and *vice versa*. Accordingly, the foregoing detailed description is to be clearly understood as being given by way of illustration and example only, the spirit and scope of the invention being limited solely by the appended claims and their equivalents.

WHAT IS CLAIMED IS:

1. A method of generating an acoustic signal in a subterranean well, the method comprising:

converting optical energy to acoustic energy downhole, thereby transmitting the acoustic signal through a downhole environment.

2. The method of claim 1, wherein the converting further comprises converting the optical energy to electrical energy downhole.

3. The method of claim 2, wherein the converting further comprises illuminating an optical to electrical transducer with light transmitted via an optical waveguide downhole.

4. The method of claim 2, wherein the converting further comprises converting the electrical energy to the acoustic energy downhole.

5. The method of claim 2, further comprising storing the electrical energy downhole.

6. The method of claim 2, further comprising triggering a release of the electrical energy downhole.

7. The method of claim 2, wherein the converting further comprises converting the electrical energy to mechanical energy downhole.

8. The method of claim 1, wherein the converting further comprises converting the optical energy to thermal energy downhole.

9. The method of claim 8, wherein the converting further comprises converting the thermal energy to the acoustic energy downhole.

10. The method of claim 8, wherein the converting further comprises converting the thermal energy to mechanical energy downhole.

11. The method of claim 10, wherein the converting further comprises converting the mechanical energy to the acoustic energy downhole.

12. The method of claim 1, wherein the converting further comprises detonating an explosive device.

13. The method of claim 12, wherein the detonating is performed by directing light transmitted via an optical waveguide in the well to the explosive device.

14. A well system, comprising:

an optical acoustic transducer disposed in the well and coupled to an optical waveguide in the well, wherein the transducer converts optical energy transmitted via the optical waveguide to acoustic energy.

15. The system of claim 14, wherein the optical acoustic transducer comprises an optical electrical transducer which converts the optical energy to electrical energy in the well.

16. The system of claim 15, wherein the optical electrical transducer is illuminated with light transmitted via the optical waveguide in the well.

17. The system of claim 15, wherein the optical acoustic transducer further comprises an electrical acoustic transducer which converts the electrical energy to the acoustic energy in the well.

18. The system of claim 15, wherein the electrical energy generated by the optical electrical transducer is stored in the well.

19. The system of claim 18, wherein the optical acoustic transducer releases the stored electrical energy in the well.

20. The system of claim 14, wherein the optical acoustic transducer comprises an optical thermal transducer which converts the optical energy to thermal energy in the well.

21. The system of claim 20, wherein the optical acoustic transducer further comprises a thermal acoustic transducer which converts the thermal energy to the acoustic energy in the well.

22. The system of claim 20, wherein the optical acoustic transducer further comprises a thermal mechanical transducer which converts the thermal energy to mechanical energy in the well.

23. The system of claim 22, wherein the optical acoustic transducer further comprises a mechanical acoustic transducer which converts the mechanical energy to the acoustic energy in the well.

24. An optical acoustic transducer for use in a subterranean well, the optical acoustic transducer comprising:

means for converting optical energy transmitted via an optical waveguide to acoustic energy in the well.

25. The optical acoustic transducer of claim 24, wherein the converting means comprises an optical electrical transducer which converts the optical energy to electrical energy in the well.

26. The optical acoustic transducer of claim 25, wherein the optical electrical transducer is illuminated with light transmitted via the optical waveguide in the well.

27. The optical acoustic transducer of claim 25, wherein the converting means further comprises an electrical acoustic transducer which converts the electrical energy to the acoustic energy in the well.

28. The optical acoustic transducer of claim 25, wherein the electrical energy generated by the optical electrical transducer is stored in the well.

29. The optical acoustic transducer of claim 28, wherein the converting means releases the stored electrical energy in the well.

30. The optical acoustic transducer of claim 24, wherein the converting means comprises an optical thermal transducer which converts the optical energy to thermal energy in the well.

31. The optical acoustic transducer of claim 30, wherein the converting means further comprises a thermal acoustic transducer which converts the thermal energy to the acoustic energy in the well.

32. The optical acoustic transducer of claim 30, wherein the converting means further comprises a thermal mechanical transducer which converts the thermal energy to mechanical energy in the well.

33. The optical acoustic transducer of claim 32, wherein the converting means further comprises a mechanical acoustic transducer which converts the mechanical energy to the acoustic energy in the well.

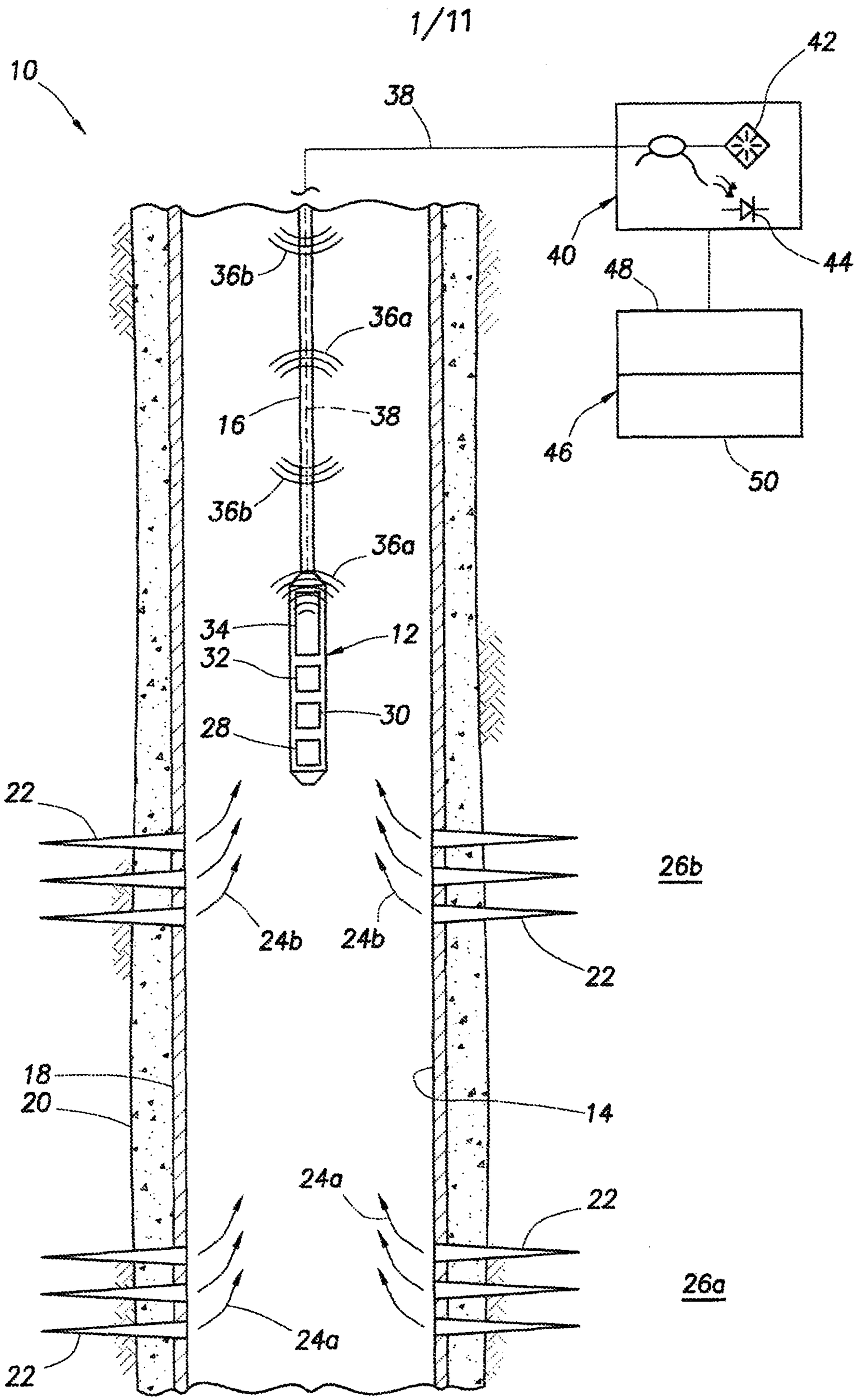

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FIG. 1

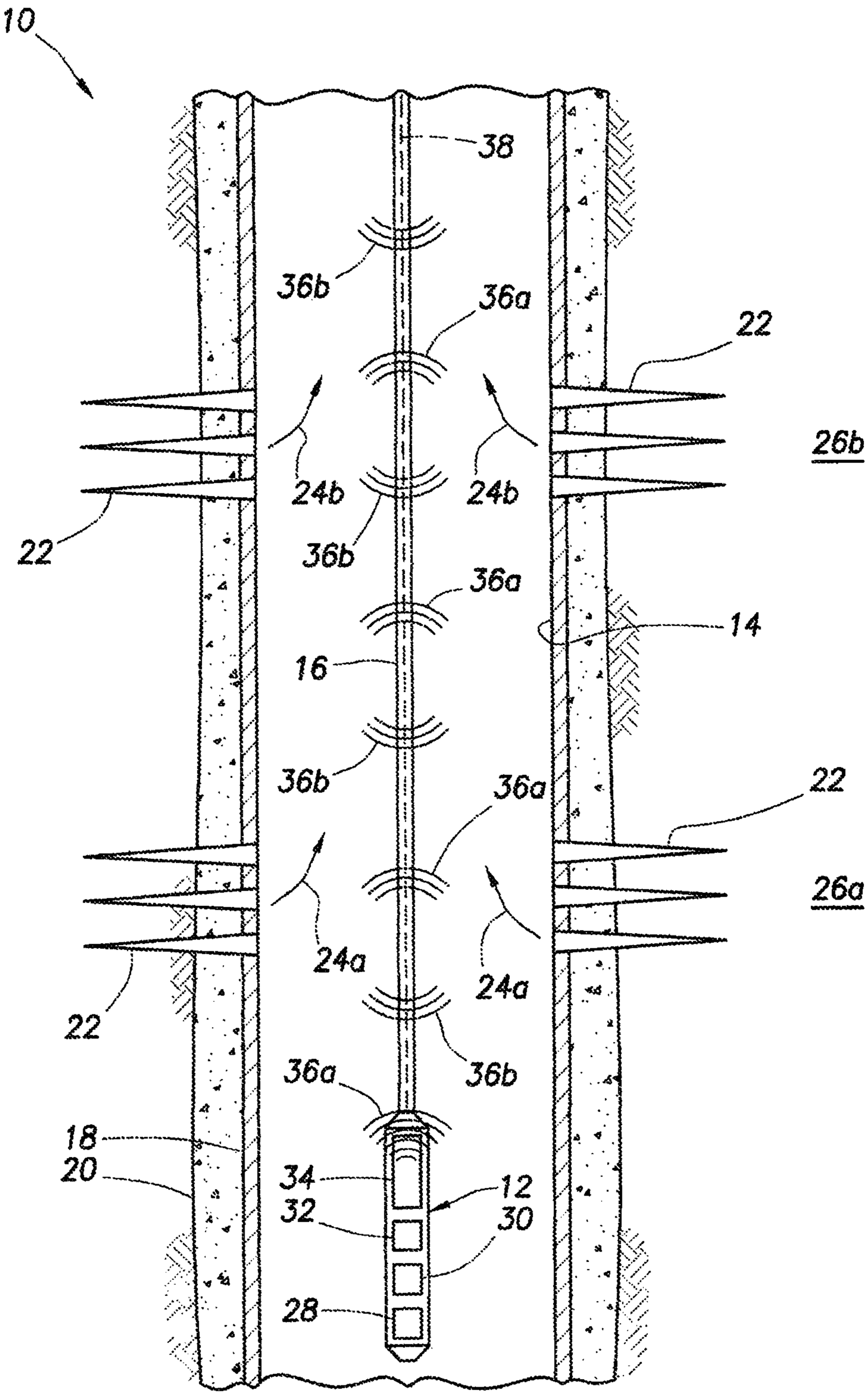

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FIG.2

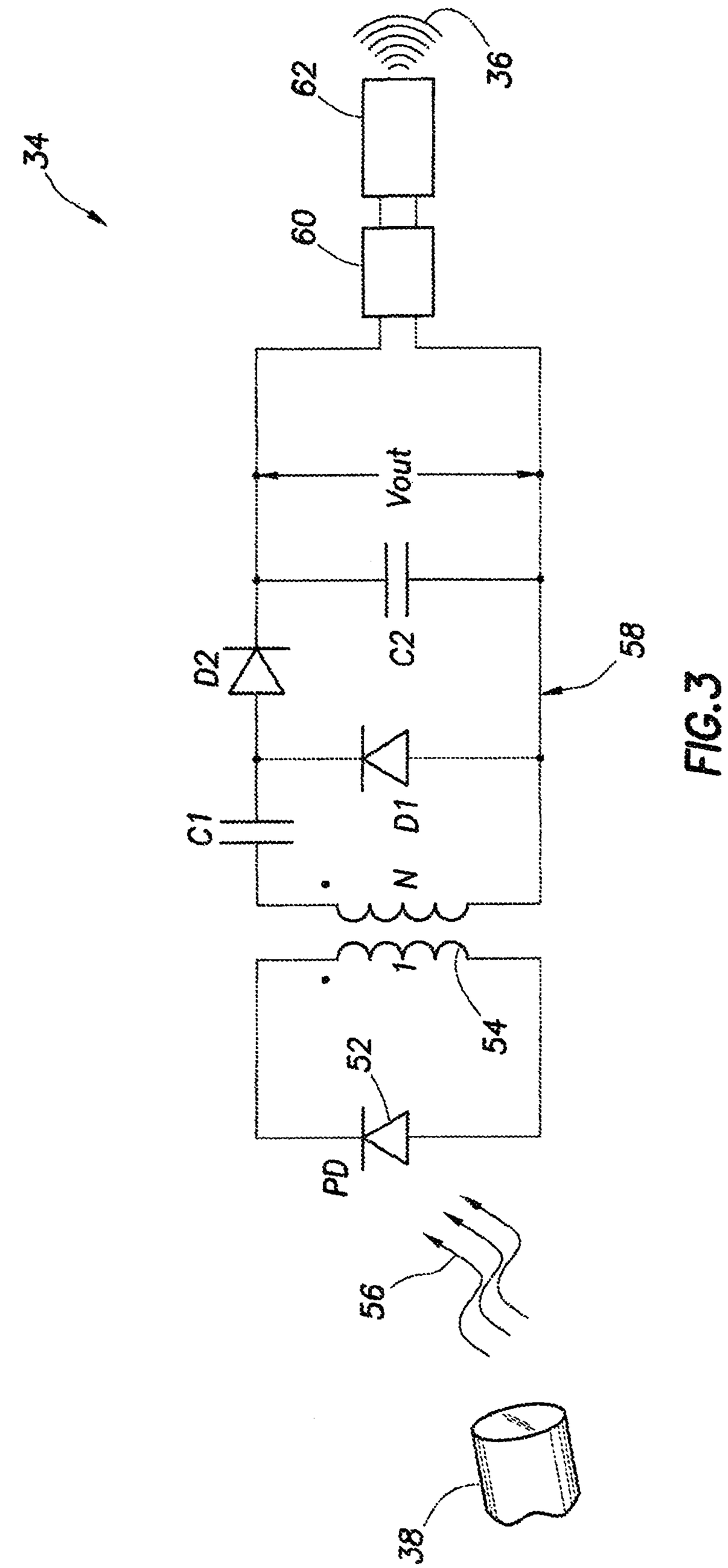


FIG.3

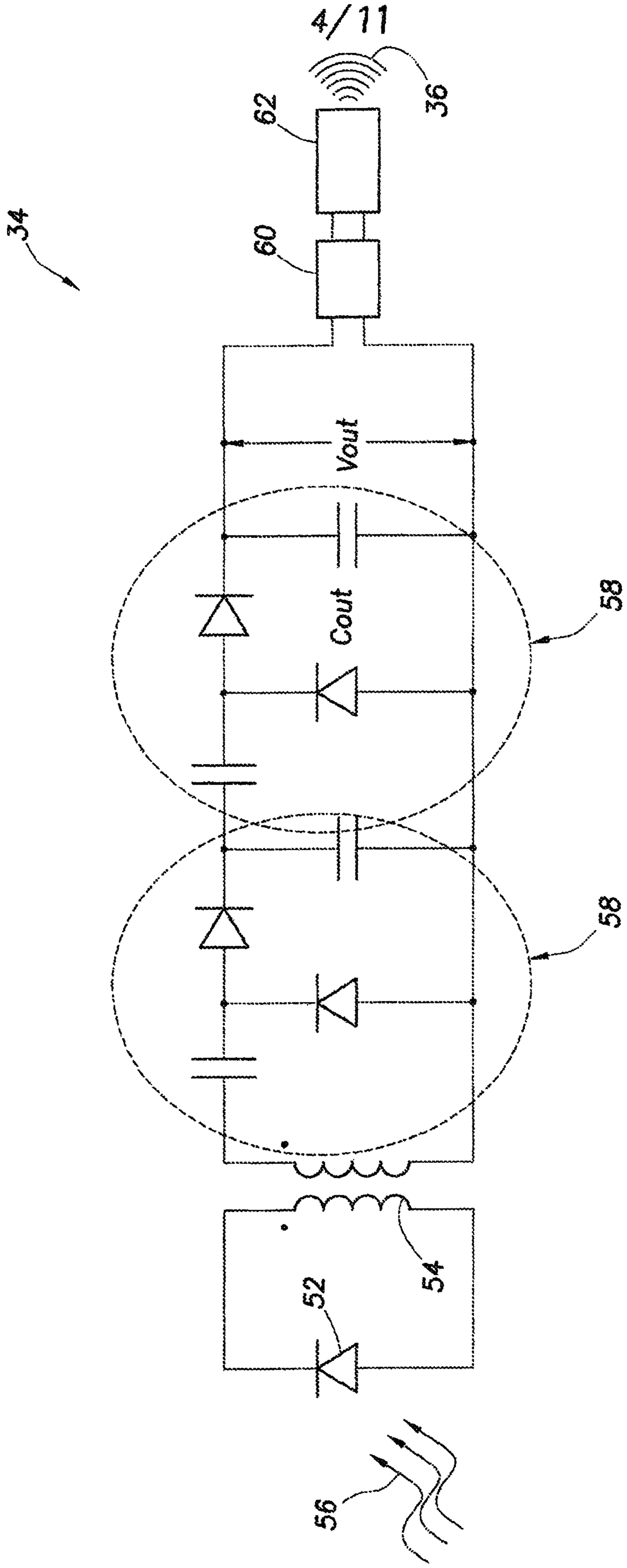


FIG.4

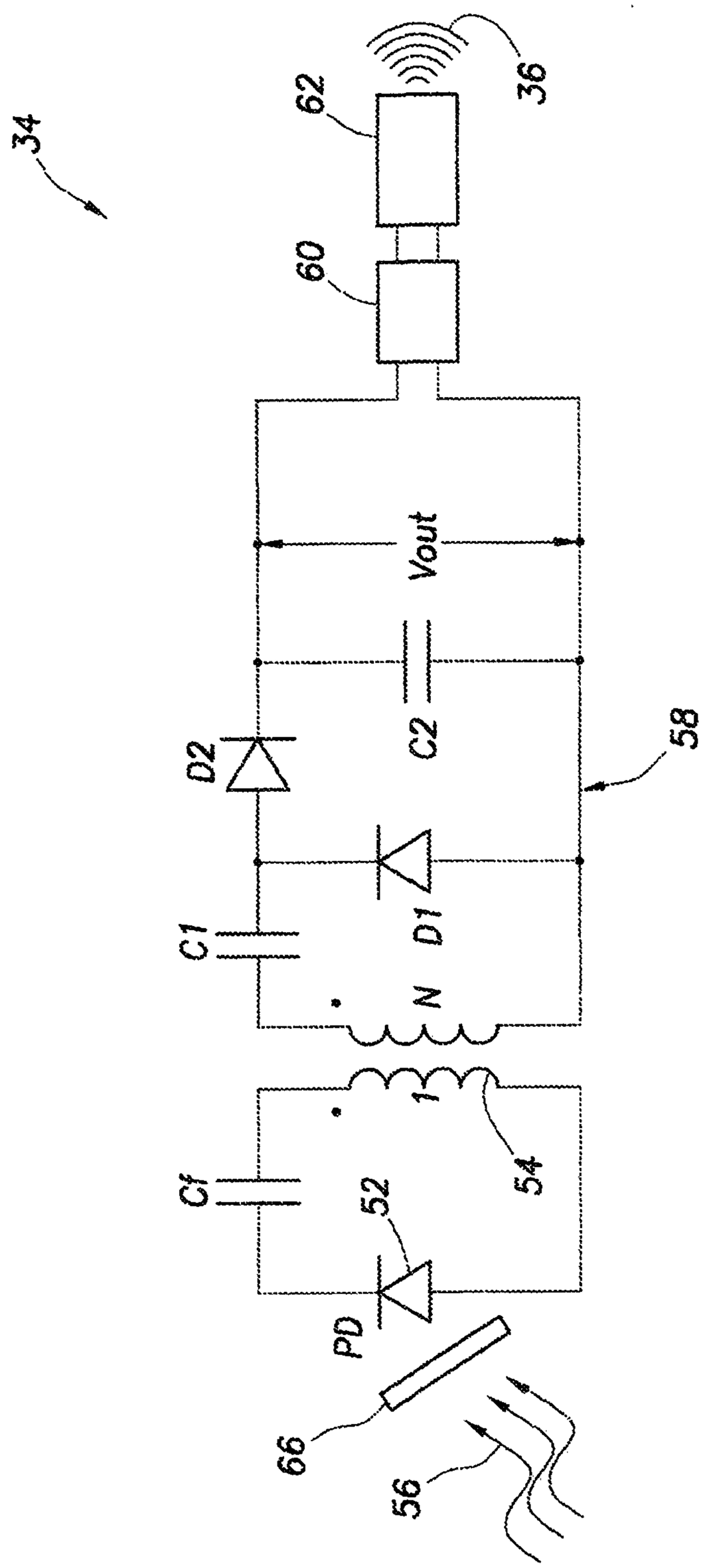


FIG.5

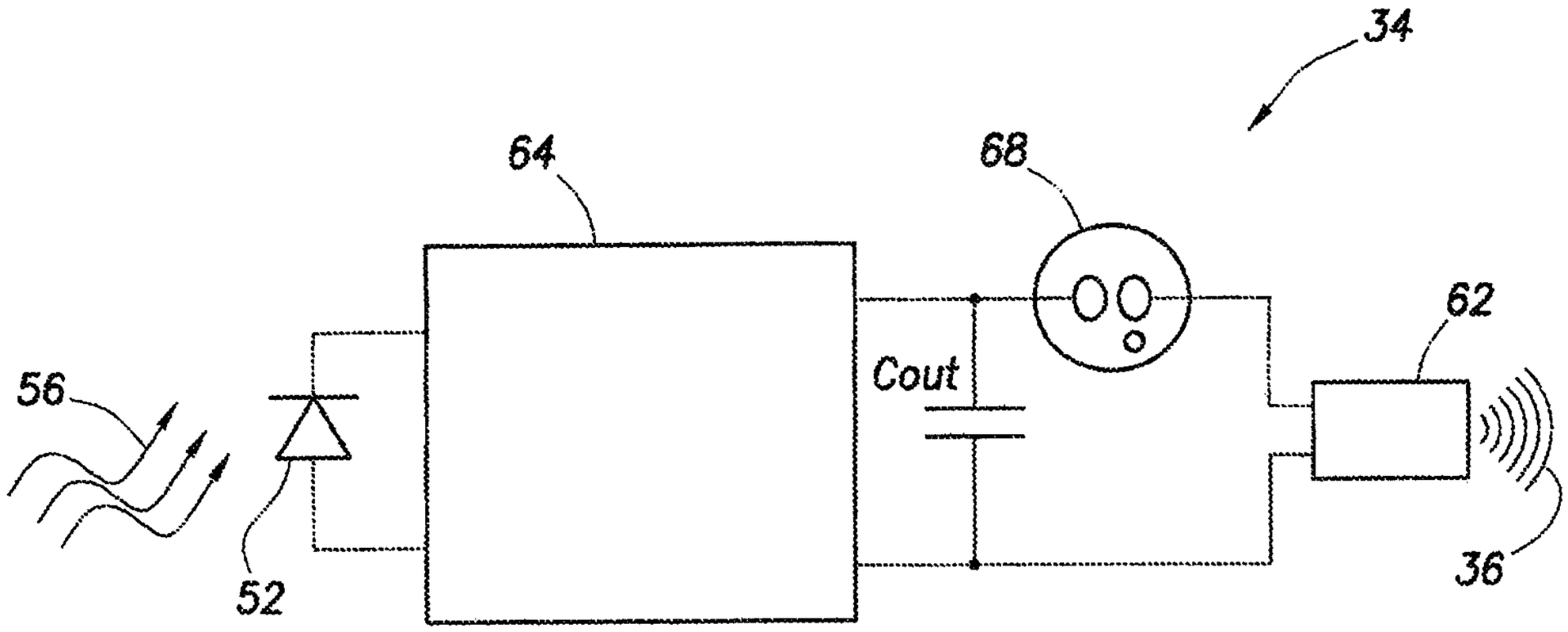


FIG.6

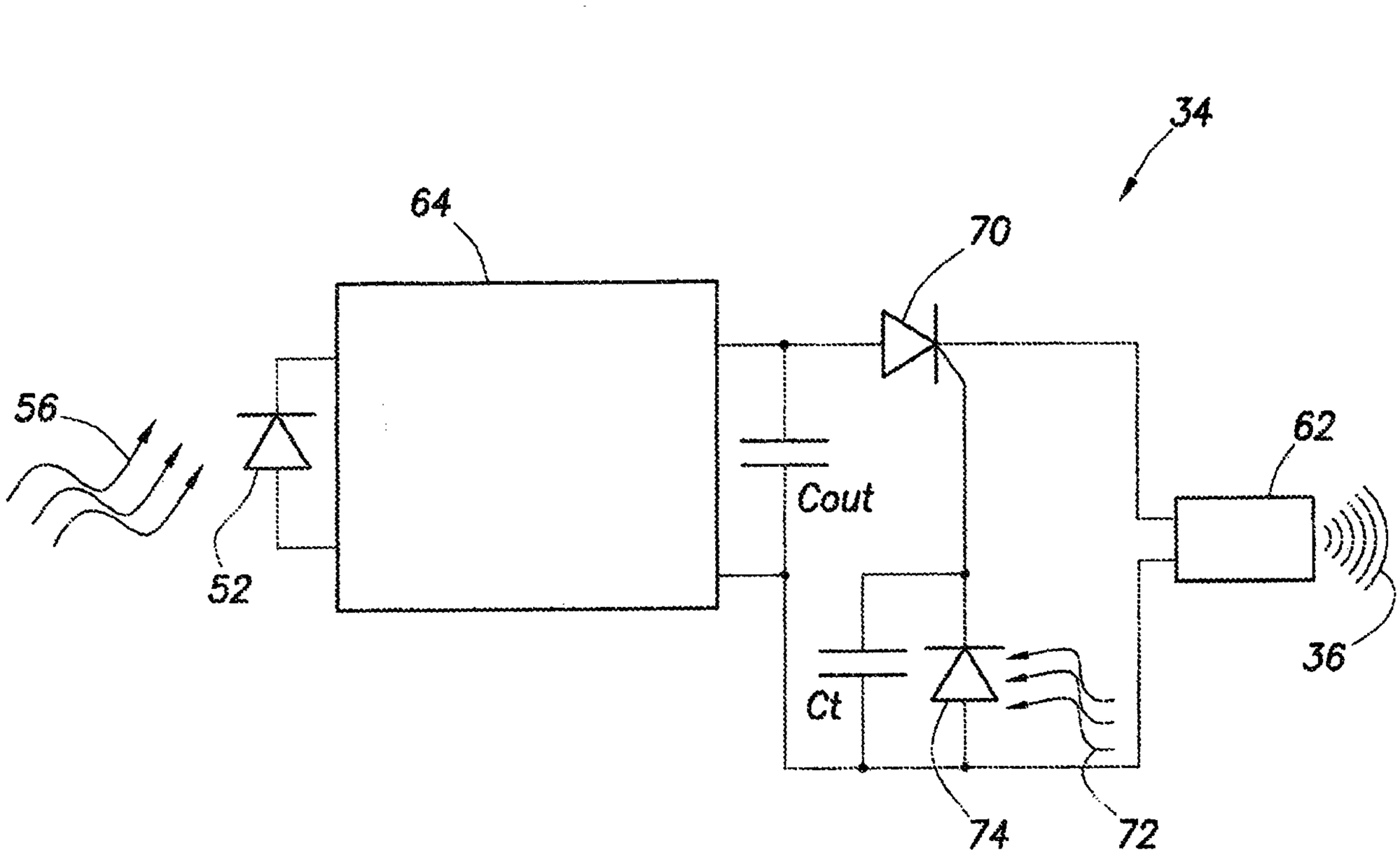


FIG.7

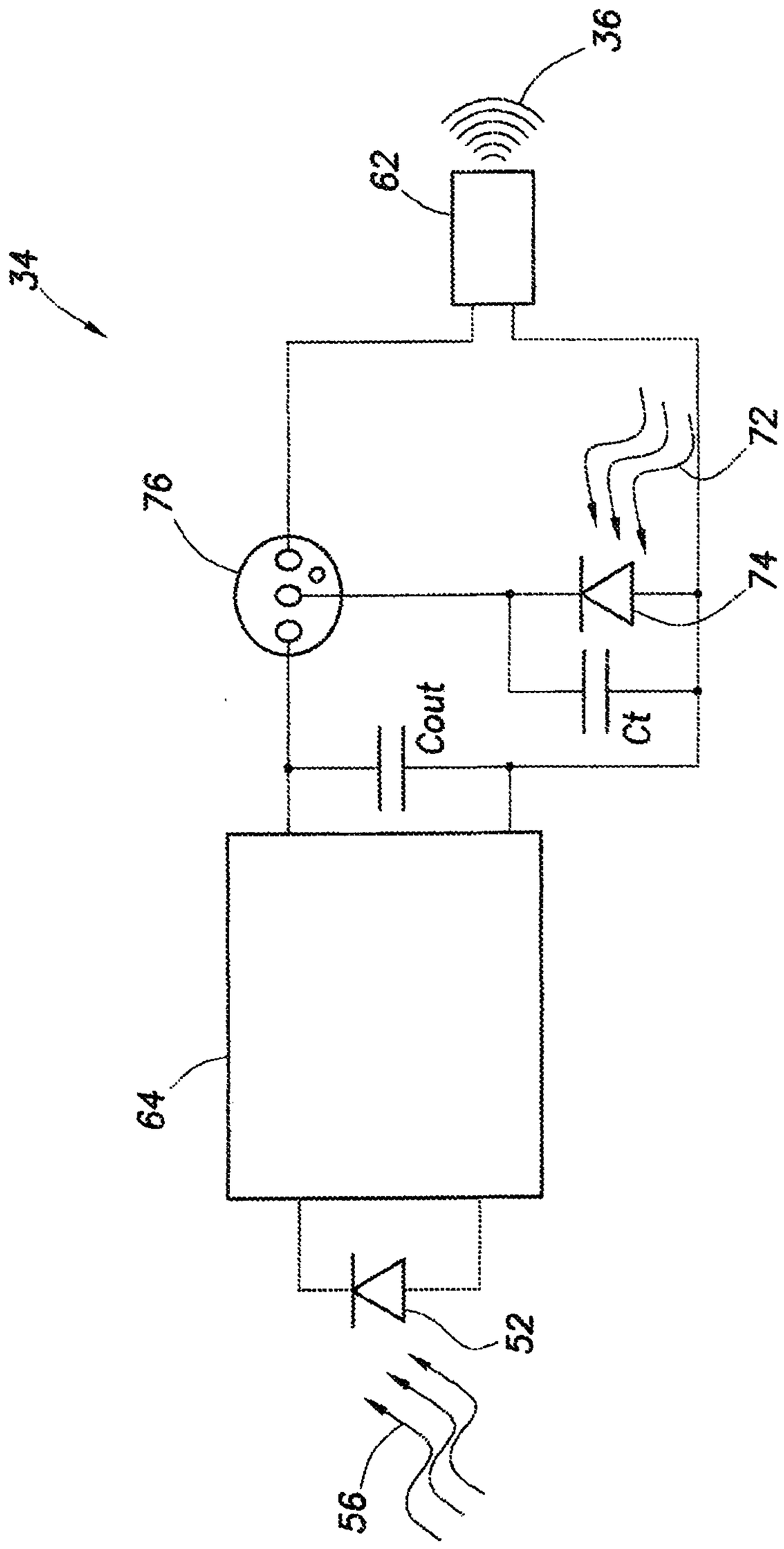


FIG.8

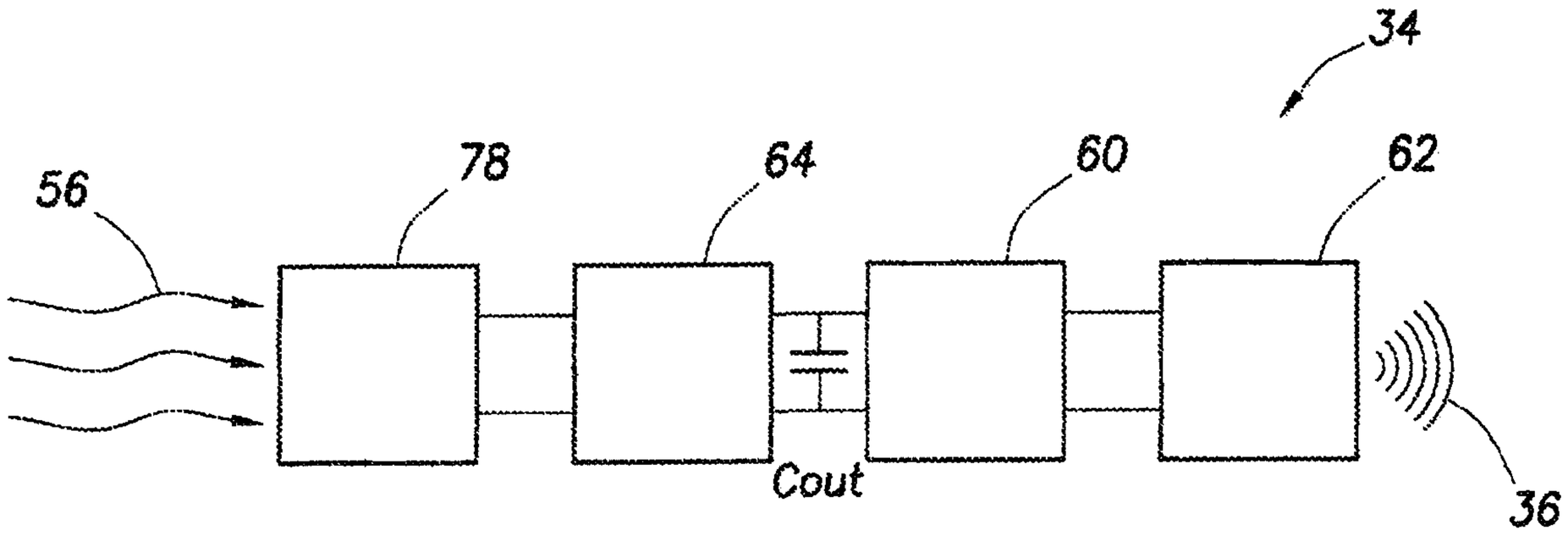


FIG.9

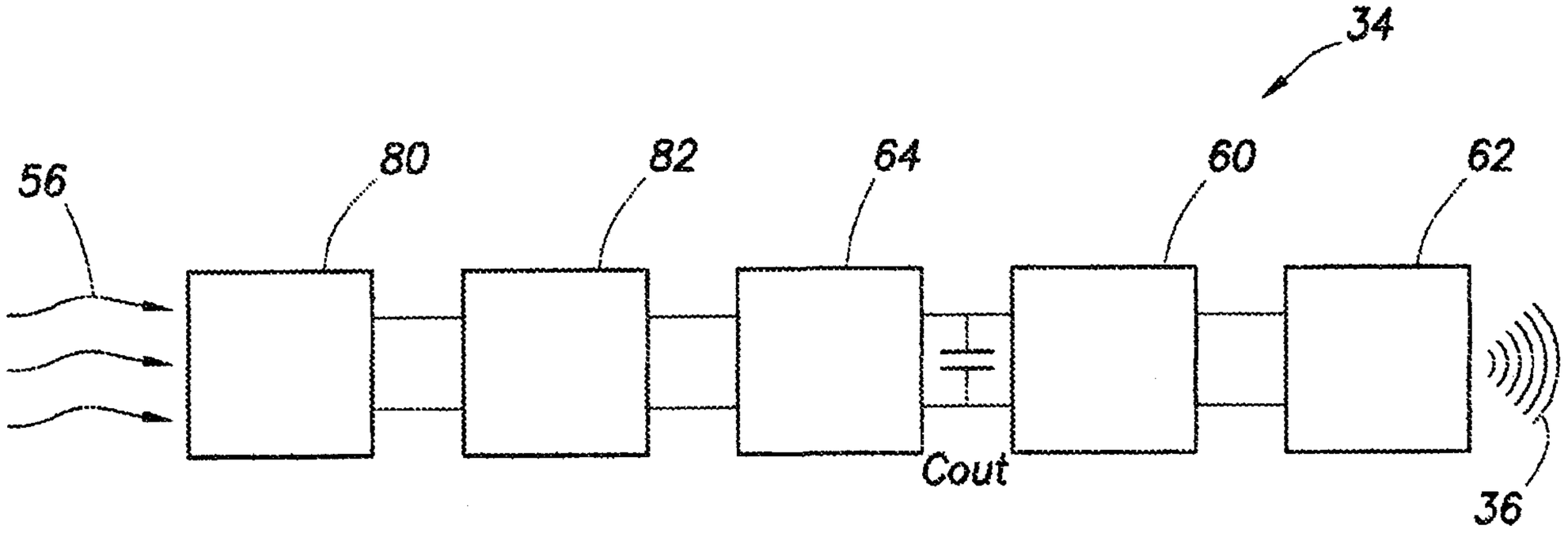


FIG.10

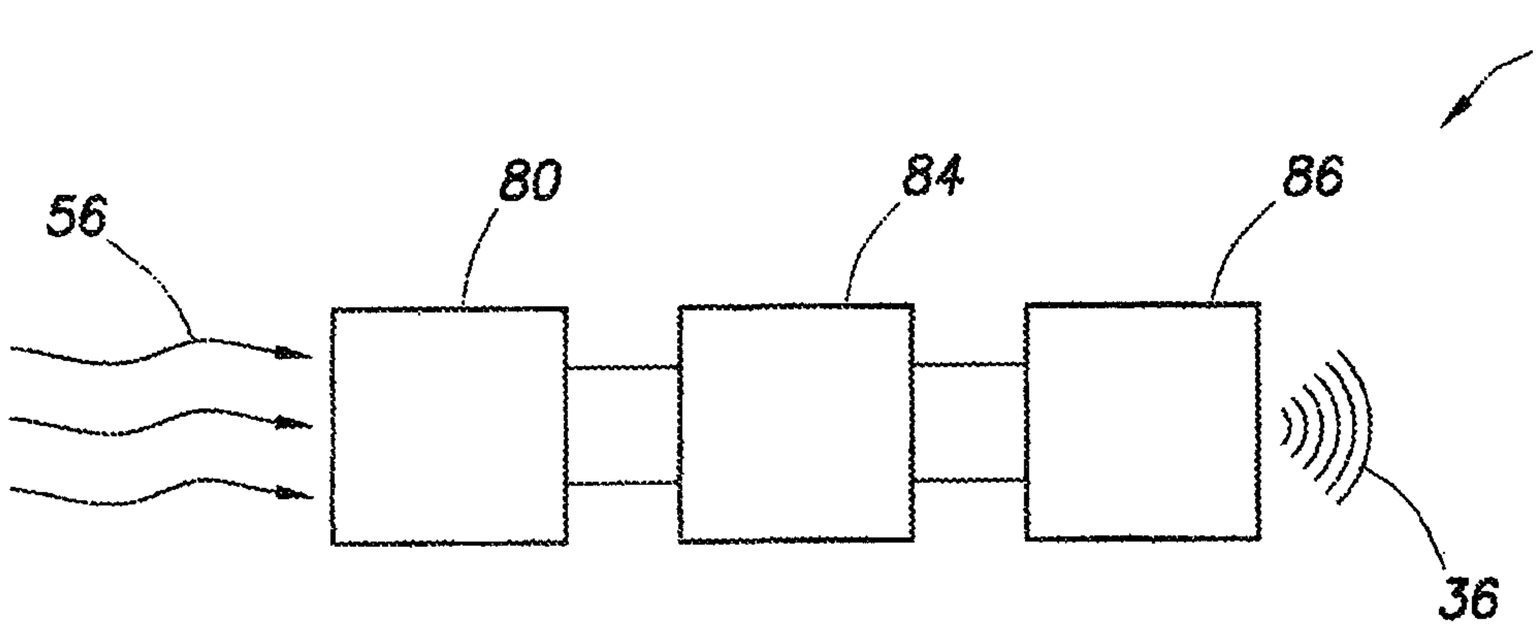


FIG.11

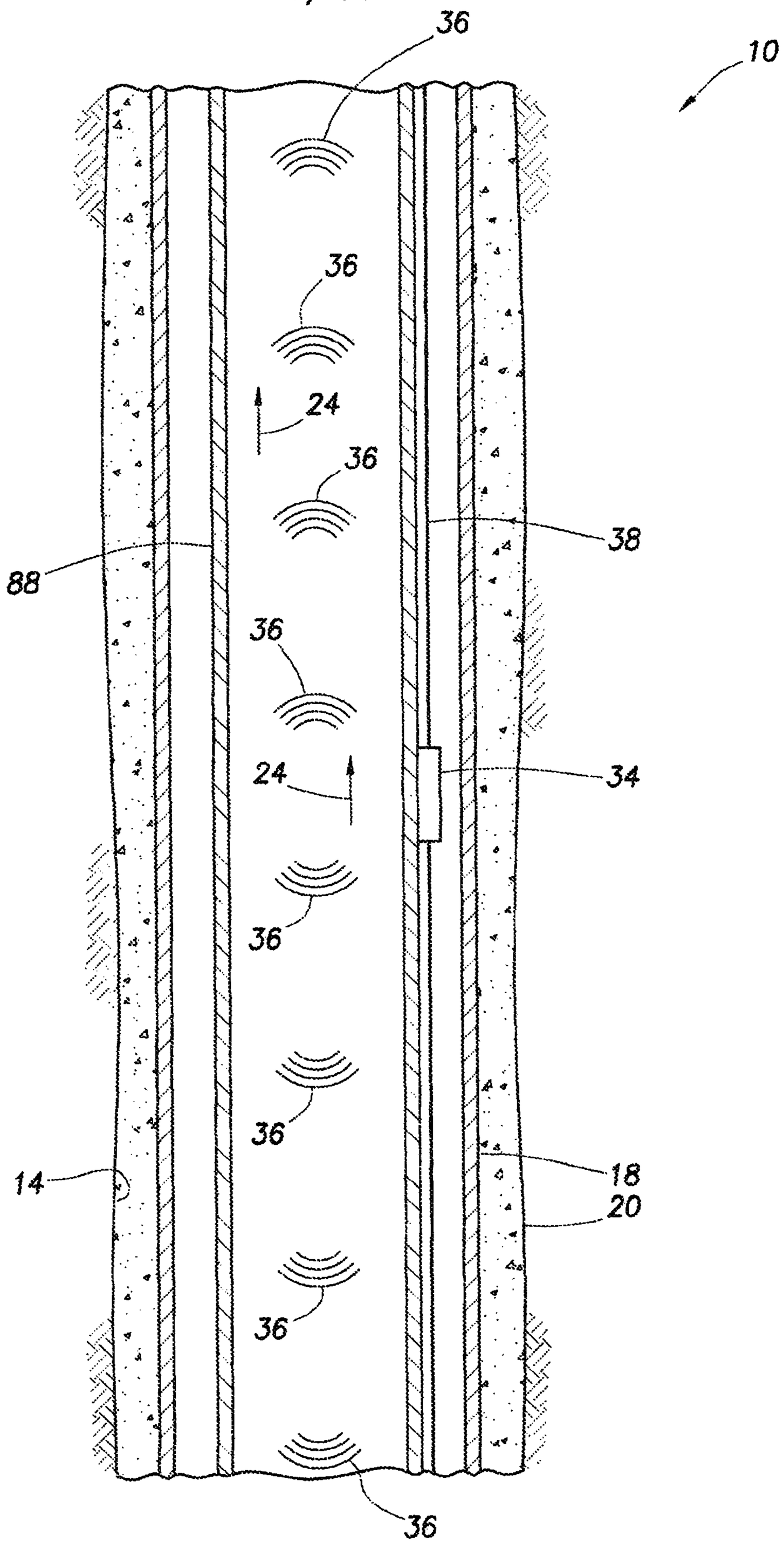


FIG. 12

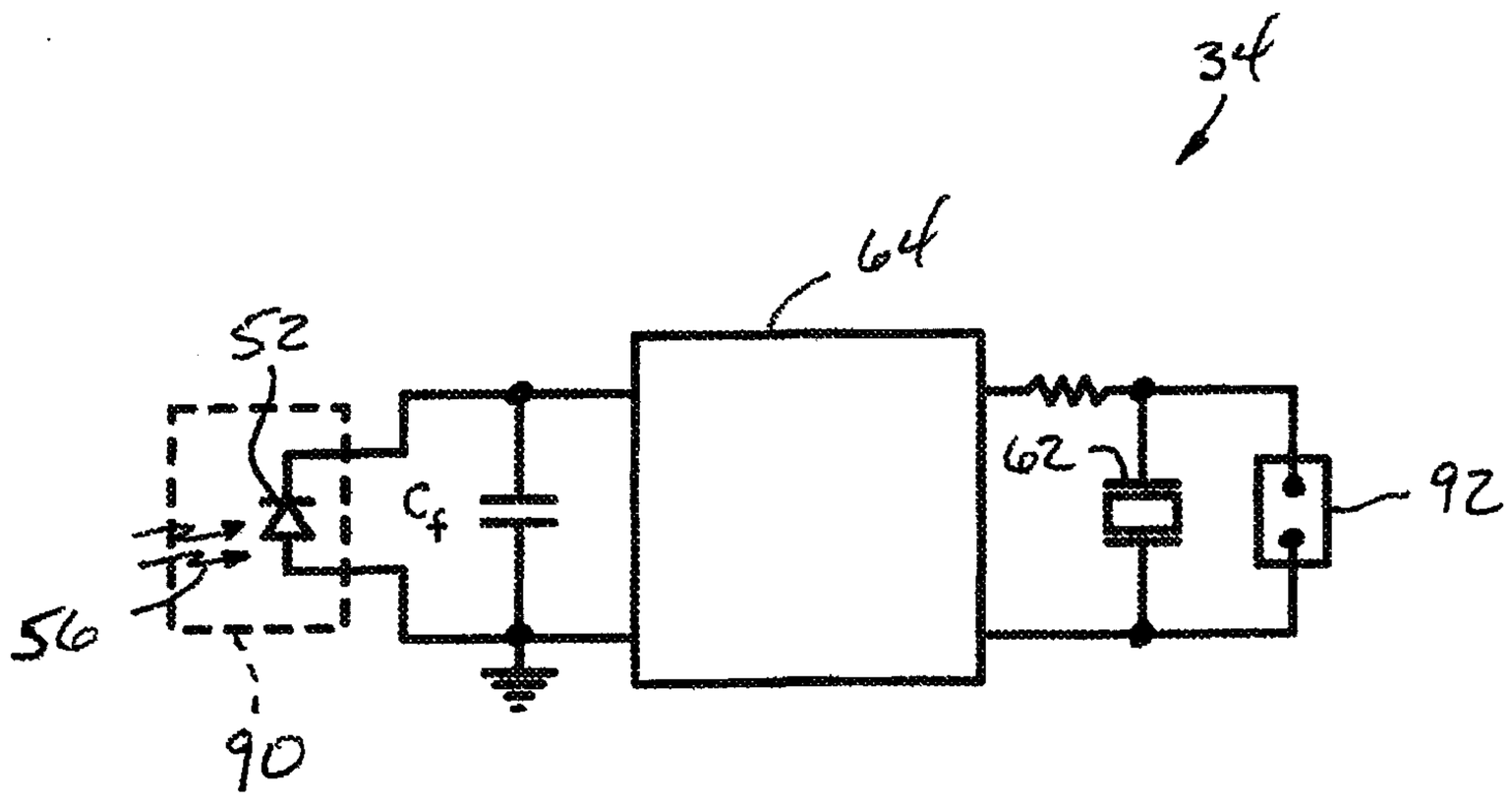


FIG. 13

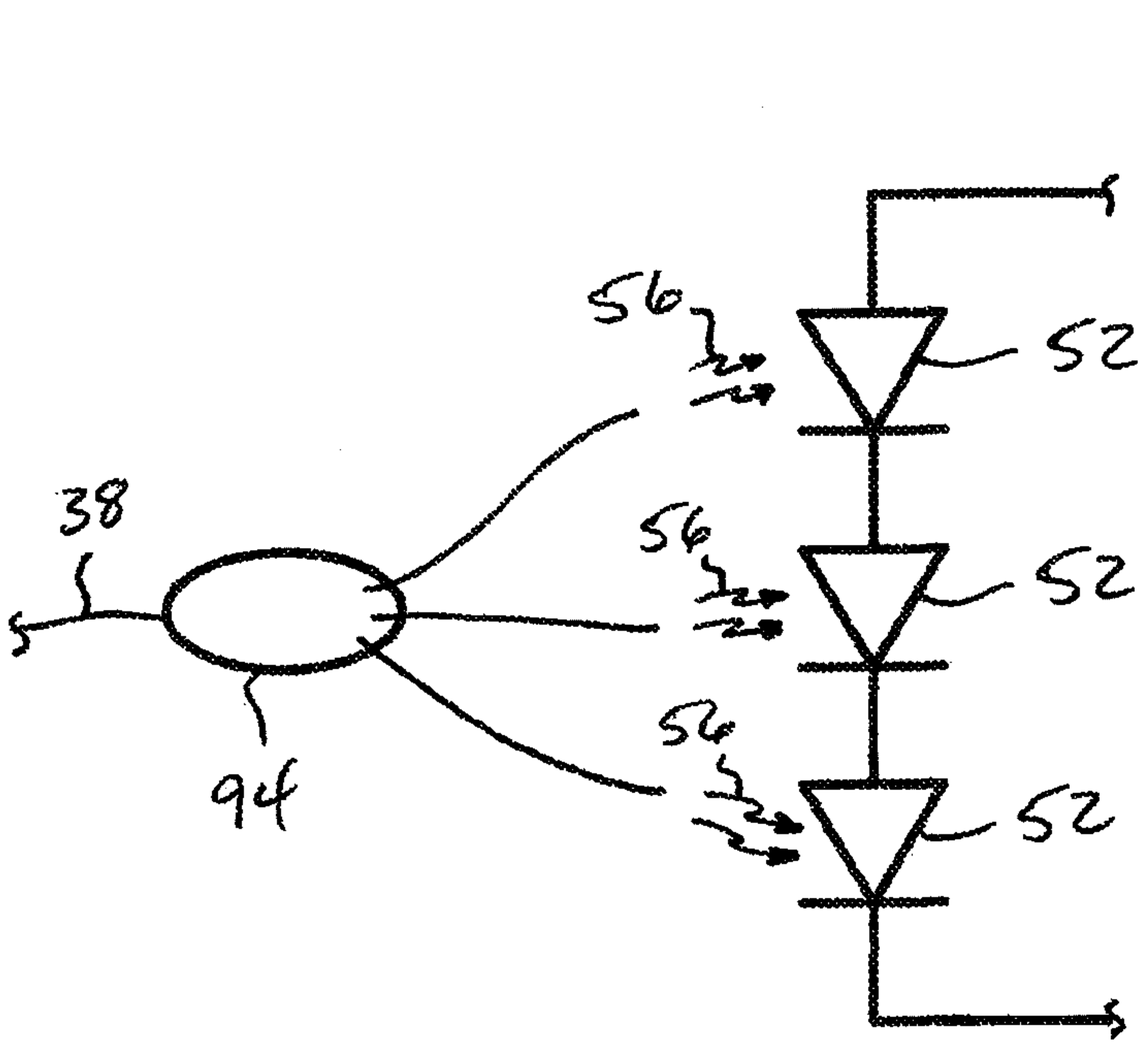


FIG. 14

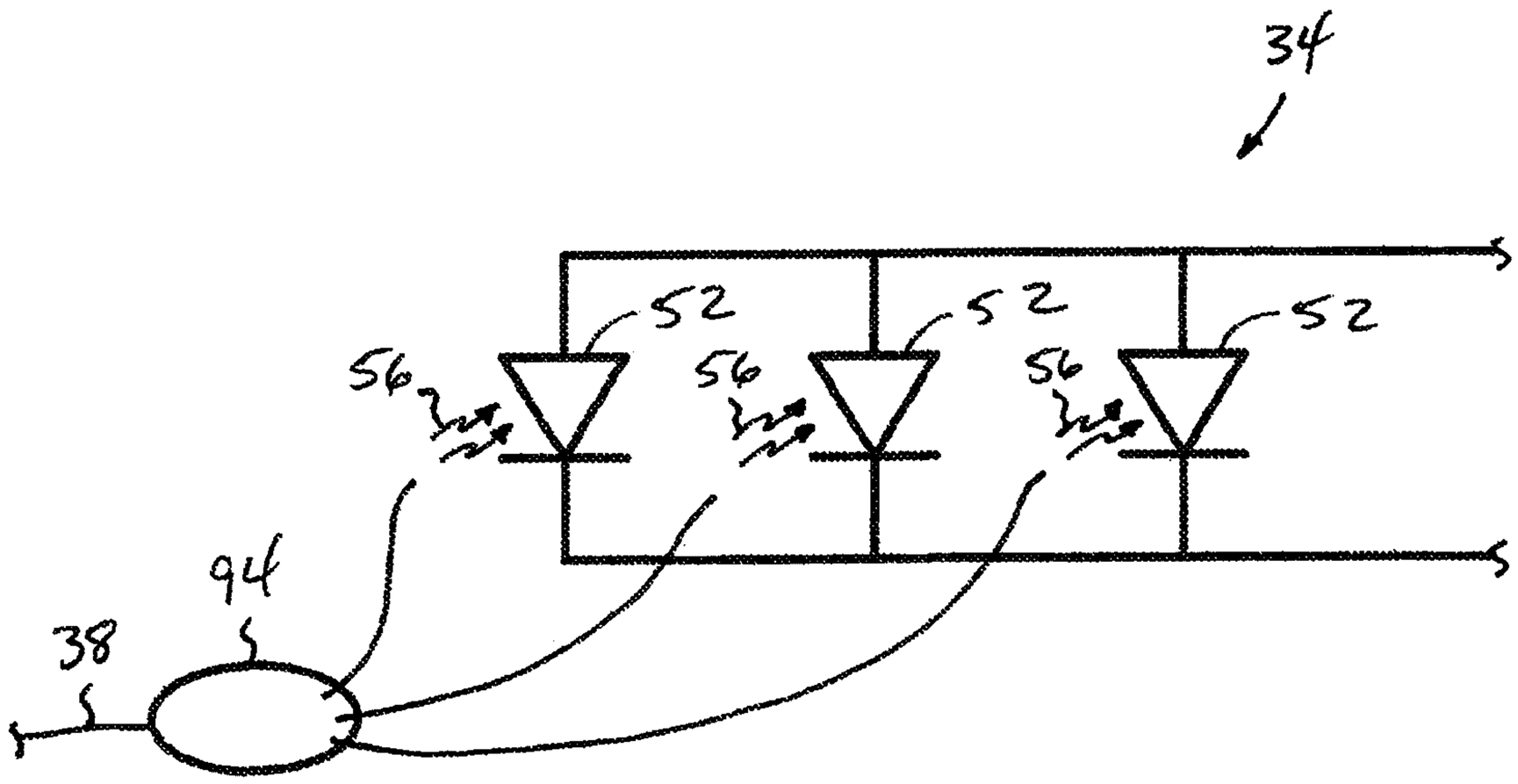


FIG. 15

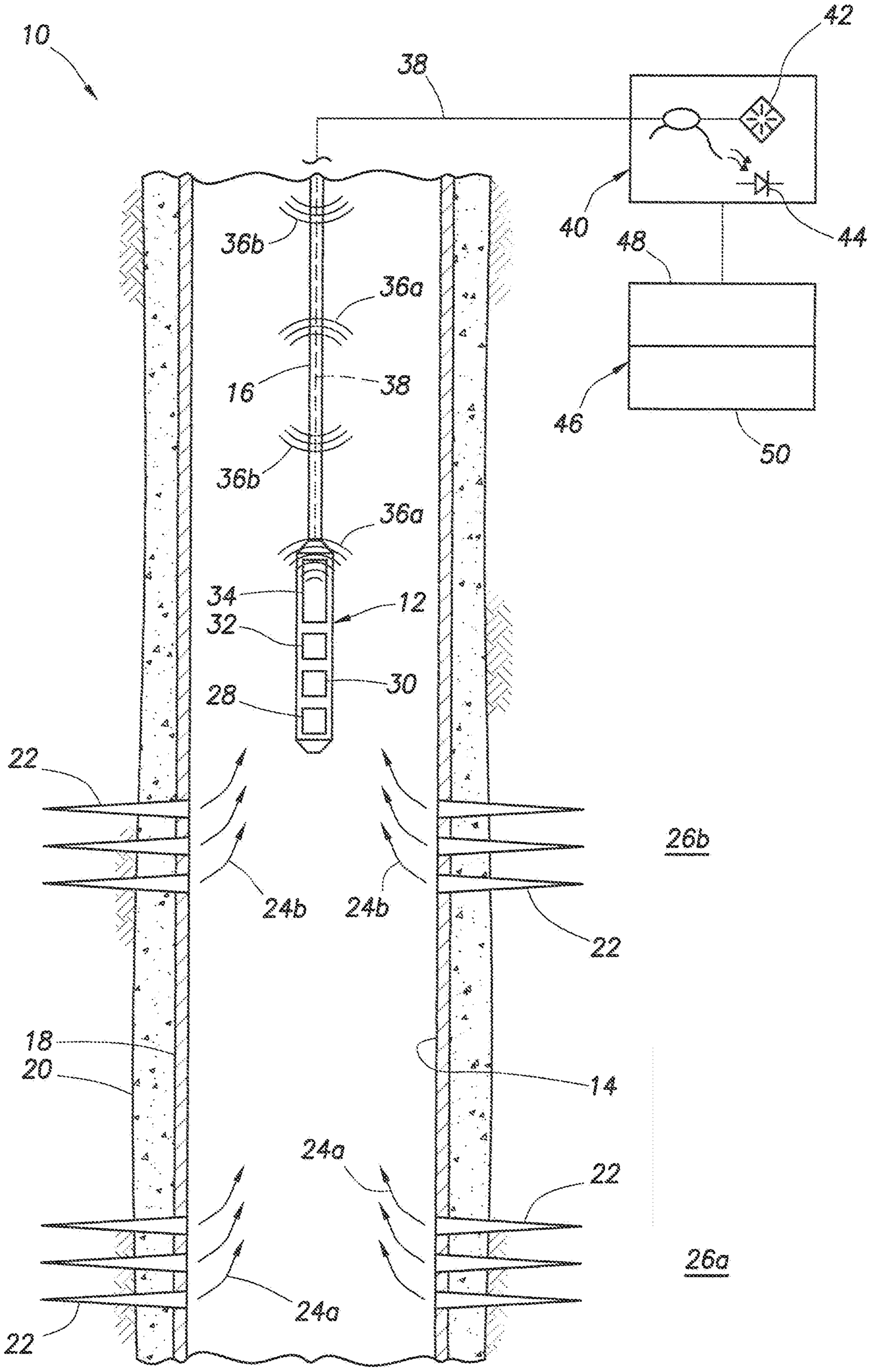

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FIG. 1