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Inventor Anthony A. Ruffa

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1 Attorney Docket No. 78611

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3 IMPROVED LASER VELOCIMETRY DETECTION OF UNDERWATER SOUND

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5 STATEMENT OF GOVERNMENT INTEREST

6 The invention described herein may be manufactured and used
7 by or for the Government of the United States of America for
8 governmental purposes without the payment of any royalties
9 thereon or therefor.

10

11 CROSS REFERENCE TO OTHER PATENT APPLICATIONS

12 Not applicable.

13

14 BACKGROUND OF THE INVENTION

15 (1) Field of the Invention

16 The present invention relates to acoustic wave systems and
17 more particularly to means for detecting of acoustic waves by
18 means of electromagnetic radiation.

19 (2) Brief Description of the Prior Art

20 The detection and measurement of sound using lasers is well
21 known. Essentially, a light beam is caused to pass through a
22 medium, which may be air or water, and detect and process
23 reflections from particles in the medium. These particles will
24 tend to have approximately the same velocity as the particle
25 velocity associated with an acoustic plane wave propagating

1 through the medium. The particle velocity for the plane wave is
2 $P/(\rho_0 c)$, where P is the pressure amplitude, ρ_0 is the density and
3 c is the speed of the sound in the medium. The elapsed time and
4 the Doppler shift of the reflected beam indicate the locations
5 and velocity of the scattering particle. This method is known as
6 laser Doppler velocimetry and is reviewed by Vignola et al. J.
7 Acoust. Soc. Am. 90, 1275-1286, 1991. It has even been
8 envisioned to create a "virtual array" by processing multiple
9 returns from a single beam and then appropriately delaying them
10 to achieve a gain against noise.

11 Various patents describe means for making use of light to
12 measure properties of acoustic waves. U.S. Patent No. 4,998,225
13 to Shajenko, for example, discloses a dual beam hydrophone
14 wherein a reference laser beam and a signal laser beam are both
15 modulated simultaneously by the movement of reflecting surfaces
16 responding to pressure variations due to an impinging acoustic
17 wave. Each beam, travels the same path length within the
18 hydrophone before being detected, thus eliminating any otherwise
19 needed signal compensation. The reference beam and signal beam
20 are acoustically modulated 180° out of phase which reduces by one
21 half the number of reflections normally required to produce the
22 same sensitivity.

23 U.S. Patent No. 5,379,270 to Connolly discloses an apparatus
24 and method for determining the velocity of sound propagation in a
25 fluid as a function of position in the fluid along an axis. A

1 wave of acoustic energy is transmitted along the axis to produce
2 a disturbance that moves in the medium at the velocity of sound.
3 A laser generator transmits a light pulse substantially along the
4 axis through the fluid medium. As the light passes through the
5 disturbance, light backscatters in a characteristic pattern that
6 a detector senses for analysis to provide information concerning
7 the distance traveled and the time of travel for the acoustic
8 wave through the fluid medium and to provide a profile of output
9 characteristic, such as the speed of sound in the medium, as a
10 function of position in the medium.

11 U.S. Patent No. 5,504,719 to Jacobs discloses a system in
12 which a hydrophone employs a laser beam which is focused upon a
13 small "focal" volume of water in which natural light scattering
14 matter is suspended and which matter vibrates in synchronism with
15 any sonic waves present. The vibration produces a wave
16 modulation of the scattered light, which may be recovered by
17 optical heterodyne and sensitive phase detection techniques. The
18 sonic waves are sensed at locations displaced from the focusing
19 lenses. Because of this remote sensing capability, the physical
20 hardware of an array of hydrophones may be confined to a small
21 area comparable to the dimensions of the lenses themselves while
22 the sensing of the sonic waves virtually occurs at widely spaced,
23 remote focal volumes. Thus, by combining the signals from these
24 remote focal volumes, a virtual array of hydrophones may be
25 formed whose dimensions are large enough in relation to the sonic

1 wavelengths of interest to achieve high directionality but
2 without the penalties of hydrodynamic drag usually associated
3 with large area arrays.

4 U.S. Patent No. 5,610,704 to Berzins et al. discloses a
5 probe which directs a light beam through a vapor plume in a first
6 direction at a first angle ranging from greater than 0° to less
7 than 90° , reflecting the light beam back through the vapor plume
8 at a 90° angle, and then reflecting the light beam through the
9 vapor plume a third time at a second angle equal to the first
10 angle, using a series of mirrors to deflect the light beam while
11 protecting the mirrors from the vapor plume with shields. The
12 velocity, density, temperature and flow direction of the vapor
13 plume may be determined by a comparison of the energy from a
14 reference portion of the beam with the energy of the beam after
15 it has passed through the vapor plume.

16 It will be appreciated that the measurement of same particle
17 velocity is more effective in air than in water. The reason for
18 this is that the ratio of the specific acoustic impedance, for
19 the two mediums is approximately 4000. Therefore, the particle
20 velocity of a scatterer will be 4000 times greater in air,
21 leading to a much greater sensitivity. In water, Vignola et al.
22 conducted experiments with standing waves that led to an estimate
23 that particle displacements of 5 nm were detectable with this
24 method. This is equivalent to a sound pressure level of 156 dB
25 re: 1μ Pa at a frequency of 1809 Hz.

1 SUMMARY OF THE INVENTION

2 It is an object of the present invention to improve the
3 efficiency of the measurement of the velocity of sound waves in a
4 liquid medium by using lasers.

5 This invention makes use of a unique feature of water, i.e.,
6 entrained bubbles, to increase the Doppler shift of a scatterer
7 by approximately three orders of magnitude.

8 Considering a single bubble in water, its resonant frequency
9 f_0 is given by:

10

$$11 \quad f = \frac{1}{2\pi a} \sqrt{\frac{3\gamma P_0}{\rho_0}} \quad (1)$$

12 where a is the radius of the bubble, γ is the ratio of
13 specific heats of the air in the bubble (~ 1.4), P_0 is the steady-
14 state pressure and ρ_0 is the density. Thus, a 1-mm radius
15 bubble in water has a resonant frequency of approximately 3300
16 Hz. The amplitude of radial velocity of such a bubble at
17 resonant frequency f_0 is given by:

18

$$U_0 = \frac{4\pi a^2 P_i}{Z_m} \quad (2)$$

19 At resonance $Z_m = R_m + R_r$, where $R_r = 4\pi a^2 \rho_0 c (ka)^2$, and $R_m \sim (1.6 \times 10^{-4})$
20 $(4\pi a^3 \rho_0) (2\pi f_0)^{1/2}$. For the above bubble, the velocity amplitude
21 is $3.49 \times 10^{-3} P_i$, compared to $6.7 \times 10^{-7} P_i$ for a plane wave in water.

1 The velocity ratio is estimated to be 5200 or a 74dB change on a
2 sound pressure level basis. The above radial velocity is
3 actually the same order of magnitude as the particle velocity
4 associated with a plane wave propagating in air.

5 Another factor applicable to this invention is that
6 detectability improves with optical scattering strength, which
7 increases with particle size. Bubbles are often much larger than
8 microparticles normally used for scattering. For example,
9 bubbles may be about 1mm which in turn, microparticles may be
10 0.01-10 μm .

11 In the present invention, it will be appreciated that the
12 measurement of same particle velocity is more effective in air
13 than in water. The reason for this is that the ratio of the
14 specific acoustic impedance, for the two mediums is approximately
15 4000. Therefore, the particle velocity of a scatterer will be
16 4000 times greater in air, leading to a much greater sensitivity.
17 In water, Vignola et al. conducted experiments with standing
18 waves that led to an estimate that particle displacements of 5 nm
19 were detectable with this method. This is equivalent to a sound
20 pressure level of 156 dB re: 1 μPa at a frequency of 1809 Hz.

21 The presence of such a bubble therefore greatly improves the
22 practicality of laser Doppler velocimetry detection of sound in
23 water. The present invention makes use of this effect in two
24 primary ways. The first way consists of directing multiple beams

1 in the region near the water surface where most bubbles reside.
2 The reflections from bubbles would be appropriately delayed and
3 summed, effectively forming a virtual volumetric array.

4 The second way of improving detection of sound in water
5 using laser Doppler velocimetry involves a towed array consisting
6 of a gel-filled hose containing bubbles with a radius
7 distribution having an appropriate mean and variance for the
8 frequency band of interest. The bubbles would respond to an
9 incident sound field and a laser inside the hose would
10 simultaneously illuminate them.

11 The gel and bubble radii distribution is selected such that
12 the desired resonant frequency band is maintained at the towed
13 array depth range causing compression of the bubbles. Such a
14 towed array has the potential to achieve a good sensitivity in a
15 compact hose.

16 In the present invention, an apparatus is provided for
17 measuring the velocity of a wave of acoustic energy in a given
18 bandwidth along an axis. In the liquid medium, a laser transmits
19 a light pulse to interact with the sound wave. Backscattered
20 light from the interaction of the light pulse is received. A
21 processor is then responsive to the detector to determine a
22 distance traveled and time of travel for the acoustic wave
23 through the fluid medium.

24

1 BRIEF DESCRIPTION OF THE DRAWINGS

2 Other objects, features and advantages of the present
3 invention will become apparent upon reference to the following
4 description of the preferred embodiments and to the drawing,
5 wherein corresponding reference characters indicate corresponding
6 parts in the drawing and wherein:

7 FIG. 1 is a schematic representation of the components of
8 the laser source and receiver employed in the apparatus of
9 present invention;

10 FIG. 2 is a schematic representation of a preferred
11 embodiment of the apparatus of the present invention; and

12 FIG. 3 is a schematic representation of an alternate
13 preferred embodiment of the apparatus of the present invention.

14
15 DESCRIPTION OF THE PREFERRED EMBODIMENT

16 Referring to FIG. 1, a sound velocity profiler is
17 constructed in accordance with this invention. Laser 14
18 transmits a light pulse along the laser pulse axis 16. The laser
19 pulse axis 16 passes through the acoustic field. Thus, this
20 circuitry responds to the backscatter from predetermined
21 positions within the acoustic field. The acoustic field at that
22 position would modulate the backscatter light at any such
23 position.

1 An optical signal generator 26 generates a signal that power
2 amplifier 28 amplifies to fire a laser cavity 30 in laser pulse
3 axis 16.

4 Optical sensors and receivers 32 that include light detector
5 circuits 34 and a signal detector 36, receive and analyze the
6 backscattered light 38 using conventional processing techniques
7 to provide input signals to a processor 40 that determines the
8 distance traveled and the time of travel for the acoustic wave
9 through the medium for visual presentation on display 42 or other
10 output device. More specifically, the processor 40 includes a
11 depth estimator 44 and a time estimator 46. The depth estimator
12 44 uses the arrival time provided by the signal detector 36 and
13 the clock pulse information representing the transmission of a
14 laser pulse to determine the round trip time and estimate the
15 depth of the wave front while a time estimator provides a
16 corresponding time value. A sound velocity computer 48 in the
17 processor 40 combine signals from the estimators 44 and 46
18 according to equation (1) to provide an output on a sound
19 velocity profile display 42.

20 Referring to FIG. 2, one embodiment of the present invention
21 includes a laser source and receiver apparatus 50, as was
22 described combined in connection with either FIG. 1. This laser
23 source and receiver apparatus 50 is positioned in a body of water
24 52 which has an upper water line 54 that separates the water 52
25 from atmosphere 56. Within the water adjacent the surface water

1 line 54 there are a plurality of bubbles 58, 60 and 62.
2 Transmitted from the laser source and receiver apparatus 50 there
3 is a laser beam 64, which is reflected from bubble 58 in
4 reflection 66. Transmitted from laser source and receiver
5 apparatus 52 at an angle from laser beam 64 there is a laser beam
6 68 which is reflected from bubble 60 in reflection 70. At a
7 still additional angler displacement there is laser beam 72,
8 which is transmitted from the laser source and receiver apparatus
9 50 and is reflected from bubble 62 in reflection 74, which is
10 received by the laser source and receiver apparatus. There is an
11 acoustic plane wave 76 with axis 78 that moves through the
12 positions of the bubbles 58, 60 and 62, to cause these bubbles to
13 resonate. This resonation is detected when the laser source and
14 receiver apparatus 50 receive the reflection 66, 68 and 70 from
15 respectably from bubbles 58, 60 and 62. By measuring the amount
16 of time which the acoustic plane wave 76 takes to progress from
17 bubble 62 to bubble 60 and then to bubble 58, the velocity of the
18 acoustic plane wave 76 is calculated at the laser source and
19 receiver 50.

20 Referring to FIG. 3, another embodiment is shown in which
21 the apparatus is submerged in water 80 and includes an elongated
22 vessel 82 having a longitudinal axis 84 and which is filled with
23 a gel 86 having a plurality of bubbles as at bubble 88 and 90
24 therein. A laser source and receiver apparatus 92 as was
25 described above in conjunction in connection with either FIG. 1

1 is positioned at one end of the elongated vessel 82. Laser beam
2 94 is generated by the laser source and receiver apparatus 92 and
3 is reflected by bubble 88 in reflection 96 which is received at
4 the laser source and receiver apparatus 82. Laser beam 98 is
5 generated by the laser source and receiver apparatus 92 and is
6 reflected from bubble 90. Reflection 100 is then received by the
7 laser source and receiving apparatus 92. There is also an
8 acoustic plane wave 102 having an axis 104, which moves
9 transversely with respect to the longitudinal axis 84 of the
10 elongated vessel 82. This acoustic plane wave 102 causes bubbles
11 as at bubble 88 and 90 in the gel 86 to resonate as a wave passes
12 them. Since the bubbles 88 and 90 are transversely displaced
13 from each other in the elongated vessel 82 the velocity of the
14 acoustic plane wave 102 may be determined by measuring the time
15 that it takes the wave to progress from bubble 88 to bubble 90.

16 The presence of such bubbles therefore greatly improves the
17 practicality of laser Doppler velocimetry detection of sound in
18 water. The present invention makes use of this effect in two
19 primary ways. The first way consists of directing multiple beams
20 in the region near the water surface where most bubbles reside.
21 The reflections from bubbles would be appropriately delayed and
22 summed, effectively forming a virtual volumetric array.

23 The second way involves a towed array consisting of a gel-
24 filled hose containing bubbles with a radius distribution having
25 an appropriate mean and variance for the frequency band of

1 interest. The bubbles would respond to an incident sound filed
2 and a laser inside the hose would simultaneously illuminate them
3 (the gel is selected such that the desired resonant frequency
4 band is maintained at the towed array depth causing compression
5 of the bubbles. Such a towed array has the potential to achieve
6 a good sensitivity in a compact hose.

7 While the present invention has been described in connection
8 with the preferred embodiments of the various figures, it is to
9 be understood that other similar embodiments may be used or
10 modifications and additions may be made to the described
11 embodiment for performing the same function of the present
12 invention without deviating therefrom. Therefore, the present
13 invention should not be limited to any single embodiment.

1 Attorney Docket No. 78611

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5 ABSTRACT OF THE DISCLOSURE

6 An apparatus for determining the velocity of sound waves
7 which includes a liquid medium having a plurality of gas bubbles.
8 In the liquid medium, a laser transmits a light pulse to interact
9 with the bubbles excited by the sound wave. Backscattered light
10 from the interaction of the light pulse is received. A processor
11 is then responsive to the detector to provide detection of the
12 acoustic wave through the fluid medium.

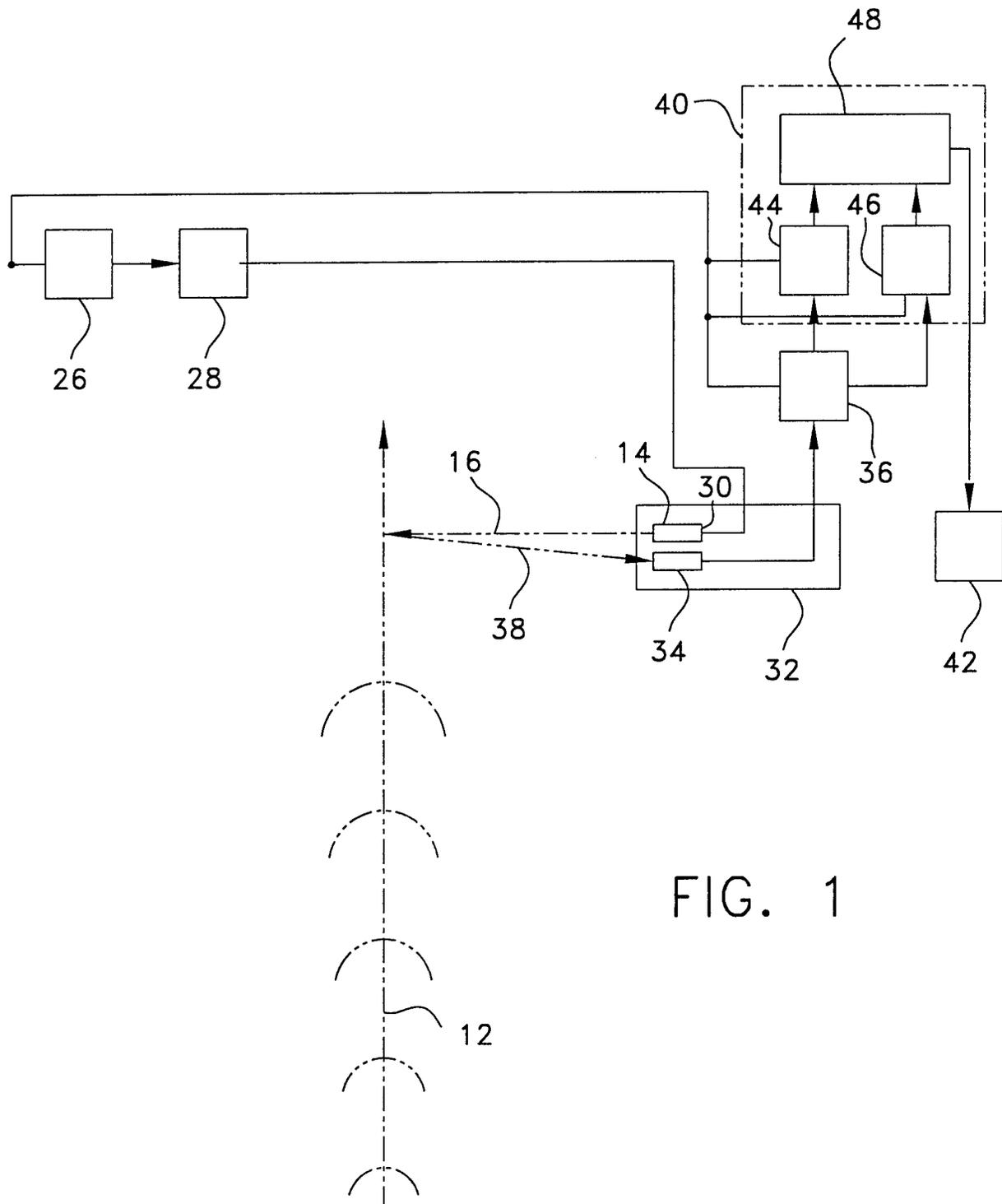


FIG. 1

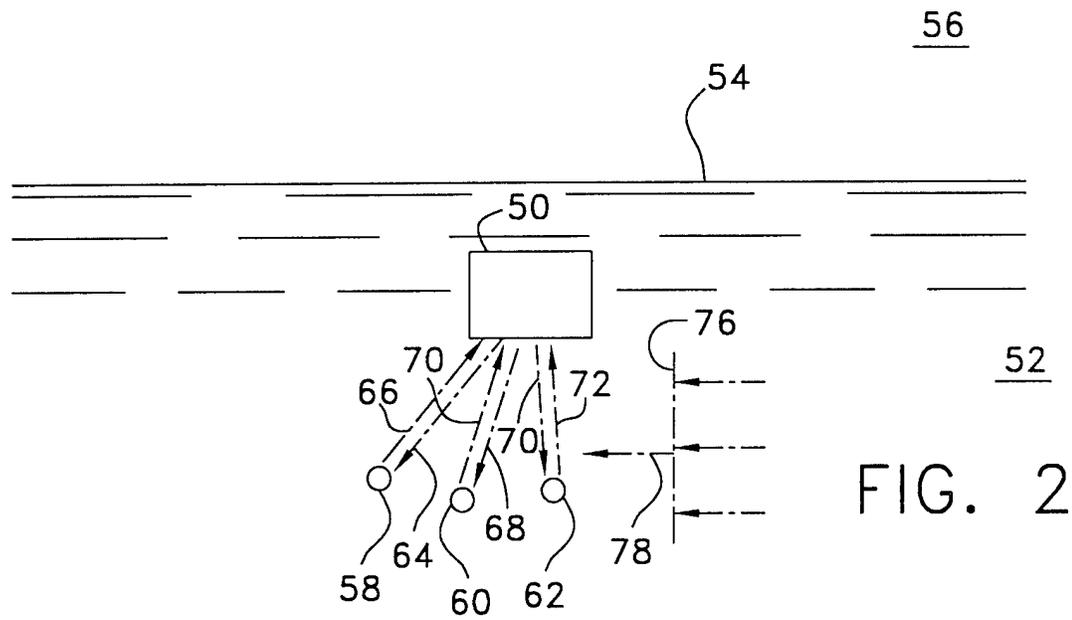


FIG. 2

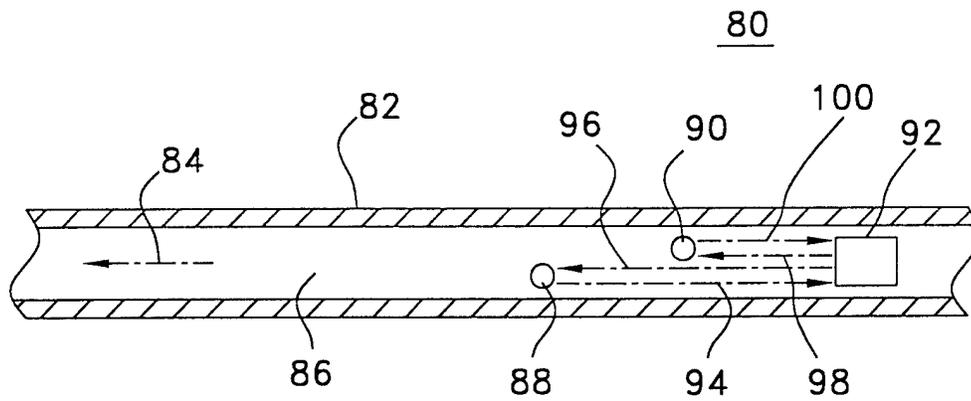


FIG. 3

