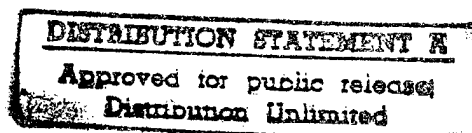


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Inventors: Frank Bucholtz et al.

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Navy Case No. 77,412

1 FIBER OPTIC INFRARED CONE PENETROMETER SYSTEM

2
3 Background of the Invention

4
5 1. Field of the Invention

6 The present invention relates to the detection and analysis
7 of chemicals (including water) in soil and particularly to a
8 system for performing remote, in-situ infrared (IR) spectroscopy
9 of soils and soil-liquid mixtures in the 2 to 12 micron
10 wavelength range.

11
12 2. Description of Related Art

13 In many places throughout the world there are industrial and
14 governmental sites that are suspected of being contaminated with
15 various chemical wastes. An extensive effort is presently
16 underway to characterize, monitor and clean these sites. The
17 first part of this process, the characterization of the waste
18 site, traditionally involves drilling wells and removing core or
19 liquid samples for analysis above ground or even off site. Such
20 characterization methods are expensive and time consuming and
21 involve considerable sampling problems, especially in the case of
22 volatile organic contaminants such as benzene, trichloroethylene
23 and toluene. To help overcome these problems, the cone

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1 penetrometer system has been developed for putting sensors
2 directly into soils.

3 Cone penetrometry is a well-established technique for the
4 measurement of a variety of subsurface soil parameters. A cone
5 penetrometer consists of a hollow steel tube containing sensing
6 and measurement instruments. The tube is pushed into the soil
7 using a hydraulic ram mounted in a truck and measurements are
8 made at various depths to a maximum depth of approximately 150
9 feet. With this system, a number of "pushes" can be made rapidly
10 at various locations.

11 For identification of various chemicals, the penetrometer is
12 typically used to extract samples of soil which are then removed
13 and transported to a laboratory for analysis using, for example,
14 gas chromatography or mass spectroscopy. This process is time
15 and labor intensive and is subject to errors, especially when
16 volatile contaminants are involved. Hence, an in-situ sensor
17 system for detecting, identifying, and quantifying chemicals is
18 needed. One system developed to address this problem is the
19 fiber optic laser-induced fluorescence (LIF) system for the cone
20 penetrometer. Here, light from a visible or near-UV laser source
21 is transmitted to the cone penetrometer by a silica optical fiber
22 where it exits the penetrometer tube through a sapphire window
23 and excites the adjacent soil. When excited by near-UV light,
24 certain classes of chemical compounds such as petroleums, oils,

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1 and lubricants fluoresce emitting broad spectrum light and, thus,
2 indicate their presence. However, it is difficult to identify
3 specific contaminants and to make quantitative estimates of
4 specific contaminant levels using LIF.

5 A more suitable technique for identification and
6 quantitative estimation of particular contaminants is infrared
7 spectroscopy. Nearly all chemical contaminants of interest have
8 unique infrared spectra allowing identification of particular
9 species even in the presence of interfering spectra due to
10 additional species. Until recently, it was not possible to
11 perform in-situ IR spectroscopy with the cone penetrometer in the
12 2 to 12 micron wavelength range because optical fibers with
13 sufficiently low transmission losses in this wavelength range
14 were not available.

15
16 Summary of the Invention

17 It is therefore an object of the invention to provide a
18 system for performing remote, in-situ infrared (IR) spectroscopy
19 of soils and soil-liquid mixtures in the 2 to 12 micron
20 wavelength range.

21 Another object of the invention is to provide a fiber optic
22 infrared spectroscopic system for use with a cone penetrometer to
23 identify and quantify organic contaminants in soil.

24 Another object of the invention is to transmit optical

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1 radiation in the 2 - 12 micron wavelength range via an infrared-
2 transmitting optic fiber to an optical system in a cone
3 penetrometer tube.

4 Another object of the invention is to provide an optical
5 system for the efficient and reproducible transmission of
6 infrared light to a region of the soil surrounding a cone
7 penetrometer tube.

8 Another object of the invention is to provide an optical
9 system for the efficient collection of infrared light after it
10 has been diffusely-scattered by the soil surrounding a cone
11 penetrometer tube.

12 Another object of the invention is to provide a means for
13 efficiently coupling light from the output of an infrared
14 transmitting optic fiber into an optical signal processor, such
15 as an infrared spectrometer.

16 A further object of the invention is to perform remote
17 spectroscopy in the infrared wavelength range using infrared
18 transmitting optical fibers which are based on chalcogenide
19 materials and specially designed transmission/collection optics
20 in order to transmit infrared light out of a window of a cone
21 penetrometer tube into soil around the window, recover some of
22 the scattered light from the soil by way of the window and the
23 transmission/collection optics, inject the recovered scattered

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1 light into the infrared transmitting fiber and send it up to the
2 surface for detection and processing.

3
4 In a preferred embodiment of the invention, a system for the
5 in-situ detection of organic contaminants in soil comprises: a
6 penetrometer for penetrating the soil, the penetrometer including
7 interior and exterior surfaces, and a window for allowing
8 infrared radiation to be transmitted between the interior and
9 exterior surfaces of the penetrometer; a driver for driving the
10 penetrometer into the soil to a plurality of different depths; a
11 source for providing infrared radiation which passes through the
12 window to irradiate the soil adjacent to the window; an infrared
13 transmitting chalcogenide fiber; an optical system disposed
14 within the penetrometer adjacent to the window for transmitting
15 infrared radiation from the source through the window into the
16 soil and for collecting infrared radiation reflected from the
17 soil back through the window into a first end of the chalcogenide
18 fiber; and a spectrometer coupled to a second end of the infrared
19 transmitting chalcogenide fiber for receiving and analyzing the
20 reflected infrared radiation passing through the chalcogenide
21 fiber to obtain information on contaminants present at various
22 depths of the soil through which the penetrometer passes.

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Brief Description of the Drawings

These and other objects, features and advantages of the invention, as well as the invention itself, will become better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein like reference numerals designate identical or corresponding parts throughout the several views and wherein:

FIG. 1 illustrates a schematic block diagram of the fiber optic infrared cone penetrometer system of the invention;

FIGS. 2A, 2B and 2C illustrate three exemplary ways of placing an infrared source in a cavity for subsequent transmission of infrared light to the transmission/collection optics;

FIGS. 2D, 2E and 2F illustrate three exemplary types of mirrors that can be selectively utilized in the transmission/collection optics;

FIG. 2G illustrates a symbol representative of light reflecting from a soil surface;

FIG. 2H illustrates a collimating or focusing lens;

FIGS. 3A, 3B and 3C illustrate exemplary configurations of some of the components shown in FIGS. 2A through 2H for use in the fiber optic infrared cone penetrometer system of the invention;

FIGS. 4 through 13 illustrate the operations of various

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1 combinations of system components between the infrared source and
2 the infrared-transmitting chalcogenide optical fiber, where the
3 infrared source is located within the cone penetrometer; and

4 FIGS. 14 through 17 illustrate the operations of various
5 combinations of system components, where the infrared source is
6 located at a remote location away from the sample site, such as
7 on the surface.

8
9 Detailed Description of the Preferred Embodiments

10 Referring now to the drawings, FIG. 1 illustrates an
11 exemplary schematic block diagram of a first embodiment of the
12 fiber optic infrared cone penetrometer system of the invention.
13 As shown in FIG. 1, the system of the invention comprises an
14 infrared (IR) source of radiation 21; an optical assembly,
15 comprised of transmission/collection optics 23, which operates
16 over the 2 to 12 micron wavelength range for transmitting light
17 from the IR source 21 to soil 33 and for collecting IR light
18 reflected by the soil 33; an infrared- or IR-transmitting
19 chalcogenide glass optical fiber 25 for transmitting the
20 reflected light recovered from the soil 33 to a remote location
21 above ground; and a remote signal processor, such as a
22 spectrometer 27 above ground which spectrometer 27 includes an
23 optical detector (FIGS. 18A and 18B), for analyzing the optical
24 signal transmitted by the optical fiber 25.

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1 Source of IR Radiation

2 The IR source 21 can be chosen to produce a wideband or
3 narrowband wavelength range within a 2 to 12 micron wavelength
4 range.

5 Sources for broadband radiation in the infrared are quite
6 simple. A source may be formed, for example, by passing
7 electrical current through a nichrome wire or a glowbar material.
8 Depending on the electrical power and the surface area of the
9 material, sources of this type act effectively as blackbody
10 radiators at effective temperatures in the 300 degree K - 1200
11 degree K range. A nichrome wire source operating at approximately
12 10 Watts and 1000 degrees K temperature was used for the
13 demonstration system described in FIG. 1. Typically, the source
14 is enclosed in a spherical chamber with highly-reflecting walls
15 and having a small exit aperture. It is also possible to use
16 enclosures having paraboloidal or ellipsoidal shapes.

17 A second possible source is the tunable IR laser based on
18 quasi-phase matched materials. A device of this type has
19 demonstrated acceptable output power with emission wavelength
20 tunable over the range of 3 to 4 microns.

21
22 Transmission/Collection Optics

23 The purpose of the transmission/collection optics 23 is
24 twofold. First, infrared radiation from the IR source 21 must be

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1 directed out through a sapphire transmission window 31 in a
2 penetrometer tube 29 to soil 33. In interacting with the soil
3 33, the radiation is scattered in effectively all directions due
4 to multiple reflections by soil particles. Some of the scattered
5 radiation must be collected and injected into the optical fiber
6 for transmission to a spectrometer 27. There are many possible
7 arrangements of lenses and various shaped mirrors to efficiently
8 accomplish this dual task of illuminating the soil 33 and
9 collecting the scattered radiation (to be discussed).

10
11 IR-Transmitting Chalcogenide Optical Glass Fiber

12 The optical fiber transmits infrared light from a location
13 underground in the soil to a spectrometer on the surface. To be
14 useful for performing infrared spectroscopy, the fiber must have
15 sufficiently low attenuation in the wavelength range of 2 to 12
16 microns. Recently, fibers have been fabricated at the Naval
17 Research Lab (NRL) in Washington, D.C., which demonstrate
18 attenuation on the order of 0.2 to 1 dB per meter in this
19 wavelength region (excluding certain known, narrow absorption
20 bands due to impurities.) The glasses manufactured at NRL are
21 based on chalcogenide materials having chemical compositions
22 As_2S_3 , As_2Se_3 and As_2Te_3 . Optical fibers made with these materials
23 have been manufactured in greater than 50 meter lengths. Other
24 possible fiber materials include fluoride-based glasses and

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1 silver-halide-based glasses. However, chalcogenide materials
2 offer the best combination of mechanical and environmental
3 stability and low optical attenuation over a wide range of
4 wavelengths.

5 The chalcogenide fibers can be produced as either core-only
6 or core-clad type and have an outer Teflon protective jacketing.
7 After fabrication, the fibers can be cabled, if necessary, for
8 use in the field. The inventors at NRL have demonstrated that no
9 degradation in performance is observed for cabled fibers compared
10 to uncabled fibers. Cables can consist of a single fiber or a
11 multiple fiber bundle to increase optical throughput.

12 An unusual feature of these fibers arises from the high
13 index of refraction ($n \approx 2.4$) of the chalcogenide materials.
14 For core-only fiber, the numerical aperture is approximately 1.0
15 representing an optical system with extremely high light-
16 gathering capacity. In order to make full use of this high
17 numerical aperture, however, non-imaging optical techniques may
18 need to be employed.

19
20 Means for Analyzing the Optical Signal Transmitted by the Optical
21 Chalcogenide Fiber.

22 After interaction with the soil, the spectral features of
23 the light must be analyzed to gain information on chemical
24 content. Typically this is achieved using an infrared
25 spectrometer. In the demonstration of the system described in

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1 this patent application, a commercially available Fourier
2 transform infrared spectrometer was used. The dispersive
3 spectrometer contains a dispersive element, typically a grating,
4 which spreads or disperses the optical signal in space as a
5 function of wavelength. The dispersive spectrometer may be a
6 monochromator, a polychromator, a scanning monochromator, or a
7 spectrograph. The Fourier transform spectrometer consists of an
8 interferometer with some means for producing a periodic, time-
9 varying optical path imbalance and a photodetector. After
10 storing the photodetector output as a function of time, a
11 computer is used to perform a Fourier transform to recover the
12 spectral shape as a function of wavelength (or wavenumber).

13 The spectrometer analyzes the spectral content of radiation
14 from the soil 33 after it has passed through the optical fiber.
15 By comparing the spectrum (intensity versus wavelength) with the
16 probe in the soil 33 to a reference spectrum taken with the probe
17 outside the soil, information on the chemical content of the soil
18 33 can be obtained. Most spectrometers for the infrared
19 wavelength fall into one of two catagories: (1) dispersive or (2)
20 Fourier transform. In the dispersive spectrometer, an optical
21 element causes light at different wavelengths to be refracted by
22 slightly different angles. Hence, by measuring the amount of
23 light at each angle, the spectrun can be obtained. In a Fourier
24 transform spectrometer, an interferometer with a time varying

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1 optical path difference causes the intensity of light at
2 different wavelengths to oscillate at slightly different
3 frequencies. By recording these oscillations as a function of
4 time and mathematically performing a Fourier transform on the
5 data, the spectrum is obtained.
6

7 Returning to the embodiment of FIG. 1, the IR source 21 and
8 the transmission/collection optics 23 are contained in a cone
9 penetrometer tube 29 which is pushed into the ground by, for
10 example, a hydraulic ram (not shown) mounted in a truck (not
11 shown) and measurements are made at various depths to a maximum
12 depth of approximately 150 feet. The spectrometer 27 is located
13 on or above the ground.

14 In the operation of FIG. 1, infrared radiation from the IR
15 source 21 is transmitted by way of the transmission/collection
16 optics 23 through a transmission window 31 in the cone
17 penetrometer tube 20 into soil 33 adjacent to the transmission
18 window 31. IR light reflected from the soil 33 passes back
19 through the transmission window 31 and is collected by the
20 transmission/collection optics 23. The infrared optics or
21 transmission/collection optics 23 are specially designed to
22 perform the transmission and collection of IR light. Reflected
23 IR light collected by the transmission/collection optics 23 is
24 injected into the infrared- or IR-transmitting chalcogenide

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1 optical fiber 31 for transmission to the above-ground remote
2 spectrometer 33 for analysis of the wavelength(s) and
3 amplitude(s) of the reflected optical signal to determine the
4 type(s) and concentration(s) of various hydrocarbon contaminants
5 in the soil at different depths.
6

7 Three exemplary ways of placing a broadband infrared source
8 in a cavity for subsequent transmission of infrared light to the
9 transmission/collection optics 23 are illustrated in FIGS. 2A, 2B
10 and 2C, which will now be discussed.

11 FIG. 2A illustrates a broadband IR source 21A in either an
12 ellipsoidal or paraboloidal shaped reflector 21B. The IR source
13 21A is located at the focus of a reflector 21B and the reflector
14 21B concentrates and reflects the light from the reflector 21B.

15 FIG. 2B illustrates a broadband IR source 21C in a spherical
16 reflecting cavity 21D.

17 FIG. 2C illustrates a broadband IR source 21E located at one
18 of the focal points in an ellipsoidal-shaped cavity 21F. In this
19 case some of the light would directly come out from the source
20 21E while the rest of the light would bounce around in the cavity
21 21F before it exits the cavity 21F.

22 Thus, FIGS. 2A, 2B and 2C illustrate three different ways of
23 placing a broadband IR source in a cavity in order to, with a
24 degree of efficiency, transmit IR light toward the

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transmission/collection optics 23 portion of the fiber optic
infrared cone penetrometer system.

Other General Component Descriptions
For Reflectance Probe Designs

Other reflective elements that can be used inside the
transmission/collection optics 23 of Fig. 1 will be discussed by
now referring to FIGS. 2D, 2E and 2F.

FIG. 2D illustrates a paraboloidal mirror in which the
reflective surface is in the shape of a portion of a paraboloid.

FIG. 2E illustrates an ellipsoidal mirror in which the
reflective surface is in the shape of a portion of an ellipsoid.
The ellipsoidal mirror has two focal points and possesses the
property wherein any light ray which passes through one focal
point and is incident on the ellipsoid surface will be reflected
on a path which passes through the second focal point. An
ellipsoidal mirror can be used either singly or as a pair to
transmit to and collect reflected light from the soil in the cone
penetrometer. In addition, an ellipsoidal mirror can be used in
conjunction with a paraboloidal mirror or with a flat mirror.

FIG. 2F illustrates a typical flat mirror. The flat mirror
offers reduced transmission and collection efficiency, but is
much easier to fabricate.

1 Other Symbols Used For The Purpose Of The Diagrams

2 FIG. 2G illustrates a rising sun symbol representative of IR
3 light reflecting from the surface of the soil 33 just outside of
4 the transmission window 31 of the cone penetrometer tube 29.

5 FIG. 2H illustrates a collimating or focusing lens.
6

7 It should be noted at this time that different combinations
8 of the optical components illustrated in FIGS. 2A through 2H can
9 be used to transmit light by way of the transmission/collection
10 optics 23 out of the transmission window 31 of the cone
11 penetrometer 29 into the soil 33, to recover or collect the light
12 that is reflected by the soil 33 back through the transmission
13 window 31 and the transmission/collection optics 23, and to
14 inject that reflected light into the IR transmitting chalcogenide
15 fiber 25.

16 FIGS. 3A, 3B and 3C illustrate three different combinations
17 of the optical components of FIGS. 2A through 2H for forming
18 exemplary configurations of the fiber optic infrared cone
19 penetrometer.

20 FIG. 3A shows a standard configuration, where the IR source
21 35 (of FIG. 2A) is located in the penetrometer tube 29 and two
22 back-to-back paraboloidal mirrors 37 and 39 (see FIG. 2D) are
23 utilized as the transmission/collection optics 23. Paraboloidal
24 mirror 37 is used to reflect IR light 41 from the source 35

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1 through the transmission window 31 into the soil 33.
2 Paraboloidal mirror 39 directs IR light 43 that is reflected from
3 the soil 33 and through the transmission window 31 toward a
4 focusing lens 45 (see FIG. 2H). The lens 45 focuses the returned
5 IR light 43 from the soil 33 into the chalcogenide fiber 47
6 which, in turn, transmits it up to a spectrometer 49 on the
7 surface for analysis.

8 FIG. 3B shows a second configurations of the fiber optic
9 infrared cone penetrometer. Again, the IR source 35 is down in
10 the penetrometer tube 29. However, only one paraboloidal mirror
11 37 (see FIG. 2D) is used as the transmission/collection optics 23
12 to only direct the IR light from the source 35 through the
13 transmission window 31 into the soil 33. Here, instead of using
14 a second paraboloidal mirror and a focusing lens, the IR
15 transmitting chalcogenide fiber 47 is brought up very close to
16 the transmission window 31 to collect the IR light that is
17 reflected from the soil 33 and transmit it to the spectrometer 49
18 for analysis. This second configuration of FIG. 3B has the
19 advantage of fewer components down in the penetrometer tube 29,
20 but it is not as efficient in collecting reflected IR light as
21 the first configuration of FIG. 3A.

22 FIG. 3C shows a third configuration which is different from
23 the configurations of FIGS. 3A and 3B. Here, the IR source 35,
24 instead of being located in the penetrometer tube 29, is located

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1 above ground along with a beam splitter 51 and the spectrometer
2 49. In the operation of the third configuration of FIG. 3C, half
3 of the light from the IR source 35 is reflected from a beam
4 splitter 51 into the chalcogenide fiber 47 and is transmitted
5 through the fiber 47 down from the surface into the penetrometer
6 tube 29 before it exits the fiber 29 and impinges on an
7 ellipsoidal mirror 53 (see FIG. 2E). The light 55 impinging on
8 the mirror 53 is reflected out through the transmission window 31
9 in the penetrometer tube 29 to the soil 33. Light 55 reflected
10 from the soil 33 through the transmission window 31 strikes the
11 ellipsoidal mirror 53 which focuses that reflected light 55 into
12 the fiber 47. This light is transmitted through the fiber 47 up
13 to the surface, before exiting the fiber 47 and passing through
14 the beam splitter 51 into the spectrometer 49 for analysis.

15 As discussed above, FIGS. 3A, 3B and 3C are just three
16 examples of arranging the elements that are shown in FIGS. 2A
17 through 2H in order to perform the operation of getting
18 transmitted IR light to interact with the soil and then inject
19 the reflected IR light into the IR-transmitting chalcogenide
20 fiber for transmission to a spectrometer for wavelength and
21 amplitude analysis.

22
23 A variety of possible combinations of mirror type and source
24 chamber geometry are shown in FIGS. 4-13. These designs all

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1 utilize a source in the penetrometer tube 29 itself such that the
2 soil sample 33 in between the IR source 21 and the spectrometer
3 27. An alternative approach is to place the IR source 21 in the
4 same remote location as the spectrometer 27 such that light is
5 transmitted in both directions through the optical chalcogenide
6 fiber 25: from the IR source 21 to the soil sample 33 and from
7 the soil sample 33 to the spectrometer 27 as shown in Fig. 12.
8 Some possible arrangements are shown in FIGS. 14-17.

9
10 FIG. 4 shows an IR source 21C in a reflecting sphere 21D, a
11 collimating lens 52, and two back-to-back paraboloidal mirrors
12 53, a focusing lens 55, a chalcogenide fiber 25 and the reflected
13 light 57 from the soil 33 (FIG. 1). FIG. 4 shows a standard
14 approach to the problem of transmitting light from the IR source
15 21C to a solid sample, such as soil 33 (FIG. 1), and for
16 collecting the diffusely-reflected IR light 57 from the soil 33
17 in the use of the pair of off-axis paraboloidal mirrors 53. The
18 foci of both paraboloidal mirrors 53 are coincident at a point on
19 or just inside the surface of the sample 33 (FIG. 1). Hence, for
20 a point source, after collimation of the beam by the lens 52, the
21 mirror pair 53 focuses the light to the focal point and emits a
22 collimated beam of the reflected light 57 which can be focused
23 into the optical fiber 25 using the focusing lens 55. In
24 practice, using a finite source, both the incident and reflected
25 light is only partially collimated. However, sufficient optical

1 throughput can be obtained for successful operation of the
2 device.

3
4 FIG. 5 shows an IR source 21C in a spherical reflecting
5 cavity 21D, a collimation lens 52, a paraboloidal mirror 53
6 onto the sample 33 (FIG. 1), an ellipsoidal mirror 59 off the
7 sample 33 and into the optical fiber 25. Here, instead of having
8 a second paraboloidal mirror, there is an ellipsoidal mirror 59.
9 With the use of the ellipsoidal mirror 59, which has a focusing
10 quality, a second lens (55) is not needed. Note that the
11 collected IR light is injected from the ellipsoidal mirror 59
12 right into the end of the fiber 25, which fiber 25 is located at
13 one of the focal points discussed before) of the ellipsoidal
14 mirror 59. Thus, any reflected light from the soil 33 that hits
15 the ellipsoidal mirror 59 will automatically be focussed into the
16 fiber 25.

17
18 FIG. 6 shows an opposite way of performing the operation
19 shown in FIG. 5. Here again an IR source 21C is located in a
20 spherical reflecting cavity 21D, but an ellipsoidal mirror 59 is
21 used to direct the IR light into the soil 33 (FIG. 1). a
22 paraboloidal mirror 53 collects the reflected light 57 from the
23 soil 33. However, in this case, a focusing lens 52 is needed to
24 focus the collected reflected light into the fiber 25.

1 FIG. 7 shows an IR source 21C located in a spherical
2 reflecting cavity 21D, two back-to-back ellipsoidal mirrors 59
3 with one ellipsoidal mirror 59 from the reflecting cavity 21D
4 onto the soil 33 (FIG. 1) and the other ellipsoidal mirror 59 off
5 the soil 33 and into the optical fiber 25. No lens is needed for
6 this implementation.

7
8 FIG. 8 uses a different type of IR source than the type
9 shown in FIGS. 4-7. Here the IR source 21A is located at one of
10 the focal points in a reflecting ellipsoidal cavity 61. IR light
11 from the IR source 21A passes out of the cavity 61, is collimated
12 by a collimating lens 52 and directed by a paraboloidal mirror 53
13 onto the soil 33 (FIG. 1). IR light reflected by the soil 53 is
14 collected by an ellipsoidal mirror 59 and focused by the
15 ellipsoidal mirror 59 into the optical fiber 25.

16
17 FIG. 9 shows an IR source 21A located at one of the focal
18 points in a reflecting ellipsoidal cavity 61, two back-to-back
19 ellipsoidal mirrors 59. IR light from the IR source 21A passes
20 out of the cavity 61, is directed by one of the ellipsoidal
21 mirrors 53 onto the soil 33 (FIG. 1), reflected off the soil 53,
22 collected and focused by the second ellipsoidal mirror 59 into
23 the optical fiber 25.

1 FIG. 10 shows an IR source 21A in a reflecting paraboloidal
2 or ellipsoidal cavity 53. IR light from the cavity 53 is
3 reflected from a flat mirror 63 onto the soil 33 (FIG. 1). IR
4 light reflected from the soil 33 is collected by a paraboloidal
5 mirror 53 and focused by a focusing lens 52 into the optical
6 fiber 25.

7
8 FIG. 11 shows an IR source 21A in a reflecting paraboloidal
9 or ellipsoidal cavity 53, a flat mirror 63 to direct IR light
10 from the IR source 21A to the soil 33 (FIG. 1), an ellipsoidal
11 mirror 59 to collect the reflected IR light 57 and focus it into
12 the fiber 25.

13
14 FIG. 12 shows an ellipsoidal reflecting cavity 55 containing
15 an IR source 21A, a lens 52 to collimate the IR light from the
16 cavity 53, two back-to-back paraboloidal mirrors 53 with a first
17 paraboloidal mirror 53 to direct light to the soil 33 (FIG. 1)
18 and the second paraboloidal mirror to collect the reflected IR
19 light 57, and a focusing lens 52 to focus the collected reflected
20 light into the fiber 25.

21
22 FIG. 13 shows an ellipsoidal reflecting cavity 55 containing
23 an IR source 21A, an ellipsoidal mirror 59 used to direct the IR
24 light from the source 21A into the soil 33 (FIG. 1), a

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1 paraboloidal mirror 53 to collect the IR light reflected from the
2 soil 33, and a lens 52 to focus the collected IR light into the
3 fiber 25.

4
5 FIGS. 4 through 13 have been discussed as embodiments
6 wherein the IR source was located in the penetrometer tube 29
7 itself such that the soil sample 33 (FIG. 1) was between the IR
8 source 21 and the spectrometer 27. FIGS. 14 through 17 show
9 alternative embodiments wherein the IR source 21 is placed in the
10 same remote location, or surface, as the spectrometer 27 such
11 that light is transmitted in both directions through the optical
12 chalcogenide optical fiber 25: from the IR source 21 to the soil
13 sample 33 and from the soil sample 33 to the spectrometer 27 as
14 shown in Fig. 12. The exemplary embodiments of FIGS. 14-17 will
15 now be discussed.

16
17 FIG. 14 shows two different techniques for placing the IR
18 source 21 on the surface. Then the IR light from the source 21
19 can be coupled down into the probe or penetrometer tube 29 below
20 ground by way of a fiber coupler 65, the transmission/collection
21 optics 23 and the transmission window 31 and into the soil 33
22 (FIG. 1), and the reflected IR light returns to the fiber coupler
23 65 by way of the transmission window 31, the
24 transmission/collection optics 23. The returned reflected IR

1 light then passes through the fiber coupler 65 to a detector 57
2 in the spectrometer 27 (FIG. 1) for analysis. In a second
3 technique in FIG. 14, IR light from the source 21 passes through
4 a beam splitter or a bulk optic beam splitter 69 down to the
5 probe 29 and also directs reflected IR light that comes back from
6 the probe 29 to a detector 71 in the spectrometer 27 (FIG. 1) for
7 analysis.

8
9 FIG. 15 shows IR light coming from (the IR source 21 on) the
10 surface to the fiber 25, exiting the fiber 25. An ellipsoidal
11 mirror 59 is then used to transmit the IR light out into the soil
12 33 (FIG. 1), recover the light reflected from the soil 33 and
13 inject it back into the fiber 25.

14
15 In FIG. 16, the same operation is accomplished as in FIG.
16 15, using the combination of a lens 52 and a paraboloidal
17 mirror 53.

18
19 In FIG. 17, the same operation is accomplished as in FIG.
20 15, using the combination of a lens 52 and a flat mirror 63.

21
22 Advantages and New Features of the Invention

23 The essential new feature of this invention is the
24 combination of components, including IR source, nonimaging
25 optics, and most-importantly, IR-transmitting chalcogenide

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1 opitiical fiber, and optical signal processor or spectrometer to
2 produce a system capable of remote, in-situ fiber optic IR
3 spectroscopy in underground locations.

4 The advantages of the new system include: 1) the ability to
5 perform remote, in-situ fiber optic IR spectroscopy in the
6 wavelength range from 2 to 12 microns; 2) the ability to detect
7 and identify chlorinated solvents in-situ, in underground
8 locations; 3) the ability to identify the presence of individual
9 chemicals, including water, from analysis of the IR spectrum
10 obtained.

11
12 Alternatives

13 A system of the type described in this patent disclosure
14 could be assembled using either fluoride-based optical fibers or
15 sapphire-based optical fibers. Sapphire-based fibers are
16 difficult to produce in lengths greater than 10-20 meters, are
17 not mechanically robust in long lengths, and are hydroscopic,
18 making them difficult to use in uncontrolled, outdoor
19 environments. Fluoride-based fibers do not transmit into the
20 infrared as far as 10 microns, are also hydroscopic and are not
21 mechanically robust in long lengths. Polycrystalline halide
22 fibers can be used for slightly longer wavelengths (4-15 microns)
23 but require special handling procedures.

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1 Therefore, what has been described in a preferred embodiment
2 of the invention is a system for performing remote, in-situ
3 infrared (IR) spectroscopy of soils and soil-liquid mixtures in
4 the 2 to 12 micron wavelength range. Specifically, the
5 invention: I) provides the means for transmitting optical
6 radiation in the 2 to 12 micron wavelength range via a fiber
7 optic cable to an optical system in a cone penetrometer tube; II)
8 provides an optical system for the efficient and reproducible
9 transmission of infrared light to a region of the soil
10 surrounding the cone penetrometer tube; III) provides an optical
11 system for the efficient collection of the infrared light after
12 it has been diffusely-scattered by the soil; and IV) provides a
13 means for efficiently coupling light from the output of the
14 optical fiber into an optical signal processor, such as an
15 infrared spectrometer.

16 The novel features of the system disclosed here in this
17 application are the use of specially designed
18 transmission/collection optics for transmitting infrared light
19 out of a transmission window of a cone penetrometer tube into
20 soil around the window and recovering some of the reflected
21 scattered infrared light from the soil by way of the window and
22 the transmission/collection optics, and the incorporation of
23 optical fibers based on chalcogenide materials (S, Se, Te) which
24 transmit infrared radiation from 2 - 12 microns in a ruggedized

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Inventors: Frank Bucholtz et al.

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1 unit suitable for use in the field. This is the wavelength
2 region where unique infrared (IR) absorption features occur for
3 many chemical compounds. In particular, unique identification can
4 be made of water and soil mineralogy and environmentally
5 important contaminants such as chlorinated hydrocarbons, BTEX
6 compounds (benzene, toluene, ethylbenzene, and xylene) and fuels.

7
8 It should therefore readily be understood that many
9 modifications and variations of the present invention are
10 possible, It is
11 therefore to be understood that

12 the invention may be practiced otherwise than as
13 specifically described.

ABSTRACT OF THE DISCLOSURE

A system for the in-situ detection of chemicals, including water, in soil comprises: a penetrometer for penetrating the soil, the penetrometer including interior and exterior surfaces, and a window for allowing infrared radiation to be transmitted between the interior and exterior surfaces of the penetrometer; a driver for driving the penetrometer into the soil to a plurality of different depths; a source for providing infrared radiation which passes through the window to irradiate the soil adjacent to the window; an infrared transmitting chalcogenide optical fiber; an optical system disposed within the penetrometer adjacent to the window for transmitting infrared radiation from the source through the window into the soil and for collecting infrared radiation reflected from the soil back through the window into a first end of the chalcogenide fiber; and a spectrometer coupled to a second end of the infrared transmitting chalcogenide optical fiber for receiving and analyzing the reflected infrared radiation passing through the chalcogenide optical fiber to obtain information on chemicals present at various depths of the soil through which the penetrometer passes.

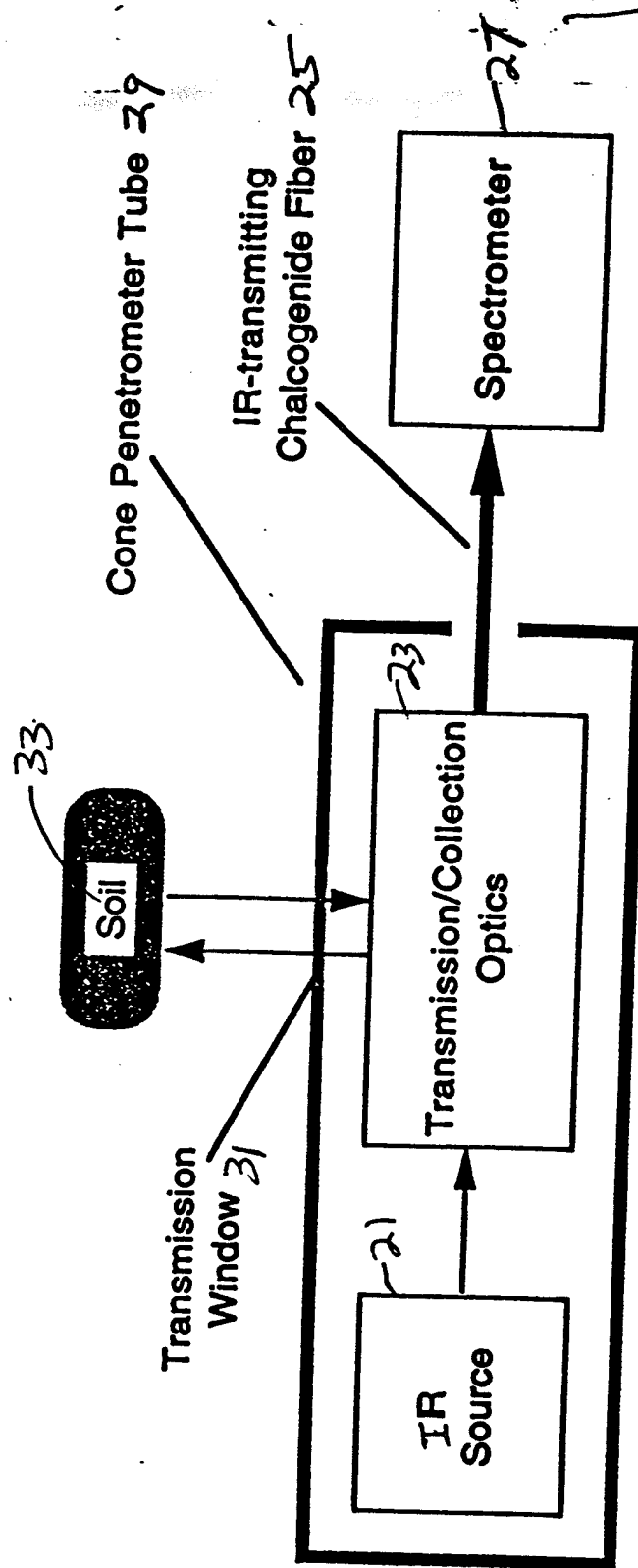


FIG. 1



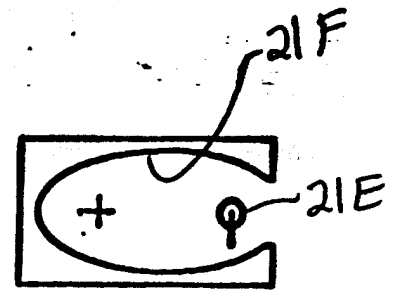
IR SOURCE IN
ELLISOIDAL OR
PARABOLOIDAL
REFLECTOR

FIG. 2A



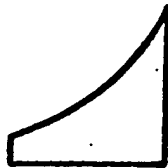
IR SOURCE IN
SPHERICAL
REFLECTING CAVITY

FIG. 2B



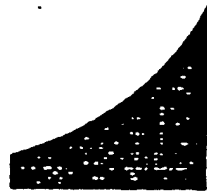
IR SOURCE IN
ELIPSOIDAL
REFLECTING CAVITY.

FIG. 2C



PARABOLOIDAL
MIRROR

FIG. 2D



ELLIPSOIDAL
MIRROR

FIG. 2E



FLAT MIRROR

FIG. 2F



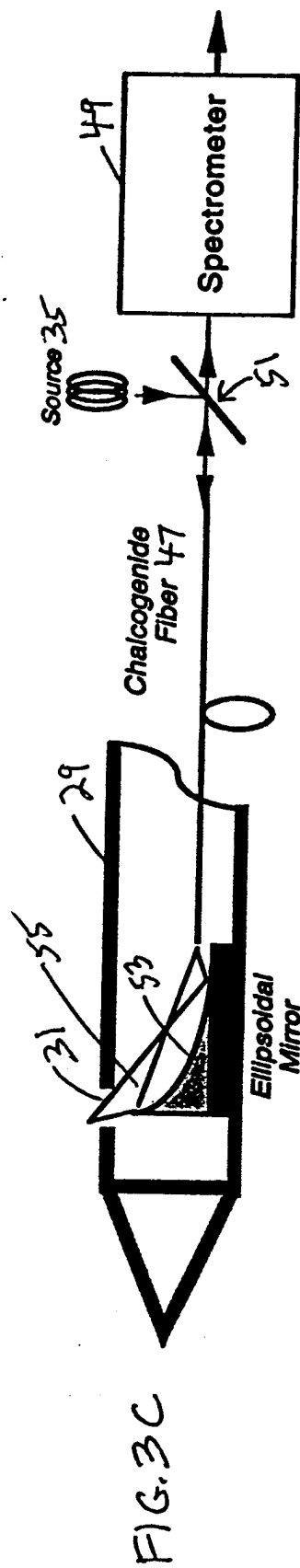
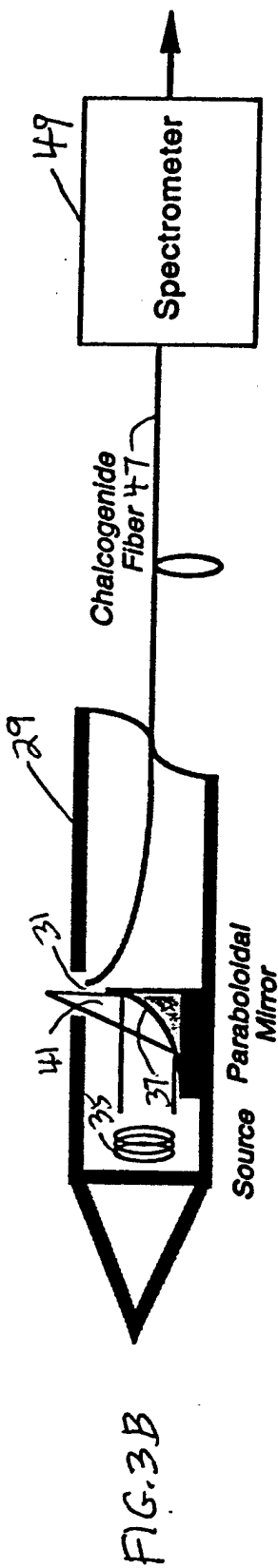
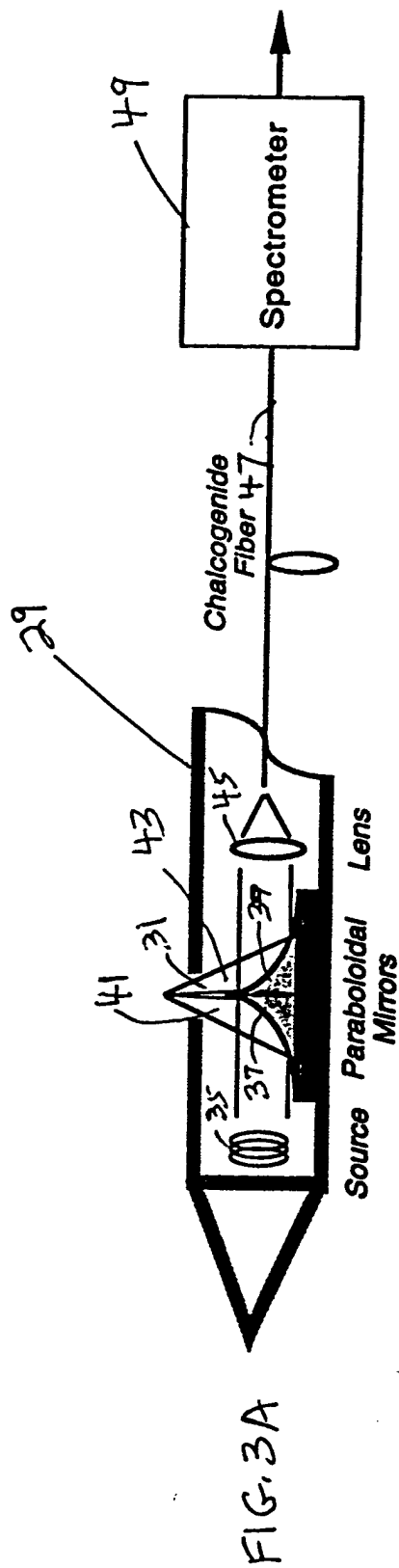
LIGHT REFLECTING
ON SOIL SURFACE.

FIG. 2G



COLLIMATING
OR FOCUSING
LENS.

FIG. 2H



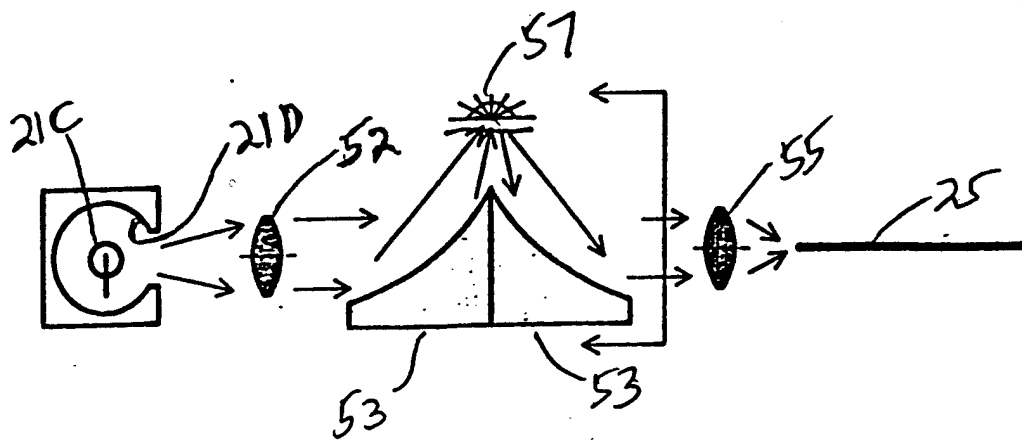


FIG. 4

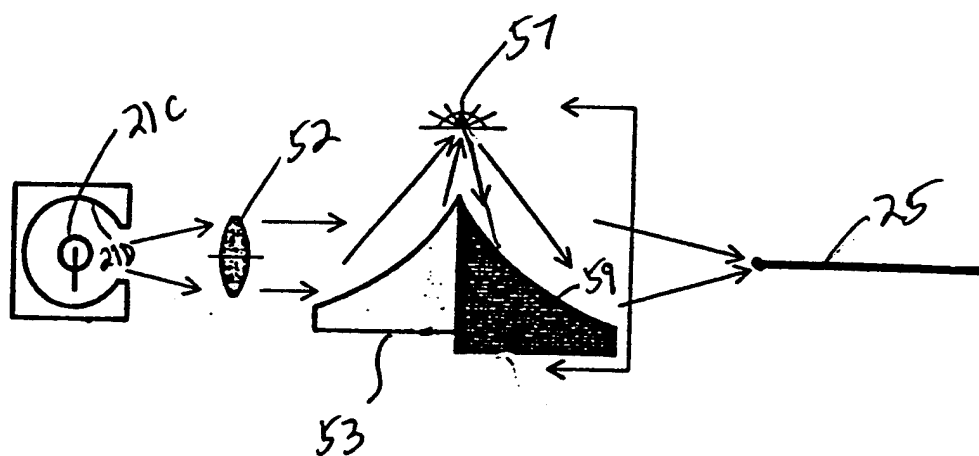


FIG. 5

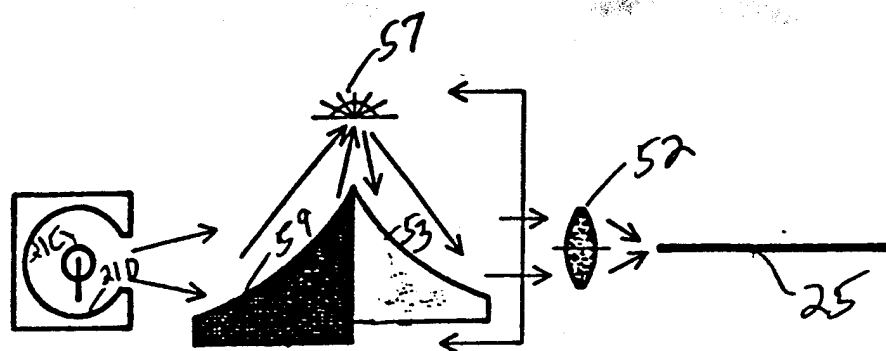


FIG. 6

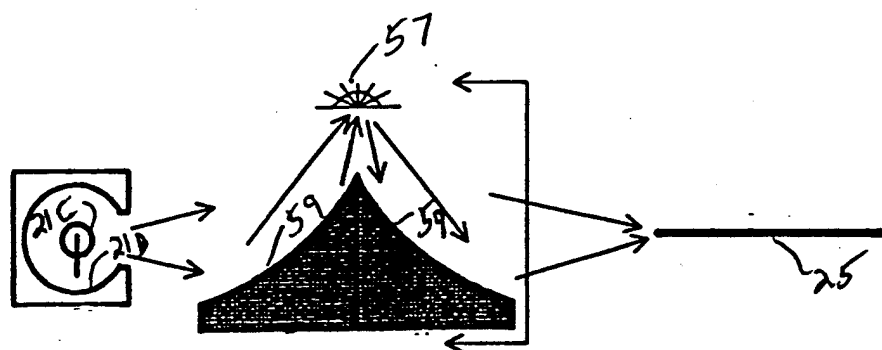


FIG. 7

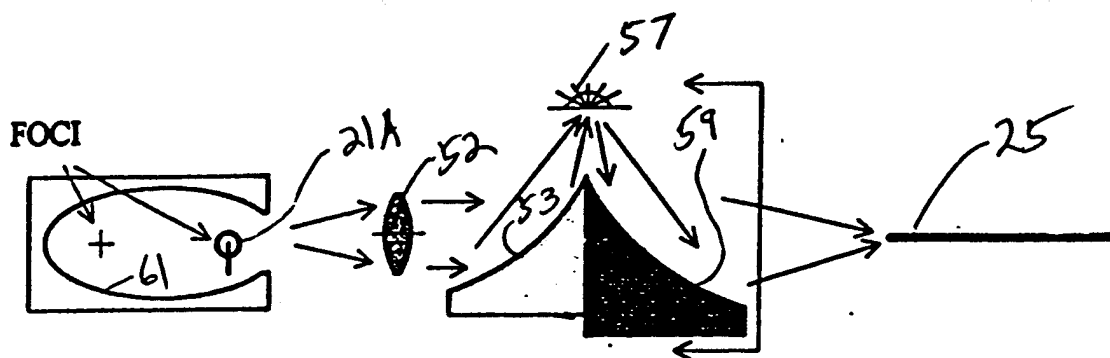


FIG. 8

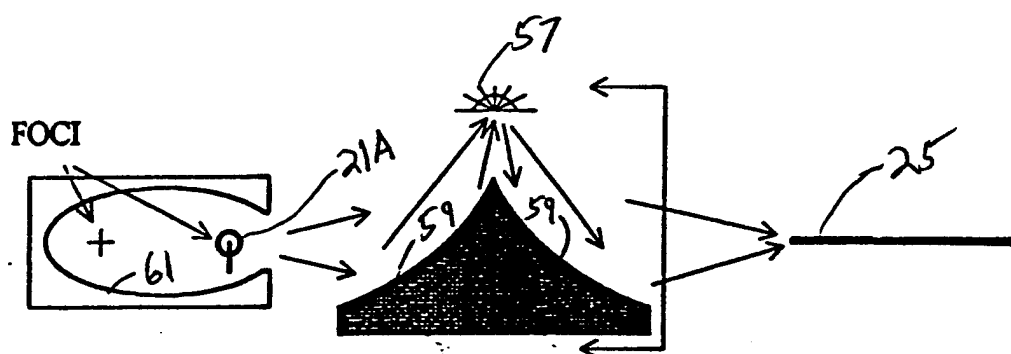


FIG. 9

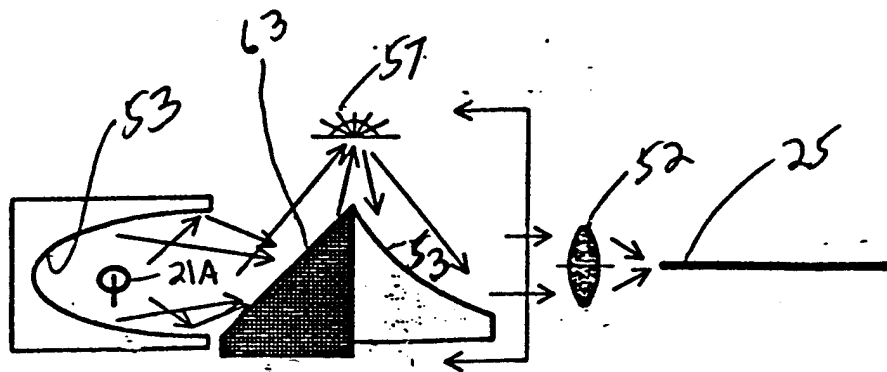


FIG. 10

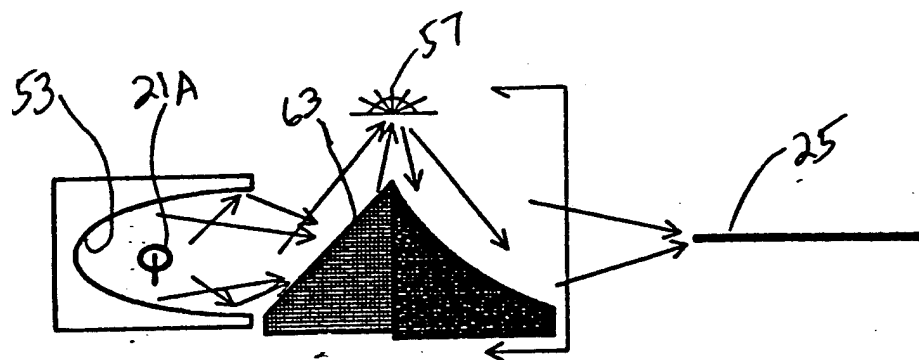


FIG. 11

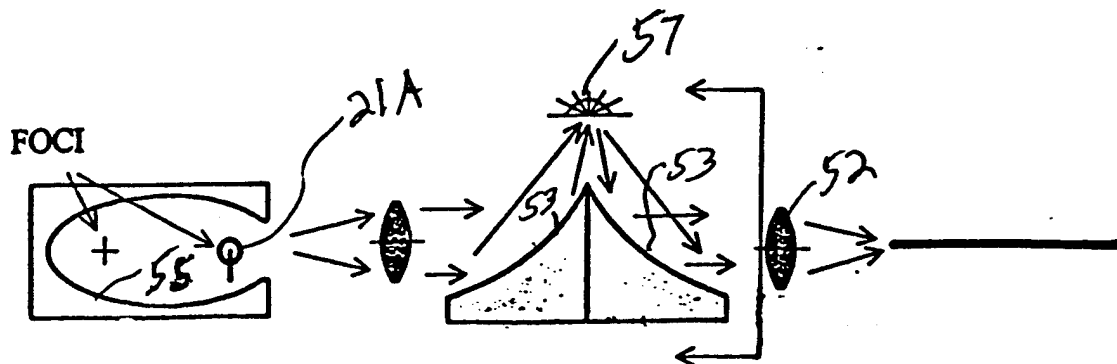


FIG. 12

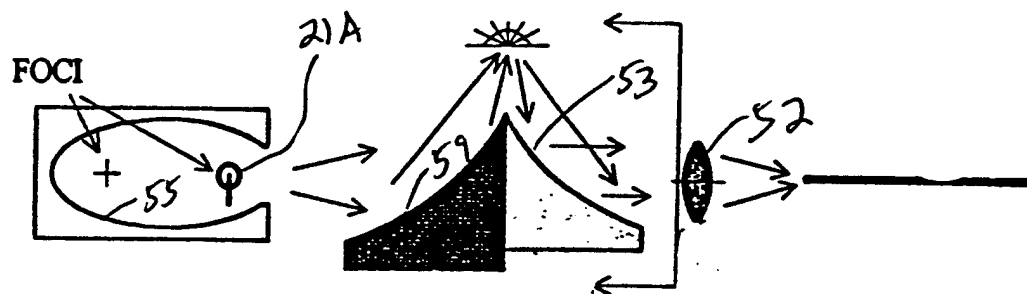


FIG. 13

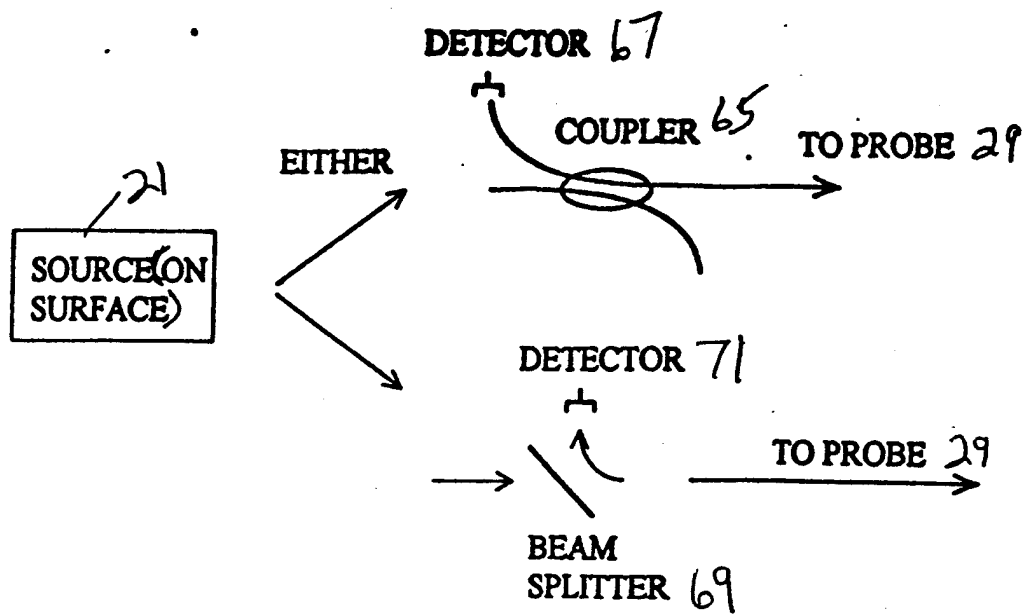


FIG. 14

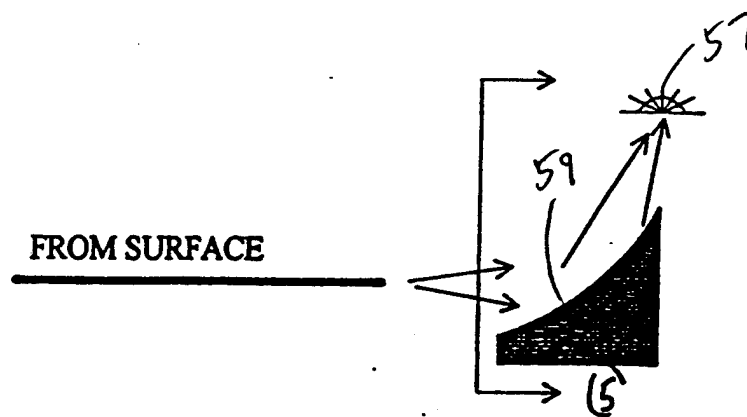


FIG. 15

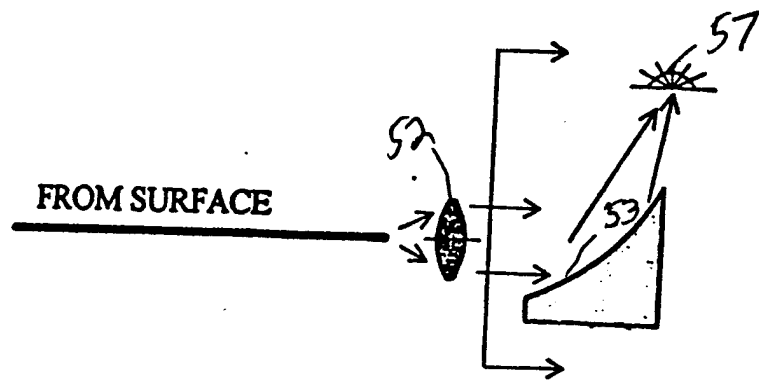


FIG. 16

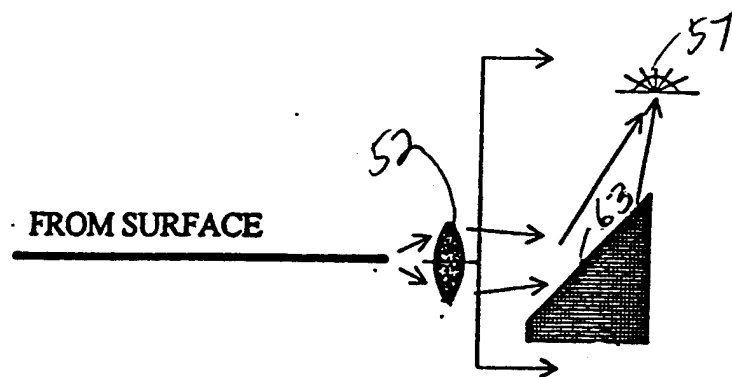


FIG. 17