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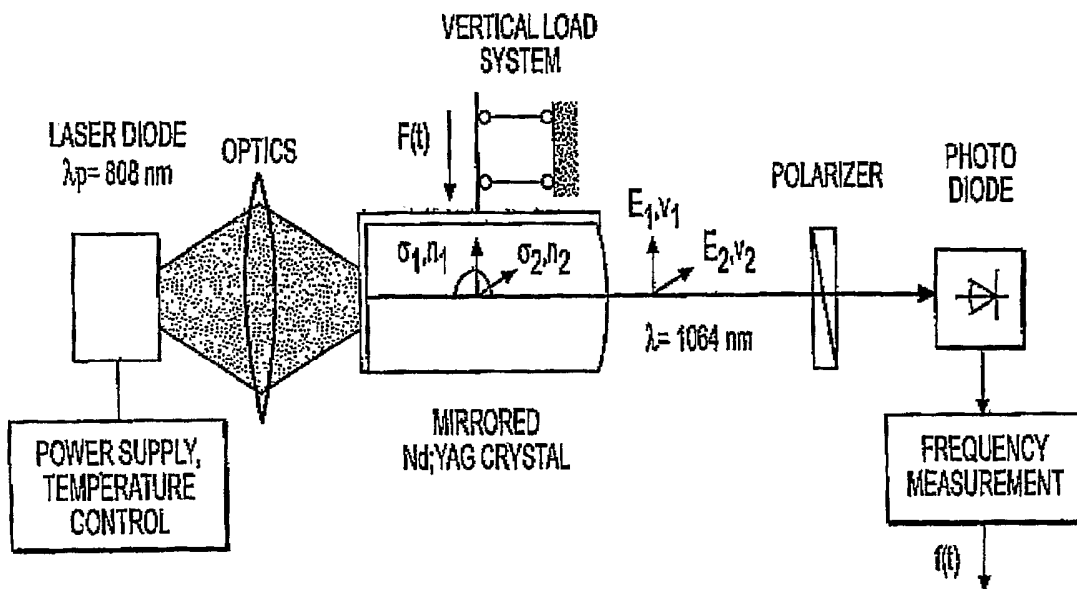
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(54) Title: COMPACT LASER SENSORS AND MONITORING SYSTEMS INCLUDING SUCH SENSORS



(57) Abstract: Improved laser sensors employing doped laser crystals for transducing output proportional to forces impinging upon the sensors. The disclosed sensors are compact, low powered and may be constructed relatively inexpensively from readily available materials. The disclosed sensors eliminate the need for costly, optical power-sapping fiber connections at the laser crystals. According to certain embodiments, the disclosed sensors are configured for local recovery of output signals using conventional digital telemetry. According to other embodiments, the sensors generate output through a dense wavelength division multiplexing (DWDM) laser, thereby allowing remote recovery without the need for frequency division multiplexing and issues involved with preloading the sensors to produce beat frequencies in unique bands.

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COMPACT LASER SENSORS AND MONITORING SYSTEMS INCLUDING SUCH
SENSORS

BACKGROUND

[0001] This application claims the benefit of U.S. provisional application no. 60/689,554, filed June 13, 2005 and entitled "Acoustic Sensor for Towed Array."

[0002] Doped lasing crystals, such as Neodymium Doped Yttrium Aluminum Garnet (Nd:YAG) crystals lase at their natural response wavelength when energized with light at their pump wavelength. Optically isotropic lasing crystals produce a single polarization of light at the natural response wavelength when pumped, whereas optically anisotropic lasing crystals produce two orthogonally oriented polarizations of light at the natural response wavelength when pumped. The generation of two orthogonally oriented polarizations is known as "birefringence."

[0003] The phenomenon of birefringence associated with doped lasing crystals enables the development of photonic sensors for simultaneous detection of various measurands. These measurands include, among others, acoustic field, depth (i.e., the imposition of a static pressure), multi-axis acceleration, particle velocity sensors, orientation sensors. It is known that the application of force to one face of an isotropic crystal creates a small shift in the lattice of the crystal, and thereby results in the temporary creation of an anisotropic crystal which results in a small change in the wavelength of the polarized light associated with the direction of the force. As the force is applied to the crystal, the unforced direction of the lasing crystal also generates light at the natural response frequency of the crystal. Thus, the crystal simultaneously produces two wavelengths of light in orthogonal polarizations that are nearly the same wavelength. The difference in wavelength can be measured as a beat frequency, which is proportional to the force imposed on the crystal.

[0004] FIG. 1 is a schematic representation of a force transducer apparatus taken from Holzapfel et al. (Holzapfel, W.; Neuschaefer-Rube, St.; Kobusch, M., "High-resolution, very broadband force measurements by solid-state laser transducers",

Measurement, vol. 28, pp. 277-291, (2000)). In the Holzapfel apparatus, a small diode laser produces a light at the pump wavelength (808 nm in the case of a Nd:YAG lasing crystal). The pump light is focused onto a first coated optical surface of the lasing crystal. A second coated surface of the lasing crystal then generates 1064 nm response light in two orthogonal polarizations. When a force is imposed on a top surface of the crystal, the vertical polarization wavelength of the response light is shifted slightly from its natural frequency. The polarized wavelengths of the response light are then combined with an optical polarizer and the difference frequency, or beat frequency, between the two polarizations are thereafter detected with a photodiode.

[0005] Holzapfel et al. used the apparatus of FIG. 1 to measure the beat frequencies for static and dynamic forces placed on Nd:YAG lasing crystals of various sizes with various loading rates. Holzapfel et al. showed that the change in the beat frequency for both statically and dynamically loaded crystals is linear for at least nine decades of force load. Furthermore, the results of the Holzapfel et al. experiments were consistent regardless of the size of the crystal or the method of loading the crystal. The results of the Holzapfel experiment lead to several observations, including: 1) the dynamic range of a sensor employing this concept is strictly limited by the ability to measure a change in the beat frequency of the polarized light; 2) the materials needed to manufacture such sensors are widely available, low-cost components; 3) accurate measurements can be made from DC to the limit of modern phase or frequency detector circuits; and 4) such sensors can be configured to measure force, acceleration, pressure and orientation.

[0006] The disclosure of U.S. Patent No. 6,693,848 to Ambs et al. builds upon the concepts disclosed by Holzapfel. In the '848 patent, Ambs et al. disclose a hydrophone that is an optically-pumped microchip laser that is powered by light at the pump frequency, and produces different beat frequencies related to a pressure field impinging on the microchip laser. Several microchip laser cavities are placed in a single fiber array using fiber splitters. Each crystal is precisely preloaded to produce beat frequencies in a unique band (analogous to wavelength division multiplexing). The pump laser is located near a dry side receiver inside a seismic exploration ship. The frequency of each sensor

is measured by placing a linear polarizer oriented at 45 degrees to one of the polarization axes of the sensor's output laser signal. The signal resulting from the polarizer is the beat frequency. Signals from the microchip lasers are reflected onto the single fiber and are converted to electrical energy by photodiodes. The beat frequency of each sensor is measured by a dry side FM receiver. The Ambs et al. approach is advantageous in comparison with conventional, passive optical fiber hydrophones which rely on intensity and/or phase modulation of a reference laser signal. In contrast to signals in passive optical fiber hydrophones, the frequency-modulated signals generated by the Ambs et al. microchip laser sensors are not affected by mechanical perturbations of the fiber telemetry link. Further, intensity fluctuations which can be problematic in interferometer-based passive techniques have no effect on the frequency modulated signals of the Ambs et al. system since the data is not encoded in the intensity.

[0007] There remains a need for laser sensors which provide improvements beyond the concepts disclosed by Holzapfel et al. and Ambs et al. In particular, one limiting factor of the seismic array design disclosed by Ambs et al. is the lack of sufficient optical power to create large, many-element arrays. Additionally, the use of fiber coupled to the laser crystals in the Ambs et al. design is costly and requires relatively high optical power for transmitting light through the fiber. Additionally, frequency division techniques are not scalable to larger arrays. It is therefore desirable to provide compact, low power laser sensors that eliminate the need for coupling fiber to the laser crystals. It is also desirable to provide laser sensors that eliminate the need for frequency division multiplexing and issues involved with preloading the sensors to produce beat frequencies in unique bands. It is further desirable to provide improved monitoring systems employing such laser sensors.

SUMMARY

[0008] The disclosure concerns improved laser sensors employing doped lasing crystals for generating output proportional to forces impinging upon the laser crystals. The disclosed sensors are compact, low powered and may be constructed relatively inexpensively from readily available materials. The disclosed sensors eliminate the need

for long, costly, optical power-sapping fiber optic cables between the lasing crystal and a pumping device for the lasing crystal and between the lasing crystal and an output detecting device for the lasing crystal. According to certain embodiments, the disclosed sensors are configured for local recovery of output signals using conventional digital telemetry. According to other embodiments, the disclosed sensors generate output signals through a dense wavelength division multiplexing (DWDM) laser, thereby eliminating the need for frequency division multiplexing and issues involved with preloading the sensors to produce beat frequencies in unique bands.

[0009] The disclosure further concerns seismic and sonar monitoring systems employing arrays of improved laser sensors. The sensor arrays are low powered and require a single fiber optic line connecting multiple sensors. Furthermore, the design of the sensor arrays is relatively simple, as there is no outboard logic in the sensor arrays and only passive electronics are employed.

[0010] According to one embodiment, a laser sensor comprises:

a doped lasing crystal arranged to generate a light at two different frequencies with two orthogonal polarizations, said light exhibiting a beat frequency between said two different frequencies which varies in accordance with a force incident upon the lasing crystal;

a pump diode generating an excitation light to drive said lasing crystal, said pump diode adjacent to and directly coupled to a first end of said lasing crystal by a direct butt-coupling integrated optic; and

a photodetector directly coupled to a second end of said lasing crystal by a direct butt-coupling integrated optic.

[0011] According to another embodiment, a monitoring system comprises:

a fiber optic transmission line;

a sensor array comprising at least two laser sensors, wherein each of said at least two laser sensors comprises:

a doped lasing crystal arranged to generate a light at two different frequencies with two orthogonal polarizations, said light exhibiting a beat frequency between said two different frequencies which varies in accordance with a force incident upon the lasing crystal;

a pump diode generating an excitation light to drive said lasing crystal, said pump diode adjacent to and directly coupled to a first end of said lasing crystal by a direct butt-coupling integrated optic;

a photodetector directly coupled to a second end of said lasing crystal by a direct butt-coupling integrated optic;

a dense wavelength division multiplexing laser in communication with said photodetector, said dense wavelength division multiplexing laser generating an output modulated by said output current and exhibiting frequency shifts proportional to said force; and

a fiber optic cable connected to said dense wavelength division multiplexing laser for transmitting said output, wherein said fiber optic cable is in communication with said fiber optic transmission line; and

a receiving unit arranged to process said output, said receiving unit comprising:

an optical demultiplexer connected to said fiber optic transmission line to demultiplex output light from said at least two laser sensors and to produce demultiplexed outputs; and

optical receivers in communication with said optical demultiplexer and arranged to process said demultiplexed outputs from said optical demultiplexer, wherein each of said optical receivers includes a photodiode for converting light into an electrical signal and an analog-to-digital converter for converting an output of said photodiode to digital data.

[0012] Other features and advantages will be come apparent from the description and drawings that follow.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. 1 is a schematic drawing of a conventional microchip laser sensor for measuring forces impinging upon the sensor.

[0014] FIG. 2 is a side sectional view of a novel laser sensor according to one embodiment.

[0015] FIG. 3 is an end view of the sensor of FIG. 2.

[0016] FIG. 4 is a partial top plan view of the sensor of FIG. 2.

[0017] FIG. 5 is a partial side view of the sensor of FIG. 2.

[0018] FIG. 6 is a partial top plan view of a novel laser sensor according to another embodiment.

[0019] FIG. 7 is a side sectional view of the laser sensor of FIG. 7.

[0020] FIG. 8 is a partial top plan view of a novel laser sensor according to yet another embodiment.

[0021] FIG. 9 is a side sectional view of the laser sensor of FIG. 8.

[0022] FIG. 10 is a partial top plan view of a novel laser sensor according to still another embodiment.

[0023] FIG. 11 is a side sectional view of the laser sensor of FIG. 10.

[0024] FIG. 12 is a graph providing an example of the response from a dense wavelength division multiplexing laser used in the sensors of FIGS. 2-7.

[0025] FIG. 13 is a graph showing an example of a typical channel response of a dense wavelength division multiplexing laser.

[0026] FIG. 14 is a graph showing applied pressure plotted against change in beat frequency for the disclosed laser sensors.

[0027] FIG. 15 is a graph showing the spectrum level associated with various sea-states.

[0028] FIG. 16 is a schematic drawing of a monitoring system according to another embodiment, wherein an array of laser sensors is parasitically powered.

[0029] FIG. 17 illustrates the connection of two laser sensors in the system of FIG. 16.

[0030] FIG. 18 is a schematic drawing of a monitoring system having a remote power source supplying power to an array of laser sensors.

DETAILED DESCRIPTION

[0031] FIGS. 2-5 show a laser sensor **10** according to one embodiment. The laser sensor **10** may be used, for example as an acoustic sensor in a towed sensor array of an aquatic seismic or sonar monitoring system. Referring to FIGS. 1 and 2, the sensor **10** includes a housing **12** encasing an internal sensing unit **14**. The sensing unit **14** is supported in the housing **12** by polymer potting **16**. As shown in FIGS. 1 and 2, the housing **12** may be cylindrical. However, other shapes are possible for the housing.

[0032] Referring to FIGS. 2, 4 and 5, the internal sensing structure **14** includes an active sensing unit **17**, a baseboard **18** and an electrical and photonic circuit **20** supported by the baseboard **18**. The circuit **20** includes a low-power pump diode **22**, an anisotropic (birefringent) crystal laser **24**, a compact, low-power photodetector (e.g., photodiode) **26** and a dense wavelength division (DWDM) laser **28**. A low-pass filter **29** may also be provided.

[0033] As shown in FIGS. 2, 3 and 5, a capacitor **44** is provided for storing electrical power to be supplied to the circuit **20**. As will be described in a further embodiment directed to a seismic and sonar monitoring system, the capacitor **44** enables powering of the sensor **10**. The capacitor **44** may be attached on a side of the baseboard

18 opposite the side on which the other elements of the circuit **20** are attached. Such an arrangement allows the capacitor **44** to be relatively large to ensure adequate power storage. A DC power regulator and trickle charger unit **46** is also provided for controlling charging of the capacitor as well as the supply of electrical power to the circuit **30**.

[0034] The lasing crystal **24** is constructed to emit an output light signal at a natural response wavelength. The lasing crystal **24** may have a cross-sectional area of 1 mm² or less and may be, for example, an Nd:YAG lasing crystal having a pump wavelength of 808 nm and a response wavelength of 1064 nm. Other possible lasing materials for the crystal **24** include, but are not limited to, Nd:YV04, Nd:YLF, Ti:Sapphire, Yb:YAG, Er:YAG ND:Ce:YAG and Ho:Cr:Tm:YAG. The pump diode **22** is located adjacent to and directly coupled to a first side of the lasing crystal **24** by a first direct butt-coupling integrated optic **30**. The size and materials of the crystal **24** can be tailored to meet the specific needs of an application. The photodetector **26** is located adjacent to and directly coupled to a second side of the lasing crystal **24** opposite the first side by a second direct butt-coupling integrated optic **32**. The direct butt-coupling integrated optics **30** and **32** may include glass feral mounts and alignment optics bonded to the crystal by a UV epoxy. When a Nd:YAG lasing crystal is used, the pump diode **22** generates pump light at a wavelength of 808 nm and the photodetector **26** converts 1064 nm wavelength light to electrical energy.

[0035] The DWDM laser **28** is connected in the circuit **20** such that it is driven by output current of the photodetector **26**. As shown in FIG. 4, the DWDM laser **28** is connected to a fiber optic cable **38** in the sensor by a fiber branch **40** at junction **41**.

[0036] The sensor **10** further includes an input fiber connector **50** connected to an input end **38a** of the fiber optic cable **38** and an output fiber connector **52** connected to an output end **38b** of the fiber optic cable **38**. The connectors **50**, **52** may be surface mounted on the baseboard **18** and extend outside the housing **12** for connection to upstream and downstream segments of an external fiber optic transmission line.

[0037] In operation of the sensor, the pump diode 22 focuses an optical beam on the laser crystal 24, causing the laser crystal 24 to lase a response light signal at the response wavelength of the crystal 24. The response light signal has two orthogonal wavelengths of slightly different frequency. The difference in the frequencies of the two polarizations is the beat frequency of the response light signal.

[0038] The photodetector 26 receives the response light signal and converts the energy from the response light signal into electrical energy in the form of an output current which is proportional to the beat frequency of the response light signal. The DWDM laser 28 generates an output light signal based on the output current of the photodetector 26. In particular, the output current of the photodetector 26 is used as a modulation signal which is applied to the DC bias current on the DWDM laser 28. Thus, the frequency of the output light signal from the DWDM laser 28 is proportional to the output current of the photodetector 26. Since the photodetector 26 is capable of generating frequencies above the frequency range in which useful information is carried, the low-pass filter 29 cuts off frequencies from the photodetector above a specified threshold.

[0039] The output light signal from the DWDM laser 28 is transmitted to the fiber optic cable 38, from which the output light signal can be transmitted into an external fiber optic transmission line (i.e., fiber telemetry link) of a seismic and sonar monitoring system. As will be described in greater detail in further embodiments, output light signals from one or more additional sensors in a sensor array may be passed through the fiber optic cable 38 of the sensor 10 via the input connector 50 and the output connector 52.

[0040] The low-pass filter 29 is a passive circuit used to limit the transmission bandwidth to the maximum bandwidth of the DWDM laser.

[0041] The active sensing element 17 couples the measurand to the lasing crystal 24 with gain that is related to its mass, impedance, and surface area. When a dynamic force is applied to the sensor 10 (e.g., acoustic pressure), the force is acts on the crystal 24 via the active sensing element 17, and causes a shift in the beat frequency of the crystal's

response light signal. The beat frequency of the response light signal is proportional to the force applied to the crystal **24**. The shift in beat frequency in proportion to applied force has been shown to be linear for over nine decades for Nd:YAG laser crystals. Since the output current of the photodetector **26** is proportional to the beat frequency of the response light signal, and the output light signal of the DWDM laser **28** is proportional to the output current of the photodetector **26**, one can determine the magnitude of dynamic forces acting on the sensor **10** based on changes in the frequency of the output light signal of the DWDM laser **28**.

[0042] A static force applied to the sensor **10** causes a DC shift in the beat frequency of the response light signal. Thus, because static pressure is directly proportional to depth, the depth of the sensor **10** can also be determined based on DC frequency changes in the output light signal due to DC shifts in the beat frequency. In other versions of the sensor **10**, one can determine the orientation of the sensor **10** with respect to the gravitational field by coupling a mass (not shown) to the crystal **24**, decoupling the mass from the pressure sensing function and reading the change in the output frequency of the DWDM laser **28**. Thus, acoustic pressure, sensor depth and the orientation of the sensor **10** relative to the gravitational field of the Earth can be measured simultaneously.

[0043] The sensitivity of the sensor **10** increases inversely in proportion to the cross-sectional area of the lasing crystal **24**. For a common crystal size of 0.1 mm^2 and using a typical design for a coupling to the measurand using an impedance-matched surface with a pin or lever coupled to the crystal transducer surface, a sensitivity of 10 GHz of change in beat frequency per Newton can be achieved. According to a conservative expectation for the sensor **10**, a pressure field of 8,000 Pa would translate to 1 N of force applied to the crystal. This is the equivalent of transferring the force applied to a flexible disc of 1 cm radius to the crystal **24**. As shown in experiments by Holzapfel et al., the stability of the beat frequency is 3 Hz over a 60-second sample period. With a sensitivity of 10 GHz of change in beat frequency per Newton, 3 Hz equates to about 0.2 μPa or -12 dB re 1 μPa . FIG. 14 shows pressure versus change in beat frequency for a crystal **24**.

[0044] For comparison, FIG. 15 illustrates the spectrum level associated with various sea-states (taken from "Principles of Underwater Sound, 3rd Edition, Urick, 1983, pg. 210). FIG. 15 shows that, at the frequency range of interest (DC to less than 25 kHz), even sea state 0 is typically above 30 dB re 1 μ Pa, although 20 dB is often used as a good sensor noise floor. Referring back to FIG. 14, the target 20 dB noise floor is indicated by the horizontal line, and a minimum of 120 dB dynamic range is indicated by the vertical arrow line. The dynamic range and noise floor of the sensor **10** is dictated by the ability to resolve the change in beat frequency. Therefore, the dynamic range of the sensor **10** is really only limited by the bandwidth of the photodetector **26** and the sampling rate of the frequency detection device being used to read the sensor output.

[0045] The sensor **10** provides significant advantages over conventional, passive optical-fiber hydrophones, which rely upon intensity and/or phase modulation of a reference laser signal, and conventional PZT sensors which have relatively low sensitivity. In contrast to the output signals of passive optical-fiber hydrophones, the frequency-modulated output signals from the DWDM laser **28** in the sensor **10** are unaffected by perturbations of the fiber telemetry link to which the sensor **10** is connected. Intensity fluctuations which can plague interferometer-based passive techniques have no effect on the frequency modulated signals of the DWDM laser **28**, since the data is not encoded in the intensity of the signal. Because the frequency modulation of the output signal is encoded at the sensor **10** and cannot be shifted or otherwise compromised by the telemetry system in which the sensor **10** is employed, the sensor **10** provides a robust noise rejection scheme that is somewhat analogous to common mode rejection in electrical circuits.

[0046] Additionally, measurement or sampling of the carrier frequency from the crystal laser **24** is not required, resulting in lower cost and simpler design of transmission and receiving systems incorporating the sensor **10**. When multiple sensors **10** are used in a sensor array, the use of the DWDM laser **28** eliminates the need for frequency division multiplexing and issues associated with pre-loading each sensor to offset the frequency response range of each sensor **10**, because each sensor **10** generates an output light signal in its own discrete wavelength. Where a 1550 nm International Telecommunications

Union (ITU) grid telemetry laser is used for the DWDM laser **28**, 25 GHz channel spacing with 166 channels on the grid is widely available for use in a sensor array. FIGS. 12 and 13 show the C-Band response and typical channel response, respectively, of a commercially available ITU grid laser having 100 GHz channel spacing (ITU G.692).

[0047] The sensor **10** is also advantageous in that it is small in size, requires no digital logic in the sensor itself and can be constructed relatively inexpensively from widely available components. The sensor **10** may be as small as 12 mm in diameter and 25 mm in length. The baseboard **18** may be as small as 10mm wide by 25mm long, including the fiber connectors **50** and **52**.

[0048] FIGS. 6 and 7 show a laser sensor **10a** according to another embodiment, wherein reference numbers repeated from FIGS. 2-5 indicate similar components. Laser sensor **10a** is similar to laser sensor **10**, except that sensor **10a** lacks the capacitor **44** and DC power regulator and trickle charger unit **46** included in the sensor **10**. Thus, the sensor **10a** must be powered by an external power supply.

[0049] FIG. 16 shows a seismic and sonar monitoring system or telemetry system **100** including a towed sensor array **110** a receiving unit **150**. The sensor array **110** is located on the wet side of the system **100** (i.e., in a body of water). The receiving unit **150** is located on the dry side of the system **100** (i.e., aboard a ship).

[0050] The sensor array **110** includes a plurality (S_1-S_n) of laser sensors **10** connected in series along a fiber optic transmission line or telemetry backbone **112**. The fiber optic transmission line **112** may be a single-mode optical fiber and is only required to carry output signals from the sensors **10** to the receiving unit **150**. The input connector **50** of each sensor **10** (except for the last sensor in the line **112**) is connected to a downstream portion of the transmission line **112** by the input connector **50**, while the output connector **52** of each sensor **10** is connected to an upstream portion of the transmission line **112**. Thus, the output light signal of each sensor **10** is carried by the transmission line and is passed through any upstream sensors (via the fiber optic cable **38** in each sensor) to the receiver unit **150**. Where 1550 nm ITU grid telemetry lasers are used for the DWDM lasers **28**, many unique 2.5 Gbps channels are available, meaning

that the number of sensors **10** that can be used per transmission line **112** is limited only by the number of ITU grid channels.

[0051] Referring to FIGS. 16 and 17, piezoelectric (PZT) fibers **114** extend between adjacent sensors **10** and are operatively connected to the capacitor **44** of each sensor. Vibration and tension in the fibers **114** parasitically powers the sensors **10**, thereby eliminating the need for a dry-side power supply. As shown in FIG. 17, slack **113** is provided in the fiber optic transmission line **112** in order to prevent stress in the fiber connection between sensors **10**. Additionally, strength members **116** that are slightly longer than the PZT fibers **114** are placed between adjacent sensors **10** in order to limit tension in the PZT fibers.

[0052] The receiver unit **150** includes a main receiver **152**, a plurality of optical receivers **154** in communication with the main receiver **152**, and an optical demultiplexer **156** connected to the optical receivers **154** and the fiber optic transmission line **112**. The optical demultiplexer demultiplexes the light output signals from each sensor **10** and transmits demultiplexed light signals to the optical receivers **154**. An optical receiver **154** is provided for each sensor **10** in the array **110**. Each optical receiver **154** includes photodiodes **158** for converting the demultiplexed light signals to electrical signals and further includes analog-to-digital converters (ADCs) or frequency modulation (FM) receiver devices **160** for converting the electrical signals from the photodiodes **158**. Other frequency detection means, including frequency-to-voltage circuits such as the commercially available Phase Locked Loops (PLLs), may be used instead of the ADCs and FM receivers **160**. The main receiver **152** decodes the output of the optical receivers **154** and communicates the decoded information to sonar equipment.

[0053] FIG. 18 illustrates another seismic or sonar monitoring system **200**, which is similar to system **100**, except that system **200** includes a towed sensor array **210** with sensors **10a** and does not employ parasitic powering of the array **210**. In stead of PZT fibers **114** and the associated tension limiting strands **116**, a power supply **170** is provided on the dry side of the system **200**. The power supply **170** is connected to each

sensor by an electrical power line 172 and branch lines 174, thereby supplying the necessary power to each sensor 10a.

[0054] The arrays 110 and 210 require three orders less power than conventional towed arrays, due in part to the location of individual, low-power pump diodes 22 in each sensor 10, and due to the elimination of fiber connections between the pump diodes 22 and the respective lasing crystals 24 and between the photodetectors 26 and the respective lasing crystals 24. The pump diode 22 and photodetector 26 require only about 5 μ W each. The DWDM laser 28 also contributes to low power consumption, as a 166-channel ITU grid laser requires only about 10 μ W of power. Due to the high bandwidth of DWDM lasers 28 and the low power consumption of the sensors 10, the disclosed towed sensor arrays can be scaled up to extremely large sizes that are not possible with conventional towed sensor arrays. Furthermore, the disclosed arrays require much fewer optical fiber connections and electrical connections than conventional arrays, resulting to less expense and simpler design. Additionally, completely redundant arrays can be achieved by using two fiber optic transmission lines 112. In the redundant configuration, two uplink fibers 112 will be used and a single ITU grid laser will be capable of driving two fibers in parallel.

[0055] FIGS. 8 and 9 show laser sensor 60 according to an additional embodiment. The laser sensor 60 shares components with the sensor 10 of FIGS. 2-5, except that the sensor 60 is modified for local recovery of the sensor's output signal. The sensor 60 includes a FM receiver 54 which decodes the output signal of the photodetector 26. Information may be recovered locally from the FM receiver 54 by known digital telemetry techniques in order to determine sensor depth, sensor orientation and acoustic pressure acting on the sensor 60. As there is no optical output signal in the sensor, there is no need for an optical fiber or optical inputs/outputs. The sensor 60 may be powered parasitically in the same manner as the sensors 10 in the embodiment of FIGS. 16 and 17.

[0056] FIGS. 10 and 11 show yet another embodiment of a laser sensor 60a. Sensor 60a is similar to sensor 60, except that it lacks the capacitor 44 and DC power

regulator and trickle charger unit **46** included in the sensor **60**. Thus, the sensor **60a** must be powered by an external power supply.

[0057] The embodiments described hereinabove are further intended to explain best modes known of practicing the invention and to enable others skilled in the art to utilize the invention in such, or other, embodiments and with the various modifications required by the particular applications or uses of the invention. Accordingly, the description is not intended to limit the invention to the form disclosed herein. Also, it is intended that the appended claims be construed to include alternative embodiments, not explicitly defined in the detailed description.

CLAIMS

We claim:

1. A laser sensor comprising:

a doped lasing crystal arranged to generate a light at two different frequencies with two orthogonal polarizations, said light exhibiting a beat frequency between said two different frequencies which varies in accordance with a force incident upon the lasing crystal;

a pump diode generating an excitation light to drive said lasing crystal, said pump diode adjacent to and directly coupled to a first end of said lasing crystal by a direct butt-coupling integrated optic; and

a photodetector directly coupled to a second end of said lasing crystal by a direct butt-coupling integrated optic.

2. The laser sensor of claim 1, further comprising an FM receiver capable of reading output current from said photodiode.
3. The laser sensor of claim 2, further comprising a baseboard including a circuit, wherein said lasing crystal, said pump diode, said photodetector and said FM receiver are attached to said baseboard and form part of said circuit.
4. The laser sensor of claim 3, wherein said circuit comprises a capacitor attached to said baseboard and arranged to store power to be supplied to said circuit.
5. The laser sensor of claim 4, wherein said circuit further comprises a DC power regulator and trickle charger unit arranged to charge said capacitor and regulate said power.

6. The laser sensor of claim 1, comprising:

a dense wavelength division multiplexing laser in communication with said photodetector, said dense wavelength division multiplexing laser generating an output modulated by output current from said photodetector and exhibiting frequency shifts proportional to said force; and

a fiber optic cable connected to said dense wavelength division multiplexing laser for transmitting said output.

7. The laser sensor of claim 6, comprising at least one fiber connector connected to said fiber optic cable, said at least one fiber connector being arranged for connection to a fiber optic transmission line.

8. The laser sensor of claim 6, comprising a baseboard including a circuit, wherein said lasing crystal, said pump diode, said photodetector and said dense wavelength division multiplexing laser are attached to said baseboard and form part of said circuit.

9. The laser sensor of claim 8, wherein said circuit comprises a capacitor attached to said baseboard and arranged to store power to be supplied to said circuit.

10. The laser sensor of claim 9, wherein said integrated circuit comprises a DC power regulator and trickle charger arranged to charge said capacitor and regulate said power.

11. The microchip laser sensor of claim 9, wherein said at least one fiber optic connector comprises:

an input connector connected to an input end of said fiber optic cable; and

an output connector connected to an output end of said fiber optic cable.

12. The microchip laser sensor of claim 6, wherein said dense wavelength division multiplexing laser is a 1550 nm ITU grid telemetry laser.
13. A seismic or sonar monitoring system comprising:
- a fiber optic transmission line;
 - a seismic or sonar sensor array comprising at least two laser sensors, wherein each of said at least two laser sensors comprises:
 - a doped lasing crystal arranged to generate a light at two different frequencies with two orthogonal polarizations, said light exhibiting a beat frequency between said two different frequencies which varies in accordance with a force incident upon the lasing crystal;
 - a pump diode generating an excitation light to drive said lasing crystal, said pump diode adjacent to and directly coupled to a first end of said lasing crystal by a direct butt-coupling integrated optic;
 - a photodetector directly coupled to a second end of said lasing crystal by a direct butt-coupling integrated optic;
 - a dense wavelength division multiplexing laser in communication with said photodetector, said dense wavelength division multiplexing laser generating an output modulated by output current from said photodetector and exhibiting frequency shifts proportional to said force; and
 - a fiber optic cable connected to said dense wavelength division multiplexing laser for transmitting said output, wherein said fiber optic cable is in communication with said fiber optic transmission line; and

a receiving unit arranged to process said output, said receiving unit comprising:

an optical demultiplexer connected to said fiber optic transmission line to demultiplex output light from said at least two laser sensors and to produce demultiplexed outputs; and

optical receivers in communication with said optical demultiplexer and arranged to process said demultiplexed outputs from said optical demultiplexer, wherein each of said optical receivers includes a photodiode for converting light into an electrical signal and an analog-to-digital converter for converting an output of said photodiode to digital data.

14. The seismic monitoring system of claim 13, wherein each of said at least two laser sensors comprises a baseboard including a circuit, wherein said lasing crystal, said pump diode, said photodetector and said dense wavelength division multiplexing laser are attached to said baseboard and form part of said circuit.

15. The seismic monitoring system of claim 14, comprising a PZT fiber extending between adjacent laser sensors among said at least two laser sensors, wherein said PZT fiber is arranged to generate power from vibration and or tension of the PZT fiber, and wherein said integrated circuit comprises a capacitor attached to said baseboard and arranged to store said power for powering said circuit.

16. The seismic or sonar monitoring system of claim 15, comprising a strength member tension limiter extending between said adjacent laser sensors.

17. The seismic or sonar monitoring system of claim 15, wherein said circuit comprises a DC power regulator and trickle charger arranged to charge said capacitor and regulate said power.

18. The seismic or sonar monitoring system of claim 13, wherein each of said at least two laser sensors comprises at least one fiber connector connecting said fiber optic cable to said fiber optic transmission line.

19. The seismic or sonar monitoring system of claim 13, wherein one or more of said at least two laser sensors comprises:

an input fiber connector connected to an input end of said fiber optic cable and a downstream portion of said fiber optic transmission line; and

an output fiber connector connected to an output end of said fiber optic cable and an upstream portion of said fiber optic transmission line.

20. The seismic or sonar monitoring system of claim 13, wherein said dense wavelength division multiplexing laser is a 1550 nm ITU grid telemetry laser.

21. The seismic or sonar monitoring system of claim 13, comprising a power supply for powering said at least two laser sensors, wherein said power is located remotely from said at least two laser sensors.

22. The seismic or sonar monitoring system of claim 13, wherein said receiving unit is located at a dry side of said monitoring system and wherein said sensor array is located at a wet side of said monitoring system.

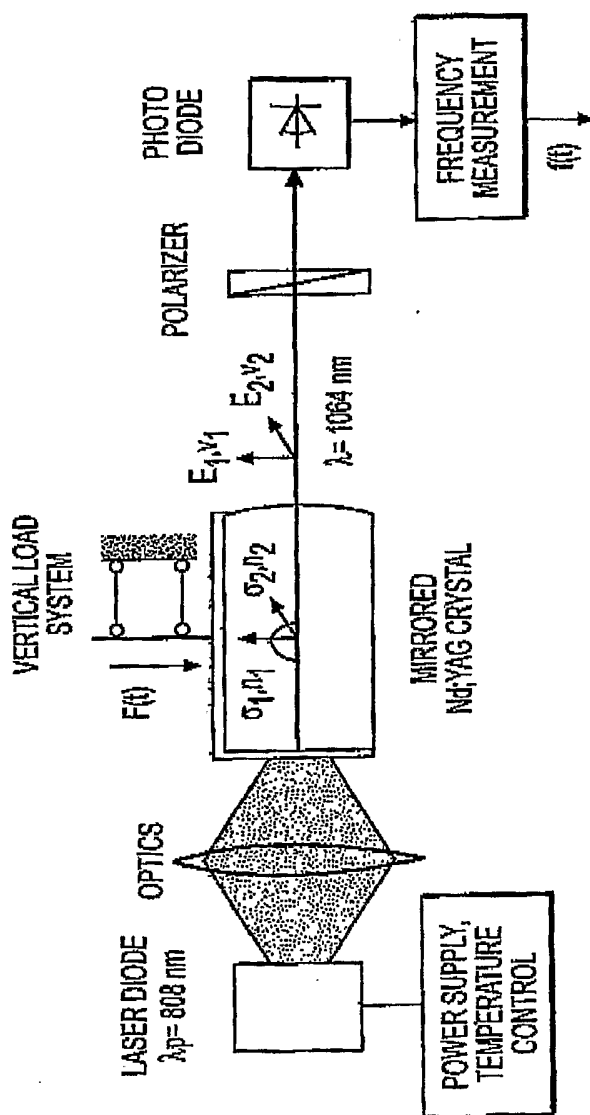


FIG. 1

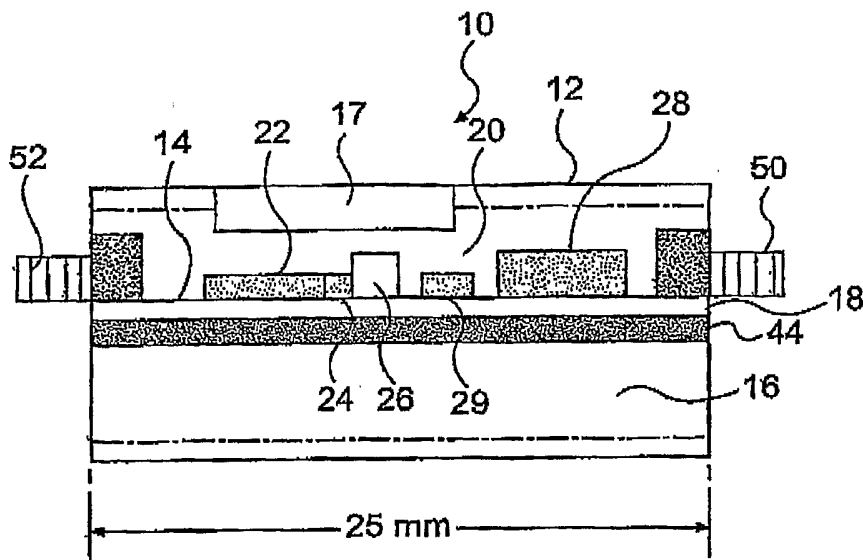


FIG. 2

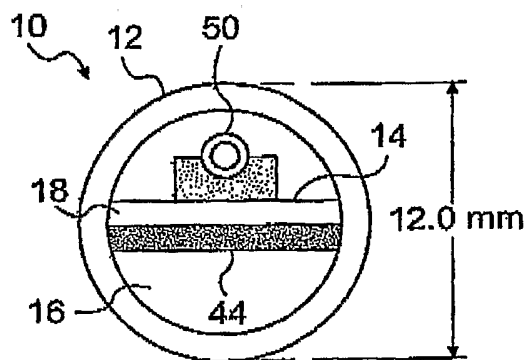


FIG. 3

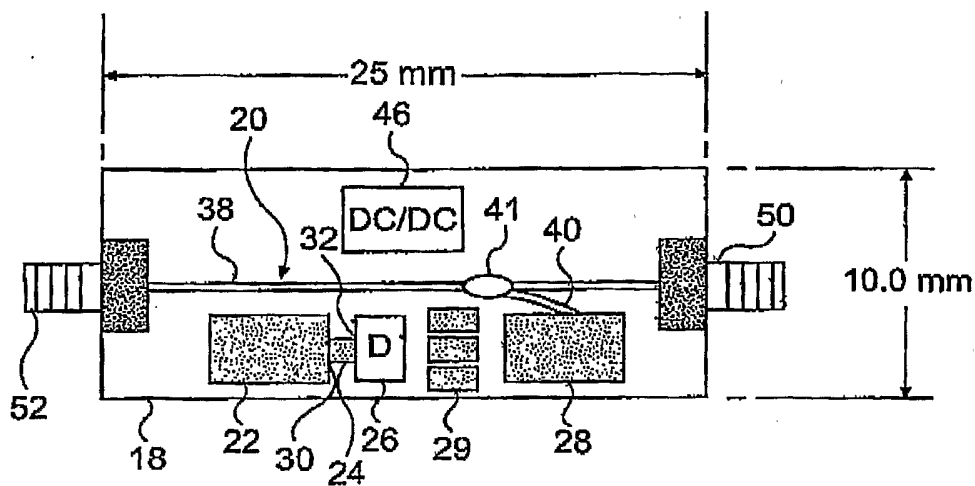


FIG. 4

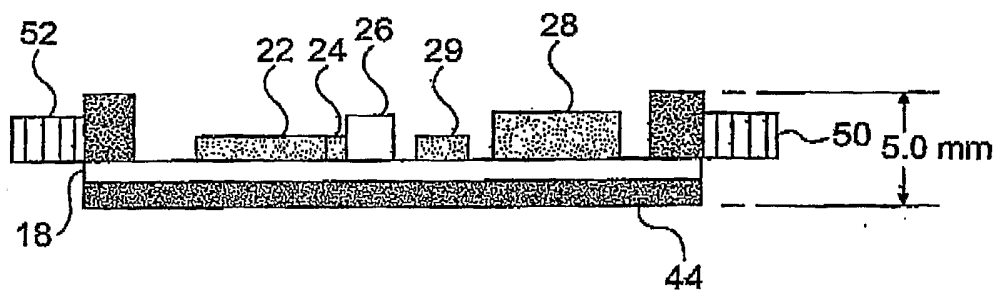


FIG. 5

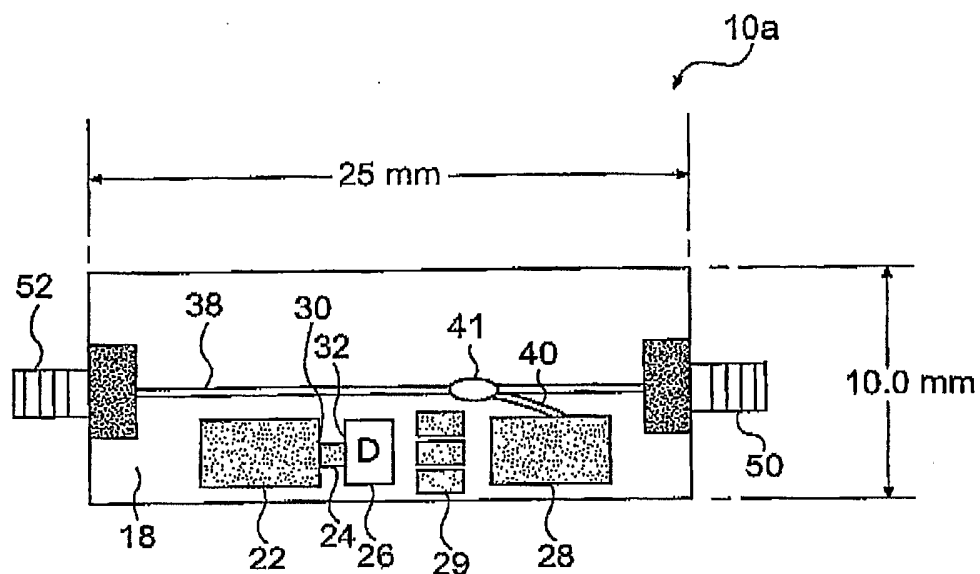


FIG. 6

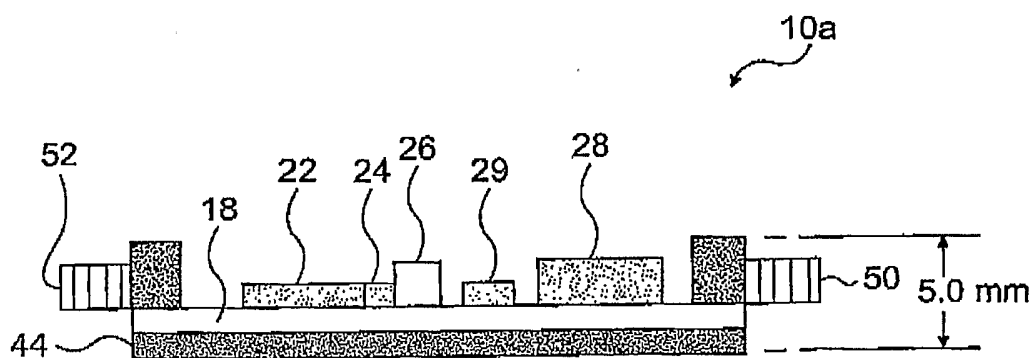


FIG. 7

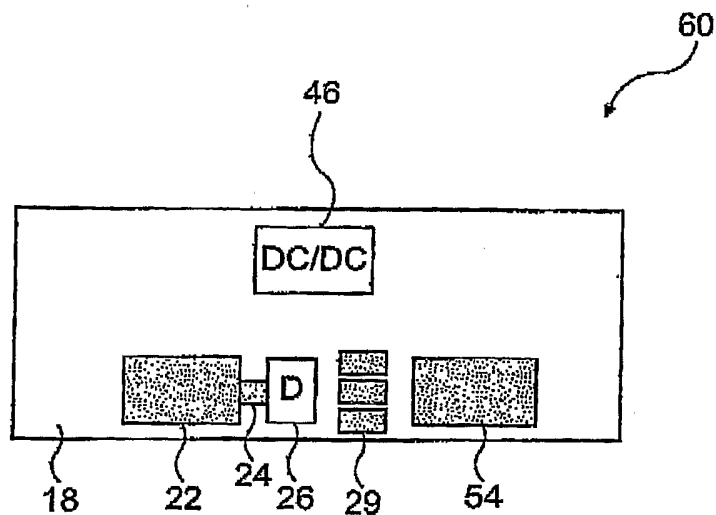


FIG. 8

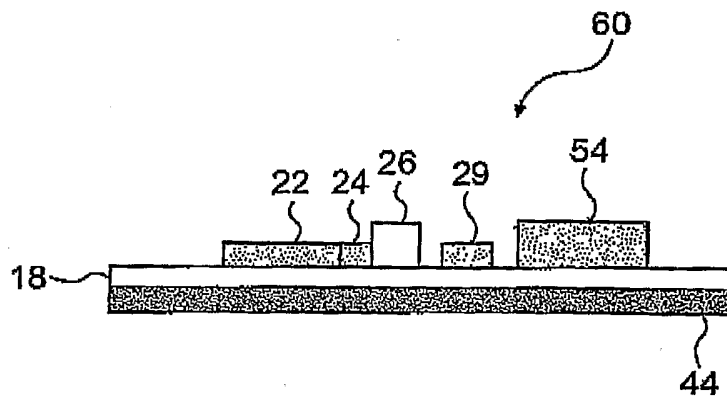


FIG. 9

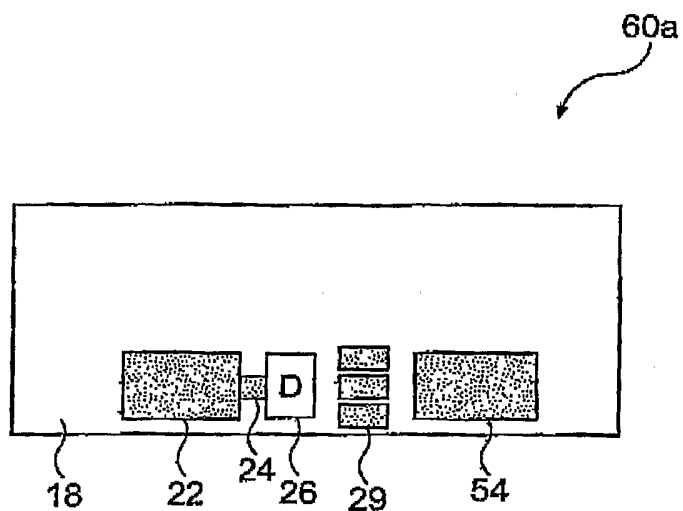


FIG. 10

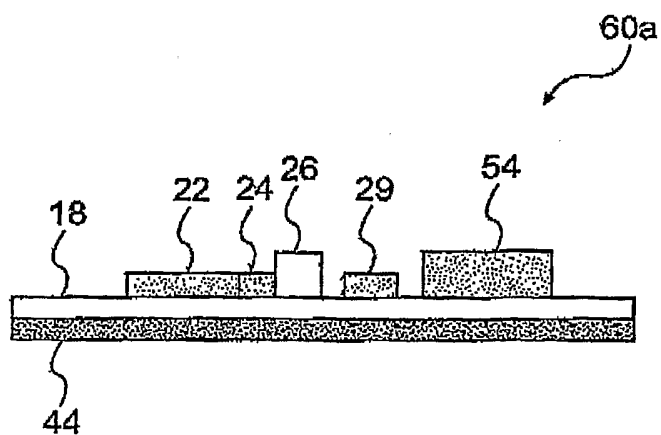


FIG. 11

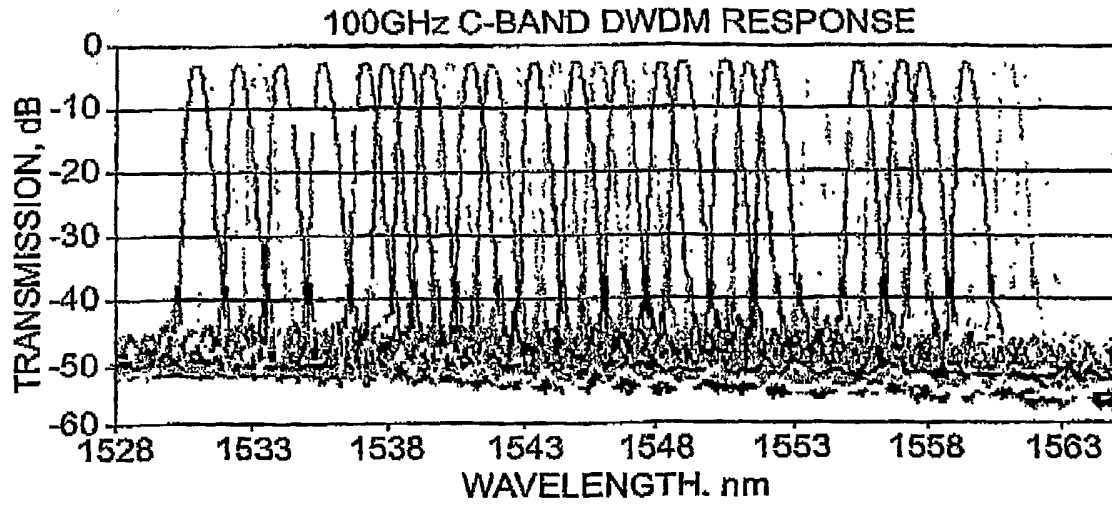


FIG. 12

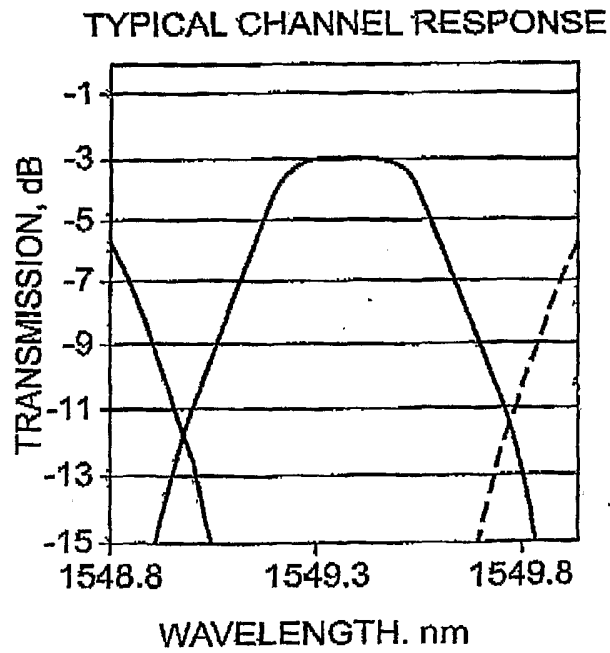


FIG. 13

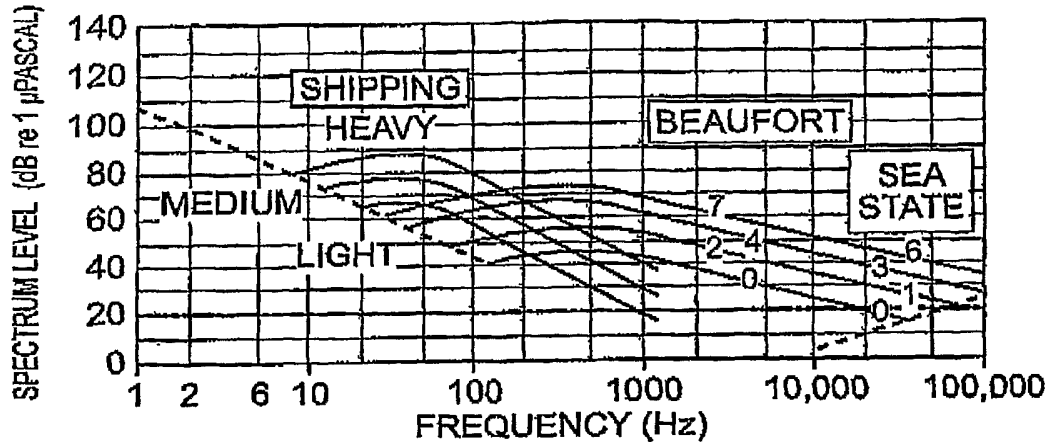


FIG. 15

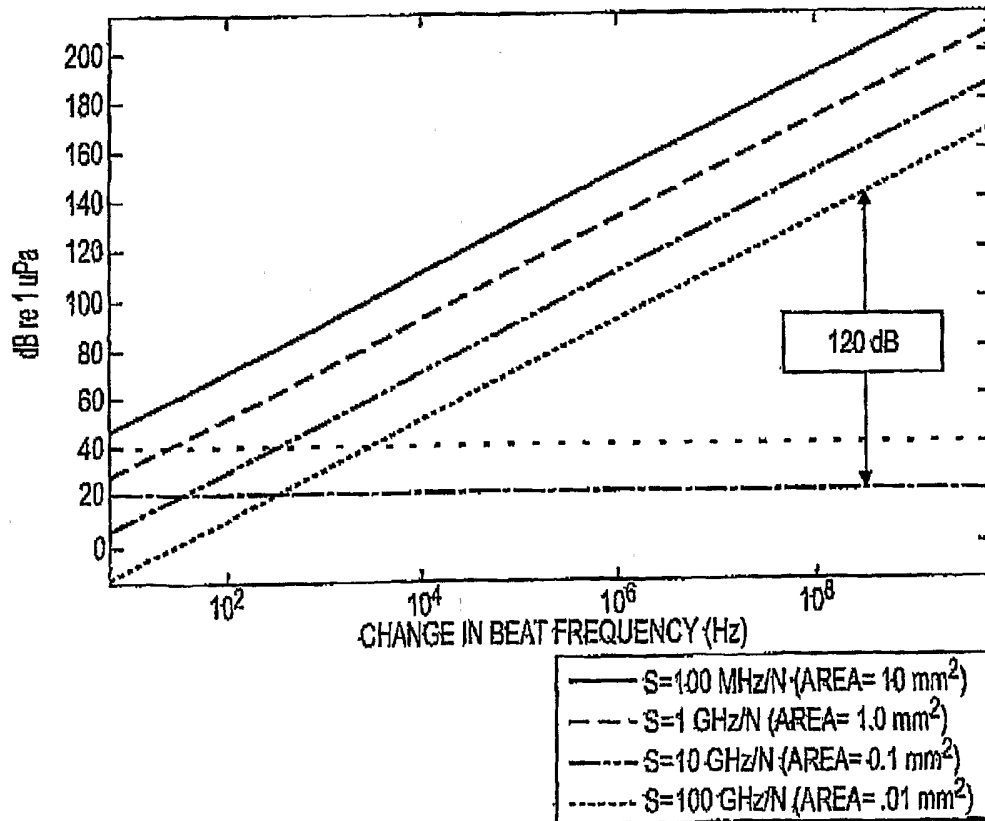


FIG. 14

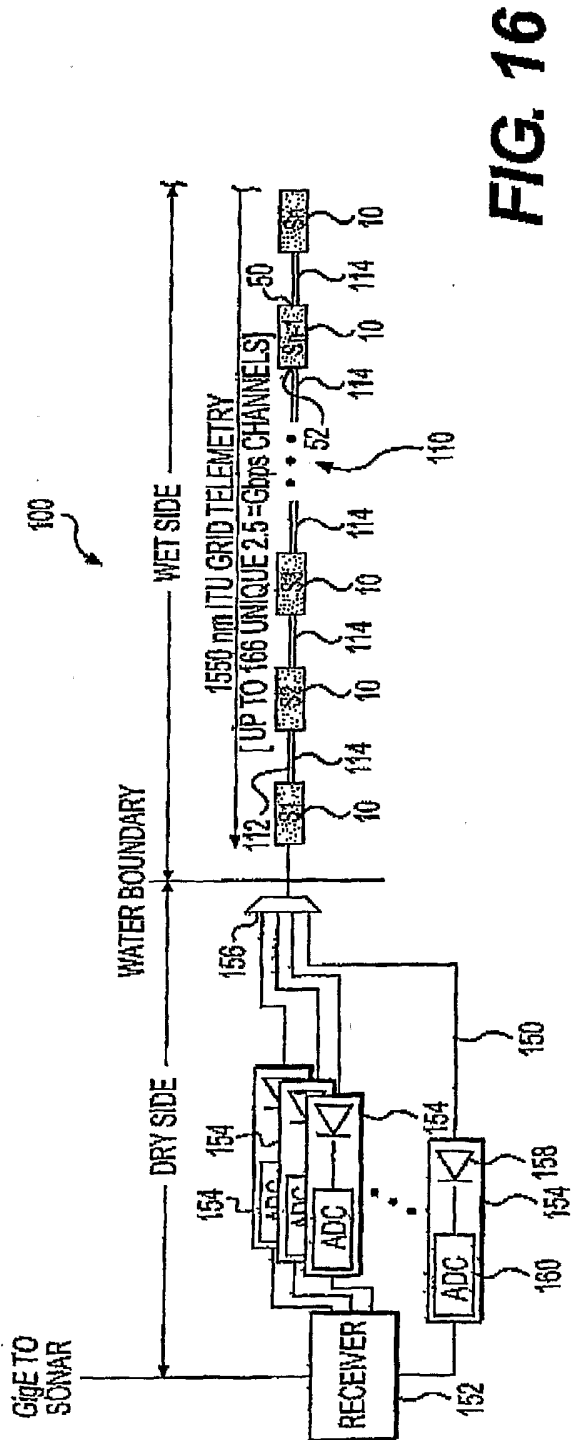


FIG. 16

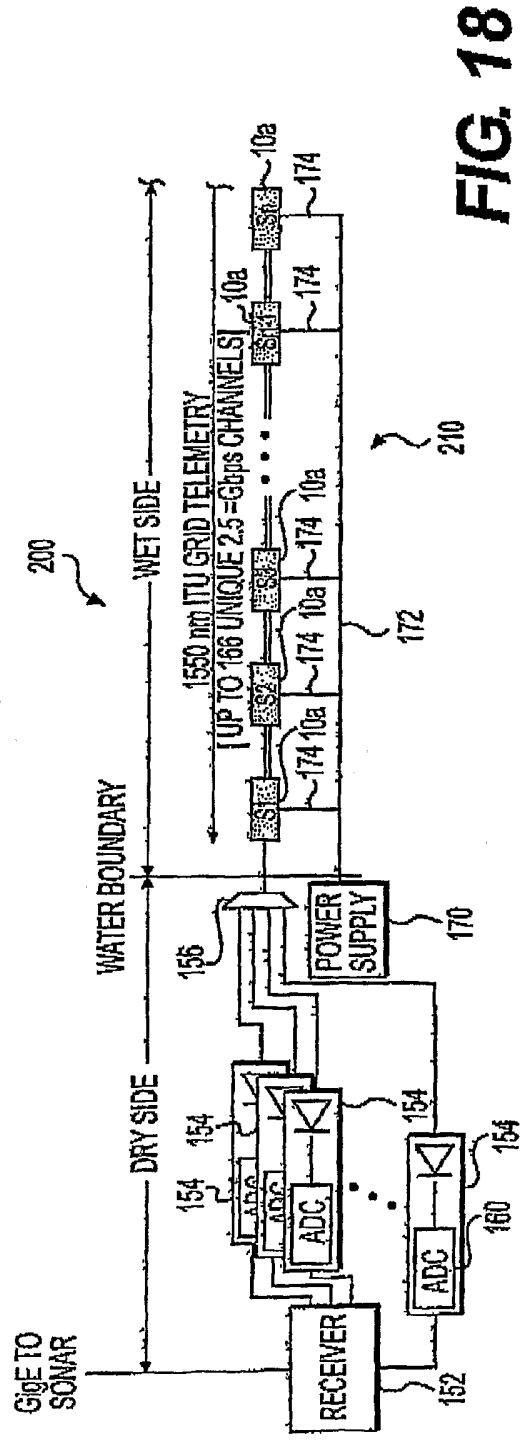


FIG. 18

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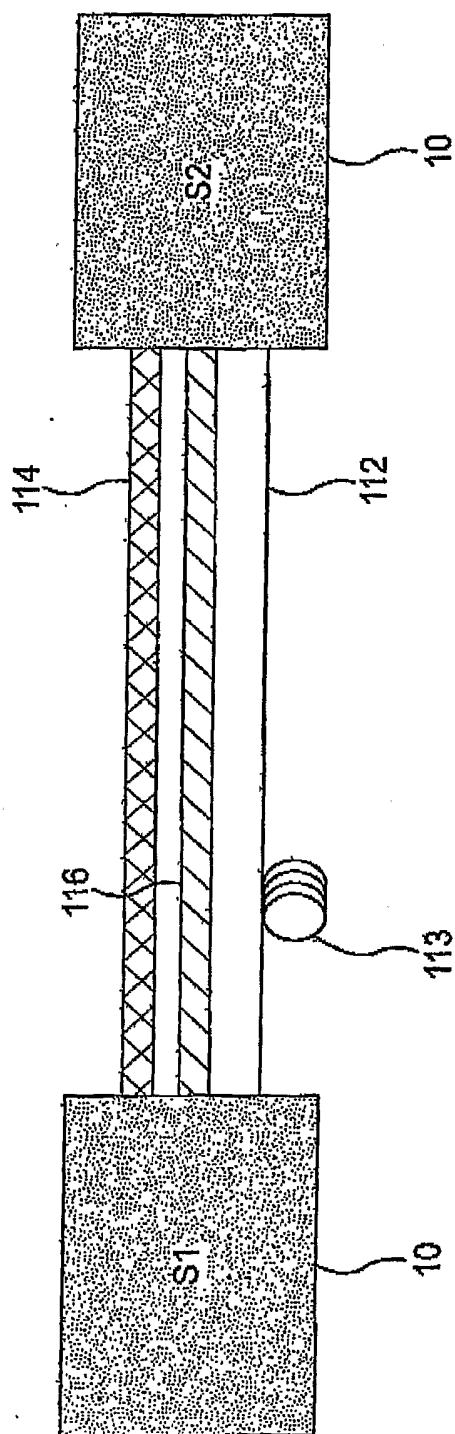


FIG. 17