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(72) Inventeur/Inventor:
FARHADIROUSHAN, MAHMOUD, GB
(73) Propriétaire/Owner:
SENSORNET LIMITED, GB
(74) Agent: MCFADDEN, FINCHAM

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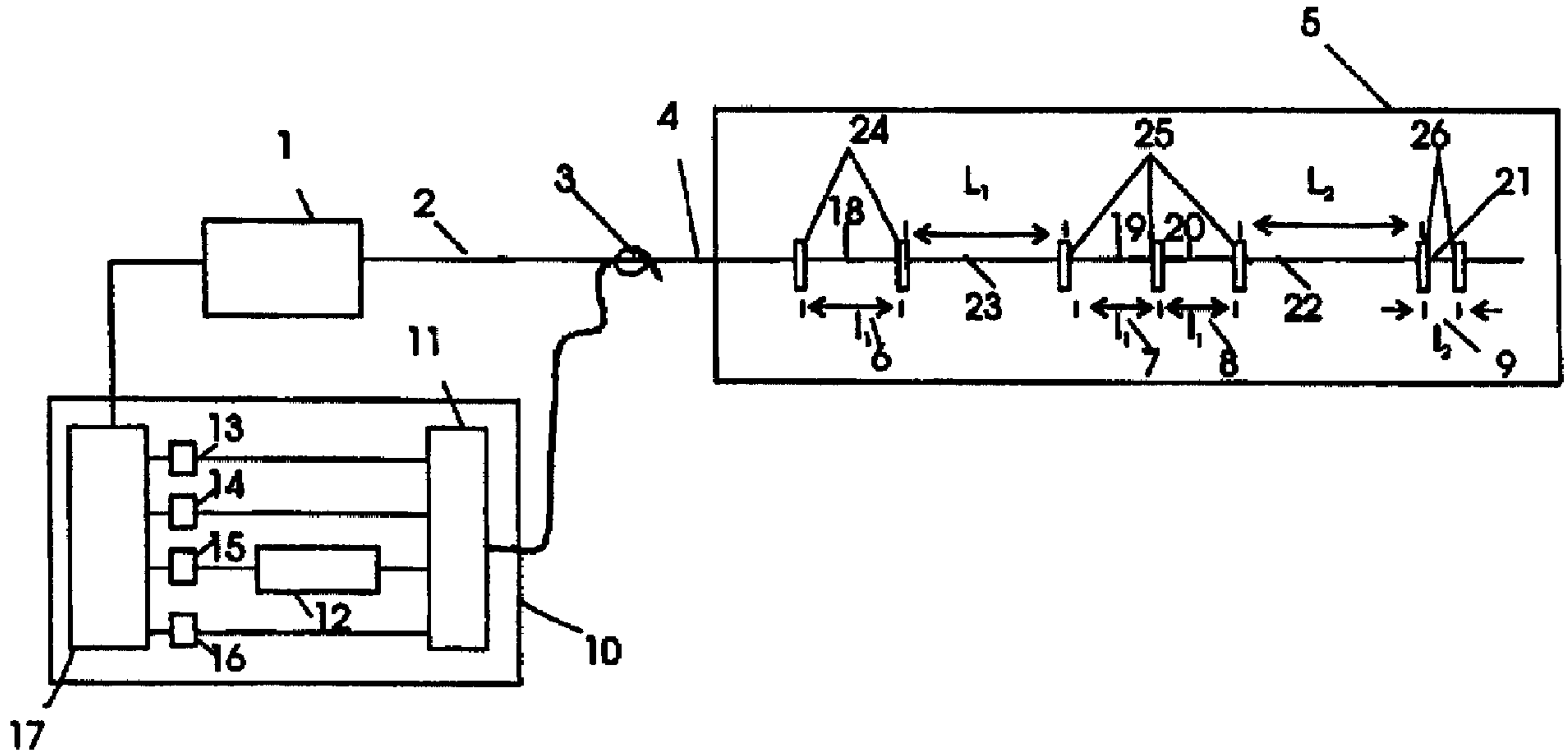

(57) Abrégé/Abstract:
A system for measuring the strain in a structure in which the temperature at the location the strain is measured is also measured in which an optic fiber is incorporated in the structure which has an interferometer positioned at the point or points where the strain is to be measured, a pulse of light is sent down the fibre and the backscattered light is split to separate the RSS light, the interferometer is used to measure the strain and the RSS is used to measure the temperature. There can be a network of fibers to monitor the strain throughout the structure.

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(71) Applicant *(for all designated States except US)*: KINGS COLLEGE LONDON [GB/GB]; The Strand, London WC2R 2LS (GB).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: FARHADIROUSHAN, Mahmoud [GB/GB]; 12 Fulmer House, Mallory Street, London NW8 8TA (GB).

(74) Agent: COHEN, Alan, Nicol; 2 Grove Place, Tatsfield, Westerham, Kent TN16 2BB (GB).

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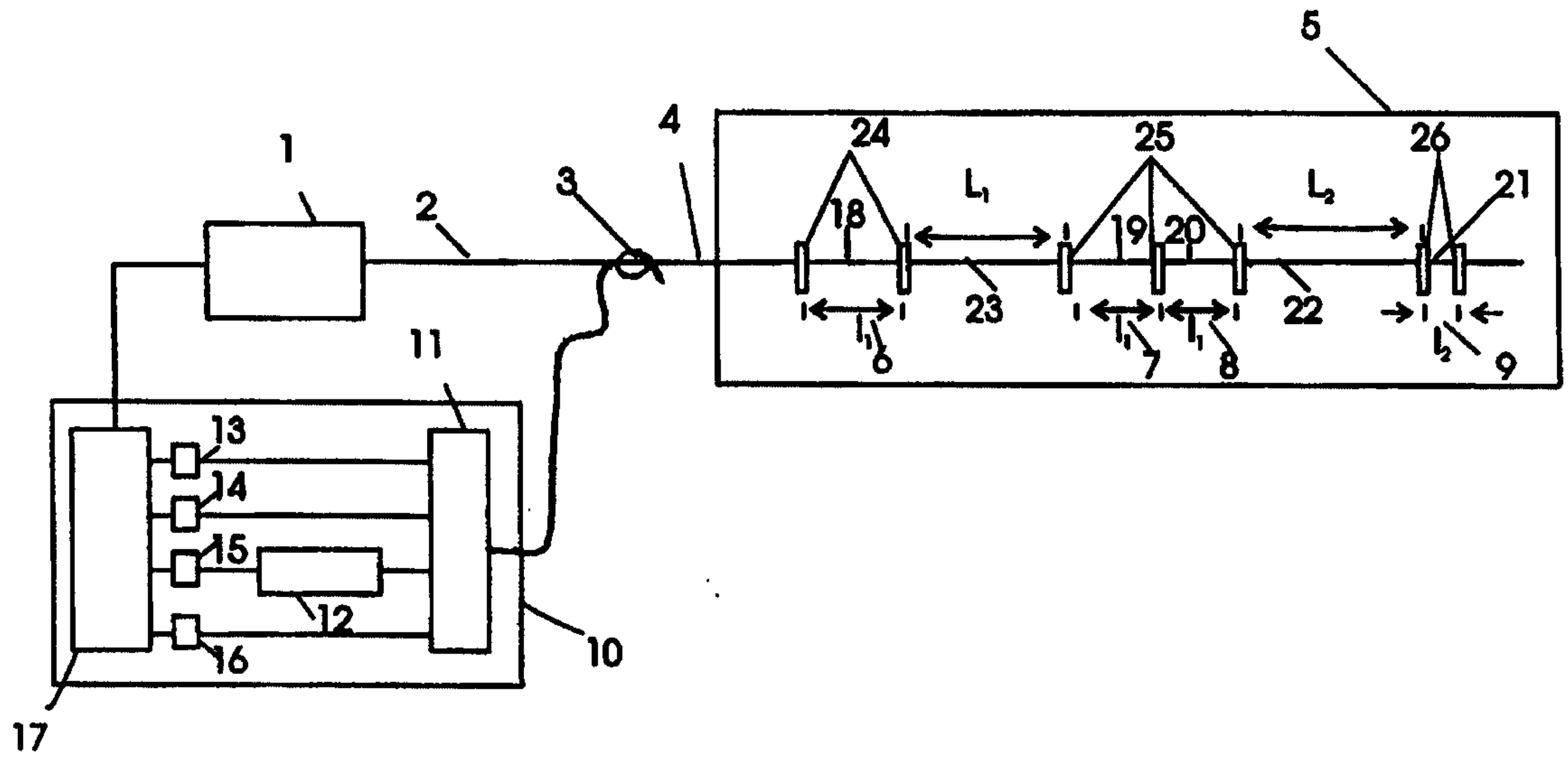

(57) Abstract

A system for measuring the strain in a structure in which the temperature at the location the strain is measured is also measured in which an optic fiber is incorporated in the structure which has an interferometer positioned at the point or points where the strain is to be measured, a pulse of light is sent down the fibre and the backscattered light is split to separate the RSS light, the interferometer is used to measure the strain and the RSS is used to measure the temperature. There can be a network of fibers to monitor the strain throughout the structure.

Distributed Sensing System

The present invention relates to an improved apparatus and method for measuring strain in materials and relates particularly to distributed sensor systems using optical fibres.

There has been considerable interest in using optical fibres for the measurement of a wide range of physical and environmental parameters, in particular where the inherent properties of optical fibres offer significant advantages. In applications such as structural monitoring, there is a need for distributed sensor systems for the measurement of strain and temperature, particularly at serial locations. Distributed and multiplexed systems are particularly attractive as they offer monitoring of physical parameters along a length of an optical fibre with benefits of high selectivity and small dimensions enabling them to be readily deployed or embodied within the structure.

It is well known to measure or detect the strain in a structure using interferometer techniques to measure the optical path length changes along a length of optical fibre. For example, when a length of optical fibre is subjected to a strain its length increases and thus the optical path for light passing down the fibre is likewise increased.

However, the temperature variation along a length of sensing fibre can also result in changes of the optical path length of the sensing fibre and make it difficult to distinguish the temperature effects from the strain effects. To try to compensate for this temperature effect the temperature can be measured using, for example, a separate fibre or segment of fibre not subjected to the strain field. However this requires the use of extra fibres and, due to the necessary displacement of this fibre or segment of fibre from the fibre used to measure the strain, accuracy cannot be assured.

We have now devised an apparatus and a method for the simultaneous measurement of temperature and strain along an optic fibre.

The method of the invention can be used in connection with the measurement of strain in which an interferometer is used to measure the variation in length along a section of a fibre, excited by a pulse of light, so as to generate interference signals which vary with change in length of the fibre. In this technique it is important to know the temperature at the location at which the strain is measured so that suitable corrections can be made.

In accordance with an embodiment of the present invention there is provided a method of measuring optical path length variations, and simultaneously measuring loss and temperature at a same location in an optical fibre in which there are reflective elements of an optical interferometer means, having the steps of: passing light down the optical fibre, using a wavelength selection means to receive the light from the optical fibre, and separate the light at a same wavelength as an input light from inelastic scattering along the optical fibre, and determining the loss and temperature from the inelastic scattering , and determining the optical path length variations from received light, to deduce changes in physical parameters.

In accordance with another embodiment of the present invention there is provided apparatus for measuring optical path length variations, and simultaneously measuring loss and temperature at a same location in an optical fibre in which there are reflecting elements of an optical interferometer means, the apparatus having: means for passing light down the optical fibre; a wavelength selection means to receive the light from the optical fibre, and separate the light at a same wavelength as input light from inelastic scattering along the optical fibre, and means for determining the loss and temperature from the inelastic scattering, and for determining the optical path length variations from received light, to deduce changes in physical parameters.

According to preferred embodiment of the invention there is provided a method for measuring the strain in a structure which method comprises using an optical interferometer means for measuring the strain at at least one location in the structure and substantially simultaneously measuring the loss and the temperature distributions by detecting and measuring the Raman Scatter Spectrum (RSS).

The strain can be measured along a length or segment of optical fibre by use of sensing interferometer means by sending a pulse of light down the optical fibre and detecting and measuring the signal reflected back from the interferometer means.

The strain can be measured using a sensing interferometer or a plurality of sensing interferometers positioned along a length of optical fibre so as to form a sensing network. The sensing interferometer can comprise a pair of reflective means, with the path length between the reflective means varying with changes in physical parameters such as the strain in the fibre and the temperature.

The interferometer means can be formed from two reflective surfaces positioned a suitable distance apart, which reflect only a small percentage of the incident light, e.g. less than 1% so that a plurality of interferometers can be positioned along a fibre without any substantial attenuation of the light. Preferably the optical path length delay of the interferometer is greater than the coherence length of the light transmitted down the optical fibre. In one embodiment the reflective surfaces can be formed by reflective splices in the optic fibre.

The path length variations in the interferometer means can be converted to an intensity modulation, e.g. by using the reference interferometer means and so as to provide a sensitive means of measuring the temperature and strain. The amplitude of the backscattered light and the reflected radiation from the interferometer means is directly detected to provide compensation and correction for fibre attenuation effects and variations in the reflectivities of the interferometer means.

By use of a wavelength selection means the light originating from the interferometer means and the scattered RSS light can be passed down different channels.

The temperature can be measured by RSS by detecting and measuring the RSS from a point or series of points along the fibre to give a temperature profile along the fibre.

If there is a discontinuity in the optical fibre due, e.g. to an irregularity in the fibre or due to coupling device through which the light passes this will affect the amplitude of the RSS in a discontinuous manner and so can be used to monitor such discontinuities. In one embodiment this can be used to measure both the loss and reflection of the light when it passes through a coupling or splicing junction in the optical fibre. Since the Raman backscatter light is generated due to in-elastic scattering in the optical fibre and its frequency is shifted relative to the input optical source frequency, it can be optically filtered from Fresnel reflections at a junction. In this case the RSS measured at various points along the fibre will show a discontinuity in the profile and this discontinuity will be a measure of the loss experienced by light passing through the junction. The reflection at the junction can be measured by detecting the light reflected at the input optical source frequency which undergoes elastic scattering.

The means for detecting and measuring the RSS preferably is able to detect the amplitude of the RSS and to measure the amplitude of the anti-Stokes and Stokes components. The anti-Stokes component provides the temperature information and the Stokes component provides information derived from losses from the fibre. This enables a temperature profile along the length of the fibre to be computed and thus the temperature at the interferometer or interferometers to be computed. The RSS signal can be acquired by means of a data acquisition means such as a router/multiplexer.

Preferably the light transmitted back down the optical fibre is fed to a detection processing means which comprises a wavelength selection means, a reference interferometer means, detection means and processing means. The wavelength selection means can select and separate the Stokes and anti-Stokes components of RSS. The amplitudes of Stokes and anti-Stokes can be measured and then processed to evaluate predominately the loss and the temperature along the optical fibre independent of the strain. The optical delay of the sensing interferometers, which varies with strain and temperature, can be monitored by passing a portion of light though a reference interferometer and detecting the output interference pattern. A portion of light can also be selected to measure the Rayleigh backscatter power, the interferometer reflectivities and the distance between the interferometers which can provide a coarse measure of the strain and temperature along the fibre.

The output of all the detection means can be passed to a computation means to compute the strain and temperature of the sensing interferometer as well as overall temperature of the sensing fibre.

A sensing network formed using the present invention can be a single mode or polarisation maintaining or multimode optical fibre comprising a plurality of sensing interferometers and means of converting the magnitude of physical parameters to a change of optical path-length of the sensing interferometers.

The sensing interferometer means may be comprised of reflective means to form in-line interferometers.

A reflective means may be formed by a reflective splice or by exposing the fibre to ultra-violet light to modify the refractive index of the fibre in a single or multiple sections.

The sensing interferometer means may be polarimetric sensors formed along a high birefringence optical fibre by introducing pairs of polarisation cross-coupling pairs such as by splicing two sections of the fibre with their polarisation axes rotated with respect to each other or by exposing the fibre to an ultra-violet light at an angle to the two polarisation axes.

The source means may be a gain-switched laser or a Q-switched laser or a mode-locked laser and its emission wavelength may be tuneable and its pulse repetition rate may be adjustable.

The source means may be constructed using semiconductor devices and optical fibre components.

The wavelength selection means can comprise directional couplers, optical gratings, optical filters, a monochromator or integrated optical filters.

The reference interferometer means may be a Mach-Zehnder interferometer or a Michelson interferometer or a Fabry-Perot interferometer and it may be constructed using fibre optic components.

The detection processing means can comprise of high sensitivity detectors such as such as photomultipliers, avalanche photodiodes and detector arrays, amplifiers, multiplexer or router, optical switches and can utilise digital electronic timing devices such as fast sampling digitizers or time-to-amplitude converters such as one utilising time-resolved photon counting.

Embodiments of the invention will now be described solely by way of example and with reference to the accompanying drawings in which:

Figure 1 is a diagram of an embodiment of the present invention in which in-line optical fibre interferometer means formed along a length of optical fibre are interrogated to simultaneously measure temperature and strain;

Figure 2 is a diagram illustrating schematically the amplitude response of the detection means to evaluate temperature and strain;

Figure 3 is a diagram of an embodiment of the present invention in which a time-resolved photon counting technique is used to measure the amplitude of the scattered photons.

An embodiment of the present invention, in which in-line optical fibre sensing interferometer means are used is shown in Figure 1. A light source means (1) which radiates pulses of light is conveyed by optical fibre (2) to optical fibre coupler (3) into optical fibre lead (4) and then into the sensing network means (5). The sensing network means contains a plurality of sensing interferometer means (6, 7, 8, 9). The optical path length of the sensing interferometer means varies with the magnitude of physical parameters such as strain and temperature. A portion of the light is reflected back by the sensing network means (5) into optical fibre coupler (3) and a portion enters detection system means (10). The detection system means (10) contains a wavelength selection means (11), a reference interferometer means (12), detector means (13, 14, 15, 16) and a computing means (17). Figure 2 illustrates the output response of the detection system means (30, 31, 32, 33).

The wavelength selection means (11) separates the Raman backscatter light into a band of anti-Stokes and Stokes components which are converted to an electrical signal by detector means (13, 14). By measuring the time delay of the backscattered light from each pulse, the position along the fibre where the backscattered light originates can be computed. The computing means (17) can then determine the temperature along the fibre and map out a temperature profile of the fibre by taking the ratio of anti-Stokes to Stokes signals (30).

The sensing interferometer means (6, 7, 8, 9) may be constructed using pairs of in-line reflective elements (24, 25, 26). The optical path delays (18, 19, 20) between the reflective elements may be greater than the timing resolution of the source and detector response so that the reflections (40, 41) of reflective elements (24, 25) can be resolved. In this case, it is possible to concatenate the sensing interferometer means (7, 8). Alternatively, the optical path delay (21) of the sensing interferometer may be shorter than the timing resolution of the source and detector response so that the reflection pair overlap (42) but the path delay between the sensing interferometers (22, 23) are resolved.

A portion of returned light enters a detector means (16) to measure the reflectivity (40, 41, 42) of the reflective elements with reference to the Rayleigh backscatter light (43). For example, when the spatial resolution is in a range of 10 cm down to 1 cm, a reflectivity of 0.1% can result in an increase of returned light by a factor of 10dB compared to the Rayleigh backscatter light. In addition, the computing means can determine the variations of the path delay between the sensing interferometer means (22, 23) as a coarse measure of strain and temperature along the fibre.

The path length variations of the sensing interferometer means are measured by detecting a portion of returned light (33) which passes through a reference interferometer means (12) where a reference path delay may be selected to match a sensor path delay and detecting coherent interference patterns (44, 45, 46) with the detector means (15).

When the reflections (42) of the reflective pair elements (25) of the sensing interferometer means (8) overlap, it is also possible to measure directly the coherent response of the sensing interferometer (32) by detecting a portion of light which has coherence greater than the optical path delay of the interferometer (47, 48, 49).

The fringe ambiguity resulting from cosinusoidal response of the interferometer may be resolved by measuring the interference amplitude at different operating wavelengths to extend the dynamic range of the interferometer.

The computing means (17) can determine the temperature, the reflectivity and optical path delay along the sensing fibre network means (5) and make the appropriate correction to enable the strain at these locations to be determined.

Figure (3) shows an embodiment of the present invention where the detection system means comprises of a time-to-amplitude converter and a multi-channel analyser to measure the arrival time and the intensity distribution for the reflected light along the optical fibre. A portion of returned light is split in the wavelength selection means (11) and the Raman Stokes and the anti-Stokes components are separated using optical filters (50, 51). The arrival of Stokes and anti-Stokes photons are detected by detector means (13, 14) such as photomultipliers. A portion of light at the wavelength emitted by the source means (1) is selected by optical filter (52) and is then passed through a reference interferometer means (12).

The resultant interference pattern is measured by the detector means (15) to determine the optical path delay of sensing interferometers. The reflected and the backscatter signals are measured by selecting a portion of light within the wavelength band of the source means (1) using an optical filter (53) and detector means (16). The output of the detector means are fed to a time-to-amplitude converter (55) via a router (54). The time-to-amplitude converter (55) and the source means (1) are synchronously triggered by a pulse-delay generator (56) and the arrival time of photons are registered in a microprocessor controlled multi-channel analyser (57). The measurement is repeated over a large number of optical pulse excitations and histograms of arrival time of photons for the detector means are obtained. The amplitude of the returned light may be balanced in such a way as to minimise distortion in the number of photons counted in each detection means.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method of measuring optical path length variations, and simultaneously measuring loss and temperature at a same location in an optical fibre in which there are reflective elements of an optical interferometer means, having the steps of:

passing light down the optical fibre,

using a wavelength selection means to receive the light from the optical fibre, and separate the light at a same wavelength as an input light from inelastic scattering along the optical fibre, and

determining the loss and temperature from the inelastic scattering , and determining the optical path length variations from received light, to deduce changes in physical parameters.

2. The method as claimed in claim 1 in which strain is measured along a length or segment of the optical fibre incorporated in a structure, the light comprises a pulse of light and Raman Scatter Spectrum (RSS) of the inelastic scattering is detected and measured.

3. The method as claimed in claim 1 or 2 in which there are a plurality of interferometers positioned along a length of the optical fibre so as to form a sensing network.

4. The method as claimed in any one of claims 1 to 3 in which the optical interferometer means comprises a pair of reflective elements, with the optical path length variations being used to deduce strain in the optical fibre and temperature.

5. The method as claimed in claim 4 in which the reflective elements reflect only a small percentage of incident light so that a plurality of interferometers can be positioned along the optical fibre without any substantial attenuation of the light.

6. The method as claimed in claim 5 in which an optical path length delay of the optical interferometer means is greater than a coherence length of the light transmitted down the optical fibre.

7. The method as claimed in any one of claims 1 to 6 in which the reflective elements are formed by reflective splices in the optical fibre.

8. The method as claimed in any one of claims 1 to 7 in which the path length variations in the interferometer means are converted to an intensity modulation by comparison with a reference interferometer means which is not subjected to strain.

9. The method as claimed in any one of claims 1 to 8 in which an amplitude of backscattered light and reflected radiation from the interferometer means is directly detected to provide compensation and correction for fibre attenuation effects and variations in reflectivities of the interferometer means.

10. The method as claimed in any one of claims 1 to 9, in which wavelength selection means causes the light originating from the interferometer means and scattered RSS light to separate and be passed down different channels of a detecting and measuring means.

11. The method as claimed in claim 10 in which the temperature is measured by detecting and measuring the RSS from a point or series of points along the optical fibre to give a temperature profile along the optical fibre.

12. The method as claimed in claim 11 in which the means for detecting and measuring the RSS is able to detect an amplitude of the RSS and to measure the amplitude of anti-Stokes and Stokes components of the RSS.

13. The method as claimed in claim 12 in which light transmitted back down the optical fibre is fed to a detection processing means which comprises the wavelength selection means, a reference interferometer means, detection means and processing means and in which the wavelength selection means selects and separates the Stokes and anti-Stokes components of the RSS.

14. The method as claimed in any one of claims 1 to 13 in which the optical path length is monitored by passing a portion of light through a reference interferometer and detecting an output interference pattern.

15. The method as claimed in any one of claims 1 to 14 in which a computation means is used to compute strain and temperature of the interferometer as well as overall temperature of the optical fibre.

16. Apparatus for measuring optical path length variations, and simultaneously measuring loss and temperature at a same location in an optical fibre in which there are reflecting elements of an optical interferometer means, the apparatus having:

means for passing light down the optical fibre;

a wavelength selection means to receive the light from the optical fibre, and separate the light at a same wavelength as input light from inelastic scattering along the optical fibre, and

means for determining the loss and temperature from the inelastic scattering, and for determining the optical path length variations from received light, to deduce changes in physical parameters.

17. The apparatus as claimed in claim 16 having the optical fibre, and in which the optical fibre is a single mode or polarisation maintaining or multimode optic fibre comprising a plurality of sensing interferometers and means of converting a magnitude of physical parameters to a change of optical path-length of the sensing interferometers.

18. The apparatus as claimed in claim 17 in which the sensing interferometers are comprised of reflective means to form in-line interferometers.

19. The apparatus as claimed in claim 18 in which the reflective means is formed by a reflective splice or by exposing the optical fibre to ultraviolet light to modify a refractive index of the optical fibre in a single or multiple sections.

20. The apparatus as claimed in any one of claims 16 to 19 in which the wavelength selection means comprises directional couplers, optical gratings, optical filters, a monochromator or integrated optical filters.

21. The apparatus as claimed in any one of claims 16 to 20 having detection processing means which comprises high sensitivity detectors selected from photomultipliers, avalanche

photodiodes and detector arrays, amplifiers, multiplexer or motor, optical switches and utilise digital electronic timing devices.

22. The method of any one of claims 1 to 15, wherein the light passed into the optical fibre comprises pulsed light with a pulse width shorter than the optical path length of the interferometer means, so that optical signals passing through the interferometer means do not interfere coherently.

23. The method as claimed in any one of claims 1 to 15 in which the interferometer means are formed by introducing cross-coupling pairs along a length of high birefringence optical fibre.

24. The apparatus as claimed in any one of claims 16 to 21 in which the interferometer means are formed by introducing pairs of polarisation cross-coupling points along a length of high birefringence optical fibre and where an optical path-length difference between the two polarisation modes separating the interferometer means are greater than a coherence of a backscattered light source and where, a small portion of the light launched mainly in one polarisation mode is coupled to the other orthogonal polarisation mode at each cross-coupling section.

25. The apparatus of any one of claims 16 to 21 and 24, where the light comprises a pulse of light and the apparatus is arranged to detect and measure Raman Scatter Spectrum (RSS) of the inelastic scattering.

26. The apparatus of any one of claims 16 to 21 and 24 to 25, arranged to deduce variations in strain in the optical fibre or temperature from the optical path length variations.

27. The apparatus of claim 26, arranged to determine time delays of the inelastic scattering, and so obtain a profile of scatter at different distances along the optical fibre.

28. The apparatus of any one of claims 16 to 21 and 24 to 27, arranged to use results from the inelastic scattering to correct measurements using path delays, or use measurements from the path delays to correct results from the inelastic scattering.

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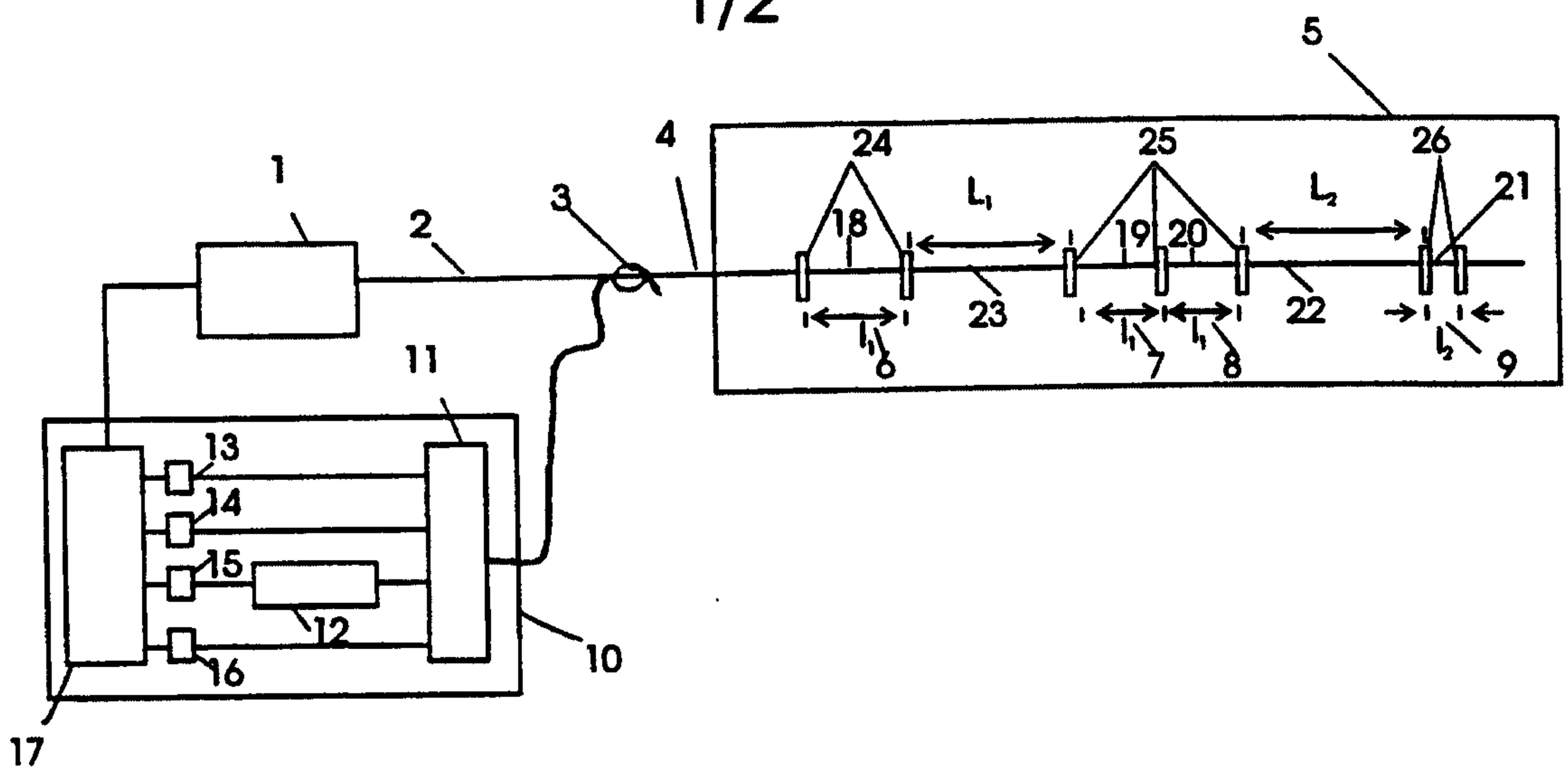

Figure 1

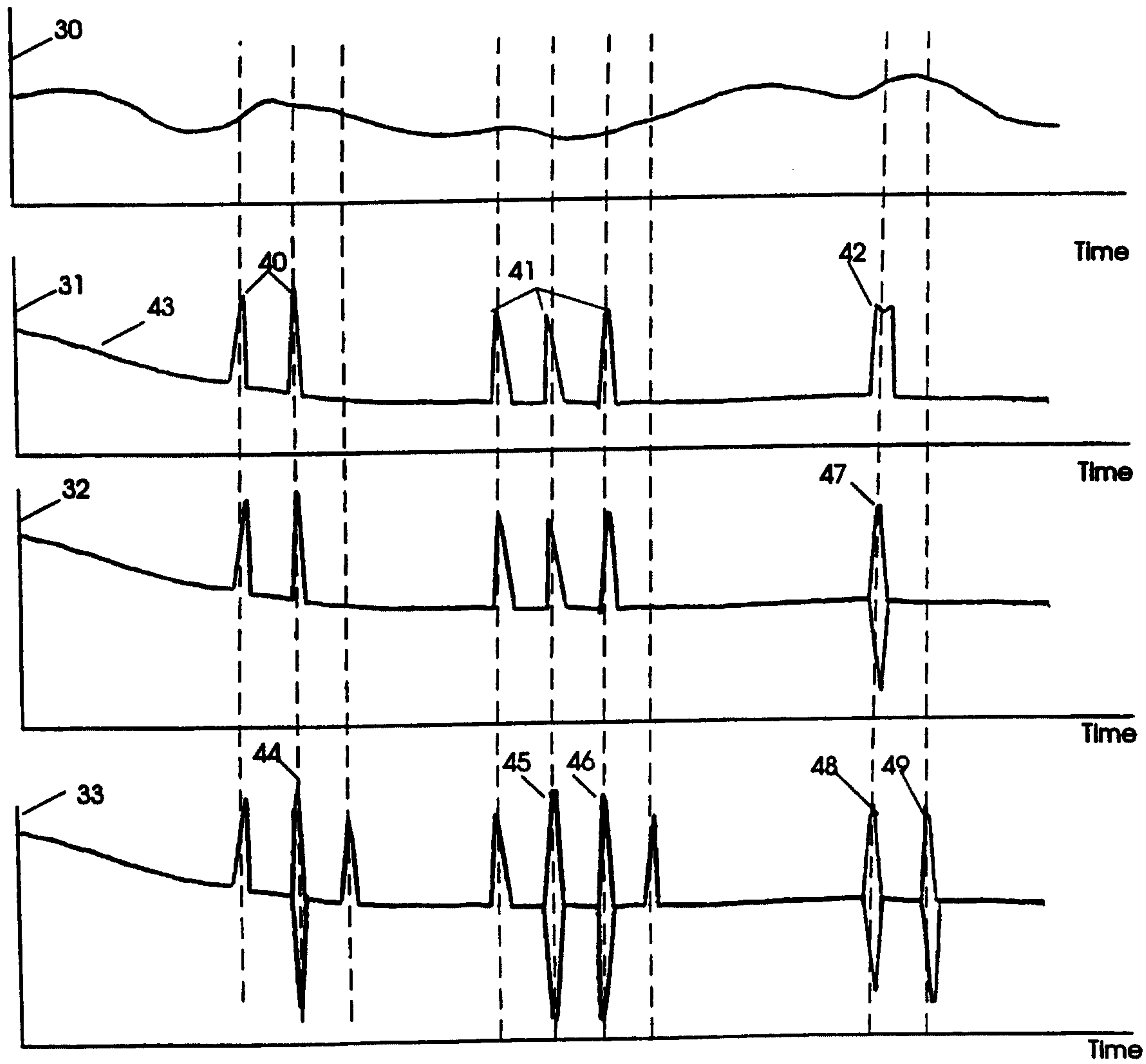

Figure 2

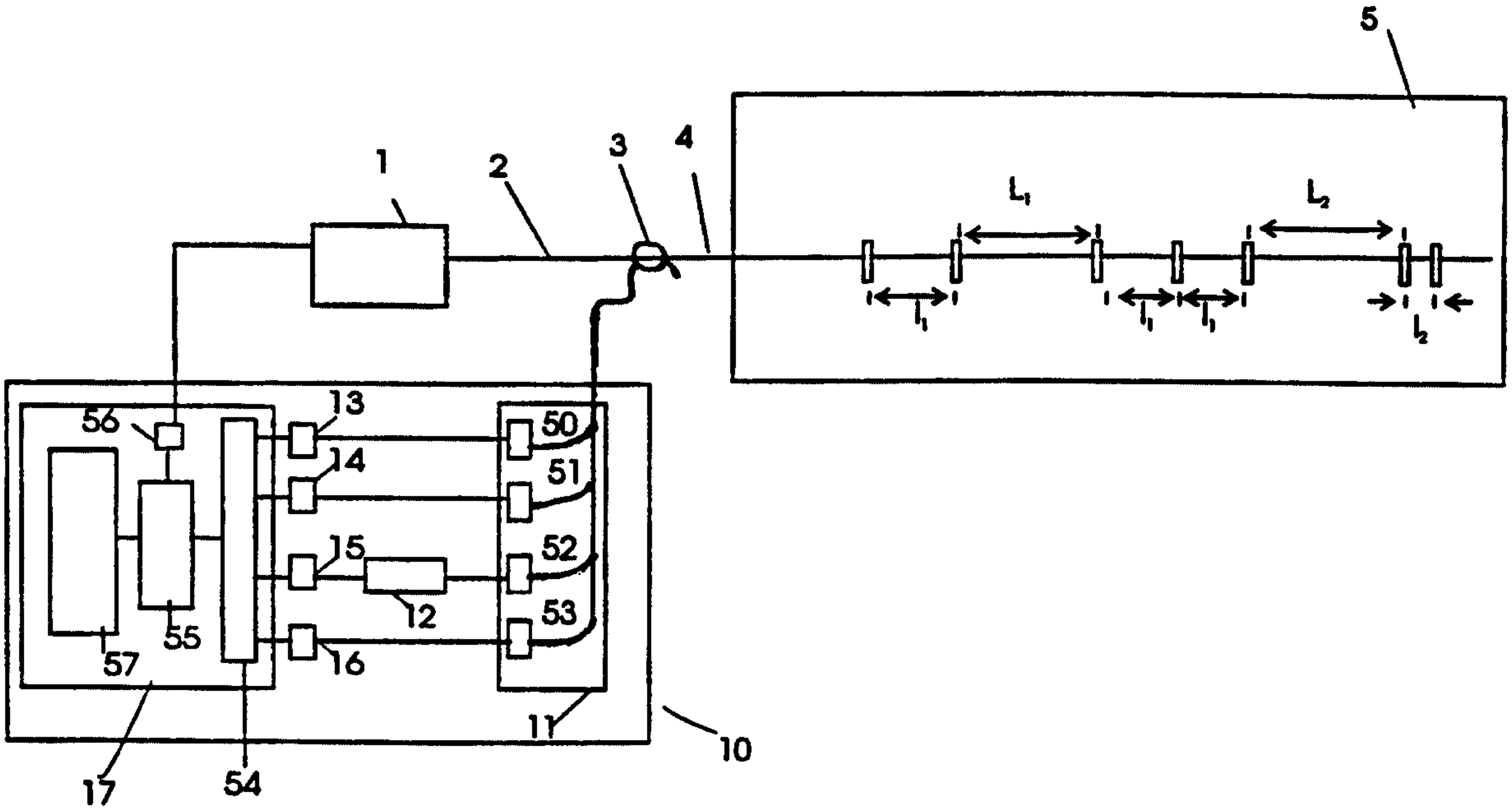

Figure 3


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