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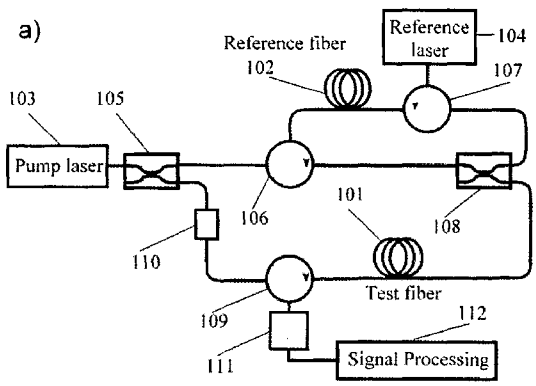

(57) Abstract: This invention relates to a method for distributed sensing with a Stokes-locked reference laser, comprising the steps of splitting an optical pump radiation in two beams, one for Brillouin pumping of an optical reference fiber and another for pulsed Brillouin pumping of a test fiber, locking a reference laser on reference fiber Stokes radiation for producing a stable seed signal which is launched into the test fiber, receiving a spontaneous back-scattered Stokes signal transmitted through the test fiber seed signal, calculating the temperature or strain distribution by sensing change in amplification of the seed signal or by processing the shift of the beat spectrum between the seed signal and the spontaneously scattered Stokes component along the test fiber. Brillouin based distributed sensors are very attractive and promising technique for truly distributed sensing of strain and/or temperature and widely used to monitor tunnels, bridges, dams, airplanes, buildings and etc. The Brillouin frequency shift is dependent on the temperature and strain conditions of the optical fiber, which provides the basis for a sensing technique capable of detecting these two parameters.

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METHOD AND APPARATUS FOR DISTRIBUTED SENSING WITH STOKES-LOCKED REFERENCE LASER

FIELD OF THE INVENTION

The present invention relates to a distributed temperature and/or strain measurement method and apparatus based on the spontaneous and/or stimulated Brillouin scattering, and more particularly, to injection locking of a reference laser on Stokes radiation in order to produce stable seed signal without a high frequency modulator.

BACKGROUND TO THE INVENTION

Brillouin based distributed sensors are very attractive and promising technique for truly distributed sensing of strain and/or temperature and widely used to monitor tunnels, bridges, dams, airplanes, buildings and etc. The Brillouin frequency shift is dependent on the temperature and strain conditions of the optical fiber, which provides the basis for a sensing technique capable of detecting these two parameters.

Different types of Brillouin-based distributed fiber optical sensor such as BOTDR, BOTDA and BOFDA have been reported.

The prior art discussed above utilizes the precise high frequency 10-12 GHz phase/intensity modulators and generators with accuracy and stability better than 1 MHz for Stokes seed signal generation and intensity modulators for short pulse production that significantly increases the complexity of such systems.

Therefore, a Brillouin based technique which provides distributed measurements without high frequency modulators would be useful.

SUMMARY OF THE INVENTION

In accordance with the invention there is provided a method for distributed sensing with a Stokes-locked reference laser, comprising the steps of splitting an optical pump radiation in two beams, one for Brillouin pumping of an optical reference fiber and another for pulsed Brillouin pumping of a test fiber, locking a reference laser on reference fiber Stokes radiation for producing a stable seed signal which is launched into the test fiber, receiving a spontaneous back-scattered Stokes signal transmitted through the test fiber seed signal, calculating the temperature or strain distribution by sensing change in amplification of the seed signal or by processing the shift of the beat spectrum between the seed signal and the spontaneously scattered Stokes component along the test fiber.

The reference laser is used as a local oscillator for heterodyne detection.

The reference laser is locked on a reference ring Brillouin laser output radiation.

A further feature of the invention provides for the reference laser to be locked on reference Fabry-Perot Brillouin laser output radiation.

The reference fiber is uniformly stressed/elongated or heated/cooled for changing the Brillouin shift of the reference fiber.

A modulation of current of the pump laser may be used instead of using the intensity modulator.

A modulation of current of the reference laser improves spatial resolution.

An intensity or phase modulator is used inside the cavity of the reference Brillouin laser to provide a stable pulsed regime.

The reference laser is locked on the n^{th} Stokes component of a Brillouin laser.

This invention extends to an apparatus for distributed sensing with Stokes-locked reference laser, comprising: a test fiber positioned along an object, a reference fiber at a predetermined temperature and strain along its length, a pump laser for producing Brillouin scattering in the test and reference fibers, a reference laser, a reference Brillouin amplifier having sufficient intensity output to lock said reference laser wavelength on the Stokes wavelength of the reference fiber, an optical intensity modulator to produce an optical pulse so that pump laser radiation is pulsed into the test fiber and the laser locked light on the amplified Stokes radiation produces a stable seed signal which is launched in said test fiber, a signal processor connected to the Stokes detector for calculating the temperature and/or strain distribution in the test fiber by measuring change in amplification of the seed signal and/or the shift of the beat spectrum between seed signal and spontaneously scattered Stokes component along the test fiber.

The signal processor is a computer and the reference fiber is a polarization maintaining fiber.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention are described below, by way of example only and with reference to the accompanying drawings in which:

Figure 1 shows a schematic of a distributed fibre optical sensor for sensing temperature or strain;

Figure 2 shows a schematic of strokes locked radiation of a reference laser used as a local oscillator for heteroclyne defection;

Figure 3 shows a schematic of a distributed optical fiber sensor with a reference laser locked on a reference ring Brillouin laser output radiation;

Figure 4 shows a schematic of a Fabry-Perat Brillouin laser used for locking of another reference laser; and

Figure 5 shows a schematic for obtaining optical signals modulated at 10 to 50 GHz using a reference laser locked on the n^{th} strokes component of a reference Brillouin laser.

DETAILED DESCRIPTION OF THE DRAWINGS

In one embodiment a method includes splitting an optical pump radiation in two beams, one for Brillouin CW pumping of an optical reference fiber and second for pulsed Brillouin pumping of a test fiber, locking a reference laser on amplified in reference fiber Stokes radiation for producing stable seed signal which is launching into test fiber, receiving a Stokes signals spontaneously scattered back and transmitted through test fiber, calculating the temperature and strain distribution by using change in amplification of the seed signal along the test fiber and/or by the shift of the beat spectrum between the seed signal and spontaneously scattered Stokes component. The method is particularly useful for sensing temperature and strain at long range distance or other applications where generation of a two optical signals separated by 10-50 GHz is required.

FIG. 1a is a simplified schematic of distributed fiber optical sensor 100 adapted to sense temperature or strain using a method and apparatus of the present invention. Sensor includes a test fiber 101 positioned along the test object, reference fiber 102 having the equal temperature and strain along all its length, a pump laser 103 having spectral and intensity parameters appropriate to produce Brillouin scattering in the test and reference fibers, and a reference laser 104. Test fiber and reference fiber can be selected with the same or different parameters such as Brillouin frequency shift, amplification or polarization property. Pump laser and reference laser selected to have nearly the same wavelengths, for example, two identical DFB semiconductor laser can be utilized. Pump laser radiation is divided on two beams by optical beamsplitter 105 and launched into reference fiber through optical beamsplitter 106 and into test fiber through intensity modulator 110 and beamsplitter 109. Reference fiber and three optical beamsplitters 105, 106, 107 comprise a reference Brillouin amplifier and provide an optical feedback for the reference laser. The wavelength of the reference laser is chosen equal to the first Stokes component wavelength for the reference fiber. The output radiation of reference laser 104 is launched into the test fiber 102 through optical beamsplitter 107. So as two optical radiations with frequency difference equal to the Brillouin shift are launching into the reference fiber in opposite directions that provide the possibility for Brillouin amplification. Amplified reference laser radiation return back into the reference laser cavity through optical beamsplitters 106,108, 107 and locked reference laser on amplified Stokes wavelength, so as reference laser wavelength follow the Stokes wavelength of the pump laser. Therefore, inside the locking range which is usually equal to 0.5-1 GHz for DFB lasers any drifts of the wavelength of the pump laser due to temperature or current variations don't change a frequency difference between pump and locked reference laser. The frequency difference is always equal to the Brillouin shift in the reference fiber. Intensity stable CW output radiation of the reference laser is used as a seed signal at the test fiber 101. For obtain a spatial distribution of temperature or strain an optical intensity modulator 110 produce an optical pulse at pump laser wavelength which is also launched into the test fiber 101 through optical beamsplitter 109 in opposite to the seed signal direction. Transmitted through the test fiber reference laser radiation and spontaneously scattered Stokes component of pump pulse are passed optical beamsplitter 109 and converted on electrical signal by photodiode 111. A signal processing 112 connected to the Stokes detector 111 calculates the temperature and strain distribution by using the shift of the beat spectrum between seed signal and spontaneously scattered Stokes component along the test fiber.

In one embodiment Fig. 1b, the reference laser is located between optical beamsplitters 106 and 108 that provide possibility for the direct launching of the reference laser radiation into the test fiber instead launching amplified reference laser radiation such as presented in Fig.1a. As well known, Brillouin amplification can induce some intensity instability due to, for example, the polarization state variation of the pump and the Stokes inside fiber if the reference fiber is not polarization preserving one. However, this effect can be eliminated by using the polarization maintaining fiber as reference fiber.

FIG. 2 schematically illustrates one embodiment where Stokes locked radiation of reference laser is used as local oscillator for heterodyne detection. In this embodiment the intensity-stable reference laser radiation with the wavelength coupled with pump wavelength so that the difference between them always equal to the Brillouin shift for the reference fiber is mixed with spontaneously back-scattered Stokes component using optical beamsplitter 113. The beat spectrum is recorded and proceeded in order to calculate temperature or strain spatial distribution along the test fiber. In this embodiment only one end of test fiber is used for the launching an optical pulse that can be useful for some applications.

FIG. 3 schematically depicts a distributed optical fiber sensor system that is in accord with the principles of the present invention where reference laser is locked on reference ring Brillouin laser output radiation. The reference fiber 102 and optical beamsplitters 106, 108 comprise a reference Brillouin ring laser where the Stokes radiation repeatedly travelling inside the loop in contra-clockwise direction and pump propagates in clockwise direction. Depending on parameters of the loop the Brillouin ring laser can operate in CW or pulsed mode.

In one embodiment (see Fig. 4) Fabry-Perot Brillouin laser is used for the locking of reference laser 104. An optical isolator 114 prevents influence of any back reflections on pump laser. The cavity of the Perot Brillouin laser can be created, for example, by two fiber optical Bragg gratings 115 or any other reflectors. Pulsed regime of the Brillouin lasers is usually achieved due to mode locking phenomena so as the repetition rate of short output pulses depends on double optical length of the resonator.

In one embodiment (see Fig. 4b) an intensity or phase optical modulator 116 is used inside the cavity of reference Brillouin laser in order to provide more stable mode locking regime and, therefore stable pulsed regime. For the pulsed seed Stokes signal regime the spatial distribution of the temperature or strain can be founded by pump depletion measurements using optical beamsplitter 117 connected to photodiode 111. Exact values of the temperature or strain in certain location can be founded if reference fiber is uniformly stressed/ elongated or heated/cooled that changes the Brillouin shift of the reference fiber.

FIG. 5 schematically illustrates one embodiment of the method to obtain optical signals modulated at 10-50 GHz when the reference laser 104 is locked on "n" Stokes component of the reference Brillouin laser. In this embodiment the first Stokes component that propagate inside the Brillouin laser cavity operates as pump radiation for the second Stokes component, second as pump for the third and so on. At list five Stokes components can be obtained for the moderate pump intensity.

In one embodiment modulation of current of pump laser 103 is used instead using intensity modulator 110 (see Fig.1). Relatively small and short pulse-like variation of laser working current slightly change the output power of the semiconductor DFB laser but can significantly change the laser frequency. This frequency change can considerably exceed the characteristic Brillouin gain bandwidth which is equal approximately to 35 MHz. For big enough length of the reference fiber 102 this short intensity and frequency changing of the pump does not affect the amplification phenomena and, therefore the locking phenomena. As result the reference laser still locked on Stokes wavelength that corresponded to undisturbed working current of pump laser and therefore seed signal do not change his frequency during this disturbance. Meanwhile the spontaneously scattered Stokes component of short disturbance have significantly differ frequency because the pump frequency is also differ during time of this pump current variation. Therefore time-domain analysis of the beat frequency shift at frequency interval which corresponds to the disturbed working current allows measuring the temperature or strain distribution along the test fiber 101.

The proposed method allows to omit all optical modulators that significantly reduce the complexity of the Brillouin based distributed sensors.

Claims

1. A method for distributed sensing with a Stokes-locked reference laser, comprising the steps of splitting an optical pump radiation in two beams, one for Brillouin pumping of an optical reference fiber and another for pulsed Brillouin pumping of a test fiber, locking a reference laser on reference fiber Stokes radiation for producing a stable seed signal which is launched into the test fiber, receiving a spontaneous back-scattered Stokes signal transmitted through the test fiber seed signal, calculating the temperature or strain distribution by sensing change in amplification of the seed signal or by processing the shift of the beat spectrum between the seed signal and the spontaneously scattered Stokes component along the test fiber.

2. The method for distributed sensing with Stokes-locked reference laser as claimed in claim 1 including the further step of using the reference laser as a local oscillator for heterodyne detection.

3. The method for distributed sensing with Stokes-locked reference laser as claimed in any one of the preceding claims in which the reference laser locks on a reference ring Brillouin laser output radiation.

4. The method for distributed sensing with Stokes-locked reference laser as claimed in any one of the preceding claims in which the reference laser locks on reference Fabry-Perot Brillouin laser output radiation.

5. The method for distributed sensing with Stokes-locked reference laser as claimed in any one of the preceding claims in which the reference fiber is uniformly stressed for changing the Brillouin shift of the reference fiber.

6. The method for distributed sensing with Stokes-locked reference laser as claimed in any one of the preceding claims in which the reference fiber is uniformly elongated for changing the Brillouin shift of the reference fiber.

7. The method for distributed sensing with Stokes-locked reference laser as claimed in any one of the preceding claims in which the reference fiber is uniformly heated for changing the Brillouin shift of the reference fiber.

8. The method for distributed sensing with Stokes-locked reference laser as claimed in any one of the preceding claims in which the reference fiber is uniformly cooled for changing the Brillouin shift of the reference fiber.

9. The method for distributed sensing with Stokes-locked reference laser as claimed in any one of the preceding claims including the step of modulating the current of the reference laser to improve spatial resolution.

10. The method for distributed sensing with Stokes-locked reference laser as claimed in any one of the preceding claims in which an intensity or phase modulator is used inside the cavity of the reference Brillouin laser to provide a stable pulsed regime.

11. The method for distributed sensing with Stokes-locked reference laser as claimed in any one of the preceding claims in which the reference laser locks on an n^{th} Stokes component of a Brillouin laser.

12. The method as claimed in any one of the preceding claims in which the reference laser is locked on the n^{th} Stokes component of a Brillouin laser.

13. An apparatus for distributed sensing with Stokes-locked reference laser, comprising a test fiber positioned along an object, a reference fiber at a predetermined temperature and strain along its length, a pump laser for producing Brillouin scattering in the test and reference fibers, a reference laser, a reference Brillouin amplifier having sufficient intensity output to lock a reference laser wavelength on the Stokes wavelength of the reference fiber, an optical intensity modulator to produce an optical pulse so that pump laser radiation is pulsed into the test fiber and the laser locked light on the amplified Stokes radiation produces a stable seed signal which is launched in said test fiber, a signal processor connected to the Stokes detector for calculating the temperature and/or strain distribution in the test fiber by measuring change in amplification of the seed signal and/or the shift of the beat spectrum between seed signal and spontaneously scattered Stokes component along the test fiber.

14. An apparatus for distributed sensing with Stokes-locked reference laser as claimed in claim 13 in which, the signal processor is a computer.

15. An apparatus for distributed sensing with Stokes-locked reference laser as claimed in claim 13 or claim 14 in which, the reference fiber is a polarization maintaining fiber.

16. A method substantially described as herein with reference to and as illustrated in the accompanying drawings.

17. An apparatus substantially described as herein with reference to and as illustrated in the accompanying drawings.

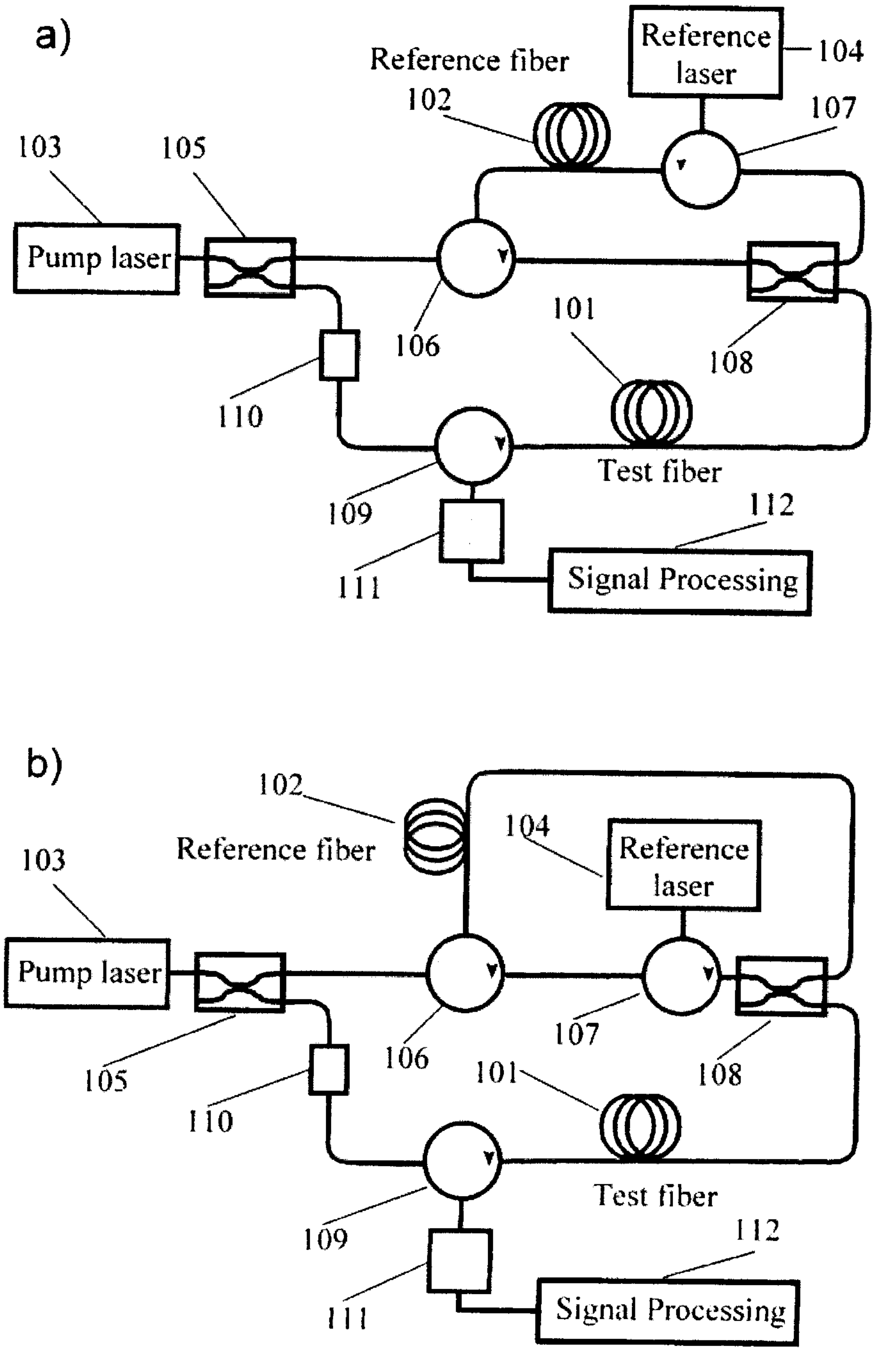

a)
Reference fiber
102
Reference laser
104
107
103
105
Pump laser
106
101
108
110
Test fiber
109
112
111
Signal Processing
b)
102
Reference fiber
104
Reference laser
103
Pump laser
105
106
107
108
110
101
Test fiber
109
112
111
Signal Processing

FIGURE 1

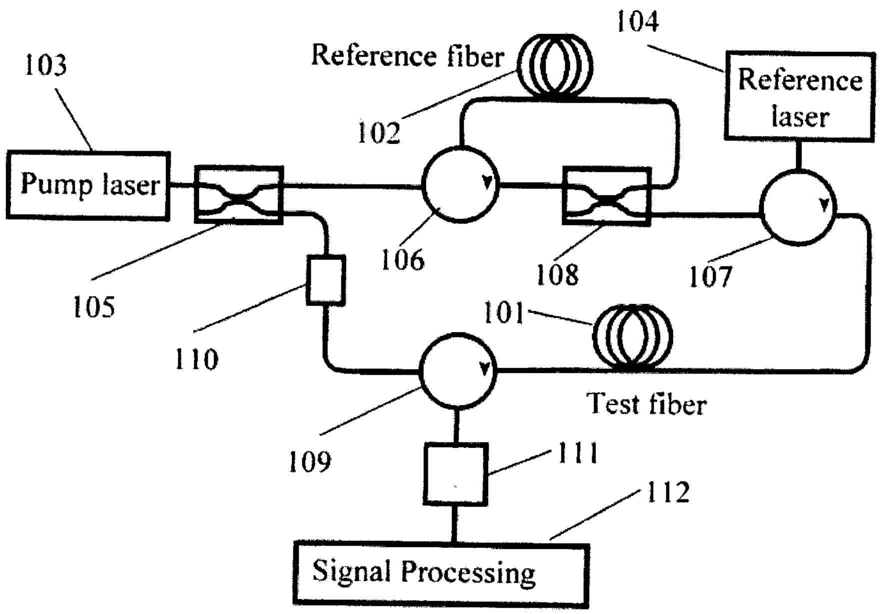

104
Reference fiber
103
Reference laser
102
Pump laser
106
108
107
105
101
110
Test fiber
109
111
112
Signal Processing

FIGURE 2

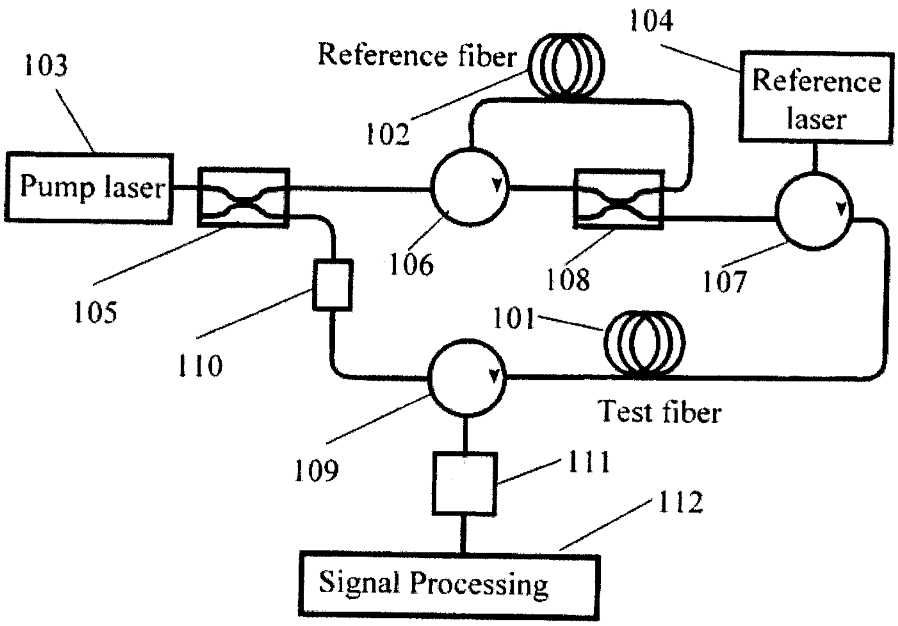
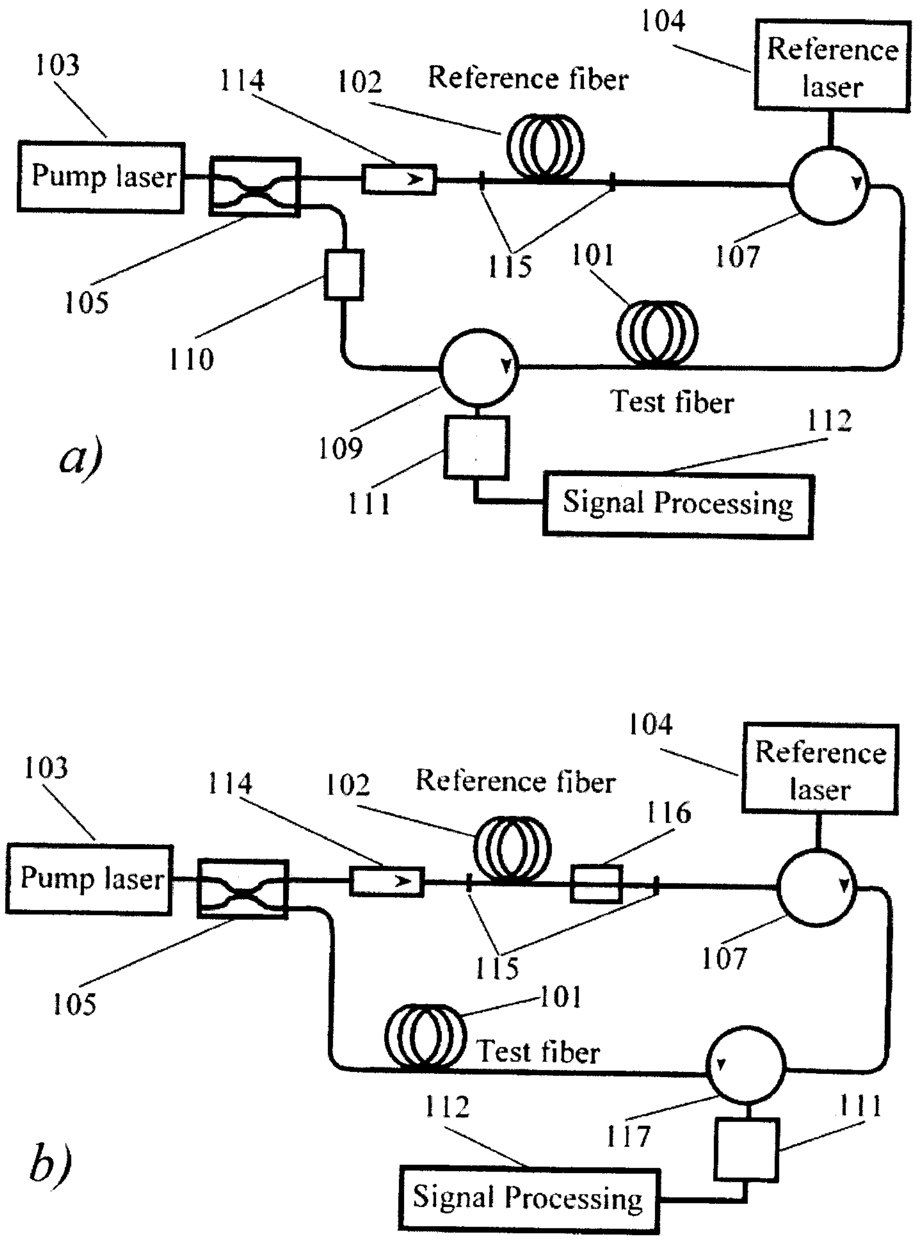

104
Reference fiber
103
Reference laser
102
Pump laser
106
108
107
105
101
110
Test fiber
109
111
112
Signal Processing

FIGURE 3



104
Reference laser
103
114
102
Reference fiber
Pump laser
105
110
115
101
107
Test fiber
109
112
a)
111
Signal Processing
104
Reference laser
103
114
102
Reference fiber
116
Pump laser
105
115
107
101
Test fiber
112
111
117
b)
Signal Processing

FIGURE 4

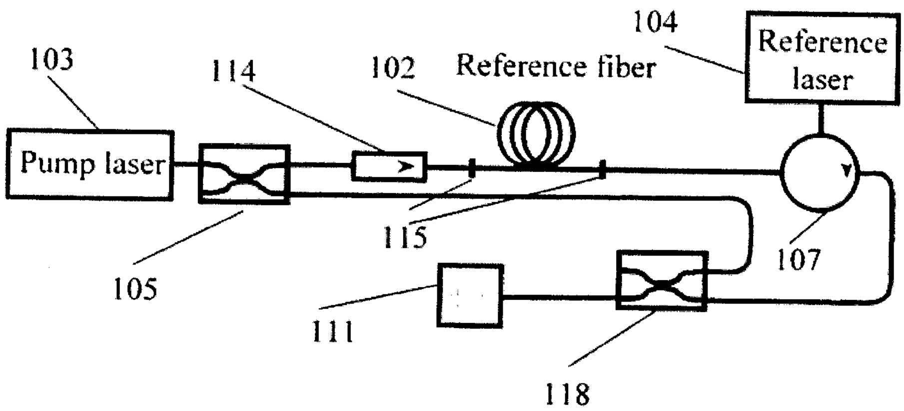

104
Reference laser
103
114
102
Reference fiber
Pump laser
115
105
107
111
118

FIGURE 5