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Brillouin gain spectrum distribution measurement method and equipment

Abstract

An object of the present invention is to provide a Brillouin gain spectrum distribution measuring method and apparatus capable of measuring a BGS, having a line width narrower than usual, in a distributed manner in the longitudinal direction of an optical fiber under test. This measuring apparatus prepares pump light in which a pulse is added to continuous light and probe light of continuous light in which a frequency is shifted from the pump light, makes the probe light incident on one end of the FUT and the pump light incident on the other end, and obtains a time waveform of a component amplified by the pump light pulse of a probe light intensity amplified by the pump light. This measuring apparatus changes an optical frequency difference between the pump light and the probe light, and obtains a time waveform for each optical frequency difference. This measuring apparatus obtains a BGS distribution of the FUT from these time waveforms.

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Background/Summary

(1) This application is a 371 U.S. National Phase of International Application No. PCT/JP2021/002547, filed on Jan. 26, 2021. The entire disclosure of the above application is incorporated herein by reference.

TECHNICAL FIELD

(2) The present disclosure relates to a measuring method and a measuring apparatus thereof capable of obtaining a Brillouin gain spectrum distribution in a longitudinal direction of an optical fiber with a narrow line width.

BACKGROUND ART

(3) Temperature sensing and strain sensing by Brillouin time domain analysis (BOTDA) have been proposed (see, for example, NPL 1). The measuring method of NPL 1 utilizes a characteristic that the amount of Brillouin frequency shift (BFS) in an optical fiber changes with temperature and strain. Since the BFS can be obtained in a distributed manner in the longitudinal direction of the fiber, distribution sensing of temperature and strain is enabled.

(4) In the BOTDA, pump light is made incident on one end of an optical fiber under test and probe light whose frequency difference is set to the pump light is made incident on the other end, and the amount of amplification (Brillouin gain) of the probe light amplified by Brillouin interaction with the pump light is observed. Here, the amount of amplification with respect to the frequency difference is a Brillouin gain spectrum (BGS), and the BFS, which is the frequency at which the amount of amplification is maximized, is obtained from this BGS.

(5) It is known that the accuracy of BFS that can be obtained from the BGS depends generally on the line width of the BGS. The BGS of a single mode fiber at a wavelength of 1,550 nm generally has a full width at half maximum (FWHM) of 30 to 40 MHz, and in this case, a measurement accuracy of the BFS of about 1 MHz is obtained. As described above, since the BFS corresponds to temperature and strain, the acquisition of a narrow line width of the BGS is important for improving the accuracy of temperature and strain measurement.

(6) It is known that the line width of the BGS depends on the Brillouin action length, and it has been reported that that of a pure silica core fiber of 40 km can be narrowed down to 3.5 MHz (see, for example, NPL 2).

CITATION LIST

Non Patent Literature

(7) [NPL 1] T. Kurashima et al., Opt. Lett., 15(18), 1038-10400(1990). [NPL 2] Iida et al., IEICE Technical Report, vol. 108, No. 245, OFT 2008-43, pp. 45-50, October 2008. [NPL 3] A. Yeniay et al., J. Light. Technol., 20(8), 1425-1432 (2002).

SUMMARY OF INVENTION

Technical Problem

(8) However, if continuous light is incident and a Brillouin action is generated in the entire section of an optical fiber under test as in the case of NPL 2, there is a problem that the BGS cannot be measured in a distributed manner in the longitudinal direction. In order to solve the above problem, an object of the present invention is to provide a Brillouin gain spectrum distribution measuring method and apparatus capable of measuring a BGS, having a line width narrower than usual, in a distributed manner in the longitudinal direction of an optical fiber under test.

Solution to Problem

(9) In order to achieve the above object, a Brillouin gain spectrum distribution measuring method and apparatus according to the present invention perform Brillouin time domain analysis (BOTDA) using pump light in which a pulse component is superimposed on a part of continuous light.

(10) Specifically, a Brillouin gain spectrum distribution measuring method according to the present invention includes making probe light of continuous light and pump light of continuous light incident from one end and the other end of an optical fiber under test, respectively, to generate a

Brillouin action in an entire section of the optical fiber under test, making pulse-like pulsed pump light having the same optical frequency as that of the pump light incident from the other end of the optical fiber under test in a state where the Brillouin action in the entire section is maintained, extracting an amplification component by the pulsed pump light from the amplified probe light output from the other end of the optical fiber under test, measuring a time waveform of the amplification component for each optical frequency difference between the probe light and the pump light, and obtaining a Brillouin gain spectrum from the time waveform of the amplification component measured for each optical frequency difference in a distributed manner in a longitudinal direction of the optical fiber under test.

(11) In addition, a Brillouin gain spectrum distribution measuring apparatus according to the present invention includes a light incident device that makes probe light of continuous light and pump light of continuous light incident from one end and the other end of an optical fiber under test, respectively, to generate a Brillouin action in an entire section of the optical fiber under test, and makes pulse-like pulsed pump light having the same optical frequency as that of the pump light incident from the other end of the optical fiber under test in a state where the Brillouin action in the entire section is maintained, a light receiver that extracts an amplification component by the pulsed pump light from the amplified probe light output from the other end of the optical fiber under test, and an analysis device that measures a time waveform of the amplification component for each optical frequency difference between the probe light and the pump light, and obtains a Brillouin gain spectrum from the time waveform of the amplification component measured for each optical frequency difference in a distributed manner in a longitudinal direction of the optical fiber under test.

(12) The BGS width can be narrowed by superimposing pulse-like pulsed pump light on continuous pump light. Therefore, the present invention can provide a Brillouin gain spectrum distribution measuring method and apparatus capable of measuring a BGS, having a line width narrower than usual, in a distributed manner in the longitudinal direction of an optical fiber under test.

(13) In the Brillouin gain spectrum distribution measuring method and apparatus according to the present invention, a light intensity of the pump light is increased to obtain the pulsed pump light.

(14) The above inventions can be combined wherever possible.

Advantageous Effects of Invention

(15) The present invention can provide a Brillouin gain spectrum distribution measuring method and apparatus capable of measuring a BGS, having a line width narrower than usual, in a distributed manner in the longitudinal direction of an optical fiber under test.

Description

BRIEF DESCRIPTION OF DRAWINGS
(1) FIG. **1** is a diagram illustrating the measurement concept of a Brillouin gain spectrum distribution measuring method according to the present invention.
(2) FIG. **2** is a diagram illustrating an example of amplified probe light in the Brillouin gain spectrum distribution measuring method according to the present invention.
(3) FIG. **3** is a diagram illustrating a Brillouin gain spectrum distribution measuring apparatus according to the present invention.
(4) FIG. **4** is a diagram illustrating the Brillouin gain spectrum distribution measuring method according to the present invention.
(5) FIG. **5** is a diagram illustrating the effects of the Brillouin gain spectrum distribution measuring method and apparatus according to the present invention. FIG. **5**(*a*) shows the BGS measured by a normal BOTDR, and FIG. **5**(*b*) shows the BGS measured by the measuring method according to

the present invention.
DESCRIPTION OF EMBODIMENTS
(6) Embodiments of the present invention will be described with reference to the accompanying drawings. The embodiments described below are examples of the present invention, and the present invention is not limited to the following embodiments. Note that, in the present specification and the drawings, components having the same reference numerals indicate the same components.
SUMMARY OF INVENTION
(7) The spectrum S(ω) obtained from the Brillouin gain can be represented by the following equation (see, for example, NPL 3).

[Math . 1]

(8)
$$S(\omega) = \frac{4h\omega_s(N+1)}{ncA\Gamma}[\exp(\frac{G(\frac{\Gamma}{2})^2}{\omega^2 + (\frac{\Gamma}{2})^2}) - 1] \quad (1)$$

(9) Here, ω is an optical frequency difference between the probe light and the pump light, h is the Planck constant, cos is an optical frequency of the probe light, and N is an average number of phonons for each acoustic mode. In addition, n is a refractive index of the core, c is the velocity of light in a vacuum, A is an effective cross-sectional area, Γ is a phonon attenuation factor, and G represents the Brillouin gain.
(10) From Equation (1), the BGS shape is determined by the Brillouin gain G and the phonon attenuation factor Γ. When the pump light is a pulse, the gain G becomes small because the Brillouin action length is short. In this case, Equation (1) becomes a Lorentzian distribution, and the spectrum width Δω of the BGS at this time is given by Δω=Γ.
(11) On the other hand, when the pump light is continuous light, the gain G becomes large because the Brillouin action length is long. In this case, Equation (1) becomes a Gaussian distribution, and the spectrum width Δω of the BGS at this time is given by the following equation.

[Math . 2]

(12)
$$\Delta\omega = \Gamma[\frac{\ln 2}{G}] \quad (2)$$

(13) Equation (2) expresses that the spectrum width narrows as the gain G increases. From Equation (2), it can be seen that generating the Brillouin action in the entire fiber section is effective in obtaining a narrow line width BGS.
(14) In the present invention, pump light in which a pulse is added to a part of continuous light in advance is used as a measurement configuration in order to measure a BGS distribution of a narrow line width in the normal BOTDA configuration.
(15) FIG. **1** is a diagram illustrating the concept of BGS measurement according to the present invention. In the BGS measurement, pump light Lpo**1** of continuous light is first made incident on an optical fiber under test (FUT) **50**, and a Brillouin action is generated in the entire fiber section by the pump light Lpo**1** and probe light Lpb. In a state where the action is maintained, pulsed pump light Lpo**2** of a pulse component added to the pump light Lpo**1** is made incident on the FUT **50**, and a probe light intensity amplified by the pulse is measured.
(16) FIG. **2** is a diagram illustrating the intensity waveform of the probe light observed after the emission of the FUT **50**. Symbol A represents the light intensity of the probe light LPb after passing through the FUT **50**, symbol B represents the amount of amplification by the continuous light component (pump light Lpo**1**) of the pump light Lpo, and symbol C represents the amount of amplification by the pulse component of the pump light (pulsed pump light Lpo**2**).
(17) As illustrated in FIG. **2**, the continuous light component of the pump light (pump light Lpo**1**) and the pulse component of the pump light (pulsed pump light Lpo**2**) amplify the probe light Lpb inside the FUT **50**. The pump light Lpo**1** always amplifies the probe light Lpb by a certain amount. On the other hand, the pulsed pump light Lpo**2** differs in timing (time t) of amplifying the probe light Lpb depending on the collision position with the probe light Lpb in the FUT **50**. In other words, in FIG. **2**, the timing of amplifying the probe light Lpb by the pulsed pump light Lpo**2**

corresponds to the length direction of the FUT **50**. Further, the amount of amplification of the probe light Lpb is gradually reduced because of attenuation due to loss on the FUT **50**.

(18) A time waveform of the probe light intensity is measured by utilizing the difference in the amplification timing, and the BGS at any position of the FUT **50** can be obtained by subtracting the probe light intensity after passing through the FUT **50** and the amplification by the pump light Lpo**1** from the waveform.

Embodiment

(19) FIG. **3** is a diagram illustrating a measuring apparatus according to the present embodiment. The measuring apparatus includes: a light incident device **10** that makes probe light Lpb of continuous light and pump light Lpo**1** of continuous light incident from one end **50***a* and the other end **50***b* of an optical fiber under test **50**, respectively, to generate a Brillouin action in an entire section of the optical fiber under test **50**, and makes pulse-like pulsed pump light Lpo**2** having the same optical frequency as that of the pump light Lpo**1** incident from the other end **50***b* of the optical fiber under test **50** in a state where the Brillouin action in the entire section is maintained; a light receiver **20** that extracts an amplification component by the pulsed pump light Lpo**1** from the amplified probe light Lpb output from the other end **50***b* of the optical fiber under test **50**; and an analysis device **30** that measures a time waveform of the amplification component for each optical frequency difference between the probe light Lpb and the pump light Lpo, and obtains a Brillouin gain spectrum from the time waveform of the amplification component measured for each optical frequency difference in a distributed manner in a longitudinal direction of the optical fiber under test **50**.

(20) The light incident device **10** includes a laser light generating means **11**, a branching element **12**, a frequency control means **13**, a pulse generating means **14**, and an optical amplification means **15**. The light receiver **20** includes a probe light extraction means **21** and a photoelectric conversion means **22**. The analysis device **30** includes an A/D conversion means **32** and a BGS analysis means **33**.

(21) The measuring apparatus makes the pump light Lpo, in which a pulse is added to continuous light, incident on the other end **50***b* of the FUT **50**, and makes the probe light Lpb, in which an optical frequency is shifted from that of the pump light Lpo, incident on one end **50***a*, and measures BGS from a Brillouin gain generated by light collision.

(22) In the light incident means **10**, the light, output from the laser light generating means **11** that generates coherent light, is branched into two by the branching element **12**; one is the probe light Lpb and the other is the pump light Lpo.

(23) The optical frequency control means **13** imparts a frequency difference of about 10 to 11 GHz corresponding to Brillouin frequency shift (BFS) to one light from the laser light generating means **11**, and makes the one light incident on one end **50***a* of the FUT **50** as the probe light Lpb. For example, the optical frequency control means **13** is an external modulator such as an SSB modulator constituted by LiNb3. In the present embodiment, although the type of branching the light, from one laser light generating means **11**, into two is described, two lasers having different frequencies (wavelengths) may be used and the light sources of the pump light and the probe light may be separately assigned thereto to control the optical frequency difference between the two lasers.

(24) On the other hand, the pulse generating means **14** pulses the other light from the laser light generating means **11**. For example, an LN intensity modulator or the like can be used as the pulse generating means **14**. In this case, a pulse having an extinction ratio of about 20 dB and slightly containing a continuous light component is generated. The pulse is amplified by the optical amplification means **15** to generate the pump light Lpo including the pump light Lpo**1**, of optical power capable of generating the Brillouin action and of continuous light, and the pulsed pump light Lpo**2** added thereto. The pump light Lpo is made incident on the FUT **50** from the other end **50***b*. The pump light Lpo may have a shape in which a pulse is added to the continuous light, and may

be generated by preparing the continuous light and the pulse separately and multiplexing them.

(25) The pump light Lpo and the probe light Lpb collide with each other in the FUT **50**, and the probe light Lpb is amplified by the Brillouin action. The amplified probe light Lpb is emitted from the other end **50***b* of the FUT **50**, passes through an optical circulator **40**, and is made incident on the probe light extraction means **21**. The probe light extraction means **21** extracts only the probe light Lpb by removing the backscattered light component of the pump light Lpo. The probe light extraction means **21** may pass only the frequency of the probe light by using an optical filter, or may perform coherent detection of the same probe light before the FUT incidence as local light and extract only the probe light component by using a difference in beat frequency.

(26) The photoelectric conversion means **22** converts the probe light Lpb from the probe light extraction means **21** into an electrical signal. The A/D conversion means **32** converts the electrical signal into digital data, and the BGS analysis means **33** analyzes the BGS distribution from the digital data.

(27) The BGS analysis means **33** first subtracts a probe light intensity component A and a component B, which is amplified by the pump light of the continuous light, from the obtained probe light intensity waveform (see FIG. **2**) to obtain only a component C, which is amplified by the pump light of the pulse. The BGS distribution is obtained by repeatedly measuring the amplification component C while changing the frequency difference between the pump light and the probe light.

(28) FIG. **4** is a diagram illustrating a measuring method of the Brillouin gain spectrum distribution measuring apparatus shown in FIG. **3**. This measuring method includes making probe light Lpb of continuous light and pump light Lpo**1** of continuous light incident from one end **50***a* and the other end **50***b* of an FUT **50**, respectively, to generate a Brillouin action in the entire section of the FUT **50** (step S**01**), making pulse-like pulsed pump light Lpo**2** having the same optical frequency as that of the pump light Lpo**1** incident from the other end **50***b* of the FUT **50** at a desired timing in a state where the Brillouin action in the entire section is maintained (step S**02**), extracting an amplification component (component C in FIG. **2**) by the pulsed pump light Lpo**2** from the amplified probe light Lpb output from the other end **50***b* of the FUT **50** (step S**03**), and measuring a time waveform of the amplification component for each optical frequency difference between the probe light Lpb and the pump light Lpo (steps S**05** and S**06**), and obtaining a Brillouin gain spectrum from the time waveform of the amplification component measured for each optical frequency difference in a distributed manner in a longitudinal direction of the FUT **50** (step S**07**).

(29) As described above, in step S**02**, the light intensity of the pump light Lpo**1** may be increased to obtain the pulsed pump light Lpo**2**.

Effects

(30) FIG. **5** is a diagram illustrating an example of the results of BGS measurement for the FUT **50** of 40 km. FIG. **5**(*a*) shows the BGS measured with a pulse width of 100 ns in normal BOTDA (where pump light is a pulse), and FIG. **5**(*b*) shows the BGS observed with the same pulse width of 100 ns in the measuring method of the present invention (pulse in which pump light is added to continuous light). From FIG. **5**(*a*), it can be confirmed that the BGS shape has a Lorentzian distribution, and the FWHM of this BGS is about 30 MHz. On the other hand, FIG. **5**(*b*), which is the result obtained by the present invention, has a Gaussian distribution, and the FWHM of this BGS is about 11 MHz. From these results, it can be seen that the line width can be made narrower than the BGS width obtained by the normal BOTDA in the measuring method of the present invention.

Other Embodiments

(31) The BGS analysis means **33** described with reference to FIG. **3** can also be realized by a computer and a program, and the program can be recorded in a recording medium or provided through a network.

REFERENCE SIGNS LIST

(32) **10**: Light incident device **11**: Laser light generating means **12**: Branching element **13**: Frequency control means **14**: Pulse generating means **15**: Optical amplification means **20**: Light receiver **21**: Probe light extraction means **22**: Photoelectric conversion means **30**: Analysis device **32**: A/D conversion means **33**: BGS analysis means **40**: Optical circulator **50**: Optical fiber under test (FUT) **50***a*: One end **50***b*: Other end

Claims

1. A Brillouin gain spectrum distribution measuring method comprising: making probe light of continuous light and pump light of continuous light incident from one end and the other end of an optical fiber under test, respectively, to generate a Brillouin action in an entire section of the optical fiber under test; making pulse-like pulsed pump light having the same optical frequency as that of the pump light incident from the other end of the optical fiber under test in a state where the Brillouin action in the entire section is maintained; measuring an intensity of the light output from the other end of the optical fiber under test; for each optical frequency difference between the probe light and the pump light, extracting an amplification component of the probe light amplified by the pulsed pump light by subtracting an intensity component of the probe light and a component of the probe light amplified by the pump light from the measured intensity of the light, thereby obtaining a Brillouin gain spectrum in a distributed manner in a longitudinal direction of the optical fiber under test.
2. The Brillouin gain spectrum distribution measuring method according to claim 1, wherein a light intensity of the pump light is increased to obtain the pulsed pump light.
3. A Brillouin gain spectrum distribution measuring apparatus comprising: a light incident device that makes probe light of continuous light and pump light of continuous light incident from one end and the other end of an optical fiber under test, respectively, to generate a Brillouin action in an entire section of the optical fiber under test, and makes pulse-like pulsed pump light having the same optical frequency as that of the pump light incident from the other end of the optical fiber under test in a state where the Brillouin action in the entire section is maintained; a light receiver that measures an intensity of the light output from the other end of the optical fiber under test; and an analysis device that, for each optical frequency difference between the probe light and the pump light, extracts an amplification component of the probe light amplified by the pulsed pump light by subtracting an intensity component of the probe light and a component of the probe light amplified by the pump light from the measured intensity of the light, thereby obtaining a Brillouin gain spectrum in a distributed manner in a longitudinal direction of the optical fiber under test.
4. The Brillouin gain spectrum distribution measuring apparatus according to claim 3, wherein the light incident device increases a light intensity of the pump light to obtain the pulsed pump light.