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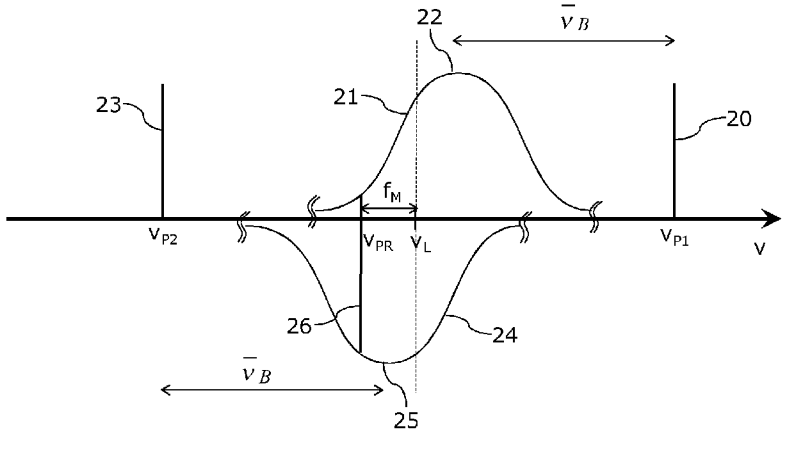

Fig. 4

(57) **Abstract**: The present invention concerns a Brillouin optical distributed sensing method, comprising steps of: (i) providing a first and a second optical pulsed pump wave (20, 23) and an optical probe wave comprising at least one probe spectral component (26), (ii) detecting a stimulated Brillouin scattering signal resulting from the interactions in a sensing optical fiber of the optical probe wave with the first and the second optical pulsed pump waves (20, 23), (iii) spectrally arranging the first and the second optical pulsed pump waves (20, 23) and the optical probe wave so that the optical probe wave comprises a probe spectral component (26) located within the Stokes Brillouin spectrum (21) of the first optical pulsed pump wave (20) and a probe spectral component (26) located within the anti-Stokes Brillouin spectrum (24) of the second optical pulsed pump wave (23), (iv) deducing the Brillouin frequency (22, 25) of the Brillouin spectra (21, 24) from the stimulated Brillouin scattering signal. The present invention concerns also a device for implementing the method.

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« Dual-pump sweep-free stimulated Brillouin optical distributed sensing method and device »

Field of the invention

The invention relates to a stimulated Brillouin optical distributed sensing method which allows fast measurement rates and improved detection sensitivity. The invention relates also to a device implementing the method.

The field of the invention is, but not limited to, distributed temperature and/or strain sensing using Brillouin scattering.

Background of the invention

The use of Brillouin scattering in optical fibers is a well-known technique for performing measurements of temperature and/or strain along long distances.

Brillouin scattering occurs when a light wave propagating in a medium (such as an optical fiber) interacts with time-dependent density variations of the medium. These density variations may be due for instance to acoustic waves or phonons propagating in the medium, and they modulate the index of refraction. The light wave interacts with these variations of index of refraction and a fraction of the light is scattered accordingly. Since acoustic waves propagate at the speed of sound in the medium, deflected light is also subjected to a Doppler shift, so its frequency changes.

The speed of sound in the medium depends on the temperature of the medium or on the strain. So, a variation of any of these parameters induces a variation of the frequency shift of the scattered light due to Brillouin scattering, and so may be measured.

In addition, when an intense beam such as a laser beam travels in a medium such as an optical fiber, the variations in the electric field of the beam itself may produce acoustic vibrations in the medium. The beam may undergo Brillouin scattering from these vibrations, usually in opposite direction to the incoming beam.

Brillouin optical time domain instruments have been done on the basis of this principle. They allow measuring the temperature and/or the strain along distributed sensors based on single-mode optical fibers which may be several kilometers long.

The applications relate mainly to the domains of geosciences, mining, oil exploitation, energy transportation, and civil engineering for the monitoring of large structures.

The distributed sensors are embedded in the environment or the structures to monitor. So, the optical fibers of these distributed sensors are subjected to the variations of temperature and strain of the environment along their path.

We know for instance systems usually referred to as Brillouin Optical Time Domain Analyzers (BOTDA), which are based on a stimulated Brillouin scattering measurement scheme. Their principle of operation is as follows.

An optical pulsed pump wave is launched into a sensing optical fiber of the distributed sensor. A continuous optical probe wave is launched into the same sensing fiber from the opposite end, so that the pump and the probe signals travel in the sensing fiber in opposite directions. So, the pump and the probe signals can interfere to activate electrostriction and mutually interact through the stimulated Brillouin scattering process (SBS). Due to the pulsed nature of the pump, the SBS interaction between the pump and the probe takes place at different position along the fiber at different time.

The SBS interaction results in an energy transfer between the pulsed pump wave and the probe wave. The probe wave emerging from the sensing fiber is detected and processed so as to determine the SBS interaction and thus the variations of temperature and/or strain along the sensing fiber.

When the frequency of the probe wave falls within the frequency range of the Stokes spontaneous Brillouin spectrum of the pump wave, an energy transfer occurs from the pump wave to the probe wave, which leads to an amplification of the probe wave (Brillouin gain mode).

When the frequency of the probe wave falls within the frequency range of the anti-Stokes spontaneous Brillouin spectrum of the pump wave, an energy transfer occurs from the probe wave to the pump wave, which leads to an attenuation of the probe wave (Brillouin loss mode).

With pump waves in the infrared, the Stokes spontaneous Brillouin spectrum is located at frequencies about 11 GHz lower than the frequency of the pump wave, while the anti-Stokes spontaneous Brillouin spectrum is located at frequencies about 11 GHz higher than the frequency of the pump wave. Both Stokes and anti-Stokes Brillouin spectra have a Lorentzian shape, with the intrinsic bandwidth of about 30 MHz at full width at half maximum (FWHM). The respective peak frequencies where the Brillouin gain and the Brillouin loss are the largest are usually defined as Brillouin frequencies. In standard conditions these Brillouin frequencies have a linear relationship with temperature and strain, typically of 1 MHz/K or 1 MHz/20$\mu\varepsilon$ respectively, ε being the axial elongation or compression of the fiber.

In classical Brillouin Optical Time Domain Analyzers, measurements are usually done in loss mode. The frequency of the probe wave is varied step-by-step across a frequency range covering the Brillouin loss spectrum. For each probe frequency step, a signal is acquired in the time domain whose local amplitude depends on the Brillouin interaction strength at the corresponding location along the sensing fiber. The measurements at different frequencies are combined to reconstruct the shape of the Brillouin loss interaction spectrum and to compute the corresponding Brillouin frequency.

An important drawback of these classical methods is that they allow only slow measurement rates because the probe frequency must be scanned over the whole gain spectrum to accurately determine the Brillouin frequency. The scanning range must be larger than the amount of change in temperature or strain which has occurred. In addition, the effective spectral width of the Brillouin spectrum is larger than its intrinsic bandwidth, as the effective Brillouin spectrum corresponds to the convolution product of the intrinsic Brillouin spectrum and the power spectrum of the pulsed pump wave. So, the measurement times are inevitably long, and the performances of the sensing systems are limited to the monitoring of slowly varying temperature and/or strain.

We know the document WO 2012/101592 which discloses a method allowing higher measurement rates. The probe wave is positioned at a frequency which is shifted relative to the Brillouin frequency (in pre-defined conditions of strain and temperature) so as to fall in a region of the Brillouin gain spectrum where the variability is high, such as for instance the frequency corresponding to the half maximum of the spectrum or the −3dB frequency. As the Brillouin gain spectrum shifts locally in frequency with variations of temperature and/or strain, the amplitude of the probe wave varies accordingly. Under these conditions, the Brillouin frequency may be obtained directly from the amplitude of the probe wave at a single frequency around the –3dB frequency.

The method disclosed in WO 2012/101592 suffers from two major drawbacks:

- The measurement range in terms of Brillouin frequency shift is limited to about the full width at half maximum (FWHM) of the Brillouin gain spectrum, which is about 30 MHz (±15 MHz) for the intrinsic gain spectrum. The measurement range in terms of temperature and/or strain is limited accordingly;
- When the probe frequency falls towards the bottom of the Brillouin gain curve where the gain is very low, the measurement sensitivity becomes also very low and the signal to noise ratio deteriorates accordingly.

Another important drawback of the known BOTDA methods is that the probe signal which is detected is a DC signal with low-frequency amplitude variations containing the Brillouin scattering information. So the noise perturbations, due for instance to the optical amplifiers and the intensity noise of the probe wave itself, have a direct impact on the sensitivity and the accuracy of the measurements.

Another drawback of the known BOTDA methods is that the systems require a tunable RF signal generator with a tuning range of ~1 GHz at 11 GHz, which is expensive.

The conventional BOTDA sensing systems preferably use a single laser to provide a pump signal and probe signal. The laser is split to two branches. Light in one branch is sent to a pulse generator, generating pump pulse. Light in the other branch is sent to a frequency shifter and the frequency-shifted light delivered by the frequency shifter is used as probe signal. In general, an external electro-optic modulator (EOM) is used as frequency shifter and the amount of the frequency shift is determined by the radiofrequency (RF) signal applied to the EOM. The amount of frequency shift must be equal or around the Brillouin frequency, so the RF signal must be tunable at or around the Brillouin frequency, typically 11GHz, with a tuning range of ~1 GHz.

Phase-lock loop (PLL) circuit is in general used to generate such RF signal, but the inevitable phase noise caused in the PLL adds random fluctuation in amplitude of the probe signal when it is detected.

It is an object of the invention to propose a Brillouin sensing method which allows mitigating the drawbacks of the prior art.

It is another object of the invention to propose a Brillouin sensing method which allows achieving fast measurement rates with high measurement accuracy.

It is still another object of the invention to propose a Brillouin sensing method which allows avoiding low-frequency noise perturbations.

It is still another object of the invention to propose a Brillouin sensing method which may be implemented in a simple set-up with moderate cost components.

Summary of the invention

Such objects are accomplished through a Brillouin optical distributed sensing method, comprising steps of:

- providing a first optical pulsed pump wave at a first pump frequency and a second optical pulsed pump wave at a second pump frequency,

- providing an optical probe wave comprising at least one probe spectral component,

- directing said first and second optical pulsed pump waves and said optical probe wave to a sensing optical fiber so that the optical probe wave propagates in said sensing optical fiber in a direction opposite to said first and second optical pulsed pump waves,

- detecting a stimulated Brillouin scattering signal resulting from the interactions in said sensing optical fiber of the optical probe wave with the first and the second optical pulsed pump waves,

characterized in that:

- the first and the second optical pulsed pump waves and the optical probe wave are spectrally arranged so that, at least for a given set of temperature and/or strain conditions along at least a part of the sensing optical fiber, the optical probe wave comprises a probe spectral component located within the Stokes Brillouin spectrum of the first optical pulsed pump wave and a probe spectral component located within the anti-Stokes Brillouin spectrum of the second optical pulsed pump wave,

- the method further comprises a step of deducing the Brillouin frequency of said Stokes Brillouin spectrum and/or said anti-Stokes Brillouin spectrum from the stimulated Brillouin scattering signal.

The Brillouin frequency of the Stokes Brillouin spectrum or of the anti-Stokes Brillouin spectrum may be defined as the frequency location of the maximum value of the respective Brillouin spectra.

Determining the Brillouin frequency allows in turn determining the strain and/or temperature conditions along the sensing fiber as it depends in a fairly linear way of these parameters.

According to the method of the invention, the Brillouin frequency may be deduced from the stimulated Brillouin scattering signal. So, in other words, the invention allows obtaining a value of Brillouin frequency for each measurement of the stimulated Brillouin scattering signal.

So there is no need to scan in frequency the whole Brillouin scattering spectrum by acquiring several stimulated Brillouin scattering signals with different relative frequency localizations as in the methods of the prior art. And so high measurement speeds may be achieved.

The method of the invention may comprise a step of calculating the Brillouin frequency of the Stokes Brillouin spectrum and/or the anti-Stokes Brillouin spectrum using a pre-established relation between the stimulated Brillouin scattering signal and the Brillouin frequency.

According to some modes of realization of the invention, at least for a given set of temperature and/or strain conditions along at least a part of the sensing optical fiber, the Stokes Brillouin spectrum and the anti-Stokes Brillouin spectrum may overlap at least partially in an overlap range comprising the average frequency located halfway between the first and second pump frequencies.

According to some modes of implementation, the optical probe wave may comprise a main probe spectral component spectrally located at a frequency which is different, but close to within a half spectral width of the Stokes or the anti-Stokes Brillouin spectrum, from the average frequency.

According to a mode of implementation, the main probe spectral component may be spectrally located at a frequency which differs from the average frequency of an amount corresponding to:

- the half spectral width at half maximum amplitude of the Stokes or the anti-Stokes Brillouin spectrum, or

- the spectral width at half maximum amplitude of the Stokes or the anti-Stokes Brillouin spectrum.

The method of the invention may further comprise steps of:

- measuring the amplitude of the stimulated Brillouin scattering signal, and

- calculating the Brillouin frequency of the Stokes Brillouin spectrum and/or the anti-Stokes Brillouin spectrum using a first pre-established relation between said amplitude and said Brillouin frequency.

The first pre-established relation may take into account gains and losses undergone by the main probe spectral component through stimulated Brillouin scattering interactions.

According to another mode of implementation, the optical probe wave may comprise a modulated signal with a carrier signal spectrally located at the average frequency and sidebands located outside the Stokes Brillouin spectrum and the anti-Stokes Brillouin spectrum.

The optical probe wave may comprises a signal modulated in intensity by a modulation wave at a modulation frequency.

The method of the invention may further comprise steps of:

- measuring the amplitude of modulation of the stimulated Brillouin scattering signal at the modulation frequency, and

- calculating the Brillouin frequency of the Stokes Brillouin spectrum and/or the anti-Stokes Brillouin spectrum using a second pre-established relation between said amplitude of modulation and said Brillouin frequency.

The second pre-established relation may take into account a modulation of the index of refraction in the sensing optical fiber at the average frequency due to the stimulated Brillouin scattering interactions.

According to a variant, the optical probe wave may comprise a signal modulated in phase.

According to some other modes of implementation, the optical probe wave may comprise a signal modulated in phase by a modulation wave at a modulation frequency, with:

- a carrier signal spectrally located at an average frequency halfway between the first and second pump frequencies and outside the Stokes Brillouin spectrum and the anti-Stokes Brillouin spectrum, and
- two sidebands located respectively, at least for a given set of temperature and/or strain conditions along at least a part of the sensing optical fiber, within the Stokes Brillouin spectrum and within the anti-Stokes Brillouin spectrum.

The method of the invention may further comprises step of:

- measuring the amplitude of modulation of the stimulated Brillouin scattering signal at the modulation frequency, and
- calculating the Brillouin frequency of the Stokes Brillouin spectrum and/or the anti-Stokes Brillouin spectrum using a third pre-established relation between said amplitude of modulation and said Brillouin frequency.

The third pre-established relation may take into account the gains and the losses respectively undergone by the sidebands through their respective stimulated Brillouin scattering interactions.

According to some other modes of implementation, the optical probe wave may comprise a signal modulated in intensity by a modulation wave at a modulation frequency, with:

- a carrier signal spectrally located at an average frequency halfway between the first and second pump frequencies and outside the Stokes Brillouin spectrum and the anti-Stokes Brillouin spectrum, and
- two sidebands located respectively, at least for a given set of temperature and/or strain conditions along at least a part of the sensing optical fiber, within the Stokes Brillouin spectrum and within the anti-Stokes Brillouin spectrum.

According to another aspect of the invention, it is proposed a Brillouin optical distributed sensing device, comprising:

- pump generation means for providing a first optical pulsed pump wave at a first pump frequency and a second optical pulsed pump wave at a second pump frequency,
- probe generation means for providing an optical probe wave comprising at least one probe spectral component,

- optical routing means for directing said first and second optical pulsed pump waves and said optical probe wave to a sensing optical fiber so that the optical probe wave propagates in said sensing optical fiber in a direction opposite to said first and second optical pulsed pump waves,

- detection means for detecting a stimulated Brillouin scattering signal resulting from the interactions in said sensing optical fiber of the optical probe wave with the first and the second optical pulsed pump waves,

wherein:

- the pump generation means and the probe generation means are able to arrange spectrally the first and the second optical pulsed pump waves and the optical probe wave so that, at least for a given set of temperature and/or strain conditions along at least a part of the sensing optical fiber, the optical probe wave comprises a probe spectral component located within the Stokes Brillouin spectrum of the first optical pulsed pump wave and a probe spectral component located within the anti-Stokes Brillouin spectrum of the second optical pulsed pump wave,

- the device further comprises calculation means for deducing the Brillouin frequency of said Stokes Brillouin spectrum and/or said anti-Stokes Brillouin spectrum from the stimulated Brillouin scattering signal.

The pump generation means may comprise:

- a pump modulator for applying an intensity modulation with suppressed carrier scheme to a continuous incoming light wave at an average frequency halfway between the first and second pump frequencies, and

- a pulse generator for generating first and second optical pulsed pump wave with synchronous pulses of the same duration.

Description of the drawings

The methods according to embodiments of the present invention may be better understood with reference to the drawings, which are given for illustrative purposes only and are not meant to be limiting. Other aspects, goals and advantages of the invention shall be apparent from the descriptions given hereunder.

- Fig. 1 shows a first optical set-up of the invention,
- Fig. 2 shows a second optical set-up of the invention,
- Fig. 3 shows the spectral arrangement of the signals in a first mode of realization of the invention for a first measurement situation,

- Fig. 4 shows the spectral arrangement of the signals in the first mode of realization of the invention for a second measurement situation,
- Fig. 5 shows the measurement range in the first mode of realization of the invention for a first configuration of the probe wave,
- Fig. 6 shows the measurement range in the first mode of realization of the invention for a second configuration of the probe wave,
- Fig. 7 shows the spectral arrangement of the signals in a second mode of realization of the invention for a first measurement situation,
- Fig. 8 shows the spectral arrangement of the signals in the second mode of realization of the invention for a second measurement situation,
- Fig 9 shows a measurement signal corresponding to the first measurement situation in the second mode of realization of the invention,
- Fig 10 shows a measurement signal corresponding to the second measurement situation in the second mode of realization of the invention,
- Fig. 11 shows the spectral arrangement of the signals in a third mode of realization of the invention,
- Fig. 12 shows the variation of index of refraction in the Stokes Brillouin spectral range in the third mode of realization of the invention,
- Fig. 13 shows the variation of index of refraction in the anti-Stokes Brillouin spectral range in the third mode of realization of the invention,
- Fig. 14 shows the modulation amplitude of the detected signal in function of the Brillouin frequency shift in the third mode of realization of the invention.

Detailed description of the invention

Optical set-up

With reference to Fig. 1 and Fig. 2, we will now describe some mode of realization of Brillouin optical distributed sensing device of the invention.

The setups shown in Fig. 1 and Fig. 2 are very similar to well-known setups based on single-mode optical fibers for implementing BOTDA systems. So, for the sake of clarity, only the components which are relevant for the description of the invention and which differ from well-known set-ups are shown on Fig. 1 and Fig. 2. Of course, the device of the invention may include any other necessary components.

The set-ups shown in Fig. 1 and Fig. 2 must be construed as synoptic schematics suitable for implementing the modes of realization of the invention which will be described below. But, of course, some components may be different or differently tuned for the implementation of the different modes of realization, as it will be explained.

In the mode of realization presented on Fig. 1, the sensing device of the invention comprises a light source 1 which is used for generating all necessary optical signals. This light source 1 comprises a distributed feedback laser diode (DFB-LD) with a wavelength around 1.5 µm, which generates a continuous wave at frequency ν_L.

A source coupler 2 directs a part of the light issued from the source 1 towards a pump modulator 3 and a pulse generator 4 for generating optical pulsed pump waves.

In all the modes of realization of the invention, the pump modulator 3 is preferably an electro-optic modulator 3 configured so as to modulate the intensity of the incoming signal according to a Dual Side Band with Suppressed Carrier (DBS-SC) modulation scheme. It generates at its output an optical signal which comprises two spectral components with respective frequencies ν_{P1} and ν_{P2} located symmetrically relative to the frequency ν_L of the laser source 1. The frequency of these spectral components may be varied by varying the control signal applied to the electro-optic modulator 3.

The electro-optic modulator 3 is preferably a lithium niobate electro-optic modulator based on a Mach-Zehnder architecture. In order to generate the Dual Side Band with Suppressed Carrier (DSB-SC) modulation, a control signal is applied, which comprises:

- a bias voltage establishing a destructive interferences condition between the optical waves in both arms of the interferometer (extinction condition), and,
- a modulation voltage at a frequency corresponding to the desired frequency shift of the spectral components of the optical probe signal relative to the optical frequency of the incoming optical signal.

The pulse generator 4 comprises a semiconductor optical amplifier (SOA) driven by an electrical pulsed signal. It is used as an optical gating device for generating simultaneously two optical pulsed pump waves 20, 23 with respective frequencies ν_{P1} and ν_{P2} located symmetrically relative to the frequency ν_L of the laser source 1, as shown for instance in Fig. 3. So, the pulses of the two pump waves 20, 23 are synchronous in time and have the same duration.

The source coupler 2 directs also a part of the light issued from the source 1 towards a probe modulator 5 for generating a probe wave.

The probe modulator 5 may be different for the different modes of realization of the invention, so it will be described below in relation with these modes of realization.

The probe wave issued from the probe modulator 5 is then directed to a sensing fiber 6 of a distributed sensor connected to the sensing device. That distributed sensor may be for instance embedded in a structure 7 for monitoring the strain and/or the temperature in that structure 7, which may be up to several kilometers long.

The device of the invention further comprises an optical circulator 8. Such optical circulator 8 is a well-known optical component which allows:

- directing an optical signal incident on a first branch (label "1") of the circulator to a second branch (label "2"), and
- directing an optical signal incident on the second branch of the circulator (label "2") to a third branch (label "3").

The optical circulator 8 is arranged so as to:

- direct the two pump waves which are incident on its first branch into the sensing fiber 6, so that the pump waves propagate in that sensing fiber in a direction opposite to the probe wave; and
- direct the stimulated Brillouin scattering signal resulting from the interactions in the sensing fiber 6 of the probe wave with the optical pulsed pump waves towards a photodetector 9, for detection and further processing.

According to some modes of realization, the pulse generator 4 may comprise an electro-optic modulator or any optical component suitable for generating the two optical pulsed pump waves 20, 23.

According to some modes of realization, the device of the invention may comprise polarization means such as polarizer(s) and/or polarization controller(s) arranged so as to allow generating pumps waves propagating in the fibers with orthogonal polarizations. The pump waves may for instance be linearly polarized along polarization axis shifted of about ±90 degrees from each other. Such orthogonal polarization allows limiting the four wave mixing between the waves, and thus may eliminate the need for polarization scrambling.

In the mode of realization presented in Fig. 2, the device of the invention comprises a first laser source 10 for generating the optical pulsed signals and a second laser source 11 for generating the optical probe signal. For instance:

- the frequencies of the two distinct lasers 10, 11 may be locked onto each other, so that the relative frequency between the two lasers is well secured and stable, but can be scanned to interrogate the distributed Brillouin gain/loss spectrum;
- the two lasers 10, 11 may be free-running with controlled variation of the mean frequency so that the relative frequency between the two lasers may be recorded and scanned. Then the recorded relative frequency may be used to compensate any possible distortion imposed onto the spectrum of the Brillouin gain/loss spectrum caused by the free-running feature of the two lasers.

Of course, the device of the mode of realization shown in Fig. 2 may be used and operated in the same way as the device of the mode of realization shown in Fig. 1, for similar results. So, everything which has been explained in relation with the mode of realization of Fig. 1 applies to the mode of realization of Fig. 2, except for the differences in the laser sources.

According to some modes of realization:

- the device of the invention may comprise two laser sources 10 for generating the two optical pump signals;
- the device of the invention may comprise laser sources 10, 11 fulfilling the functions of the pump modulator 3, the pulse generator 4, and/or the probe modulator 5, in which case the corresponding modulator or pulse generator may not be present.

First mode of realization

With reference to Fig. 3 to Fig. 6, we will now describe a first mode of realization of the invention.

As explained before, the pump modulator 3 is configured so as to generate a first pulsed pump wave 20 and a second pulsed pump wave 23 with respective frequencies ν_{P1} and ν_{P2} located symmetrically relative to the frequency ν_L of the laser source 1.

Each of the pulsed pump waves 20, 23 may generate a Stokes Brillouin spectrum and an anti-Stokes Brillouin spectrum by propagating in the sensing fiber 6. In particular:

- the maximum value 22 of the Stokes Brillouin spectrum is shifted towards the lower frequencies, relative to the pulsed pump frequency ν_{P1}, of an amount corresponding to a Brillouin frequency shift $\bar{\nu}_{B1}$;

- the maximum value 25 of the anti-Stokes Brillouin spectrum is shifted towards the upper frequencies, relative to the pulsed pump frequency ν_{P2}, of an amount corresponding to a Brillouin frequency shift $\bar{\nu}_{B2}$;

In practice, the Brillouin frequency shifts $\bar{\nu}_{B1}$ and $\bar{\nu}_{B2}$ are very close to each other. So, for the sake of clarity, we can assume in the following that the Stokes Brillouin spectrum generated by the first pulsed pump wave 20 and the anti-Stokes Brillouin spectrum generated by the second pulsed pump wave 23 are shifted of a similar amount corresponding to a Brillouin frequency shift $\bar{\nu}_B$, with $\bar{\nu}_B \cong \bar{\nu}_{B1} \cong \bar{\nu}_{B2}$.

The maxima 22, 25 of the Brillouin spectra are usually referred to as Brillouin frequencies. They depend on the Brillouin frequency shift $\bar{\nu}_B$ which depends on the temperature and the strain along the sensing fiber 6.

When the probe optical wave 26 at frequency ν_{PR} falls within the frequency range of a Brillouin spectrum generated by a pulsed optical wave 20 or 23, a resonance condition is established, leading to the efficient stimulation of the Brillouin scattering:

- when the frequency of the probe optical wave 26 falls within the frequency range of the Stokes Brillouin spectrum 21, this stimulation induces an energy transfer from the pulsed optical wave 20 to the probe optical wave and an amplification of the probe optical wave (gain mode);

- when the frequency of the probe optical wave 26 falls within the frequency range of the anti-Stokes Brillouin spectrum 24, this stimulation induces an energy transfer from the probe optical wave 26 to the pulsed optical wave 23 and an attenuation of the probe optical wave (loss mode).

In these configurations, the resulting optical signal emerging from the sensing optical fiber 6 corresponds essentially to the probe optical wave 26 whose amplitude varies in function of the resonance conditions met along the fiber at the frequencies of the respective spectral components of that probe wave. So, with respect to that probe optical wave 26, the Stokes Brillouin spectrum 21 may be considered as a gain spectrum and the anti-Stokes Brillouin spectrum 24 may be considered as a loss spectrum.

If the probe optical wave or some of its spectral components falls within a Stokes Brillouin spectrum 21 and within an anti-Stokes Brillouin spectrum 24, the gains and the losses cancel out mutually to their respective magnitudes. In that case the measured stimulated Brillouin signal delivers differential information about the gains and losses encountered by the probe optical wave 26 or some of its spectral components along the path.

In the first mode of realization, the pump modulator 3 is configured so as to generate a first pulsed pump wave 20 and a second pulsed pump wave 23 which are shifted in frequency, relative to the frequency ν_L of the laser source 1, of an amount substantially corresponding to the Brillouin frequency shift $\bar{\nu}_B$ for a given set of temperature and strain conditions along the sensing fiber 6 (corresponding to reference conditions). So, the Stokes Brillouin spectrum 21 of the first pulsed pump wave 20 and the anti-Stokes Brillouin spectrum 24 of the second pulsed pump wave 23 overlap at least partially in an overlap area.

If the frequency shift introduced by the pump modulator 3 corresponds exactly to the Brillouin frequency shift $\bar{\nu}_B$, the Stokes Brillouin spectrum 21 and the anti-Stokes Brillouin spectrum 24 overlap completely, and their respective Brillouin frequencies 22, 25 correspond to the frequency ν_L of the laser source 1. That situation is illustrated in Fig. 3.

If the conditions of temperature and/or strain along the sensing fiber 6 vary, the Brillouin frequency shift $\bar{\nu}_B$ varies accordingly. The respective frequencies ν_{P1} and ν_{P2} of the first pulsed pump wave 20 and the second pulsed pump wave 23 being held constant, the corresponding Stokes Brillouin spectrum 21 and anti-Stokes Brillouin spectrum 24 shift in frequency in opposite directions, symmetrically relative to the frequency ν_L of the laser source 1. In that case, they only partially overlap as illustrated in Fig. 4, until they separate completely, which may happen for large variations of Brillouin frequency shift $\bar{\nu}_B$.

In that mode of realization, the probe wave is generated by shifting in frequency of an amount f_M the light of the laser source 1. This frequency shift is done by the probe modulator 5 which may comprise for instance an acousto-optic modulator.

The frequency shift f_M is chosen so that the frequency $\nu_{PR} = \nu_L - f_M$ of the probe wave 26 falls:

- within the Brillouin spectra, at least when they overlap as illustrated in Fig. 3;
- within a region in which at least one of the Brillouin gain or loss spectra 21, 24 varies substantially when the Brillouin frequency shift $\bar{\nu}_B$ varies.

According to a particularly important aspect of the invention, in these conditions, if the shape of the Brillouin spectra is known, it is possible to deduce directly from the variations of amplitude of the stimulated Brillouin signal at the frequency ν_{PR} of the probe wave 26 the variations of Brillouin frequency shift $\bar{\nu}_B$. So it is possible to perform real-time measurements of the Brillouin frequency shift $\bar{\nu}_B$ (and thus of temperature and/or strain variations) without the need for scanning the Brillouin spectrum by varying the frequency of the probe wave, as in the prior art methods.

The frequency shift f_M of the probe wave 26 may be chosen so as to correspond substantially to the half maximum frequency of the Brillouin spectrum (or the −3dB frequency), which is about 15 MHz for an intrinsic Brillouin spectrum, or about 30MHz for an effective Brillouin spectrum corresponding to a spatial resolution in the order of 3 meters. This is the situation illustrated in Fig. 3 and Fig. 5 for an effective Brillouin spectrum.

Fig. 5 shows the variations of the Brillouin gain at the frequency ν_{PR} of the probe wave 26 with respect to the variations of the Brillouin frequency shift $\bar{\nu}_B$, in these conditions.

The Brillouin net gain accounts for the gains and the losses due to the stimulated Brillouin interactions of the probe wave 26 with the first pulsed pump wave 20 and the second pulsed pump wave 23, respectively.

The amplitude of the stimulated Brillouin signal at the frequency ν_{PR} of the probe wave 26 depends on that Brillouin net gain. So the curve of Fig. 5 is also representative of the variations of amplitude of the stimulated Brillouin signal such as measured on the photo-detector 9.

The reference Brillouin frequency shift $\bar{\nu}_{B0}$ is the Brillouin frequency shift in the reference conditions, when the Stokes spectrum 21 and the anti-Stokes spectrum 24 are entirely superposed, as illustrated in Fig. 3. In these conditions, if the first pulsed pump wave 20 and the second pulsed pump wave 23 are well balanced, the Brillouin net gain is zero.

When the Stokes spectrum 21 and the anti-Stokes spectrum 24 shift in frequency as illustrated in Fig. 4, due to variations of the Brillouin frequency shift $\bar{\nu}_B$, the Brillouin net gain varies also in a well-defined and unambiguous manner in a measurement range. So the determination of that Brillouin net gain allows determining directly the Brillouin frequency shift $\bar{\nu}_B$.

It is interesting to note that when the frequency shift f_M of the probe wave 26 corresponds substantially to the frequency at half maximum (−3dB frequency) of the Brillouin spectrum (which is assumed to have a Lorentzian shape), as illustrated in Fig. 5, the Brillouin net gain variations are fairly linear with respect to the Brillouin frequency shift $\bar{\nu}_B$ in a measurement range which corresponds to about two times the −3dB frequency, hence about 60 MHz (±30 MHz) for an effective Brillouin spectrum corresponding to a spatial resolution in the order of 3 meters, showing the capability of temperature or strain variation measurement of about ±30 °C or ±600 με, respectively.

With reference to Fig. 6, the measurement range may be further extended by shifting in frequency the probe wave 26 of an amount f_M larger than the −3dB frequency of the Brillouin spectrum.

Fig. 6 shows the variations of the Brillouin net gain at the frequency ν_{PR} of the probe wave 26 with respect to the variations of the Brillouin frequency shift $\bar{\nu}_B$, for a frequency shift f_M corresponding to two times the −3dB frequency of the Brillouin spectrum.

In these conditions, the measurement range is extended to about four times the −3dB frequency, hence about 120 MHz (±60 MHz) for an effective Brillouin spectrum corresponding to a spatial resolution in the order of 3 meters, showing the capability of temperature or strain variation measurement of about ±60 °C or ±1200 με, respectively. The Brillouin net gain variation is less linear than in the case of Fig. 5, but such response nonlinearity can be compensated by accurate pre-calibration process, which means the precise measurement of Brillouin net gain with respect to the Brillouin frequency $\bar{\nu}_B$.

So, the method of the invention may be used for instance to monitor rapid variations of temperature or strain in the vicinity of reference values, or to do high speed acquisitions.

The measurements can be done as follows.

In a first step, the respective frequencies ν_{P1} and ν_{P2} of the first pulsed pump wave 20 and the second pulsed pump wave 23 are adjusted using the pump modulator 3 so as to superpose the Stokes Brillouin spectrum 21 and the anti-Stokes Brillouin spectrum 24 over at least a short section of the sensing fiber 6. This can be achieved by detecting a null net gain condition on the stimulated Brillouin signal (Fig. 3 and Fig. 5).

The reference Brillouin frequency shift $\bar{\nu}_{B0}$ is then known as it corresponds to the frequency of the modulation signal applied to the pump modulator 3 for generating the pulsed wave frequencies ν_{P1} and ν_{P2}.

Then, for each pulse of the first pulsed pump wave 20 and of the second pulsed pump wave 23 (which are synchronous and of the same duration):

- a stimulated Brillouin signal at the frequency ν_{PR} of the probe wave 26 is acquired;

- a time variation of the Brillouin frequency shift $\bar{\nu}_B$ (relative to the reference Brillouin frequency shift $\bar{\nu}_{B0}$) is deduced from the amplitude variation of that stimulated Brillouin signal at the frequency ν_{PR};

- knowing the speed of the light in the sensing fiber 6, a distribution of the Brillouin frequency shift $\bar{\nu}_B$ variations is computed over the fiber length.

The reference Brillouin frequency shift $\bar{\nu}_{B0}$ can be re-adjusted periodically to take into account slower variations of temperature and/or strain in the sensing fiber 6 and to keep the measurements in the available measurement range.

It is interesting to note that the fact of doing differential measurements with superposed Brillouin spectra in gain and loss mode allows:

- extending the measurement range (with respect to real time methods using only a Stokes or an anti-Stokes Brillouin spectrum);

- and also achieving a good sensitivity over the whole measurement range, because the magnitude of the gain or the loss applied to the probe wave 26 is similar at both ends of the measurement range. The low Brillouin gain at the bottom of Brillouin gain spectrum, which it acts as a limiting factor in prior art in terms of measurement accuracy and measurement range of temperature change is mitigated, due to the transition of Brillouin gain to Brillouin loss when the Brillouin gain reaches to the low gain. Consequently, the intensity variation of the probe signal 26 continuously changes from positive to negative, improving the signal-to-noise ratio, hence extending the measurement range of temperature change.

Second mode of realization

With reference to Fig. 7 to Fig. 10, we will now describe a second mode of realization of the invention.

As explained before, the pump modulator 3 is configured so as to generate a first pulsed pump wave 20 and a second pulsed pump wave 23 with respective frequencies ν_{P1} and ν_{P2} located symmetrically relative to the frequency ν_L of the laser source 1.

In the second mode of realization, the pump modulator 3 is configured so as to generate a first pulsed pump wave 20 and a second pulsed pump wave 23 which are shifted in frequency, relative to the frequency ν_L of the laser source 1, of respective amounts $(\nu_{P1} - \nu_L)$ and $(\nu_L - \nu_{P2})$ which are different from the Brillouin frequency shift $\bar{\nu}_B$, and which ensure that the Stokes Brillouin spectrum 21 of the first pulsed pump wave 20 and the anti-Stokes Brillouin spectrum 24 of the second pulsed pump wave 23 do not overlap. So the Brillouin spectra 21, 24 do not cross or do not comprise the source frequency ν_L.

These frequency shifts $(\nu_{P1} - \nu_L)$ and $(\nu_L - \nu_{P2})$ of the first pulsed pump wave 20 and of the second pulsed pump wave 23 may be larger or smaller than the Brillouin frequency shift $\bar{\nu}_B$. As the same reasoning applies in both cases, the description of this mode of realization will be done for frequency shifts $(\nu_{P1} - \nu_L)$ and $(\nu_L - \nu_{P2})$ larger than the Brillouin frequency shift $\bar{\nu}_B$.

If the conditions of temperature and/or strain along the sensing fiber 6 vary, the Brillouin frequency shift $\bar{\nu}_B$ varies accordingly. The respective frequencies ν_{P1} and ν_{P2} of the first pulsed pump wave 20 and the second pulsed pump wave 23 being held constant, the corresponding Stokes Brillouin spectrum 21 and anti-Stokes Brillouin spectrum 24 shift in frequency in opposite directions, symmetrically relative to the frequency ν_L of the laser source 1. This situation is illustrated in Fig. 7 and Fig. 8 for two different values of Brillouin frequency shift $\bar{\nu}_B$.

In that mode of realization, the probe wave is generated by modulating in phase the light of the laser source 1. This phase modulation is done by the probe modulator 5 which comprises a phase modulator driven by a continuous wave radiofrequency (RF) signal at modulation frequency f_S.

This phase modulator may for instance be done using an electro-optic lithium-niobate modulator.

The spectrum of the probe wave comprises then three spectral components: a carrier 30 at the frequency ν_L of the laser source 1, and two symmetric sidebands 31 around respective frequencies $\nu_L \pm f_S$. The sidebands 31 have equal amplitude but opposite polarity (π-phase shifted).

Fig. 9 shows the electrical signal 35 delivered by the photodetector 9 in the configuration of Fig. 7, when the sidebands 31 are not in the Brillouin spectra 21, 24. In that case, the electrical signal 35 shows no modulation and only contains a DC component. This is due to the fact that the two sidebands 31 produce on the photodetector 9 a beating with the carrier 30 that shows equal amplitude and opposite phase, so that they exactly cancel out.

In that case, the signal incident on the photodetector 9 corresponds essentially to the phase-modulated probe wave which emerges from the sensing fiber 6 without having been subjected to any stimulated Brillouin scattering.

If now the modulation frequency f_S and the Brillouin frequency shift $\bar{\nu}_B$ are such that the sidebands 31 are positioned respectively within the Stokes Brillouin spectrum 21 and anti-Stokes Brillouin spectrum 24 as illustrated in Fig. 8, the sidebands 31 interacts respectively with the first pulsed pump wave 20 and the second pulsed pump wave 23. One sideband 31 which interacts with the anti-Stokes Brillouin spectrum 24 is attenuated, while the other sideband 31 which interacts with the Stokes Brillouin spectrum 21 is amplified. As a result, the respective beatings of the sidebands 31 with the carrier 30 on the photodetector 9 do not have the same amplitude and they no longer cancel exactly. This effect is often referred to as FM-IM conversion.

Fig. 10 shows the electrical signal 35 delivered by the photodetector 9 in that configuration, corresponding to Fig. 8. This electrical signal 35 comprises now a signal at the modulation frequency f_S, with an amplitude which is proportional to the amount of gain and loss resulting from the stimulated Brillouin scattering at the respective frequencies of the sidebands 31.

So, according to a particularly important aspect of the invention, in this mode of realization, the stimulated Brillouin scattering information is coded in the amplitude of an AC signal 35 at the modulation frequency f_S. This configuration is much more favorable in terms of signal to noise characteristics than the prior art schemes in which the Brillouin information is coded in the low-frequency amplitude variations of the detected DC signal. It allows rejecting the low-frequency noise contributions which are important in practice, due for instance to the source optical noise and the optical amplifiers.

According to a first detection scheme, for determining the Brillouin frequency shift $\bar{\nu}_B$, it is possible to:

- scan the spectral range of the Stokes and the anti-Stokes Brillouin spectra 21, 24 by varying the modulation frequency f_S;

- determine the modulation frequency $f_S = f_{SM}$ for which the modulation amplitude of the detected AC signal 35 is the largest, and which corresponds to the respective maximum 22, 25 of gain and loss of the Brillouin spectra 21, 24,

- computing the corresponding Brillouin frequency shift :

$\bar{\nu}_B = \nu_{P1} - (\nu_L + f_{SM}) = (\nu_L - f_{SM}) - \nu_{P2}$.

This detection scheme corresponds to the classical methods with a scan in frequency. So it has the drawback of being quite slow.

However, in prior art methods, the frequency shift required for scanning the Brillouin spectra must be in the order of the Brillouin frequency shift $\bar{\nu}_B$ (~11 GHz). It requires expensive generators.

In the invention, the modulation frequency f_S can be made much lower than that. It is limited towards the low frequencies only by the fact that the Brillouin spectra 21, 24 must not overlap. So, in practice the modulation frequency f_S is chosen in the range from 0.1 to 1 GHz. This allows using much less expensive generators, much less expensive generator using a more mature and developed technology, with more advanced capabilities.

According to a second detection scheme, for improving the measurement rate, it is also possible to implement a sweep-free detection scheme.

This is possible because, again, the amplitude of the modulation at frequency f_S of the detected signal 35 depends in an unambiguous way of the gain and the loss encountered by the sidebands 31, which in turn depend in an unambiguous way of the frequency location of the sidebands 30 relative to the respective maxima 22, 25 of the Brillouin spectra 21, 24. By knowing the shape of the Brillouin spectra, it is possible to determine a relation between the amplitude of the modulation of the detected signal 35 and the Brillouin frequency shift $\bar{\nu}_B$ corresponding to the respective maxima 22, 25 of the Brillouin spectra 21, 24.

So, the method of the invention may be used for instance to monitor rapid variations of temperature or strain in the vicinity of reference values, or to perform high speed acquisitions.

In a calibration step, a reference Brillouin frequency shift $\bar{\nu}_{B0}$ may be determined by scanning the Brillouin spectra in reference conditions of temperature and/or strain, for instance as described in the first detection scheme. A corresponding reference modulation frequency f_{SO} and maximum modulation amplitude may also be determined.

The modulation frequency f_S may then be adjusted so as to position the sidebands 31 in the ascending or descending slopes of the Brillouin spectra, where the variations are unambiguous. It may for instance be chosen around the frequency at half maximum of these Brillouin spectra (-3dB frequency), in order to maximize the unambiguous measurement range.

Then, for each pulse of the first pulsed pump wave 20 and of the second pulsed pump wave 23 (which are synchronous and of the same duration):

- a modulated signal 35 is acquired on the photodetector 9;
- a time variation of the Brillouin frequency shift $\bar{\nu}_B$ (relative to the reference Brillouin frequency shift $\bar{\nu}_{B0}$) is deduced from the time variations of the amplitude of the modulation of the signal 35 at the frequency f_S;
- knowing the speed of the light in the sensing fiber 6, a distribution of the Brillouin frequency shift $\bar{\nu}_B$ variations is computed.

The modulation frequency f_S can be re-adjusted periodically to take into account slower variations of temperature and/or strain in the sensing fiber 6 and to keep the measurements in the available measurement range.

According to another variant of the second mode of realization, the probe wave may be generated by modulating in intensity the light of the laser source 1. This intensity modulation may be done by the probe modulator 5 which comprises an intensity modulator driven by a continuous wave radiofrequency (RF) signal at modulation frequency f_s. This intensity modulator may for instance be done using an electro-optic lithium-niobate modulator.

The spectrum of the probe wave comprises then three spectral components: a carrier 30 at the frequency ν_L of the laser source 1, and two symmetric sidebands 31 around respective frequencies $\nu_L \pm f_S$. The sidebands 31 have equal amplitude and same phase.

When the sidebands 31 are not in the Brillouin spectra 21, 24 (as shown in Fig. 7), the electrical signal 35 shows a modulation with a maximum amplitude, corresponding to the intensity modulation introduced by the probe modulator 5.

If now the modulation frequency f_S and the Brillouin frequency shift $\bar{\nu}_B$ are such that the sidebands 31 are positioned respectively within the Stokes Brillouin spectrum 21 and anti-Stokes Brillouin spectrum 24 as illustrated in Fig. 8, the sidebands 31 interacts respectively with the first pulsed pump wave 20 and the second pulsed pump wave 23. One sideband 31 which interacts with the anti-Stokes Brillouin spectrum 24 is attenuated, while the other sideband 31 which interacts with the Stokes Brillouin spectrum 21 is amplified. In addition, both sidebands 31 experience a phase shift.

As a result, the amplitude of modulation of the electrical signal 35 depends on the amount of Brillouin gain and loss. It reaches a minimum value when the frequency of the sidebands 31 corresponds to the frequencies of the respective maxima 22, 25 of gain and loss of the Brillouin spectra 21, 24.

So, again, the stimulated Brillouin scattering information is coded in the amplitude of an AC signal 35 at the modulation frequency f_S, and the Brillouin frequency shift $\bar{\nu}_B$ may be determined in the same ways as what has been explained in relation with the phase modulation variant.

Third mode of realization

With reference to Fig. 11 to Fig. 14, we will now describe a third mode of realization of the invention.

As explained before, the pump modulator 3 is configured so as to generate a first pulsed pump wave 20 and a second pulsed pump wave 23 with respective frequencies ν_{P1} and ν_{P2} located symmetrically relative to the frequency ν_L of the laser source 1.

In the third mode of realization, the pump modulator 3 is configured so as to generate a first pulsed pump wave 20 and a second pulsed pump wave 23 which are shifted in frequency, relative to the frequency ν_L of the laser source 1, of an amount substantially corresponding to the Brillouin frequency shift $\bar{\nu}_B$ for a given set of temperature and strain conditions along the sensing fiber 6 (corresponding to reference conditions). So, the Stokes Brillouin spectrum 21 of the first pulsed pump wave 20 and the anti-Stokes Brillouin spectrum 24 of the second pulsed pump wave 23 overlap at least partially in an overlap area.

If the frequency shift introduced by the pump modulator 3 corresponds exactly to the Brillouin frequency shift $\bar{\nu}_B$, the Stokes Brillouin spectrum 21 and the anti-Stokes Brillouin spectrum 24 overlap completely, and their respective Brillouin frequencies 22, 25 corresponds to the frequency ν_L of the laser source 1.

If the conditions of temperature and/or strain along the sensing fiber 6 vary, the Brillouin frequency shift $\bar{\nu}_B$ varies accordingly. The respective frequencies ν_{P1} and ν_{P2} of the first pulsed pump wave 20 and the second pulsed pump wave 23 being held constant, the corresponding Stokes Brillouin spectrum 21 and anti-Stokes Brillouin spectrum 24 shift in frequency in opposite directions, symmetrically relative to the frequency ν_L of the laser source 1. In that case, they only partially overlap as illustrated in Fig. 11, until they separate completely, which may happen for large variations of Brillouin frequency shift $\bar{\nu}_B$.

In that mode of realization, the probe wave is generated by modulating in intensity the light of the laser source 1. This intensity modulation is done by the probe modulator 5 which comprises an intensity modulator driven by a continuous wave radiofrequency (RF) signal at modulation frequency f_S.

This intensity modulator may for instance be done using an electro-optic lithium-niobate modulator based on Mach-Zehnder interferometer architecture adjusted such as to work for instance around the 1/2 or the 2/3 constructive interference point.

As illustrated in Fig. 11, the spectrum of the probe wave comprises then three spectral components: a carrier 30 at the frequency ν_L of the laser source 1, and two symmetric sidebands 31 around respective frequencies $\nu_L \pm f_S$. The sidebands 31 are arranged so that to remain outside the Brillouin spectra 21, 24. So, stimulated Brillouin scattering may occur only at the frequency ν_L of the carrier 30.

Fig. 12 and Fig. 13 show a detailed view of the spectra around the frequency ν_L.

Fig. 12 shows an enlarged view of the Stokes Brillouin gain spectrum 21. The arrow 43 indicates the direction of the frequency shift of that spectrum when the Brillouin frequency shift $\bar{\nu}_B$ increases.

Due to the complex response of the stimulated Brillouin scattering (SBS) resonance, the refractive index of the sensing optical fiber 6 is modulated over the spectral region where the SBS resonance is present. The curve 40 depicts the modulation of the refractive index Δn over the gain resonance 21 generated by the first pump pulsed wave 20. As can be seen, the refractive index 40 increases in frequency along the central part of that spectral region.

Similarly, Fig. 12 shows an enlarged view of the anti-Stokes Brillouin loss spectrum 24. The arrow 43 indicates the direction of the frequency shift of that spectrum when the Brillouin frequency shift $\bar{\nu}_B$ increases.

The curve 41 depicts the modulation of the refractive index Δn over the loss resonance 24 generated by the second pump pulsed wave 23. As can be seen, the refractive index 41 decreases in frequency along the central part of that spectral region.

So, when the Brillouin frequency shift $\bar{\nu}_B$ increases, the Brillouin spectra 21, 24 move in opposite directions, respectively in the direction of the arrows 43:

- as the carrier 30 is at the frequency ν_L of the laser source 1, it does not experience any amplitude modulation because the Brillouin gain spectrum 21 and the Brillouin loss spectrum 24 are always of the same and opposite value at that central frequency ν_L.

- However, the respective modulation 40, 41 of the refractive index Δn shift in the same direction, and thus their effects cumulate. So the carrier 30 experiences an optical phase shift Φ_{SBS} whose amount depends on the Brillouin frequency shift $\bar{\nu}_B$.

As a result, the electric signal at the output of the photodetector 9 comprises a spectral component U_{fs} at the modulation frequency f_S whose amplitude depends on the cosine of the optical phase shift Φ_{SBS}:

$$U_{fs} \sim \cos(\Phi_{SBS}) \cos(2\pi f_S t) \; .$$

Fig. 14 shows the amplitude 42 of that modulation component U_{fs} at frequency f_s in function of the variation of the Brillouin frequency shift $\bar{\nu}_B$:

- when the Brillouin frequency shift $\bar{\nu}_B$ corresponds to a reference Brillouin frequency shift $\bar{\nu}_{B0}$ for which the Brillouin spectra 21, 24 are fully superposed (or for which the respective Brillouin frequencies 22, 25 are equal to the frequency ν_L of the laser source 1), the amplitude 42 of the modulation at frequency f_S is at the maximum value 41;

- when the Brillouin frequency shift $\bar{\nu}_B$ varies around the reference Brillouin frequency shift $\bar{\nu}_{B0}$, the amplitude of the modulation 42 at frequency f_S decreases to a minimum;

- beyond that minimum, the amplitude of the modulation 42 at frequency f_S returns to its maximum value. This corresponds to the fact that when the Brillouin spectra 21, 24 do not overlap anymore, no more stimulated Brillouin scattering occurs and the measured electric signal corresponds to the modulated probe wave.

So, according to a particularly important aspect of the invention, in this mode of realization, the stimulated Brillouin scattering information is coded in the amplitude 42 of a signal at the modulation frequency f_S. This configuration is much more favorable in terms of signal to noise characteristics than the prior art schemes in which the Brillouin information is coded in the low-frequency amplitude variations of the detected signal. It allows rejecting all the low-frequency noise contributions which are important in practice, due for instance to the source optical noise and the optical amplifiers.

According to a first detection scheme, for determining the Brillouin frequency shift $\bar{\nu}_B$, it is possible to:

- scan the spectral range of the Stokes and the anti-Stokes Brillouin spectra 21, 24 by varying the respective frequencies ν_{P1} and ν_{P2} of the first pulsed pump wave 20 and the second pulsed pump wave 23;

- determine the frequencies ν_{P1} and ν_{P2} for which the modulation amplitude 42 of the detected signal is the largest, which corresponds to the case where the gain and loss Brillouin spectra 21, 24 overlap, and the respective Brillouin frequencies 22, 25 are equal to the frequency ν_L of the laser source 1;

- computing the corresponding Brillouin frequency shift, which corresponds actually to the frequency of the modulation signal applied to the pump modulator 3:

$\bar{\nu}_B = \nu_{P1} - \nu_L = \nu_L - \nu_{P2}$.

This detection scheme corresponds to the classical methods with a scan in frequency. So it has the drawback of being quite slow.

According to a second detection scheme, for improving the measurement rate, it is also possible to implement a sweep-free detection scheme.

This is possible because, again, the amplitude 42 of the modulation at frequency f_S of the detected signal depends in an unambiguous way of the index modulation introduced in the sensing fiber 6 by the Brillouin resonances at the frequency ν_L of the carrier 30 of the probe wave, which in turn depend in an unambiguous way of the Brillouin frequency shift $\bar{\nu}_B$ corresponding to the respective maxima 22, 25 of the Brillouin spectra 21, 24.

So, the method of the invention may be used for instance to monitor rapid variations of temperature or strain in the vicinity of reference values, or to perform high speed acquisitions.

In a first step, the respective frequencies ν_{P1} and ν_{P2} of the first pulsed pump wave 20 and the second pulsed pump wave 23 are adjusted using the pump modulator 3 so as to superpose the Stokes Brillouin spectrum 21 and the anti-Stokes Brillouin spectrum 24 over at least a short section of the sensing fiber 6. This can be achieved by detecting the frequencies ν_{P1} and ν_{P2} for which the modulation amplitude 42 of the detected signal is the largest, which corresponds to the case where the gain and loss Brillouin spectra 21, 24 overlap, and the respective Brillouin frequencies 22, 25 are equal to the frequency ν_L of the laser source 1;

The reference Brillouin frequency shift $\bar{\nu}_{B0}$ is then known as it corresponds to the frequency of the modulation signal applied to the pump modulator 3 for generating the pulsed wave frequencies ν_{P1} and ν_{P2}.

The respective frequencies ν_{P1} and ν_{P2} of the first pulsed pump wave 20 and the second pulsed pump wave 23 must then be shifted by an offset frequency shift so that the modulation amplitude 42 of the detected signal for that reference Brillouin frequency shift $\bar{\nu}_{B0}$ is the fast varying area 44 of the curve 42. This ensures that the detected signal varies unambiguously with the variations of the Brillouin frequency shift $\bar{\nu}_B$.

This offset frequency shift may for instance correspond to the half width at half maximum (−3dB) frequency shift of the Brillouin spectra 21, 24. This situation is illustrated in Fig. 11.

Then, for each pulse of the first pulsed pump wave 20 and of the second pulsed pump wave 23 (which are synchronous and of the same duration):

- a modulated signal is acquired on the photodetector 9;
- a time variation of the Brillouin frequency shift $\bar{\nu}_B$ (relative to the reference Brillouin frequency shift $\bar{\nu}_{B0}$) is deduced from the time variations of the amplitude modulation 42 of the detected signal 35 at the frequency f_S;
- knowing the speed of the light in the sensing fiber 6, a distribution of the Brillouin frequency shift $\bar{\nu}_B$ variations is computed.

The modulation frequency f_S can be re-adjusted periodically to take into account slower variations of temperature and/or strain in the sensing fiber 6 and to keep the measurements in the available measurement range.

According to another variant of the third mode of realization, the probe wave may be generated by modulating in phase the light of the laser source 1. The detection schemes which have been described in relation with the intensity modulation variant may be easily adapted to that variant.

While this invention has been described in conjunction with a number of embodiments, it is evident that many alternatives, modifications and variations would be or are apparent to those of ordinary skill in the applicable arts. Accordingly, it is intended to embrace all such alternatives, modifications, equivalents and variations that are within the spirit and scope of this invention.

CLAIMS

1. A Brillouin optical distributed sensing method, comprising steps of:

- providing a first optical pulsed pump wave (20) at a first pump frequency and a second optical pulsed pump wave (23) at a second pump frequency,

- providing an optical probe wave comprising at least one probe spectral component (26, 30, 31),

- directing said first and second optical pulsed pump waves (20, 23) and said optical probe wave to a sensing optical fiber (6) so that the optical probe wave propagates in said sensing optical fiber (6) in a direction opposite to said first and second optical pulsed pump waves (20, 23),

- detecting a stimulated Brillouin scattering signal resulting from the interactions in said sensing optical fiber (6) of the optical probe wave with the first and the second optical pulsed pump waves (20, 23),

characterized in that:

- the first and the second optical pulsed pump waves (20, 23) and the optical probe wave are spectrally arranged so that, at least for a given set of temperature and/or strain conditions along at least a part of the sensing optical fiber (6), the optical probe wave comprises a probe spectral component (26, 30, 31) located within the Stokes Brillouin spectrum (21) of the first optical pulsed pump wave (20) and a probe spectral component (26, 30, 31) located within the anti-Stokes Brillouin spectrum (24) of the second optical pulsed pump wave (23),

- the method further comprises a step of deducing the Brillouin frequency (22, 25) of said Stokes Brillouin spectrum (21) and/or said anti-Stokes Brillouin spectrum (24) from the stimulated Brillouin scattering signal.

2. The method of claim 1, which comprises a step of calculating the Brillouin frequency (22, 25) of the Stokes Brillouin spectrum (21) and/or the anti-Stokes Brillouin spectrum (24) using a pre-established relation between the stimulated Brillouin scattering signal and the Brillouin frequency (22, 25).

3. The method of claim 1 or 2, wherein, at least for a given set of temperature and/or strain conditions along at least a part of the sensing optical fibe (6), the Stokes Brillouin spectrum (21) and the anti-Stokes Brillouin spectrum (24) overlap at least partially in an overlap range comprising the average frequency located halfway between the first and second pump frequencies.

4. The method of claim 3, wherein the optical probe wave comprises a main probe spectral component (26) spectrally located at a frequency which is different, but close to within a half spectral width of the Stokes or the anti-Stokes Brillouin spectrum (21, 24), from the average frequency.

5. The method of claim 4, wherein the main probe spectral component (26) is spectrally located at a frequency which differs from the average frequency of an amount corresponding to:

- the half spectral width at half maximum amplitude of the Stokes or the anti-Stokes Brillouin spectrum (21, 24), or
- the spectral width at half maximum amplitude of the Stokes or the anti-Stokes Brillouin spectrum (21, 24).

6. The method of any of claims 3 to 5, which further comprises steps of:

- measuring the amplitude of the stimulated Brillouin scattering signal, and
- calculating the Brillouin frequency (22, 25) of the Stokes Brillouin spectrum and/or the anti-Stokes Brillouin spectrum (21, 24) using a first pre-established relation between said amplitude and said Brillouin frequency (22, 25).

7. The method of claim 6, wherein the first pre-established relation takes into account gains and losses undergone by the main probe spectral component (26) through stimulated Brillouin scattering interactions.

8. The method of claim 3, wherein the optical probe wave comprises a modulated signal with a carrier signal (30) spectrally located at the average frequency and sidebands (31) located outside the Stokes Brillouin spectrum (21) and the anti-Stokes Brillouin spectrum (24).

9. The method of claim 8, wherein the optical probe wave comprises a signal modulated in intensity by a modulation wave at a modulation frequency.

10. The method of claim 9, which further comprises steps of:

- measuring the amplitude of modulation of the stimulated Brillouin scattering signal at the modulation frequency, and

- calculating the Brillouin frequency (22, 25) of the Stokes Brillouin spectrum (21) and/or the anti-Stokes Brillouin spectrum (24) using a second pre-established relation between said amplitude of modulation and said Brillouin frequency (22, 25).

11. The method of claim 10, wherein the second pre-established relation takes into account a modulation of the index of refraction in the sensing optical fiber (6) at the average frequency due to the stimulated Brillouin scattering interactions.

12. The method of claim 8, wherein the optical probe wave comprises a signal modulated in phase.

13. The method of claim 1 or 2, wherein the optical probe wave comprises a signal modulated in phase by a modulation wave at a modulation frequency, with:

- a carrier signal (30) spectrally located at an average frequency halfway between the first and second pump frequencies and outside the Stokes Brillouin spectrum (21) and the anti-Stokes Brillouin spectrum (24), and

- two sidebands (31) located respectively, at least for a given set of temperature and/or strain conditions along at least a part of the sensing optical fiber (6), within the Stokes Brillouin spectrum (21) and within the anti-Stokes Brillouin spectrum (24).

14. The method of claim 13, which further comprises steps of:

- measuring the amplitude of modulation of the stimulated Brillouin scattering signal at the modulation frequency, and

- calculating the Brillouin frequency (22, 25) of the Stokes Brillouin spectrum (21) and/or the anti-Stokes Brillouin spectrum (24) using a third pre-established relation between said amplitude of modulation and said Brillouin frequency (22, 25).

15. The method of claim 14, wherein the third pre-established relation takes into account the gains and the losses respectively undergone by the sidebands (31) through their respective stimulated Brillouin scattering interactions.

16. The method of claim 1 or 2, wherein the optical probe wave comprises a signal modulated in intensity by a modulation wave at a modulation frequency, with:

- a carrier signal (30) spectrally located at an average frequency halfway between the first and second pump frequencies and outside the Stokes Brillouin spectrum (21) and the anti-Stokes Brillouin spectrum (24), and
- two sidebands (31) located respectively, at least for a given set of temperature and/or strain conditions along at least a part of the sensing optical fiber (6), within the Stokes Brillouin spectrum (21) and within the anti-Stokes Brillouin spectrum (24).

17. A Brillouin optical distributed sensing device, comprising:

- pump generation means (1, 2, 3, 4, 10) for providing a first optical pulsed pump wave (20) at a first pump frequency and a second optical pulsed pump wave (23) at a second pump frequency,
- probe generation means (1, 2, 5, 11) for providing an optical probe wave comprising at least one probe spectral component (26, 30, 31),
- optical routing means (8) for directing said first and second optical pulsed pump waves (20, 23) and said optical probe wave to a sensing optical fiber (6) so that the optical probe wave propagates in said sensing optical fiber (6) in a direction opposite to said first and second optical pulsed pump waves (20, 23),
- detection means (9) for detecting a stimulated Brillouin scattering signal resulting from the interactions in said sensing optical fiber (6) of the

optical probe wave with the first and the second optical pulsed pump waves (20, 23),

characterized in that:

- the pump generation means (1, 2, 3, 4, 10) and the probe generation means (1, 2, 5, 11) are able to arrange spectrally the first and the second optical pulsed pump waves (20, 23) and the optical probe wave so that, at least for a given set of temperature and/or strain conditions along at least a part of the sensing optical fiber (6), the optical probe wave comprises a probe spectral component (26, 30, 31) located within the Stokes Brillouin spectrum (21) of the first optical pulsed pump wave (20) and a probe spectral component (26, 30, 31) located within the anti-Stokes Brillouin spectrum (24) of the second optical pulsed pump wave (23),

- the device further comprises calculation means for deducing the Brillouin frequency (22, 25) of said Stokes Brillouin spectrum (21) and/or said anti-Stokes Brillouin spectrum (24) from the stimulated Brillouin scattering signal.

18. The device of claim 17, in which the pump generation means comprise:

- a pump modulator (3) for applying an intensity modulation with suppressed carrier scheme to a continuous incoming light wave at an average frequency located halfway between the first and second pump frequencies, and

- a pulse generator (4) for generating first and second optical pulsed pump wave with synchronous pulses of the same duration.

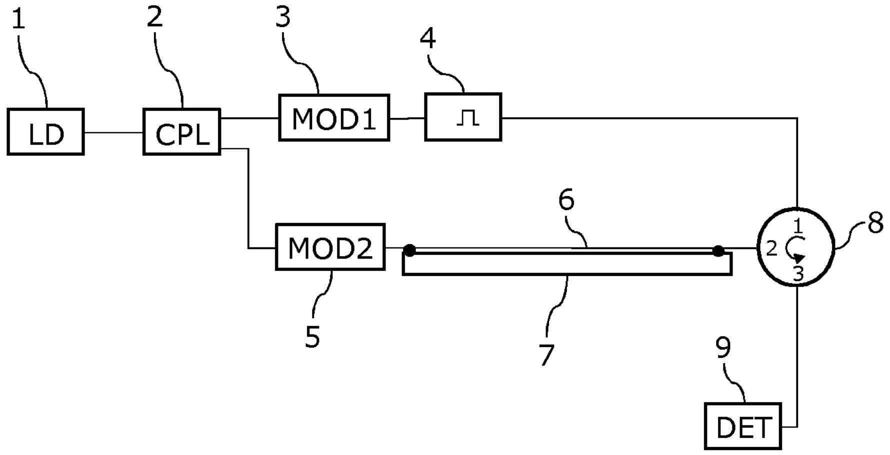
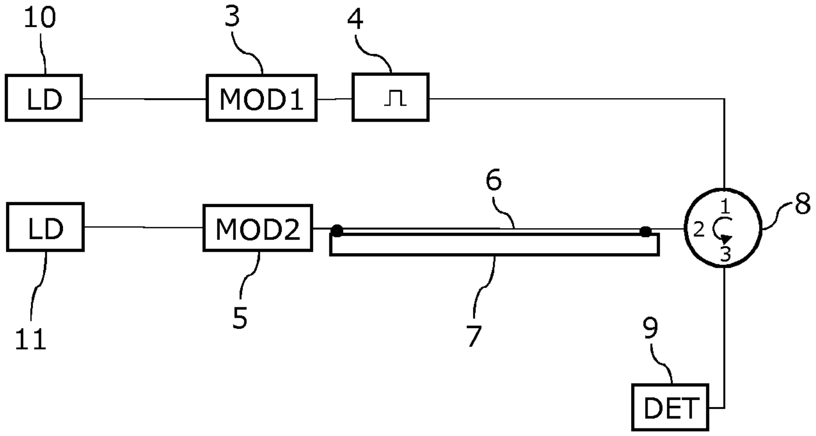

1
2
3
4
LD
CPL
MOD1
6
8
1
2
3
MOD2
5
7
9
DET

Fig. 1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4
LD
MOD1
6
8
1
2
3
LD
MOD2
11
5
7
9
DET

Fig. 2

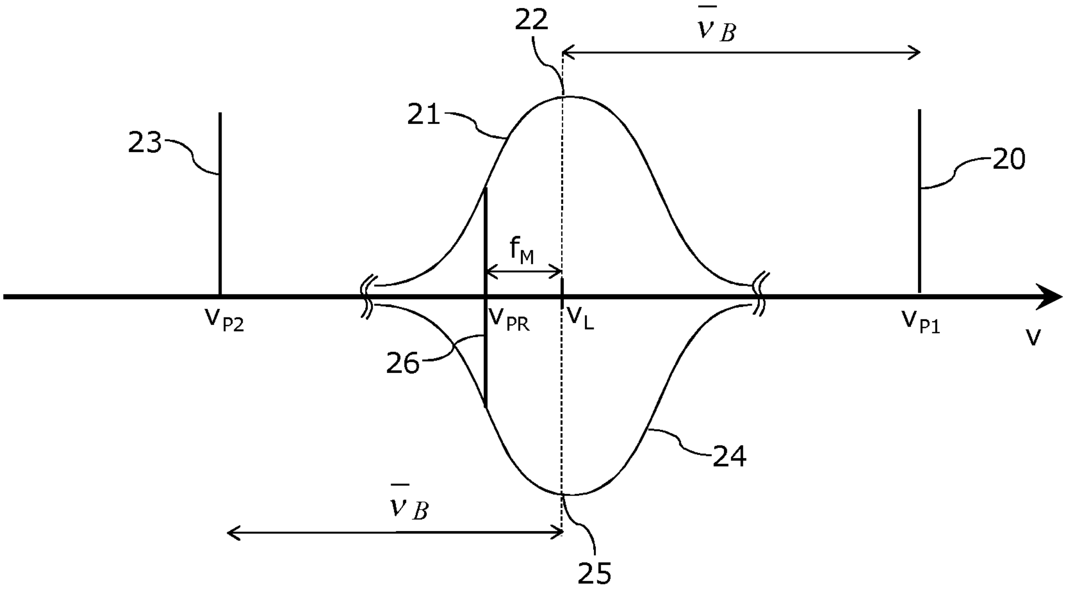

22
$\bar{\nu}_B$
21
23
20
f_M
ν_{P2}
ν_{PR}
ν_L
ν_{P1}
ν
26
24
$\bar{\nu}_B$
25

Fig. 3

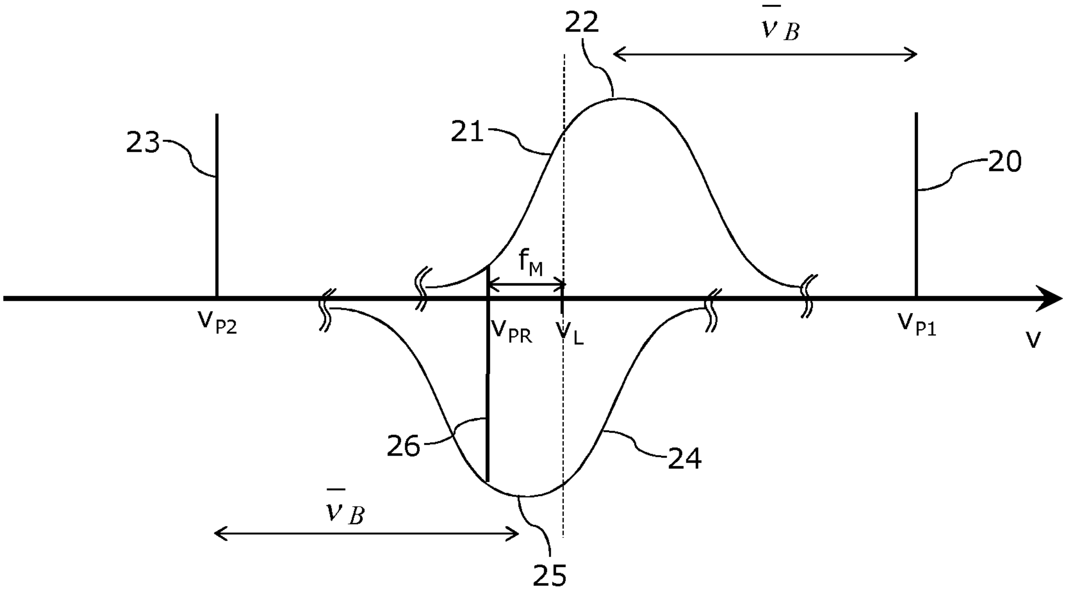
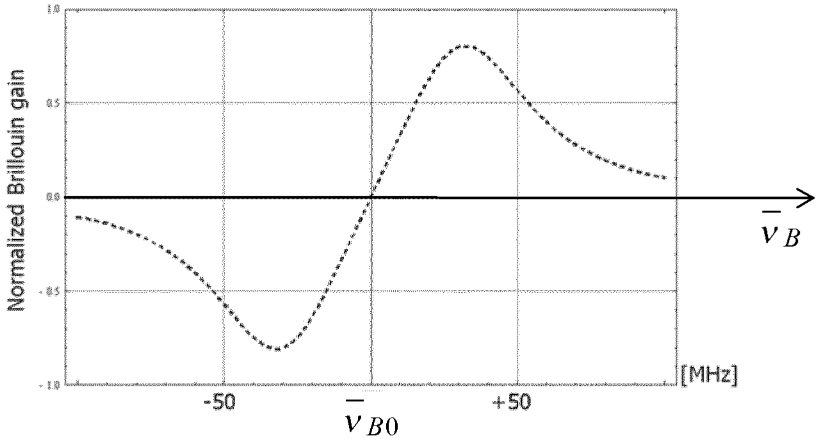

22
$\bar{\nu}_B$
21
23
20
f_M
ν_{P2}
ν_{PR}
ν_L
ν_{P1}
ν
26
24
$\bar{\nu}_B$
25

Fig. 4


Normalized Brillouin gain
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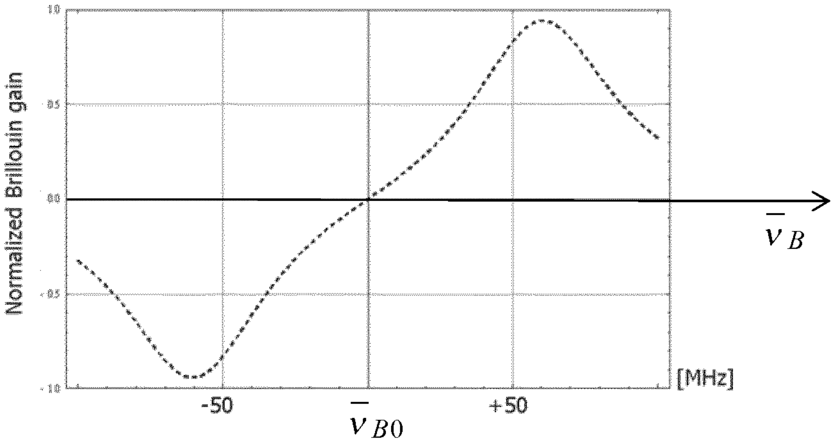
0.5
0.0
-0.5
-1.0
$\bar{\nu}_B$
[MHz]
-50
+50
$\bar{\nu}_{B0}$

Fig. 5


Normalized Brillouin gain
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0.0
-0.5
-1.0
$\bar{\nu}_B$
[MHz]
-50
+50
$\bar{\nu}_{B0}$

Fig. 6

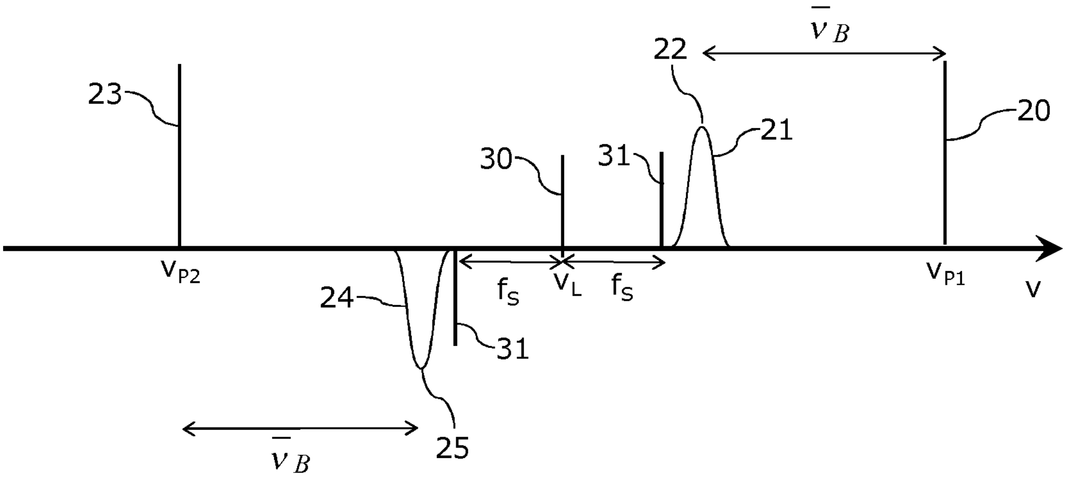
$\bar{\nu}_B$
22
23
20
21
30
31
ν_{P2}
f_S
ν_L
f_S
ν_{P1}
ν
24
31
25
$\bar{\nu}_B$

Fig. 7

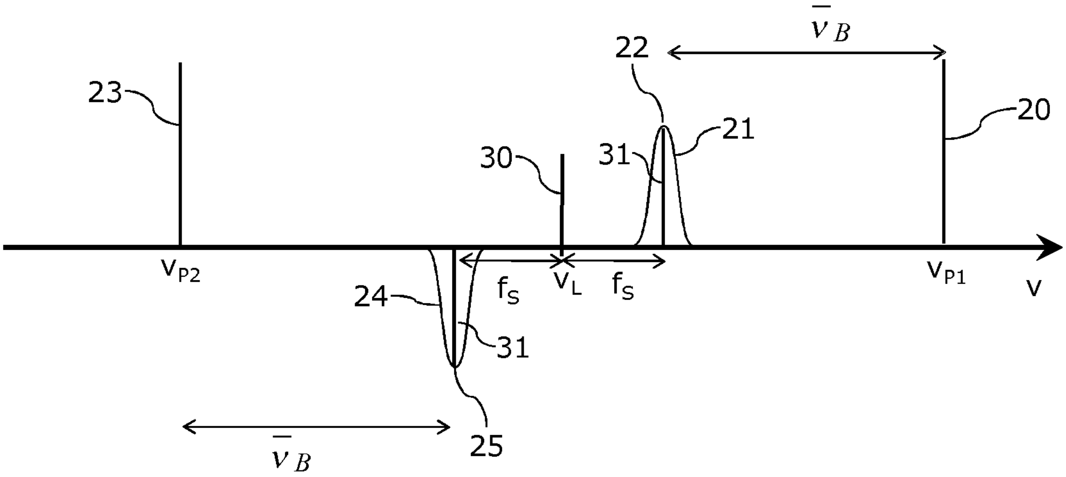
$\bar{\nu}_B$
22
23
20
21
30
31
ν_{P2}
f_S
ν_L
f_S
ν_{P1}
ν
24
31
25
$\bar{\nu}_B$

Fig. 8

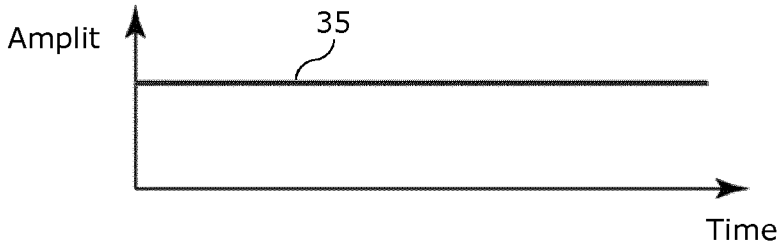

Fig. 9

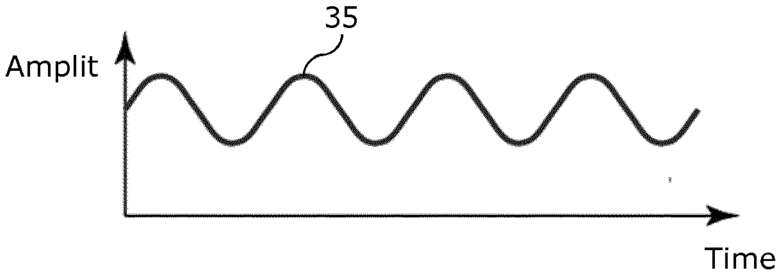

Fig. 10

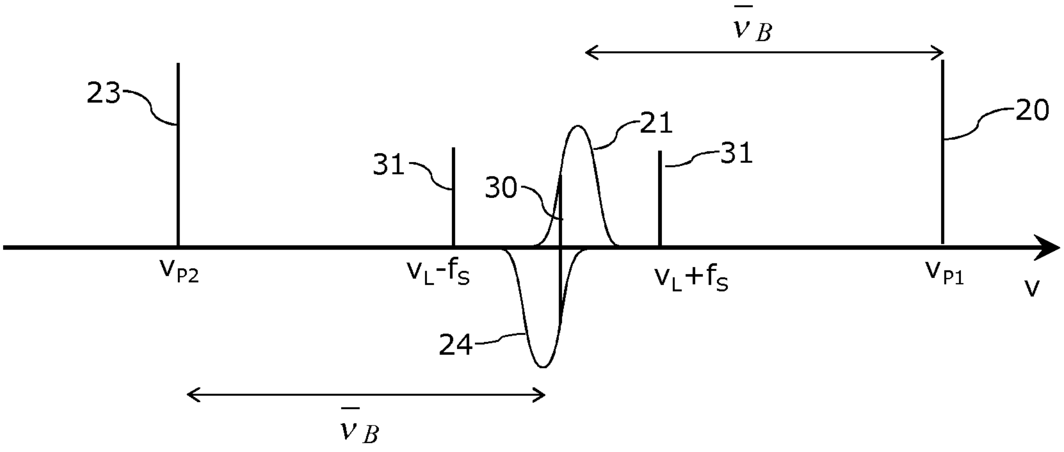

Fig. 11

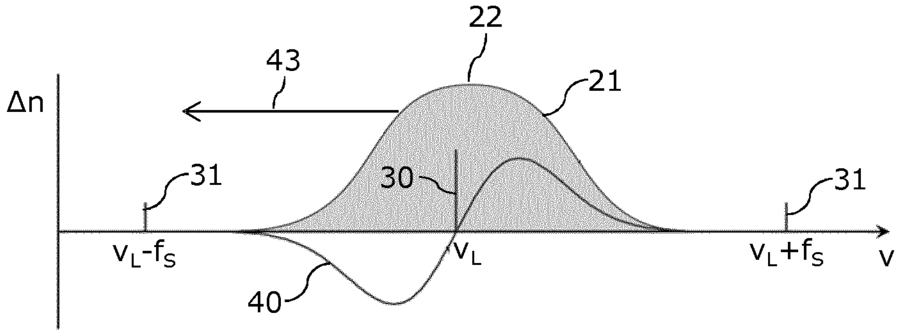

Fig. 12

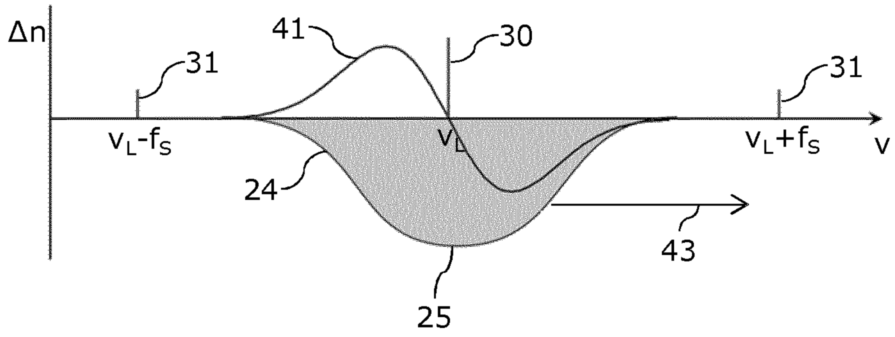

Fig. 13

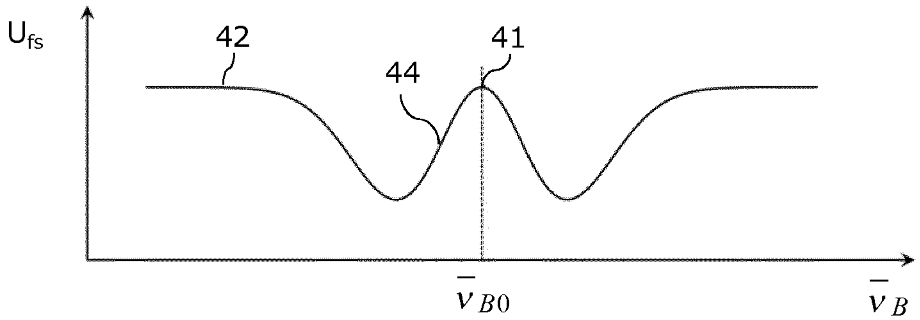

Fig. 14

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/059023

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01D5/353 G01M11/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01D G01M G01L G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	XIAOYI BAO ET AL: "Recent Progress in Brillouin Scattering Based Fiber Sensors", SENSORS, vol. 11, no. 12, 7 December 2011 (2011-12-07), pages 4152-4187, XP055063132, ISSN: 1424-8220, DOI: 10.3390/s110404152	1-3,6,7, 17,18
Y	abstract page 4163, paragraph 3 - page 4168, paragraph 1	8-10, 12-16
A	page 4174 - page 4176 -----	4,5,11

-/--

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
27 November 2013

Date of mailing of the international search report
10/12/2013

Name and mailing address of the ISA/
European Patent Office, P.B. 5818 Patentlaan 2
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Authorized officer
Stenger, Michael

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/059023

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	YUN LI ET AL: "A Novel Distributed Brillouin Sensor Based on Optical Differential Parametric Amplification", JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 28, no. 18, 15 September 2010 (2010-09-15), pages 2621-2626, XP011312887, ISSN: 0733-8724	1-3,6,7, 17,18
Y	the whole document	8-10, 12-16
A		4,5,11

Y	US 2006/285850 A1 (COLPITTS BRUCE G [CA] ET AL) 21 December 2006 (2006-12-21) abstract paragraph [0135] - paragraph [0151] paragraph [0208] - paragraph [0217]	8-10, 12-16

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2013/059023

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2006285850 A1	21-12-2006	NONE	