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(54) **Title**: OPTICAL PROCESS AND OPTICAL DEVICE, ALLOWING TO AVOID UNWANTED NONLINEAR EFFECTS IN AN OPTICAL FIBER

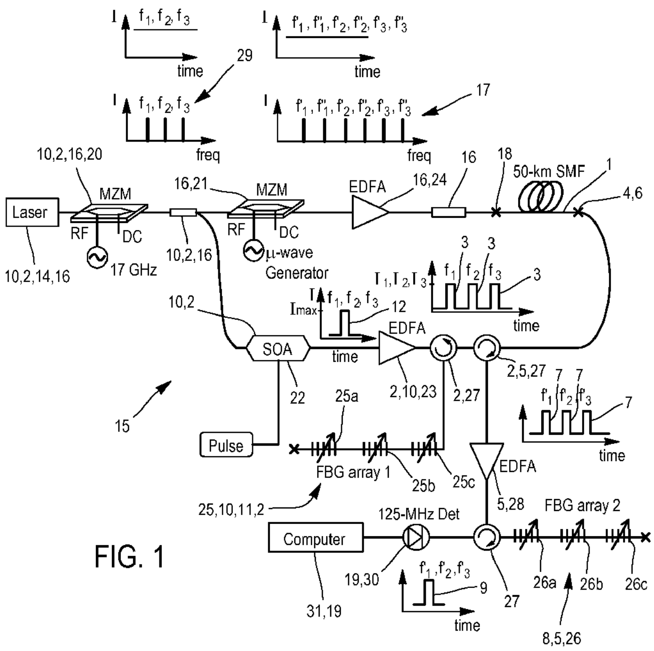

FIG. 1

(57) **Abstract**: The invention concerns a process comprising the following steps: injecting, in an optical fiber (1), N time limited replica optical signals (3) at distinct frequencies, each replica signal being temporally shifted relative to the other replica signals; then propagating the temporally shifted replica signals (3) along the optical fiber (1); then receiving, at an output (6) of the optical fiber, N output time-limited optical signals (7) at distinct frequencies resulting from the replica signals, each output signal (7) being temporally shifted relative to the other output signals; and constructing a useful signal (9) by temporally superimposing the N output signals (7), such that the useful signal (9) comprises a combination of the N output signals (7) that are not temporally shifted anymore. Application to distributed sensors.

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«Optical process and optical device, allowing to avoid unwanted nonlinear effects in an optical fiber »

Technical field

The present invention relates to an optical process and an optical device, allowing to avoid unwanted nonlinear effects in an optical fiber.

The invention preferably (but not necessarily) relates to distributed or fully distributed sensors, in which an optical fiber is a long uninterrupted sensor, and the measured information is extracted from the analysis of backcoupled light.

The backscattered light can typically come from the following scatterings:

- Rayleigh scattering is the interaction of a light pulse with material impurities (a typical example would be the scattering of sunlight by dust particles in the atmosphere giving to the sky different colors depending on the incident angle of the sun light). It is the largest of the three backscattered signals in silica fibers and has the same wavelength as the incident light. Rayleigh scattering is the physical principle behind Optical Time Domain Reflectometer (OTDR).
- Brillouin scattering is the interaction of a light pulse with thermally excited acoustic waves (also called acoustic phonons). Acoustic waves, through the elasto-optic effect, slightly and locally modify the index of refraction. The corresponding moving grating reflects back a small amount of the incident light and shifts its frequency (or wavelength) due to the Doppler Effect. The shift depends on the acoustic velocity in the fiber while its sign depends on the propagation direction of the travelling acoustic waves. Thus, Brillouin backscattering is created at two different frequencies around the incident light, called the Stokes and the Anti-Stokes components. In silica fibers, the Brillouin frequency shift is in the 10GHz range (0.1nm in the 1550nm wavelength range) and is temperature and strain dependent.

- Raman scattering is the interaction of a light pulse with thermally excited atomic or molecular vibrations (optical phonons) and is the smallest of the three backscattered signals in intensity. Raman scattering exhibits a large frequency shift of typically 13THz in silica fibers, corresponding to 100nm at a wavelength of 1550nm. The Raman Anti-Stokes component intensity is temperature dependent whereas the Stokes component is nearly temperature insensitive.

State of the Art

The low attenuation of state-of-the-art optical fibers has made possible the transmission of optical signals along many tens and hundreds of kilometers. This feature makes the optical fiber an almost-ideal transmission medium, which has been exploited for long-range applications such as optical communications systems, as well as distributed optical fiber sensing. However, the high concentration of light over a micrometric surface in optical fibers turns them into a highly nonlinear medium too; as a result, in order to transmit signals without distortion, the peak power that can be launched into the fiber has to remain below a given threshold level. This imposes a fundamental limitation to many applications in which long optical fibers are required, since power levels are highly attenuated after many tens or hundreds of kilometers. The input optical power limited by nonlinearities and the fiber attenuation lead to signals with very low power levels after long propagation lengths, making them difficult or impossible to detect at the photo-receiver stage. Although in some cases optical amplification methods can be used to recover the signal power, in several applications no electrical power is available for optical amplifiers located at remote locations.

One of the application fields being affected by this problem is distributed optical fiber sensing, which has been recently turned into one of the most interesting solutions to monitor very large structures and long pipelines, among other industrial applications. One of the most interesting characteristics of this technology is the possibility to perform distributed measurements covering very long distances, i.e. tens of kilometer ranges, with metric spatial resolutions. The interrogation methods typically employ optical pulses, which are launched into the fiber and generate scattered light during propagation. Scattering processes are typically affected by some environmental variables, such as temperature or strain, and therefore they result to be an efficient method for distributed sensing.

One of the main limitations in long-range distributed optical fiber sensors is related to the maximum pump power that can be launched into the sensing fiber, which eventually limits the available power near the distant end. In particular, the peak pump power is limited by the threshold of nonlinearities, which ultimately limits the response of the sensor and therefore the signal-to-noise ratio (SNR) of the measurements. This imposes a limitation to the best performance that an optimized sensor system can reach. This performance is mainly rated by parameters such as the maximum sensing distance, the spatial resolution, the measurement time and the measurement accuracy/resolution. Under optimized system conditions, these variables are interrelated with a fixed and well-defined relation, and every time one of these parameters is improved, at least one of the others turns downgraded.

One of the schemes that offers the highest performance in the field of distributed optical fiber sensing is called Brillouin optical-time domain analysis (BOTDA), which is based on the interaction of two optical waves by stimulated Brillouin scattering (SBS). The prior art BOTDA scheme uses a high-power pulsed pump and a counter-propagating continuous-wave (CW) probe signal and the interaction takes place solely at fiber positions where the 2 waves are simultaneously present. The probe signal is a continuous wave; hence, the interaction will be successively activated all along the fiber, since sequentially scanned by the propagating pump pulse. Since both probe and pump powers equally contribute to the response of the sensor along the entire fiber, the ultimate limit in long-range Brillouin sensing is related to the maximum powers that can be launched into the fiber. More specifically, the peak pump power of Brillouin sensors is limited by the threshold of nonlinearities, essentially modulation instability (MI), limiting its peak pump power to about 100-150 mW in standard single-mode fibers. As far as the CW probe power is concerned, with a proper sensor design, the probe power is ultimately limited to ~5 mW by the onset of amplified spontaneous Brillouin scattering. Under these conditions, the sensing distance (the fiber length that can be used for measurement) is limited to around 50km with a useful spatial resolution of typically 3m, whilst the total fiber distance (a BOTDA is based on a loop configuration; along a linear structure, half of the loop is for sensing, the other half to carry the CW probe to the end of the sensing section) is around 100km.

Other methods such as optical pulse coding and distributed Raman amplification can be used to avoid the onset of nonlinear effects and to enhance the

Brillouin interaction along the sensing fiber, thus increasing the optical power reaching the receiver.

Optical pulse coding methods employ several pulse sequences, which are launched into the sensing fiber, thus increasing the total pump power. The useful signal is then retrieved by a post-processing method based on the measured coded traces. However, the generation of homogenous powerful coded pulses is difficult and the decoding techniques are complex, resulting in a costly and difficult implementation.

Distributed Raman amplification, based on the intrinsic fiber amplification properties when pumped with high power Raman pumps provides gain for both the Brillouin pump and probe signals during propagation along the fiber so that the peak power inside the fiber remains below the threshold power for nonlinearities whilst the propagation distance can be increased but this scheme also suffers from strong limitations, as seeded second or third order Raman pumping and high power (>1W) handling are necessary to achieve significant distance improvement.

The goal of the invention is to present an optical process or device which avoids unwanted nonlinear effects, and preferably does not suffer from the complexity of pulse coding/decoding neither from the inherent difficulties to distributed amplification, in order for example to allow a high response and performance compared to prior art, i.e. for example with a better signal-to-noise ratio (SNR) and/or with an extended sensing range and/or a reduced measurement time, and/or an improved spatial and/or measured resolutions.

Summary of the Invention

An aspect of the invention concerns a process comprising the following steps:

- Injecting N replica signals, at a first input of an optical fiber, each replica signal being a time-limited and optical signal, N being an integer greater than or equal to 2, each replica signal having an intensity maximum at a given optical frequency distinct from a given optical frequency of an intensity maximum of each other replica signal, each replica signal being temporally shifted relative to the other replica signals, then
- propagating the temporally shifted replica signals along the optical fiber, then
- Receiving, at an output of the optical fiber, N output time-limited optical signals, each output signal resulting from one of the replica signals,

each output signal having an intensity maximum at a given optical frequency distinct from a given optical frequency of an intensity maximum of each other output signal, each output signal being temporally shifted relative to the other output signals, then

- constructing a useful signal by temporally superimposing the N output signals, such that the useful signal comprises a combination of the N output signals that are not temporally shifted anymore.

The N replica signals are preferably emitted by temporally and/or spectrally fractioning an initial time-limited optical signal into the N replica signals, each replica signal having preferably an intensity maximum lower than or equal to an intensity maximum of the initial time-limited optical signal.

Each replica signal has preferably an intensity maximum lower than the maximum intensity that can be launched in the fiber without triggering non-linear interaction.

The temporal superposition, for the construction of the useful signal, is preferably optically obtained, not electronically.

Each output signal can comprise (or consist of):

- one of the replica signals, and/or
- a signal generated in the fiber by scattering or backscattering resulting from one of the replica signals, and/or
- a signal generated in the fiber by a linear or nonlinear optical effect resulting from of one of the replica signals.

Each output signal can comprise or can be a signal generated in the fiber by scattering or backscattering resulting from the propagation of one of the replica signals and/or a signal generated in the fiber by a linear or nonlinear optical effect resulting from the propagation of one of the replica signals.

The useful signal can be detected for:

- Optical Time Domain Reflectometry, preferably for Coherent Optical Time Domain Reflectometry or Phase-Sensitive Optical Time Domain Reflectometry or Brillouin Optical Time Domain Reflectometry, or
- Optical Frequency Domain Reflectometry, preferably for Coherent Rayleigh Optical Frequency Domain Reflectometry, Phase-Sensitive Optical Frequency Domain Reflectometry or Brillouin Optical Frequency Domain Reflectometry.

The process according to the invention can further comprise injecting an optical multi-frequency probe wave at a second input of the optical fiber, the second input being preferably (but not necessarily) distinct from the first input, the multi-frequency probe wave comprising at least N components at a given optical frequency, the given optical frequency of each component being distinct from the given optical frequency of the other components, each output signal can comprise or can be a result from the interaction, in the fiber, between a group of signals comprising at least one of the components of the optical multi-frequency probe wave and at least one of the replica signals. In this case:

- the spectral separation of the N components can be at least larger than a Brillouin frequency of the fiber but smaller than twice the Brillouin frequency of the fiber, ,and/or
- the optical multi-frequency probe wave and the replica signals can be generated from a common source signal.

The useful signal can be detected for Optical Time Domain Analysis, preferably for Brillouin Optical Time Domain Analysis, or Optical Frequency Domain Analysis, preferably for Brillouin Optical Frequency Domain Analysis.

N is preferably an integer greater than or equal to 3.

Each considered replica signal is preferably temporally shifted relative to the other replica signals by a time superior to the full temporal width at half Intensity maximum of this considered replica signal, more preferably by a time superior to the duration of this considered replica signal.

Each replica signal can be composed by a group of elementary optical signals. In this case, each replica signal can be temporally shifted relative to the other replica signals but can be also partially interleaved to at least one of the other replica signals, such that for a first replica signal and a second replica signal partially interleaved, each considered elementary signal of the first replica signal is preferably temporally shifted relative to each elementary signal of the second replica signal by a time superior to the full temporal width at half Intensity maximum of this considered elementary signal, more preferably by a time superior to the duration of this considered elementary signal.

Another aspect of the invention concerns a device comprising:

- an optical fiber,

- means for injecting N replica signals, at a first input of the optical fiber, each replica signal being a time-limited and optical signal, N being an integer greater than or equal to 2, each replica signal having an intensity maximum at a given optical frequency distinct from a given optical frequency of an intensity maximum of the other replica signals, each replica signal being temporally shifted relative to the other replica signals,
- means for receiving, at an output of the optical fiber, N output time-limited optical signals, each output signal resulting from one of the replica signals, each output signal having an intensity maximum at a given optical frequency distinct from a given optical frequency of an intensity maximum of the other output signals, each output signal being temporally shifted relative to the other output signals,
- means for constructing a useful signal by temporally superimposing the N output signals, such that the useful signal comprises a combination of the N output signals that are not temporally shifted anymore.

The device according to the invention can comprise means for emitting the N replica signals by temporally and/or spectrally fractioning an initial time-limited optical signal into the N replica signals, each replica signal having preferably an intensity maximum lower than or equal to an intensity maximum of the initial time-limited optical signal.

The means for constructing the useful signal by temporally superimposing the output signals can be arranged for optically superimposing the outputs signals, not electronically.

Each output signal preferably comprises (or consists of):

- one of the replica signals, and/or
- a signal generated in the fiber by scattering or backscattering resulting from one of the replica signals, and/or
- a signal generated in the fiber by a linear or nonlinear optical effect resulting from of one of the replica signals.

Each output signal can comprise or can be a signal generated in the fiber by scattering or backscattering resulting from the propagation of one of the replica signals and/or a signal generated in the fiber by a linear or nonlinear optical effect resulting from the propagation of one of the replica signals.

The device according to the invention can further comprise means for detecting the useful signal, arranged for:

- Optical Time Domain Reflectometry, preferably for Coherent Optical Time Domain Reflectometry or Phase-Sensitive Optical Time Domain Reflectometry or Brillouin Optical Time Domain Reflectometry, or
- Optical Frequency Domain Reflectometry, preferably for Coherent Rayleigh Optical Frequency Domain Reflectometry, Phase-Sensitive Optical Frequency Domain Reflectometry or Brillouin Optical Frequency Domain Reflectometry.

The device according to the invention can further comprise means for injecting an optical multi-frequency probe wave at a second input of the optical fiber, the second input being preferably (but not necessarily) distinct from the first input, the multi-frequency probe wave comprising at least N components at a given optical frequency, the given optical frequency of each component being distinct from the given optical frequency of the other components, each output signal can comprise or can be a result from the interaction, in the fiber, between a group of signals comprising at least one of the components of the optical multi-frequency probe wave and at least one of the replica signals. In this case:

- the spectral separation of the N components can be at least larger than the Brillouin frequency of the fiber but smaller than twice the Brillouin frequency of the fiber, and/or
- the device according to the invention can further comprise means for generating the optical multi-frequency probe wave and the replica signals from a common source signal.

The device according to the invention can further comprise means for detecting the useful signal, arranged for optical-time domain analysis, preferably for Brillouin Optical Time Domain Analysis, or Optical Frequency Domain Analysis, preferably for Brillouin Optical Frequency Domain Analysis.

N is preferably an integer greater than or equal to 3.

Each considered replica signal is preferably temporally shifted relative to the other replica signals by a time superior to the full temporal width at half Intensity maximum of this considered replica signal, more preferably by a time superior to the duration of this considered replica signal.

Each replica signal can be composed by a group of elementary optical signals. In this case, each replica signal can be temporally shifted relative to the other replica signals but can be also partially interleaved to at least one of the other replica signals, such that for a first replica signal and a second replica signal partially interleaved, each considered elementary signal of the first replica signal is preferably temporally shifted relative to each elementary signal of the second replica signal by a time superior to the full temporal width at half Intensity maximum of this considered elementary signal, more preferably by a time superior to the duration of this considered elementary signal.

Detailed description of the figures and of realization modes of the invention

Other advantages and characteristics of the invention will appear upon examination of the detailed description of embodiments which are in no way limitative, and of the appended drawings in which:

- Figure 1 illustrates a first embodiment of a device 15 according to the invention, corresponding to an experimental setup for proposed BOTDA sensor based on multi-frequency time-shifted pump pulses 3 (in the particular case where N=3),

- Figure 2 illustrates, for the first embodiment, the frequency allocation of probe signal 17 (also called probe wave or probe light, corresponding to frequencies f'_1, f'_2, f'_3, f'_4, ... f'_N, and optionally f''_1, f''_2, f''_3, f''_4, ... f''_N,) and pump signals 3 (also called replica signals, or pump pulses 3 or replica pulses 3 or replicas 3 or pumps 3, each replica signal 3 corresponding to one frequency among f_1, f_2, f_3, f_4, ... f_N) in the proposed BOTDA scheme of the first embodiment of device 15 according to the invention (in the particular case where N=4),

- Figures 3 (N=4), 4 (N=4) and 5 (N=5) illustrate, for the first embodiment, three possible spectral allocation of pump signals 3 and probe signal 17 to implement the invention in a BOTDA sensor,

- Figure 6 illustrates a part of the experimental setup of the first embodiment showing the recombination of the backscattered signals 7,.

- Figure 7 illustrates, for the first embodiment, a signal-to-noise ratio (SNR) measured at a peak gain frequency, and illustrates a comparison between the prior art BOTDA (N=1) and the proposed invention using N=3 and delayed pump pulses 3,

- Figure 8 illustrates, for the first embodiment, a signal-to-noise ratio (SNR) measured at a peak gain frequency, and illustrates traces measured with N=3 frequency components with or without delay between pump pulses 3,

- Figure 9 illustrates, for the first embodiment, a measured Brillouin gain spectrum versus distance, and illustrates, in an inset, a retrieved Brillouin frequency profile; This is the result of the construction of the useful signal 9 (N=3, after time shift correction),

- Figure 10 illustrates, for the first embodiment, frequency uncertainty versus distance, for BOTDA schemes using N=1 (prior art) and N=3 (invention) frequency components; the frequency uncertainty is here calculated as one standard deviation of the Brillouin frequency measured at each fiber location over five measurements,

- Figure 11 illustrates, for the first embodiment, a hot-spot detection at the far fiber end (around 50 km distance), demonstrating 2 m spatial resolution,

- Figure 12 illustrates, for the first embodiment, three replica signals 3, each replica signal 3 comprising three elementary pulses 13 (also called elementary signals 13),

- Figure 13, illustrates a second embodiment of a device 32 according to the invention for reflectometry, and

- Figure 14 illustrates a third embodiment of a device 33 according to the invention for the simple delivery of a time-limited optical signal.

These embodiments being in no way limitative, we can consider variants of the invention including only a selection of characteristics subsequently described or illustrated, isolated from other described or illustrated characteristics (even if this selection is taken from a sentence containing these other characteristics), if this selection of characteristics is sufficient to give a technical advantage or to distinguish the invention over the state of the art. This selection includes at least one characteristic, preferably a functional characteristic without structural details, or with only a part of the structural details if that part is sufficient to give a technical advantage or to distinguish the invention over the state of the art.

We are now going to describe, in references to all the figures, a general example of embodiment of a device and of a process or method according to the invention.

A general example of embodiment of a device according to the invention comprises an optical fiber 1.

The general example of embodiment of the device according to the invention comprises means 2 for injecting N replica signals 3, at a first input 4 of the optical fiber

1, each replica signal 3 being a time-limited and optical signal, N being an integer greater than or equal to 2 (preferably greater than or equal to 3) according to the invention.

In the present description each optical signal (in particular referenced 12, 3, 17, 7, 9) is a light signal as a function of time, for example a light intensity as a function of time (and eventually as a function of an optical frequency f_i corresponding to a wavelength λ_i , each frequency corresponding to a component of this signal), i.e I(t) or I(t, f_i). This signal can be continuous as a function of time (for example probe 17) or can vary as a function of time (for example pulses 3).

Each replica signal 3 number 1 to N has an intensity maximum I_1 to I_N at a given optical frequency f_1 to f_N (corresponding respectively to a wavelength λ_1 to λ_N). All the frequency f_1 to f_N are distinct: each replica signal 3 number i (with i an integer comprised between 1 and N) has an intensity maximum I_i at a given optical frequency f_i , with f_i being distinct from a given optical frequency f_k (with k an integer comprised between 1 and N but different from i) of the intensity maximum I_k of each other replica signals 3.

Each replica signal 3 is temporally shifted relative to all the other replica signals 3.

The general example of embodiment of the device according to the invention comprises means 10 for emitting the N replica signals 3 comprising means 11 for temporally fractioning an initial time-limited optical signal 12 into the N replica signals 3.

Each replica signal 3 number i has an intensity maximum I_i lower than or equal to an intensity maximum I_{max} of the initial time-limited optical signal 12 (also called pump signal 12).

I_{max} is preferably equal to the maximum intensity that can be launched in the fiber 1 without triggering non-linear interaction.

Each replica signal 3 number i has preferably an intensity maximum I_i lower than the maximum intensity that can be launched in the fiber 1 without triggering non-linear interaction.

In this document, each maximum I_i, I_k, I_{max}, I'_i, I'_k, I'_{max}, etc. of a signal is considered to be the maximum of the total intensity (i.e. all optical frequencies added of this signal at a given time) versus time.

The general example of embodiment of the device according to the invention comprises means 5 for receiving, at an output 6 of the optical fiber 1, N output time-limited optical signals 7.

Each output signal 7 results from (at least) one of the replica signals 3, i.e. that each output signal 7 typically:

- comprises one of the replica signals 3, and/or
- comprises a signal generated in the fiber 1 by a scattering or backscattering resulting (typically by propagation in fiber 1 or by interaction with another signal in fiber 1) from one of the replica signals 3, and/or
- comprises a signal generated in the fiber 1 by a linear or nonlinear optical effect resulting from of one of the replica signals 3.

Each output signal 7 number 1 to N has an intensity maximum I'_1 to I'_N at a given optical frequency f'_1 to f'_N (corresponding respectively to a wavelength λ'_1 to λ'_N). All the frequency f'_1 to f'_N are distinct: each output signal 7 number i (with i an integer comprised between 1 and N) has an intensity maximum I'_i at a given optical frequency f'_i , with f'_i being distinct from a given optical frequency f'_k (with k an integer comprised between 1 and N but different from i) of the intensity maximum I'_k of each other output signals 7.

Each output signal 7 is temporally shifted relative to all the other output signals 7.

The general example of embodiment of the device according to the invention comprises means 8 for constructing a useful signal 9 by temporally superimposing the N output signals 7, such that the useful signal 9 comprises a combination of the N output signals 7 that are not temporally shifted anymore.

The means 8 for constructing the useful signal 9 by temporally superimposing the output signals 7 are arranged for optically superimposing the outputs signals 7, preferably not electronically.

The general example of embodiment of a process according to the invention implemented by the general example of embodiment of the device according to the invention comprises the following steps:

- Emitting, by means 10, the N temporally shifted replica signals 3; The N replica signals 3 are emitted by temporally and/or spectrally fractioning, by means 11, the initial time-limited optical signal 12 into the N replica signals; temporally fractioning means temporally shifting N wavelengths from the initial signal 12; spectrally fractioning means obtaining a plurality of distinct wavelengths from a monochromatic initial signal 12;

- Injecting, by means 2, the N temporally shifted replica signals 3 at the first input 4 of the optical fiber 1, then
- propagating the N temporally shifted replica signals 3 along the optical fiber 1, then
- Receiving, by means 5, the N output optical signals 7 at the output 6 of the optical fiber 1, then
- Constructing, by means 11, the useful signal 9 by temporally superimposing the N output signals 7, such that the useful signal 9 comprises a combination of the N output signals 7 that are not temporally shifted anymore; the temporal superposition, for the construction of the useful signal 9, is optically obtained, not electronically.

Each considered replica signal 3 is temporally shifted relative to the other replica signals 3 by a time superior to the full temporal width at half Intensity maximum of this considered replica signal 3, preferably by a time superior to the duration of this considered replica signal 3.

All the replica signals 3 have preferably the same duration.

The amplitudes or maximum intensities I_i to I_N of all the replica signals 3 can differ but are preferably the same.

All the replica signals 3 have the same shape.

Each replica signal 3 is preferably a single pulse. Typically, each replica signal 3 has the shape of a square pulse or each replica signal 3 has the shape of a Gaussian pulse or each replica signal 3 has the shape of a Lorentzian pulse.

In another variant illustrated in figure 12, each replica signal 3 is composed by a group of elementary optical signals 13, each replica signal 3 being temporally shifted relative to all the other replica signals but being also partially interleaved to at least one of the other replica signals 3 such that for a first replica signal 3 and a second replica signal 3 partially interleaved, each considered elementary signal 13 of the first replica signal 3 is temporally shifted relative to each elementary signal 13 of the second replica signal 3 by a time superior to the full temporal width at half Intensity maximum of this considered elementary signal 13, preferably by a time superior to the duration of this considered elementary signal 13.

Each elementary signal 13 is preferably a single pulse. Typically, each elementary signal 13 is a square pulse or each elementary signal 13 is a Gaussian pulse or each elementary signal 13 is Lorentzian pulse.

In this description, when a first and a second signals are temporally shifted, that means that the time of the maximum intensity of the first signal is temporally shifted compared to the time of the maximum intensity of the second signal. In case of a signal comprising, during time, more than one point at the maximum intensity, the first time for which this signal reaches its maximum intensity is considered to be "the time of the maximum intensity".

This general example of the invention employs time and frequency multiplexing to split and recombine the initial time-limited signal 12, so that the equivalent of very high peak power can be propagated along the optical fiber 1 with no (or limited) stimulation of unwanted nonlinear effects. The invention only applies to time-limited signals 3 such as light pulses (or a train 3 of time-limited signals 13, such as a train 3 of optical pulses 13 as illustrated in figure 12) and the principle is based on the fractioning of the signal 12 into multiple replicas 3 at distinct optical frequencies, each of them having a power lower than the threshold of unwanted nonlinear effects in fiber 1. Each signal replica 3 at distinct frequency has to be temporally shifted in order to avoid temporal overlapping and cross-interaction during propagation along the optical fiber 1, ensuring negligible stimulation of unwanted nonlinear effects. The method also requires to reconstruct the useful signal 9 by applying the inverse temporal shift. This reconstruction acts on each output signal 7 comprising (or consisting of):

- one of the replicas 3 of the original (transmitted) signal 12, and/or
- a new output signal 7 created by an interaction or propagation, in fiber 1, of one of the replicas 3 of the original signal 12.

The invention applies to a time-limited replica signal 3 (such as a light pulse) or a periodic time-limited replica signal 3 (such as a train of light pulses, as illustrated in figure 12).

Its principle is the fractioning of the time-limited initial signal 12 into multiple replicas 3 at distinct optical frequencies, all temporally delayed. In other words the method requires the generation of the initial signal 12 distributed over N different spectral components and the obtained signal replicas 3 at distinct frequencies are delayed to avoid temporal overlapping and cross-interaction during propagation along the fiber 1. On the side of the receiver 5, this requires to reconstruct the useful signal

9 before photo-detection by applying the inverse delay on the distinct output signals 7. This way, employing time and frequency multiplexing to split and recombine time-limited signals, the equivalent of very high peak power can be propagated along an optical fiber 1 with no stimulation of unwanted nonlinear effects.

In this example, the light from an optical source 14 composed of several frequency components is used to generate the initial high-power optical pulse 12. Actually, not only square pulses, as depicted in the followings Figures, but any kind of time-limited signal 3 or 12 can be used together with the invention. Thus, the total pulse power can be spectrally distributed in N different frequencies. Each of these N frequency components is selectively and distinctively delayed in distinct replicas 3 to limit (or ideally suppress) any temporal overlapping and to thus avoid mutual interaction along the fiber 1. Although here optical pulses are used to explain the principle of the proposed method, in a more general context, this equally applies to any kind of time-limited signal that can be generated to be transmitted along the fiber 1.

It is worth mentioning that if optical pulses 3 or 13 at different frequencies and with high peak power are launched simultaneously into the fiber 1, their unwanted nonlinear parametric interaction during propagation will mutually seed unwanted nonlinear processes. In order to maximize the power 12 of the initial pulse 12 and to avoid parametric interaction among the different frequency components, the pulses 3 or 13 at the N frequencies have to be temporally separated. This wavelength-dependent delay that is imposed to the pulses 3 or 13 must be ideally at least equal to the duration of a single pulse 3 or 13 to secure that pulses 3 or 13 do not coexist in time and location anywhere along the fiber. This also ensures high and optimized peak power: although each pulse 3 or 13 is still limited by the onset of unwanted nonlinear effects, the total signal power supported by the fiber can be multiplied by an integer factor equal to the number N of frequency components. It is important to mention that the delay between pulses 3 or 13 can still be reduced below the pulse duration; however, this might result in few unwanted nonlinear interaction between pulses, reducing the interest of the method.

The situation can be extrapolated to a more complex time-limited signal 12 (e.g. a sequence of multiple pulses in a given pattern, repeated over time). The required amount of delaying of the replicas 3 can be securely defined as being equal or larger than the duration of signal 12 (equal to the duration of each signal 3). However, the time-limited signal 12 may contain occurrences where the signal is zero (absence of light). For instance this is the case of a return-to-zero pulse sequence. In this case the delayed replicas 3 may be judiciously interleaved, so that a pulse of a given replica 3 of the sequence is present at a moment when all other signal replicas 3 are zero between their pulses, as illustrated in figure 12. The necessary condition is that a given replica 3 of the time-limited signal has light on only when all other replicas have light off.

Concerning the construction of the useful signal 9, in order to avoid distortion due to synchronization problems, the N different signal frequency components (i.e. the N output signals 7) have to be properly time-shifted before photo-detection by applying a delay opposite to the one originally set to the corresponding replicas 3. For example, we can assume that the output signals 7 result from an interaction (a continuous backscattering process) that may deeply alter the temporal distribution given by the replica signals 3, and the outputs signals 7 may overlap in time after the interaction. This is in the vast majority of situations not an issue, since the output signals 7 after the interaction show a very low power level, usually order of magnitudes lower than the high power activating signal limited by unwanted nonlinear effects.

We are now going to describe, in reference to figures 1 to 12, a first embodiment of a device 15 and a process according to the invention for a OTDA (Optical-Time Domain Analysis) sensor, preferably for a Brillouin Optical-Time Domain Analysis (BOTDA) sensor.

Further to the previous description, the device 15 further comprises means 16 for injecting an optical multi-frequency probe wave 17 at a second input 18 of the optical fiber, the second input being 18 distinct from the first input 4, the multi-frequency probe wave 17 comprising at least N components (typically N or 2N components) at distinct optical frequencies f'_i (or eventually f''_i) (with i an integer between 1 and N), the given optical frequency f'_i (and eventually f''_i) of each component being distinct from the given optical frequency of all the other components, each output signal 7 resulting from the interaction, in the fiber 1, between a group of signals 3 comprising at least one of the components at frequency f'_i (or f''_i) of the optical multi-frequency probe wave 17 and at least one of the replica signals 3 at frequency f_i. Each output signal 7 corresponds to a BOTDA trace at a distinct frequency component of the probe 17.

The first input 4 and the output 6 correspond to the same end of the fiber 1.

In case of Brillouin or Raman scattering, the given optical frequency f'_i (or eventually f''_i) of each component of the probe signal 17 is distinct from the given optical frequency f_i of each replica signal 3. On the contrary, for a similar setup used in case of Rayleigh scattering the given optical frequency f'_i of each output signal 7 is similar to the given optical frequency f_i of one replica signal 3..

Device 15 further comprises means 19 for detecting the useful signal 9, arranged for optical-time domain analysis, more precisely for Brillouin Optical Time Domain Analysis (BOTDA).

Device 15 comprises means 14 for generating the optical multi-frequency probe wave 17 and the replica signals 3 from a common source signal 29.

This first embodiment of process according to the invention thus comprises injecting the optical multi-frequency probe wave 17 at a second input 18 of the optical fiber 1, the second input 18 being distinct from the first input 4.

The optical multi-frequency probe wave 17 and the replica signals 3 are generated from a common source signal 29.

The useful signal 9 is detected for optical-time domain analysis, more precisely for Brillouin Optical Time Domain Analysis.

The implementation of the proposed technique in BOTDA sensors requires the creation of pump pulses 3 at distinct optical frequencies interacting with a matching multi-frequency CW probe wave 17. The multi-frequency CW probe 17 can be generated from the same multi-frequency optical source 14 that is used to generate the pump pulses 3. In contrast to the prior art BOTDA scheme, in which a single frequency pump is used, pump pulses 3 corresponding to N optical frequency components f_1 to f_N are in this case employed to produce Brillouin amplification along the sensing fiber 1. Each of these N pump frequency components f_1 to f_N interacts only with the unique probe wave 17 properly located near the pump spectral line to maximize the interaction, as schematically shown in Figure 2. In this case the use of N frequency components f_1 to f_N can be interpreted as a spectral parallelization of the Brillouin interaction occurring along the distributed sensor. Since the sensor response depends linearly on the pump power in the small gain approximation, the N pulses 3 will generate a response equivalent to a single pulse with an N-times larger power.

However, the compound signals contains several spectral lines that can all potentially interact; thus, the Brillouin interaction within each pump-probe pair has to remain independent from other pair interactions. A smart choice of the frequency separation Δf must be made to avoid unwanted Brillouin interactions with other frequency components 3.

There are different means of generating multiple frequency signals. Two are given as example here. It must be understood that the generation of multiple frequency source is known from the art and that any method can be used within the scope of this invention:

- An electro-optic modulator (EOM) can be used to generate odd numbers of spectral line by properly adjusting the Radio Frequency (RF) power and the bias control. Also, the RF frequency is used to control the line spacing. The resulting comb can be split in two branches, one for the pumps 3, the other one for the probe 17. The probe branch is again modulated using an EOM in a carrier suppressed mode so that the probe frequency comb is automatically created.
- Multiple lasers can be used as well. In this case, their frequency spacing must be controlled, for instance by locking on adjacent lines of a Fabry-Perot. Laser locking on reference line is a known method in the field and is not further described.
  - A Fabry-Perot multimode laser is a single laser producing self referenced multiple wavelength.
- Dual wavelength lasers would provide a N=2 concept. In this case, the laser design and driving provide the wanted frequency differences.

Figure 1 shows the possible device 15 for BOTDA sensing. In this example a multi-wavelength optical source is generated by modulating the intensity of the light produced by a single-wavelength laser 14. More specifically, this example makes use of a comb with N=3 frequency components, which is generated by modulating the intensity of a CW laser source using a Mach-Zehnder modulator 20 (MZM) driven by a microwave signal at 17 GHz. The DC bias voltage of the modulator 20 has been adjusted so that three frequency components f_1, f_2 and f_3 (carrier and sidebands) are obtained with the same amplitude. This multi-frequency signal 29 is then split into two branches to generate pump signals 3 and the probe wave 17.

In this example the probe light 17 is created from the multi-frequency signal 29 using a Mach-Zehnder modulator 21 (MZM) operating in carrier-suppression mode, giving rise to two sidebands around each of the N=3 original frequencies f_1, f_2 and f_3, for a total of six lines f'_1, f'_2 , f'_3 , f''_1, f''_2 and f''_3 in this case. The probe sidebands are located at the Brillouin shift, namely around 10-11GHz for silica fiber in the 1550nm band.

In this case we have:

$f_i \neq f'_q$ with i an integer comprised between 1 and N, with q an integer comprised between 1 and N.

$f_i \neq f''_q$ with i an integer comprised between 1 and N, with q an integer comprised between 1 and N.

Meanwhile, initial pulse 12 is created from the multi-frequency signal 29 with high extinction ratio, using in this case a semiconductor optical amplifier 22 (SOA), in which the gain is gated using a 20 ns-long electrical pulse. This pulse duration corresponds to a spatial resolution of 2m.

Adjusting the output power of erbium-doped fiber amplifiers 23, 24 (EDFAs), probe and pump powers are separately optimized at the inputs 4, 18 of fiber 1 to avoid unwanted nonlinear effects.

Once the initial pump signal 12 is created by any means as described above, the frequency time shifter 11 is applied. In this block each replica 3 of the initial pump pulse 12 at distinct frequencies is delayed with respect to each other, so that the potential interaction among the different frequency components is avoided since they never co-exist at the same time and position. The wavelength-dependent delay that is imposed to the replica pump pulses 3 must be at least equal to the duration of a single pulse 3 to secure that pulses 3 do not coexist in time and location anywhere along the fiber 1.

Note that delay between pulses 3 can be reduced below the duration of a pulse 3. In this case, some unwanted nonlinear interaction between pulses will take place so that the invention loses some of its efficiency.

After the Brillouin pump-probe interaction, the BOTDA traces 7 at the different frequency components of the probe 17 have to be time-shifted before photo-detection by applying a delay opposite to the one originally set to the corresponding pump pulse components 3. Although this second time-shifter is preferably performed optically before photo-detection, following a scheme identical to the first time-shifter, it can be also carried out in the electrical domain after photo-detection. In such a case, the multiple output signals 7 (BOTDA traces) can be independently detected using several parallel photo-detectors, or obtained by heterodyne detection followed by electrical filtering. Thus, the different output signals 7 in the electrical-domain can be time-shifted electrically before they are combined to generate a unique high-amplitude BOTDA trace.

An example of frequency-time shifter uses discrete FBGs and fiber delay line, for the pump replicas 3 and/or for the output signals 7.

Another example is based on dispersive element that split the different spectral components into different fibers like Arrayed Waveguide Gratings (AWG) or cascaded WDM filter. The same unit can be used at the detection side for recombination by swapping the short/long delay in between the AWGs.

In the implementation of figure 1, the delay between the different frequency components (for the optical pulses 3 in the transmitter and output signals 7 in the receiver 5) is carried out by arrays of cascaded fiber Bragg gratings 25, 26 (FBGs), with each grating tuned at one of the different frequency component of the optical comb. Using an optical circulator 27, the initial pump light 12 is sent into a first array 25 of three 7 cm-long FBGs 25a, 25b, 25c, having central wavelength at 1551.1 nm (at room temperature), transmission band of 33 pm full-width at half-maximum (FWHM), high reflectivity (nearly 99%), and positioned every 5 m. The distance between FBGs defines the delay between the multiple pulses 3, as well as between the output signals 7 to be detected. Each FBG 25a, 25b, 25c has been mounted on a distinct translation stage for a selective fine tuning on the N=3 distinct frequencies delivered by the first MZM 20. Thus, by simply adjusting the FBGs 25, three pulses 3 separated spectrally by 17 GHz and temporally by 50 ns are obtained in this case.

The three pulses 3 and the components of the probe 17 are launched into the sensing fiber 1, which in this example corresponds to a 50 km-long standard single-mode fiber (SMF).

Figure 2 illustrates the frequency allocation of probe signal 17 (also called probe wave, corresponding to frequencies f'_1, f'_2, f'_3, f'_4) and pump signals 3 (also called replica signals, each replica signal corresponding to one frequency among f_1, f_2, f_3, f_4) in the proposed BOTDA scheme of the first embodiment of device 15 according to the invention. The straight lines represent the frequency components of each pump, and the dashed lines represent the counter-propagating probe components.

This implementation can be equally applied to a configuration using a pair of probe components respectively f'_1 and f''_1, f'_2 and f''_2, f'_3 and f''_3 , or f'_4 and f''_4 symmetrically positioned around each pump frequency respectively f_1, f_2, f_3, or f_4, as shown in Figures 3 to 6. This configuration massively decreases the biasing effect due to pump depletion, as a result of an equal and simultaneous gain and loss interaction, and is normally preferred in practical systems. This frequent particular case will be addressed in the rest of the description.

Additionally, considering that the Brillouin interaction between each of the N pump-probe pairs remains independent from each other, the power allowed in the fiber 1 can also be safely multiplied by a factor N, while each line is still limited at 5 mW. However, it is important to notice that the delay between the N pulses 3 is expected to generate independent and delayed BOTDA traces. The output signals 7 containing the Brillouin gain information have therefore to be properly rearranged in time domain before photo-detection by applying a delay opposite to the one originally set to the corresponding pump pulse 3. Actually this temporal realignment of the N BOTDA traces (carried by the probe components) is essential to avoid ruining the spatial resolution of the sensor. In other words, for BOTDA, the time delay is applied on the pump frequencies f_1, f_2, f_3, f_4 ... whilst the inverse time delay is applied on the resulting interactions which are at the probe frequencies f'_1, f'_2, f'_3, f'_4 ... or f''_1, f''_2, f''_3, f''_4 ...

As illustrated in figures 3 to 5, pump and probe components can be allocated in the spectral domain following different configurations. Figures 3 to 5 shows three possibilities:

1. The first case, depicted in Figure 3, shows a case where the spectral separation Δf of the N replicas is at least larger than twice the Brillouin frequency $\Delta\nu_B$ of the fiber 1 ; i.e. $\Delta f > 2\Delta\nu_B$ (being $\Delta\nu_B \approx$10-11 GHz for standard single-mode fibers at telecommunication wavelength around 1550nm), ensuring that no spectral lines are overlapping and interactions generated by distinct pump lines are not competing on the same probe line.

2. The second case is shown in Figure 4, in which the pump-probe pairs are interleaved, so that the frequency separation Δf fulfils the condition $\Delta\nu_B < \Delta f < 2\Delta\nu_B$. This solution is more spectrally efficient than the previous one;

however, it might require narrower optical filtering at the receiver 5. Thus the spectral separation Δf of the N components is larger than a Brillouin frequency $\Delta\nu_B$ of the fiber but smaller than twice the Brillouin frequency $\Delta\nu_B$ of the fiber.

3. Finally, Figure 5 shows a third configuration in which the frequency separation Δf is lower than the Brillouin frequency $\Delta\nu_B$; i.e. $\Delta f < \Delta\nu_B$. Although this configuration could be easier to implement since it requires lower frequencies, the scheme may be practically difficult to implement if optical filters are used to separate and to delay the different N replicas 3. It may certainly require more sophisticated filtering techniques based for instance on coherent detection followed by electrical filtering.

It is worth mentioning that the invention can also be combined with optical pulse coding methods and Raman amplification for a higher performance improvement. On the one hand, the coding method makes use of time-limited signals, corresponding to sequences of optical pulses 3 arranged in particular distributions given by the code. Therefore, the invention can be straightforwardly applied to this kind of signals, so that each code sequences can be generated at N different frequencies. This leads to a multi-frequency coded pump signal that interacts with a multi-frequency probe signal, generating N time-shifted coded BOTDA traces that have to be properly time-shifted to regenerate the useful Brillouin trace 9. On the other hand, the multi-frequency pump and probe signals can be amplified along the sensing fiber by distributed Raman amplification, similarly to standard Raman-assisted BOTDA sensors.

At the receiver 5, the multi-frequency probe wave is first amplified by an EDFA 28, and then sent into a second array 26 of FBGs. This is depicted in Figure 1, which shows the three probe frequency components (denoted as f’1, f’2 and f’3) containing the time-shifted traces 7 resulting from the Brillouin pump-probe interaction (gain mode) along the sensing fiber 1. Note that the three other probe frequency components (denoted as f”1, f”2 and f”3) containing the time-shifted traces 7 resulting from the Brillouin pump-probe interaction (loss mode) along the sensing fiber 1 could be used alternatively. The frequency selective time recombiner 8 corresponds to the second array 26 of FBGs, in which each FBG 26a, 26b, 26c, is properly tuned at f’1, f’2 or f’3 in order to apply a selective reverse delay to the output signals 7, so that the time differences resulting from the delayed pump pulses 3 are compensated. This way the BOTDA traces 7 (or output signals 7) are automatically properly rearranged to obtain the equivalent trace 9 (or useful signal 9) corresponding to the interaction of the summed pulses 3. In addition to the delay provided by this second array 26 of FBGs, each FBG also filters out unwanted frequency components as well as the amplified spontaneous emission (ASE) noise originated by the EDFA 28. The signal is detected by a photo-detector 30 (in this case with a bandwidth of 125 MHz), and then measured with an acquisition system connected to a computer 31. The invention can be implemented as well by placing the arrays 25, 26 of FBGs before their respective EDFA 23, 28, but the FBGs cannot filter ASE in this case, which must be performed by a specific filtering device if needed.

To experimentally validate the invention, BOTDA traces at the peak gain frequency have been acquired for both N=3 (the invention) and N=1 (prior art case). The peak power of the pump pulses 3 has been adjusted to the maximum of 100 mW per pulse 3 to avoid modulation instability; so that the total pump power is 300 mW for N=3. The three pulses 3 are properly ordered in time and frequency to avoid unwanted nonlinearities, as above described. Figure 7 compares the signal SNR of the BOTDA traces for both cases, indicating that the use of 3 frequency components increases the signal-to-noise ratio by 4.8 dB. Using the prior art scheme (N=1) with a 2 m spatial resolution and 2000 time-averaged traces, a SNR equal to 6.1 dB is experimentally observed at the fiber far end. However, using N=3 components, the SNR has been improved up to 10.9 dB. Expectedly much higher SNR enhancement will be reached if the number of frequency components N is increased.

It is worth noticing that no distortion (potentially originated from unwanted nonlinear effects) is observed in BOTDA traces measured with N=3, even though high pump power (300 mW) is launched into the fiber 1. Actually the delay between pulses 3 at different frequencies plays a crucial role in the method: if the three 100 mW pulses at distinct frequencies are simultaneously sent into the fiber, the parametric interaction among the spectral components leads to distorted traces.

Figure 8 actually compares the SNR of the BOTDA traces obtained with and without delays between pulses 3. Interestingly, the same SNR enhancement is observed in both cases at the fiber input (due to the same input pump power); however, when no delay is applied, unwanted nonlinearities resulting from parametric interaction among pulses produce strong oscillations in the effective pump power, and hence in the measured Brillouin gain. These oscillations are eliminated using the wavelength-dependent delays, leading to a trace with no distortion. This demonstrates that the delay of the multiple replicas 3 of the pump pulse 12 is essential to avoid unwanted nonlinearities resulting from the interaction of pulses 3 eventually overlapping inside the fiber 1. It has also been experimentally demonstrated that the proposed method does not increase the amount of pump depletion, even though higher probe power is used. In this case pump depletion has been measured to be below 4%, resulting in negligible additional distortion in the traces.

When the frequency difference f_i-f'_i (with i an integer between 1 and N) between one of the pump signals 3 and one component of the probe signal 17 corresponds to the Brillouin frequency shift of the fiber 1, an energy transfer takes place from this pump signal 3 to this component of the probe signal 17. It is seen as an amplification of the intensity of the probe signal 17. The Brillouin gain corresponds to the total magnitude of the amplification of the probe signal 17. The Brillouin gain is normally given in % and the Brillouin gain profile corresponds to the Brillouin gain value at each measured position along the sensing fiber.

The Brillouin Frequency Shift corresponds to the frequency difference f_i-f'_i (between each couple of interacting pump signal 3 and component of the probe signal 17) that produces the maximum Brillouin Gain or larger amplification of the probe signal 17. The Brillouin Frequency profile corresponds to the Brillouin Frequency value at each measured position along the sensing fiber. In the particular case of figure 1, it is easy to set f_i-f'_i equal to a common value for all the i comprised between 1 and N.

The Time Domain Analysis is used to measure the Brillouin gain as a function of the distance for each frequency difference f_i-f'_i, so that after scanning the frequency difference f_i-f'_i within a range of several hundred MHz, the Brillouin gain spectrum can be obtained at each fiber location. Analyzing the measured spectrum at each fiber position, the local Brillouin frequency can be retrieved from the peak gain frequency. Time Domain Analysis allows to locate the measurement along the sensing fiber 1. Alternatively, the Brillouin gain as a function of the distance for each frequency difference f_i-f'_i can be obtained by Frequency Domain Analysis. The Brillouin gain spectrum obtained by Frequency Domain Analysis can be then processed, similarly to the OTDA system, to retrieve the local Brillouin frequency at each fiber location.

Due to the pulsed nature of each pump signal 3, the pump/probe interaction takes place at different location along the fiber 1 at different times. For any given location, the portion of probe signal 17 which interacted with a pump signal 3 arrives on the detector 30 after a time delay equal to twice the travelling time from the fiber input 4 to the specified location. Thus, monitoring the backscattered intensity with respect to time, while knowing the speed of light in the fiber 1, provides information on the position (or "distance") where the scattering/interaction took place. The recording of an output signal 7 as a function of time at a given frequency difference f_i-f'_i is referred to as Trace or Temporal Trace.

The Temporal Trace provides the Brillouin Gain value at every distance point along the fiber 1 recorded at a given frequency difference f_i-f'_i. The time to distance conversion takes into account the index of refraction of the fiber and cable structure (fiber overlength, cable layloss).

Although described here based on the Brillouin gain mode (namely the f_i-f'_i interaction) the same description applies to Brillouin loss mode corresponding to the f''_I-f_i interaction.

Figure 9 shows the Brillouin gain spectrum versus distance and versus the frequency difference f_i-f'_i typically obtained in BOTDA sensing, measured using 1 MHz frequency difference step and N=3 spectral components. For varying the frequency difference f_i-f'_i, the frequencies f'_i and f''_i of the components of the probe 17 are varied while the frequencies f_i of the pump signals 3 are fixed. Figure 9 is plotted:

- by varying the frequency difference f_i-f'_i (X axis of figure 9) and,

- for each set of N output signals 7 as a function of time obtained for a given frequency difference f_i-f'_i , by constructing the useful signal 9 (from which the gain is calculated an reported on Z axis of figure 9) as a function of "time" and thus as a function of the distance in the fiber 1 (Y axis of figure 9), i.e. by combining these N output signals 7 in order to represent them on a common "temporal" axis (corresponding to the distance axis Y of figure 9) without temporal shift between them.

Thus, fitting the spectrum with a parabolic curve or by any other fitting means, the Brillouin frequency profile is obtained, as shown in Figure 9 inset. Calculating the standard deviation of the measured Brillouin frequency along the fiber 1, the final uncertainty of the sensor can be estimated for the prior art BOTDA configuration (N=1) and for the scheme according to the invention using N=3 spectral components.

Figure 10 shows the frequency uncertainty (one standard deviation) versus distance for both cases, indicating that the uncertainty of 1.8 MHz - obtained with the prior art scheme (N=1) at a distance of 50 km - can be improved down to 0.6 MHz using the proposed method according to the invention with N=3. This corresponds to a factor 3 in the uncertainty reduction, in perfect agreement with the prediction of a 4.8 dB SNR enhancement.

The temperature/strain information is coded in the Brillouin frequency shift. Scanning the frequency difference f_i-f'_i while monitoring the intensity of the useful signal 9 as a function of "time" (or distance inside the fiber 1) allows one to find a Brillouin gain peak, and thus:

- the corresponding Brillouin frequency shift, from which the value of the temperature stress or the strain stress applied on fiber 1 can be computed, and

- the position or distance of this stress in the fiber 1.

The spatial resolution of the method has been experimentally verified. For this purpose, 2 m of the sensing fiber 1 close to the most distant end 18 have been heated up to 50°C, while the rest of the fiber 1 is kept at room temperature (24°C). This is actually a crucial test for this method, considering the pulses de-synchronisation followed by the re-synchronisation of the traces. Possible imprecisions in the reverse delays delivered by the second FBGs array will certainly jam the spatial information. Figure 11 shows the hot-spot detection measured near a 50 km distance using the proposed technique with N=3 frequencies. Experimental results indicate a correct determination of the temperature within the hot region and no penalty on the 2.0 m spatial resolution is observed with the 20 ns de-synchronised pump pulses.

As demonstrated, the proposed method increases both pump and probe powers by a factor N, and therefore the signal-to-noise ratio of the measurements is improved by the same proportion. This provides higher sensing response, which translates into longer sensing distances, better spatial resolution, lower measurement time and/or better measurand accuracy.

The onset of unwanted nonlinear effects is not only limiting the performance BOTDA systems. Any other kind of distributed optical fiber sensor is affected by the same limitation. One fundamental difference between BOTDA and other distributed optical fiber sensors is that BOTDA systems require the interaction between two counter-propagating optical signals, while other schemes are typically based on reflectometry, i.e. the signal to be measured corresponds to the backscattered light that is generated directly from the pump pulse propagating along the optical fiber; and therefore the system typically does not need a counter-propagating probe signal, as in BOTDA schemes. This means that a high-power pulse is launched into the fiber 1, similarly to BOTDA, and then the light backscattered along the fiber is measured at the receiver. We are now going to describe, in reference to figure 13, a second embodiment of a device 32 and a process according to the invention for reflectometry.

This second embodiment will be only described for its differences compared to the previously described first embodiment.

Device 32 comprises means 19 for detecting the useful signal 9, arranged for (and in the second embodiment of process according to the invention, useful signal 9 is detected for):

- Optical Time Domain Reflectometry, preferably for Coherent Optical Time Domain Reflectometry or Phase-Sensitive Optical Time Domain Reflectometry or Brillouin Optical Time Domain Reflectometry, or
- Optical Frequency Domain Reflectometry, preferably for Coherent Rayleigh Optical Frequency Domain Reflectometry, Phase-Sensitive Optical Frequency Domain Reflectometry or Brillouin Optical Frequency Domain Reflectometry.

Under this kind of schemes of the second embodiment, the invention only requires the generation of multiple delayed replicas 3 of the pump pulse 12 at different frequencies f_1 to f_N, as described in Figure 1, but without the need of creating a probe signal. When this multi-frequency pump signals 3 are launched into the fiber 1, scattering processes, such as Rayleigh, Raman or Brillouin scattering, which are required for sensing, can be measured at the receiver 5. Before photo-detection, each spectral component of the multi-frequency backscattered light resulting from the multi-frequency pump has to be properly time-shifted by applying a delay opposite to the one originally set to the corresponding pulse components, as described by Figure 2.

Under this kind of schemes of the second embodiment, each output signal 7 (respectively at frequency f'_1 to f'_N) is a signal generated in the fiber 1 by scattering or backscattering resulting from the propagation of one of the replica signals 3 and/or a signal generated in the fiber by a linear or nonlinear optical effect resulting from the propagation of one of the replica signals 3, typically a Raman backscattering signal or a Brillouin backscattering signal or a Rayleigh backscattering signal.

Note that the scheme is well adapted to spontaneous Brillouin scattering (BOTDR) and Rayleigh backscattering (especially for coherent Rayleigh (COTDR) that are based on narrow linewidth laser).

The scheme can also be applied to frequency scanned pumped as in Brillouin optical frequency domain reflectometer (BOFDR), provided that within the frequency scan, the backscattered frequency components do not overlap.

This way, this invention gives the possibility to increase the total pump power in a factor equal to the number of frequency components N used to replicate the original pump pulse 12. In consequence, the total backscattered power is also increased by a factor N, resulting in an increase of the sensor response and signal-to-noise ratio.

In the particular case of Rayleigh, we have:

$f_i = f'_i$ with i an integer comprised between 1 and N

In other case (Brillouin, Raman), we have:

$f_i \neq f'_q$ with i an integer comprised between 1 and N, with q an integer comprised between 1 and N.

We are now going to describe, in reference to figure 14, a third embodiment of a device 33 and a process according to the invention for the simple delivery of a time-limited signal, only for its differences compared to the first embodiment.

It has to be mentioned that the invention is not strictly limited to the examples of implementation described here above in the field of distributed optical fiber sensing, but it can be implemented in any type of system requiring to deliver a high power time-limited signal along an optical fiber. A general implementation is shown in Figure 14, in which an initial time-limited optical signal 12 is generated at different optical frequencies f_1 to f_N , each replica 3 being delayed by a time longer than the duration of signal 12 (equal to the duration of each signal 3). The signal 12 to be transmitted can have any kind of shape, and the only requirement is that replicas 3 preferably do not overlap with each other in time, thus avoiding unwanted nonlinear interaction among them during propagation along the fiber. The delay of the multiple replicas can be implemented using optical dispersive elements, optical delay lines, optical mirror or grating, among many other possible techniques.

Since each spectral replica 3 has to carry a low enough power to avoid activating any unwanted nonlinear effects in the fiber 1, no distortion in the signal shape is expected after propagation. At the stage of the receiver 5, the N different signal frequency components f'_1 to f'_N (corresponding to the N time shifted output signals 7) have to be properly time-reordered before photo-detection by applying a delay opposite to the one originally set to the corresponding signal components. Each output signal 7 comprises (and consist of) one of the replica signals 3. We have in this case: $f_i=f'_i$ with i an integer comprised between 1 and N. This signal reconstruction has to be implemented optically, employing for instance the same method used in the transmitter to delay the replicas of the time-limited optical signal. The multiple replicas 3 at different frequencies can be directly launched into a photo-detector, which generates an electrical signal N times larger than the expected one from the independent detection of each frequency component. The bandwidth of the photo-detector is lower than the spectral separation of the replicas 3; this avoids beat notes at high frequency between signals that might distort the useful electrical signal.

The first input 4 and the output 6 correspond to two opposite ends of the fiber 1.

Of course, the invention is not limited to the examples which have just been described and numerous amendments can be made to these examples without exceeding the scope of the invention.

The initial multi-frequency time-limited signal 12 can be created from:

- A single wavelength source (such a monochromatic laser), and the original single-wavelength optical signal from this source is copied into different frequencies. This copy can be carried out by light (intensity or phase) modulation or by the activation of a nonlinear effect. This copy can be done simultaneously to or after the time shifting, preferably simultaneously in order to obtain directly the time shifted replicas 3.
- A multi-wavelength source. The multi-wavelength optical source can be obtained directly from a multi-wavelength laser. The multi-wavelength optical source can be generated by any method that produces an optical frequency combination, such as a combination of a plurality of single wavelength sources.

The replicas 3 can be created from a combination of a plurality of single wavelength sources emitting signals that can be time shifted before or simultaneously or after the combination.

The time shifting of the replicas 3 can be carried out using one of the following methods, among others:

a. one possibility to implement the delay between replicas to be transmitted and/or between signals 7 to be detected is to use optical dispersive elements.

b. another alternative to implement the delay is to use wavelength-dependent optical delay lines, obtained from single elements performing this function, or from a spectral demultiplexing of the optical signal into distinct optical channels showing different propagation times followed by a recombination, or generated by the interaction with some nonlinear effect.

c. another alternative to implement the delay is to use arrays of mirrors or gratings, such as fiber Bragg gratings.

d. the time delay or time shift between the replicas 3 can be achieved in the optical domain and/or in the electrical domain.

The time shifted replicas 3 do not need to be evenly spaced in time. Actually, unequal spacing could be preferred if a sensing fiber with low dispersion is used; this way the efficiency of unwanted nonlinear effects such as four-wave mixing can be reduced.

The replicas do not need to have the same amplitude or maximum intensity. However, uniform amplitude might be beneficial to optimize pump and probe powers, but this is not an essential requirement for the invention.

The signal replicas 3 at different frequencies can have the same or different polarization state.

It is not strictly required that the spectral lines f_i are evenly separated, even though it may ease the design and the practical implementation.

The reconstruction of the useful signal 9 from the output signals 7 can be performed by:

e. any of the optical delay methods described in above points a. to d. followed by direct or heterodyne detection. This also includes the possibility to use balanced detector.

f. heterodyne optical detection combined with electrical filtering, and followed by the electrical delay of each frequency component containing the useful information.

g. each spectral component can be split in different optical channels using optical filters or demutiplexing methods. Then each optical signal can be independently detected by several photo-detectors.

h. each signal 7 can be time-shifted in the optical domain (before photo-detection) or in the electrical domain (after photo-detection). Then, the useful electrical signal 9 can be obtained by simply combining the multiple electrical signals resulting from photo-detection.

In a variant the first embodiment of figure 1, in each couple of frequency f'_i f''_i (i an integer between 1 and N), f'_i can be superior to f''_i instead of what is illustrated in figures 1 and 3 to 6.

A variant of the first embodiment of figure 1 could be used for Raman backscattering or Rayleigh backscattering instead of Brillouin backscattering.

In a variant of the first embodiment of figure 1, the second input of fiber 1 is not distinct from the first input of fiber 1: this is the case of a single end BOTDA, with all signals 3 and 17 injected in the same end of fiber 1 and with a reflector (for example any mirror) at the other end of the fiber 1.

In a variant of the first embodiment of figure 1, the probe wave 17 and the replica signals 3 are generated from distinct sources.

Of course, the different characteristics, forms, variants and embodiments of the invention can be combined with each other in various combinations to the extent that they are not incompatible or mutually exclusive. In particular all variants and embodiments described above can be combined with each other.

CLAIMS

1. Process comprising the following steps:
- injecting N replica signals (3), at a first input (4) of an optical fiber (1), each replica signal (3) being a time-limited optical signal, N being an integer greater than or equal to 2, each replica (3) signal having an intensity maximum at a given optical frequency distinct from a given optical frequency of an intensity maximum of each other replica signal, each replica signal (3) being temporally shifted relative to the other replica signals, then
- propagating the temporally shifted replica signals (3) along the optical fiber (1), then
- receiving, at an output (6) of the optical fiber (1), N output time-limited optical signals (7), each output signal (7) resulting from one of the replica signals (3), each output signal (7) having an intensity maximum at a given optical frequency distinct from a given optical frequency of an intensity maximum of each other output signal, each output signal (7) being temporally shifted relative to the other output signals, then
- constructing a useful signal (9) by temporally superimposing the N output signals (7), such that the useful signal comprises a combination of the N output signals that are not temporally shifted anymore.

2. Process according to the previous claim, characterized in that the N replica signals (3) are emitted by temporally and/or spectrally fractioning an initial time-limited optical signal (12) into the N replica signals, each replica signal (3) having an intensity maximum lower than or equal to an intensity maximum (12) of the initial time-limited optical signal.

3. Process according to the any one of the previous claims, characterized in that the temporal superposition, for the construction of the useful signal (9), is optically obtained, not electronically.

4. Process according to the any one of the previous claims, characterized in that each output signal (7) comprises one of the replica signals (3).

5. Process according to the any one of the previous claims, characterized in that each output signal (7) comprises a signal generated in the fiber by scattering or backscattering resulting from one of the replica signals.

6. Process according to the any one of the previous claims, characterized in that each output signal (7) comprises a signal generated in the fiber by a linear or nonlinear optical effect resulting from of one of the replica signals.

7. Process according to claim 5 or 6, characterized in that each output signal (7) is a signal generated in the fiber by scattering or backscattering resulting from the propagation of one of the replica signals (3) and/or a signal generated in the fiber by a linear or nonlinear optical effect resulting from the propagation of one of the replica signals (3).

8. Process according to claim 7, characterized in that the useful signal (9) is detected for:

- Optical Time Domain Reflectometry, preferably for Coherent Optical Time Domain Reflectometry or Phase-Sensitive Optical Time Domain Reflectometry or Brillouin Optical Time Domain Reflectometry, or
- Optical Frequency Domain Reflectometry, preferably for Coherent Rayleigh Optical Frequency Domain Reflectometry, Phase-Sensitive Optical Frequency Domain Reflectometry or Brillouin Optical Frequency Domain Reflectometry.

9. Process according to claim 5, or 6, or 7, characterized in that it further comprises injecting an optical multi-frequency probe wave (17) at a second input (18) of the optical fiber (1), the multi-frequency probe wave (17) comprising at least N components at a given optical frequency, the given optical frequency of each component being distinct from the given optical frequency of the other components, each output signal (7) resulting from the interaction, in the fiber (1), between a group of signals comprising at least one of the components of the optical multi-frequency probe wave (17) and at least one of the replica signals (3).

10. Process according to claim 9, characterized in that the spectral separation of the N components is larger than a Brillouin frequency of the fiber (1) but preferably smaller than twice the Brillouin frequency of the fiber (1).

11. Process according to the any one of claims 9 to 10, characterized in that the useful signal (9) is detected for optical-time domain analysis, preferably for Brillouin Optical Time Domain Analysis, or Optical Frequency Domain Analysis, preferably for Brillouin Optical Frequency Domain Analysis.

12. Process according to the any one of claims 9 to 11, characterized in that the optical multi-frequency probe wave (17) and the replica signals (3) are generated from a common source signal (29).

13. Process according to the any one of the previous claims, characterized in that N is an integer greater than or equal to 3.

14. Process according to the any one of the previous claims, characterized in that each considered replica signal (3) is temporally shifted relative to the other replica signals (3) by a time superior to the full temporal width at half Intensity maximum of this considered replica signal, preferably by a time superior to the duration of this considered replica signal.

15. Process according to the any one of previous claims 1 to 13, characterized in that each replica signal (3) is composed by a group of elementary optical signals (13), each replica signal being temporally shifted relative to the other replica signals but being also partially interleaved to at least one of the other replica signals, such that for a first replica signal and a second replica signal partially interleaved, each considered elementary signal of the first replica signal is temporally shifted relative to each elementary signal of the second replica signal by a time superior to the full temporal width at half Intensity maximum of this considered elementary signal, preferably by a time superior to the duration of this considered elementary signal.

16. Device comprising:

- an optical fiber (1),

- means (2) for injecting N replica signals (3), at a first input (4) of the optical fiber, each replica signal (3) being a time-limited optical signal, N being an integer greater than or equal to 2, each replica (3) signal having an intensity maximum at a given optical frequency distinct from a given optical frequency of an intensity maximum of the other replica signals, each replica signal (3) being temporally shifted relative to the other replica signals,
- means (5) for receiving, at an output (6) of the optical fiber, N output time-limited optical signals (7), each output signal (7) resulting from one of the replica signals (3), each output signal (7) having an intensity maximum at a given optical frequency distinct from a given optical frequency of an intensity maximum of the other output signals, each output signal (7) being temporally shifted relative to the other output signals,
- means (8) for constructing a useful signal (9) by temporally superimposing the N output signals (7), such that the useful signal comprises a combination of the N output signals that are not temporally shifted anymore.

17. Device according to the previous claim, characterized in that it comprises means (10) for emitting the N replica signals by temporally and/or spectrally fractioning an initial time-limited optical signal (12) into the N replica signals (3), each replica signal having an intensity maximum lower than or equal to an intensity maximum of the initial time-limited optical signal.

18. Device according to the any one of previous claims 16 to 17, characterized in that the means (8) for constructing the useful signal (9) by temporally superimposing the output signals are arranged for optically superimposing the outputs signals (7), not electronically.

19. Device according to any one of previous claims 16 to 18, characterized in that each output signal (7) comprises one of the replica signals (3).

20. Device according to any one of previous claims 16 to 18, characterized in that each output signal (7) is a signal generated in the fiber by scattering or backscattering resulting from the propagation of one of the replica signals (3) and/or a signal generated in the fiber by a linear or nonlinear optical effect resulting from the propagation of one of the replica signals (3).

21. Device according to any one of previous claims 16 to 18, characterized in that it further comprises means (16) for injecting an optical multi-frequency probe wave (17) at a second input (18) of the optical fiber, the multi-frequency probe wave comprising at least N components at a given optical frequency, the given optical frequency of each component being distinct from the given optical frequency of the other components, each output signal (7) resulting from the interaction between a group of signals comprising at least one of the components of the optical multi-frequency probe wave (17) and at least one of the replica signals (3).

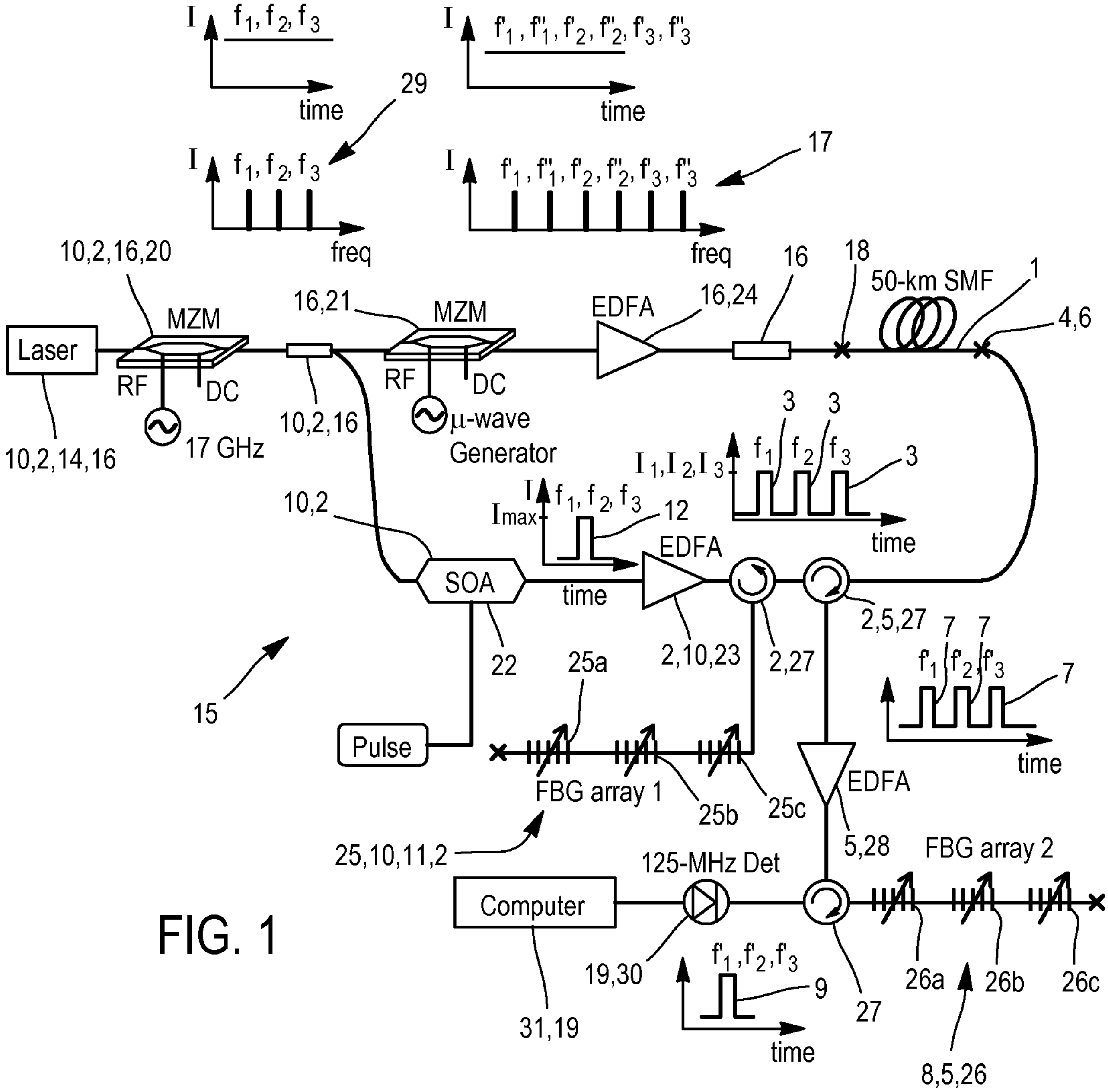

FIG. 1

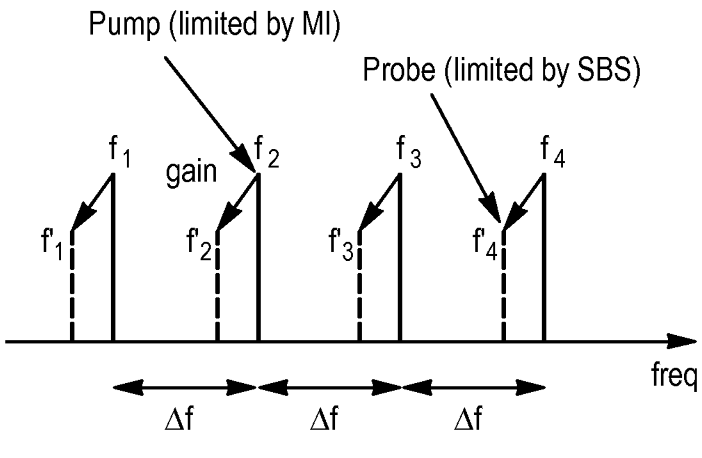

FIG. 2

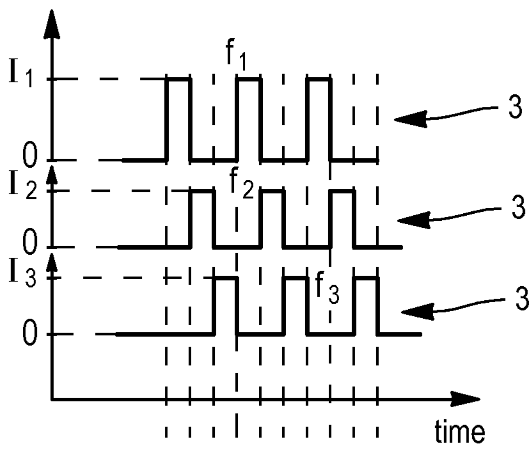

FIG. 12

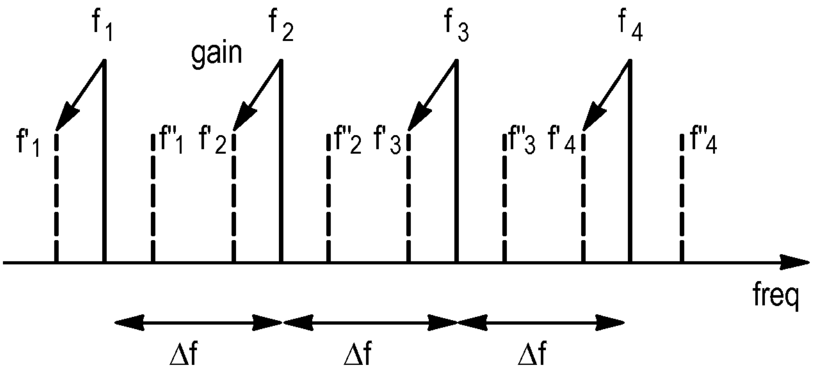

FIG. 3

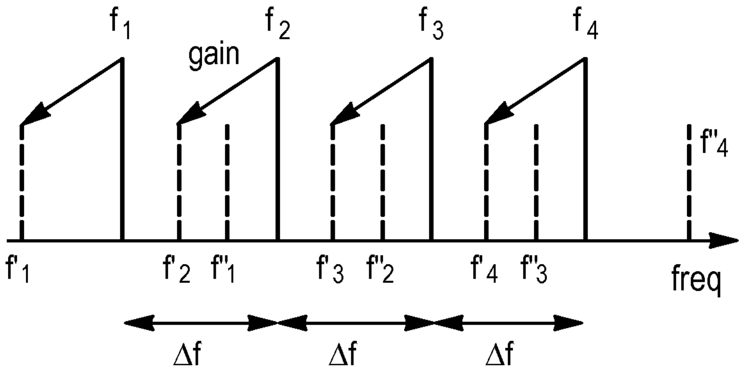

FIG. 4

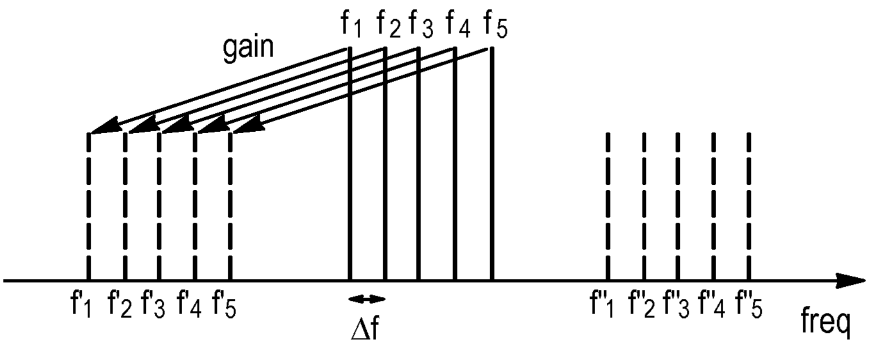

FIG. 5

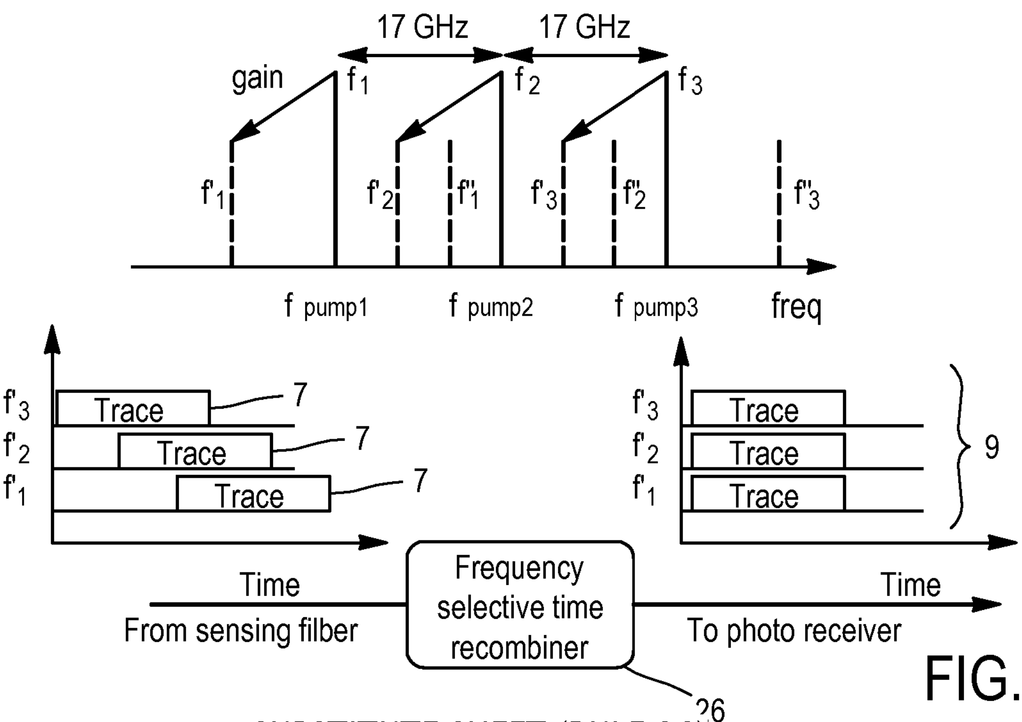

FIG. 6

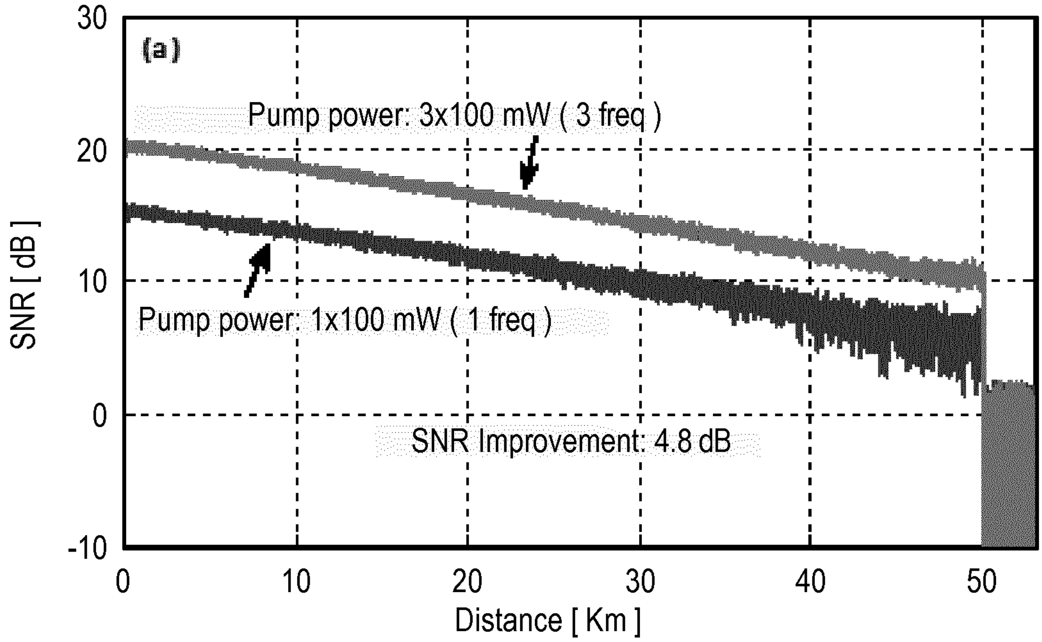

FIG. 7

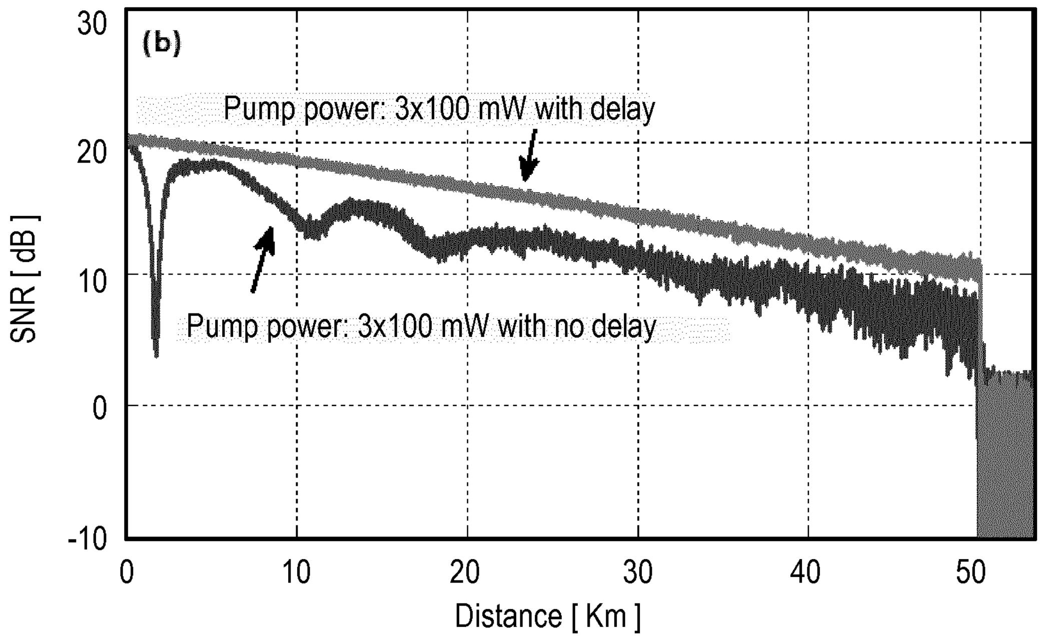

FIG. 8

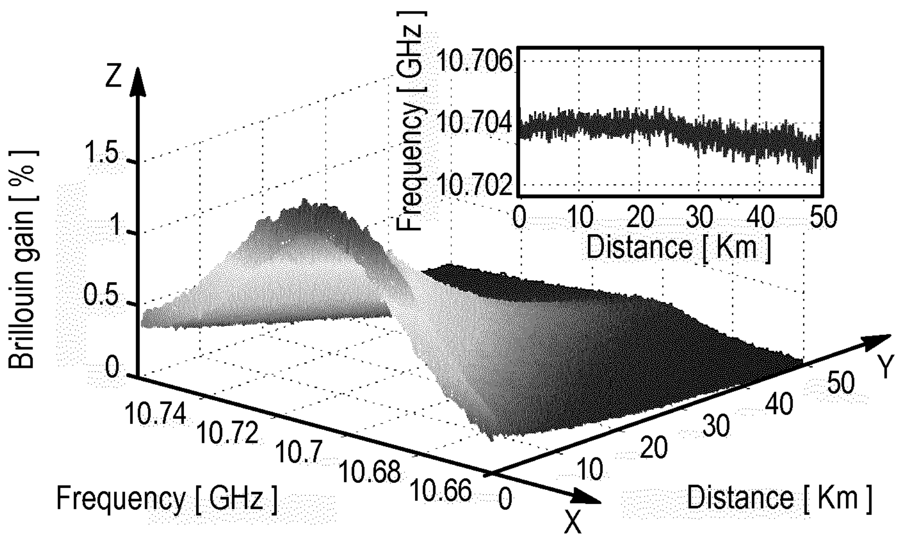

FIG. 9

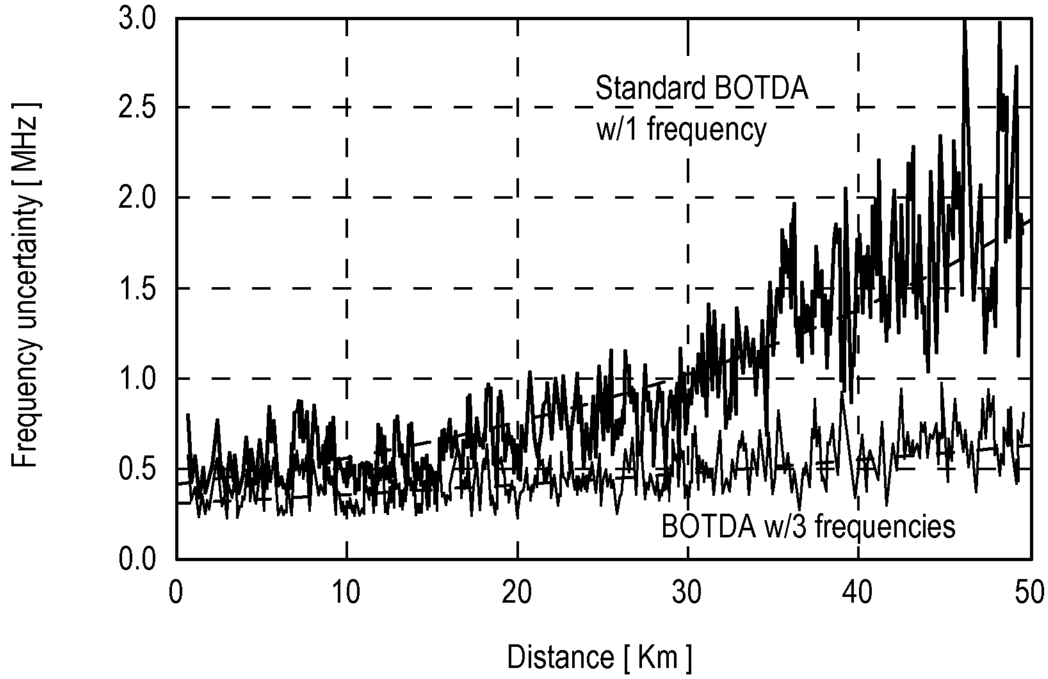
Frequency uncertainty [MHz]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
Distance [Km]
Standard BOTDA
w/1 frequency
BOTDA w/3 frequencies

FIG. 10

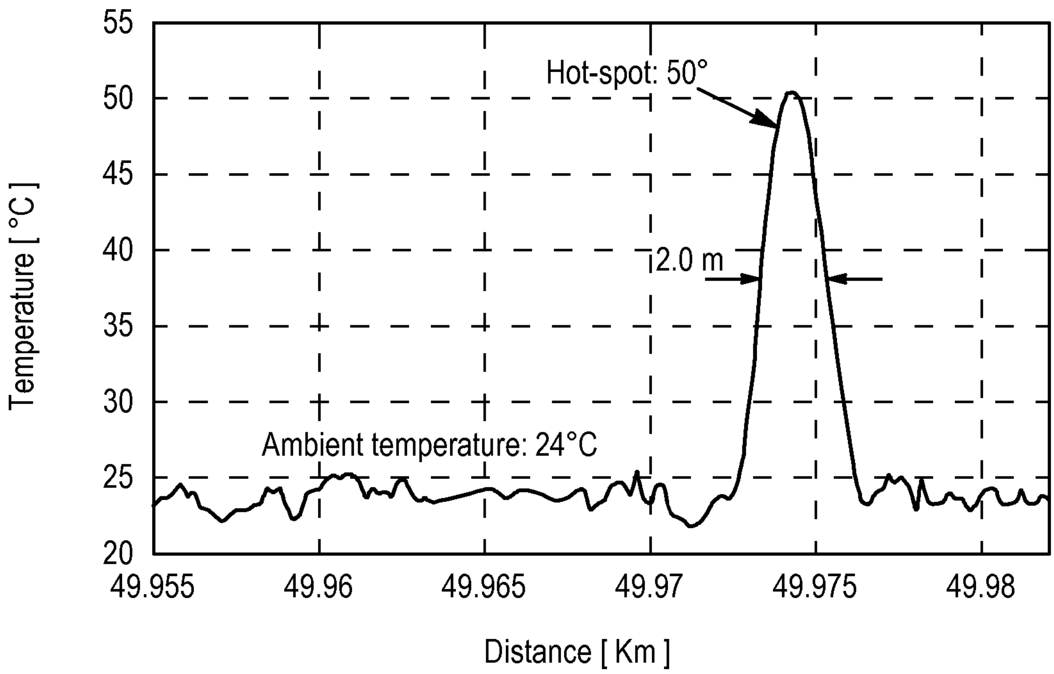
Temperature [°C]
55
50
45
40
35
30
25
20
49.955
49.96
49.965
49.97
49.975
49.98
Distance [Km]
Hot-spot: 50°
2.0 m
Ambient temperature: 24°C

FIG. 11

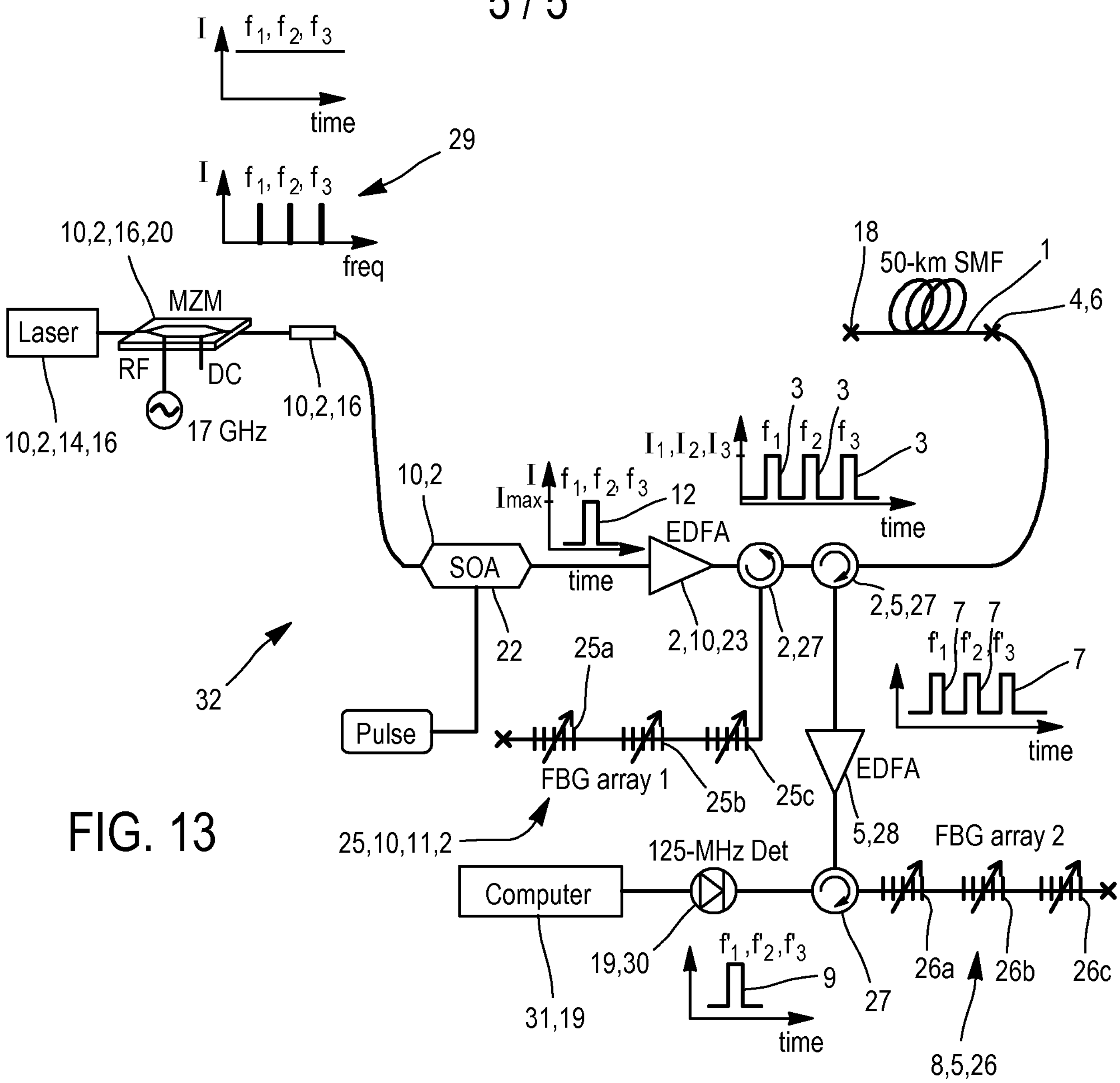
I
f1, f2, f3
time
29
freq
10,2,16,20
MZM
Laser
RF
DC
17 GHz
10,2,14,16
10,2,16
10,2
SOA
22
Pulse
Imax
12
EDFA
2,10,23
2,27
2,5,27
18
50-km SMF
1
4,6
I1, I2, I3
3
f'1, f'2, f'3
7
25a
25b
25c
FBG array 1
25,10,11,2
32
EDFA
5,28
FBG array 2
125-MHz Det
Computer
31,19
19,30
9
27
26a
26b
26c
8,5,26

FIG. 13

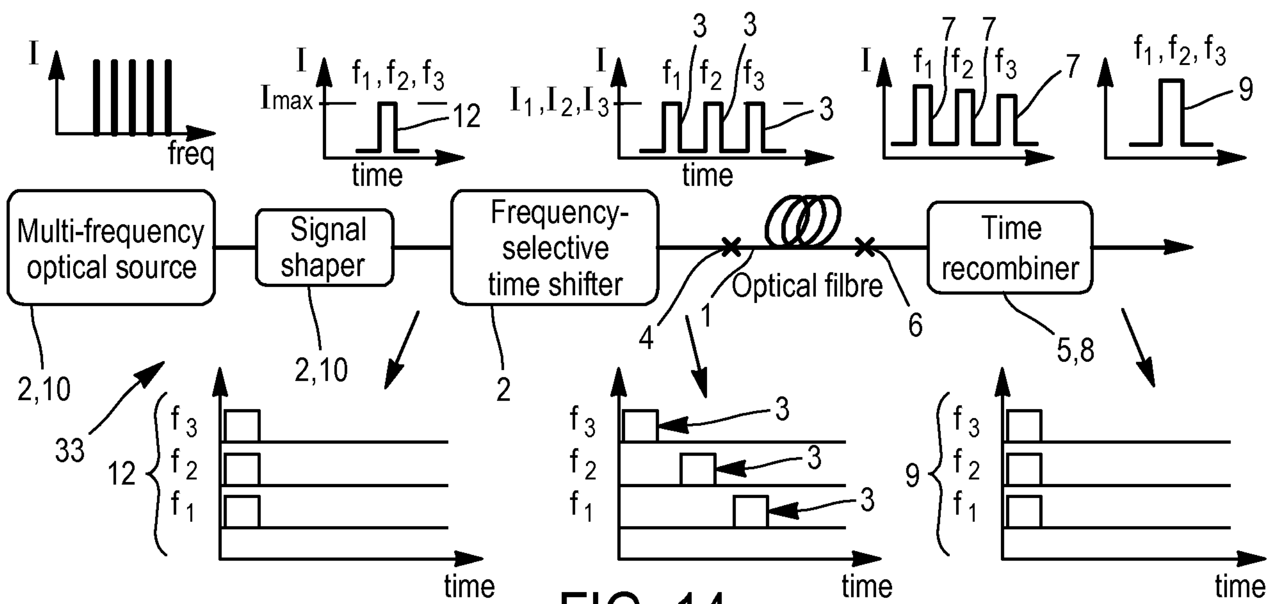
I
freq
Imax
f1, f2, f3
12
I1, I2, I3
3
7
9
time
Multi-frequency optical source
Signal shaper
Frequency-selective time shifter
Optical filbre
Time recombiner
2,10
2,10
2
4
1
6
5,8
33

FIG. 14

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2014/061247

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B10/071 H04B10/2543 H04B10/508
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)
H04B H04J

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	US 2009/087186 A1 (HOLMAN KEVIN W [US] ET AL) 2 April 2009 (2009-04-02) paragraphs [0008] - [0011]; figure 1	1-21
X	US 2003/058504 A1 (CHO PAK SHING [US] ET AL) 27 March 2003 (2003-03-27) paragraph [0103]; figure 8 paragraphs [0126], [0131]; figure 11	1-21
A	US 4 918 751 A (PESSOT MAURICE [US] ET AL) 17 April 1990 (1990-04-17) column 1, lines 10-23; figure 1 column 1, line 48 - column 3, line 55	1-21

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"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	Date of mailing of the international search report
19 March 2015	27/03/2015

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	De Vries, Jane

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International application No
PCT/EP2014/061247

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 892 516 A2 (NIPPON TELEGRAPH & TELEPHONE [JP] NIPPON TELEGRAPH ANDTELEPHONE [JP] N) 20 January 1999 (1999-01-20) column 1, lines 7-18 column 3, line 40 - column 5, line 5; figure 1	1-21
A	US 5 767 956 A (YOSHIDA HARUO [JP]) 16 June 1998 (1998-06-16) column 1, line 18 - column 6, line 27; figure 1	1-21
A	US 6 314 115 B1 (DELFYETT PETER J [US] ET AL) 6 November 2001 (2001-11-06) column 2, lines 30-57; figure 1	1,3,16, 18

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2014/061247

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