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(54) **Title**: INTERFEROMETER WITH FREQUENCY COMBS AND POSTERIORI CORRECTION SCHEME

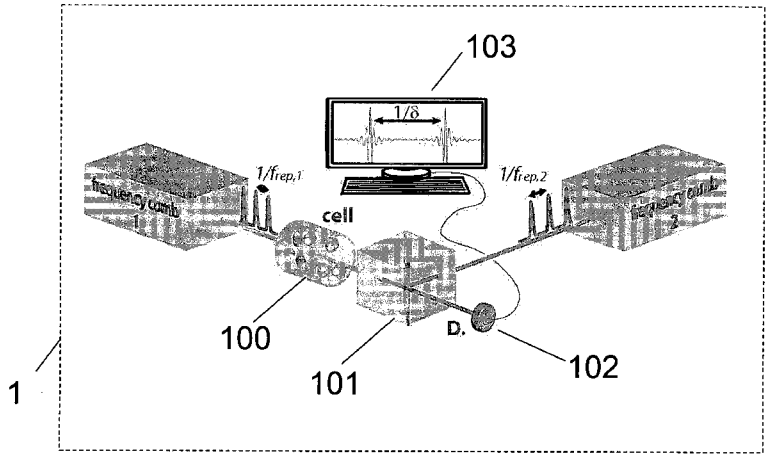


FIG. 1

(57) **Abstract**: The present invention relates to an interferometer comprising: 1) a first frequency comb 2) a second frequency comb adapted to interact with the first frequency comb in order to produce interferences. 3) means for isolating at least one beating signal between a subset of frequency components among the frequency components of the two combs. This subset of frequency components is preferably but not necessarily a single line of the first frequency comb and a single line of the second frequency comb. 4) means for monitoring at constant time intervals, simultaneously, at least this beating signal between a subset of frequency components among the frequency components of the two combs and the beating interference signal between the entire frequency components of the first and the second frequency combs.

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INTERFEROMETER WITH FREQUENCY COMBS AND A POSTERIORI CORRECTION SCHEME

REFERENCE TO RELATED APPLICATIONS

[0001]The present application claims the benefit of U.S Provisional Application No 61/083620 filed July 25th, 2008, the content of which is hereby incorporated by reference in its entirety into the present disclosure.

FIELD OF THE INVENTION

[0002]The invention relates to the field of interferometers. It is directed to an interferometer and to a method for measuring interferences in such an interferometer.

SUMMARY

[0003] The present invention is more particularly directed to an interferometer comprising:

1) a first frequency comb

2) a second frequency comb adapted to interact with the first frequency comb in order to produce interferences.

3) means for isolating at least one beating signal between a subset of frequency components among the frequency components of the two combs. This subset of frequency components is preferably but not necessarily a single line of the first frequency comb and a single line of the second frequency comb.

4) means for monitoring at constant time intervals, simultaneously, at least this beating signal between a subset of frequency components among the frequency components of the two combs and the beating interference signal between the entire frequency components of the first and the second frequency combs.

The invention therefore provides an improved interferometer with an internal sampling base scheme based on the monitoring of the fringes variation versus time. The a posteriori correction method described herein is based on the determination of the beating frequency for a narrowband part of the two combs and the use of its knowledge to provide a corrected sampling grid of the interferometric

signal with a new grid, at constant fringe intervals, independently of the combs instabilities versus time. The invention is based on the idea that if at least one sinusoidal interference signal generated from isolated comb lines of the first and second frequency combs is measured simultaneously with the full interferometric signal between the two combs, it is possible to reconstruct a posteriori the right sampling of the interferometric signal even if the positions of at least one of the frequency combs are fluctuating as a function of time.

[0005] According to a second aspect of the invention, there is provided an interferometric method for analyzing a sample having spectroscopic absorption and dispersion signatures. The interferometric method comprises:

1) a first frequency comb which probes the sample under study

2) a second frequency comb adapted to interact with the first frequency comb in order to produce interferences. This second comb may or may not be probing the sample.

3) means for isolating at least one beating signal between a subset of frequency components among the frequency components of the two combs. This subset of frequency components is preferably but not necessarily a single line of the first frequency comb and a single line of the second frequency comb.

4) means for monitoring at constant time intervals, simultaneously at least this beating signal between a subset of frequency components among the frequency components of the two combs and the beating interference signal between the entire frequency components of the first and the second frequency combs.

DESCRIPTION OF RELATED ARTS

[0006] An optical Frequency Comb (FC) is an optical spectrum, which consists of phase-coherent equidistant laser lines. Frequency combs are well known in the art, for example from the patents "Generation of stabilized, ultra-short light pulses and the use thereof for synthesizing optical frequencies" R. Holzwarth, J. Reichert, T. Udem, T.W. Hänsch, US patent 6785303, 2004 or "Method and device for producing radio frequency waves", R. Holzwarth, T. Udem, T.W. Hänsch, US patent 7026594, 2006 or the publication "Optical frequency metrology" T. Udem, R. Holzwarth, T.W. Hänsch *Nature* **416,** 233 (2002) and are most often used in frequency metrology.

[0007] Interferometers based on two frequency combs are also well known in the art, for example from the publications "Time-Domain mid-infrared frequency comb spectrometer", Keilmann et al, *Opt. Lett.* **29**, 1542-1544 (2004), or "Spectrometry with frequency combs", Schiller,S. *Opt. Lett.* **27**, 766-768 (2002). In these systems, the time-domain interference pattern between the two similar frequency combs with slightly different repetition rates is recorded. The key is to make a down conversion of the optical frequencies characterizing the spectrum of interest so to allow practical measurements. A single detector may be used to record, generally as a function of time, the data called interferogram. This interferogram may be Fourier transformed for spectroscopic purposes. As this interferometer does not involve moving parts, it may lead to very fast acquisition times.

[0008] If the first comb is expressed as:

$$f_{01} + n.\ f_{rep1}$$

and the second comb is expressed as:

$$f_{02} + n.\ f_{rep2}$$

with f_{01} and f_{02} being the respective offsets of the first and second frequency combs and f_{rep1} and f_{rep2} the respective repetition rates of the first and second frequency combs and n an integer typically ranging between 10^5 and 10^6, their beating signal is as follows:

$$I(t) = \sum_n A_n \cos((f_{01} - f_{02} + n(f_{rep1} - f_{rep2}))t)$$

and only depends on the differences between combs repetition rates and offsets, which are required to be constant at the time scale of a recording sequence.

[0009] The optical frequency down conversion is obtained from the interference between two similar FC. The two combs are named hereafter by FC1 and FC2. They have slightly different repetition rate frequencies f_{rep1} and f_{rep2} related to each other by

$$f_{rep1} = f_{rep2} (1 + a) ; 0 < a << 1$$

The beating difference frequency b_n between the respective comb components $f_{1,n}$ and $f_{2,n}$, is given by

$$b_n = f_{1,n} - f_{2,n} = a\, n\, f_{rep2} + (f_{01} - f_{02})$$

which shows that *a* is the down conversion factor. In other words, the beat notes between pairs of lines from the two combs, which occur typically in the radio-frequency domain, provide a down-converted image of the optical spectrum. To avoid aliasing, *a* must be chosen such as $a < f_{rep2}/2$. This is however more than three orders of magnitude higher than the down-conversion factors induced by a moving mirror. Additionally, due to heterodyne detection of coherent signals in the radio-frequency domain, very weak signals may be detected with efficient technical noise rejection and co-additions are not necessary, unlike with an incoherent light source. This approach is multiplex and enables the simultaneous analysis of an extended spectral domain with a single detector. With the benefit of a much reduced measurement time when compared to sequential or multichannel methods, the multiplex approach has the unique advantage of extended spectral domains observation.

[0010] However, these known systems do not take into account the residual instabilities of the two combs. Even when the combs are locked, the parameters f_{rep1}, f_{rep2}, f_{01}, f_{02}, encounter, on short time scales (few μs or longer), slight fluctuations, which can be lower than one part in 10^6. Because of these residual instabilities, the difference between the repetition rates of the two combs can vary, thus leading to errors in the interference pattern sampling. Such interferometers indeed require to keep *a* f_{rep2} and $(f_{01} - f_{02})$ constant during the time of a measurement with a very high level of constraint on the stability of the repetition

rates of both frequency combs and on the stability of the carrier-envelope offset frequencies, when applicable. In other words, the relative coherence between the two independent comb sources must be forced within the time of a measurement, which may be very short. This constraint is stringent and prevents the practical implementation of the method with simple means. Using state-of-the-art reference cavities to lock the combs, as shown in I. Coddington, W. C. Swann and N. R. Newbury, *"Coherent multiheterodyne spectroscopy using stabilized optical frequency combs"*, Physical Review Letters 100, 013902 (2008), excellent results may be obtained, but such systems require an extensive knowledge of the most modern and expensive tools of frequency metrology and cannot be used in a standard spectroscopy laboratory, in the industry or in field measurements. This stability constraint on the difference in repetition rates and carrier-envelop offsets of the two combs is different from those of Fourier Transform Spectroscopy (FTS) with a Michelson interferometer, where the Doppler-shifted replica of a comb source is produced by appropriate control of the moving mirror of the interferometer, independently of the comb stability. It also differs from the use that is made of frequency combs in metrology, where the phase-coherence of the comb with a radio-frequency or optical clock is needed on long time scales (several seconds).

[0011] An object of the invention is to provide an improved interferometer, based on two frequency combs, accounting for the instabilities of the combs. In other words, the proposed device and method enable measurement of the interferences between two frequency combs where at least one comb has its line positions which are varying as a function of time. In other words, e.g., for at least one comb, the frequency of a n^{th} comb line is given by the relation $f_0 + n.\ f_{rep,}$ (with f_0 equal to or different from zero and n integer) where f_{rep} and/or f_0 are varying as a function of time. The proposed device allows for monitoring the time variations of at least the beating signal of a couple of lines from the two frequency combs and for using the knowledge of these time variations to provide a corrected sampling grid for the interferometric signal in order to overcome the accuracy and measurement time limitations of the prior art. Constraints on frequency comb stability are consequently reduced.

[0012] According to the invention, the interferometer comprises:

- a first frequency comb
- a second frequency comb adapted to interact with the first frequency comb in order to produce interferences.
- means for isolating at least one beating signal between a subset of frequency components among the frequency components of the two combs. This subset of frequency components is preferably but not necessarily a single line of the first frequency comb and a single line of the second frequency comb.
- means for monitoring at constant time intervals, simultaneously at least this beating signal between a subset of frequency components among the frequency components of the two combs and the beating interference signal between the entire frequency components of the first and the second frequency combs

[0013] The invention also relates to Frequency Comb Fourier Transform Spectroscopy (FC-FTS) and is directed to a spectroscopic device for measuring the spectrum of a sample, the device comprising an interferometer according to any of the preceding claims, at least one of said first frequency comb generator and said second frequency comb generator being adapted to interact with the sample.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Preferred embodiments of the present invention will be set forth in detail with reference to the drawings in which:

- FIG. 1 shows a schematic view of a frequency comb interferometer adapted in an absorption spectrometer for Fourier transform spectroscopy;

- FIG. 2 comprises Fig. 2A and Fig. 2B which are plots respectively showing an example of two optical frequency comb spectra and the corresponding beating spectrum of

an example frequency comb sources;

- FIG. 3 shows a conceptual view of the system described in the first embodiment, which enables to monitor a reference signal simultaneously to the interferometric signal;

- FIG. 4 shows a detailed example of the first embodiment of an interferometer according to the invention, where the spectral filtering of the combs reference beating signal is performed with the aid of a cw laser;

- FIG. 5 shows an example of the first embodiment of an interferometer according to the invention, where the spectral filtering of the combs reference beating signal is performed with passive filters;

- FIG. 6 shows a conceptual view of the system described in the second embodiment, which enables to monitor two reference signals, each of them being related to one of the combs, simultaneously to the interferometric signal;

- FIG. 7 comprises Fig. 7A, Fig. 7B and Fig. 7C which are plots respectively showing an example of the optical layout for using the interferometer of the invention as a spectrometer probing absorption and/or dispersion of a sample.

- FIG. 8 shows an interferogram obtained with an interferometer.

- FIG. 9 illustrates an embodiment of the interferometer of the invention with differential measurements;

- FIG. 10 comprises Fig. 10A, Fig. 10B, Fig 10C and Fig. 10D and illustrates an aspect of the invention for velocity modulation;

- FIG. 11 illustrates an aspect of the invention for Zeeman spectroscopy;

- FIG. 12 illustrates an aspect of the invention with polarization modulation.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0015] Preferred embodiments of the present invention will be set forth in detail with reference to the drawings, in which like reference numeral refers to like elements throughout. The herein presented interferometer with a posteriori correction

technique of the sampling of the signal is best understood considering the illustrative example of frequency comb Fourier Transform Spectroscopy and all related instrumental methodologies (hyperspectral imaging, microscopy, vibrational circular dichroism, attenuated total reflection, Zeeman modulation, velocity modulation, selective detection techniques, time-resolved spectroscopy...), but it is noted that the interferometer with a posteriori correction technique can also be used beyond the herein described applications. For example, the herein described interferometer with synchronization technique can be adapted to be used in Optical Coherence Tomography (OCT), interferometric length measurements, LIght Detection And Ranging (LIDAR), reflectometry, linear optical sampling, cross-correlation measurements between electrical fields. Other interferometric applications, based on wavefront or amplitude recombination, not specifically described herein may also benefit from the a posteriori correction technique.

[0016] As known in the art, a frequency comb is a spectral source made of phase-coherent laser monochromatic emission lines regularly spaced over a spectral range. Most often, femtosecond lasers are used, leading to a femtosecond frequency comb (FFC). Alternatively, the combs can be produced by four-wave mixing in appropriate material, including toroidal microresonators or optical fibers. The combs may be also produced by a phase-modulated electro-optic device.

[0017] Summarizing, when using a mode-locked laser, ultra short pulses are periodically emitted by the mode-locked laser with a time period $T=l/v_g$ where l is the length of the laser cavity and v_g is the net group velocity. Due to dispersion in the cavity, the group and phase velocities differ, resulting in a phase shift of the carrier with respect to the peak of the envelope of each pulse. In the frequency domain the spectrum, Fourier transform of the train of periodic pulses, is made of a comb of laser modes, which are separated by the pulse repetition frequency f_{rep}. The modes frequencies obey the relation: $f_n = n f_{rep} + f_0$, with n integer and f_0 due to carrier-envelop pulse-to-pulse phase-shift. Presently the output spectrum of the comb can span more than one octave and the best level of stabilization of f_{rep} and f_0 is such that there is no deviation from a perfect grid larger than one part in 10^{19}.

[0018] In other words, a frequency comb is an optical spectrum which consists of equidistant lines. The generation of a frequency comb from a mode-locked laser requires that the periodicity applies not only to the pulse envelopes, but to the whole electric field of the pulses, including their optical phase, apart from a constant phase. Coherence between the pulses is therefore required.

[0019] As shown in FIG. 1 and known per se, a specific layout of an interferometer 1 comprises a frequency comb "Frequency Comb 1" and a frequency comb "Frequency Comb 2". "Frequency Comb 1" probes a sample contained in a cell 100. The interferences that are generated from the recombination on a beam-splitter 101 of the frequency combs "Frequency Comb 1" and "Frequency Comb 1" are measured by a detector 102 and an interferogram is measured at a computer 103. The beat notes between pairs of lines from two combs having slightly different repetition rates, which occur in the radio-frequency domain, provide a down-converted image of the optical spectrum.

[0020] Note that the interferometer does not necessarily probes a sample 100, and that the sample 100, if present, may interact with both combs. Wavefront recombination instead of amplitude recombination may also be used. In such case, the beam-splitter 101 is not needed.

[0021] According to the invention, the frequency combs FC1 and FC2 have slightly different repetition rate frequencies f_{rep1} and f_{rep2} related to each other by

$$f_{rep1} = f_{rep2} (1 + a); 0<a<<1$$

[0022] According to the invention, frequency combs FC1 and FC2 can be generated by femtosecond mode-locked lasers with repetition rates and carrier-envelop offset stabilized or free-running. The mode-locked laser may be broadened by a non-linear optical fiber and it may be coupled to a frequency conversion system such as difference/sum frequency generation, harmonic generation and/or parametric interaction. Frequency combs FC1 and FC2 can also be generated by four-wave mixing effect or by an electro-optic modulator seeded by a continuous wave laser.

[0023] The spectrometer according to the invention comprises an interferometer 1 on Fig.1 as described above. The spectrum of each laser (as shown in Figure 2A), numbered 1 or 2, is a comb of laser modes $f_{n,i}$ separated by the pulse repetition frequency $f_{rep,i}$:

$$f_{n,i}=f_{0,i}+n\, f_{rep,i}$$

where i=1 or 2, integer n typically in the range of 10^5 to 10^6, and $f_{0,i}$ is the carrier-envelope offset frequency, induced by the difference between the group and phase velocities of the pulses in the laser cavities, in the case of a frequency comb based on a mode-locked laser. Repetition frequencies are generally in the radio-frequency domain (in the present example they are close to 100 MHz with $f_{rep,1}$-$f_{rep,2}$ ranging from 10 Hz to 20 kHz, depending on the free spectral range). One laser probes (Fig.1) the absorbing sample and both beams are combined on a beam-mixer. Their beating signal *I*, recorded on a fast photodetector, is amplified and sampled using a high-resolution digitizer on a personal computer..

[0024] The beating difference frequency b_n between the respective comb components $f_{1,n}$ and $f_{2,n}$, as shown in Figure 2B, is given by

$$b_n = f_{1,n} - f_{2,n} = n\, a\, f_{rep2} + (f_{01} - f_{02})$$

which shows that *a* is the down conversion factor.

[0025] The interferogram which is recorded on the photodetector can therefore be written

$$I(t) = \sum_n A_n \cos((f_{0,1} - f_{0,2} + n(f_{rep,1} - f_{rep,2}))t)$$

where A_n is the product of the amplitude of the electric fields of the two lasers, attenuated by sample absorption. Similarly to what happens with a Michelson interferometer, the frequencies of the optical spectrum $f_{n,i}=f_{0,i}+nf_{rep,i}$ are down-converted to $f_{0,1}$-$f_{0,2}$+n($f_{rep,1}$-$f_{rep,2}$). However, thanks to the absence of moving parts, the down-conversion, limited by aliasing, can lead to the radio-frequency domain between 0 and $f_{rep,i}/2$, and not to the audio-range like in Michelson-based FTS. This results in a drastic reduction of the recording time. The signal *I(t)* is then Fourier-transformed to reveal the spectrum; the longer the measurement time, the better

the optical resolution. The interferometric signal exhibits a periodic succession of huge bursts occurring every $1/\delta=1/(f_{rep,1}-f_{rep,2})$ when femtosecond pulses from the two lasers coincide. Fourier-transforming a temporal sequence including more than two such bursts resolves the comb lines. As the combs parameters (f_{rep1}, f_{rep2}, f_{01}, f_{02}) may be straightforwardly measured with radio-frequency counters, the optical absolute frequency scale may be easily retrieved afterwards. It is also possible to use known molecular or atomic lines present in the spectrum to rescale the optical frequency axis.

[0026] During the time of the measurement of the beating signals (which may be as short as a few microseconds), at least one parameter of one of the combs (f_{rep1}, f_{rep2}, f_{01}, f_{02}) may be slightly fluctuating as a function of time. In other words, b_n is a function of time. Figure 2B therefore only provides therefore an instantaneous image of the down-converted spectrum. In practice, the fluctuations of the repetition rates (f_{rep1}, f_{rep2}) of the combs are much more troublesome than the fluctuations of the carrier-envelop offset frequencies (f_{01}, f_{02}) because the fluctuations on the repetition rates are amplified by the harmonic index n. Therefore, only sampling the interferogram at constant time intervals leads to distorted information.

[0027] The main part of this invention provides a simple way of re-sampling the interferogram in a manner that corrects to the most troublesome comb fluctuations as a function of time. A new sampling grid, synchronous to the combs fluctuations versus time, is provided. The idea consists in isolating (optically, electronically and/or by computing means) at least the beating signal (called hereafter reference signal) between two individual lines from the interfering combs and to sample (preferably at constant time intervals) the resulting sinewave simultaneously to the sampling of the interferometric signal between the two entire combs. The reference and interferometric signals are preferably oversampled by the acquisition unit. Appropriate a posteriori correction, such as interpolation of the reference and interferometric signals, reconstructs the desired sampling grid at constant fringe intervals. If the comb lines are not isolated well enough, i.e. if the reference beating signal consists in the beat note of more than one couple of lines,

the referencing and correcting scheme still works but within a more limited time sequence, i.e. with a more limited resolution for Fourier transform spectroscopy.

[0003]FIG. 3 shows an interferometer according to a first embodiment of the invention. The interferometer comprises first isolating means 3 adapted to isolate a single optical frequency of frequency comb FC1 and second isolating means 4 adapted to isolate a single optical frequency of frequency comb FC2. The isolating means can comprise for example an optical filter and/or a Fabry-Perot etalon and/or the single comb line can also be isolated by beating the comb with a continuous wave laser and with electronic filtering. The beating of the isolated frequencies, using a beating means 5, produces a signal S as illustrated in FIG. 3, which would be sinusoidal if the FC1 or FC2 line positions were not fluctuating with time. The full interferogram I corresponds to the interferences between frequency combs FC1 and FC2 which are obtained with the beating means 6, which can be based on wavefront or amplitude recombination of the FC1 and FC2 beams. The interferogram I is measured simultaneously with the reference beating signal S, so that they have identical time-sampling. The right sampling, at equidistant fringe intervals, can therefore be reconstructed a posteriori for instance by interpolation of the reference beating signal S and of the interferometric signal I, independently of the fluctuations of the line positions of the combs as a function of time.

According to an example of the first embodiment shown in Figure 4, the reference signal device consists first in isolating a single line from each comb. A part of the optical signal delivered by "frequency comb 1" is sent to a fast photo-detector 501 with the aid of a beam-splitter, while most of the signal is used for the interferometric measurements (some examples are described hereafter). The beam of a continuous-wave laser 503 falls also on the same detector 501. The continuous wave laser 503 emits at the frequency f_{cw} in the same spectral region as the combs. It may be locked to a reference or free-running and its spectral purity, as well as its frequency stability, mainly determines the maximum sampling duration of the interferometric measurement. The beating signal between the frequency comb 1 and the cw laser is a comb of down-converted modes lying

partly in the radio-frequency and microwave domains. With proper choice of the photodetector 501 bandwidth and further electronic filtering 502, the beating signal between a single comb line and the cw laser, which may be written ($n f_{rep1} + f_{01} - f_{cw}$), may be isolated. The same procedure is applied to the frequency comb 2, with photodetector 504 and electronic filter 505, in order to isolate the electric beating signal of a single line of the frequency comb 2 with the same cw laser 503, ($m f_{rep2} + f_{02} - f_{cw}$). The two beating signals, obtained as described herein, are mixed with an electronic mixer 506 in order to suppress the contribution of the cw laser and to provide the reference beating signal between the two comb lines ($n f_{rep1} + f_{01} - m f_{rep2} - f_{02}$). The reference beating signal ($n f_{rep1} + f_{01} - m f_{rep2} - f_{02}$) is sampled as a function of time on Channel 2 of Acquisition Unit 508. If there were no time fluctuation of the comb line positions, it would be a sinewave for time sampling at equidistant intervals. The data acquisition of the interferometric signal is performed simultaneously on Channel 1 of acquisition unit 508. Preferably the reference and interferometric signals are oversampled. The acquisition unit 508 can be for instance a high speed digitizer onboard a personal computer, equipped with two channels or two independent digitizers synchronized to a same external clock. The data points from the two channels are then for instance stored on the hard drive of the computer. The reference and interferometric signal may be then processed according to an algorithm, e.g. based on interpolation, in order to provide a sampling at equidistant fringe intervals. These fringe intervals may be a small portion of the optical signal. The new grid which is provided is then distortion free. It is noted that monitoring more than one reference beating signal simultaneously leads to more accurate a posteriori corrections and consequently to the possibility to Fourier transform longer time sequences.

[0029] Alternative configurations may be utilized to produce the reference beating signal ($n f_{rep1} + f_{01} - m f_{rep2} - f_{02}$) between the two combs. For instance, a second example of this first embodiment may be lying on optical filtering, instead of using a cw laser in the synchronization scheme. As shown in Figure 5, each comb may be frequency filtered with optical filters or fiber Bragg gratings or Fabry-Perot cavities or any combination of these items with or without a cw laser. The two filtered

combs beat on a fast photodiode. After proper electronic filtering, the clock beating signal ($n f_{rep1} + f_{01} - m f_{rep2} - f_{02}$) is used as a reference beating signal for the acquisition unit, which simultaneously samples the interferometric signal coming from the beat between the two combs.

[0004] FIG. 6 shows an interferometer according to a second embodiment of the invention.

[0005] The interferometer comprises a first external optical reference 5, such as a continuous wave laser which may be locked to an molecular/atomic reference or to a reference cavity beating with a single isolated line of frequency comb FC1 or a frequency comb. The single line of frequency comb is isolated by isolating means 3 as described before in reference to the first embodiment. The beating of the external optical reference 5 with the single isolated line of frequency comb FC1 produces a signal S1, which would be sinusoidal if the FC1 line positions were not fluctuating with time. This sinusoidal signal which has a frequency of ($n f_{rep1} + f_{01} - f_{cw5}$) brings the knowledge of the fluctuations of the frequency ($nf_{rep1} + f_{01}$) of one line of the comb FC1 with the optical reference 5 (f_{cw5}). If the fluctuations are negligeable, then the variations of ($nf_{rep1} + f_{01}$) may be retrieved a posteriori.

Similarly, a second external optical reference 6, of the same type of 5, beats with a single line of frequency comb FC2, the single line being isolated by isolating means 4 as described before. The beating of the external optical reference 6 with the single isolated line of frequency comb FC2 produces a sinusoidal signal S2.

If the same device is used as an optical reference for 5 and 6, then this optical reference 5 may be fluctuating with time and it can be for instance a free-running cw laser. Indeed, the two quantities ($n f_{rep1} + f_{01} - f_{cw5}$) and ($m f_{rep2} + f_{02} - f_{cw5}$) may be subtracted a posteriori to remove the contribution of f_{cw5} and they then bring only the knowledge of the relative fluctuations of $n f_{rep1} + f_{01} - m f_{rep2} + f_{02}$, which is the information needed for a posteriori correction of the interferogram.

The full interferogram I corresponding to the interferences between frequency combs FC1 and FC2, signals S1 and S2 are measured simultaneously to signal I,

which provides identical time-sampling. As in the first embodiment, the data acquisition of the interferometric signal is performed simultaneously. Preferably all the reference and interferometric signals are oversampled. The reference signals and interferometric signal may be then processed according to an algorithm, e.g. based on interpolation, in order to provide a sampling at equidistant fringe intervals. These fringe intervals may be a small portion of the optical signal. The new grid which is provided is then distortion free. As in the first embodiment, monitoring more than two such reference beating signals simultaneously leads to more accurate a posteriori corrections and consequently to the possibility to Fourier transform longer time sequences.

[0031] Further aspects of the invention are described below. These aspects can be used in combination with the aforementioned first and second embodiments of the interferometer or can be used as such.

[0032] The aforementioned first and second embodiments of the invention can be used according to a specific example embodiment aimed at Frequency Comb Fourier transform spectroscopy of an absorbing sample. Several optical configurations may be implemented, as illustrated in FIG. 7. In Figure 7A, only frequency comb FC1 interacts with the sample 1000. The sample 1000 may be directly probed or it may be inserted inside a single pass cell, or inside a multipass cell, or inside a high finesse cavity that is resonant to the comb FC1. The two beams from combs FC1 and FC2 are recombined on a beam combiner. One or both outputs of the beam combiner can be used to measure the interferometric signal on fast photodetectors. The detectors may consist of simple photodetectors (photodiode, bolometer, antenna) or non-linear frequency converters, e.g frequency doubling devices, coupled to photodetectors. The detectors may be microphones. In Figure 7B, both frequency combs FC1 and FC2 interact with the sample 1000. For simultaneous absorption and dispersion measurements, the optical layout of the interferometer may be implemented as displayed in Figure 7C. Two frequency combs, FC1 and FC2, have slightly different line spacing. One of these combs, FC1, is transmitted through the cell and heterodyned against the second comb,

yielding a down-converted radio-frequency comb containing information on the absorption and dispersion experienced by each line of the comb FC1. Appropriate optics transmits the combs beams to two interferometers. The interferometer probing the sample contains the cell and leads to the sample interferogram $I_1(t)$ while the interferometer serving as a reference without the sample provides the normalization interferogram ($I_2(t)$). The two interferograms (with and without sample) are measured simultaneously and computed with a complex Fourier transform. The phase and module of the complex ratio of these two spectra give respectively the phase-shift and attenuation imposed on the detected radiation by the sample, providing access to the full characterization of the optical constants of the medium, its refractive index and absorption coefficient. Alternatively, the difference between the two interferograms $I_1(t)$ and $I_2(t)$ can be measured directly with an appropriate differential amplifier before digitization. In such case, only the interferogram of the spectral signatures of the sample are measured, with an improved signal to noise ratio.

[0033] The frequency combs interact with a sample and experience attenuation and phase-shift due to absorption and dispersion. This interaction may be written as $\exp(-\delta(\omega)- i\ \phi(\omega))$ where δ is the amplitude attenuation and ϕ is the phase shift. The following convention is adopted: $\delta_{i,n}$ and $\phi_{i,n}$ denotes the respective components experienced by the comb i (i=1 or 2) at the frequency $f_{0,i}+n\ f_{rep,i}$. As illustrated in FIG. 7A, only comb FC1 interacts with the sample 1000. The expression of the interferogram I contains the following interesting terms:

$$I(t) \subset \sum_n \left(\begin{array}{l} e^{-\delta_{1,n}} \left[\begin{array}{l} \cos\left(2\pi\left((f_{0,1}-f_{0,2})+anf_{rep2}\right)t\right)\cos\varphi_{1,n} \\ +\sin\left(2\pi\left((f_{0,1}-f_{0,2})+anf_{rep2}\right)t\right)\sin\varphi_{1,n} \end{array} \right] \\ +2e^{-\delta_{1,n}}\cos\left(2\pi f_{rep2}t\right)\left[\begin{array}{l} \cos\left(2\pi\left((f_{0,1}-f_{0,2})+anf_{rep2}\right)t\right)\cos\left(\varphi_{1,n}\right) \\ +\sin\left(2\pi\left((f_{0,1}-f_{0,2})+anf_{rep2}\right)t\right)\sin\left(\varphi_{1,n}\right) \end{array} \right] \end{array} \right) \quad (1)$$

[0034] The first term of Eq.(1) tells that the spectral information at frequency $f_{0,1}+n\ f_{rep,1}$ is down-converted at frequency $\left((f_{0,1}-f_{0,2})+anf_{rep2}\right)$. The interferogram is similar to an interferogram from classical FTS. Making a synchronous detection of

the signal at frequency $f_{rep,2}$ is not interesting, as it does not bring additional information.

[0035] Both combs FC1 and FC2 may also interact with the sample 1000 as shown in FIG. 7B. The expression of the interferogram contains the following interesting terms:

$$
\begin{aligned}
I(t) \subset \sum_n & e^{-\delta_{1,n}-\delta_{2,n}}\left(\cos\left(2\pi\left((f_{c1}-f_{c2})+anf_{rep2}\right)t\right)\cos\left(\varphi_{1,n}-\varphi_{2,n}\right)+\sin\left(2\pi\left((f_{c1}-f_{c2})+anf_{rep2}\right)t\right)\sin\left(\varphi_{1,n}-\varphi_{2,n}\right)\right) \\
& +e^{-\delta_{1,(n-1)}-\delta_{2,n}}\left\{\cos\left(2\pi f_{rep2}t\right)\left\{\begin{matrix}\cos\left(2\pi\left((f_{c1}-f_{c2})+a(n-1)f_{rep2}\right)t\right)\cos\left(\varphi_{1,(n-1)}-\varphi_{2,n}\right)\\ +\sin\left(2\pi\left((f_{c1}-f_{c2})+a(n-1)f_{rep2}\right)t\right)\sin\left(\varphi_{1,(n-1)}-\varphi_{2,n}\right)\end{matrix}\right\}+\sin\left(2\pi f_{rep2}t\right)\left\{\begin{matrix}\sin\left(2\pi\left((f_{c1}-f_{c2})+a(n-1)f_{rep2}\right)t\right)\cos\left(\varphi_{1,(n-1)}-\varphi_{2,n}\right)\\ -\cos\left(2\pi\left((f_{c1}-f_{c2})+a(n-1)f_{rep2}\right)t\right)\sin\left(\varphi_{1,(n-1)}-\varphi_{2,n}\right)\end{matrix}\right\}\right\} \\
& +e^{-\delta_{2,(n+1)}-\delta_{1,n}}\left\{\cos\left(2\pi f_{rep2}t\right)\left\{\begin{matrix}\cos\left(2\pi\left((f_{c1}-f_{c2})-anf_{rep2}\right)t\right)\cos\left(\varphi_{2,(n-1)}-\varphi_{1,n}\right)\\ -\sin\left(2\pi\left((f_{c1}-f_{c2})-anf_{rep2}\right)t\right)\sin\left(\varphi_{2,(n-1)}-\varphi_{1,n}\right)\end{matrix}\right\}-\sin\left(2\pi f_{rep2}t\right)\left\{\begin{matrix}\sin\left(2\pi\left((f_{c1}-f_{c2})-anf_{rep2}\right)t\right)\cos\left(\varphi_{2,(n-1)}-\varphi_{1,n}\right)\\ +\cos\left(2\pi\left((f_{c1}-f_{c2})-anf_{rep2}\right)t\right)\sin\left(\varphi_{2,(n-1)}-\varphi_{1,n}\right)\end{matrix}\right\}\right\} \\
& +e^{-\delta_{1,n}-\delta_{2,(n+1)}}\left\{\cos\left(2\pi f_{rep2}t\right)\left\{\begin{matrix}\cos\left(2\pi\left((f_{c1}-f_{c2})+anf_{rep2}\right)t\right)\cos\left(\varphi_{1,n}-\varphi_{2,(n+1)}\right)\\ +\sin\left(2\pi\left((f_{c1}-f_{c2})+anf_{rep2}\right)t\right)\sin\left(\varphi_{1,n}-\varphi_{2,(n+1)}\right)\end{matrix}\right\}+\sin\left(2\pi f_{rep2}t\right)\left\{\begin{matrix}\sin\left(2\pi\left((f_{c1}-f_{c2})+anf_{rep2}\right)t\right)\cos\left(\varphi_{1,n}-\varphi_{2,(n+1)}\right)\\ -\cos\left(2\pi\left((f_{c1}-f_{c2})+anf_{rep2}\right)t\right)\sin\left(\varphi_{1,n}-\varphi_{2,(n+1)}\right)\end{matrix}\right\}\right\} \\
& +e^{-\delta_{2,n}-\delta_{1,(n+1)}}\left\{\cos\left(2\pi f_{rep2}t\right)\left\{\begin{matrix}\cos\left(2\pi\left((f_{c1}-f_{c2})-a(n+1)f_{rep2}\right)t\right)\cos\left(\varphi_{2,n}-\varphi_{1,(n+1)}\right)\\ -\sin\left(2\pi\left((f_{c1}-f_{c2})-a(n+1)f_{rep2}\right)t\right)\sin\left(\varphi_{2,n}-\varphi_{1,(n+1)}\right)\end{matrix}\right\}-\sin\left(2\pi f_{rep2}t\right)\left\{\begin{matrix}\sin\left(2\pi\left((f_{c1}-f_{c2})-a(n+1)f_{rep2}\right)t\right)\cos\left(\varphi_{2,n}-\varphi_{1,(n+1)}\right)\\ +\cos\left(2\pi\left((f_{c1}-f_{c2})-a(n+1)f_{rep2}\right)t\right)\sin\left(\varphi_{2,n}-\varphi_{1,(n+1)}\right)\end{matrix}\right\}\right\}
\end{aligned}
$$

Eq. (2)

[0036] The first line of the expression (2) is the quantity measured by direct detection of the interferogram, without synchronous detection. Compared with what is obtained from the interferogram of Eq.(1), the detection is more sensitive, because both combs FC1 and FC2 experience interaction with the sample, but the instrumental line shape is a bit more complicated as it is frequency dependent: as frequency grows, the difference between the frequencies of the two combs increases. Also, synchronous detection at $f_{rep,2}$ frequency is interesting since the absorption and dispersion may be retrieved thanks to in-phase and in-quadrature detections.

[0037] Any interferogram may present a ratio of about 10^6 between its highest and smallest samples. The important decrease of the interferometric signal as a function of time is illustrated with the interferogram shown in FIG. 8. As a consequence, one of the main difficulties associated with Fourier transform spectroscopy, in particular -but not only- at high spectral resolution, is due to the limited dynamic range of the measurements. In Frequency comb Fourier Transform Spectroscopy, the dc component I_0 is no more a constant but becomes a function $I_0(t)$ of time t, linked to the Fourier components of the pulse repetition rates. Therefore it is difficult to satisfactorily eliminate it by electronic filtering, since this could seriously degrade the sampling. A technical consideration of importance is that, nowadays, the most performing fast acquisition board offers a limited dynamic range of 16 bits, i.e. of 65538 different levels of measurement, which essentially characterize the ADC converters. As a consequence, the recording procedure cannot make directly use of a commercial product.

[0038] A specific example embodiment provides a dynamic range solution that is a combination of several points. Fast Detector signals I_A and I_B delivered, as shown on FIG. 9, at two outputs A and B of the interferometer are balanced and subtracted so to remove the unmodulated background, and to obtain only the modulated part of the interferogram. In practice, two electronic gains G_A and G_B, respectively applied to I_A and I_B, are determined before the experiment, by minimizing the difference signal $(G_A I_A - G_B I_B)$. These gains are fixed within an experiment. Different electronic gains G_T are applied to the difference signal, depending on time to adapt at best the interferometric signal to the maximum input value of the acquisition unit.

[0039] The gain may be switched in real time or several recording channels may be used for a posteriori selection. Alternatively the gain change is made in a predetermined manner by computer program. In this latter case, the best measured sample is chosen a posteriori, by computer program, and the final value $G_T(G_A I_A - G_B I_B)$ is normalized to give back the whole interferogram, well measured. Synchronous detection may be performed before digitalization as discussed below.

[0040] According to a specific embodiment of the invention, the signal measured by the two receivers, A and B, is synchronously detected at the frequency repetition rate f_{rep}. Since f_{rep} lies typically in the radio-frequency range 0.1-5 GHz, the time-domain method reduces considerably the technical noise when compared to the presently best commercial interferometers detecting interferograms at audio frequencies around 20 kHz. Additionally, absorption and dispersion parameters are given at once from the Fourier Transform of the in-phase and in-quadrature radio-frequency signals, as it can be seen from Eq (2). The method is similar to frequency-modulation spectroscopy with tunable lasers. It has the additional benefits of broadband coverage, optimal modulation index and no need of external modulation.

[0041] The invention can also be adapted to selective-spectroscopy methodologies as described below.

[0042] Firstly, velocity modulation is intended to selectively detect the transitions of atomic or molecular ions. With FC-FTS, different schemes may be implemented as illustrated in FIG. 10. Figure 10A and Figure 10B make use of a dc discharge 1300. Neutral species are insensitive to the electric field, while due to the electric field, ions acquire a net drift velocity. The effect of this velocity is that the frequencies of the transitions of the ions are Doppler-shifted. Each comb, as in Figure 10A, or only one of them, as in Figure 10B, can be split into two counter propagating beams in order to form two interferometers. Difference between the two resulting interferograms or spectra, which can be made by differential detection as shown in Fig.10A and Fig.10B (where the two output of the two interferometers, respectively S1 and S2, and S3 and S4, are used according to a specific embodiment of the present invention) or a posteriori, brings the selective information, as in one spectrum all the ion frequencies are blue shifted and in the other red shifted. All neutral signals and systematic errors are suppressed from the spectra, leaving only the two Doppler-shifted components of the ion transitions.

[0043] The Figure 10C and Figure 10D exploit an ac modulated discharge 1301 to acquire two interferograms with opposite Doppler shifts at a frequency rate

depending on the discharge modulation or the recording time of the interferogram. Synchronous detection at the ac modulation cancels the neutral signatures. It is noted that the double differential detection scheme shown in Fig. 10A, Fig. 10B, Fig. 10C, Fig. 10D, is preferable for signal to noise ratio improvement but not mandatory. For selective detection in the scheme of Fig10A or Fig10B, it is for instance enough to consider the difference between the interferograms measured at detectors S1 and S3 (or S2 and S4) or the difference between the resulting spectra. For selective detection in the scheme of Fig10C or Fig10D, it is for instance enough to consider only the signal at detector S1 (or S2).

[0044] Secondly, Zeeman spectroscopy may be performed. In a first scheme as illustrated in FIG. 11A, a magnetic field 1400 interacting with the source 1401 is periodically varied. After synchronous or differential detection, only the frequency shifted transitions by the magnetic field are be detected. However, one must consider the symmetry of the Zeeman splitting: one has to modulate the field between $B_c + B_M$ *and* $B_c - B_M$, where B_c and B_M are two constants values of the magnetic field. B_c can be equal to B_M but cannot be zero, otherwise no signal variation will be detected. Alternatively, as shown in Fig 11B, the combs beams may be split into two beams, one probing a cell 1402 with a constant magnetic field $B_c + B_M$ while the other probes a cell 1403 with a constant magnetic field $B_c - B_M$ for differential detection. As it is the case for velocity modulation, it is preferable but not mandatory to use the two outputs of the interferometers to achieve selective detection. In Figure 11A, only the signal at detector S1 (or S2) may be measured. In Figure 11B, it is for instance enough to consider the difference between the interferograms measured at detectors S1 and S3 (or S2 and S4) or the difference between the resulting spectra.

[0045] Similarly to Zeeman spectroscopy, an electric field may be applied and modulated to selectively detect transitions that are sensitive to the Stark effect.

[0046] Thirdly, different schemes for polarization modulation FCFTS may be implemented as illustrated in FIG. 12. As schematized in Fig. 12A, it is possible to use a polarization modulator 1500 on one (as illustrated in FIG.12A with comb FC1

probing the sample 1501) or both combs FC1 and FC2 and to measure in a quick succession one interferogram with a given polarisation and one second with the other polarization and to subtract them. As shown in Fig. 12B, it is also possible to split one (FC1 in Fig.12B) or both combs beams into two beams, with complementary polarization provided by the polarizers 1502 and 1503. The two beams from FC1 in Fig.12B probe the sample 1504 and a direct differential detection is performed, as illustrated in Fig 12B. Alternatively two interferograms may be acquired and subtracted a posteriori. Polarization modulation is useful to selectively detect polarisation-sensitive transitions. It is also called linear (comparison between s and p polarization) or vibrational circular dichroism (comparison left and right circularly polarized radiation). Some examples of the subject of studies are chiral molecules or the orientation of molecules in thin solid films, liquid crystals, or Zeeman transitions from paramagnetic species. The difference between the absorption of radiation by two polarization states is often extremely small. The idea is to compare, in a quick succession, spectra resulting from the interaction of the sample with light polarized in two different states. In Figure 12, the use of the two output of the interferometer is a specific example embodiment of the invention. As already noted for velocity and Zeeman modulations, a single detector S1 or S2 in the configuration of Figure 12A may be used. In Figure 12B, it is for instance enough to consider the difference between the interferograms measured at detectors S1 and S3 (or S2 and S4) or the difference between the resulting spectra.

[0047] The invention can also be adapted to time-resolved applications as described below. In conventional spectroscopy, time-resolved FTS has been a powerful tool to investigate dynamic phenomena, with all the well-known advantages of FTS, especially the wide-spectral range of observation. It consists in performing a time sampling of the evolution of the observed sample, which is excited at every optical path-difference positions. At the end of the experiment, as many interferograms as time samples of the evolution of the source are obtained and transformed to give spectra, each characterizing the light source at a given

time. However a major limitation is that the observed sample has to behave in a well repetitive and reproducible manner.

[0048] Time-resolved FC-FTS for dynamic studies may overcome this limitation. Various schemes may be implemented depending of the time-resolution which is looked at. Furthermore, as acquisition time for a high resolution spectrum is only of the order of 1 millisecond or even 1 microsecond for low resolution information, a way to real-time broadband spectroscopy or single-event spectroscopy is opened with the invention.

[0049] For time-resolutions that are worse than the time required for measuring a full interferogram, the measurement principle is straightforward. It consists of measuring the interferograms in sequence. It is possible to improve the time resolution up to a few μs by varying the repetition rate of one of the combs in order to provoke the burst which occur when laser pulses from the two combs overlap. This variation in the repetition rate of one of the combs may for instance be achieved by modulating the length of one of the laser cavity with a piezo-electric transducer. If the source behaves in a repetitive manner, it is possible to repeat several times this method to improve signal-to-noise ratio.

[0050] When the time-resolution or repetition rate of the source cannot fit the optimal sampling requirements, then specific sampling and synchronization schemes have to be developed. The idea is to lower the interferogram sampling rate by adjusting the frequency difference between the two combs so to meet the source operating conditions.

[0051] If the desired time-resolution is higher than the sampling step of each individual interferogram resulting from the optimal frequency difference between the two combs and if the source of interest has a high repetition rate, it is possible to perform a high frequency sampling of the time-domain interferogram and to rearrange a posteriori the samples so to generate several interferograms each of them characteristic of the absorption of the source at a given time. The source has

then to be synchronized to the sampling step of the first time-sample interferogram.

[0052] The invention can also be adapted to reflection measurements as described below. With FC-FTS, instead of looking at the light which is transmitted by the sample, it is possible to look at the light which is reflected by the sample. The sample can be a bulk material, a layer of material (thinner or thicker than the wavelength of the comb radiation) present on a flat reflective surface.

[0053] Furthermore, attenuated total reflection enables to probe samples in liquid or solid phase with very easy sample preparation. A probing light beam is passed through a well chosen crystal in such a way that it reflects at least once on the internal surface in direct contact with the sample. This reflection forms an evanescent wave which extends into the sample, typically by a few micrometers. The attenuated energy from each evanescent wave is passed back to the light beam and the beam transmitted by the crystal is then collected by the second comb of the FT spectrometer as it exits the crystal. Attenuated total reflection FC-FTS may also be implemented with the two combs probing the crystal/sample assembly.

[0054] The invention can also be adapted to spatially resolved measurements as described below.

[0055] Firstly, as the section of a laser beam can be small, it is possible to selectively probe tiny spatial regions of a macroscopic sample.

[0056] Secondly, an efficient way with FCFTS to map the composition of a sample is to measure all the FT spectra simultaneously with an array detector. The object is imaged on the array detector with appropriate optics. Simultaneous measurement of spectra from each point of an image brings hyperspectral imaging.

[0057] Thirdly, microscopy with FC-FTS brings together the advantages of microscopy with Fourier transform spectroscopy and microscopy with laser

sources. Increase of spatial resolution can be obtained together with accurate spectral diagnostics and extremely short measurement times.

[0058] Fourthly, due to the low divergence and high intensity of laser beams, FC-FTS can probe long columns of sample. Alternatively, a laser beam may propagate into a long distance before reaching the sample of interest. LIDAR-type FC-FTS experiment can also be implemented: the sample-scattered light from an intense frequency comb can be collected and analysed with the second comb.

CLAIMS

1. An interferometer (1) comprising:
- a first frequency comb generator (FC1)
- a second frequency comb generator (FC2) adapted to interact with the first frequency comb generator (FC1) in order to produce interferences (I);
wherein the interferometer comprises means (3, 4) for isolating a first single line of the first frequency comb and a second single line of the second frequency comb and beating means for generating at least one beating signal from the first single line and the second single line.

2. An interferometer according to claim 1 further comprising a first external optical reference generator and a second external optical reference generator, wherein the beating means are adapted to generate a first beating signal of the first single line and the first external optical reference and a second beating signal of the second single line and the second external optical reference.

3. An interferometer according to claim 1 wherein the beating means are adapted to generate a beating signal of the first single line and the second single line.

4. An interferometer according to any of the preceding claims wherein the isolating means comprise an optical fiber and/or a Fabry-Perot etalon.

5. An interferometer according to any of claims 1 to 4, wherein the isolating means comprise a continuous wave laser and a electronic filtering adapted to beat with the first frequency comb generator and the second frequency comb generator.

6. An interferometer according to any of the preceding claims further comprising measuring means adapted to simultaneously measure said at least one beating signal and said interferences.

7. An interferometer according to the preceding claim wherein the measuring means are adapted to simultaneously measure said the first beating signal, the second beating signal and said interferences.

8. An interferometer according to any of the preceding claims having two outputs (A, B), and means for differentially measuring the two outputs.

9. A spectroscopic device for measuring the spectrum of a sample, the device comprising an interferometer according to any of the preceding claims, at least one of said first frequency comb generator and said second frequency comb generator being adapted to interact with the sample.

10. A spectroscopic device according to the preceding claim wherein only one of said first frequency comb generator and said second frequency comb generator is adapted to interact with the sample.

11. A spectroscopic device according to claim 8 wherein said first frequency comb generator and said second frequency comb generator are adapted to interact with the sample.

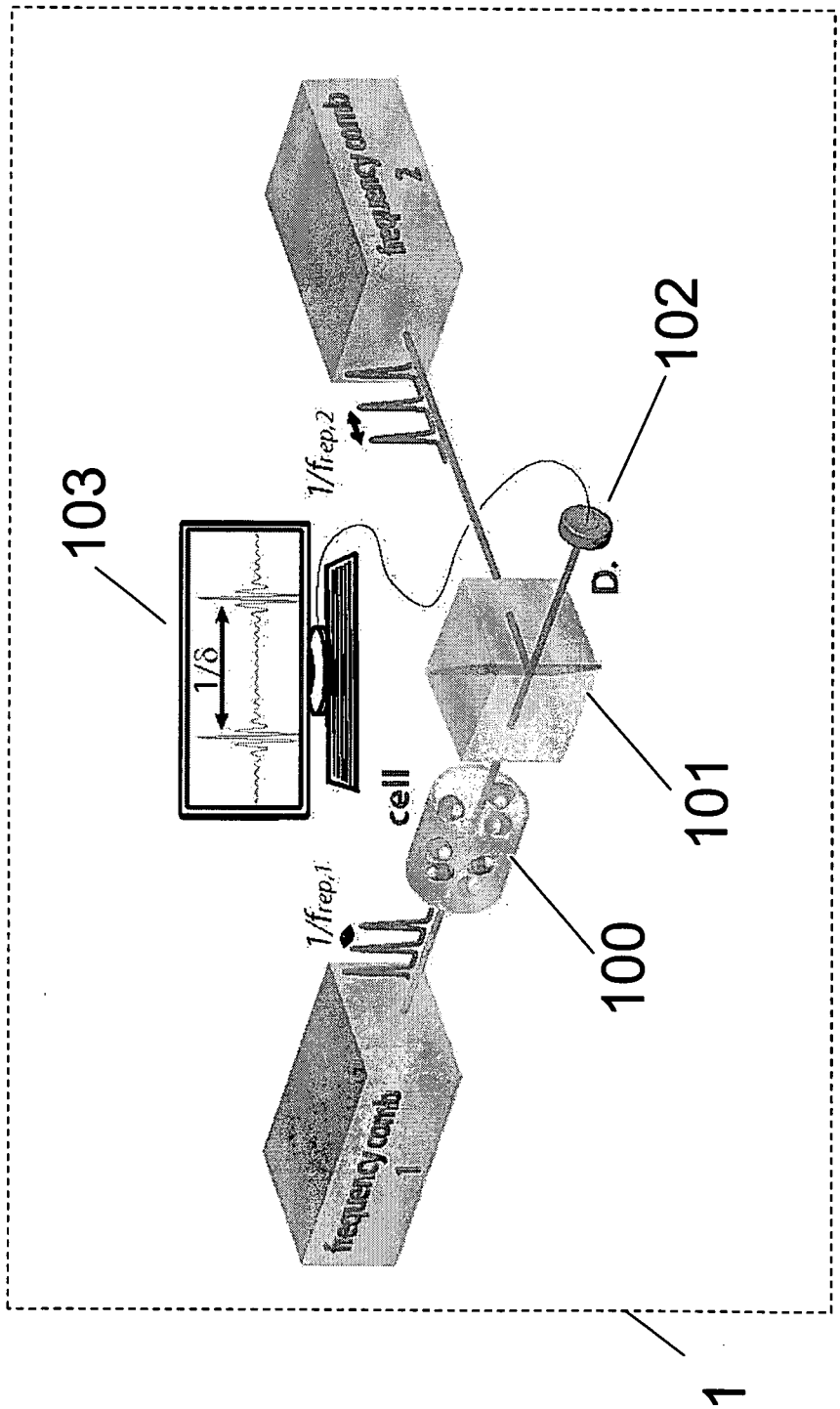

frequency comb 2
frequency comb 1
1/frep,2
1/frep,1
1/δ
cell
D.
103
102
101
100
1

FIG. 1

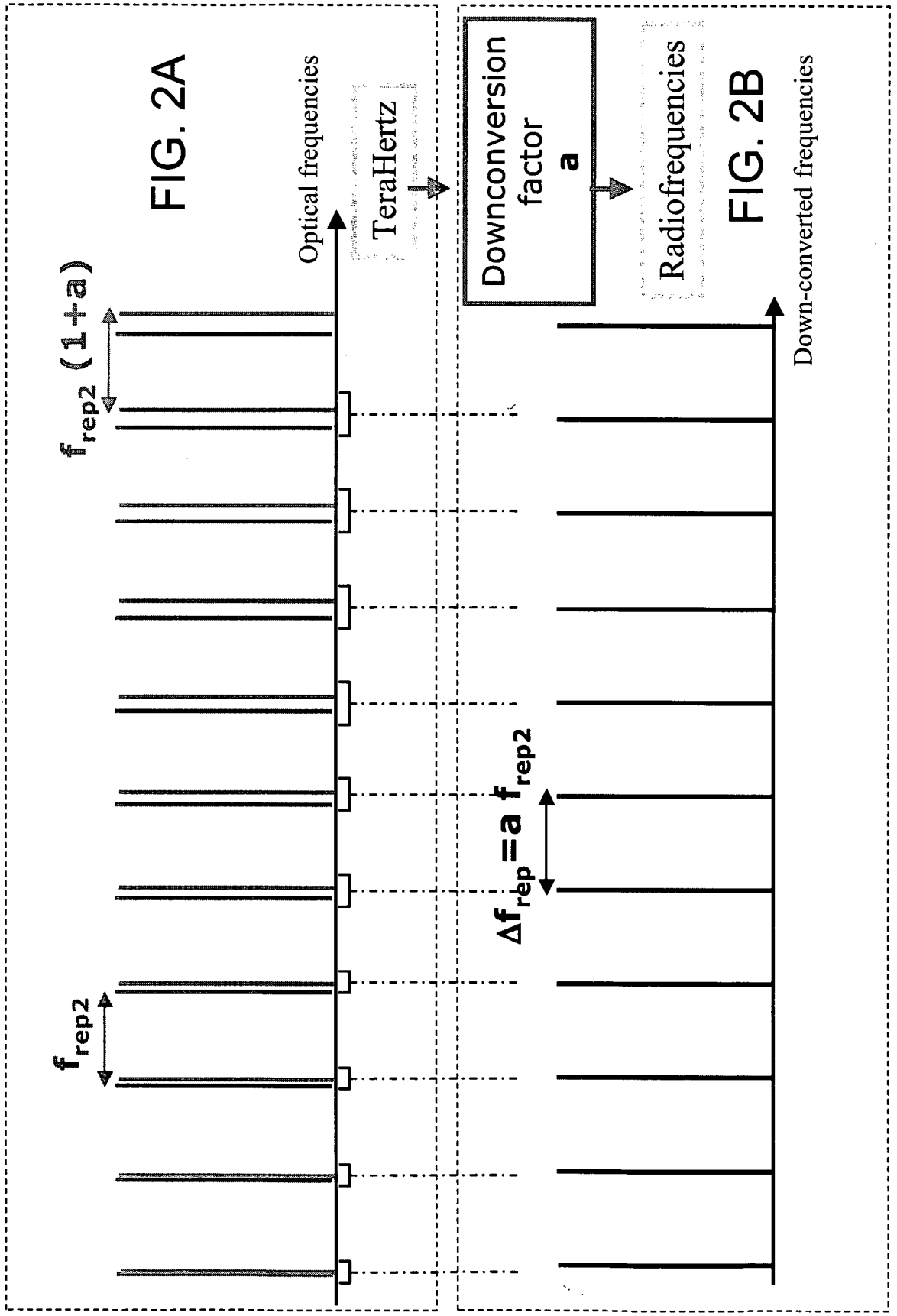

FIG. 2A
Optical frequencies
TeraHertz
$f_{rep2}(1+a)$
f_{rep2}
Downconversion factor a
Radiofrequencies
FIG. 2B
Down-converted frequencies
$\Delta f_{rep} = a f_{rep2}$

FIG. 2

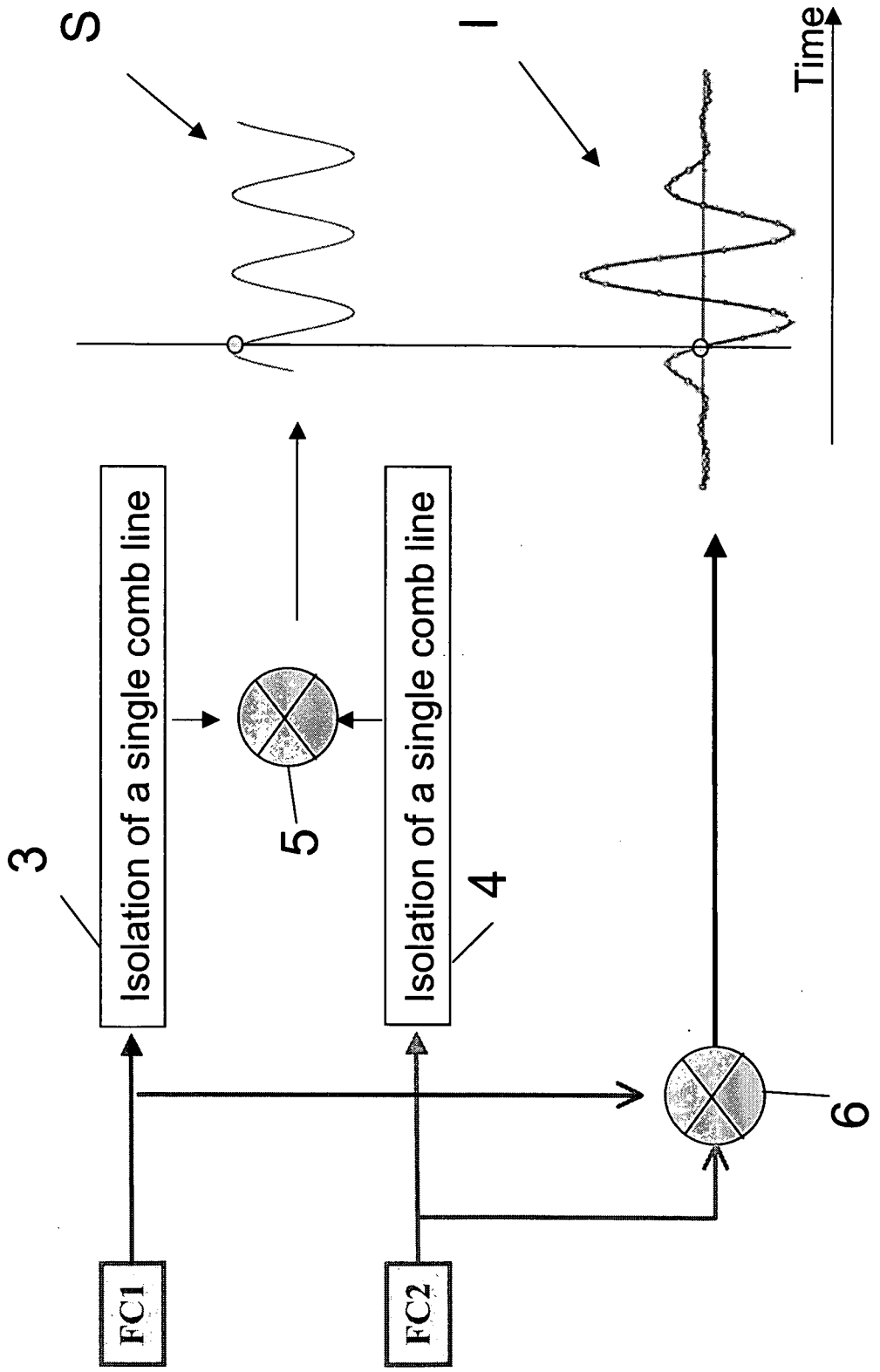

S
I
Time
Isolation of a single comb line
Isolation of a single comb line
3
4
5
6
FC1
FC2

FIG. 3

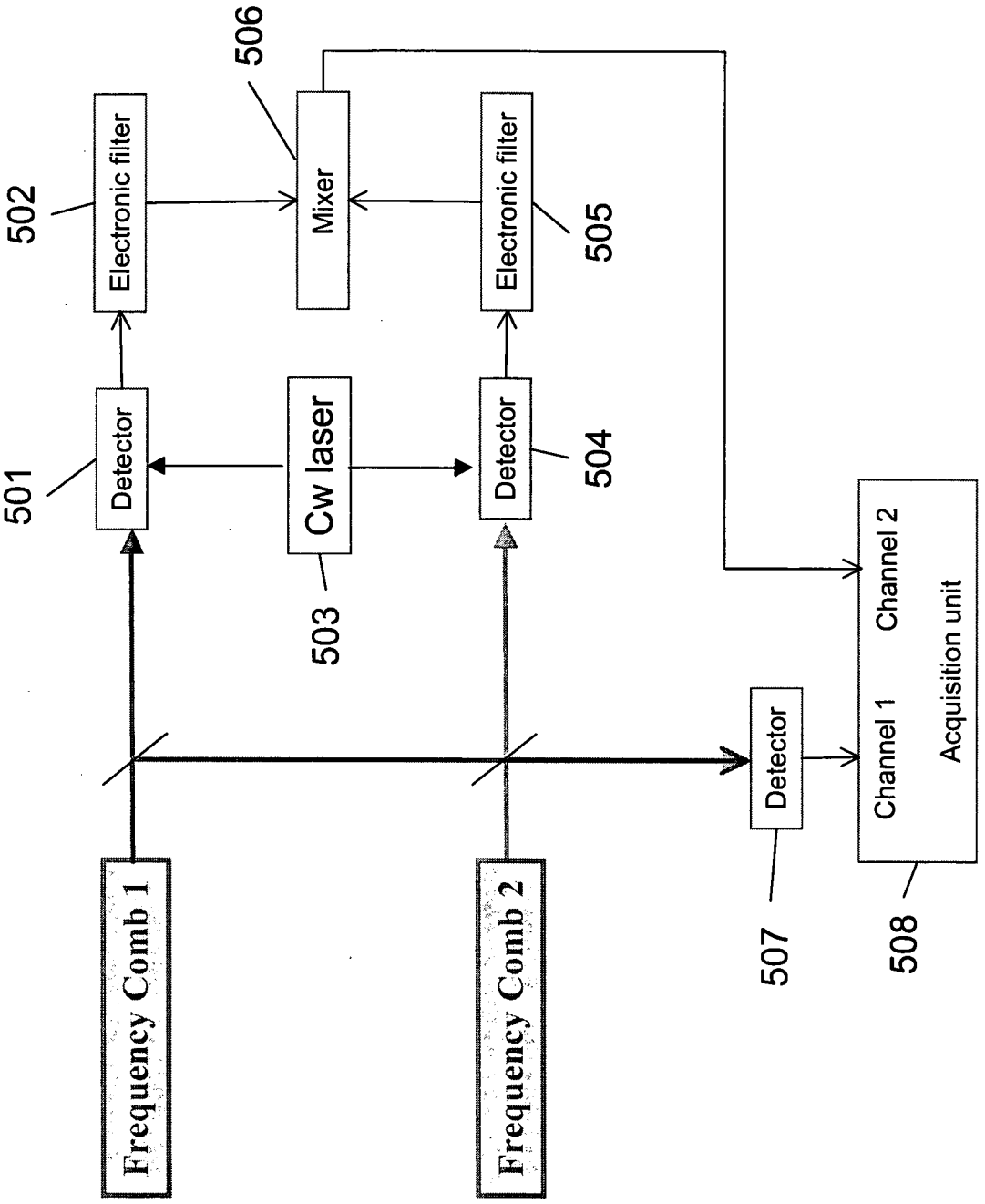

Frequency Comb 1
Frequency Comb 2
Detector
Detector
Cw laser
Detector
Electronic filter
Mixer
Electronic filter
Detector
Channel 1
Channel 2
Acquisition unit
501
502
503
504
505
506
507
508

FIG. 4

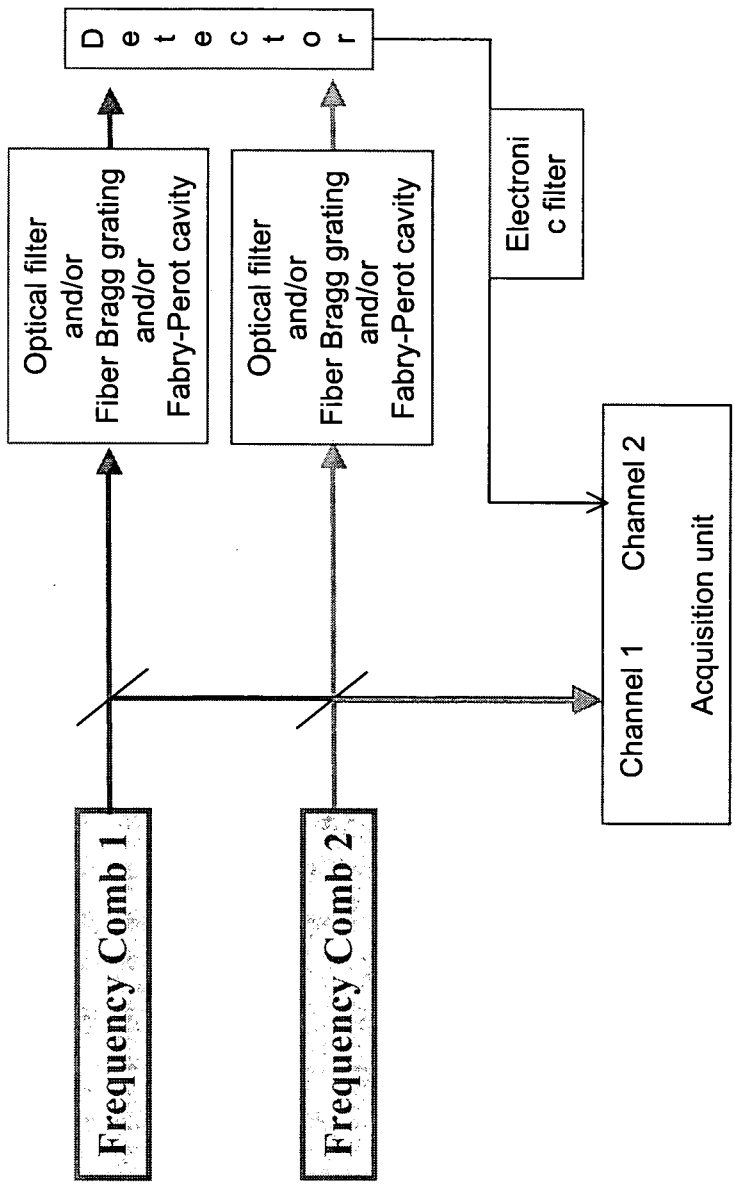

Detector
Optical filter and/or Fiber Bragg grating and/or Fabry-Perot cavity
Optical filter and/or Fiber Bragg grating and/or Fabry-Perot cavity
Electronic filter
Frequency Comb 1
Frequency Comb 2
Channel 1
Channel 2
Acquisition unit

FIG. 5

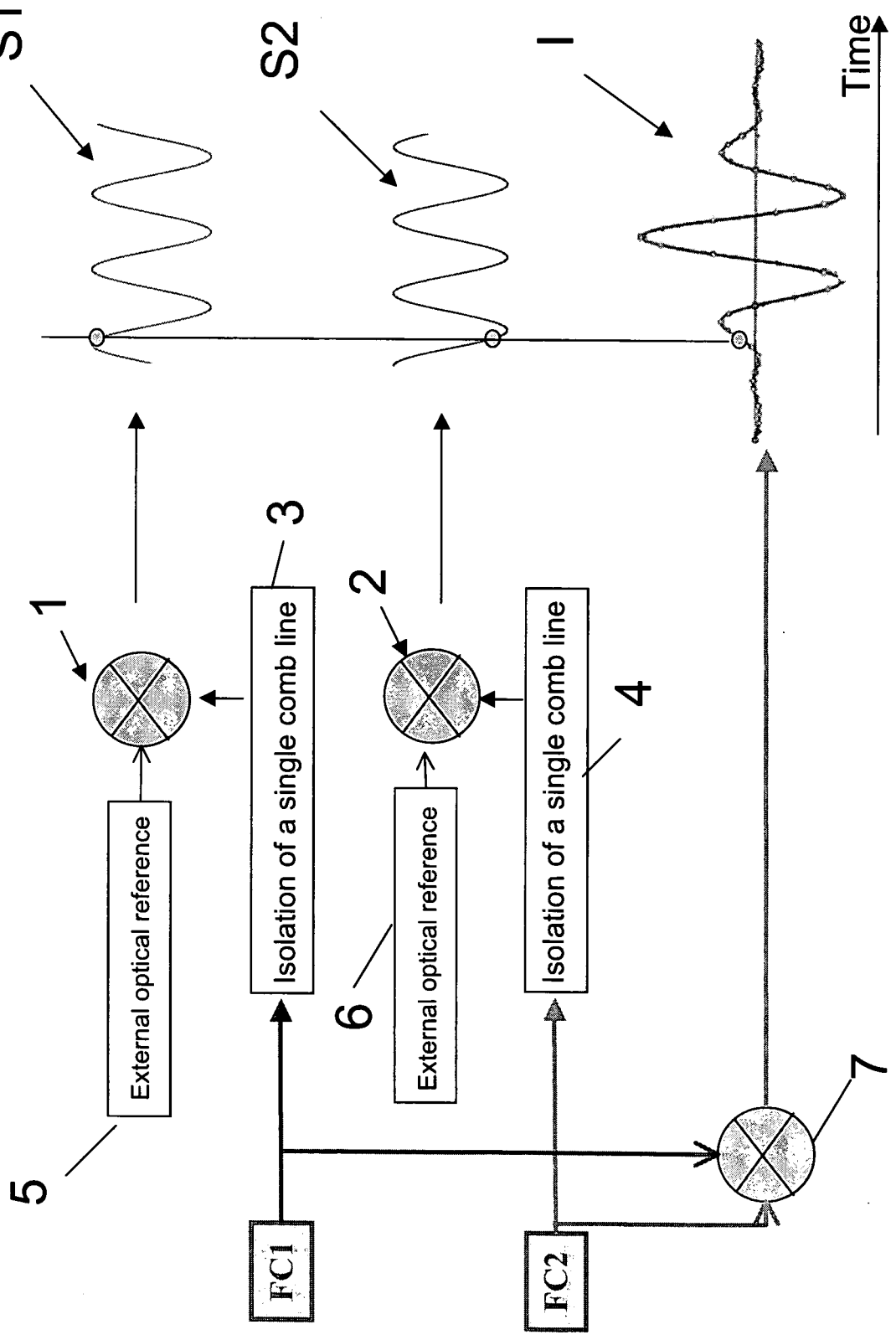

S1
S2
I
Time
1
2
3
4
5
6
7
External optical reference
Isolation of a single comb line
External optical reference
Isolation of a single comb line
FC1
FC2

FIG. 6

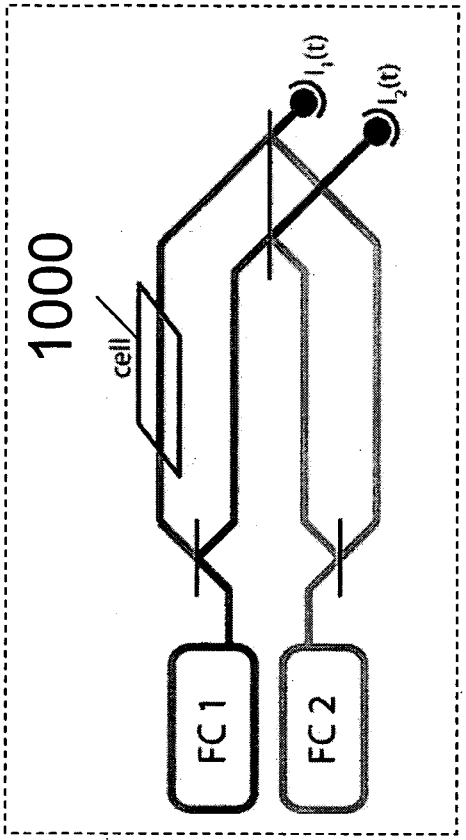


FIG. 7C

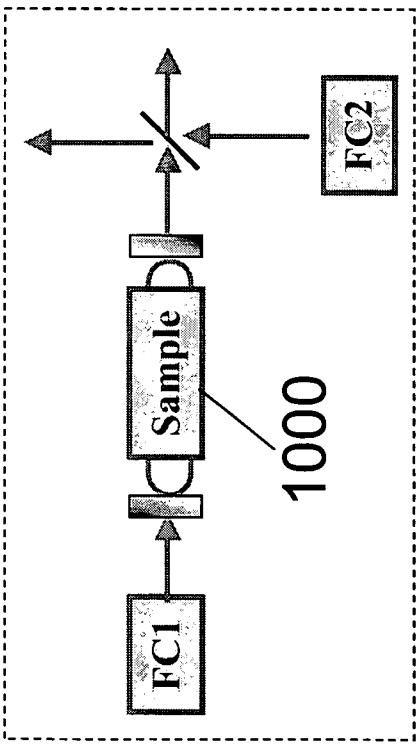


FIG. 7A

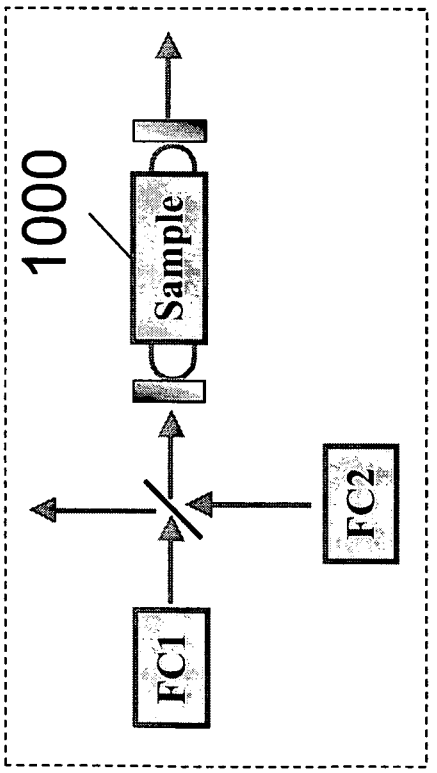


FIG. 7B

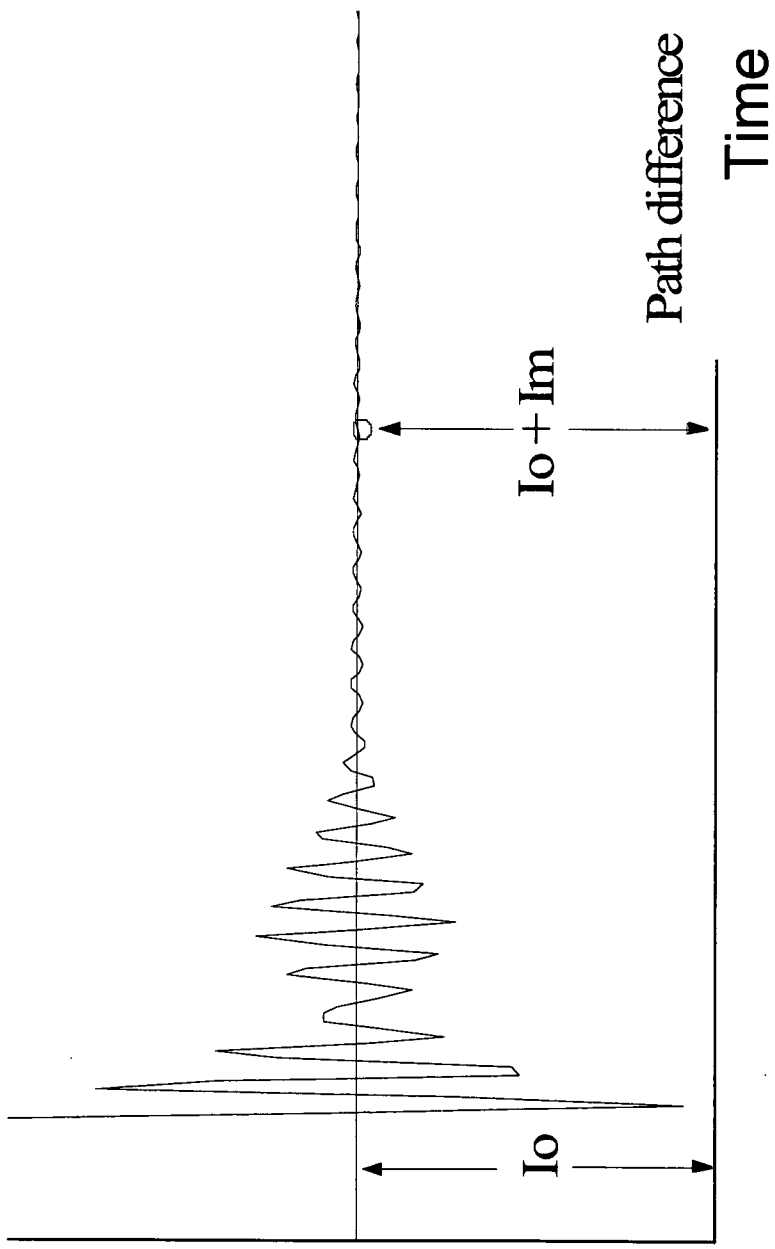


FIG. 8

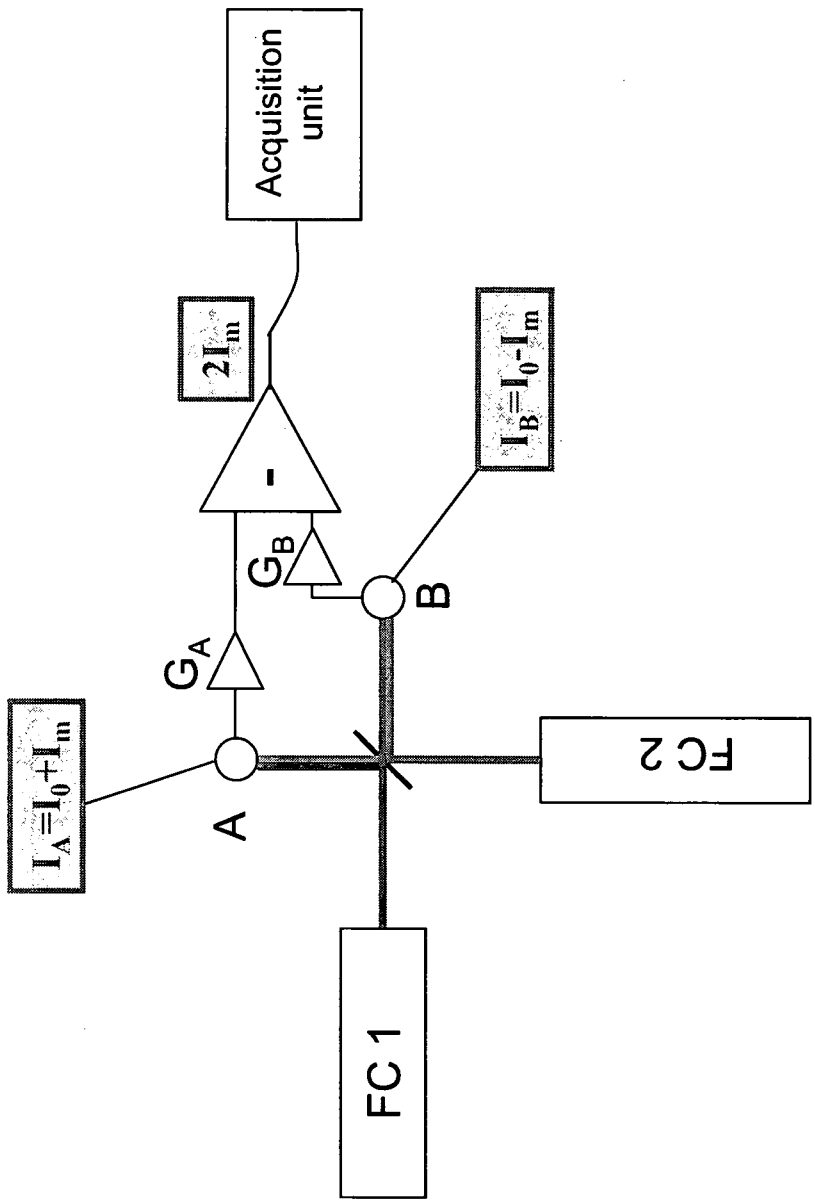


FIG. 9

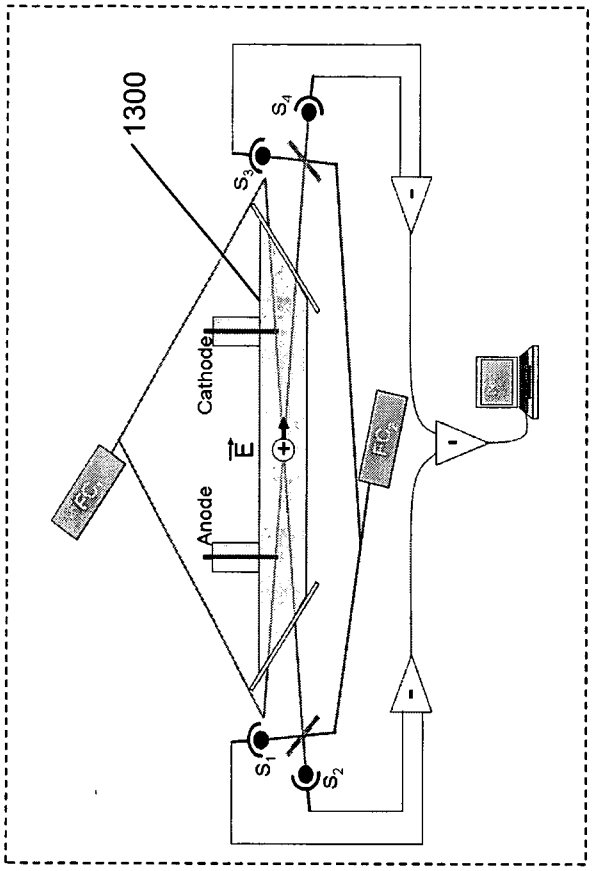


FIG. 10B

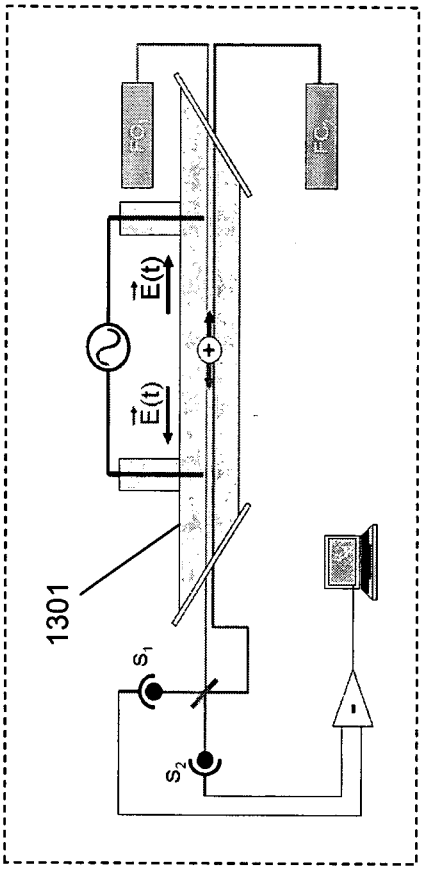


FIG. 10D

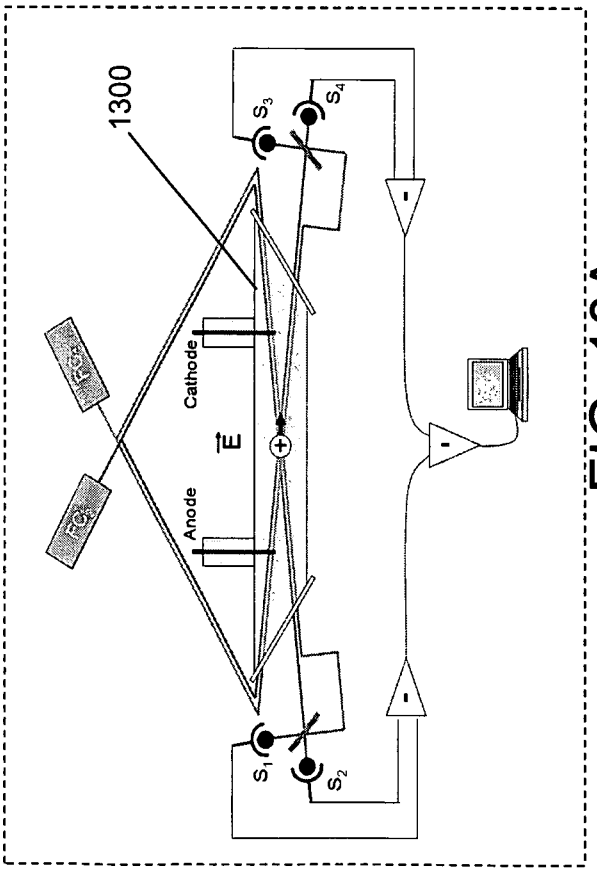


FIG. 10A

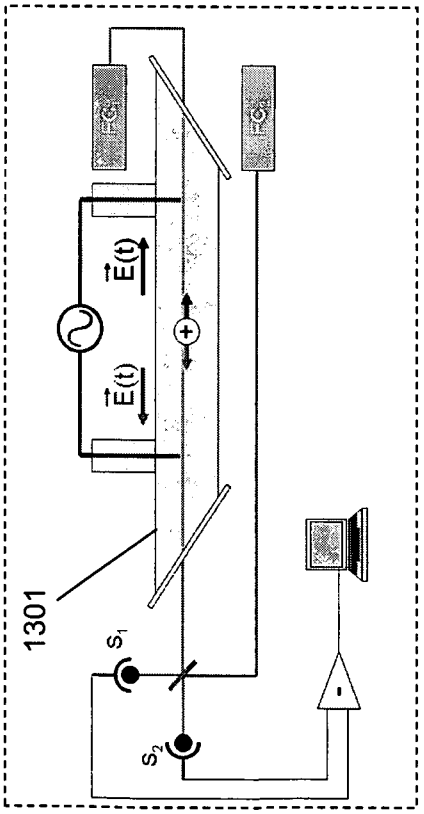


FIG. 10C

FIG. 10

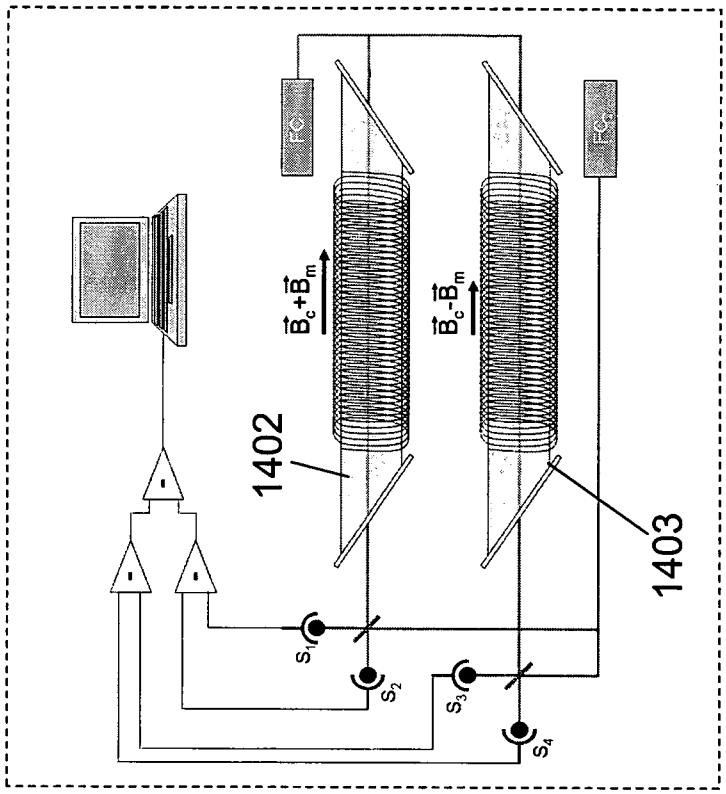


FIG. 11B

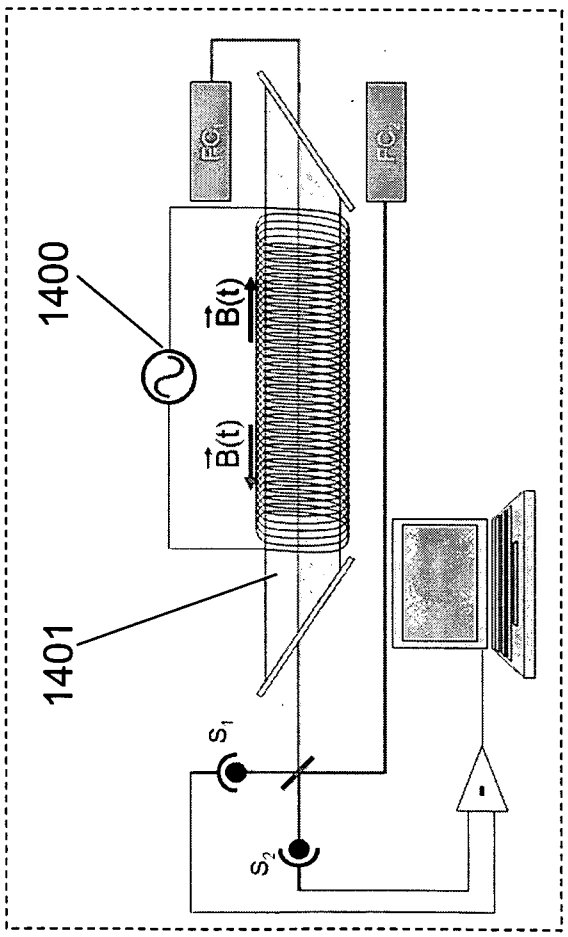


FIG. 11A

FIG. 11

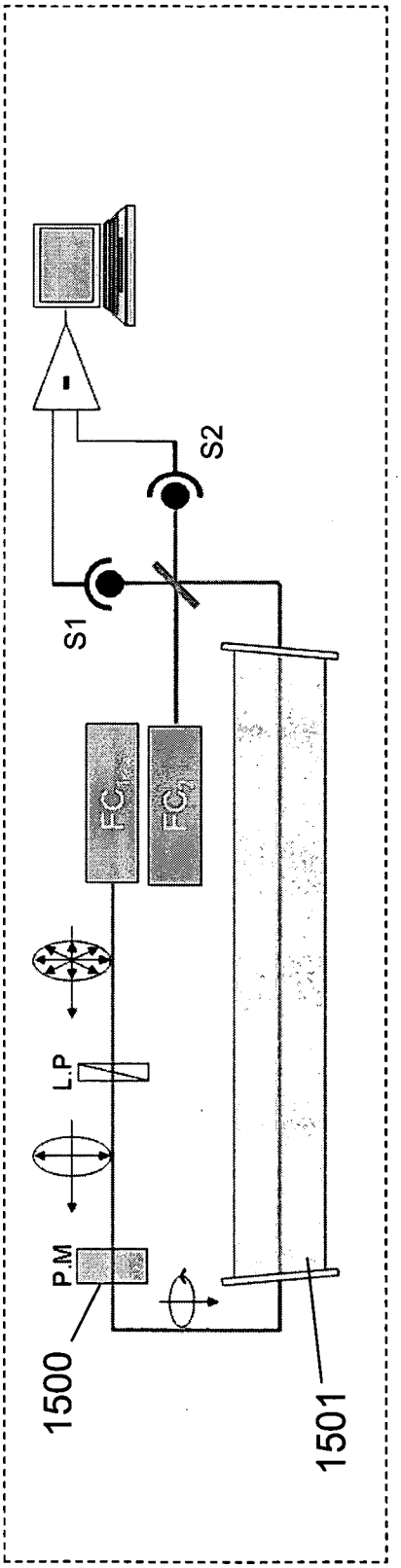


FIG. 12A

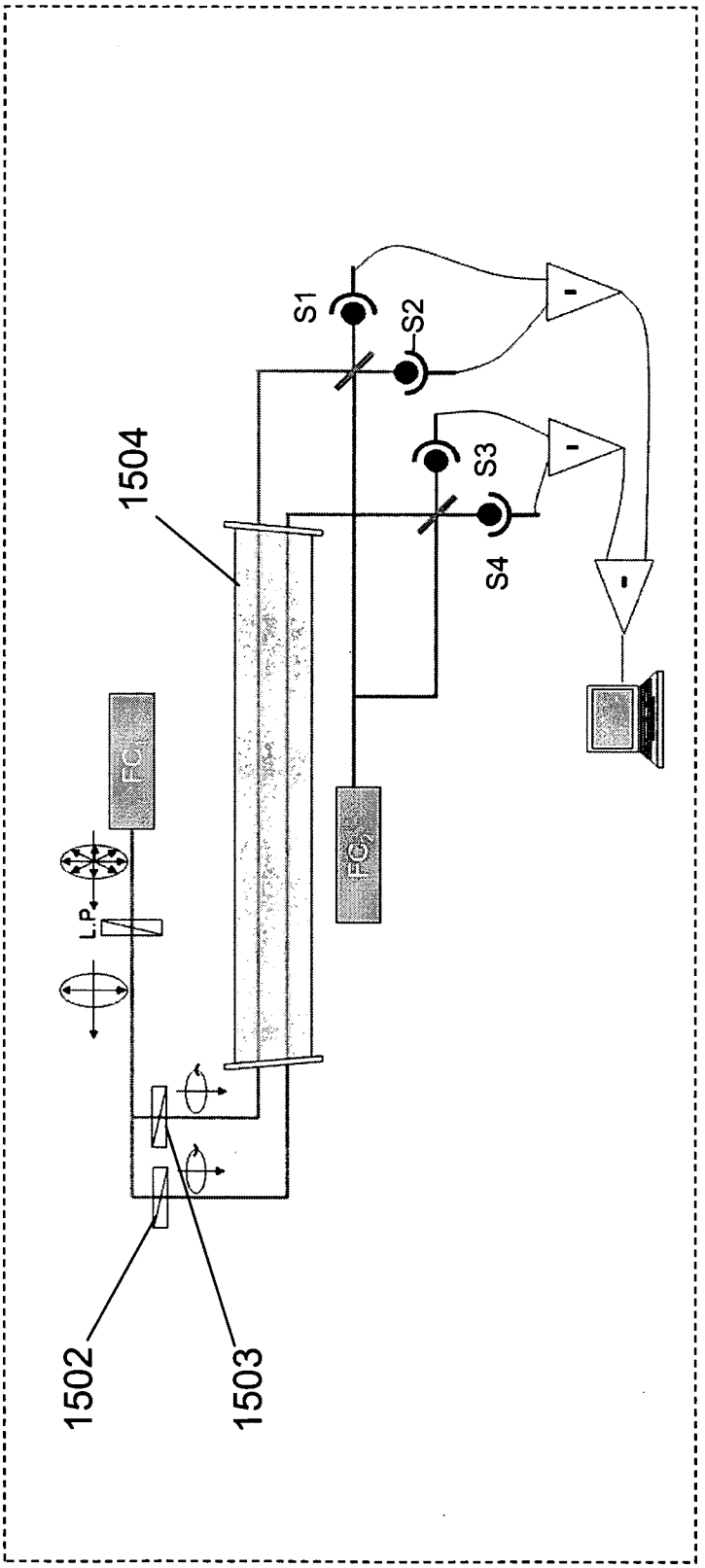


FIG. 12B

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2009/006307

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01J3/453

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)
G01J

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

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PHILIPPE GIACCARI ET AL: "Active Fourier-transform spectroscopy combining the direct RF beating of two fiberbased mode-locked lasers with a novel referencing method" OPTICS EXPRESS, OSA (OPTICAL SOCIETY OF AMERICA), WASHINGTON DC, (US), vol. 16, no. 6, 14 March 2008 (2008-03-14) , pages 4347-4365, XP007910152 ISSN: 1094-4087 abstract; figure 4 page 4358, paragraph 3. page 4361, paragraph 4.1 ----- -/--	1-11

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

[X] See patent family annex.

* Special categories of cited documents :

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

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

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

"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
16 October 2009	26/10/2009

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	Varelas, Dimitrios

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2009/006307

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	WO 2009/000079 A1 (UNIV LAVAL [CA]; GIACCARI PHILIPPE [CA]; GENEST JEROME [CA]; TREMBLAY) 31 December 2008 (2008-12-31) abstract; figures 2,7-12 page 3, line 15 - page 5, line 16 page 9, lines 3-14 page 10, line 29 - page 11, line 7 page 15, lines 7-26 page 17, line 30 - page 18, line 27	1-11
A	DE 10 2005 050151 B3 (MAX PLANCK GESELLSCHAFT [DE]) 2 November 2006 (2006-11-02) the whole document	1-11

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2009/006307

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2009000079 A1	31-12-2008	NONE	
DE 102005050151 B3	02-11-2006	WO 2007045461 A1	26-04-2007