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MITCHELL, PH. ET AL.: "Development of a High Speed Wideband Frequency Tunable Infra-Red Laser Source for Real Time Wind Turbine Array Sensing Applications", PROC. OF SPIE, Bd. 8069, 2011, Seiten 806907-1-806907-1, XP040560240,

The invention relates to a LIDAR measuring device and to a method for determining the velocity of particles in a measuring volume. With the help of the described device and also the method, the measurement of a wind velocity in a remote measuring volume is realized using a narrow-band continuous wave laser light source. The light emitted by the continuous wave laser light source is coupled into a measuring branch and a reference branch, wherein at least part of the light coupled into the measuring branch is at least partially emitted by a transmitting device in the direction of the measuring volume, in such a manner that the emitted light is at least partially scattered and/or reflected by the particles in the measuring volume, so that at least part of the scattered and/or reflected light is received by a receiving device. This scattered and/or reflected light which is received is finally coherently superimposed with the light leaving the reference branch and the light radiation resulting from this is directed onto a detector to generate a detector signal characteristic of the resulting light radiation. The velocity of the particles in the measuring volume is determined in an analysis unit, taking account of the detector signal.

In general, land-based measuring methods for determining the wind velocity and wind direction for different altitude regions of the atmosphere, in order to monitor emitters of industrial pollutants, for example, for weather forecasting and also for atmospheric and climate research, have been known in the art for many years. In this context, for example, so-called SODAR measuring systems are used for wind measurements, wherein they use the Doppler effect in the case of soundwaves which are scattered back from the atmosphere. Due to the use of wind power, which has become increasingly important in recent years, a new and important area of application has opened up for measuring methods of this kind to measure wind velocity and direction in areas remote from the actual measuring device. In addition to SODAR systems, which are known in the art, so-called LIDAR measuring systems, in which light is used instead of sound and which are partially superimposed on the SODAR, have recently been used for measurements of this kind.

LIDAR (Light Detection and Ranging) is a method, related to radar, for the optical measurement of distance and velocity, and for the measurement of atmospheric parameters. LIDAR systems for atmospheric measurement emit laser radiation and detect the light scattered back from the atmosphere. The distance from the location of the scattering is calculated from the light propagation time of the signals. In particular, clouds and dust particles in the air

scatter the laser light and allow a high-resolution selection and distance measurement of clouds and aerosol layers.

Furthermore, it is possible to determine the wind velocity prevailing at a location remote from the measuring device using LIDAR measuring systems, by measuring light which is scattered or reflected on particles moved by wind. This type of measurement can be used, in particular, to measure the wind velocity prevailing upstream of a wind turbine up to several hundred metres away and to adapt control parameters of the wind turbine based on the measured wind velocity. On one hand, the most effective possible use of a wind turbine and, on the other hand, system overloads due to special wind events should thereby be guaranteed. In this way, emergency measures can be promptly introduced, for example when there are extreme gusts of wind, so that damage to the wind turbine is largely prevented.

The LIDAR measuring systems known in the art for determining wind velocities are based on the detection and evaluation of the Doppler frequency shift of the scattered light caused by the scattering of laser light on the particles moved with the wind, by comparison with the emitted light (cf.: C. Weitkamp, LIDAR-range-resolved optical remote sensing of the atmosphere, Springer 2005).

Typically, the Doppler frequency shift is determined interferometrically by superimposing the scattered light received by the measuring device with light which is coupled within the measuring device by the laser light source by means of a second optical path. To this end, highly coherent laser light sources which emit light with coherence lengths of several hundred metres, in which the bandwidth of the frequency falls in the sub-MHz range, are used with the LIDAR measuring devices known in the art.

In order to guarantee the spatial resolution which is necessary or desired in each case, two different procedures are essentially known in the art. A first technical variant provides for the use of continuous wave laser sources which are focused on the desired target area in each case with the help of a suitable optical system, for example a lens or a telescope. A corresponding technical solution is described in WO 2005/1142531. Insofar as the desired focus area is to be changed, this is achieved with the help of mechanical elements which usually have, however, a comparatively complex design and are expensive. Moreover, adjusting elements of this kind carry the risk of additional faults, primarily during prolonged operation.

A second technical variant for achieving and changing the desired spatial resolution is based on the use of pulsed laser sources. In this case, the location is determined by means of a propagation time measurement of the laser pulses. In this way, multiple measuring regions can be measured by the measuring system one after the other with a pulse, the pulse width of which determines the spatial resolution which is 30 m, for example, for pulses with a width of 200 ns. In this case, the individual measuring regions measured one after the other may each represent subsections of the entire measuring volume to be tested.

However, the illumination of an individual measuring region by a pulse, said illumination only occurring for a short time in each case, results in poor signal-to-noise ratios. Furthermore, the frequency resolution, and therefore also the resolution of the wind velocity, is limited due to the short pulse widths.

Starting from the previously described measuring systems, WO 2014/072514 discloses a further technical solution for recording the wind velocity in a remote spatial area, which achieves a change in the spatial resolution using alternative technical measures. It is essential for this technical solution that a narrowband light source which is modulated with a defined phase pattern is used instead of the laser light sources typically used. Firstly, a relatively low transmission power is required due to the use of a continuous wave laser source, as compared with pulsed LIDAR. Moreover, the spatial resolution does not have to be balanced against the velocity resolution, as is the case of a pulse LIDAR, but rather both parameters can be selected independently of one another within broad limits. In comparison with the focused continuous wave LIDAR (CW-LIDAR), this solution also offers the advantage that the spatial resolution does not become coarser as the distance increases, but rather is independent of the distance.

An essential component of the LIDAR measuring device described is a modulator which is based, for example, on the electro-optical effect in a suitable material and which guarantees desired phase modulation of the frequency of the light emitted by a laser diode. In relation to the measuring device, this modulator represents a comparatively expensive component, which further requires a suitable actuation and power supply.

A problem with the LIDAR measuring systems hitherto known in the art is that a spatial resolution can only be guaranteed either with a comparatively large amount of effort and components which are in some cases liable to fail, or comparatively expensive opto-electronic components are required. This makes the provision of reliable and, at the same time,

economically viable LIDAR measuring devices significantly more difficult, particularly for use in wind power. Furthermore, with the LIDAR measuring devices known in the art, it is often not possible to differentiate in a satisfactory manner a positive Doppler shift, caused by different movements of the particles in the measuring region, from a negative Doppler shift.

5 Further measuring devices often have to be used for this purpose, in addition to the LIDAR measuring device.

Furthermore, Seiichi Kakuma describes: "Frequency-modulated continuous-wave laser radar using dual vertical-cavity surface-emitting laser diodes for real-time measurements of distance and radial velocity" (XP036152994) an "FMCW Laser Radar" for measuring the distance of particles and also the radial velocity. The essential thing about the solution which is described is that the laser light source has two surface emitters (VCSEL), the frequency of which can be changed over a range of 850 GHz in each case, wherein the frequency of the one laser is increased linearly during measurement and the frequency of the other laser is reduced. In order to vary the frequencies, the injection currents are synchronously modulated in this case.

Philip Mitchell et al.: "Development of a High Speed Wideband Frequency Tunable Infra-Red Laser Source for Real Time Wind Turbine Array Sensing Applications" (XP040560240) discloses a laser light source for determining wind velocities, wherein by varying the injection current, a change in frequency of the emitted light can likewise be brought about.

Taking account of the technical solutions known from the prior art for recording the velocity and direction of movement of particles in a remote measuring volume with the help of a LIDAR measuring system, and the previously explained problems, the problem addressed by the invention is that of developing a LIDAR measuring system in such a manner that a highly precise velocity measurement of particles moved in the remote measuring region is possible with the help of a comparatively simple construction. The technical solution to be specified in this case should primarily enable a comparatively simple adjustment and setting of the spatial resolution. It should further be ensured that a direction of movement of the particles in the measuring region can also be reliably determined using simple means, in particular without the additional measuring devices and/or complex components being absolutely necessary.

The aforementioned problem is solved with a device according to Claim 1, as well as a method according to Claim 14. Particularly suitable uses of the invention are specified in Claims 12

and 13. Advantageous embodiments of the invention are the subject matter of the dependent claims and will be explained in greater detail in the following description with occasional reference to the exemplary embodiments.

5 The invention is based on a LIDAR measuring device for determining the velocity of particles in a measuring volume with a narrowband continuous wave laser light source which emits light modulated in its optical frequency and then coupled into a measuring branch and a reference branch. The light coupled into the measuring branch is at least partially emitted in the direction of the measuring volume by a transmitting device, in such a way that the emitted light is at
10 least partially scattered and/or reflected by the particles in the measuring volume, so that at least part of the scattered and/or reflected light is received by a receiving device. Furthermore, the received light is coherently superimposed with the light leaving the reference branch, and the light radiation resulting from this is directed onto a detector in order to generate a detector signal characteristic of the resulting light radiation. The velocity of the particles in the
15 individual measuring regions of the measuring volume is finally determined in an analysis unit taking account of the detector signal. Using a control unit, the frequency of the light emitted by the laser light source is varied in a predefined manner, and a spectral analysis of the detector signal is carried out in the analysis unit, in order to calculate the velocity of the particles in the individual measuring regions of the measuring volume, while taking account of the predefined
20 frequency change and/or frequency modulation. The expressions "frequency modulation" and/or "frequency change" should be understood as having the same meaning with reference to the description of the invention.

When evaluating the received radiation, a Doppler frequency shift is determined and evaluated
25 in each case between the radiation entering the respective measuring region and the received, scattered or reflected radiation. In contrast with the technical solutions known in the art, it is essential to the invention that the frequency of the light emitted by the laser light source is changed and/or modulated. Due to the modulation of the frequency, it is possible, with the help of a known function, to select the spatial resolution and to precisely define the distance
30 between the measuring device and the measuring region to be measured in each case with the particles contained therein.

This is achieved in that a spectral broadening and deformation of the at least largely monochromatic light is achieved based on the change in frequency of the light emitted,

wherein the bandwidth determines the coherence length. It is therefore possible to realize various coherence lengths, and therefore spatial resolutions, with the same laser light source. A narrowband laser light source, which is preferably light with a bandwidth which is less than 1 MHz, preferably less than 100 kHz, particularly preferably less than 10 kHz, is used as the laser light source. The measuring device preferably contains an optical amplifier which may be located behind the laser source before the split-off into the measuring and reference branch or in the measuring branch.

In an advantageous manner, the power supply of the laser light source is modulated directly, which ultimately leads to a variation in the frequency of the emitted light radiation, and therefore of the power spectral density. Due to the technical solution used, that is the frequency modulation of the emitted light, a highly precise measurement of the velocity of the particles moved in a remotely placed measuring volume can be carried out without the use of comparatively expensive components.

According to a special embodiment of the invention, the laser light source is configured as a laser diode which emits at least approximately monochromatic light. In a preferred manner, the injection current of the laser diode is varied in this case with the help of a suitably configured control unit and/or with the help of the control signal generated by the control unit. This variation in the supply current leads, on one hand, to a typical, insignificant change in the output power and, on the other hand, to a desired variation in the optical frequency and/or wavelength of the emitted light. In this way, it is possible with a DFB laser, for example, which emits light in a wavelength range of 1530 to 1570 nm, preferably of 1550 nm, to achieve a change in the optical frequency per injection current change in the range of 0.5 to 1 GHz/mA. However, lasers of this kind typically have a line width of 1 to 3 MHz, which is not particularly well-suited to the described application, at least. If smaller line widths, for example of 50-100 kHz, are required, so-called extended cavity lasers (ECLs) can be used in an advantageous manner, which have a tuning coefficient that is greater than 0.1 GHz/mA.

Instead of implementing the intended frequency modulation through a modulation of the injection current, special laser diodes with frequency tuning ranges and special tuning electrodes can also be used.

In a particular development, in addition to the frequency modulation of the light emitted by the laser light source the analysis unit is configured in such a manner that, on one hand, the known frequency function and, on the other hand, an additional time shift value are considered when evaluating the generated detector signal. The time shift value is selected in such a manner that the result of the function corresponds to the detector signal which would result when selecting a reference branch, which has a propagation time modified by the time shift value and therefore also a correspondingly modified optical path length, as compared with the actual reference branch.

This embodiment is based on the knowledge that the detector signal not only contains the information required for the evaluation regarding particles in the measuring range corresponding to the actual optical path length of the reference branch and the coherence length, which measuring range only represents part of the total illuminated region, but also information in each case regarding particles and other illuminated regions which do not correspond to the selected measuring region and/or the selected spatial resolution in the measurement being taken at the time.

In an advantageous manner, a continuous wave laser light source is used, the emitted light of which has a coherence length in a range from 0.1 to 100 m based on the frequency modulation.

Particularly suitable is a coherence length in a range from 1 to 100 m and quite particularly suitable in a range from 1 to 50 m. When selecting the laser light source and/or defining the coherence length, consideration should be given to the fact that coherent interference on the detector is only possible for scattered light from particles and/or only reflected light from objects, for which the optical path length of the measuring branch within the coherence length matches the optical path length of the reference branch. For this reason, a high spatial resolution, which is adjustable through the selection of the coherence length, is achieved by means of a greatly limited coherence length. In contrast, the scattered light reaching the detector array, said scattered light coming from particles located outside the coherence range, leads only to a broadband background in the detector signal, which can lead to a small reduction in the signal-to-noise ratio, but does not impact the spatial resolution. If the coherence range is smaller than the maximum extent of the measuring volume, only a partial section, namely the measuring region in each case, is measured, and by shifting the coherence range, for example with the help of an optionally available device to change the optical path length of the reference branch, which is preferably done with computing means, a spatial

resolution determined by means of its optical length, the coherence length, can be achieved. In an advantageous manner, the spatial resolution is independent of the distance of the measuring region tested in each case.

- 5 The invention is characterized in that the control unit is configured in such a manner that the variation in frequency of the light emitted from the laser light source takes place based on a control signal generated by the control unit, said control signal corresponding to a pseudo-noise signal caused by a predefined frequency function. In this way, it is possible to modulate the frequency of the emitted light in a desired manner and, in this case, to adapt the optical
10 power spectral density, in particular, in a desired manner. Because the frequency function used in the control unit in each case is known in the art, the respective laser light source can be used to implement various coherence lengths and therefore various spatial resolutions.

- In a particular development of the invention, the frequency of the light emitted by the
15 continuous wave light source varies in such a way that it has a time-linear portion, said portion being generated by an approximately time-linear portion in the laser diode injection current, for example. This may be combined with the pseudo-noise profile described above.

- This measure enables, in a preferred manner, the sign to be detected during the frequency shift
20 between the frequency of the emitted and received light caused by the Doppler effect.

- The signal derived from the scattered and/or reflected light received does not contain information on the frequency of the light, but on the difference compared with the frequency of a reference light which was guided from the laser light source via the reference branch. The
25 velocity of the particles moved in the measuring volume is derived from this difference, taking account of the Doppler effect. In the simplest case, the reference light is branched off from the transmitter and then has the same frequency as the emitted light.

- In this context, however, it must be considered that the frequency difference may have a
30 positive or negative sign, depending on whether the direction of movement of the particles in the measuring volume is towards the LIDAR or away from the LIDAR. Due to the modulation provided according to the invention of the frequency of the light emitted by the laser light source, it is preferably conceivable for the frequency of the light to be superimposed with a further linear time-dependent signal, so that the transmitting frequency of the light emitted

towards the measuring volume changes linearly. In an advantageous manner, it is provided in this case that a difference between the transmitting frequency and a frequency of the scattered and/or reflected light received by the receiving device is selected to be large enough that a sign of the difference does not change despite a Doppler shift in the frequency of the received light compared with the transmitting frequency, said shift being caused by the movement of the particles. As soon as a particularly large difference between the transmitting frequency and the receiving frequency is selected in a suitable manner, the Doppler shift can no longer change the sign of the difference and there is clarity in relation to the direction of movement of the particles in the measuring volume.

With the previously described design of the linear frequency modulation, the frequency resolution can be worsened in an undesirable manner. This can be avoided by means of a corresponding limit on the slope of the linear frequency modulation. The sign of the difference between the transmitting frequency and the receiving frequency, which may then possibly change, can be detected by triangular frequency modulation and separate analysis of the ascending and descending branch. The total appears in one branch and the difference between the Doppler shift and the frequency shift, based on propagation time, appears in the other branch.

In a further particular embodiment of the invention, the frequency of the light emitted by the continuous wave laser light source is changed and/or modulated upwards and downwards. The resulting frequency shift of the received signal compared with the transmitting signal then depends on the distance between the measuring region and/or the volume region in which the scattering takes place on the particles, and on the Doppler shift. The frequency resolution is determined, as in the previously described method, using superimposed stochastic and linear frequency modulation by means of the slope of the modulation and the spatial resolution. The spatial resolution in this case is generated in a known manner by means of focusing, particularly with the help of suitably adjustable optical elements. Due to the triangular modulation of the transmitting signal, the sign of the frequency shift can also be determined in a preferred manner during the evaluation of the difference frequencies in the ascending and descending branch, as previously described. Compared with the methods known in the art, which provide for the determination of the wind direction using an additional measuring device, in particular a weather vane, or the determination of the distance share based on a separate measurement, in this case triangular modulation represents a particularly economical

method for achieving clarity when determining the direction of movement of the particles in the measuring volume. A further advantage of triangular modulation is that not only the Doppler shift, but also the precise effective distance of the focus, can be derived through evaluation of the difference frequencies in the ascending and descending branch. Depending on whether the Doppler shift brings about a sign change of the difference frequencies or not, the Doppler shift is equal to half the difference (total) of the difference frequencies and the distance of the focus is equal to a quarter of the light velocity multiplied by the total (difference) of the difference frequencies. It is easy to decide which case it is, because the approximate distance of the focus is known.

A special development of the invention is characterized in that an optical switch, for example an acousto-optic modulator, is used in the measuring branch. The pulse lengths in this case should be selected in such a manner that they are longer than what corresponds to the desired spatial resolution, so that the spatial resolution is furthermore determined by the frequency modulation of the laser source. In this operating mode, the detector signal is no longer continuously available. Despite this, there are advantages in certain applications, for example when inner reflexes from the measurement setup cannot be sufficiently suppressed, when a strongly incoherent background can greatly worsen the signal-to-noise ratio due to strong scattering outside of the measuring volume, or when special properties of the optical amplifier in pulse mode mean that a significant advantage can be expected. The advantages of a measuring system designed according to the invention with a pulsed laser exist in that longer ranges can be achieved compared with non-pulsed operation, without normal pulsed systems being limited with respect to spatial resolution and velocity resolution.

A special development of the invention is characterized in that the light emitted by the laser light source is fed to an optical amplifier, in particular an erbium-doped fibre amplifier, before the branching of the measuring and reference branch. In addition, polarization-maintaining fibres are preferably used for the measuring device designed according to the invention. If fibres of this kind are not used, it is generally conceivable to provide at least one light-polarizing element, preferably a polarization regulator, particularly in the reference branch.

A LIDAR measuring device designed according to the invention, as has previously been described, is particularly suitable for recording wind velocity and/or a wind direction prevailing on the windward side of a wind turbine. In this context, it is further conceivable for

a corresponding LIDAR measuring device to be mounted on the spinner of a wind turbine, so that the velocity and wind direction of the wind flowing to the wind turbine can be detected at a sufficient distance, in order to enable, on one hand, effective operation of the wind turbine and, on the other hand, to prevent damage to the wind turbine, for example due to sudden gusts of wind, primarily by adjusting the pitch of the rotor blades, in order to reduce the load, or by initiating an emergency shutdown.

Furthermore, the invention also relates to a method for determining the velocity of particles in a measuring volume, in which light is transmitted using a narrowband continuous wave laser light source and coupled into a measuring branch and a reference branch. The light coupled into the measuring branch is at least partially emitted in the direction of the measuring volume by a transmitting device, in such a way that the emitted light is at least partially scattered and/or reflected by the particles in the measuring volume. At least part of the scattered and/or reflected light is received by a receiving device of the LIDAR measuring device and is coherently superimposed with the light leaving the reference branch, and the light radiation resulting from this is directed onto a detector in order to generate a detector signal characteristic of the resulting light radiation. The velocity of the particles in the measuring volume is finally determined in an analysis unit taking account of the detector signal. Using a control unit, a frequency of the light emitted by the laser light source is varied in a predefined manner, and a spectral analysis of the detector signal is carried out in the analysis unit, in order to calculate the velocity of the particles in the individual measuring regions of the measuring volume, while taking account of the predefined frequency modulation. A laser diode, the injection current of which is varied based on a suitable control signal, is advantageously used as the laser light source.

Based on a corresponding variation in the frequency of the light emitted by the laser diode, it is possible to change the spatial resolution of the LIDAR measuring device without having to use a different laser light source or perform a mechanical adjustment for this purpose.

The method configured according to the invention is characterized in that the variation in frequency of the light emitted from the laser light source takes place based on a control signal generated by the control unit, said control signal corresponding to a pseudo-noise signal selectively caused by a predefined frequency function.

In the following, the invention is explained in greater detail by means of exemplary embodiments with reference to the figures, without limiting the general concept on which the invention is based. In the drawings:

- 5 Figure 1: shows a principle structure of a LIDAR measuring device configured according to the invention;
- Figure 2: shows the profile of the electrical power spectral density as a function of the frequency;
- Figure 3: shows the profile of a modulated frequency over a period of time;
- 10 Figure 4: shows the profile of the modulated injection current over a period of time.

Figure 1 schematically depicts a LIDAR measuring device configured according to the invention. The LIDAR measuring device has a continuous wave laser light source 1 with an output power of 10 mW which emits light with a wavelength of 1550 nm. The light emitted by the laser light source 1 is coupled, on one hand, into an at least partially fibre-optically defined measuring branch 3 and, on the other hand, into a completely fibre-optically defined reference branch 4 with the help of a fibre-optic coupler, which assumes the function of a beam splitter 2. The optic fibres used are preferably single mode fibres with low damping and a field radius of advantageously 5 μm . Polarization-maintaining fibres, so-called PM fibres, are preferably used.

20 A further fibre-optic coupler 5 for combining the light from the measuring branch 3 and from the reference branch 4 is arranged at the end of the measuring branch 3 and the reference branch 4. The light leaving the reference branch 4 is coherently superimposed with the received light and the resulting light radiation is guided to the detector 6. According to this exemplary embodiment, the detector has two separate photodetectors which are preferably

25 configured as InGaAs detectors. Signals which are characteristic of the detected radiation are generated with the help of the detector 6, wherein the two signals are subtracted from one another in a subtraction element 14, in order to eliminate faults (balanced detection). The difference signal is finally supplied to an analysis unit 11 by means of an analog-digital converter 12, in which analysis unit the different signal is evaluated to detect the presence

30 and/or movement of particles.

If no PM fibres are being used, an adjustable, fibre-optic polarization regulator and a diverting path, for example in the form of a wound section of fibre, are provided in the reference branch 4.

The measuring branch has an erbium-doped fibre amplifier with a preferred output power of 1 W and an optic circulator 7 arranged sequentially as the amplifier 8. From the circulator 7, the light coupled into the measuring branch 3 via the fibre portion is fed to a transmitting and receiving lens 10 with a focal length of 250 mm, for example, and from there it is focused in the direction of the measuring volume to be measured and/or the respective measuring region.

The radiation scattered and/or reflected on particles in the measuring volume then reaches, at least in part, the transmitting and receiving lens 10 of the LIDAR measuring device. In the exemplary embodiment shown here, the transmitting and receiving devices are combined in the transmitting and receiving lens 10. The scattered and/or reflected light received in this way is subsequently coupled into the remaining fibre-bonded portion of the measuring branch 3 via the circulator 7.

The continuous wave laser light source 1 has a laser diode 9 and is coupled to a control unit 13 which varies the injection current of the laser diode 9 in a suitable manner, so that the frequency of the light emitted by the laser diode is also changed. A frequency function is stored in the control unit 13, depending on the desired spatial resolution in each case, so that the light emitted by the laser light source 1 is changed, in particular broadened and deformed, compared with the light typically emitted by the laser diode 9 by means of modulation as a function of the frequency function in the optical power spectral density. With the help of the control unit 13, the frequency of the emitted light is therefore changed based on a suitable frequency function defining a pseudo-noise signal. By considering different time-shift values during evaluation by the analysis unit, the detection of particles, and the movement thereof, can be carried out separately in a spatially resolved manner for various measuring regions at different distances from the lens 10, in purely mathematical terms without changing the described setup.

It is essential to the invention that the frequency of the light emitted by a laser light source 1 is selectively varied, so that no phase modulator is required for the laser light source and, furthermore, no acousto-optic modulator (AOM) is required, in contrast with the technical solutions known from the prior art.

In order to achieve suitable frequency modulation, so that the phase modulator used according to the prior art can be dispensed with and modulation of the frequency of the emitted light is

still achieved, which achieves the same effect as with the phase modulation $\Theta(t)$ used in known measuring systems, the instantaneous frequency of the laser diode according to

$$f_{\text{mod}}(t) = \frac{1}{2\pi} \cdot \frac{d\Theta(t)}{dt}$$

must be changed, wherein $\Theta(t)$ corresponds to the value of the respective phase. To do this, a

5 modulation of the injection current of

$$\delta i_{\text{mod}}(t) = \frac{1}{\gamma_{\text{lin}}} f_{\text{mod}}(t) = \frac{1}{2\pi \gamma_{\text{lin}}} \cdot \frac{d\Theta(t)}{dt}$$

is necessary.

However, this leads to an unwanted modulation of the laser output power

$$10 \quad \delta P_{\text{ol,mod}}(t) = \beta \cdot \delta i_{\text{mod}}(t) = \frac{\beta}{2\pi \gamma_{\text{lin}}} \cdot \frac{d\Theta(t)}{dt}$$

where $\beta = dP_0/di$ characterizes the slope efficiency, for which 0.2 mW/mA can be assumed to be the reference value.

From the laser output power $P_0 + \delta P_{\text{ol,mod}}$ a part ρ is coupled into the LO branch, wherein the

15 modulation-based variation in the transmission power is insignificant:

$$P_{\text{LO}} + \delta P_{\text{LO}}(t) = \rho (P_0 + \delta P_{\text{ol,mod}}(t)) = \rho P_0 + \rho \beta \cdot \delta i_{\text{mod}}(t) = \rho P_0 + \frac{\rho \cdot \beta}{2\pi \gamma_{\text{lin}}} \cdot \frac{d\Theta(t)}{dt}$$

With an ideal, balanced reception, the variation in the LO power is not noticeable. With a real, balanced reception, an AC signal of

$$20 \quad \delta i_{\text{Det}} = \varepsilon \cdot \mathcal{R} \cdot \delta P_{\text{LO}}(t) = \frac{\varepsilon \cdot \mathcal{R} \cdot P_{\text{LO}} \cdot \beta}{2\pi \gamma_{\text{lin}} \cdot P_0} \cdot \frac{d\Theta(t)}{dt}$$

with the photodiode response sensitivity $\mathcal{R} = 1 \text{ A/W}$ applicable to the detector is received at the output. By comparison, a detector current with the root mean square

$$i_{\text{signal,eff}} = \mathcal{R} \cdot \frac{1}{\sqrt{2}} \sqrt{P_{\text{signal}} \cdot P_{\text{LO}}}$$

25 results for a (corrected) useful signal of the power P_{signal} .

For a rough comparison, the squared root mean square of $f_{\text{mod}}(t)$ where

$$\overline{f_{\text{mod}}^2(t)} = \frac{1}{2} f_{\text{max}}^2$$

is estimated. This results in

$$\frac{\overline{(\delta i_{Det})^2}}{\overline{(i_{signal,eff})^2}} \cong \left(\frac{\varepsilon \mathcal{R} P_{LO} \beta \cdot f_{max}}{\gamma_{tun} \cdot P_0} \right)^2 \cdot \frac{1}{\mathcal{R}^2 \cdot P_{signal} \cdot P_{LO}} = \left(\frac{\varepsilon \beta \cdot f_{max}}{\gamma_{tun} \cdot P_0} \right)^2 \cdot \frac{P_{LO}}{P_{signal}}$$

where

5 $\varepsilon = 0.01$; $\beta = 0.2 \text{ mW} / \text{mA}$, $y_{tun} = 100 \text{ MHz} / \text{mA}$; $P_0 = 20 \text{ mW}$; $f_{max} = 10 \text{ MHz}$; $P_{LO} = 100 \text{ }\mu\text{W}$
results in

$$\frac{\overline{(\delta i_{Det})^2}}{\overline{(i_{signal,eff})^2}} \cong \frac{10^{-14} \text{ W}}{P_{signal}}$$

10 This comparison makes it clear that with a root means square of this kind, the modulation-based noise background can be disregarded. In addition, it should be taken into account that the signal is narrowband, for example 100 kHz, while the modulation-based noise is broadband and is focused on the low-frequency frequency range, as shown in Figure 2.

15 In the case of the phase modulation known from the prior art with the electro-optical phase modulator, the predefined phase $\Theta(t)$ is used for correction. The phase modulator is actuated with a signal proportional to the phase. This may result in a scaling error, so that the phase impressed on the optical signal is $\tilde{\Theta}(t) = \eta_{scale} \cdot \Theta(t)$. In this context, it is known that values of $\eta_{scale} = 0.9 \dots 1.1$ are non-critical.

20 With the direct modulation provided according to the invention of the laser light source with the help of a suitable frequency function, a modulation signal according to

$$\delta i_{mod}(t) = \frac{1}{\gamma_{tun}} f_{mod}(t) = \frac{1}{2\pi \gamma_{tun}} \cdot \frac{d\Theta(t)}{dt}$$

25 is impressed on the injection current. If a scaling error occurs in this case as well, to which the following applies

$$\delta \tilde{i}_{mod}(t) = \eta_{scale} \cdot \frac{1}{2\pi \gamma_{tun}} \cdot \frac{d\Theta(t)}{dt} = \frac{1}{2\pi \gamma_{tun}} \cdot \frac{d(\eta_{scale} \Theta(t))}{dt}$$

30

the effects are the same. This immediately means that the LIDAR measuring device according to the invention, with which frequency modulation is performed directly on the laser light source, can be realized, so that the phase modulator which was previously used can be dispensed with.

5

As the above embodiments have already shown, it is known from the prior art to subject the optical wave emitted by a laser light source to a predefined phase modulation $\Theta(t)$ with the help of a phase modulator and to shift the optical frequency in an interferometer arm by f_{AOM} by means of an acousto-optic modulator (AOM). A stationary target at distance z then

10

supplies a detector signal.

$$u(t) \propto \exp \left\{ j \left[2\pi f_{AOM} t + \Theta \left(t - \frac{2z}{c} \right) - \Theta(t) \right] \right\} \quad (1)$$

If the target moves at velocity v in the $+z$ direction, a Doppler shift

15

$$f_{Doppler} = -\frac{2}{\lambda} v$$

also occurs:

$$u(t) \propto \exp \left\{ j \left[2\pi f_{AOM} t + 2\pi f_{Doppler} t + \Theta \left(t - \frac{2z}{c} \right) - \Theta(t) \right] \right\} \quad (2)$$

For correction, this signal can be multiplied by the known function

20

$$h(t; z) \propto \exp \left\{ -j \left[\Theta \left(t - \frac{2z}{c} \right) - \Theta(t) \right] \right\} \quad (3)$$

The corrected signal for position z is then purely sinusoidal:

25

$$u_{ent}(t) = u(t) \cdot h(t; z) \propto \exp \left\{ j \left[2\pi f_{AOM} t + 2\pi f_{Doppler} t \right] \right\} \quad (4)$$

In the spectrum, it provides a narrow line for $f_{AOM} + f_{Doppler}$.

If this correction function $h(t; z)$ is used, the target is, however, at locations

30

$$z_1 < z - \frac{\Delta z_{LC}}{2}$$

or

$$z_2 > z + \frac{\Delta z_{LC}}{2}$$

meaning that the electrical power spectral density is broad. The width depends on $\Theta(t)$.

Likewise, the variable Δz_{LC} depends on the phase pattern $\Theta(t)$ and is characterized as the spatial resolution, due to the modulation-based low coherence. Corresponding phase patterns, e.g. for $\Delta z_{LC} = 5\text{m}, 10\text{m}, 15\text{m}$ can be found numerically by means of a special iteration process.

Targets within the range

$$\left[z - \frac{\Delta z_{LC}}{2}, z + \frac{\Delta z_{LC}}{2} \right] \quad (5)$$

therefore provide approximately a narrow spectrum at the frequency $f_{AOM} + f_{Doppler}$ having a width

$$\delta f = \frac{q}{T}$$

which is essentially provided by the measuring time T . Outside this range, a broad spectrum is obtained.

According to a further embodiment of the invention, the frequency of the light emitted by the laser light source, particularly a laser diode, is changed into two types. In this context, there is a stochastic modulation of the frequency and, in addition, the frequency of the light emitted by the laser light source is changed in a time-linear manner. The following applies in this case:

$$f_{laser} = f_{laser,0} + \Gamma \cdot t \quad (6)$$

so that a detector signal is obtained according to

$$u(t) \propto \exp \left\{ j \left[2\pi \Gamma \cdot \frac{2z}{c} \cdot t + 2\pi f_{Doppler} t + \Theta \left(t - \frac{2z}{c} \right) - \Theta(t) \right] \right\} \quad (7)$$

In contrast to equation (2), in this case the location-dependent, chirp-based frequency

$$f_{chirp}(z) = \Gamma \cdot \frac{2z}{c}$$

replaces the constant frequency f_{AOM} .

If there is a correction $h(t;z)$ according to equation (3), a result according to equation (4) is obtained:

$$u_{ert}(t) = u(t) \cdot h(t; z) \propto \exp \left\{ j \left[2\pi \Gamma \cdot \frac{2z}{c} \cdot t + 2\pi f_{Doppler} t \right] \right\} \quad (8)$$

Because the chirp rate Γ and the location z are defined and are therefore known, the Doppler frequency $f_{Doppler}$ can be determined from this.

5

If the location of the target is then in turn changed, but the correction function $h(t; z)$ is retained, modified chirp-based frequencies are therefore obtained at the edges

$$z \pm \frac{\Delta z_{LC}}{2}$$

of the spatial resolution

$$f_{chirp} \left(z \pm \frac{\Delta z_{LC}}{2} \right) = \Gamma \cdot \frac{2z}{c} \pm \Gamma \cdot \frac{\Delta z_{LC}}{c} = f_{chirp}(z) \pm \frac{\delta f_{chirp}}{2} \quad (9)$$

10

Within the interval

$$\left[z - \frac{\Delta z_{LC}}{2}, z + \frac{\Delta z_{LC}}{2} \right]$$

the frequency in the spectrum is therefore smeared by δf_{chirp} . To ensure that the Doppler resolution is not substantially worsened as compared with the solution known from the prior art, which uses an acousto-optical modulator (AOM), the following must apply

15

$$\delta f_{chirp} \leq \delta f$$

(10)

20

This results in

$$\Gamma \cdot \frac{2\Delta z_{LC}}{c} \leq \delta f \quad \Rightarrow \quad \Gamma \leq \frac{c}{2\Delta z_{LC}} \cdot \delta f$$

(11)

25 If the largest possible

$$\Gamma = \frac{c}{2\Delta z_{LC}} \cdot \delta f$$

is selected and measurements where $\Gamma = |\Gamma|$ and $\Gamma = -|\Gamma|$ are carried out, which corresponds to a triangular frequency modulation, following correction spectral lines are obtained at the frequencies

$$\begin{aligned} f_+ &= \left| |\Gamma| \cdot \frac{2z}{c} - f_{Doppler} \right| = \left| \frac{z}{\Delta z_{LC}} \cdot \delta f - f_{Doppler} \right| \quad \text{and} \\ f_- &= \left| -|\Gamma| \cdot \frac{2z}{c} - f_{Doppler} \right| = \left| \frac{z}{\Delta z_{LC}} \cdot \delta f + f_{Doppler} \right| \end{aligned} \quad (12)$$

5

The following therefore applies to the Doppler frequency:

$$f_{Doppler} = - \frac{f_+^2 - f_-^2}{4 \cdot \frac{z}{\Delta z_{LC}} \cdot \delta f} \quad (13)$$

If one of the frequencies is $f_{\pm} < \delta f$ and cannot therefore be determined, it is once again the case that $f_{Doppler}$ can also be determined from the other one in each case:

10

$$\text{If } f_- > f_+, \text{ then } f_{Doppler} > 0 \rightarrow f_{Doppler} = f_- - \frac{z}{\Delta z_{LC}} \cdot \delta f \quad (14a)$$

$$\text{If } f_- < f_+, \text{ then } f_{Doppler} < 0 \rightarrow f_{Doppler} = \frac{z}{\Delta z_{LC}} \cdot \delta f - f_- \quad (14b)$$

A few specific sample calculations are shown in the following:

$$\begin{aligned}
 \Delta z_{LC} &= 10m, \quad \delta f = 0.5 MHz, \quad q = 2 \\
 \Rightarrow T &= 4\mu s, \quad \Gamma = 7.5 \cdot 10^{12} Hz/s = 7.5 MHz/\mu s, \\
 \Gamma \cdot T &= 30 MHz, \quad \Delta i_{tot} = \Gamma \cdot T / \gamma_{lum} = 37.5 \mu A \\
 (i) \ z &= 10m, \quad f_{Doppler} = 10 MHz \Rightarrow f_{+} = 9.5 MHz, \quad f_{-} = 10.5 MHz \\
 (ii) \ z &= 50m, \quad f_{Doppler} = 10 MHz \Rightarrow f_{+} = 7.5 MHz, \quad f_{-} = 12.5 MHz \\
 (iii) \ z &= 100m, \quad f_{Doppler} = 10 MHz \Rightarrow f_{+} = 5 MHz, \quad f_{-} = 15 MHz \\
 (iv) \ z &= 20m, \quad f_{Doppler} = 1 MHz \Rightarrow f_{+} = 0 MHz, \quad f_{-} = 2 MHz
 \end{aligned} \tag{15}$$

The following considerations are important to the frequency modulation of the supply current of the laser light source, particularly of the injection current of a laser diode. In this way, a suitable frequency modulation and the linear frequency chirp can be implemented.

With a predefined phase pattern $\Theta(t)$, in order to implement a spatial resolution Δz_{LC} and a desired linear frequency chirp (chirp rate Γ), the total phase modulation of the optical wave must be

$$\Theta_{tot}(t) = \Theta(t) + \frac{1}{2} 2\pi \Gamma \cdot t^2$$

and the associated frequency modulation and current modulation

$$f_{tot}(t) = \frac{1}{2\pi} \cdot \frac{d\Theta_{tot}(t)}{dt} = \frac{1}{2\pi} \cdot \frac{d\Theta(t)}{dt} + \Gamma \cdot t$$

$$\delta i_{mod}(t) = \frac{1}{\gamma_{lum}} f_{tot}(t) = \frac{1}{2\pi \gamma_{lum}} \cdot \frac{d\Theta(t)}{dt} + \frac{\Gamma}{\gamma_{lum}} \cdot t$$

Figures 3 and 4 each show exemplary measurements which demonstrate the previous calculations. In this case, Figure 3 shows the curve of the frequency f_{tot} in MHz and Figure 4 shows the modulated injection current δi_{mod} in μA over a period of 4 μs ($\Gamma = 7.5 MHz/\mu s$; $\gamma_{lum} = 800 MHz/mA$) in each case.

List of reference signs

- 1 Laser light source
- 2 Beam splitter

	3	Measuring branch
	4	Reference branch
	5	Fibre-optic coupler
	6	Detector
5	7	Circulator
	8	Amplifier
	9	Laser diode
	10	Lens
	11	Analysis unit
10	12	Analog-digital converter
	13	Control unit
	14	Subtraction element

Patentkrav

1. LIDAR-måleanordning til bestemmelse af partikelhastigheden i et målevolumen, med en smalbåndskontinuerlig bølgelaserlyskilde (1), der udsender lys, som er koblet til en målegren (3) og en referencegren (4), idet det lys, der er koblet til målegrenen (3), i det mindste delvist udsendes i retning af målevolumenet via en sendeanordning på en sådan måde, at det udsendte lys i det mindste delvist spredes og/eller reflekteres af partiklerne i målevolumenet, og at i det mindste en del af det spredte og/eller reflekterede lys modtages af en modtageenhed, overlejres kohærent med det lys, der forlader referencegrenen (4), og at den deraf resulterende lysstråling ledes mod en detektor (6) til generering af et detektorsignal, der er karakteristisk for den resulterende lysstråling, idet partikelhastigheden i målevolumenet bestemmes i en evalueringsenhed (11) under hensyntagen til detektorsignalet,

hvor frekvensen af det lys, der udsendes af laserlyskilden (1), varieres med en styreanordning (13), og hvor evalueringsenheden (11) er indrettet til at bestemme partiklernes hastighed i mindst ét måleområde i målevolumenet på grundlag af en spektralanalyse af detektorsignalet under hensyntagen til den forudbestemte frekvensmodulation,

kendetegnet ved, at styreanordningen (13) er konstrueret til at generere et styresignal, som svarer til et pseudo-støjsignal forårsaget af en forudbestemt frekvensfunktion, og som anvendes som grundlag for variationen i frekvensen af lyset udsendt af laserlyskilden (1).

20

2. LIDAR-måleanordning ifølge krav 1,

kendetegnet ved, at styreanordningen (13) ændrer en strømstyrke af forsyningsstrømmen til laserlyskilden (1) for at variere frekvensen af det udsendte lys.

25 3. LIDAR-måleanordning ifølge krav 1 eller 2,

kendetegnet ved, at laserlyskilden (1) omfatter en laserdiode (9), hvis injektionsstrøm ændres for at variere frekvensen af det udsendte lys.

4. LIDAR-måleanordning ifølge et af kravene 1 til 3,

30 **kendetegnet ved**, at frekvensmodulationen er valgt på en sådan måde, at laserlyskilden (1) udsender lys med en kohærenslængde på 0,1 til 100 m.

5. LIDAR-måleanordning ifølge et af kravene 1 til 4,

kendetegnet ved, at laserlyskilden (1) udsender lys med en kohærenslængde på 1 til 50 m.

6. LIDAR-måleanordning ifølge et af kravene 1 til 5,

kendetegnet ved, at styreanordningen (13) tilfører et ekstra signal til laserlyskilden på en sådan måde, at der tilføjes en ekstra tidslineær komponent til frekvensen af det udsendte lys.

7. LIDAR-måleanordning ifølge krav 6,

kendetegnet ved, at den tidslineære ændring af frekvensen af det udsendte lys vælges så stor, at forskellens fortegn ikke ændres på trods af en dopplerforskydning af frekvensen af det modtagne lys i forhold til sendefrekvensen forårsaget af partiklernes bevægelse.

8. LIDAR-måleanordning ifølge et af kravene 1 til 7,

kendetegnet ved, at styreanordningen (13) ændrer strømintensiteten på en sådan måde, at frekvensen af lyset udsendt af laserlyskilden (1) varieres lineært op og ned.

9. LIDAR-måleanordning ifølge et af kravene 1 til 8,

kendetegnet ved, styreanordningen (13) er udformet, således at det udsendte lys er pulserende, idet pulslængden er valgt længere end den ønskede rumlige opløsning, således at den rumlige opløsning yderligere bestemmes af frekvensmodulationen af laserlyskilden.

10. LIDAR-måleanordning ifølge et af kravene 1 til 9,

kendetegnet ved, at en optisk omskifter, især en akusto-optisk modulator, er anbragt i målegrenen (3).

11. LIDAR-måleanordning ifølge et af kravene 1 til 9,

kendetegnet ved, at mindst et element, der polariserer lyset, er anbragt i referencegrenen (4).

12. Anvendelse af en LIDAR-måleanordning ifølge et af kravene 1 til 11 til detektering af en vindhastighed og/eller en vindretning på vindsiden af et vindmølle anlæg.

13. Anvendelse af en LIDAR-måleanordning ifølge et af kravene 1 til 11 til detektering af en vindhastighed og/eller en vindretning på vindmølleanlæggets vindside, idet måleanordningen er fastgjort til vindmøllens spinner.

5 14. Metode til bestemmelse af partikelhastigheden i et målevolumen, hvor lys udsendes af en smalbånds-kontinuerlig bølgelaserlyskilde (1) og kobles til en målegren (3) og en referencegren (4), hvor det lys, der er koblet ind i målegrenen (3), i det mindste delvist udsendes via en sendeanordning i retning af målevolumenet på en sådan måde, at det udsendte lys i det mindste delvist spredes og/eller reflekteres af partiklerne i målevolumenet, og at i det mindste
10 en del af det spredte og/eller reflekterede lys modtages af en modtageanordning, overlejres kohærent med det lys, der forlader referencegrenen (4), og den deraf resulterende lysstråling ledes på en detektor (6) for at frembringe et detektorsignal, der er karakteristisk for den resulterende lysstråling, og hvor partiklernes hastighed i målevolumenet bestemmes i en evalueringsenhed (11) under hensyntagen til detektorsignalet,

15 hvor frekvensen af det lys, der udsendes af laserlyskilden (1), varieres ved hjælp af en styreanordning (13), og der foretages en spektralanalyse af detektorsignalet i evalueringsenheden (11) til beregning af partiklernes hastighed i mindst ét måleområde i målevolumenet under hensyntagen til den forudbestemte frekvensmodulation, **kendetegnet ved**, at variationen af frekvensen af det lys, der udsendes af laserlyskilden (1), sker på grundlag af et styresignal, der
20 genereres af styreanordningen (13), og som svarer til et pseudostøjssignal forårsaget af en forudbestemt frekvensfunktion.

15. Fremgangsmåde ifølge krav 14,

kendetegnet ved, at variationen af frekvensen af det lys, der udsendes af laserlyskilden
25 (1), er baseret på et styresignal, der genereres af styreanordningen (13), og som indeholder en tidslinær komponent.

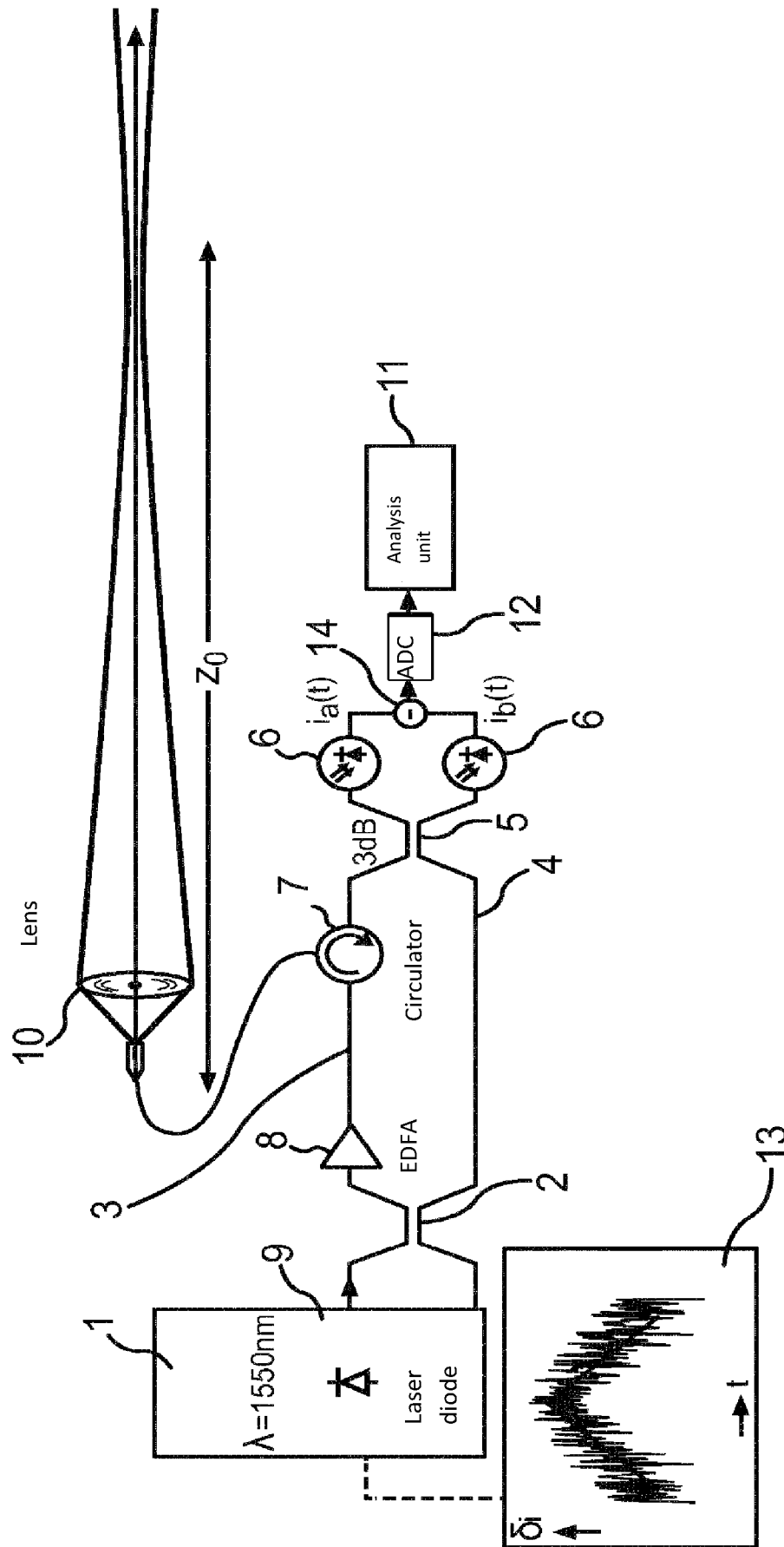


Fig.1

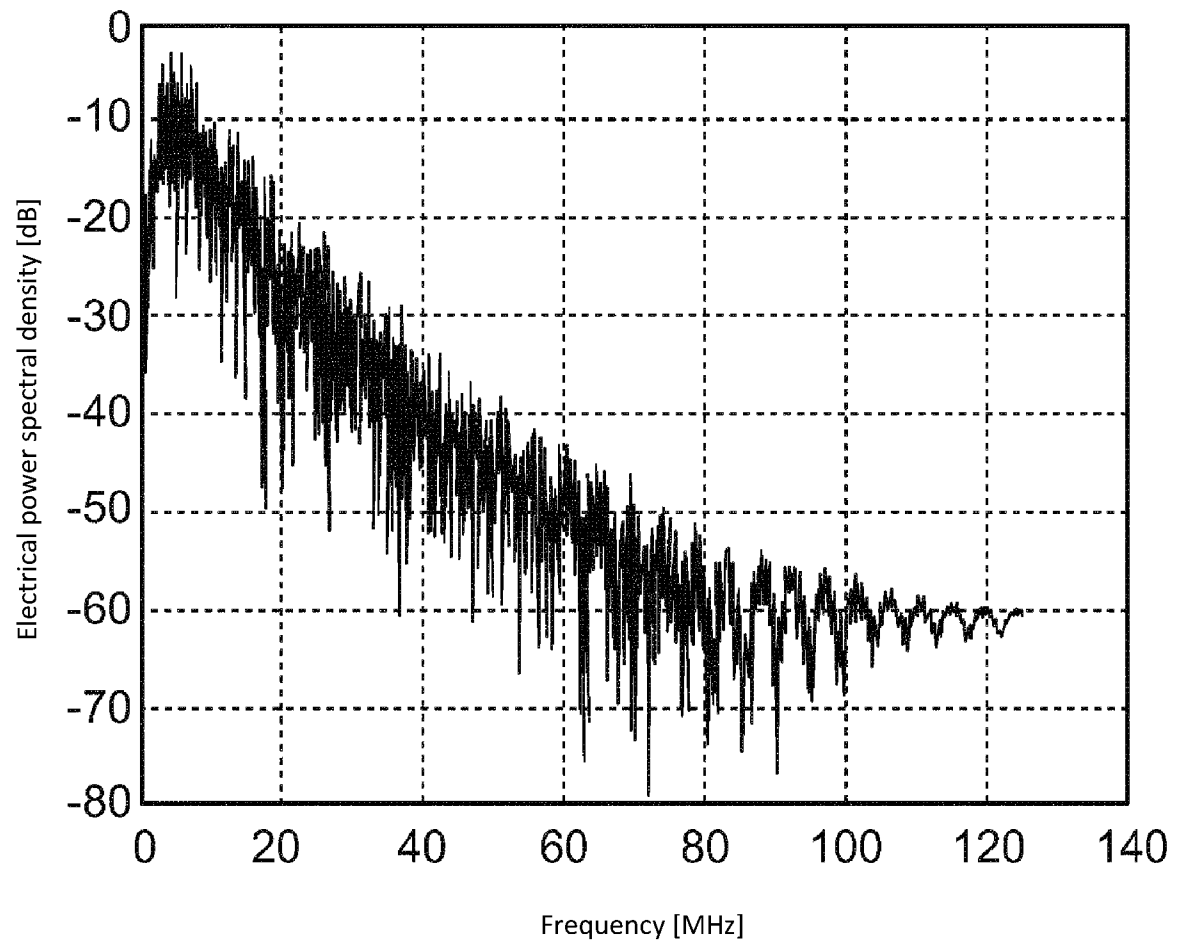


Fig.2

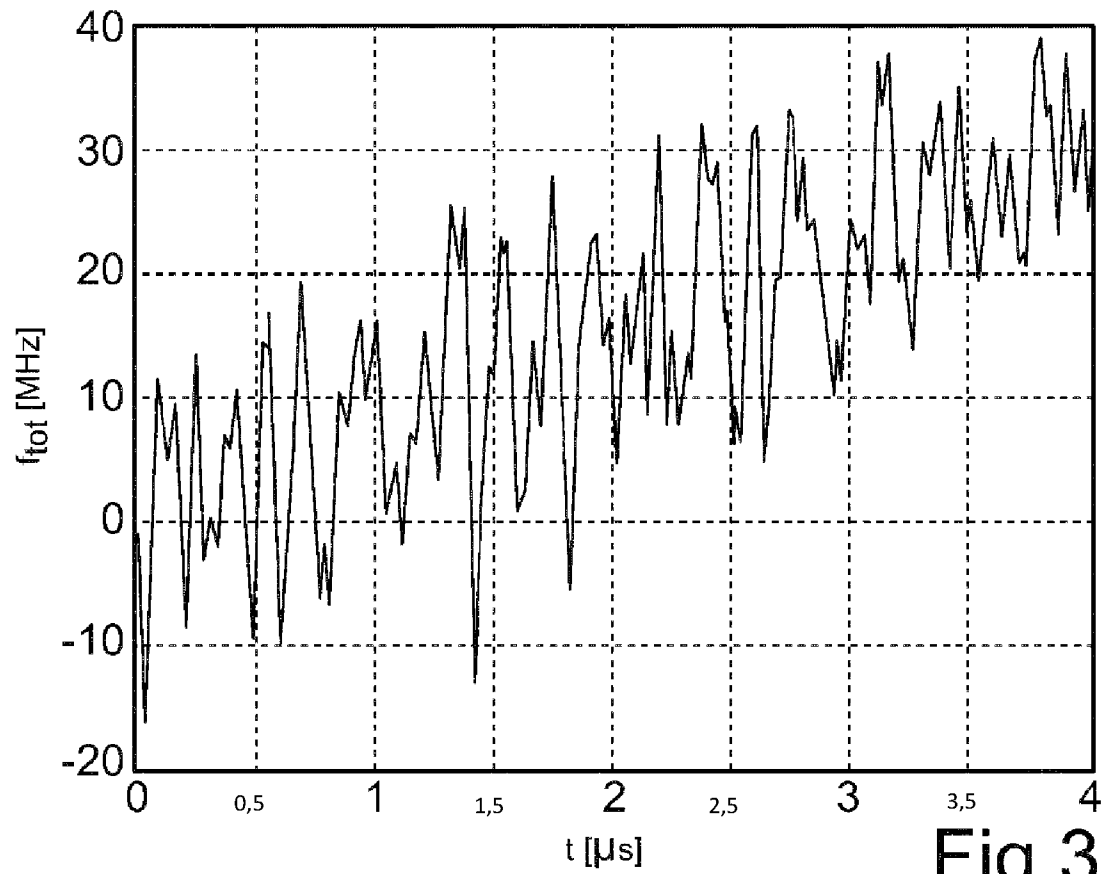


Fig.3

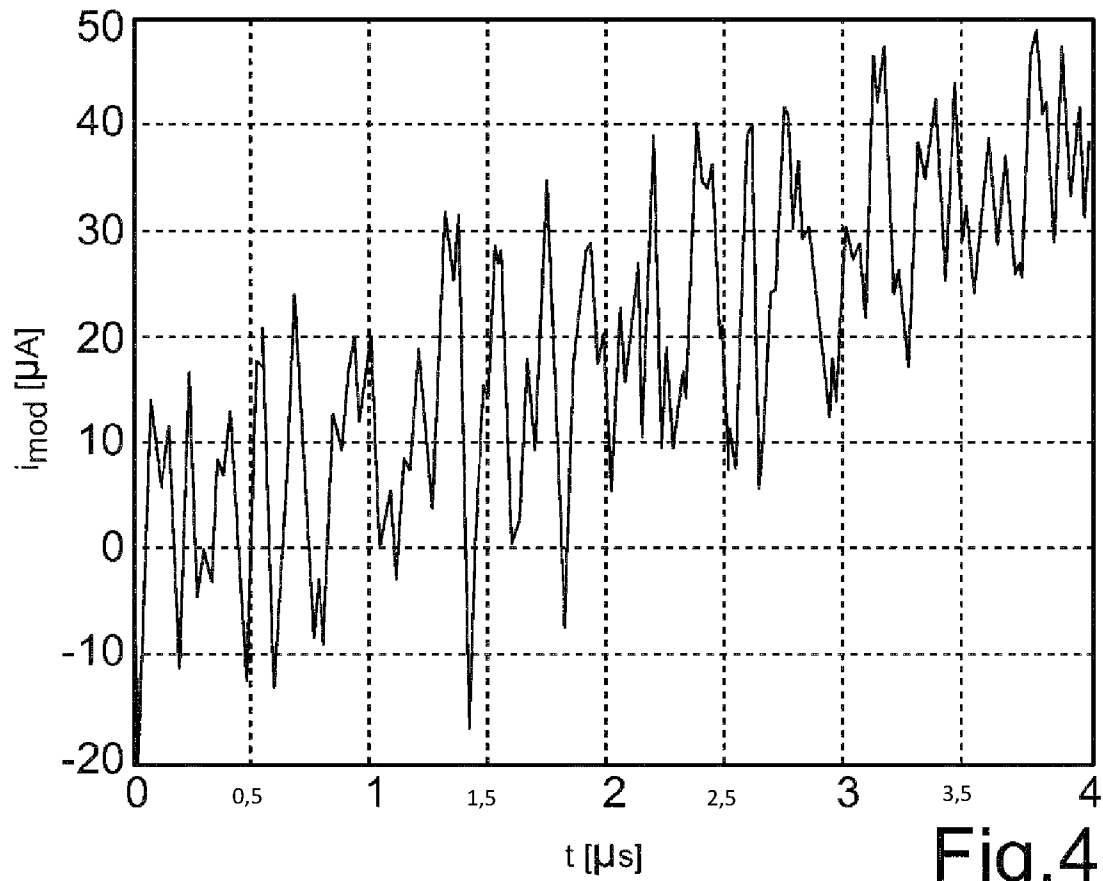


Fig.4