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INTERFEROMETRIC MEASUREMENT APPARATUS

Abstract

An interferometric measurement apparatus includes a light source that outputs a terahertz wave and reference light with a wavelength of 3 μm or more, an interferometric optical system that includes: a beam splitter that splits the terahertz wave and the reference light into a first split light and a second split light; a first optical path on which the first split light is reflected by a first mirror and re-enters the beam splitter; and a second optical path on which the second split light is reflected by a rotating mirror and re-enters the beam splitter, an interference intensity measurement unit that measures the intensity of the first interference light based on the electrical signal output from the photomultiplier tube, and an analysis unit that performs Fourier transform based on the intensity of the first interference light and the detection result of the second interference light to analyze an analyze-target object.

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Background/Summary

TECHNICAL FIELD

[0001] The present disclosure relates to an interferometric measurement apparatus.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] This application claims the benefit of priority from Japanese Patent Application No. 2024-024434 filed on Feb. 21, 2024, the entire contents of which are incorporated herein by reference.

BACKGROUND

[0003] Terahertz waves are light in the intermediate region between light waves and radio waves (band around a frequency of 1 THz) and have unique absorption spectra for analytes such as pharmaceuticals that are not seen in other wavelength bands. Therefore, their use in the identification of analytes is expected. Various techniques using terahertz waves for analysis are known.

[0004] Terahertz Time Domain Spectroscopy (THz-TDS) measures the time waveform of terahertz waves transmitted, reflected, or totally reflected by an analyte, and analyzes the analyte by Fourier transforming the time waveform of the electric field amplitude of the terahertz waves obtained by this measurement (Non-Patent Document 1: Jens Neu, et al, “Tutorial: An introduction to terahertz time domain spectroscopy (THz-TDS),” J. Appl. Phys. 124, 231101 (2018)). Hereinafter, this will be referred to as “Related Art 1”. In Related Art 1, a lock-in amplifier is used when measuring the time waveform of terahertz waves.

[0005] By using a terahertz wave source with a variable output wavelength and detecting the terahertz waves transmitted, reflected, or totally reflected by the analyte, the analyte can be analyzed (Non-Patent Document 2: K. Murate, et al, “Perspective: Terahertz wave parametric generator and its applications,” J. Appl. Phys. 124, 160901 (2018)). Hereinafter, this will be referred to as “Related Art 2”. In Related Art 2, a thermal detector is used for detecting terahertz waves.

[0006] Furthermore, Fourier spectroscopy using interferometric measurement with terahertz waves, similar to Fourier Transform Infrared Spectroscopy (FTIR), can also be used to analyze analytes (Non-Patent Document 3: Masashi Yamaguchi, et al, “Terahertz wave generation in nitrogen gas using shaped optical pulses,” J. Opt. Soc. Am. B, Vol. 26, No. 9 (2009)). Hereinafter, this will be referred to as “Related Art 3”. In Related Art 3, a thermal detector is used for detecting the interference of terahertz waves.

SUMMARY

[0007] In Related Art 1, a long integration time using a lock-in amplifier is required when measuring the time waveform of terahertz waves. In Related Arts 2 and 3, thermal detectors with slow response are used, resulting in long measurement times. Conventional analysis techniques using terahertz waves, including Related Arts 1 to 3, require a long time for measurement.

[0008] Therefore, one aspect of the present disclosure aims to provide an interferometric measurement apparatus capable of performing interferometric measurement using terahertz waves quickly and suitably.

[0009] The present disclosure includes the following interferometric measurement apparatuses [1] to [9]. [0010] [1] An interferometric measurement apparatus including: [0011] a light source that outputs a terahertz wave for interferometric measurement and a reference light with a wavelength of 3 μm or more for measuring optical path length difference; [0012] an interferometric optical

system that includes: a beam splitter that splits the terahertz wave and the reference light output from the light source and incident coaxially into a first split light and a second split light; a first optical path on which the first split light from the beam splitter is reflected by a first mirror and re-enters the beam splitter; and a second optical path on which the second split light from the beam splitter is reflected by a second mirror and re-enters the beam splitter, and wherein the interferometric optical system is configured to combine the first split light and the second split light re-entered into the beam splitter, wherein the optical path length difference between the first split light and the second split light is variable; [0013] a photomultiplier tube sensitive to the terahertz wave, and configured to output an electrical signal value in accordance with an incident light intensity of a first interference light that is an interference light of the terahertz wave generated by the combination of the first split light and the second split light at the beam splitter; [0014] a detector configured to detect a second interference light that is an interference light of the reference light generated by the combination of the first split light and the second split light at the beam splitter; [0015] an interference intensity measurement unit configured to measure an intensity of the first interference light based on the electrical signal output from the photomultiplier tube; and [0016] an analysis unit configured to perform Fourier transform based on the intensity of the first interference light measured by the interference intensity measurement unit and a detection result of the second interference light by the detector, thereby analyzing an analyze-target object disposed on the optical path through which the terahertz wave passes.
[0017] Conventionally, when incorporating a mechanism using reference light for measuring optical path length difference into an interferometric measurement apparatus, it is common to use light with a relatively short wavelength as the reference light to measure the optical path length difference as finely as possible. In contrast, in the interferometric measurement apparatus of [1], light with a relatively long wavelength (3 μm or more) is purposely used as the reference light. This allows for suitable resolution and dynamic range in measuring the optical path length difference in Fourier spectroscopy analysis using terahertz waves. Furthermore, a beam splitter for transmitting terahertz waves generally does not transmit visible to near-infrared light, but by using reference light with a wavelength of 3 μm or more (i.e., mid-infrared to far-infrared light), a common beam splitter can be used for both the terahertz wave and the reference light. This allows the optical path for the terahertz wave to generate the first interference light and the optical path for the reference light to generate the second interference light to be set on the same optical path (i.e., the first optical path and the second optical path). As a result, the optical path length difference in the first interference light can be accurately measured based on the second interference light of the reference light generated on the same optical path as the terahertz wave. According to the above configuration, while continuously changing the optical path length difference between the first split light and the second split light, measurement can be performed while appropriately monitoring the change in the optical path length difference in real-time based on the second interference light, enabling fast and suitable interferometric measurement using terahertz waves. [0018] [2] The interferometric measurement apparatus according to [1], wherein the analysis unit is configured to: [0019] convert the intensity of the first interference light measured by the interference intensity measurement unit into an electric field amplitude value based on a relationship between the electric field amplitude value of the light incident on the photomultiplier tube and the electrical signal value output from the photomultiplier tube, thereby calculating the electric field amplitude value of the first interference light for each value of time difference corresponding to the optical path length difference; and [0020] perform Fourier transform based on dependency of the calculated electric field amplitude value of the first interference light on the value of the time difference to analyze the analyze-target object.
[0021] According to the configuration of [2], by obtaining the electric field amplitude value of the first interference light for each value of time difference corresponding to the optical path length difference through conversion based on the relationship between the electric field amplitude value

and the electrical signal value, Fourier spectroscopy using interferometric measurement with terahertz waves can be performed quickly and accurately. [0022] [3] The interferometric measurement apparatus according to [1] or [2], wherein the interferometric optical system is configured to be capable of changing an optical path length of the first optical path by driving the first mirror and capable of changing an optical path length of the second optical path by driving the second mirror.

[0023] According to the configuration of [3], one mirror (e.g., the first mirror) can be used as an initial setting mirror for adjusting the optical path length difference to be near zero in the initial state, and the other mirror (e.g., the second mirror) can be used as a mirror for changing the optical path length difference during interferometric measurement, enabling a suitable configuration for interferometric measurement. [0024] [4] The interferometric measurement apparatus according to any one of [1] to [3], wherein the interferometric optical system further includes a third mirror, [0025] wherein the second mirror is configured to be rotationally driven so that an optical path length of the second optical path changes, and [0026] wherein the second optical path is configured by an optical path from the beam splitter to the third mirror via the second mirror and an optical path returning to the beam splitter via the second mirror after being reflected by the third mirror.

[0027] According to the configuration of [4], by rotationally driving the second mirror configured as a rotating mirror, measurement can be performed while changing the optical path length difference quickly compared to using a mirror that can be moved parallel to the direction perpendicular to the reflecting surface. As a result, the analysis by the interferometric measurement apparatus can be sped up. [0028] [5] The interferometric measurement apparatus according to any one of [1] to [4], wherein the detector is any one of a quantum cascade detector, an MCT detector, a superlattice infrared detector element, an InSb detector element, an InAs detector element, and an InAsSb detector element.

[0029] According to the configuration of [5], by using a detector that operates with high sensitivity and high speed as a light detector in the mid-infrared region, the second interference light (interference light of the reference light) can be efficiently detected. [0030] [6] The interferometric measurement apparatus according to any one of [1] to [5], wherein the light source includes a first light source that outputs the terahertz wave and a second light source that outputs the reference light, and the second light source is constituted by a quantum cascade laser element.

[0031] To detect the second interference light with high precision in the detector, it is preferable to use light with as narrow a spectral linewidth (wavelength linewidth) as possible as the reference light. According to the configuration of [6], by using a quantum cascade laser element with the property of outputting light with a relatively narrow spectral linewidth as the second light source, the detection precision of the second interference light in the detector can be enhanced. [0032] [7] The interferometric measurement apparatus according to any one of [1] to [5], wherein the light source is constituted by a single quantum cascade laser element having a dual upper subband level structure and capable of generating both the terahertz wave and the reference light by multiple intersubband transitions.

[0033] According to the configuration of [7], it is possible to output both the terahertz wave for interferometric measurement and the reference light for measuring optical path length difference with a single light source (quantum cascade laser element). As a result, compared to the case where the light source is constituted by two light sources (i.e., a first light source that outputs the terahertz wave and a second light source that outputs the reference light), the number of light sources can be reduced. Furthermore, it is unnecessary to use a member for adjusting the terahertz wave output from the first light source and the reference light output from the second light source to be incident coaxially on the beam splitter (e.g., a second beam splitter different from the above beam splitter). Therefore, according to the configuration of [7], the configuration of the light source and the interferometric optical system can be simplified. [0034] [8] The interferometric measurement apparatus according to any one of [1] to [6], further including a light source control unit configured

to control a driving of the light source, wherein the light source includes a first light source that outputs the terahertz wave and a second light source that outputs the reference light, and the light source control unit synchronizes the first light source and the second light source in pulse mode.
[0035] According to the configuration of [8], by synchronizing and pulse-driving the first light source and the second light source, cooling of the first light source and the second light source can be made unnecessary. Furthermore, compared to the case where the first light source and the second light source are continuously driven, the device life of the first light source and the second light source can be extended. [0036] [9] The interferometric measurement apparatus according to any one of [1] to [8], wherein the interferometric optical system is configured to be capable of changing an optical path length of the second optical path by driving the second mirror, and a range of periodic change in the optical path length difference between the first split light and the second split light by the driving of the second mirror is 3 mm or more.
[0037] According to the configuration of [9], appropriate resolution and measurement dynamic range can be obtained for the optical path change of the terahertz wave.
[0038] According to one aspect of the present disclosure, it is possible to provide an interferometric measurement apparatus capable of performing interferometric measurement using terahertz waves quickly and suitably.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0039] FIG. **1** is a diagram showing a configuration example of an interferometric measurement apparatus according to the first embodiment.
[0040] FIG. **2** is a diagram showing a configuration example of a photomultiplier tube **30**.
[0041] FIG. **3**A is a graph showing the input-output characteristics of the photomultiplier tube **30**.
[0042] FIG. **3**B is a graph showing the time dependence of the voltage signal V output from the photomultiplier tube **30**.
[0043] FIG. **4** is a diagram showing an example of the intensity of the interference light IL**2** detected by the detector **40** according to the optical path length difference.
[0044] FIG. **5**A is a graph showing the optical path length difference Δd dependence of Vp−p.
[0045] FIG. **5**B is a graph showing the time difference Δt dependence of Vp−p.
[0046] FIG. **6**A is a graph showing the time difference Δt dependence of the electric field amplitude value E of the interference light.
[0047] FIG. **6**B is a diagram showing the amplitude spectrum and phase spectrum of the electric field amplitude value E of the interference light.
[0048] FIG. **7**A is a graph showing the time difference Δt dependence of the electric field amplitude value E of the interference light.
[0049] FIG. **7**B is a graph showing the phase spectrum of the electric field amplitude value E of the interference light.
[0050] FIG. **8**A is a graph showing the amplitude spectrum of the electric field amplitude value E of the interference light.
[0051] FIG. **8**B is a graph showing the spectrum of the absorption coefficient α(ω).
[0052] FIG. **8**C is a graph showing the spectrum of the refractive index n(ω).
[0053] FIG. **9** is a diagram showing a configuration example of an interferometric measurement apparatus according to the second embodiment.
[0054] FIG. **10** is a diagram showing an example of pulse synchronization control in the interferometric measurement apparatus of the second embodiment.
[0055] FIG. **11** is a diagram showing a configuration example of an interferometric measurement apparatus according to the third embodiment.

DETAILED DESCRIPTION

[0056] Hereinafter, an embodiment of the present disclosure will be described in detail with reference to the drawings. In the following description, the same or corresponding elements are denoted by the same reference numerals, and redundant descriptions are omitted.

First Embodiment

[0057] The interferometric measurement apparatus **1**A of the first embodiment will be described with reference to FIGS. **1** to **8**C. As shown in FIG. **1**, the interferometric measurement apparatus **1**A includes a light source **10**, an interferometric optical system **20**, a photomultiplier tube **30**, a detector **40**, and a measurement device **50**.

[0058] The light source **10** outputs a terahertz wave L**1** for interferometric measurement and a reference light L**2** for measuring optical path length difference. In this embodiment, the light source **10** includes a light source **11** (first light source) that outputs the terahertz wave L**1** and a light source **12** (second light source) that outputs the reference light L**2**.

[0059] The terahertz wave L**1** output from the light source **11** may be a pulsed light or a continuous light. Examples of light sources capable of outputting pulsed terahertz waves include a configuration combining a femtosecond laser light source (e.g., Ti:sapphire laser light source) and a nonlinear optical crystal (e.g., ZnTe), and an injection-seeded terahertz parametric generator (is-TPG). Examples of light sources capable of outputting continuous terahertz waves include a resonant tunneling diode (RTD), an IMPATT diode (Impact Avalanche and Transit Time Diode), a quantum cascade laser light source, and a THz gas laser light source.

[0060] The reference light L**2** output from the light source **12** is light with a wavelength of 3 μm or more. The reference light L**2** is, for example, mid-infrared to far-infrared light with a wavelength of 3 μm to 100 μm. A quantum cascade laser element is cited as a light source that suitably outputs such reference light L**2**. In this embodiment, the light source **12** is constituted by a quantum cascade laser element that outputs mid-infrared light with a wavelength of 10 μm. The reference light L**2** may be pulsed light or continuous light, but when both the terahertz wave L**1** and the reference light L**2** are pulsed light, it is necessary to control the synchronization of the output of the terahertz wave L**1** and the reference light L**2**. In this embodiment, the case where the terahertz wave L**1** is pulsed light and the reference light L**2** is continuous light will be described, and the case where both the terahertz wave L**1** and the reference light L**2** are pulsed light will be described in the second embodiment.

[0061] The interferometric optical system **20** includes a beam splitter **21**, a beam splitter **22**, a mirror **23** (first mirror), a rotating mirror **24** (second mirror), a mirror **25** (third mirror), a beam splitter **26**, and a lens **27**. The beam splitters **21**, **22**, and **26** are all made of silicon. By using beam splitters made of silicon, both the terahertz wave L**1** and the reference light L**2** can be suitably split into components reflected by the beam splitter and components transmitted through the beam splitter.

[0062] The beam splitter **21** is disposed between the light source **10** (light sources **11** and **12**) and the beam splitter **22**. The beam splitter **21** is a member for combining the terahertz wave L**1** output from the light source **11** and the reference light L**2** output from the light source **12** and making the terahertz wave L**1** and the reference light L**2** incident coaxially on the beam splitter **22**. The beam splitter **21** is arranged such that the terahertz wave L**1** is incident on the opposite side of the reference light L**2** incident surface of the beam splitter **21**. In the example shown in FIG. **1**, the terahertz wave L**1** component transmitted through the beam splitter **21** and the reference light L**2** component reflected by the beam splitter **21** are combined and incident on the beam splitter **22**.

[0063] The beam splitter **22** splits the terahertz wave L**1** and the reference light L**2**, which are output from the light source **10** (light sources **11** and **12**) and incident coaxially, into a split light La (first split light) and a split light Lb (second split light). This forms an optical path Pa (first optical path) through which the split light La passes and an optical path Pb (second optical path) through which the split light Lb passes in the interferometric optical system **20**.

[0064] For example, the split light La is light that includes the components of the terahertz wave L**1** and the reference light L**2**, each reflected by the beam splitter **22**. The optical path Pa of the split light La is an optical path in which the split light La from the beam splitter **22** is reflected by the mirror **23** and re-enters the beam splitter **22** (the exit surface of the split light La in the beam splitter **22**). In this embodiment, the optical path Pa is constituted by an optical path from the beam splitter **22** to the mirror **23** (outward path) and an optical path from the mirror **23** to the beam splitter **22** (return path).
[0065] For example, the split light Lb is light that includes the components of the terahertz wave L**1** and the reference light L**2**, each transmitted through the beam splitter **22**. The optical path Pb of the split light Lb is an optical path in which the split light Lb from the beam splitter **22** is reflected by the rotating mirror **24** and re-enters the beam splitter **22** (the exit surface of the split light Lb in the beam splitter **22**). In this embodiment, the optical path Pb is constituted by an optical path from the beam splitter **22** to the mirror **25** via the rotating mirror **24** and the lens **27** (outward path) and an optical path returning to the beam splitter **22** via the lens **27** and the rotating mirror **24** after being reflected by the mirror **25** (return path). The lens **27** is an optical member disposed between the rotating mirror **24** and the mirror **25** to ensure that the split light Lb reflected by the rotating mirror **24** reaches the mirror **25** and that the split light Lb reflected by the mirror **25** reaches the rotating mirror **24** again, even when the rotation angle of the rotating mirror **24** becomes large. The lens **27** converts both the terahertz wave L**1** and the reference light L**2** into convergent or parallel light. The lens **27** may be formed of plastic materials such as Tsurupica (registered trademark) or ZEONEX (registered trademark), or silicon. Alternatively, an optical member such as a reflective convex mirror or an off-axis parabolic mirror that does not depend on the wavelength of the incident light may be used instead of the lens **27**.
[0066] The mirror **23** is disposed downstream of the beam splitter **22** in the optical path Pa. In this embodiment, the mirror **23** is configured to be movable in the direction DI along the optical path Pa (the direction perpendicular to the reflecting surface of the mirror **23**). The position of the mirror **23** in the direction DI is set such that the optical path length difference Δd between the split light La (optical path Pa) and the split light Lb (optical path Pb) is near zero in the initial state. The split light La incident on the reflecting surface **23***a* of the mirror **23** is reflected by the reflecting surface **23***a* and returned to the beam splitter **22**. In this embodiment, the analyte S is disposed between the beam splitter **22** and the mirror **23** in the optical path Pa. The analyte S may be, for example, lactose, sucrose, or other sugars.
[0067] The analyte S may be disposed on the optical path through which the terahertz wave L**1** passes. For example, the analyte S may be disposed on the optical path Pb (e.g., between the beam splitter **22** and the rotating mirror **24**). However, in this embodiment, since the optical path Pb changes during measurement due to the driving of the rotating mirror **24**, the conditions (e.g., the position through which the terahertz wave L**1** passes and the amplitude of the terahertz wave L**1** at the passing position) of the terahertz wave L**1** passing through the analyte S (the component of the terahertz wave L**1** included in the split light Lb) are not constant. This may cause unexpected measurement errors. From this perspective, it is preferable to dispose the analyte S on the optical path Pa, which does not change during measurement. Alternatively, the analyte S may be disposed on the optical path through which the terahertz wave L**1** passes outside the optical paths Pa and Pb (e.g., between the light source **11** and the beam splitter **21**, between the beam splitters **21** and **22**, between the beam splitters **22** and **26**, or between the beam splitter **26** and the photomultiplier tube **30**). Disposing the analyte S outside the optical paths Pa and Pb can suppress the reduction of the interference signal (interference light IL) due to the influence of the wavefront distortion of the analyte S. On the other hand, when the analyte S is disposed outside the optical paths Pa and Pb, information on the absorption spectrum of the analyte S can be obtained, but information on the refractive index of the analyte S cannot be obtained. In other words, by disposing the analyte S on the optical path Pa or the optical path Pb, information on both the absorption spectrum and the

refractive index of the analyte S can be obtained.

[0068] The rotating mirror **24** is disposed downstream of the beam splitter **22** in the optical path Pb. The rotating mirror **24** is configured to be rotatable (oscillatable) within a predetermined angle range around an axis X extending in a direction perpendicular to the optical path Pb (in the example of FIG. **1**, a direction perpendicular to the paper surface). The axis X of the rotating mirror **24** is located at a position offset from the optical path Pb. The rotating mirror **24** is configured to be rotatable around the axis X at high speed so as to change the distance between the beam splitter **22** and the reflecting surface **24***a* of the rotating mirror **24** in the optical path Pb. For example, the rotating mirror **24** is configured to rotate within a predetermined angle θmax in the direction in which the optical path length of the optical path Pb increases (i.e., the direction in which the distance from the beam splitter **22** to the reflecting surface **24***a* in the optical path Pb increases (clockwise direction in FIG. **1**)) when the angle at which the optical path length difference Δd between the optical path Pa and the optical path Pb becomes zero (i.e., when the angle of the rotating mirror **24** is θr). In other words, the rotating mirror **24** is configured to be rotatable at a predetermined frequency such that the angle of the rotating mirror **24** periodically changes between the angle θr when the optical path length difference Δd is zero and the angle θr+θmax when the optical path length difference Δd ("the optical path length of the optical path Pb—the optical path length of the optical path Pa" in this embodiment) is maximum dmax.

[0069] The width of the periodic change in the optical path length difference Δd due to the rotational driving of the rotating mirror **24** (dmax in this embodiment) is set to 3 mm or more, for example. For example, the position of the rotating mirror **24** (i.e., the position of the axis X) is adjusted such that the optical path length difference Δd changes by about 1 μm when the angle of the rotating mirror **24** changes by 0.0025°. In this case, by rotating the rotating mirror **24** with θmax=25°, the optical path length difference Δd can be periodically changed between the state where the optical path length difference Δd is zero (i.e., when the angle of the rotating mirror **24** is θr) and the state where the optical path length difference Δd is dmax (10 μm) (i.e., when the angle of the rotating mirror **24** is θr+θmax).

[0070] The mirror **25** is disposed downstream of the rotating mirror **24** in the optical path Pb. The position of the mirror **25** is fixed. The split light Lb incident on the reflecting surface **24***a* of the rotating mirror **24** is reflected by the reflecting surface **24***a* and directed to the reflecting surface **25***a* of the mirror **25** via the lens **27**. Subsequently, the split light Lb is reflected by the reflecting surface **25***a* of the mirror **25** and returned to the reflecting surface **24***a* of the rotating mirror **24** via the lens **27** again, and is reflected by the reflecting surface **24***a* again to re-enter the beam splitter **22** (the exit surface of the split light Lb in the beam splitter **22**).

[0071] In the interferometric optical system **20**, as described above, the optical path length difference Δd is variable by rotationally driving the rotating mirror **24**. The beam splitter **22** combines the split light La re-entering the beam splitter **22** via the optical path Pa and the split light Lb re-entering the beam splitter **22** via the optical path Pb. In this embodiment, the interference light IL generated by combining the component of the split light La re-entering the beam splitter **22** and transmitted through the beam splitter **22** and the component of the split light Lb re-entering the beam splitter **22** and reflected by the beam splitter **22** is emitted from the beam splitter **22** toward the beam splitter **26**.

[0072] The interference light IL includes the interference light IL**1** (first interference light) of the terahertz wave L**1** generated by combining the split light La and the split light Lb and the interference light IL**2** (second interference light) of the reference light L**2** generated by combining the split light La and the split light Lb. The interference light IL**1** is light formed by the interference of the terahertz wave L**1** included in the split light La and the terahertz wave L**1** included in the split light Lb. The interference light IL**2** is light formed by the interference of the reference light L**2** included in the split light La and the reference light L**2** included in the split light Lb.

[0073] The beam splitter **26** splits the interference light IL emitted from the beam splitter **22** into light reflected by the beam splitter **26** and light transmitted through the beam splitter **26**.

[0074] The photomultiplier tube **30** is disposed downstream of the beam splitter **26** at a position where the light transmitted through the beam splitter **26** is directed. The photomultiplier tube **30** is sensitive to the terahertz wave (i.e., the wavelength range of the terahertz wave L**1**) and outputs an electrical signal value corresponding to the incident light intensity of the interference light IL**1**. In this embodiment, the photomultiplier tube **30** outputs an electrical signal value corresponding to the incident light intensity of the interference light IL**1** included in the component of the interference light IL transmitted through the beam splitter **26**.

[0075] FIG. **2** is a block diagram showing the configuration of the photomultiplier tube **30**. The photomultiplier tube **30** includes an electron emission part **31**, an electron multiplication part **32**, and a signal output part **33**, all of which are disposed inside a housing **34** maintained in a vacuum. The housing **34** is provided with a window part **35**.

[0076] The electron emission part **31** emits electrons e when light v transmitted through the window part **35** is incident. The electron emission part **31** is a photoelectric conversion part designed to be sensitive to the light band including the terahertz wave L**1** to be detected. The electron emission part **31** has a configuration in which a metamaterial structure (metasurface) is formed on the main surface of a substrate, and electrons e can be emitted by the incidence of light on the metasurface.

[0077] The electron multiplication part **32** multiplies the electrons e emitted from the electron emission part **31**. The electron multiplication part **32** includes multiple stages of dynodes or a microchannel plate. The electron multiplication factor in the electron multiplication part **32** depends on the voltage applied to the multiple stages of dynodes or the microchannel plate. The signal output part **33** collects the electrons e multiplied by the electron multiplication part **32** and outputs them as a current signal J. The interference intensity measurement unit **51**, described later, may input the current signal J output from the signal output part **33** or the voltage signal after the current signal J is converted by an IV conversion circuit. In this embodiment, the voltage signal is input to the interference intensity measurement unit **51** as the electrical signal value output by the photomultiplier tube **30**.

[0078] FIG. **3**A is a diagram showing an example of the input-output characteristics of the photomultiplier tube **30**. The horizontal axis represents the electric field amplitude value E of the light (interference light IL**1**) incident on the photomultiplier tube **30**. The vertical axis represents the electrical signal (voltage signal V) output by the photomultiplier tube **30**. As shown in this figure, the input-output characteristics of the photomultiplier tube **30** are not linear. These input-output characteristics of the photomultiplier tube **30** are obtained in advance. For example, by performing fitting processing using multiple (five in this example) measurement values shown in FIG. **3**A, a fitting function R representing the relationship between the electric field amplitude value E and the voltage signal V can be obtained. Such a fitting function R is stored in the measurement device **50** in advance, for example.

[0079] FIG. **3**B is a graph showing the time dependence of the voltage signal V output by the photomultiplier tube **30**. Such a voltage signal V corresponds to the optical path length difference Δd between the split light La (optical path Pa) and the split light Lb (optical path Pb). In other words, the amplitude of the voltage signal V output by the photomultiplier tube **30** (Vp−p) corresponds to the optical path length difference Δd. The analysis unit **52**, described later, can read Vp−p from the output result of the photomultiplier tube **30** as shown in FIG. **3**B.

[0080] The detector **40** is disposed downstream of the beam splitter **26** at a position where the light reflected by the beam splitter **26** is directed. The detector **40** is sensitive to the wavelength range of the reference light L**2** and detects the interference light IL**2**. In this embodiment, the detector **40** outputs an electrical signal value corresponding to the incident light intensity of the interference light IL**2** included in the component of the interference light IL reflected by the beam splitter **26**. The detector **40** may be constituted by any one of a quantum cascade detector, an MCT detector, a superlattice infrared detector element, an InSb detector element, an InAs detector element, and an InAsSb detector element. According to the above configuration, by using the detector **40** that operates with high sensitivity and high speed as a light detector in the mid-infrared region, the interference light IL**2** of the reference light L**2** can be efficiently detected.

[0081] FIG. **4** is a diagram showing an example of the intensity of the interference light IL**2** detected by the detector **40** in accordance with the optical path length difference Δd. The horizontal axis of the graph shown in FIG. **4** represents the optical path length difference Δd (in this embodiment, the delay amount of the split light Lb relative to the split light La), and the vertical axis represents the intensity of the detected interference light IL**2**. When the optical path length difference Δd is an integer multiple of the wavelength of the reference light L**2** (including the case where the optical path length difference Δd is zero), the reference light L**2** included in the split light La and the reference light L**2** included in the split light Lb overlap, and the intensity of the interference light IL**2** is the largest. In contrast, when the optical path length difference Δd is an odd multiple of half the wavelength of the reference light L**2**, the reference light L**2** included in the split light La and the reference light L**2** included in the split light Lb cancel each other out, and the intensity of the interference light IL**2** is the smallest. Therefore, when the optical path length difference Δd is continuously changed at a constant frequency by the rotational driving of the rotating mirror **24** as described above, a signal value showing the upper waveform in FIG. **4** is obtained when the wavelength λ of the reference light L**2** is set to 0.63 μm, and a signal value showing the lower waveform in FIG. **4** is obtained when the wavelength A is set to 10 μm. In other words, when the angle of the rotating mirror **24** is set to an angle corresponding to a certain optical path length difference, a signal value with an intensity corresponding to that optical path length difference can be obtained. Therefore, based on the intensity of the interference light IL**2** detected by the detector **40**, the optical path length difference Δd at the time the interference light IL**2** is detected can be accurately estimated.

[0082] The measurement device **50** performs Fourier spectroscopy analysis using terahertz waves L**1** based on the output values of the photomultiplier tube **30** and the detector **40**. The measurement device **50** includes an interference intensity measurement unit **51** and an analysis unit **52**. The measurement device **50** may be constituted by a computer system including a processor, memory, storage, communication devices, etc. Each function provided by the measurement device **50** (interference intensity measurement unit **51** and analysis unit **52**) is executed by these hardware elements operating according to a predetermined program.

[0083] The interference intensity measurement unit **51** measures the intensity of the interference light IL**1** based on the electrical signal (voltage signal V in this embodiment) output by the photomultiplier tube **30**. In this embodiment, the interference intensity measurement unit **51** acquires the amplitude of the voltage signal V (Vp−p) as shown in FIG. **3**B at each measurement point (e.g., at each pulse of the pulsed terahertz wave L**1**) as a value indicating the intensity of the interference light IL**1**.

[0084] The analysis unit **52** performs Fourier transform based on the intensity of the interference light IL**1** measured by the interference intensity measurement unit **51** and the detection result of the interference light IL**2** by the detector **40**, thereby analyzing the analyze-target object S disposed on the optical path Pa or Pb. In this embodiment, as an example, the analysis unit **52** executes the following first and second processes.

First Process

[0085] The analysis unit **52**, as the first process, converts the intensity of the interference light IL**1** measured by the interference intensity measurement unit **51** (Vp−p) into an electric field amplitude value E based on the relationship (fitting function R shown in FIG. **3**A) between the electric field amplitude value E of the light incident on the photomultiplier tube **30** and the electrical signal value (voltage signal V) output from the photomultiplier tube **30**, thereby calculating the electric field amplitude value E of the interference light IL**1** for each value of the time difference Δt corresponding to the optical path length difference Δd. Note that there is a relationship "Δt=Δd/c" between the optical path length difference Δd and the time difference Δt, where c is the speed of light in a vacuum.

[0086] For example, the analysis unit **52** can estimate the optical path length difference Δd at each measurement point based on the detection result of the interference light IL**2** by the detector **40** (i.e., the signal value corresponding to the intensity of the interference light IL**2**). This allows the analysis unit **52** to associate the Vp−p measured by the interference intensity measurement unit **51** at each measurement point with the corresponding optical path length difference Δd, thereby obtaining Vp−p corresponding to each value of the optical path length difference Δd. As a result, a graph showing the dependence of Vp−p on the optical path length difference Δd as shown in FIG. **5**A can be obtained.

[0087] The process for obtaining Vp−p corresponding to each value of the optical path length difference Δd using the detection result of the interference light IL**2** is not limited to the above process. As another example, the analysis unit **52** may be configured to perform a correction process using the detection result of the interference light IL**2** by the detector **40**. For example, the analysis unit **52** may obtain the first information (Vp−p corresponding to each value of the optical path length difference Δd) without using the detection result of the interference light IL**2** by the detector **40**, and then correct the first information based on the detection result of the interference light IL**2** by the detector **40**. For example, when the rotating mirror **24** is continuously driven at a constant frequency, the angle of the rotating mirror **24** at each measurement point (i.e., the optical path length difference Δd corresponding to the angle) can be estimated with a certain degree of accuracy based on the elapsed time from the start of the driving of the rotating mirror **24**. By associating the Vp−p measured at each measurement point with the estimated optical path length difference Δd at each measurement point, the first information can be obtained. The analysis unit **52** may compare the optical path length difference Δd estimated based on the elapsed time with the optical path length difference Δd accurately estimated based on the detection result of the interference light IL**2** by the detector **40**, and correct the waveform of the first information based on the comparison result, thereby obtaining the final information (Vp−p corresponding to each value of the optical path length difference Δd).

[0088] Subsequently, the analysis unit **52** can obtain Vp−p corresponding to each value of the time difference Δt by converting the optical path length difference Δd into the time difference Δt using the relationship "At =Δd/c" between the optical path length difference Δd and the time difference Δt. As a result, a graph showing the dependence of Vp−p on the time difference Δt as shown in FIG. **5**B can be obtained.

[0089] Subsequently, the analysis unit **52** converts the intensity of the interference light IL**1** (Vp−p) into the electric field amplitude value E based on the fitting function R representing the input-output characteristics of the photomultiplier tube **30** (see FIG. **3**A). As a result, a graph showing the dependence of the electric field amplitude value E of the interference light IL**1** on the time difference Δt as shown in FIG. **6**A can be obtained.

Second Process

[0090] The analysis unit **52** performs Fourier transform based on the dependence of the electric field amplitude value E of the interference light IL**1** on the value of the time difference Δt calculated in the first process, thereby analyzing the analyze-target object S. The Fourier transform described above provides a graph showing the amplitude spectrum (solid line) and phase spectrum (dashed line) of the electric field amplitude value E of the interference light IL**1** as shown in FIG. **6**B. Hereinafter, an example of the analysis (identification) of the analyze-target object S by the analysis unit **52** will be described.

[0091] In the interferometric measurement apparatus **1**A, which includes an interferometric optical system **20** having a Michelson interferometer configuration, the terahertz wave L**1** passes through the analyze-target object S twice. Let the phase refractive index of the analyze-target object S be n(ω), the extinction coefficient be k(ω), and the complex refractive index be n′(ω)=n(ω)+ik(ω), where ω is the angular frequency of the terahertz wave. If the frequency of the terahertz wave L**1** is f, then ω=2πf, where π is the circular constant and i is the imaginary unit.

[0092] Let E.sub.sample(ω) be the electric field amplitude value of the interference light IL**1** obtained with the analyze-target object S disposed, and E.sub.ref(ω) be the electric field amplitude value of the interference light IL**1** obtained without the analyze-target object S. The ratio T(ω) of these values is expressed by the following equation (1). The interface amplitude transmittance from air to the analyze-target object S is t.sub.as, which is expressed by the following equation (2). The interface amplitude transmittance from the analyze-target object S to air is t.sub.sa, which is expressed by the following equation (3). The thickness of the analyze-target object S is d, and c is the speed of light in a vacuum.

[00001]

$$T(\ ) = \frac{E_{\text{sample}}(\ )}{E_{\text{ref}}(\ )} = (t_{as}t_{sa})^2 \exp[2i\frac{\{n'(\ )-1\}\ d}{c}] = (t_{as}t_{sa})^2 \exp[-\frac{2k\ d}{c}]\exp[2i\frac{\{n(\ )-1\}\ d}{c}] \quad (1)$$

$$t_{as} = \frac{2}{n(\ )+1} \quad (2) \quad t_{sa} = \frac{2n(\ )}{n(\ )+1} \quad (3)$$

[0093] By decomposing the above equation (1) into real and imaginary parts, the following equations (4) to (6) are obtained. φ(ω) is the phase spectrum, and α(ω) is the absorption coefficient. In the interferometric measurement apparatus **1**A, the analysis unit **52** can analyze the analyze-target object S based on these equations.

[00002] $$n(\ ) = 1 + \frac{c}{2\ d}(\ ) \quad (4) \quad k(\ ) = \frac{c}{2\ d}[\ln\{\frac{4n(\ )}{n(\ )+1}\}^2 - \ln\{T(\ )\}] \quad (5)$$

$$(\ ) = \frac{2\ k(\ )}{c} \quad (6)$$

[0094] FIGS. **7**A, **7**B, **8**A, **8**B, and **8**C are graphs showing examples of the measurement and analysis results by the interferometric measurement apparatus **1**A. The graph in FIG. **7**A is obtained by the first process of the analysis unit **52** (corresponding to the graph in FIG. **6**A). The graphs in FIGS. **7**B, **8**A, **8**B, and **8**C are obtained by the second process of the analysis unit **52** (corresponding to the graph in FIG. **6**B and the graphs derived from it).

[0095] FIG. **7**A is a graph showing the dependence of the electric field amplitude value E of the interference light IL**1** on the time difference Δt. FIG. **7**B is a graph showing the phase spectrum of the electric field amplitude value E of the interference light IL**1**. FIG. **8**A is a graph showing the amplitude spectrum of the electric field amplitude value E of the interference light IL**1**. These figures show the cases where the analyze-target object S is disposed and not disposed. In this example, lactose is used as the analyze-target object S.

[0096] FIG. **8**B is a graph showing the spectrum of the absorption coefficient α(ω). FIG. **8**C is a graph showing the spectrum of the refractive index n(ω). These figures show the analysis results according to this embodiment and the analysis results by the THz-TDS of Related Art 1.

[0097] As can be seen by comparing the analysis results according to this embodiment with the analysis results by the THz-TDS of Related Art 1, the positions of the absorption peaks appearing in the spectrum of the absorption coefficient α(ω) are consistent between the two. This indicates that the analyze-target object S can be analyzed according to this embodiment.

Effects of the First Embodiment

[0098] Conventionally, when incorporating a mechanism using reference light for measuring optical path length difference into an interferometric measurement apparatus, it is common to use light with a relatively short wavelength (e.g., 0.63 μm wavelength as shown in the upper part of FIG. **4**) as the reference light to measure the optical path length difference as finely as possible. In contrast, in the interferometric measurement apparatus **1**A, light with a relatively long wavelength (3 μm or more) is purposely used as the reference light L**2**. This allows for suitable resolution and dynamic range in measuring the optical path length difference in Fourier spectroscopy analysis using terahertz waves L**1**.

[0099] More specifically, in this embodiment, by making the sweep width of the optical path length difference Δd relatively long (10 mm width) and rotating the rotating mirror **24** within an appropriate angle range (e.g., 25° rotation width), the optical path length difference Δd changes by about 1 μm with a slight rotation of the rotating mirror **24** by 0.0025°. Therefore, when using light with a wavelength of 0.63 μm as the reference light L**2** as shown in the upper part of FIG. **4**, the resolution is too fine (i.e., the wavelength is shorter than the change width of the optical path length difference Δd (1 μm)), making it difficult to measure the change amount of the optical path length difference Δd appropriately. In contrast, in this embodiment, by using light with a relatively long wavelength (e.g., 10 μm) as the reference light L**2** as shown in the lower part of FIG. **4**, the change in the optical path length difference Δd of about 1 μm can be measured appropriately.
[0100] Furthermore, a beam splitter for transmitting terahertz waves generally does not transmit visible to near-infrared light, but by using reference light with a wavelength of 3 μm or more (i.e., mid-infrared to far-infrared light), a common beam splitter **22** can be used for both the terahertz wave L**1** and the reference light L**2**. This allows the optical path for the terahertz wave L**1** to generate the first interference light IL**1** and the optical path for the reference light L**2** to generate the second interference light IL**2** to be set on the same optical path (i.e., optical paths Pa and Pb). As a result, the optical path length difference Δd in the first interference light IL**1** can be accurately measured based on the second interference light IL**2** of the reference light L**2** generated on the same optical path as the terahertz wave L**1**. According to the above configuration, while continuously changing the optical path length difference Δd between the split light La and the split light Lb, measurement can be performed while appropriately monitoring the change in the optical path length difference Δd in real-time based on the second interference light IL**2**, enabling fast and suitable interferometric measurement using terahertz waves L**1**.
[0101] Furthermore, the analysis unit **52** is configured to analyze the analyze-target object S by executing the first process and the second process described above. According to the above configuration, by obtaining the electric field amplitude value E of the interference light IL**1** corresponding to each value of the time difference Δt based on the conversion relationship (e.g., the fitting function R shown in FIG. **3**A) between the electric field amplitude value E and the electrical signal value (Vp−p), Fourier spectroscopy using interferometric measurement with terahertz waves L**1** can be performed quickly and accurately.
[0102] Furthermore, the interferometric optical system **20** is configured to be capable of changing the optical path length of the optical path Pa by driving the mirror **23** and capable of changing the optical path length of the optical path Pb by driving the rotating mirror **24**. According to the above configuration, one mirror (e.g., the mirror **23**) can be used as an initial setting mirror for adjusting the optical path length difference Δd to be near zero in the initial state, and the other mirror (e.g., the rotating mirror **24**) can be used as a movable mirror for changing the optical path length difference Δd during interferometric measurement, enabling a suitable configuration for interferometric measurement.
[0103] Furthermore, the rotating mirror **24** is configured to be rotationally driven so that the optical path length of the optical path Pb changes, and the optical path Pb is constituted by the optical path from the beam splitter **22** to the mirror **25** via the rotating mirror **24** and the optical path returning to the beam splitter **22** via the rotating mirror **24** after being reflected by the mirror **25**. According to the above configuration, by rotationally driving the rotating mirror **24**, measurement can be performed while changing the optical path length difference Δd quickly compared to using a mirror that can be moved parallel to the direction perpendicular to the reflecting surface like the mirror **23**. As a result, the analysis by the interferometric measurement apparatus **1**A can be sped up.
[0104] Furthermore, the light source **12** that outputs the reference light L**2** is constituted by a quantum cascade laser element. To detect the second interference light IL**2** with high precision in the detector **40**, it is preferable to use light with as narrow a spectral linewidth (wavelength linewidth) as possible as the reference light L**2**. By using a quantum cascade laser element with the

property of outputting light with a relatively narrow spectral linewidth compared to lamp light source and so on as the light source **12**, the detection precision of the second interference light IL**2** in the detector **40** can be enhanced. From the above perspective, it is more preferable that the light source **12** is a distributed feedback (DFB) quantum cascade laser element.

[0105] Furthermore, the width of the periodic change in the optical path length difference Δd due to the rotational driving of the rotating mirror **24** is 3 mm or more (10 mm in this embodiment). According to the above configuration, appropriate resolution and measurement dynamic range can be obtained for the optical path change of the terahertz wave L**1**.

Second Embodiment

[0106] The interferometric measurement apparatus **1**B of the second embodiment will be described with reference to FIGS. **9** and **10**. The interferometric measurement apparatus **1**B differs from the interferometric measurement apparatus **1**A in that it includes a measurement device **50**B instead of the measurement device **50**. The measurement device **50**B differs from the measurement device **50** in that it further includes a light source control unit **53**. The interferometric measurement apparatus **1**B also differs from the interferometric measurement apparatus **1**A in that both the light source **11** and the light source **12** are pulse-driven (i.e., both the terahertz wave L**1** and the reference light L**2** are pulsed light). Hereinafter, the differences between the interferometric measurement apparatus **1**B and the interferometric measurement apparatus **1**A will be described, and redundant descriptions of the same configurations as those of the interferometric measurement apparatus **1**A will be omitted.

[0107] The light source control unit **53** controls the driving of the light source **11** and the light source **12**. Specifically, the light source control unit **53** synchronizes the light source **11** and the light source **12** in pulse mode. For example, as shown in FIG. **10**, the light source control unit **53** generates a pulse P with a pulse width W**1** at a constant period (longer than the pulse width W**3** of the reference light L**2** described later) and outputs the pulse P as a trigger signal to the light source **11** and the light source **12**. This allows the light source **11** and the light source **12** to output the terahertz wave L**1** as pulsed light with a pulse width W**2** and the reference light L**2** as pulsed light with a pulse width W**3** at the same timing (the generation timing of the pulse P). For example, the pulse width W**1** of the pulse P is set to about 50 fs, the pulse width W**2** of the terahertz wave L**1** is set to about 1 ps, and the pulse width W**3** of the reference light L**2** is set to a sufficiently larger value (e.g., about 100 ns) than the pulse width W**2** of the terahertz wave L**1**.

[0108] According to the interferometric measurement apparatus **1**B, the same measurement as that of the interferometric measurement apparatus **1**A can be performed, and by synchronizing and pulse-driving the light source **11** and the light source **12**, cooling of the light source **11** and the light source **12** can be made unnecessary. Furthermore, compared to the case where the light source **11** and the light source **12** are continuously driven, the device life of the light source **11** and the light source **12** can be extended.

Third Embodiment

[0109] The interferometric measurement apparatus **1**C of the third embodiment will be described with reference to FIG. **11**. The interferometric measurement apparatus **1**C differs from the interferometric measurement apparatus **1**A in that it includes a single light source **10**C instead of the light source **10** constituted by the light sources **11** and **12**. The interferometric measurement apparatus **1**C also differs from the interferometric measurement apparatus **1**A in that it includes an interferometric optical system **20**C instead of the interferometric optical system **20**. The interferometric optical system **20**C differs from the interferometric optical system **20** in that the beam splitter **21** is omitted. Hereinafter, the differences between the interferometric measurement apparatus **1**C and the interferometric measurement apparatus **1**A will be described, and redundant descriptions of the same configurations as those of the interferometric measurement apparatus **1**A will be omitted.

[0110] The light source **10**C is constituted by a single quantum cascade laser element having a dual upper subband level structure and capable of generating both the terahertz wave L**1** and the reference light L**2** by multiple intersubband transitions. The light source **10**C may be constituted by a quantum cascade laser element having a configuration similar to that disclosed in Patent Document 1 (Japanese Patent No. 6276758).

[0111] For example, the light source **10**C is configured to generate the first light with a first frequency ω.sub.1 and the second light with a second frequency ω.sub.2 by multiple intersubband transitions, and to generate the terahertz wave L**1** with a difference frequency ω.sub.THz (ω.sub.THZ=|ω.sub.1−ω.sub.2|) of the first frequency ω.sub.1 and the second frequency ω.sub.2 by difference frequency generation. For example, the first light and the second light are mid-infrared light. Furthermore, one of the first light and the second light (e.g., the first light) may be light with a fixed wavelength, and the other (e.g., the second light) may be light with a variable wavelength (or broadband light). In this case, the first light with a fixed wavelength can be suitably used as the reference light L**2**. Additionally, by making the second light variable in wavelength (or broadband), the wavelength sweep width of the terahertz wave L**1** can be increased.

[0112] According to the interferometric measurement apparatus **1**C, it is possible to output both the terahertz wave L**1** for interferometric measurement and the reference light L**2** for measuring optical path length difference with a single light source (quantum cascade laser element). As a result, compared to the case where the light source is constituted by two light sources (i.e., a first light source that outputs the terahertz wave L**1** and a second light source that outputs the reference light L**2**), the number of light sources can be reduced. Furthermore, it is unnecessary to use a member for adjusting the terahertz wave L**1** output from the first light source and the reference light L**2** output from the second light source to be incident coaxially on the beam splitter **22** (e.g., the beam splitter **21** provided in front of the beam splitter **22** in the first embodiment). Therefore, according to the interferometric measurement apparatus **1**C, the configuration of the light source and the interferometric optical system can be simplified.

MODIFICATIONS

[0113] The present disclosure has been described with reference to several embodiments, but the present disclosure is not limited to the configurations shown in the above embodiments. The materials and shapes of the respective components are not limited to the specific materials and shapes described above, and various other materials and shapes can be adopted. Furthermore, some of the configurations included in the above embodiments may be omitted or changed as appropriate, and may be combined arbitrarily.

[0114] For example, the photomultiplier tube **30** may be capable of imaging the intensity distribution of the incident light. When the electron multiplication part **32** includes a microchannel plate (e.g., image intensifier), the intensity distribution of the incident light can be imaged. By using such a photomultiplier tube **30**, it is possible to perform imaging analysis of the analyze-target object S.

[0115] The analysis unit **52** performs the analysis (identification) of the analyze-target object S by converting the intensity (Vp−p) of the interference light IL**1** measured by the interference intensity measurement unit **51** into the electric field amplitude value and performing Fourier transform based on the dependence of the electric field amplitude value on the time difference Δt. However, the analysis unit **52** may perform the analysis of the analyze-target object S by other methods. For example, the analysis unit **52** may perform the analysis of the analyze-target object S by other methods without converting the intensity (Vp−p) of the interference light IL**1** corresponding to each value of the time difference Δt into the electric field amplitude value. Even in such cases, the same effects as those of the interferometric measurement apparatus **1**A described above can be achieved. In other words, based on the second interference light IL**2** of the reference light L**2** generated on the same optical path as the terahertz wave L**1**, the optical path length difference Δd in the first interference light IL**1** can be accurately measured, and measurement can be performed while appropriately monitoring the change in the optical path length difference Δd in real-time based on the second interference light IL**2**, enabling fast and suitable interferometric measurement using terahertz waves L**1**.

[0116] The components constituting the interferometric optical systems **20** and **20**C may be changed or omitted as appropriate within the range that allows the measurement by the interferometric measurement apparatuses **1**A to **1**C described above. Similarly, the arrangement of the components constituting the interferometric optical systems **20** and **20**C may be changed as appropriate. Furthermore, other optical components not described in the above embodiments may be added to the interferometric optical systems **20** and **20**C as appropriate. For example, a lens may be disposed between the beam splitter **26** and the photomultiplier tube **30** to enhance the efficiency of the interference light IL**1** incident on the photomultiplier tube **30**. Similarly, a lens may be disposed between the beam splitter **26** and the detector **40** to enhance the efficiency of the interference light IL**2** incident on the detector **40**.

Claims

1. An interferometric measurement apparatus comprising: a light source that outputs a terahertz wave for interferometric measurement and a reference light with a wavelength of 3 μm or more for measuring optical path length difference; an interferometric optical system that includes: a beam splitter that splits the terahertz wave and the reference light output from the light source and incident coaxially into a first split light and a second split light; a first optical path on which the first split light from the beam splitter is reflected by a first mirror and re-enters the beam splitter; and a second optical path on which the second split light from the beam splitter is reflected by a second mirror and re-enters the beam splitter, and wherein the interferometric optical system is configured to combine the first split light and the second split light re-entered into the beam splitter, wherein the optical path length difference between the first split light and the second split light is variable; a photomultiplier tube sensitive to the terahertz wave, and configured to output an electrical signal value in accordance with an incident light intensity of a first interference light that is an interference light of the terahertz wave generated by the combination of the first split light and the second split light at the beam splitter; a detector configured to detect a second interference light that is an interference light of the reference light generated by the combination of the first split light and the second split light at the beam splitter; an interference intensity measurement unit configured to measure an intensity of the first interference light based on the electrical signal output from the photomultiplier tube; and an analysis unit configured to perform Fourier transform based on the intensity of the first interference light measured by the interference intensity measurement unit and a detection result of the second interference light by the detector, thereby analyzing an analyze-target object disposed on the optical path through which the terahertz wave passes.

2. The interferometric measurement apparatus according to claim 1, wherein the analysis unit is configured to: convert the intensity of the first interference light measured by the interference intensity measurement unit into an electric field amplitude value based on a relationship between the electric field amplitude value of the light incident on the photomultiplier tube and the electrical signal value output from the photomultiplier tube, thereby calculating the electric field amplitude value of the first interference light for each value of time difference corresponding to the optical path length difference; and perform Fourier transform based on dependency of the calculated electric field amplitude value of the first interference light on the value of the time difference to analyze the analyze-target object.

3. The interferometric measurement apparatus according to claim 1, wherein the interferometric optical system is configured to be capable of changing an optical path length of the first optical path by driving the first mirror and capable of changing an optical path length of the second optical path by driving the second mirror.

4. The interferometric measurement apparatus according to claim 1, wherein the interferometric optical system further includes a third mirror, wherein the second mirror is configured to be rotationally driven so that an optical path length of the second optical path changes, and wherein the second optical path is configured by an optical path from the beam splitter to the third mirror via the second mirror and an optical path returning to the beam splitter via the second mirror after being reflected by the third mirror.

5. The interferometric measurement apparatus according to claim 1, wherein the detector is any one of a quantum cascade detector, an MCT detector, a superlattice infrared detector element, an InSb detector element, an InAs detector element, and an InAsSb detector element.

6. The interferometric measurement apparatus according to claim 1, wherein the light source includes a first light source that outputs the terahertz wave and a second light source that outputs the reference light, and the second light source is constituted by a quantum cascade laser element.

7. The interferometric measurement apparatus according to claim 1, wherein the light source is constituted by a single quantum cascade laser element having a dual upper subband level structure and capable of generating both the terahertz wave and the reference light by multiple intersubband transitions.

8. The interferometric measurement apparatus according to claim 1, further comprising a light source control unit configured to control a driving of the light source, wherein the light source includes a first light source that outputs the terahertz wave and a second light source that outputs the reference light, and the light source control unit synchronizes the first light source and the second light source in pulse mode.

9. The interferometric measurement apparatus according to claim 1, wherein the interferometric optical system is configured to be capable of changing an optical path length of the second optical path by driving the second mirror, and a range of periodic change in the optical path length difference between the first split light and the second split light by the driving of the second mirror is 3 mm or more.