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Description

Title

MINIATURE SPECTROMETER AND SPECTROSCOPIC METHOD

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The present invention relates to a miniature spectrometer and a method to identify a spectrum of radiation reflected, transmitted or emitted by an object.

State of the art

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The invention is based on a miniature spectrometer and a method for determining a spectrum of radiation reflected or emitted by an object according to the preamble of the independent patent claims.

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"A static polarisation imaging spectrometer based on a Savart polariscope" (Zhang et al., *Optics Communication* 203 (2002), 21-26) describes an imaging polarisation spectrometer (PIS) based on a simple Savart polariscope two-dimensional intensity distribution, which contains in one spatial direction the interferogram and in the orthogonal direction the image information. Both components are present at the same time and must be separated from each other. This two-dimensional distribution is captured by means of a two-dimensional CCD (charge-coupled device) detector. The PIS comprises infinity optics, a polarisation interferometer that has a polariser, a Savart polariscope and an analyser, an imaging lens and a system for signal acquisition and signal processing. The infinity optics generates from the rays arriving from each object point parallel ray bundles with different angles. The resolution of the PIS can be adjusted according to the size of the CCD detector and the thickness of the CCD birefringent layers forming the Savart polariscope.

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The resolution increases with increasing size of the CCD detector and increasing thickness of the birefringent layers. Moreover, the spectral resolution depends on the usable angle range, the refractive index contrast between the two polarisation directions and on the focal length of the lens between the Savart polariscope and detector.

Advantages of invention

The present invention provides a miniature spectrometer and a method for determining a spectrum of radiation reflected, transmitted or emitted by an object by means of a miniature spectrometer according to invention.

A miniature spectrometer is a spectrometer with dimensions in the range of centimetres, including smaller dimensions below the centimetre range as well. The invention with the features of the independent patent claim has the advantage that the miniature spectrometer according to the invention has a compact, miniaturisable structure. In addition, cost-effective production of the miniature spectrometer according to the invention is possible. The miniature spectrometer according to invention stands out by a high level of user-friendliness and reduction of measurement errors, as the measurement result is independent of the angle of incidence of the light and the distance between the miniature spectrometer and the measurement object in a large area. Another advantage that arises from the homogenisation of spatial image information is that only spectral information is present in the data, and that no complex background signal must be taken into account. This increases the accuracy and reproducibility of the miniature spectrometer according to invention.

This is achieved by a miniature spectrometer, comprising an optical system, a polarisation interferometer comprising a polariser, a Savart element and an analyser, a detection unit comprising a detector and a data unit, wherein the optical system is configured as a diffuser. The resolution of the miniature spectrometer according to invention advantageously does not depend on the nature of the object and the type of light source, because in the miniature spectrometer according to invention, the diffuser always ensures utilisation

of the acceptance angle of the Savart element of the miniature spectrometer. The diffuser completely illuminates the acceptance angle of the light coming from the object to be examined.

5 In a further development of the miniature spectrometer according to invention, the detection unit comprises focusing optics, wherein the focusing optics is arranged in the ray path between the polarisation interferometer and the detector. As a result, rays with the same path difference are advantageously focused on a common point of the
10 detector. Thus, a spatially resolved interferogram can be generated.

Additionally or alternatively, the miniature spectrometer according to invention may have a light source. Thus, it is possible to illuminate the object to be examined with this light source, so that advantageously the
15 light intensity coming from the object to be examined increases, and the measurement result can be improved or sufficiently detailed measurement becomes possible. Depending on application, only by this method the necessary knowledge of the spectral characteristics of the light illuminating the object can be ensured. In addition, the light source allows
20 the use of ambient light independent wavelengths and spectral intensities. Thus, it is also possible to excite spectra in frequency ranges, which are not or only insufficiently covered by the ambient light, such as ultraviolet or infrared light. Furthermore, by modulation of the light source, a selection of the radiation excited, absorbed or transmitted by this source
25 can be made. Hence, the measured spectrum emitted by the object is not distorted by spectral components of ambient radiation and also allows measurements in non-darkened rooms. This is particularly important in everyday use outside of a controlled laboratory environment and thus indispensable for use in everyday goods. Also, a specific area can be
30 selectively illuminated by such a light source, which is particularly advantageous in the case of wide range of samples having an inhomogeneous nature.

In an advantageous embodiment, the diffuser is arranged on the polariser of the
35 polarisation interferometer. This allows a compact construction and miniaturisation of

the miniature spectrometer according to invention.

5 In an advantageous embodiment, the data unit of the miniature spectrometer according to the invention may comprise a reference database. This allows an internal evaluation of the spectrum of the radiation reflected or emitted by an object. The miniature spectrometer according to the invention can be used independent of the availability of Internet access or external reference databases.

10 Alternatively, the data unit of the miniature spectrometer according to the invention may be configured as a communication interface for data transmission between the miniature spectrometer and an external evaluation element, which comprises a reference database and data processing unit. As
15 the evaluation can be done externally, the miniature spectrometer according to invention has in this embodiment fewer components than the embodiment above, and can thus be advantageously produced more cost-effectively. Moreover, the external evaluation element can be used by several users and
20 an improvement of the reference database can be made by sending a feedback regarding the quality of the evaluation. In addition, the reference database can thus be updated.

25 In another embodiment of the miniature spectrometer according to invention, the detector is configured as one-dimensional sensor matrix. It is an advantage that a compact construction and miniaturisation of the miniature spectrometer according to invention are made possible.

30 In an alternative embodiment, the detector is configured as two-dimensional sensor matrix. It is an advantage of this embodiment that the interferogram is displayed in one dimension and is repeated several times in the direction of the second dimension, so that the interferogram can be averaged over this
35 second dimension, and thus the signal-to-noise ratio is improved

as compared to the use of a one-dimensional sensor matrix.

In another embodiment, the optical system is configured as directed diffuser.
This diffuser can be advantageously adapted to an opening angle of the
Savart element.

Brief description of drawings

Embodiments of the invention are shown in the drawings and are explained in detail in the following description. Identical reference numbers in the figures indicate the same or similar elements.

As shown is:

Fig. 1a shows the configuration of the part of of a miniature spectrometer according to the invention;

Fig. 1b is a schematic representation of the principle of operation of a miniature spectrometer according to the invention, wherein the individual components are shown separated from each other for better clarity;

Fig. 2 shows a data unit of a miniature spectrometer according to the invention and its operating principle;

Fig 3 shows a miniature spectrometer according to the invention with an external evaluation element; and

Fig 4 shows a miniature spectrometer according to invention with integrated light source.

Embodiments of invention

Fig. 1a shows the configuration of a miniature spectrometer 8 according to the invention. A data unit 13 is not shown in Fig 1a. An embodiment of a miniature spectrometer 8 according to invention comprises an optical system, which is a diffuser 1, a polariser 2, a first birefringent crystal 3, a second birefringent crystal 4, an analyser 5, a lens 6 and a detector 7. The birefringent crystals 3, 4 together form a Savart element 14. The polariser 2 and the analyser 5 are positioned in the ray path on two opposite sides of the Savart

element. Together with the Savart element 14, they form a polarisation interferometer 15. The diffuser 1 is positioned on one side of the polariser 2 opposite the Savart element 14. In this embodiment, the diffuser 1 is mounted directly on the polarisation interferometer 15, resulting in a compact arrangement. In the ray path, focusing optics 6 are positioned on one side of the analyser 5 opposite the Savart element 14. In this embodiment, the focusing optics is a lens 6. The lens 6 is formed as converging lens, so that parallel rays that impinge on the lens 6 intersect in the focal plane of lens 6. The detector 7 is arranged so that its radiation-sensitive surface 7a is located in the focal plane of the lens 6. The radiation-sensitive surface 7a serves to detect radiation. In this embodiment, the radiation-sensitive surface 7a is realised by a two-dimensional arrangement of individual radiation sensors, so-called two-dimensional sensor matrix, in the focal plane of the lens 6. In an alternative embodiment, the radiation-sensitive surface 7a is formed by one-dimensional array of radiation sensors, a so-called one-dimensional sensor matrix, in the focal plane of lens 6.

Alternatively, the focusing optics 6 may comprise at least one of the following elements: refractive element, diffractive element, holographic-optical element or reflective element.

Fig. 1b shows a schematic representation of a radiation path through the various elements of the miniature spectrometer 8 according to the invention. The data unit 13 is not shown in Fig 1b. For better clarity, the individual components of the miniature spectrometer 8 are shown spaced apart from each other. Solid lines are situated in the drawing plane, dashed lines show a component in the drawing plane. A ray path is shown by way of example for two rays S1, S2, which strike the polariser 2 at angles different from each other. In addition, the path of these rays S1, S2 is shown, which starts from a further point on the diffuser 1. The diffuser 1 is an optical component. It has numerous small diffraction centres.

Hence, radiation incident on a first side 11 of the diffuser 1 is deflected into different directions while passing through the diffuser 1. The angle dependence of the intensity of the radiation intensity emerging from the diffuser has a defined form and is independent of the angle and the intensity distribution of the radiation incident on the first side 11 of the diffuser 1. Therefore, the object to be examined can be arranged at a plurality of distances and angles to the miniature spectrometer without changing the measurement result of the miniature spectrometer. The radiation emerging from the diffuser 1 is linear polarised by the polariser 2 arranged in the ray path. After passing through the polariser 2, the linear polarised radiation enters first an initial birefringent crystal 3 having a first optical axis OA1, and subsequently passes through a second birefringent crystal 4 having a second optical axis OA2. A main section of the birefringent crystal 3, 4 is described by the plane perpendicular to the entry surface 3a and containing the optical axes OA1, OA2. In this embodiment, the angle between the first optical axis OA1 and the entry surface 3a is 45° . The main section of the second birefringent crystal 4 is rotated by 90° with respect to the main section of the first birefringent crystal 3. Birefringent materials have different refractive indices for different polarisation of incident radiation. In birefringence, the incident radiation is split into two mutually perpendicularly polarised components. On the one hand, into an ordinary ray whose electrical field is perpendicular to the main section, on the other hand, into an extraordinary ray whose electrical field oscillates in the main section of the birefringent crystal 3, 4. The wave fronts of the ordinary and extraordinary ray, hereinafter referred to as partial rays of the ray incident on the birefringent crystal, have different propagation velocities determined by the different refractive indices. As a result, after passing through a birefringent crystal 3, 4, the ordinary ray and the extraordinary ray have a phase difference, which depends on the difference of the various refractive indices, the thickness of the birefringent crystal 3, 4 and the angle of incidence. This phase difference is proportional to a path difference of the partial rays. In this embodiment, the polariser 2 is selected such that the ordinary ray and the extraordinary ray in the Savart element 14 have the same intensity.

The direction of polarisation is thus selected so that it has an angle of 45° with respect to the main sections of the birefringent crystal 3, 4. The first ray S1 incidents the first birefringent crystal 3 perpendicularly. In the first birefringent crystal, it is split into an ordinary ray S1O and into an extraordinary ray S1A. The ordinary ray S1O is refracted according to the Snell's law of refraction, therefore it passes through the first birefringent crystal 3 without deflection. A dielectric constant indicates the permittivity of a material for electrical fields. In general, it is described by a tensor. Thus, the electrical field is generally not parallel to the electrical flux density. A propagation vector is perpendicular to the electrical flux density both inside and outside the material. The direction of the propagation vector also remains unchanged in the extraordinary ray S1A. However, the propagation direction of the extraordinary ray S1A is still determined by a Poynting vector, which is perpendicular to the electrical field. The angle between the propagation vector and the Poynting vector is equal to the angle between the electrical field and the electrical flux density. Hence, from the components of the electrical field, that angle at which the extraordinary ray S1A passes through the first birefringent crystal 3 can be determined. The main section of the second birefringent crystal 4 is perpendicular to the main section of the first birefringent crystal 3. Thus, the electrical field of the extraordinary ray S1A oscillates perpendicularly to the main section of the second birefringent crystal 4. Upon entering the second birefringent crystal 4, it becomes the new ordinary ray of the second birefringent crystal 4 and is refracted according to Snell's law of refraction. The electrical field of the ordinary ray S1O oscillates in the main section of the second birefringent crystal 4. Therefore, it becomes the new extraordinary ray upon entering the second birefringent crystal 4 and traverses the second birefringent crystal at an angle, which can be determined by the components of the electrical field of the new extraordinary ray. After passing through the Savart element 14, the partial rays of ray S1 thus emerge from different points of the Savart element 14, and subsequently proceed in parallel to one another and perpendicular to the entry surface 3a due to the Snell's law of refraction.

However, they have a phase difference as described above. The phase difference of the two partial rays as described above depends, inter alia, on the angle of incidence into the Savart element 14, and is zero for the vertical ray S1. The analyser 5, which polarises the radiation in the same direction as the polariser 2, is arranged in the ray path behind the Savart element 14. After passing through the analyser 5, the two partial rays have identical polarisation. Hence, the partial rays may interfere. The partial rays are focused to a point in their focal plane by means of the converging lens 6. The two partial rays do interfere. This results in an intensity spot on the detector 7, which is arranged in the focal plane of the lens 6. As the converging lens 6 focuses all the rays incident on it in parallel to a point in the focal plane, all the rays incident on the Savart element 14 perpendicularly like the first ray S1 form a common intensity spot on the detector. The second ray S2 impinges on the Savart element 14 at a different angle than the first ray S1. The schematic path of the second ray S2 is shown in Fig. 1b, starting at different positions of the diffuser 1. It is also split into an ordinary ray S2O and into an extraordinary ray S2A). The ordinary ray S1O is refracted in the material according to the Snell's law of refraction. The path of the extraordinary ray S2A is determined as described above. All the rays incident on the Savart element 14 at the same angle as the second ray S2 are focused on a common intensity spot in the focal plane of the lens 6 after passing through the polarisation interferometer 15. This intensity spot is detected by the detector 7. Hence, each intensity spot on the detector 7 corresponds to a different path difference. The Savart element 14 generates different path differences. With increasing distance from the centre of the detector 7, the intensity spots of interfering partial rays are generated with ever-increasing path difference. Thus, a spatially resolved interferogram is generated on the detector. This is required for Fourier-transform spectroscopy.

In a typical embodiment, the diffuser 1 comprises a 1mm thick quartz glass plate with diffuser particles, being adhered to a polarisation film 2 with 0.5mm thickness, mounted on a Savart element 14 comprising of two 3mm thick rutile plates, each configured so that the optical

axes OA1, OA2 are at an angle of 45° to the entry surface and arranged 90° to each others' main sections. Alternatively in another embodiment, the rutile plates may be replaced by calcite plates. On the exit surface of the Savart

element 14, another 0.5 mm thick polarisation film is applied, acting as analyser 5. The exiting light is then typically imaged via an achromatic focusing lens 6 with typical focal length of typically 4 mm onto a 2-dimensional photo detector array 7A with typical 4mm diagonal and 5 million pixels.

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The signals of the individual pixels contain in one direction (for example, in a row) the interferogram, from which the spectrum of the light striking the diffuser 1 can be obtained by Fourier transformation. In the other direction, this information is repeated, so that signal improvement can be achieved by averaging. The spectrum obtained in this way can be compared either directly with the reference spectra or chemo-metrically evaluated and subsequently compared with reference values in order to conclude on the composition of the examined object.

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In another embodiment, the angle between the first optical axis OA1 and the entry surface 3a is selected between 30° and 60°.

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In another embodiment, where the detector unit 12 cannot be permanently fixed, the camera of a mobile device or a security camera, which is externally mounted, may be used instead. In this case, the diffuser 1 and the polarisation interferometer 15 form a unit that can be mounted on the camera, when in use.

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In a further embodiment, a directed diffuser 1, which is adjusted to a suitable opening angle of the Savart element, may be used.

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Fig. 2 shows the functional principle of a data unit 13, which in one embodiment is integrated in the miniature spectrometer 8. A spatially resolved interferogram 20a is generated in the detector unit 12. The interferogram is transmitted to the data unit 13. In this embodiment, the data unit 13 comprises a data processing unit 16,

a reference database 17 and a comparison unit 18. The spatially resolved interferogram 20a is transmitted to the data processing unit 16, where the interferogram is Fourier-transformed. The Fourier-transformed
5 interferogram is a spectrum 16b of the radiation reflected, transmitted or emitted by an object to be examined. In the reference database 17, spectra of known objects, chemical compounds, materials etc. are stored. In the comparison unit 18, the spectrum 16b of the radiation reflected, transmitted or emitted by an object to be examined is compared with the known
10 spectra; this may take place before or after the application of chemometric algorithms. Thus, the spectrum 16b of the radiation reflected, transmitted or emitted by an object to be examined is assigned to a known object, a known chemical compound, a known material etc. This provides information about the object to be examined. The output of the data unit 13
15 forms the spectral information 18b, or higher value information subsequently determined therefrom, such as, for example, material properties of the object to be examined. In this case, the user can optionally display raw data 20a, the Fourier-transformed spectrum 16b or the information about the object obtained after the chemometric analysis.

Fig. 3 shows an embodiment in which the data unit is configured as a communication interface 19. In this case, the miniature spectrometer 8 is integrated in an electronic device 22. The communication interface 19
25 facilitates data transmission 18b, 20a, 20b between the miniature spectrometer 8 and an external evaluation element 20. The data transmission 18b, 20a, 20b may be realised for example via an Internet connection, LAN, WLAN, USB, Bluetooth or infrared radiation. The evaluation element 20 is configured to receive the data from the
30 communication interface 19. In this embodiment, the interferogram 20a recorded by the detector 7 is not evaluated in the miniature spectrometer 8, but in the external evaluation element 20. The external evaluation element 20 comprises a data processing unit 16, a reference database 17 and a comparison unit 18. The spatially resolved interferogram 20a is transmitted
35 via data transmission 18b, 20a, 20b to the data processing unit 16,

for example, in a cloud. By means of Fourier transformation, the latter generates therefrom the spectrum 16b of the radiation reflected, transmitted or emitted by an object to be examined. As described above, the spectrum 16b of the radiation reflected, transmitted or emitted by an object to be examined is compared in the comparison unit 18 with the known spectra of the reference database 17; this may take place before or after the application of chemometric algorithms. The spectral information 18b of the object to be examined is an evaluation result, which is sent back to the communication interface 19 via data transmission. In this embodiment, a response 20b of the user of the electronic device 22 is provided via data transmission 18b, 20a, 20b. As far as possible, the user evaluates the evaluation result regarding its quality. As a result, the reference database 17 of the external evaluation element 20 can be updated and improved. In particular, the external evaluation element 20 can be used by several users. The evaluations of the users improve the quality of the evaluation results. Hence, the user may record spectra of substances known to him and evaluate whether they were correctly detected by the device.

In an embodiment not shown here, the external evaluation element 20 comprises a reference database 17 and a comparison unit 18. The data unit in this embodiment is configured as a communication interface 19 and comprises the data processing unit 16. The communication interface 19 allows data transmission between the miniature spectrometer 8 and the external evaluation element 20. The data transmission may be realised, for example, via an Internet connection, LAN, WLAN, USB, Bluetooth or infrared radiation. The evaluation element 20 is configured to receive the data from the communication interface 19. The spectrum 16b of the radiation reflected, transmitted or emitted by an object to be examined is determined in the data processing unit 16, and transmitted to the external evaluation element 20 via data transmission, where the evaluation takes place as described above.

Fig. 4 shows an embodiment of a miniature spectrometer 8 with integrated light source 9. By means of the light source, the object 10 to be examined is

irradiated S in order to increase the intensity of the reflected radiation or to excite the object to be examined for the emission of radiation.

Claims

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1. Miniature spectrometer (8) comprising
 - an optical system;
 - a polarisation interferometer (15), comprising of a polariser (2), a Savart element (14) and an analyser (5);
 - a detection unit (12), comprising of a detector (7) and a data unit (13);**characterised in that** the optical system is configured as a diffuser (1).

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2. Miniature spectrometer (8) according to claim 1, **characterised in that** the detection unit (12) has focusing optics (6), wherein the focusing optics (6) is arranged in a ray path between the polarisation interferometer (15) and the detector (7).

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3. Miniature spectrometer (8) according to one of the preceding claims, **characterised in that** the miniature spectrometer (8) has a light source (9).

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4. Miniature spectrometer (8) according to one of the preceding claims, **characterised in that** the diffuser (1) is arranged on the polariser (2) of the polarisation interferometer (15).

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5. Miniature spectrometer (8) according to one of the preceding claims, **characterised in that** the data unit (13) comprises a reference database (17).

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6. Miniature spectrometer (8) according to one of the claims 1 to 3, **characterised in that** the data unit (13) is configured as communication interface for data transmission (18b, 20a, 20b) between the miniature spectrometer (8) and an external evaluation element (20)

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comprising a reference database (17) and a data processing unit (16).

- 5 7. Miniature spectrometer (8) according to one of the preceding claims,
 characterised in that the detector (7) is configured as one-
 dimensional sensor matrix.
- 10 8. Miniature spectrometer (8) according to one of the claims 1 to 6,
 characterised in that the detector (7) is configured as two-
 dimensional sensor matrix.
- 15 9. Miniature spectrometer according to one of the preceding claims,
 characterised in that the optical system is a directed diffuser (1).
10. Method for identification of a spectrum (18b) of radiation reflected,
 transmitted or emitted by an object by means of a miniature
 spectrometer (8) according to one of the preceding claims.