(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
13 August 2020 (13.08.2020)

WIPO | PCT

(10) International Publication Number
WO 2020/163492 A1

(51) International Patent Classification:
G01J 3/02 (2006.01) *G01J 3/26* (2006.01)
G01J 3/51 (2006.01) *G01J 3/28* (2006.01)
G01J 3/12 (2006.01)

(21) International Application Number:
PCT/US2020/016819

(22) International Filing Date:
05 February 2020 (05.02.2020)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/801,762 06 February 2019 (06.02.2019) US
16/782,674 05 February 2020 (05.02.2020) US

(71) Applicant: **CALIFORNIA INSTITUTE OF TECHNOLOGY** [US/US]; 1200 E. California Blvd, MC 6-32, Pasadena, California 91125 (US).

(72) Inventors: **SCHERER, Axel**; PO Box 5, Barnard, Vermont 05031 (US). **JEON, Taeyoon**; 146 S. Michigan Ave., #204, Pasadena, California 91106 (US).

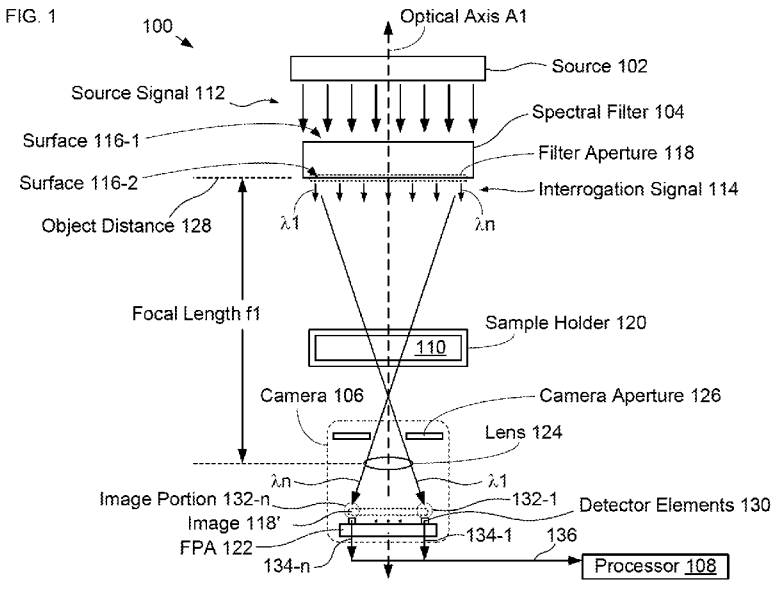
(74) Agent: **WALKER, James A.**; Kaplan Breyer Schwarz, LLP, 90 Matawan Road, Suite 201, Matawan, New Jersey 07747 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH,

(54) Title: COMPACT HYPERSPECTRAL MID-INFRARED SPECTROMETER

FIG. 1



(57) **Abstract:** An infrared spectrometer for operation in the mid-infrared spectral range is presented, where the spectrometer includes a Bragg-mirror-based spectral filter that is operative for providing an interrogation signal whose spectral content is dispersed along a first direction at a filter aperture. The filter aperture is imaged through a sample by a thermal-imaging camera to create a focused image that is based on the interrogation signal and the absorption characteristics of the sample. As a result, embodiments in accordance with the present disclosure can be smaller, less complex, and less expensive than infrared spectrometers known in the prior art.

WO 2020/163492 A1

[Continued on next page]

GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

Compact Hyperspectral Mid-Infrared Spectrometer

Related Applications

[0001] This application claims the benefit of U.S. Provisional Application No. 62/801,762 filed February 6, 2019 (Attorney Docket: CIT-8189-P), which is incorporated herein by reference. If there are any contradictions or inconsistencies in language between this application and one or more of the cases that have been incorporated by reference that might affect the interpretation of the claims in this case, the claims in this case should be interpreted to be consistent with the language in this case.

Field of the Invention

[0002] The present invention relates to spectroscopy in general and, more particularly, to hyperspectral spectrometers for use in the mid-infrared spectrum.

Background of the Invention

[0003] Infrared spectroscopy enables analysis of the chemical composition of a sample by interrogating the material with light (or, alternatively, radiation) within a spectral range and determining the absorption spectrum of the sample material. Infrared spectroscopy is widely used in many applications, such as medical diagnostics, petroleum exploration, environmental monitoring, and drug testing.

[0004] Every chemical and compound has a unique absorption spectrum, which manifests as a specific set of wavelengths at which light is measurably absorbed. As a result, the "absorption peaks" identified for the material of a sample provide a chemical "finger print" that enables its chemical composition to be determined. The mid-infrared (MIR) spectral range (*i.e.*, the wavelength range from approximately 5 microns to 25 microns) is particularly attractive for spectroscopy because it normally includes a wealth of absorption peaks for most chemicals; therefore, the MIR spectral range is often referred to as the "fingerprint region" for most molecules.

[0005] Prior-art spectrometers are typically based on Fourier Transform Infrared (FTIR) spectroscopy. Unfortunately, FTIR spectrometry requires large, highly complex interferometers having long optical paths and optical components, such as mirrors and beam splitters, whose alignment must be precisely maintained. As a result, such systems are large, complex, and expensive to manufacture and maintain over their lifetime.

[0006] Although there have been attempts to miniaturize FTIR spectroscopy systems for operation in the MIR spectral range, such systems still require the fabrication and alignment of a number of precisely controlled structures. Furthermore, they require that the sample be located very close to the sensor surface. As a result, prior-art miniaturized FTIR spectroscopy systems are not well suited for use in many applications, such as point of care health monitoring, pollution investigation and pharmaceutical testing.

[0007] Furthermore, operation in the MIR spectral range gives rise to additional challenges due to the fact that the set of materials suitable for use in optical components operable at MIR wavelengths is limited and such materials are often prohibitively expensive.

[0008] As a result, to date, conventional infrared spectrometers for operation in the MIR spectral range remain quite large and complex and, typically, suffer from narrow bandwidth or wavelength resolution that is too coarse to effectively identify many chemicals and compounds.

[0009] The need for a small, low-cost spectrometer capable of performing a high-quality chemical and/or molecular analysis of a sample remains, as yet, unmet in the prior art.

Summary

[0010] An advance is made in the art according to aspects of the present disclosure directed to infrared spectrometers that include a thermal imaging camera and a spectral filter having a filter aperture at which a portion of a source signal is provided as an interrogation signal containing a plurality of wavelength signals. The camera images the filter aperture through the sample and focuses an image of the filter aperture at a focal-plane array that comprises a plurality of detector elements. The absorption characteristics of the sample are determined from output signal from the camera and used to estimate the chemical composition of the sample. Embodiments of the present invention are particularly well suited for use in hyperspectral imaging spectrometers, hyperspectral detection spectrometers, and high-resolution spectrometers.

[0011] Like the prior art, a spectrometer in accordance with the present disclosure employs a spectral filter comprising a Fabry-Perot (FP) cavity having a pair of Bragg-reflector-based mirrors, where the separation between the mirrors changes linearly along a first direction to give rise to a cavity length that varies linearly along that direction. A

source signal is filtered by the spectral filter to realize an interrogation signal whose spectral content includes wavelength signals that are dispersed along the first direction at a filter aperture of the spectral filter. This interrogation signal propagates through the sample and the absorption characteristics of the sample are then determined.

[0012] In contrast to prior-art spectrometers, embodiments in accordance with the present disclosure employ a compact thermal imaging camera comprising a focusing lens and a focal-plane array to image the filter aperture through the sample and focus an image of the filter aperture onto its focal-plane array. The resultant image includes the plurality of wavelength signals, as impacted by absorption in the sample, and each wavelength signal is detected at a different detector element of the focal-plane array. By imaging the filter aperture through the sample using a compact thermal imager, spectrometers in accordance with the present disclosure can be more compact and lower cost than prior-art spectrometers. In addition, by locating the filter aperture such that its image is focus at the detector elements, the divergence of the light in the interrogation signal is reduced, thereby reducing the spectral range that surrounds the center wavelength of each wavelength signal. Furthermore, the readout rate of the infrared imaging camera is fast enough to enable spectral acquisition times of one second or less.

[0013] An illustrative embodiment is a mid-infrared spectrometer for analyzing a sample, where the spectrometer includes a blackbody radiation source for providing a source signal that includes a plurality of wavelength signals, a spectral filter that filters the source signal to provide an interrogation signal such that the wavelength signals are dispersed along a first direction at a filter aperture, and a thermal-imaging camera comprising an imaging lens and focal-plane array comprising a plurality of detector elements. The camera images the filter aperture through the sample to form an image that is focused on the detector elements such that each detector element receives a different wavelength signal. The detector elements are then read out as an output signal that is used by a processor to estimate the chemical composition of the sample.

[0014] The spectral filter is a Bragg-mirror-based Fabry-Perot cavity whose mirrors include alternating layers of silicon and air. The mirrors are separated by a linearly increasing distance along a first axis that is aligned with the row-direction of the focal-plane array. In some embodiments, the first axis is slightly misaligned with the row direction of the focal-plane array to enable finer spectral resolution. In some embodiments, the mirrors

include alternating layers of different high-index and/or low-index materials, such as other semiconductors (*e.g.*, germanium, gallium arsenide, *etc.*), and the like.

[0015] In addition, the spectral filter is configured such that the spectral range of the interrogation signal is limited such that only one wavelength signal is passed at each location along the first axis. In some embodiments, the spectral filter limits the spectral range of the interrogation signal to a narrower spectral range than the operational range of the detector elements.

[0016] In some embodiments, the operating spectral range is other than the MIR spectral range, such as the long-wavelength infrared spectral range, the near infrared spectral range, the visible spectral range, or a different spectral range.

[0017] In some embodiments, the spectral filter is configured to reduce the dispersion angle of the wavelength signals in the source signal as it provides the interrogation signal; therefore, at least some of the wavelength signals received at the detector elements include a narrower range of wavelengths that surround their center wavelength. Furthermore, the divergence of the wavelength signals is also reduced by the fact that the spectral filter is positioned such that its image is in focus on the detector arrays.

[0018] An embodiment in accordance with the present disclosure is a spectrometer (100) for analyzing a sample (110), the spectrometer comprising: a source (102) that provides a source signal (112) having a first spectral range (SR1) that includes a plurality of wavelength signals (λ1-λn), wherein each wavelength signal of the plurality thereof is characterized by a different wavelength; a spectral filter (104) that receives the source signal at a first surface (116-1) and provides at least a portion of the source signal as an interrogation signal (114) at a filter aperture (118) included in a second surface (116-2), wherein the interrogation signal has a second spectral range (SR2) that includes the plurality of wavelength signals, and wherein the plurality of wavelength signals is dispersed along a first direction at the filter aperture; and a camera (106) that includes a lens (124) and a plurality of detector elements (130), wherein the camera is operative for providing an output signal (132) based on light incident on the plurality of detector elements; wherein the camera and spectral filter are arranged such that the camera images the filter aperture through the sample and forms an image (118′) of the filter aperture that is focused on the

plurality of detector elements such that each detector element receives a different image-portion of the image.

[0019] Another embodiment in accordance with the present disclosure is a spectrometer (100) for analyzing a sample (110), the spectrometer comprising: a source (102) that provides a source signal (112) having a first spectral range (SR1) that includes a plurality of wavelength signals (λ1-λn), wherein each wavelength signal of the plurality thereof is characterized by a different wavelength; a spectral filter (104) that receives the source signal at a first surface (116-1) and provides at least a portion of the source signal as an interrogation signal (114) at a filter aperture (118) included in a second surface (116-2), the interrogation signal having a second spectral range (SR2) that includes the plurality of wavelength signals, wherein the plurality of wavelength signals is dispersed along a first direction at the filter aperture; and a camera (106) that includes a plurality of detector elements (130) and a lens (124) having a focal length (f1) that defines an object distance (128), wherein the camera is operative for providing an output signal (132) based on light incident on the plurality of detector elements; wherein the camera and spectral filter are arranged such that the filter aperture is located at the object distance, and wherein the sample is between the lens and the spectral filter.

[0020] Yet another embodiment in accordance with the present disclosure is a method for analyzing a sample (110), the method including: providing an interrogation signal (114) at a filter aperture (118) of a spectral filter (104), wherein the interrogation signal includes a plurality of wavelength signals (λ1-λn) that are dispersed along a first direction at the filter aperture; imaging the spectral filter through the sample to form an image (118') that is focused at a focal-plane array (122) comprising a plurality of detector elements (130), wherein the image is based on the interrogation signal and an absorption spectrum of the sample, and wherein each detector element receives a different image-portion of the image and provides a detector output that is based on the intensity of the image-portion it receives; and providing an output signal (132) that includes the plurality of detector outputs.

Brief Description of the Drawings

[0021] **FIG. 1** depicts a schematic drawing of schematic drawing of an illustrative embodiment of an MIR spectrometer in accordance with the present disclosure.

[0022] **FIG. 2** depicts operations of a method for performing mid-infrared spectroscopy in accordance with the illustrative embodiment.

[0023] **FIG. 3** depicts a schematic drawing of a cross-sectional view of a spectral filter in accordance with the present disclosure.

[0024] **FIG. 4A** depicts the simulated transmittance spectrum of spectral filter **104**.

[0025] **FIG. 4B** depicts measured transmittance spectra as a function of location across the width of a spectral filter in accordance with the present disclosure.

[0026] **FIG. 5** depicts a schematic drawing of spectrometer **100** showing optical configuration of three representative wavelength signals as they propagate from source **102** to FPA **122**.

[0027] **FIG. 6** depicts a schematic drawing of a cross-section of a portion of a spectral filter in accordance with the present disclosure.

[0028] **FIG. 7** depicts a plot of wavelength shift as a function of incident angle. Plot **700** shows the resonance-frequency position shift for incident angle (θ_i^{Si}) as compared to an incident angle of zero degrees for a cavity length equal to 4.5 microns.

[0029] **FIG. 8A** depicts the transmittance of a spectral filter over a range of cavity lengths and incident angles in accordance with the present disclosure.

[0030] **FIG. 8B** depicts the total transmittance of spectral filter **104** at three different positions along the x-direction.

[0031] **FIGS. 9A-H** depict comparisons of transmission spectra for different sample materials as measured by a conventional FTIR system and a spectrometer in accordance with the present disclosure.

Detailed Description

[0032] **FIG. 1** depicts a schematic drawing of schematic drawing of an illustrative embodiment of an MIR spectrometer in accordance with the present disclosure. Spectrometer **100** includes source **102**, spectral filter **104**, camera **106**, and processor **108**, where source **102**, spectral filter **104**, and camera **106** are aligned along optical axis **A1**, which passes through sample **110**.

[0033] **FIG. 2** depicts operations of a method for performing MIR spectroscopy in accordance with the illustrative embodiment. Method **200** is described herein with continuing reference to FIG. 1, as well as reference to FIGS. 3-4A-B. Method **200** begins with operation **201**, wherein spectral filter **104** receives source signal **112** from source **102**.

[0034] Source **102** is a conventional broadband blackbody light source that provides source signal **112**. In the depicted example, source signal **112** is has a continuous spectral range having spectral width, **SR1**, which extends from λ**min** to λ**max** with center wavelength λ**c1**. In the depicted example, **SR1** extends from λ**min** of approximately 2 microns to λ**max** of approximately 20 microns.

[0035] At operation **202**, spectral filter **104** provides interrogation signal **114** based on source signal **112**.

[0036] Spectral filter **104** is a Bragg-mirror-based Fabry-Perot (FP) cavity filter having outer surfaces **116-1** and **116-2**, where a portion of surface **116-2** defines filter aperture **118**. Spectral filter **104** is configured to receive source signal **112** at surface **116-1** and pass a portion of the source signal to filter aperture **118** as interrogation signal **114** such that the interrogation signal includes wavelength signals λ**1** through λ**n**, which are dispersed along the x-direction at the filter aperture. For the purposes of this Specification, including the appended claims, the term "**wavelength signal**" is defined as light signal whose spectral content is characterized by a center wavelength and a narrow spectral range that surrounds it.

[0037] As will be apparent to one skilled in the art, the size of a spectrometer is dictated by the required propagation length of light within it. Typical prior-art spectrometers require long propagation lengths, which limits their miniaturization. Furthermore, long propagation lengths require precisely aligned optical elements, such as mirrors and beam splitters, which adds to their complexity and manufacturing costs. In

addition, these optical components must be kept carefully aligned throughout the operational lifetime of a system, which increases operating expense as well.

[0038] By configuring spectral filter **104** as an FP-cavity-based spectral filter, however, embodiments in accordance with the present disclosure have greater potential for miniaturization, as well as reduced complexity as comparted to conventional spectrometers. These advantages arise, in part, from the fact that an FP cavity is an optically resonant cavity in which light at the resonant frequency of the cavity is reflected back and forth many times, thereby multiplying the path-length of the photons in the light by the number of roundtrips they take within the cavity.

[0039] **FIG. 3** depicts a schematic drawing of a cross-sectional view of a spectral filter in accordance with the present disclosure. Spectral filter **104** includes substantially identical mirrors **302-1** and **302-2**, which are separated by a small, non-uniform separation that defines optical cavity **304** (hereinafter referred to as "cavity **304**").

[0040] Each of mirrors **302-1** and **302-2** (referred to, collectively, as mirrors **302**) is a multilayer Bragg reflector designed to realize high-reflectivity (> 99.9999%) over the extent of the spectral range, **SR2**, of interrogation signal **114**. Each of mirrors **302** includes at least one Bragg-layer-pair **312** disposed on a surface of a substrate **306**, where Bragg-layer-pair **312** includes one high-refractive-index (HR) layer **308** and one low-refractive-index (LR) layer **310**.

[0041] HR layer **308** comprises material having a relatively higher refractive index and has a thickness substantially equal to an odd multiple of one-quarter of a target wavelength, $\lambda\mathbf{t}$, within spectral range **SR2** (*i.e.*, $k\lambda t/4$, where k= 1, 3, 5, ...) as measured within its material. In similar fashion, LR layer **310** comprises relatively lower refractive-index material and has a thickness substantially equal to an odd multiple of one-quarter of a target wavelength, $\lambda\mathbf{t}$, within its material. It should be noted that the target wavelength is a matter of design choice and is selected to enable operation of spectral filter **104**; therefore, $\lambda\mathbf{t}$ can be virtually any wavelength within spectral range **SR2**. Preferably, however, target wavelength, $\lambda\mathbf{t}$, has a value that is equal to, or nearly equal to, the center wavelength of this spectral range. In the depicted example, $\lambda\mathbf{t}$ is selected as approximately 9 microns.

[0042] In the depicted example, substrate **306** is a conventional single-crystal-silicon substrate and each mirror includes two Bragg-layer-pairs, each having one HR layer **308**

and one LR layer **310**. HR layer **308** is a layer of amorphous silicon deposited using plasma-enhanced chemical-vapor deposition (PECVD) such that the amorphous silicon has a refractive index of approximately 2.8 and a thickness of approximately 803 nm. LR layer **310** is a layer of air having a thickness of approximately 2.25 microns. It should be noted that the materials and design parameters provided for mirrors **302** are merely exemplary and that myriad alternative designs for the mirrors of spectral filter **104** are within the scope of the present disclosure. However, embodiments comprising Bragg mirrors made of alternating layers of silicon and air are afforded significant advantages over the prior art because the fabrication of silicon layers is a well-known and well-understood process and can be done at low cost. Furthermore, the mechanical and optical properties of silicon are well suited to their use in mirrors **302**.

[0043] The separation between mirrors **302** (*i.e.*, the cavity length of cavity **304**) at any point, dictates what wavelengths pass through spectral filter **104** at that point and what wavelengths are reflected by the spectral filter. Light having wavelength λ resonates back and forth between the mirrors inside an optically resonant cavity when the spacing between them (*i.e.*, the cavity length, L) is equal to an integer number, m, of half-wavelengths (*i.e.*, when $L=m\lambda/2$). As a result, the light having wavelength λ is transmitted through the cavity with low loss while light characterized by other wavelengths is reflected by the FP cavity. The cavity length, therefore, dictates the wavelength of light selectively passed by the FP cavity.

[0044] Mirrors **302-1** and **302-2** are arranged at non-zero angle, Φ, to one another along the x-direction such that the cavity length of cavity **304** changes linearly along the x-direction. As a result, at each location, **x**, mirrors **302-1** and **302-2** are separated by cavity length **L(x)**, which increases from **Lmin** at location **xm** to **Lmax** at location **xn**. In the depicted example, **Lmin** is approximately 3.28 microns and **Lmax** is approximately 7.05 microns. In some embodiments, the cavity length decreases linearly along the x-direction. In some embodiments, the spacing and/or angle between mirrors **302** is controllable.

[0045] The linearly increasing cavity length of spectral filter **104** enables it to, at each location x, receive source signal **112** as a multispectral input optical signal and selectively pass a narrow transmission peak (*i.e.*, one wavelength signal) within spectral range **SR2**. In other words, at each location along the x-direction, spectral filter **104** selectively passes a different wavelength signal λi, where $m \leq i \leq n$ such that its spectral

content is dispersed along the x-direction from λ**1** at location **xm** to λ**n** at location **xn**. In the depicted example, λ**1** is approximately 7.5 microns, λ**n** is approximately 12 microns.

[0046] **FIG. 4A** depicts the simulated transmittance spectrum of spectral filter **104**. Plot **400** shows that, for a cavity length equal to half of target wavelength, λt, (*i.e.*, a cavity length of 4.5 microns in the depicted example), a single narrow wavelength signal corresponding to λt is passed by the spectral filter.

[0047] **FIG. 4B** depicts measured transmittance spectra as a function of location across the width of a spectral filter in accordance with the present disclosure. Plot **402** shows that, at location x, a single wavelength signal is passed by spectral filter **104**. It should be noted, however, that the transmission spectra shown in plot **402** were taken using an FTIR spectrometer having an aperture of millimeter scale. As a result, the peaks in the measured spectra are artificially broadened due to the cavity-thickness variation within the millimeter aperture area in each measurement.

[0048] In some embodiments, mirrors **302** are arranged at a second angle to one another along the y-direction, such that the cavity length of cavity **304** also has a linear gradient along the y-direction. In such embodiments, spectral filter is configured to disperse the spectral content of interrogation signal **114** along each of the x- and y-directions.

[0049] Returning now to method **200**, at operation **203**, camera **106** images filter aperture **118** through sample **110** and sample holder **120** to form image **118'** on focal-plane array (FPA) **122**.

[0050] Camera **106** is a thermal-imaging camera comprising FPA **122**, lens **124**, and camera aperture **126**. In some embodiments, camera **106** is a different camera operative for imaging filter aperture **118**.

[0051] FPA **122** comprises a two-dimensional array of substantially identical detector elements **130-1** through **130-n** (referred to, collectively, as detector elements **130**), each of which is suitable for detecting light within spectral range **SR2**. In the depicted example, each of the detector elements **130** is a bolometer configured to enable detection of light within the wavelength range from approximately 7.5 microns to approximately 13.5 microns.

[0052] It is an aspect of the present disclosure that operation within the wavelength range from approximately 7.5 microns to approximately 13.5 microns corresponds to an atmospheric transparency window and transmission passband in the infrared spectral range. As a result, only light corresponding to the specific wavelength passed by spectral filter **104** reaches its corresponding detector element **130**. Therefore, embodiments in accordance with the present disclosure do not require additional optical filters, such as those needed in prior-art infrared spectrometers, which enables such embodiments to have lower complexity and/or cost.

[0053] In some embodiments, FPA **122** includes a different suitable light detector. Alternative light detectors suitable for use in FPA **122** include, without limitation, semiconductor detectors, mercury-cadmium-telluride detectors, and the like.

[0054] Lens **124** is an imaging lens suitable for operation over spectral range **SR2**. Lens **124** is configured to form image **118'** of the filter aperture of spectral filter **104** on FPA **122**. Lens **124** has focal length **f1** and object distance **128**, which defines a separation between spectral filter **104** and lens **122** that enables the lens to form a focused image of the spectral filter on FPA **122**. As will be apparent to one skilled in the art, after reading this Specification, lens **124** can include any lens design or configuration (*e.g.*, multi-element, compound, telescope, diffractive, refractive, *etc.*) that enables it to form a focused image of spectral filter **106** on FPA **122**.

[0055] In the depicted example, the focal length, **f1**, of lens **124** is approximately 6.35 cm. By employing a lens with a short focal length, spectrometer **100** can made compact without the need to include additional optical components, such as beam splitters, mirrors and lasers for beam collimation. As a result, spectrometers in accordance with the present disclosure can be significantly smaller and have lower complexity than prior-art spectrometers. For instance, in the depicted example, spectrometer **100** has a total length along the y-direction of only approximately 10 cm, without requiring the optical path from source **102** to FPA **122** to be folded.

[0056] Camera aperture **126** is a clear aperture that is optionally included in camera **106** to function as a camera "stop" that reduces the divergence angle of light received at some or all of detector elements **130**.

[0057] Spectrometer **100** is arranged such that filter aperture **118** is located at object distance, **128**, which is defined by the focal length, **f1**, of lens **124** as it images the

filter aperture through sample **110** and sample holder **SH**. As a result, camera **106** focuses the filter aperture on FPA **122** to form image **118'**. In some embodiments, spectrometer **100** is arranged such that a different plane within spectral filter **104** is located at focal length **f1**.

[0058] It should be noted that, although detector elements **130** can detect light having any wavelength within the range from approximately 7.5 microns to approximately 13.5 microns, one or more higher-order resonance peaks exist at wavelengths greater than 12 microns, which could give rise to interference in spectrometer **100**. As a result, the spectral range, **SR2**, of spectral filter **104** is capped at a maximum wavelength signal, **λn**, of 12 microns, thereby limiting the measurement range for spectrometer **100** to at or below 12 microns.

[0059] Image **118'** is a convolution of the dispersed spectral content of interrogation signal **114** and the absorption characteristics of sample **110**. As a result, image **118'** includes absorption peaks whose positions, magnitudes, and inflections provide a "spectral fingerprint" that is indicative of the chemical composition of sample **110**.

[0060] Image **118'** includes image-portions **132-1** through **132-n**, which correspond to wavelength signals **λ1** through **λn**, respectively.

[0061] At operation **204**, detector elements **130** are readout by camera **106** and provided to processor **108** as output signal **132**, which includes detector outputs **134-1** through **134-n**.

[0062] Since the spectral content of interrogation signal **114** is dispersed along the x-direction at filter aperture **118**, detector elements **130-1** through **130-n** detect image-portions **132-1** through **132-n**, respectively, and provide detector outputs **134-1** through **134-n**. The magnitude of each of detector outputs **134-1** through **134-n** is based on the intensity of the wavelength signal (*i.e.*, image portion) incident upon its respective detector element. As discussed below, range of wavelengths that surround the center wavelength of each wavelength signal is a function of the optical design of spectrometer **100**, the size of detector elements **130**, the spacing between adjacent detector elements, and the angle of incidence for the light included in the wavelength signal.

[0063] It is another aspect of the present disclosure that, because the readout rate of a micro-bolometer array can be as fast as 9 Hz, embodiments in accordance with the

present disclosure can obtain molecular absorption spectra for a sample in less than one second without the need for scanning optics that are typically necessary in the prior art.

[0064] At operation **205**, processor **108** generates an estimate of the chemical composition of sample **110** based on output signal **132**.

[0065] Processor **108** is a conventional processor comprising circuitry operative for receiving output signal **132**, executing instructions, storing and retrieving data, and estimating the material composition of sample **110**, among other functions.

[0066] It should be noted that, typically, method **200** is preceded by a calibration routine in which the optical transfer function of spectrometer **100** is determined by performing at least some of operations **201** through **205** with an empty sample holder **SH**. Such a calibration provides processor **108** a baseline against which output signal **132** can be compared to develop the estimation of the chemical composition of sample **110**.

[0067] As will be appreciated by one skilled in the art, after reading this Specification, the transmittance of spectral filter **104** can be affected by the angle at which light is received from source **102**; therefore, the wavelength of light illuminated onto each detector element **130** can be based on both cavity length and incident angle of the light received from the spectral filter.

[0068] It is an aspect of the present disclosure, however, that the range of wavelengths incident on at least some of detector elements **130** (*i.e.*, the range of wavelengths that surround the center wavelength of at least some of the wavelength signals) can be reduced by:

i. focusing an image of filter aperture **118** on the detector elements of FPA **122**; or

ii. providing spectral filter **104** such that it is configured to reduce the divergence angle of the wavelength signals; or

iii. a combination of i and ii.

[0069] Because filter aperture **118** is focused onto detector elements **130** of FPA **122**, each of the detector elements receives a different wavelength signal corresponding to a different portion of cavity **304**, where each portion of the cavity has a different cavity length. Furthermore, detector elements **130** are configured such that they are very small; therefore, the variation in the cavity length across the cavity portion from which each

detector element receives light is substantially insignificant and is ignored for the purposes of the discussion provided herein.

[0070] It should be noted that the angular spread (*i.e.*, divergence angle) of the propagation direction of photons arriving at detector element **130** is a function of the size of source **102**, the size of lens **124**, and the distance between the lens and spectral filter **104**. As a light ray within source signal **112** is incident on spectral filter **104**, the angle at which it propagates (relative to optical axis **A1**) is reduced by a factor based on the refractive-index difference at surface **116-1**. By forming spectral filter such that it includes Bragg mirrors having high-refractive-index materials, light passing through the spectral filter is highly refracted. As a result, wavelength signals included in the light become more collimated as they transition from source signal **112** to interrogation signal **114**, thereby reducing their divergence angle.

[0071] **FIG. 5** depicts a schematic drawing of spectrometer **100** showing optical configuration of three representative wavelength signals as they propagate from source **102** to FPA **122**. FIG. 5 shows the paths and shapes of wavelength signals λ**1** and λ**n**, which are received at the outermost detector elements of FPA **122** (*i.e.*, detector elements **130-1** and **130-n**), as well as the central wavelength signal (*i.e.*, wavelength signal λ**c**), which is received at the center detector element of FPA **122** (*i.e.*, detector element **130-c**).

[0072] In source signal **112**, waveguide signals λ**1** through λ**n** all have the same divergence angle. In other words, θ**d1-1**, θ**d1- c**, θ**d1-n** all have the same value. In the depicted example, this value is approximately 5.4°, which gives rise to the incident angles for outermost rays within each of wavelength signals λ**1** and λ**n**, **LRmin** and **LRmax**, as 7.5° and 12.9°, respectively.

[0073] **FIG. 6** depicts a schematic drawing of a cross-section of a portion of a spectral filter in accordance with the present disclosure. Section **600** is a region of mirror **302-1**, at which light ray **LRmax** in wavelength signal λ**1** of source signal **112** is incident.

[0074] As indicted in FIG. 6,by virtue of the large change in refractive index between air and the material of substrate **306** (*i.e.*, silicon), according to Snell's law, the angle, θ_i^{Air}, at which a light ray propagates in air (relative to optical axis **A1**) is reduced at surface **116-1** by a factor based on this refractive-index difference to (θ_i^{Si}) within substrate **306**.

[0075] In the depicted example, air has a refractive index of 1.0, the silicon of substrate **306** has a refractive index of approximately 3.4, and each of HR layers **308** has a

refractive index of 2.8. As discussed above, when **LRmin** and **LRmax** are received at surface **116-1**, their incidence angles (θ_i^{Air}) at surface **116-1** (*i.e.*, 7.5° and 12.9°, respectively). When received at FPA **122** after passing through spectral filter **104**, however, these incident angles are reduced to 2.67° and 4.57°, respectively. For an exemplary cavity length of 4.5 microns, a light ray incident on a detector element **130** at an angle (θ_i^{Si}) of 4.57° gives rise to a wavelength shift of approximately 0.174 microns, as compared an incident angle of 0°.

[0076] **FIG. 7** depicts a plot of wavelength shift as a function of incident angle. Plot **700** shows the resonance-frequency position shift for the angle (θ_i^{Si}) at which light propagates in substrate **306**, as compared to light that is received normal to spectral filter **104**, for a cavity length equal to 4.5 microns.

[0077] It should be noted, however, that the spectral range surrounding the center wavelength of the wavelength signal received at each detector element is a function of both the cavity length that passes a wavelength signal and the incident angles of its outermost light rays on the detector element.

[0078] **FIG. 8A** depicts the transmittance of a spectral filter over a range of cavity lengths and incident angles in accordance with the present disclosure. Plot **800** includes traces **802** and **804**, which denote the transmittance for the extreme outer rays within the dispersion angle of a wavelength signal.

[0079] It can be seen from plot **800** that the divergence of the transmittance of spectral filter **104** is greatest at each end of cavity **304**, while its divergence at the center of the cavity is very small, since light rays passing through this point is substantially aligned with the center of lens **126**. The larger divergence at the extreme ends of spectral cavity **104** arises because the light passes off-center through the spectral filter giving rise to a larger incidence angle for the same divergence angle.

[0080] **FIG. 8B** depicts the total transmittance of spectral filter **104** at three different positions along the x-direction. The spectra shown in plot **806** were obtained from the integration of all divergence angles at positions along the x-direction located at either end of cavity **304**, **xm** and **xn**, as well as at the center of the cavity, **xc**. In the depicted example, cavity lengths L(xm), L(xc), and L(xn) are equal to 3.7, 4.7, and 5.7 microns, respectively.

[0081] **FIGS. 9A-H** depict comparisons of transmission spectra for different sample materials as measured by a conventional FTIR system and a spectrometer in accordance with the present disclosure.

[0082] Plots **900A-D** show transmission spectra for glucose, acetaminophen, polystyrene, and low-density polyethylene, respectively, measured using a conventional FTIR system.

[0083] Plots **900E-H** show transmission spectra for glucose, acetaminophen, polystyrene, and low-density polyethylene, respectively, measured using a spectrometer analogous to spectrometer **100**.

[0084] As evinced by plots **900A-H**, the performance of spectrometer **100** is comparable to that of a more expensive, more complex, and larger FTIR system. In addition, each of the measurements taken with spectrometer **100** were obtained in less than one second – markedly faster than can be achieved using conventional FTIR systems.

[0085] It is to be understood that the disclosure teaches just one example of the illustrative embodiment and that many variations of the invention can easily be devised by those skilled in the art after reading this disclosure and that the scope of the present invention is to be determined by the following claims.

What is claimed is:

1. A spectrometer (100) for analyzing a sample (110), the spectrometer comprising:

a source (102) that provides a source signal (112) having a first spectral range (SR1) that includes a plurality of wavelength signals (λ1-λn), wherein each wavelength signal of the plurality thereof is characterized by a different wavelength;

a spectral filter (104) that receives the source signal at a first surface (116-1) and provides at least a portion of the source signal as an interrogation signal (114) at a filter aperture (118) included in a second surface (116-2), wherein the interrogation signal has a second spectral range (SR2) that includes the plurality of wavelength signals, and wherein the plurality of wavelength signals is dispersed along a first direction at the filter aperture; and

a camera (106) that includes a lens (124) and a plurality of detector elements (130), wherein the camera is operative for providing an output signal (136) based on light incident on the plurality of detector elements;

wherein the camera and spectral filter are arranged such that the camera images the filter aperture through the sample and forms an image (118') of the filter aperture that is focused on the plurality of detector elements such that each detector element receives a different image-portion (132) of the image.

2. The spectrometer of claim 1 wherein the spectral filter includes a first mirror (302-1) and a second mirror (302-2) that collectively define an optical cavity (304) having a cavity length (L(x)) that changes linearly along the first direction, and wherein each of the first and second mirrors is a multilayer Bragg reflector comprising at least one Bragg-layer-pair that includes a first layer (308) of a first material that has a first refractive index and a second layer (310) of a second material that has a second refractive index that is lower than the first refractive index.

3. The spectrometer of claim 2 wherein the first material comprises a material selected from the group consisting of silicon and germanium and the second material is air.

4. The spectrometer of claim 1 wherein the lens has a first focal length that defines a first object distance (128), and wherein the spectral filter and camera are arranged such that the filter aperture is located at the first object distance.

5. The spectrometer of claim 1 further comprising a processor (108) for estimating a chemical composition of the sample based on the output signal.

6. The spectrometer of claim 1 wherein each detector element of the plurality thereof comprises a bolometer that is operative for detecting light within the second spectral range.

7. The spectrometer of claim 6 wherein each bolometer is characterized by an operational spectral range that is larger than the second spectral range.

8. The spectrometer of claim 1 wherein a first wavelength signal of the plurality thereof is characterized by a first dispersion angle (θd1) at the first surface, and wherein the first wavelength signal is characterized by a second dispersion angle (θd2) at the filter aperture, the second dispersion angle being smaller than the first dispersion angle.

---

9. A spectrometer (100) for analyzing a sample (110), the spectrometer comprising:

a source (102) that provides a source signal (112) having a first spectral range (SR1) that includes a plurality of wavelength signals (λ1-λn), wherein each wavelength signal of the plurality thereof is characterized by a different wavelength;

a spectral filter (104) that receives the source signal at a first surface (116-1) and provides at least a portion of the source signal as an interrogation signal (114) at a filter aperture (118) included in a second surface (116-2), the interrogation signal having a second spectral range (SR2) that includes the plurality of wavelength signals, wherein the plurality of wavelength signals is dispersed along a first direction at the filter aperture; and

a camera (106) that includes a plurality of detector elements (130) and a lens (124) having a focal length (f1) that defines an object distance (128), wherein the camera is operative for providing an output signal (136) based on light incident on the plurality of detector elements;

wherein the camera and spectral filter are arranged such that the filter aperture is located at the object distance, and wherein the sample is between the lens and the spectral filter.

10. The spectrometer of claim 9 wherein the spectral filter includes:

a first mirror (302-1) comprising a first Bragg reflector that includes at least one Bragg-layer-pair (312) having a first layer (308) that comprises a first material and a second layer (310) that comprises air, wherein the first material has a refractive index that is greater than that of air; and

a second mirror (302-1) comprising a second Bragg reflector that includes at least one Bragg-layer-pair having the first and second layers, wherein the second mirror includes the filter aperture;

wherein the first and second mirror are arranged such that they define a first angle (Φ) along the first direction, and wherein the first angle is a non-zero angle, and

wherein the first and second mirrors are separated by a cavity length (L(x)) that changes linearly along the first direction.

11. The spectrometer of claim 9 wherein a first wavelength signal ($\lambda 1$) of the plurality thereof is characterized by a first dispersion angle ($\theta d1$) at the first surface, and wherein the first wavelength signal is characterized by a second dispersion angle ($\theta d2$) at a first detector element (130-1) of the plurality thereof, the second dispersion angle being smaller than the first dispersion angle.

12. The spectrometer of claim 9 further comprising a processor (108) for estimating a chemical composition for the sample based on the output signal.

13. The spectrometer of claim 9 wherein the camera and spectral filter are arranged such that the camera images the filter aperture through the sample and focuses an image (118') of the filter aperture on the plurality of detector elements such that each detector element receives a different image portion (132) of the image.

---

14. A method for analyzing a sample (110), the method including:

providing an interrogation signal (114) at a filter aperture (118) of a spectral filter (104), wherein the interrogation signal includes a plurality of wavelength signals ($\lambda 1$-λn) that are dispersed along a first direction at the filter aperture;

imaging the spectral filter through the sample to form an image (118') that is focused at a focal-plane array (122) comprising a plurality of detector elements (130), wherein the image is based on the interrogation signal and an absorption spectrum of the sample, and wherein each detector element receives a different image-portion (132) of the

image and provides a detector output (134) that is based on the intensity of the image-portion it receives; and

providing an output signal (136) that includes the plurality of detector outputs.

15. The method of claim 14 further including estimating a chemical composition of the sample based on the output signal.

16. The method of claim 14 further including providing the spectral filter such that it includes a first mirror (302-1) and a second mirror (302-2) that collectively define an optical cavity (304) having a cavity length (L(x)) that changes linearly along the first direction, and wherein each of the first and second mirrors is a multilayer Bragg reflector comprising at least one Bragg-layer-pair that includes a first layer (308) of a first material that has a first refractive index and a second layer (310) of a second material that has a second refractive index that is lower than the first refractive index.

17. The method of claim 16 wherein the spectral filter is provided such that the first material comprises a material selected from the group consisting of silicon and germanium and the second material is air.

18. The method of claim 16 further comprising:

providing a camera (106) for imaging the spectral filter through the sample, wherein the camera includes a lens (124) and the plurality of detector elements, and wherein the lens has a focal length (f1) that defines an object distance (128); and

locating the spectral filter such that the filter aperture is located at the object distance.

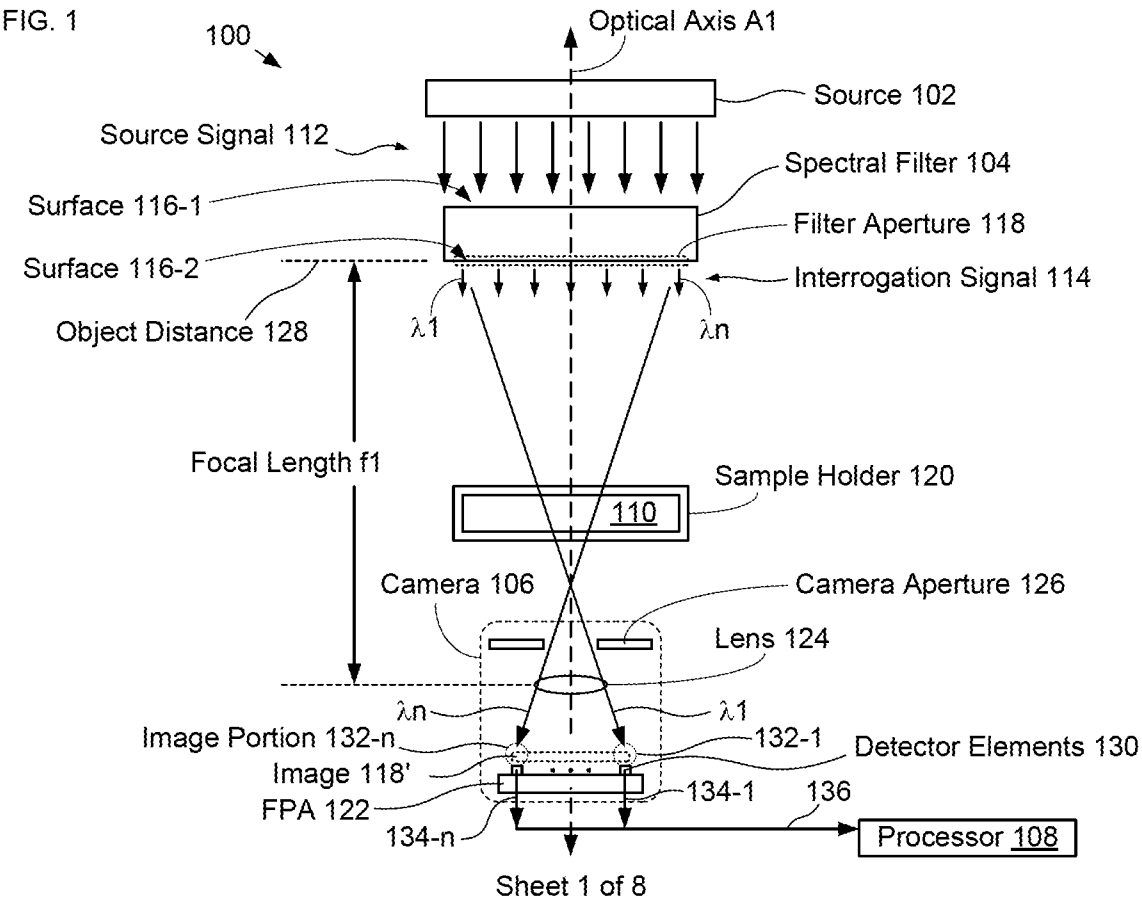
19. The method of claim 18 wherein each detector element of the plurality thereof comprises a bolometer that is characterized by an operational spectral range that is larger than the second spectral range and includes the second spectral range.

20. The method of claim 16 further comprising:

providing a source (102) that transmits a source signal (112) to the spectral filter, wherein the source signal includes the plurality of wavelength signals, and wherein a first wavelength signal of the plurality thereof is characterized by a first dispersion angle (θd1) when it is received at the spectral filter;

wherein the interrogation signal is provided at the filter aperture such that the first wavelength signal has a second dispersion angle (θd2) that is smaller than the first dispersion angle.

FIG. 1



Sheet 1 of 8

FIG. 2

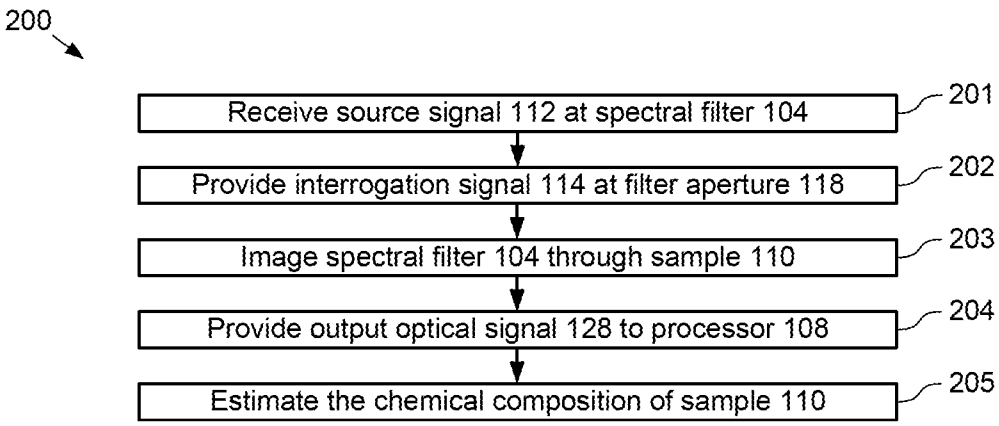
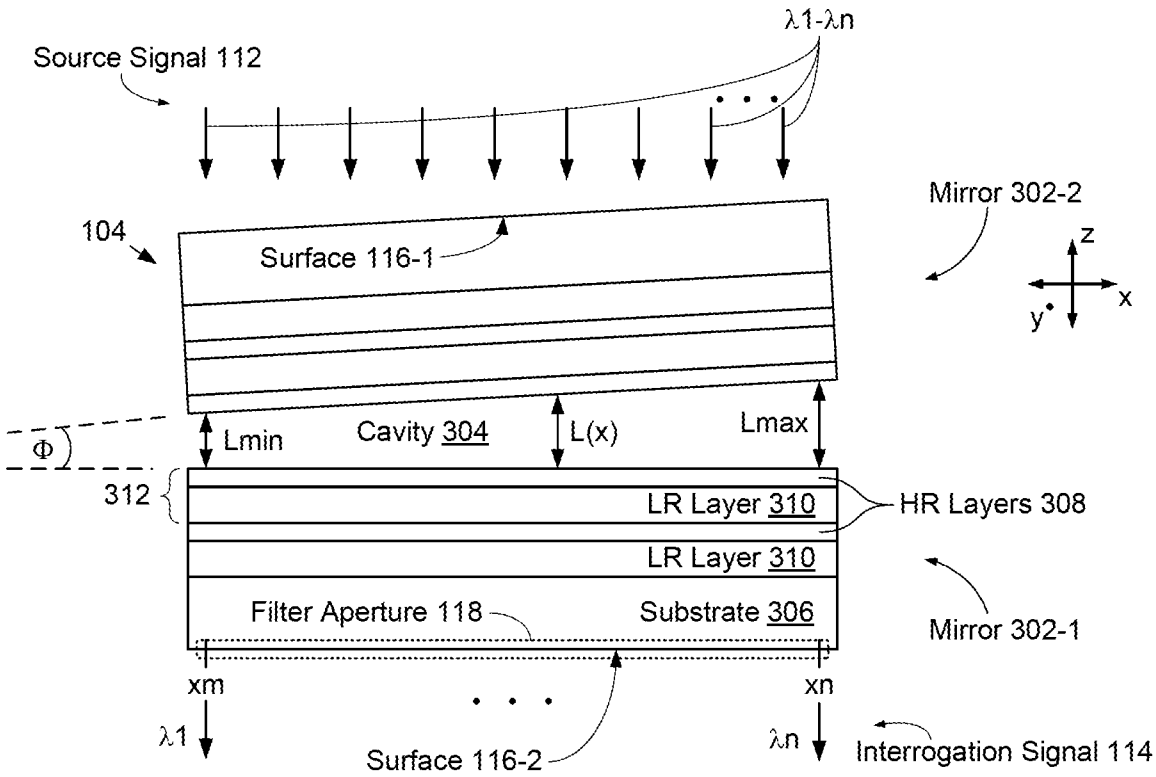

200
Receive source signal 112 at spectral filter 104
201
Provide interrogation signal 114 at filter aperture 118
202
Image spectral filter 104 through sample 110
203
Provide output optical signal 128 to processor 108
204
Estimate the chemical composition of sample 110
205

FIG. 3



Sheet 3 of 8

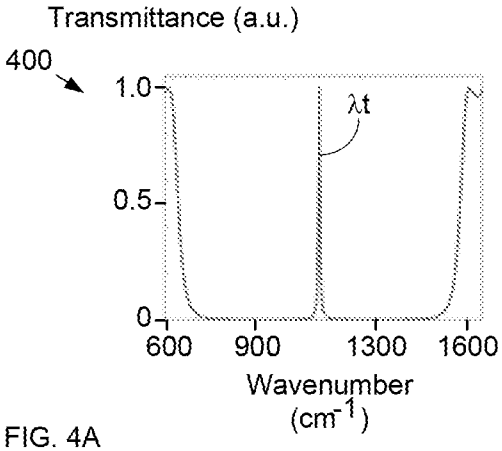

Transmittance (a.u.)
400
1.0
0.5
0
λt
600
900
1300
1600
Wavenumber
(cm-1)

FIG. 4A

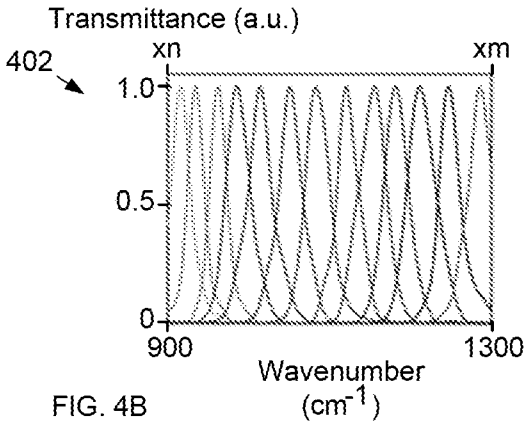
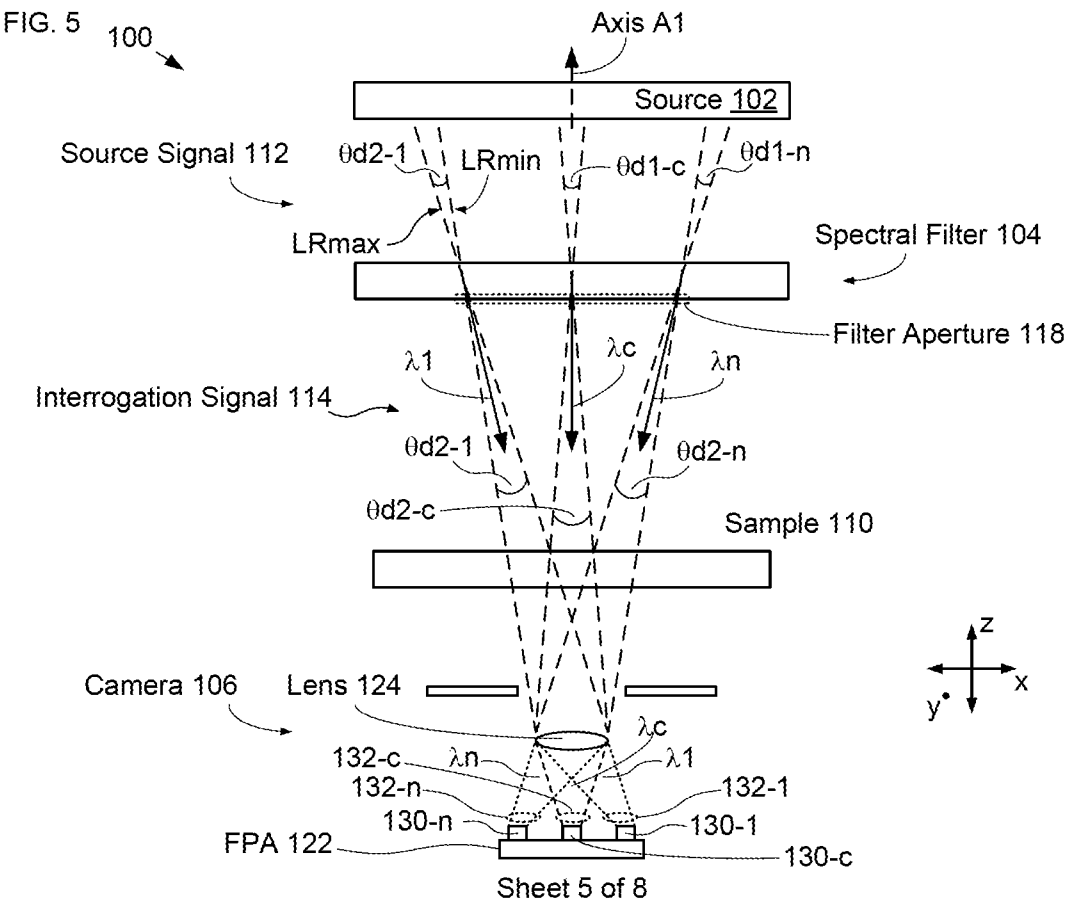

Transmittance (a.u.)
402
xn
xm
1.0
0.5
0
900
1300
Wavenumber
(cm-1)

FIG. 4B

FIG. 5


100
Axis A1
Source 102
Source Signal 112
θd2-1
LRmin
θd1-c
θd1-n
LRmax
Spectral Filter 104
Filter Aperture 118
λ1
λc
λn
Interrogation Signal 114
θd2-1
θd2-n
θd2-c
Sample 110
z
x
y
Camera 106
Lens 124
λc
132-c
λn
λ1
132-n
132-1
130-n
130-1
FPA 122
130-c

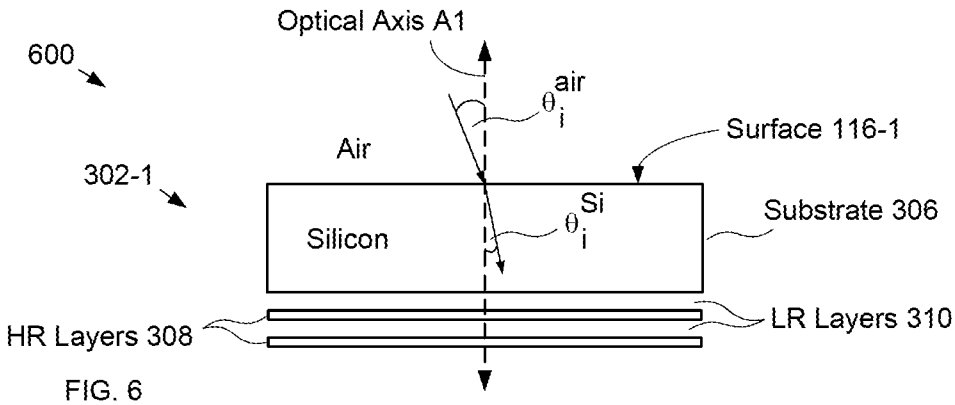

600
Optical Axis A1
θ_i^{air}
Air
Surface 116-1
302-1
Si
θ_i
Silicon
Substrate 306
HR Layers 308
LR Layers 310

FIG. 6

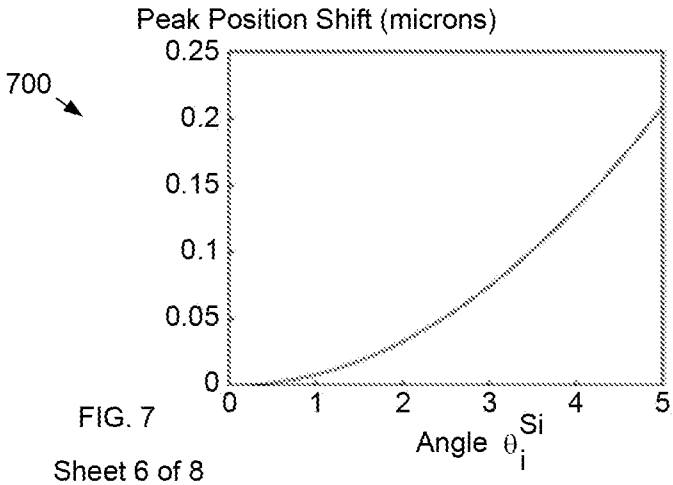

700
Peak Position Shift (microns)
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
Angle θ_i^{Si}

FIG. 7

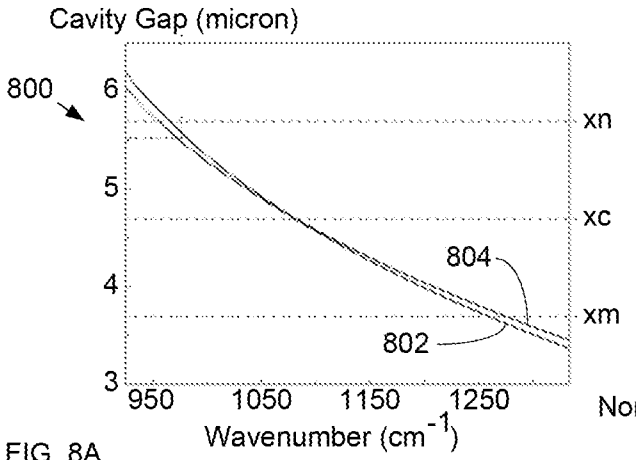


FIG. 8A

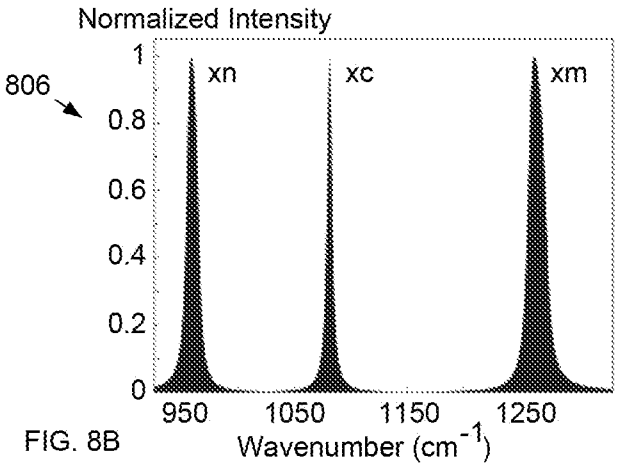


FIG. 8B

Sheet 7 of 8

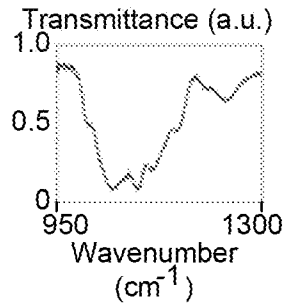


FIG. 9A

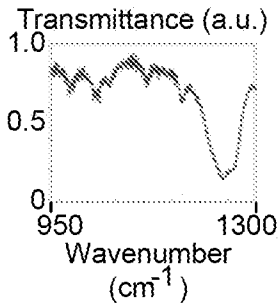


FIG. 9B

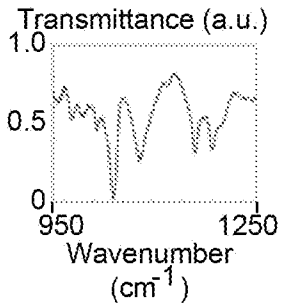


FIG. 9C

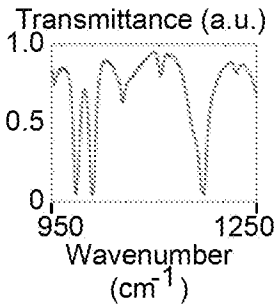


FIG. 9D

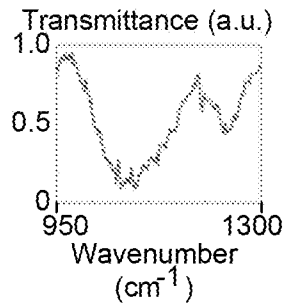


FIG. 9E

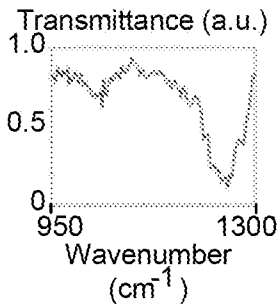


FIG. 9F

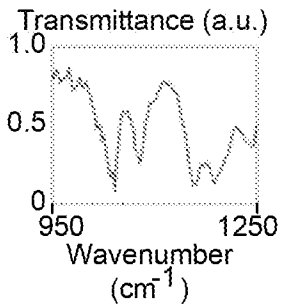


FIG. 9G

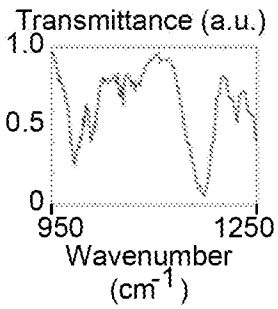


FIG. 9H

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/016819

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G01J 3/02; G01J 3/51; G01J 3/12; G01J 3/26; G01J 3/28 (2020.01)

CPC - G01J 3/51; G01J 3/0291; G01J 3/1256; G01J 3/26; G01J 3/2823 (2020.02)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

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

USPC - 356/519; 356/631 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2015/0138533 A1 (AGILENT TECHNOLOGIES, INC.) 21 May 2015 (21.05.2015) entire document	1-20
Y	US 2015/0136981 A1 (REBELLION PHOTONICS, INC.) 21 May 2015 (21.05.2015) entire document	1-8, 13-20
Y	US 2006/0039009 A1 (KIESEL et al) 23 February 2006 (23.02.2006) entire document	2, 3, 10, 16-20
Y	US 2013/0235256 A1 (KODAMA) 12 September 2013 (12.09.2013) entire document	4, 9-13
Y	US 5,777,329 A (WESTPHAL et al) 07 July 1998 (07.07.1998) entire document	6, 7, 19
Y	US 6,243,170 B1 (ERSHOV) 05 June 2001 (05.06.2001) entire document	8, 11, 20

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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

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

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

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

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

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

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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 March 2020	24 APR 2020
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774