US008203716B2

(12) **United States Patent**
Badleirostami et al.

(10) **Patent No.: US 8,203,716 B2**
(45) **Date of Patent: Jun. 19, 2012**

(54) **TANDEM FABRY-PEROT ETALON CYLINDRICAL BEAM VOLUME HOLOGRAM FOR HIGH RESOLUTION/LARGE SPECTRAL RANGE DIFFUSE LIGHT SPECTROSCOPY**

(75) Inventors: **Majid Badleirostami**, Atlanta, GA (US); **Omid Momtahan**, Foothill Ranch, CA (US); **Chao Ray Hsieh**, Atlanta, GA (US); **Ali Adibi**, Suwanee, GA (US)

(73) Assignee: **Georgia Tech Research Corporation**, Atlanta, GA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 478 days.

(21) Appl. No.: **12/447,992**

(22) PCT Filed: **Aug. 3, 2007**

(86) PCT No.: **PCT/US2007/075145**

§ 371 (c)(1),
(2), (4) Date: **Apr. 30, 2009**

(87) PCT Pub. No.: **WO2008/054908**

PCT Pub. Date: **May 8, 2008**

(65) **Prior Publication Data**

US 2010/0110442 A1 May 6, 2010

Related U.S. Application Data

(60) Provisional application No. 60/855,836, filed on Oct. 30, 2006.

(51) **Int. Cl.**
G01J 3/45 (2006.01)

(52) **U.S. Cl.** **356/454**

(58) **Field of Classification Search** 356/451, 356/454, 456, 457, 458

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,603,685	A *	9/1971	Heflinger et al.	356/458
3,970,390	A *	7/1976	Heflinger et al.	356/458
5,235,440	A *	8/1993	Clark et al.	359/11
5,638,173	A	6/1997	Smith et al.	
5,686,988	A *	11/1997	Garrett	356/318
5,817,462	A *	10/1998	Garini et al.	506/9
5,978,112	A	11/1999	Psaltis et al.	
6,055,325	A *	4/2000	Garini et al.	382/129
6,486,948	B1 *	11/2002	Zeng	356/301
7,092,101	B2 *	8/2006	Brady et al.	356/456

(Continued)

OTHER PUBLICATIONS

D.J. Brady, Multiplex Sensors and the Constant Radiance Theorem, Optics Letters 27, 16-18 (2002).

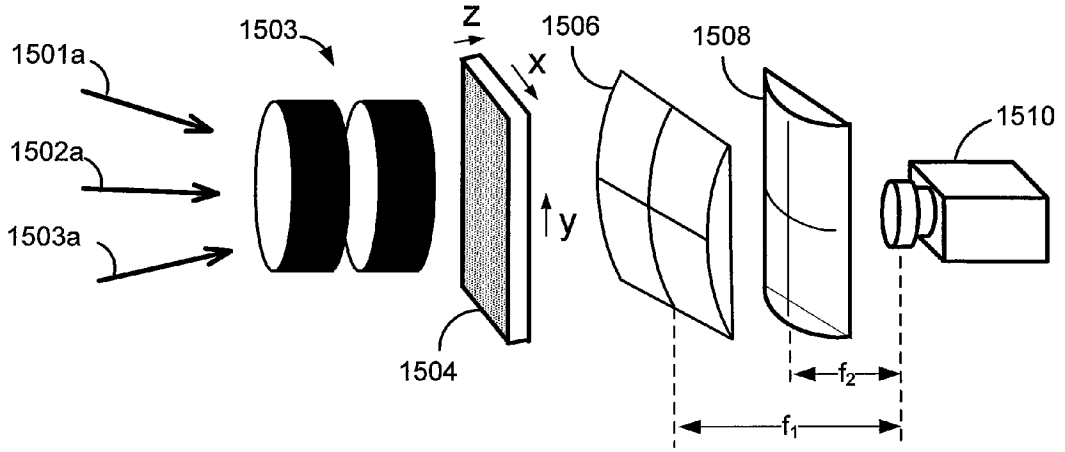
(Continued)

Primary Examiner — Tarifur Chowdhury
Assistant Examiner — Jonathan Hansen
(74) *Attorney, Agent, or Firm* — Thomas, Kayden, Horstemeyer & Risley LLP.

(57) **ABSTRACT**

Systems and methods for performing two-dimensional (2D) high resolution spectral-spatial mapping are described. At least one embodiment includes a spectrometer for performing two-dimensional (2D) high resolution spectral-spatial mapping comprising a Fabry-Perot component configured to receive a diffuse input beam and provide a high resolution spectral mapping of the diffuse input beam in a first direction. The spectrometer further comprises a volume hologram for increasing a spectral operating range, the volume hologram configured to perform spectral mapping in a second direction orthogonal to the first direction to increase the spectral operating range. The spectrometer further comprises a charged coupled device (CCD) configured to receive output beams, the output beams used to provide spectral analysis of the input beams.

26 Claims, 16 Drawing Sheets



U.S. PATENT DOCUMENTS

7,158,228	B2 *	1/2007	Psaltis et al.	356/326
7,262,889	B2 *	8/2007	Sun et al.	359/15
7,515,319	B2	4/2009	Adibi et al.	
7,660,039	B2 *	2/2010	Santoro et al.	359/599
7,826,062	B2 *	11/2010	Weitzel	356/498
2005/0264808	A1 *	12/2005	Wang	356/328
2006/0103904	A1	5/2006	Adibi et al.	
2010/0201979	A1 *	8/2010	Momtahan et al.	356/319

OTHER PUBLICATIONS

J.T. Verdeyen, Laser Electronics, 3rd ed., Englewood Cliffs, NJ: Prentice Hall, 1995. Chapter 3,pp. 63-73.

P.C. Clemmow, The Plane Wave Spectrum Representation of Electromagnetic Fields, Oxford University Press-IEEE Press, New York, 1996, Chapter 2, pp. 11-37.

George Barbastathis, Michael Levene, and Demetri Psaltis, "Shift Multiplex with Spherical Reference Wave", Appl. Op. 35, (1996) pp. 2403-2417.

Shepherd, G., C. Lake, et al. (1965). "A Spatial Spectral Scanning Technique for Fabry-Perot Spectrometer." Applied Optics 4(3): 267-272.

Conde, M. (2002). "Deriving wavelength spectra from fringe images from a fixed-gaps Single-Etalon Fabry-Perot Spectrometer." Applied Optics 41(14): 2672-2678.

Xu, Z. C., Z. L. Wang, et al. (2003). "Multimodal Multiplex Spectroscopy Using Photonic Crystals." Optics Express 11 (18): 2126-2133.

International Search Opinion and Written Opinion of the International Searching Authority for PCT/US2007/075145 mailed Apr. 2, 2008.

B. Bates, D. J. McCartney, C. D. McKeith, A. McQuoid, and O. E. Sproule, "Interferometer-grating Spectrograph for High Resolution Astronomical Spectroscopy in the Middle uv," Applied Optics 14, 2119-2124 (1978).

C. Hsieh, O. Momtahan, A. Karbaschi, and A. Adibi, "A Compact Fourier Transform Volume Holographic Spectrometer for Diffuse Source Spectroscopy," Opt. Lett. 30, 836-838 (2005).

E.D. Nelson and M.L. Fredman, "Hadamard Spectroscopy," J. Opt. Soc. Am. 60, 1664-1669 (1970).

O. Momtahan, C. Hsieh, A. Karbaschi, A. Adibi, M.E. Sullivan, and D.J. Brady, "Spherical Beam Volume Holograms for Spectroscopic Applications: Modeling and Implementation," Appl. Opt. 43, 6557-6567 (2004).

* cited by examiner

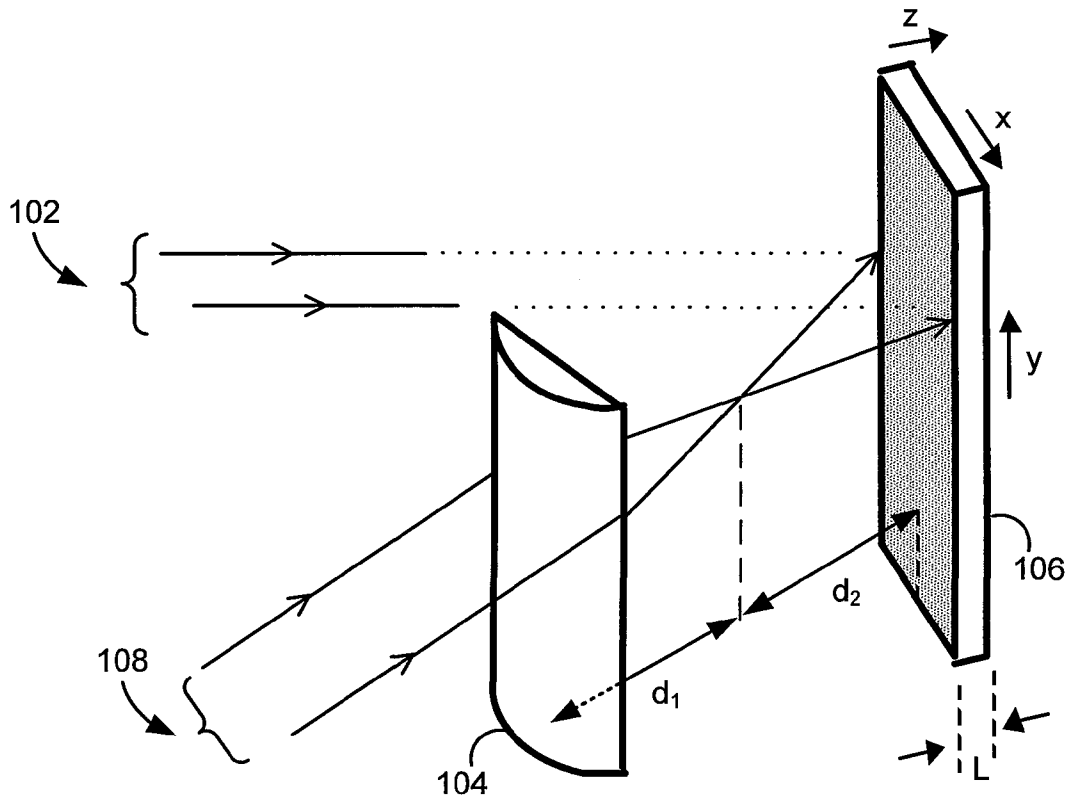


FIG. 1

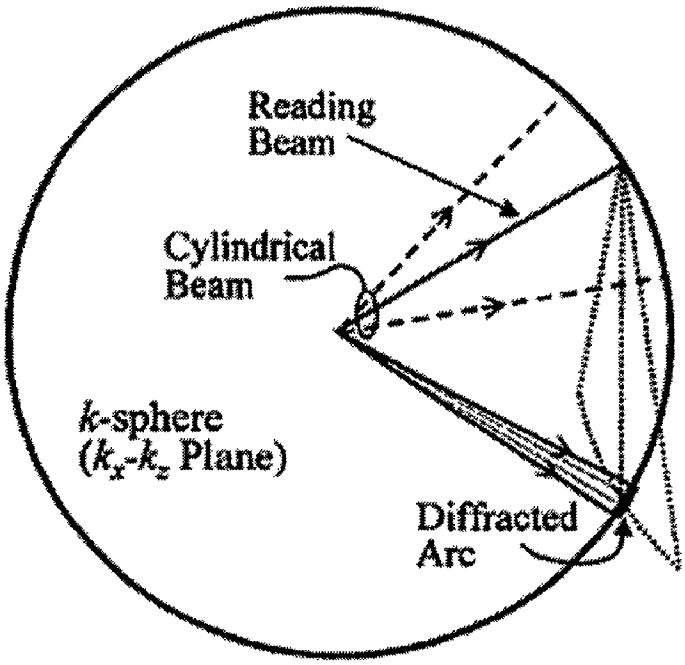

Reading
Beam
Cylindrical
Beam
k-sphere
(k_x-k_z Plane)
Diffracted
Arc

FIG. 2

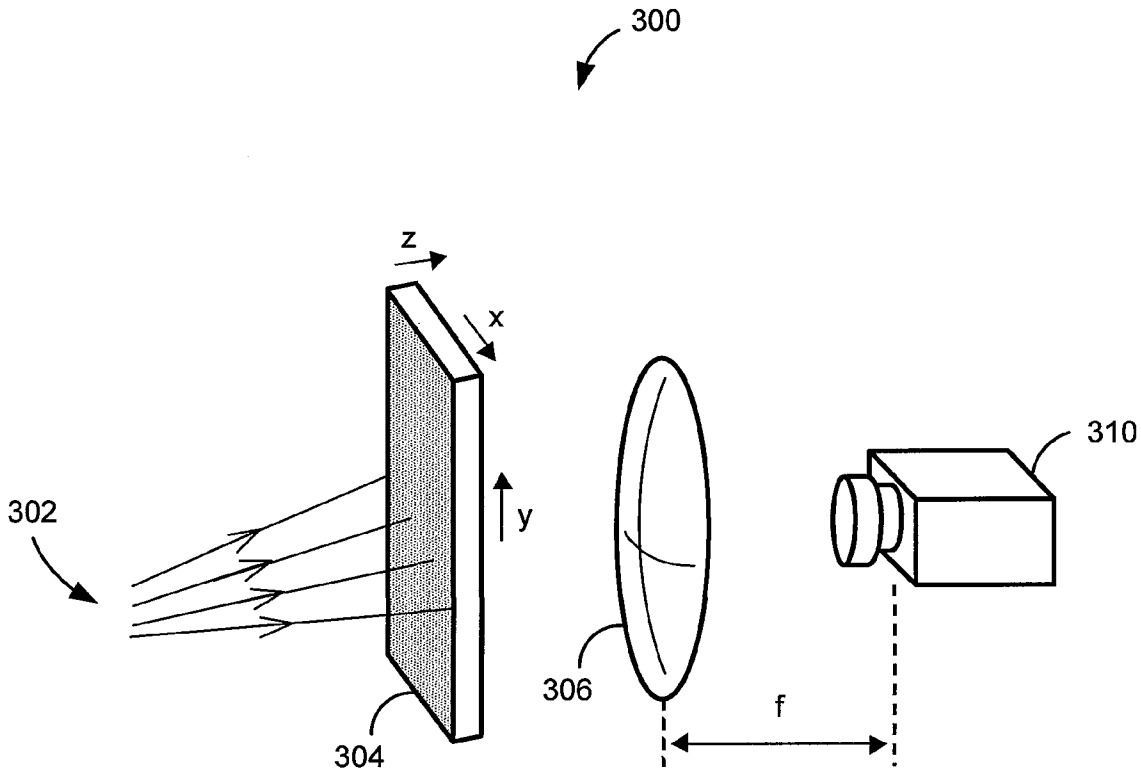


FIG. 3

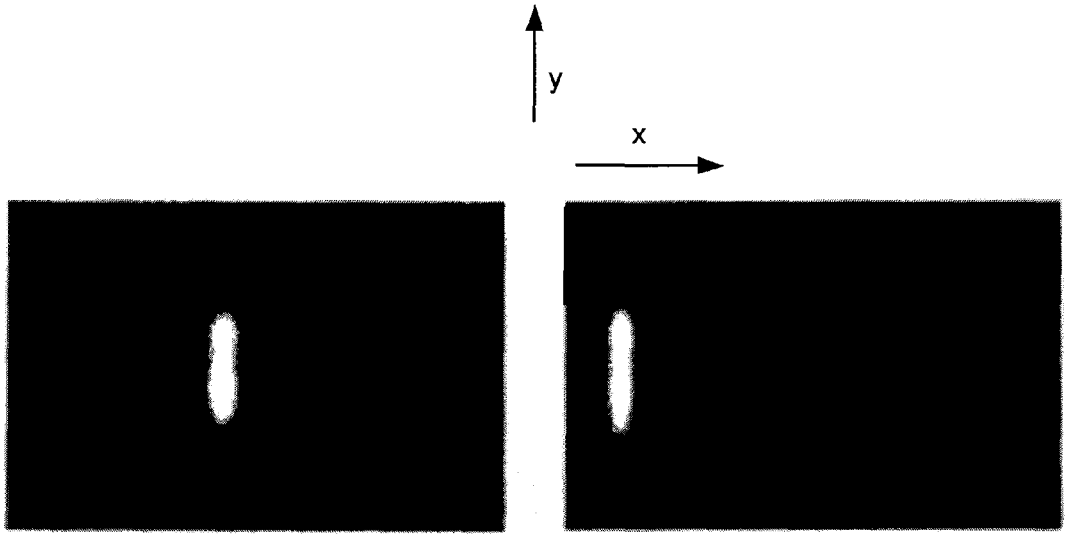


FIG. 4A

FIG. 4B

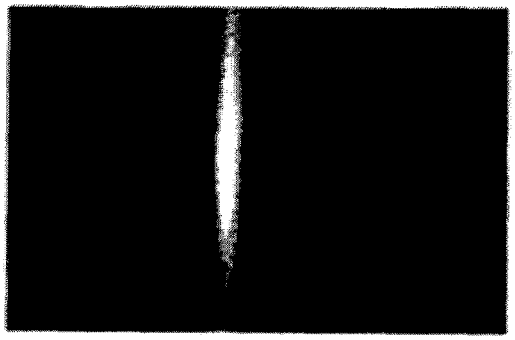


FIG. 4C

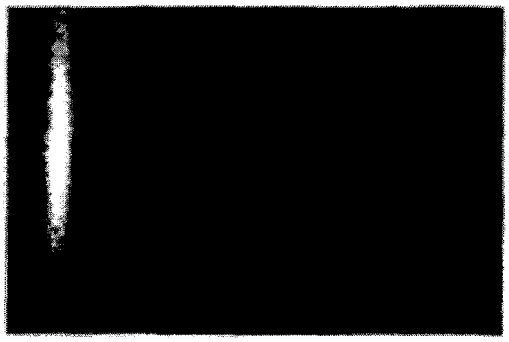


FIG. 4D

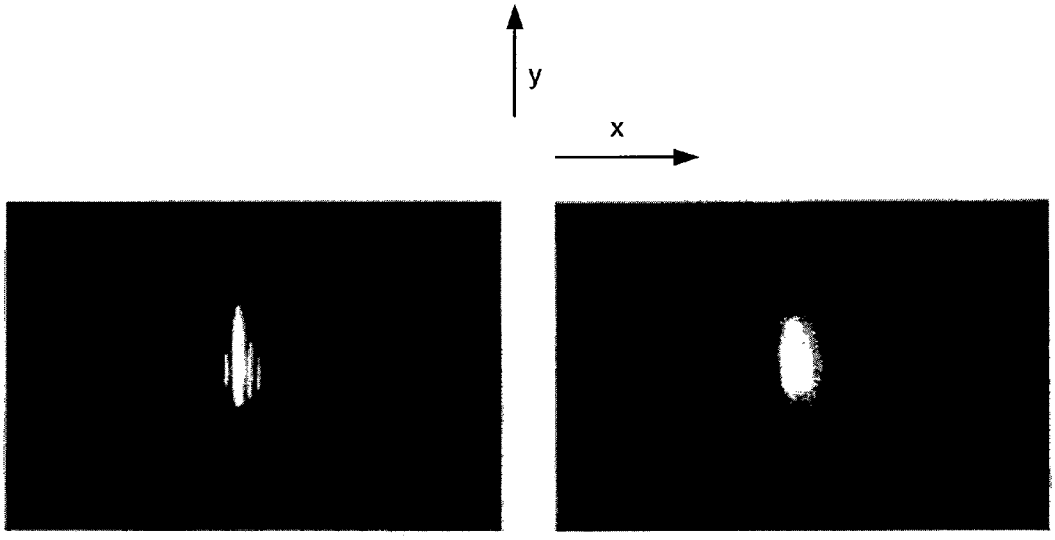


FIG. 5A

FIG. 5B

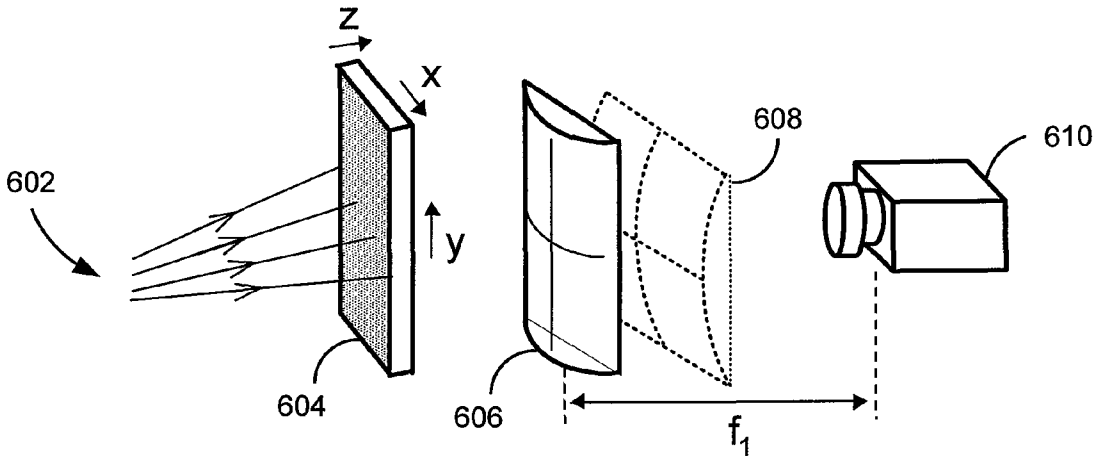


FIG. 6

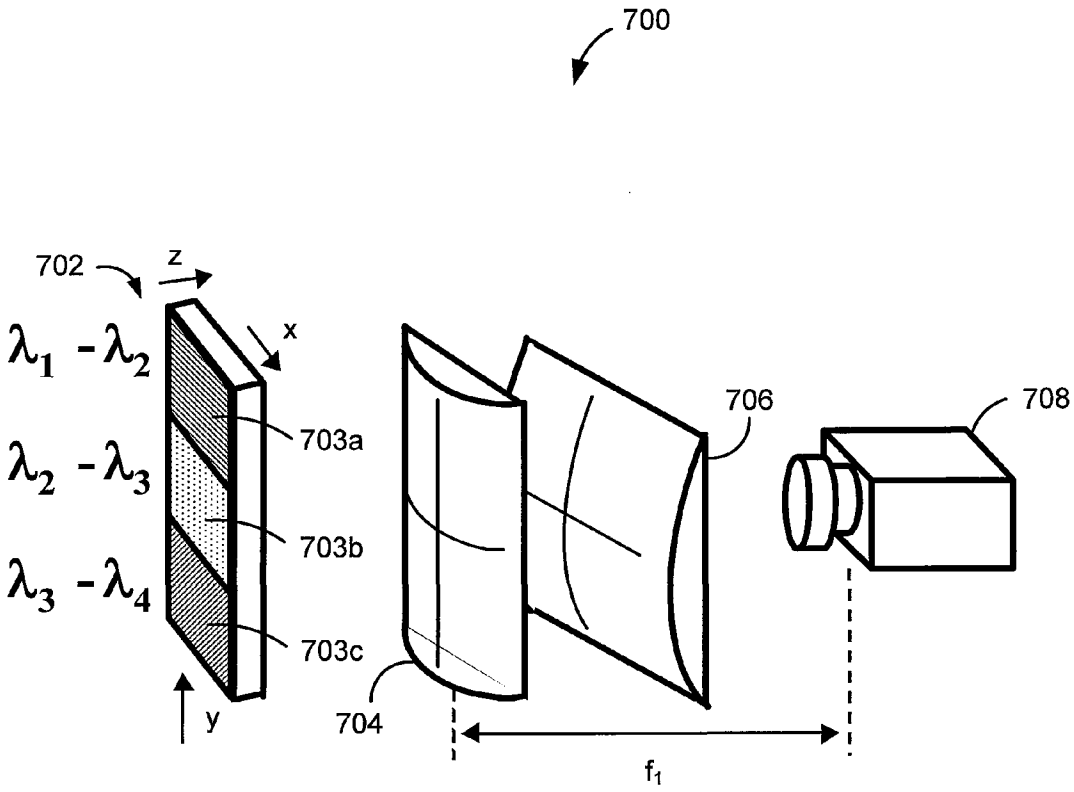

700
702
z
x
$\lambda_1 - \lambda_2$
$\lambda_2 - \lambda_3$
$\lambda_3 - \lambda_4$
703a
703b
703c
y
704
706
708
f_1

FIG. 7

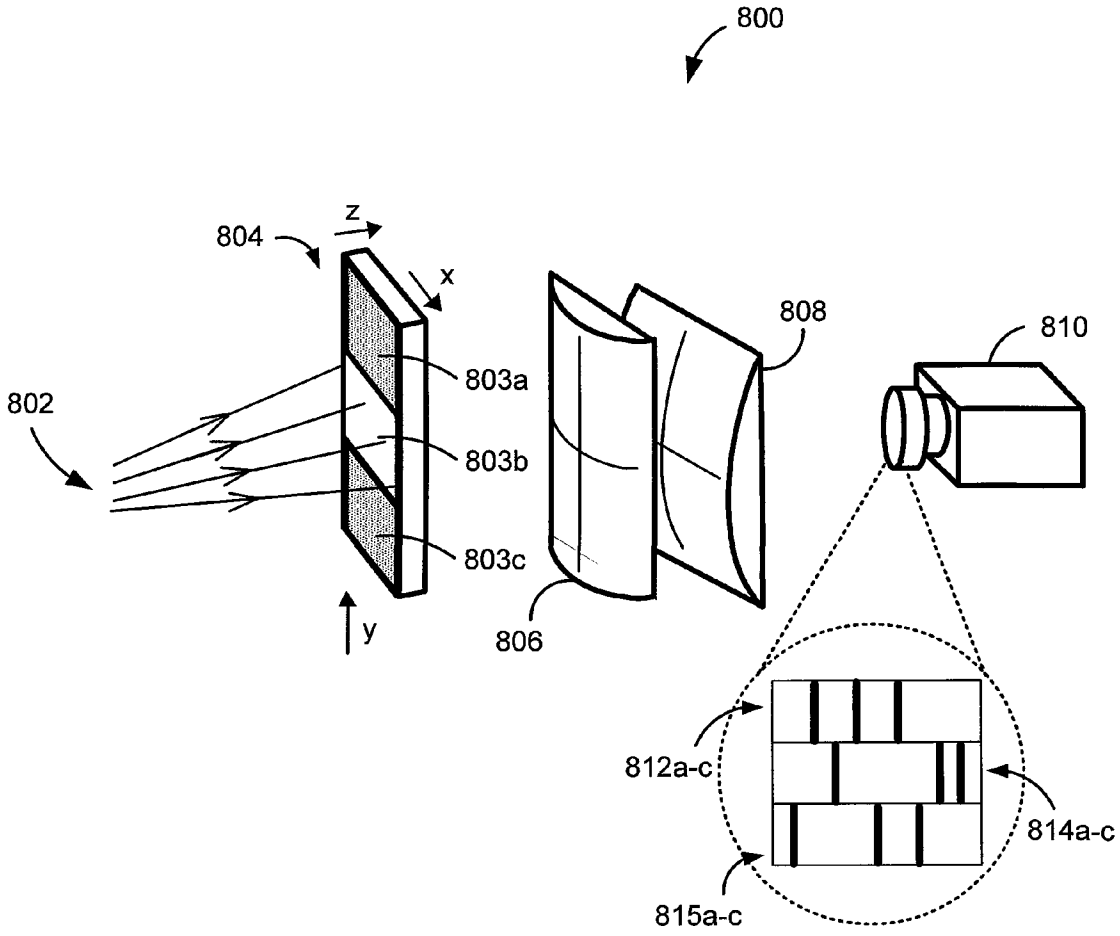


FIG. 8

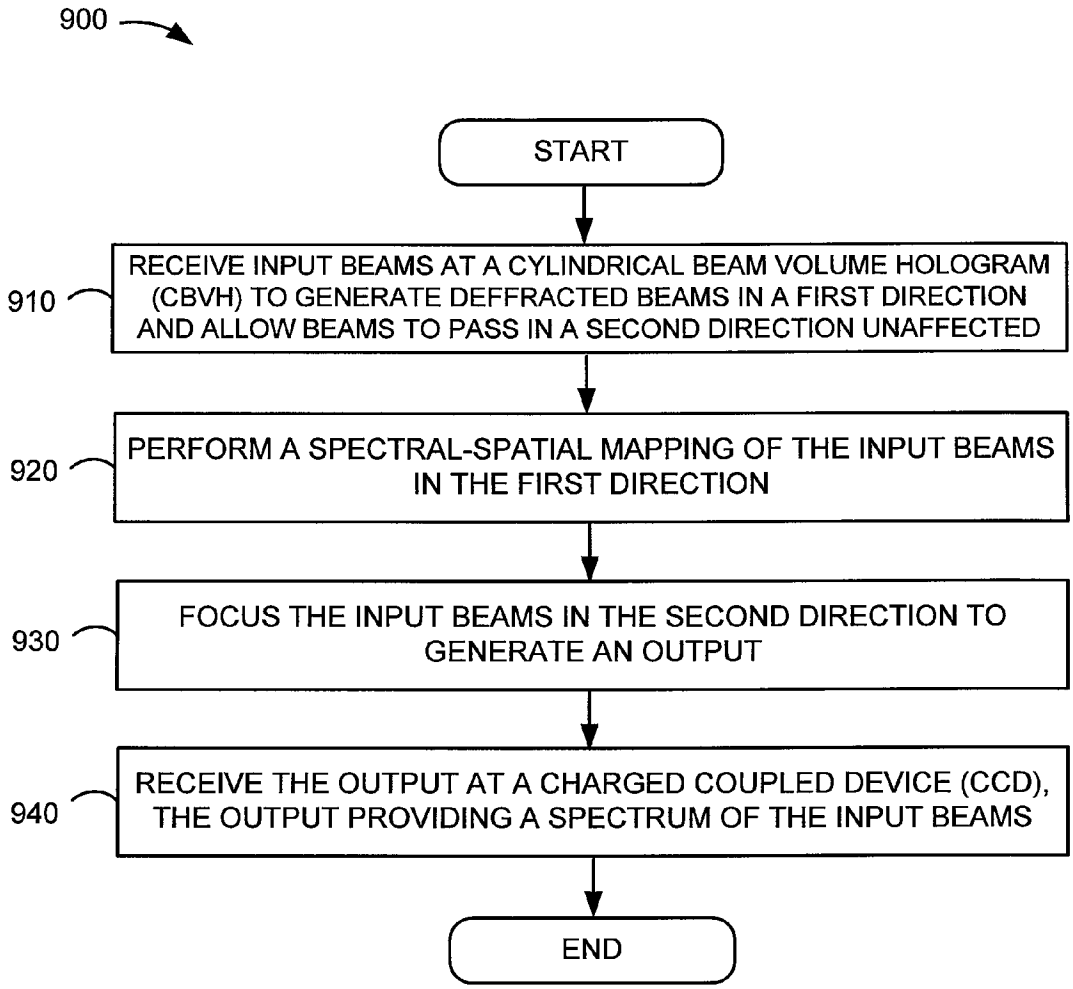

900
START
910
RECEIVE INPUT BEAMS AT A CYLINDRICAL BEAM VOLUME HOLOGRAM (CBVH) TO GENERATE DEFFRACTED BEAMS IN A FIRST DIRECTION AND ALLOW BEAMS TO PASS IN A SECOND DIRECTION UNAFFECTED
920
PERFORM A SPECTRAL-SPATIAL MAPPING OF THE INPUT BEAMS IN THE FIRST DIRECTION
930
FOCUS THE INPUT BEAMS IN THE SECOND DIRECTION TO GENERATE AN OUTPUT
940
RECEIVE THE OUTPUT AT A CHARGED COUPLED DEVICE (CCD), THE OUTPUT PROVIDING A SPECTRUM OF THE INPUT BEAMS
END

FIG. 9

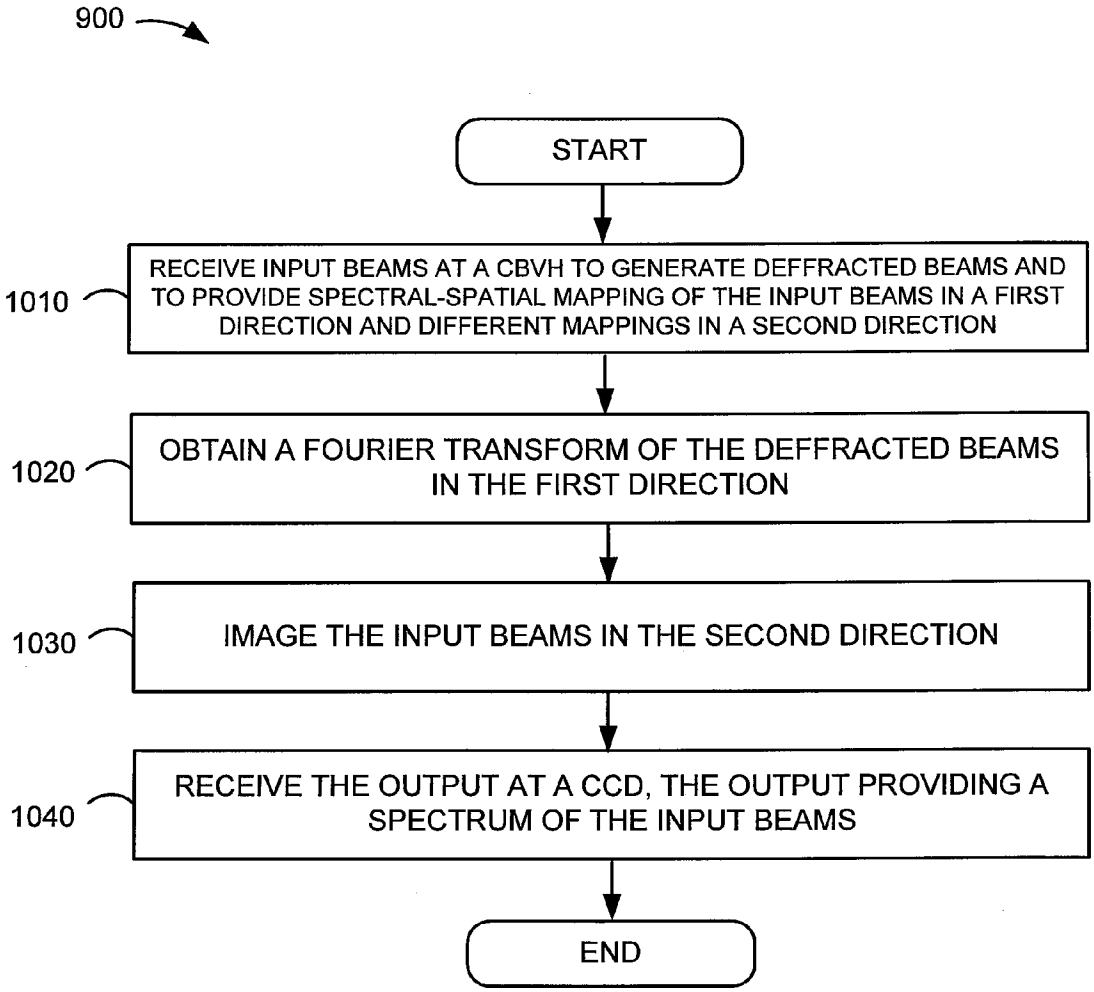

900
START
1010
RECEIVE INPUT BEAMS AT A CBVH TO GENERATE DEFFRACTED BEAMS AND TO PROVIDE SPECTRAL-SPATIAL MAPPING OF THE INPUT BEAMS IN A FIRST DIRECTION AND DIFFERENT MAPPINGS IN A SECOND DIRECTION
1020
OBTAIN A FOURIER TRANSFORM OF THE DEFFRACTED BEAMS IN THE FIRST DIRECTION
1030
IMAGE THE INPUT BEAMS IN THE SECOND DIRECTION
1040
RECEIVE THE OUTPUT AT A CCD, THE OUTPUT PROVIDING A SPECTRUM OF THE INPUT BEAMS
END

FIG. 10

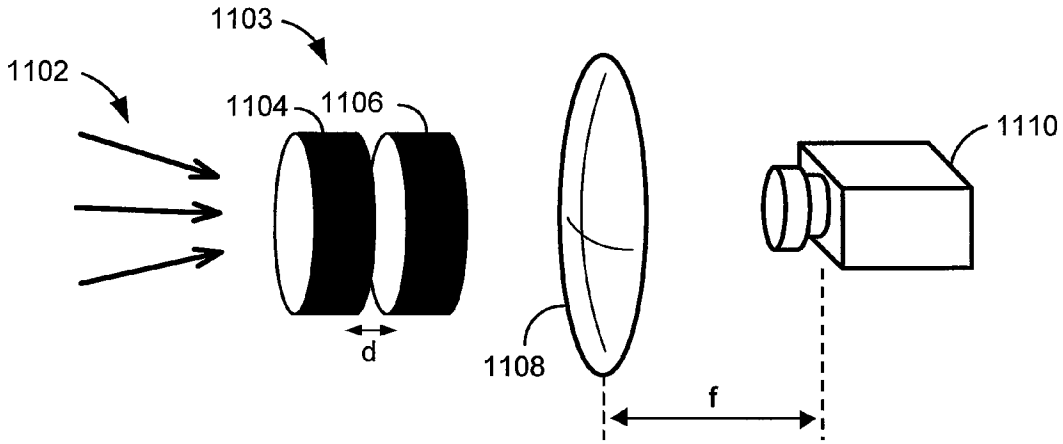


FIG. 11A

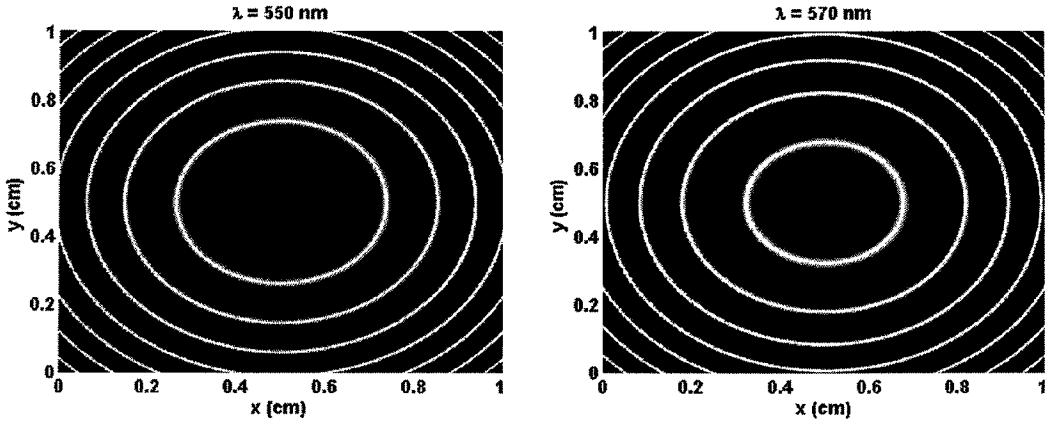


FIG. 11B

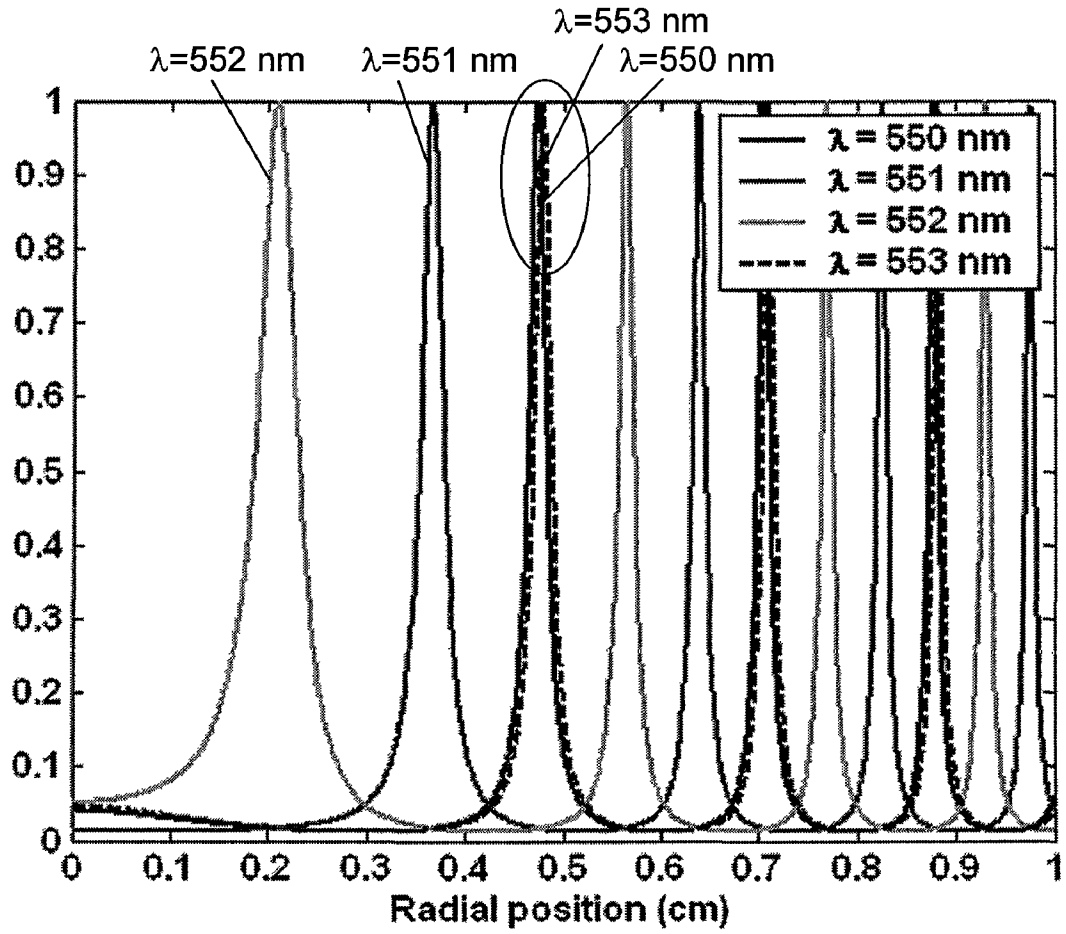

λ=552 nm
λ=551 nm
λ=553 nm
λ=550 nm
λ = 550 nm
λ = 551 nm
λ = 552 nm
λ = 553 nm
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Radial position (cm)

FIG. 12

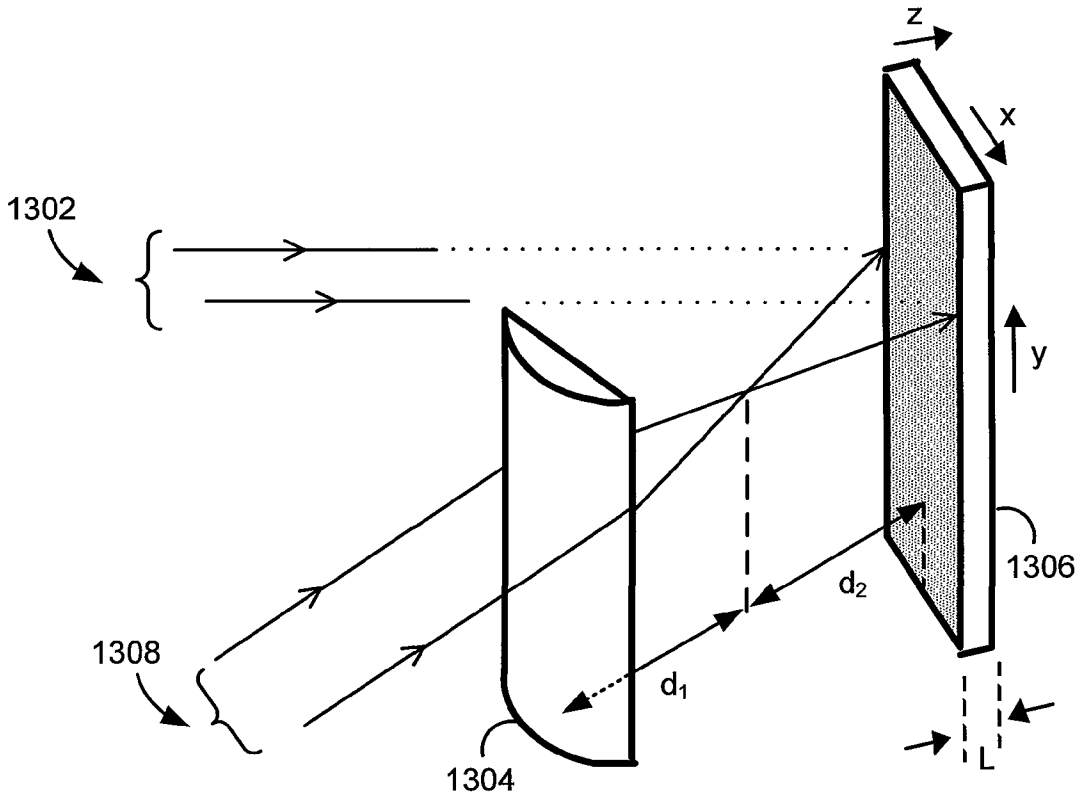


FIG. 13

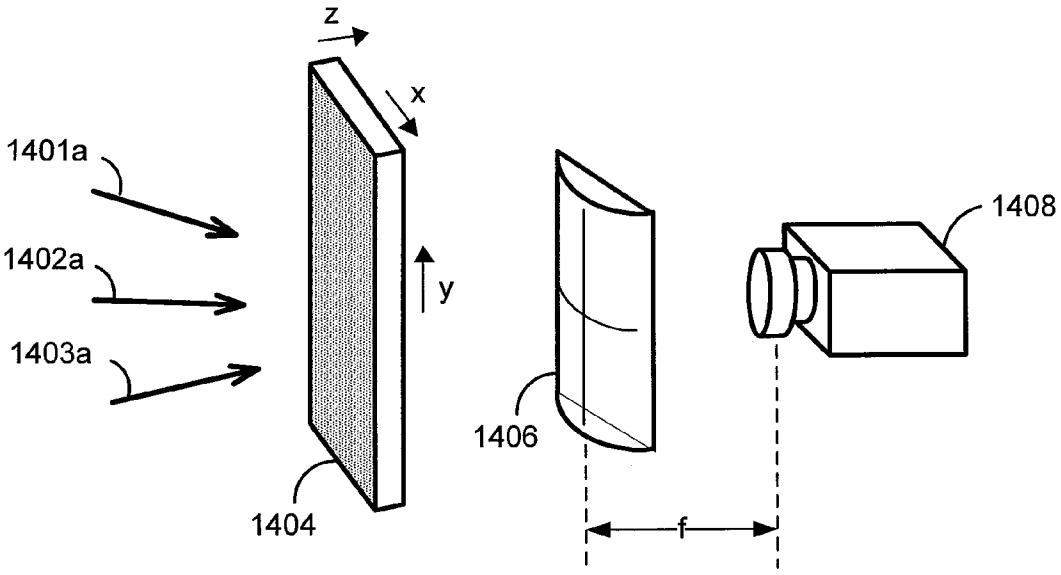


FIG. 14A

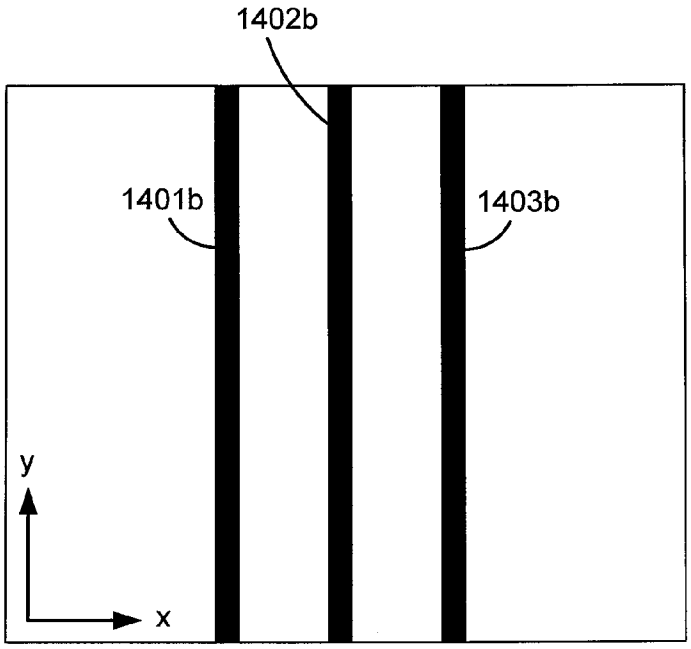


FIG. 14B

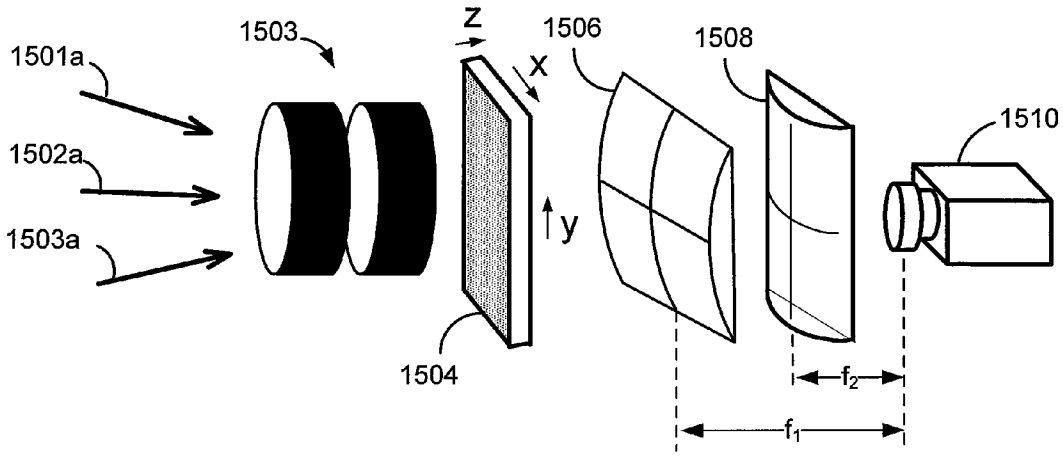


FIG. 15A

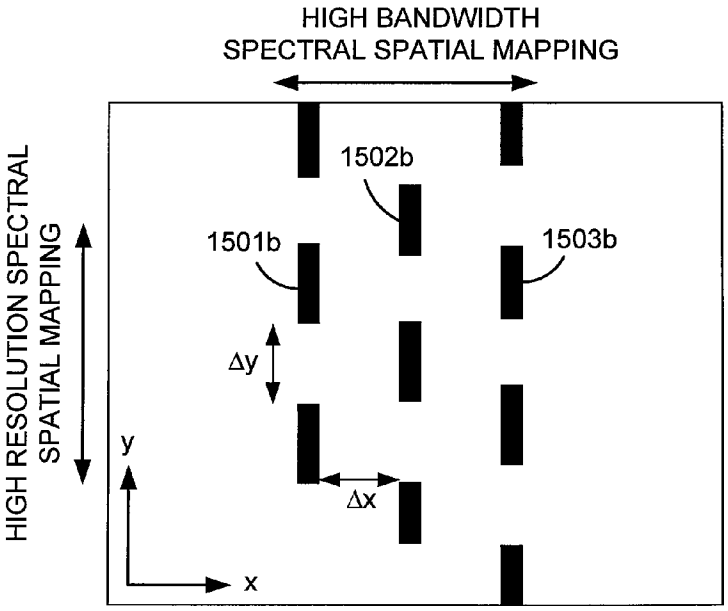


FIG. 15B

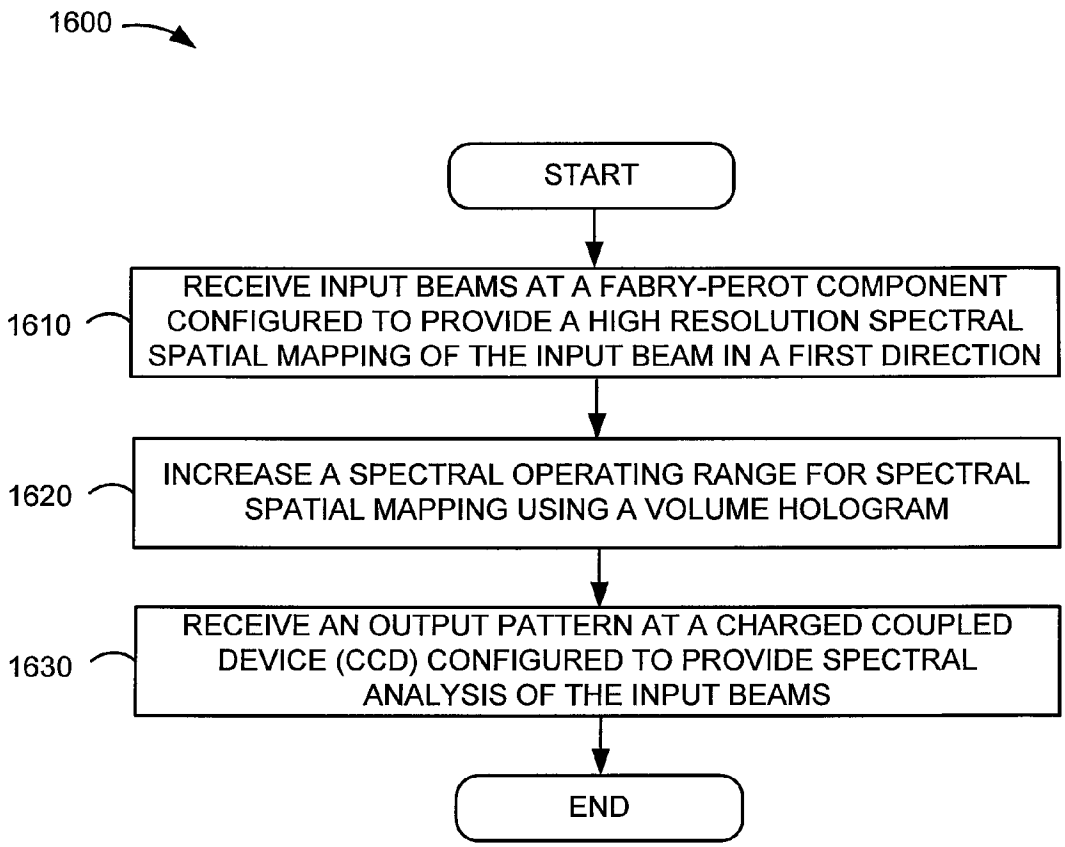

1600
START
1610
RECEIVE INPUT BEAMS AT A FABRY-PEROT COMPONENT CONFIGURED TO PROVIDE A HIGH RESOLUTION SPECTRAL SPATIAL MAPPING OF THE INPUT BEAM IN A FIRST DIRECTION
1620
INCREASE A SPECTRAL OPERATING RANGE FOR SPECTRAL SPATIAL MAPPING USING A VOLUME HOLOGRAM
1630
RECEIVE AN OUTPUT PATTERN AT A CHARGED COUPLED DEVICE (CCD) CONFIGURED TO PROVIDE SPECTRAL ANALYSIS OF THE INPUT BEAMS
END

FIG. 16

TANDEM FABRY-PEROT ETALON CYLINDRICAL BEAM VOLUME HOLOGRAM FOR HIGH RESOLUTION/LARGE SPECTRAL RANGE DIFFUSE LIGHT SPECTROSCOPY

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to, and the benefit of, U.S. Provisional Patent Application entitled, "TANDEM FABRY-PEROT ETALON CYLINDRICAL BEAM VOLUME HOLOGRAM FOR HIGH RESOLUTION LARGE SPECTRAL RANGE DIFFUSE LIGHT SPECTROSCOPY," having Ser. No. 60/855,836, filed on Oct. 30, 2006, which is incorporated by reference in its entirety. This application also claims priority to, and the benefit of, PCT Application No. PCT/US2007/075145 entitled, "TANDEM FABRY-PEROT ETALON CYLINDRICAL BEAM VOLUME HOLOGRAM FOR HIGH RESOLUTION LARGE SPECTRAL RANGE DIFFUSE LIGHT SPECTROSCOPY," filed on Aug. 3, 2007, which is entirely incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with Government support under Agreement Number N01AA23013, awarded by the National Institutes of Health. The Government has certain rights in the invention.

TECHNICAL FIELD

The present disclosure generally relates to the field of spectroscopy and more particularly, relates to utilizing a Fabry-Perot etalon in tandem with a cylindrical beam volume holograms to perform diffuse light spectroscopy.

BACKGROUND

The basic principle behind most spectrometers involves the separation of different wavelength channels within an input beam onto different locations of an output plane using some type of dispersive element. The output may be detected using some type of detector array or a charged coupled device (CCD). Because of the scalar nature of the spectrum, such dispersive elements (e.g., gratings and prisms) generally provide a mapping between the different wavelengths and various spatial locations along a line on the detector. For example, for the case of a simple sinusoidal grating, dispersion is obtained across a line in a direction parallel to the grating vector. Thus, in the direction perpendicular to the grating vector, the output beam is almost uniform and does not carry any spectral information. Generally for most applications, a CCD, which is a two-dimensional array of detectors, will be used in the output plane. However, the output in the direction perpendicular to the dispersion direction is almost useless in most conventional implementations.

There are several parameters involved in the design of an efficient spectrometer. Two important performance attributes of a spectrometer are the resolution and spectral operating range of the spectrometer. The resolution of a spectrometer is generally defined as the smallest difference in the wavelengths of two monochromatic input beams that can be resolved at the corresponding outputs at a detector. The operating range of the spectrometer is defined as the maximum

range of wavelengths over which the spectrometer can determine the spectrum of the input. While both the resolution and the operating range of any spectrometer depend on several design parameters, it is difficult to maximize both parameters using conventional design techniques.

SUMMARY

Systems and methods for performing two-dimensional (2D) high resolution spectral-spatial mapping are described. Briefly described, one embodiment, among others, includes a spectrometer for performing two-dimensional (2D) high resolution spectral-spatial mapping comprising a Fabry-Perot component configured to receive a diffuse input beam and provide a high resolution spectral mapping of the diffuse input beam in a first direction. The spectrometer further comprises a volume hologram for increasing a spectral operating range, the volume hologram configured to perform spectral mapping in a second direction orthogonal to the first direction to increase the spectral operating range. The spectrometer further comprises a charged coupled device (CCD) configured to receive output beams, the output beams used to provide spectral analysis of the input beams.

Another embodiment includes a spectrometer for performing two-dimensional (2D) high resolution spectral-spatial mapping comprising a volume hologram for increasing a spectral operating range, the volume hologram configured to perform spectral mapping in a second direction orthogonal to a first direction to increase a spectral operating range. For some embodiments, the CBVH comprises an integrated Fabry-Perot component configured to receive a diffuse input beam and provide a high resolution spectral mapping of the diffuse input beam in the first direction in addition to two cylindrical lenses. The spectrometer further comprises a charged coupled device (CCD) configured to receive the outputs beams, the output beams used to provide spectral analysis of the input beams.

Another embodiment includes a method for performing two-dimensional (2D) high resolution spectral-spatial spectroscopy comprising receiving input beams at a Fabry-Perot component configured to provide a high resolution spectral-spatial mapping of the input beam in a first direction, increasing a spectral operating range for spectral-spatial mapping using a volume hologram, the volume hologram configured to perform spectral mapping in a second direction orthogonal to the first direction to increase a spectral operating range and receiving an output pattern at a charged coupled device (CCD) configured to provide spectral analysis of the input beams.

Yet another embodiment includes an apparatus for performing two-dimensional (2D) high resolution spectral-spatial mapping comprising means for receiving a diffuse input beam and providing a high resolution spectral mapping of the diffuse input beam in a first direction, means for increasing a spectral operating range by performing spectral mapping in a second direction orthogonal to the first direction, means for receiving beams at a first cylindrical lens and focusing the received beams in the first direction, means for focusing the beams in the second direction to generate an output pattern, and means for receiving the output pattern, the output pattern used to provide spectral analysis of the input beams.

Other systems, methods, features, and advantages of the present disclosure will be or become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features, and advantages be included

within this description, be within the scope of the present disclosure, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Many aspects of the disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

FIG. **1** is a diagram of an exemplary setup for recording a cylindrical beam volume hologram.

FIG. **2** depicts a k-sphere holographic representation of the cylindrical beam volume hologram from FIG. **1**.

FIG. **3** is a diagram of an exemplary spectrometer incorporating the cylindrical beam volume hologram recorded from FIG. **1**.

FIGS. **4**A-**4**D illustrate various outputs detected by a charge coupled device in the exemplary spectrometer from FIG. **3**.

FIGS. **5**A-**5**B illustrate various outputs detected by a charge coupled device in the exemplary spectrometer from FIG. **3** where a lens with higher focusing power compared to the one used in FIGS. **4**A-**4**D is utilized.

FIG. **6** is a diagram of an exemplary embodiment of a spectrometer incorporating the cylindrical beam volume hologram from FIG. **1** showing how one or two cylindrical lenses are utilized.

FIG. **7** is a diagram of an alternative embodiment of a spectrometer incorporating the cylindrical beam volume hologram from FIG. **1** where different wavelength ranges are diffracted from different locations of the hologram and mapped to different segments on the CCD in the y-direction.

FIG. **8** is a diagram of an alternative embodiment of a spectrometer incorporating the cylindrical beam volume hologram from FIG. **1** where different segments of the hologram in the y-direction are angularly multiplexed to provide different spatial-spectral maps on different segments of the CCD in the y-direction.

FIG. **9** is a flowchart for an embodiment of a method for performing spectral analysis using the spectrometer in FIG. **6**.

FIG. **10** is a flowchart for an alternative embodiment of a method for performing spectral analysis using the spectrometer in FIG. **6**.

FIG. **11**A shows an embodiment of a Fabry-Perot spectrometer.

FIG. **11**B shows the transmission response as a function of frequency for the Fabry-Perot spectrometer in FIG. **11**A.

FIG. **12** shows the periodic spectral transmission response for the Fabry-Perot spectrometer from FIG. **11**A where the spectrometer has a free spectral range (FSR) of 3 nm.

FIG. **13** is a diagram of an exemplary setup for recording a cylindrical beam volume hologram (CBVH).

FIG. **14**A is a diagram of an embodiment of a spectrometer incorporating the CBVH recorded from FIG. **13**.

FIG. **14**B illustrates the output detected by a charge coupled device (CCD) in the CBVH spectrometer in FIG. **14**A.

FIG. **15**A is a diagram of an exemplary embodiment of a spectrometer incorporating a Fabry-Perot etalon in tandem with a CBVH.

FIG. **15**B illustrates the output detected by a CCD in the exemplary spectrometer in FIG. **15**A.

FIG. **16** is a flowchart for an embodiment of a method for performing spectral analysis using the tandem spectrometer in FIG. **15**A.

DETAILED DESCRIPTION

Embodiments described herein include systems and methods for expanding the spectral-spatial mapping into one or two dimensions and for performing coded spectroscopy. Embodiments of cylindrical beam volume holograms (CBVHs) provide spectral diversity in one direction without affecting the beam in the other direction. In addition, various embodiments of a spectrometer system utilizing a CBVH can be realized due to the independent treatment of the input beam in different directions. As a non-limiting example, in the direction parallel to the axis of the cylindrical beam in the recording configuration, different segments of the hologram can be recorded with different recording conditions (e.g., different plane waves) in order to provide two-dimensional spectral-spatial mapping at the output. This results in an increase in the range of the operating wavelength and/or the resolution of the system. Thus, embodiments of CBVHs provide for spatial mapping in two dimensions rather than in just one dimension, as provided by most conventional approaches to spectroscopy. Furthermore, it should be emphasized that the CBVH replaces the functionality of the input slit, the input collimating element, and the grating found in conventional spectrometers. Thus, embodiments of CBVHs provide spectrometers that have a fewer number of elements, thereby resulting in more compact, relatively low cost, and robust spectrometers. Other embodiments of the spectrometer system described herein incorporate angular multiplexing where multiple holograms are multiplexed into each segment of the CBVH and different segments are spatially multiplexed into the CBVH in order to provide a coded mapping of the input spectrum onto a two-dimensional output. Simple post processing may then be performed in order to derive the spectrum of the input beam from the coded output with a high degree of accuracy.

Generally, to determine the spectral characteristics of an arbitrary beam, a mapping is performed of the scalar quantity of the spectrum i.e., light intensity vs. different wavelengths) associated with the beam onto different spatial locations in an output plane. Typically, the spectrum of the input beam is spatially mapped onto a line in the output plane. This mapping can be efficiently implemented by modifying the beam only in one direction while the beam remains intact in the other direction.

As briefly described above, a key component in spectrometers is the wavelength sensitive (or dispersive) component that provides separation of different wavelength channels for detection purposes. Thin holograms (or gratings) are well-known candidates for achieving this because of their wavelength selectivity, which results in non-uniform diffraction of different wavelength channels of a collimated optical beam. Most of the optical spectrometers built based on this phenomenon exploit surface relief or thin film gratings, which primarily have single grating vectors. Exemplary embodiments of CBVHs described herein comprise thick volume holograms recorded using one or more plane waves and a cylindrical beam formed by a cylindrical lens. Because of the Bragg selectivity of the volume holograms, the separation of different wavelength channels is obtained for either a collimated beam or a diffuse beam. It should be appreciated that because of this unique property, the CBVH replaces various elements found in conventional spectrometers, including the input slit, the collimating lens or, mirror, and the thin hologram or

grating. In this respect, exemplary embodiments of the CBVH provide for compact and robust slitless spectrometers.

For embodiments of the spectrometer systems described herein, the spectral properties of the input beam are detected in a specific direction in the output plane while the orthogonal direction can be used to independently modify the beam through the system. It should be emphasized that embodiments of the spectrometer provide independent functionality in two orthogonal directions. As a result, unique applications can be realized by using embodiments of the CBVHs described herein. As a non-limiting example of one application, spectral-spatial mapping can be performed in two dimensions with a charged coupled device (CCD) placed at the output by recording different CBVHs into different segments of the hologram. Furthermore, multiple CBVHs may be multiplexed within each segment through angular multiplexing. As a result, coding can be performed on the mapping from the spectrum of the input beam into the various segments at the output.

In accordance with certain aspects of CBVHs described herein, FIG. **1** is a block diagram of an exemplary setup for recording a CBVH. Shown in FIG. **1** is a hologram (i.e., CBVH) **106** recorded using a plane wave **102** and a beam **108** focused by a cylindrical lens **104**. For alternative embodiments, the hologram **106** may be recorded using two cylindrical beams formed by two cylindrical lenses. As illustrated in FIG. **1**, the focus point of the cylindrical beam occurs at a distance d_1 behind the lens **104** and at a distance d_2 in front of the hologram **106**. Furthermore, as depicted in FIG. **1**, the hologram **106** has a thickness L. Depending on the application, the exemplary setup shown in FIG. **1** may be modified by adjusting the incident angles of the plane wave **102** and the cylindrical beam **108**. It should be noted that beyond the cylindrical lens **104**, the beam **108** is focused in the x-direction while it remains unmodified in the y-direction. The interference pattern between the cylindrical beam and the plane wave is recorded onto the hologram **106**.

The properties of the CBVH can be explained from the plane wave expansion of the cylindrical beam. The electric field in the y-direction corresponding to a cylindrical beam **108** with the axis parallel to the y-axis, originated from a line source at $r_0=(0,y,-d)$ and monitored at $r=(x,y,z)$, is represented by a Hankel function of the zeroth order and of the first kind $H_0^{(1)}$. The field may be expressed by its Fourier transform as follows:

$$H_0^{(1)}(k|r-r_0|)=\frac{1}{\pi}\int\frac{1}{k_z}e^{jk_z(z+d)}e^{jk_x x}\,dk_x \qquad (1)$$

In the equation above, k_x and k_z are the x- and z-components of the wave vector k. The amplitude of the wave vector k is the wave number $k=2\pi/\lambda$, where λ is the wavelength. It should be noted that in the equation above, the k_y component is 0 and therefore, the following holds true: $k_x^2+k_z^2=k^2$. Furthermore, it should be noted that the relation in the equation above is valid for all values of y. The hologram that is recorded by the cylindrical beam and a plane wave can be represented as the superposition of several simple gratings formed by the interference of each plane wave component of the cylindrical beam with the recording plane wave. Therefore, the diffraction from the CBVH can be found by superposing the diffracted components from the simple gratings. From Equation (1), it is clear that the cylindrical beam has no plane wave propagating in the y-direction. Therefore, no grating is formed in the y-direction and the recorded CBVH does not affect the reading beam in the y-direction.

Reference is now made to FIG. **2**, which depicts a k-sphere holographic representation of the CBVH from FIG. **1**. The k-domain representation of the CBVH is depicted as a circle in the x-z plane and further illustrates some of the novel characteristics of the CBVH disclosed herein. The diverging beam coming from the cylindrical lens is represented by a sector. As neither the cylindrical beam nor the plane wave carry any propagation component in the y-direction, the two-dimensional k-domain representation shown in FIG. **2** is used for recording the CBVH. When the hologram is read by a plane wave mainly propagating in the direction of the cylindrical beam, a small set of k-vectors will be Bragg-matched to form the diffracted beam. If the angle of the reading beam is changed (within the angular extent of the recording cylindrical beam), another set of k-vectors will be Bragg-matched, but the direction of the diffracted beam will be unchanged. It should be noted that this is the main property of the CBVH which allows diffraction of a collimated or a diffuse input beam into a beam with very small spatial frequency (close to a plane wave). The CBVH exhibits this property even if the wavelength of the reading beam is different from the recording wavelength. In this respect, the spectrometer based on a CBVH does not require any collimating optics (i.e., an input slit and a collimating lens or mirror) to operate. It should be noted that the y-component of the reading beam will not be affected by the CBVH. Therefore, the hologram will only modify the properties of the beam in the x-direction. Furthermore, these properties are independent of those in the y-direction.

Reference is now made to FIG. **3**, which is a diagram of an exemplary spectrometer incorporating the CBVH recorded from FIG. **1**. In FIG. **3**, the input beam **302** illuminates the hologram **304** primarily in the direction of the recording cylindrical beam. The diffracted beam from the hologram is then Fourier transformed using a lens **306** with a focal length f. For some embodiments, the lens **306** used in the spectrometer **300** may be either a spherical lens or a cylindrical lens, depending on the application. The output of the system is obtained using a CCD **310** located at the focal plane of the lens **306**. In this regard, the spectrometer **300** may be utilized for two-dimensional spectral mapping. Furthermore, it should be emphasized that the CBVH **304** is not sensitive to the incident angles of the input beams (as explained above). This makes the use of CBVHs **304** suitable for diffuse light spectroscopy. As such, the spectrometer **300** is capable of dispersing diffuse light beams without the use of an input slit and a collimating lens or mirror.

FIGS. **4**A-**4**D illustrate various outputs detected by a charge coupled device in the exemplary spectrometer from FIG. **3**. To further illustrate some of the novel features of the CBVH, a white light is first passed through a monochromator. The output of the monochromator serves as the input into the spectrometer **300**. As a non-limiting illustration, a spherical lens with a focal length of f=10 cm is utilized in the spectrometer setup of FIG. **3**. Furthermore, the spherical lens is selected such that the ratio of the focal length for the lens to the lens diameter is F#=3.8. FIGS. **4**A and **4**B illustrate the outputs detected at the CCD **310** where the input beams have wavelengths λ=500 nm and λ=532 nm, respectively. It should be noted that while the spatial locations of the outputs vary in the x-direction as the wavelength changes, the outputs remain unchanged in the y-direction. The limited size in the y-direction is attributed to the limited divergence angle of the input beams in the y-direction.

To increase the divergence angle of the input beams in the y-direction, a rotating diffuser is inserted after the monochromator but in front of the CBVH **304**. The addition of the rotating diffuser simulates an incoherent input beam. The outputs which correspond to the diffuse input beams at wavelengths λ=500 nm and λ=532 nm, respectively, are shown in FIGS. **4**C and **4**D. It should be noted that the spatial locations of the outputs in the x-direction remain the same as those in FIGS. **4**A and **4**B. However, the outputs span a greater distance in the y-direction. This is attributed to the wider range of incident angles in the input beam. Thus, as can be seen in FIGS. **4**A-**4**D, a spectrometer **300** incorporating a CBVH **304** performs spectral separation in the x-direction for both diffuse and non-diffuse input beams while not affecting the beam in the y-direction. For the results shown in FIGS. **4**A-**4**D, the input beam **302** undergoes a Fourier transformation in the y-direction because it is only affected by the spherical lens. It should be noted that if a cylindrical lens is used after the CBVH **304** rather than a spherical lens, the input beam **302** remains unchanged in the y-direction. That is, the input beam **302** is only affected in the x-direction and not the y-direction.

FIGS. **5**A-**5**B illustrate various outputs detected by a charge coupled device in the exemplary spectrometer from FIG. **3** where a lens with higher focusing power compared to the one used in FIGS. **4**A-**4**D is utilized. In another non-limiting illustration, the spherical lens has a smaller focal length-to-lens diameter ratio (F#=0.75) and smaller focal length (f=1.9 cm) is compared to the lens used for FIGS. **4**A-**4**D. These parameters are chosen in order to provide a higher degree of focusing in the y-direction. The results are shown in FIGS. **5**A and **5**B for the incident wavelength of λ=532 nm.

FIG. **5**A reflects the output detected with no diffuser place in front of the CBVH such that a non-diffuse input beam enters the spectrometer. FIG. **5**B shows the output detected with a rotating diffuser incorporated into the system (to generate a diffuse input beam). When compared to FIGS. **4**A-**4**D, the distance in which the output spans in the y-direction is notably smaller in FIGS. **5**A and **5**B. Thus, the power distributed over a vertical strip in the y-direction is localized to a limited distance in the y-direction and the intensity to be detected is accordingly increased. It should be noted that the increase in the intensity achieved by focusing the input beam in the y-direction is ultimately limited by the Lagrange invariant of the system (or more generally by the constant radiance theorem). However, maximum intensity at the output can be achieved utilizing exemplary embodiments of the CBVH for even partially incoherent sources.

FIG. **6** is a diagram of an exemplary embodiment of a spectrometer incorporating the cylindrical beam volume hologram from FIG. **1** showing how one or two cylindrical lenses are utilized. It should be noted that for exemplary embodiments, a cylindrical lens **606** is used to perform a Fourier transform in the x-direction. Using another cylindrical lens **608** perpendicular to the cylindrical lens **606** used for performing the Fourier transform, the input beam **602** can be modified in the y-direction independently. This second lens **608** can be used to provide a higher degree of focusing in the y-direction. As discussed earlier, the input beam is unaffected by the hologram in the y-direction. Therefore, if the input beam is diverging in nature, the output at the CCD **610** will also be diverging in nature after the beam passes through the hologram and the first lens. Thus, the second cylindrical lens **608** is placed after the first cylindrical lens **606** such that the second lens **608** is orthogonal with respective to the first cylindrical lens **606** in order to focus the output in the y-direction.

In this case, the input beams can be mapped (or focused) to different spatial locations in the y-direction at the CCD **610**. In this regard, the second cylindrical lens **608** focuses the output to specific locations at the CCD **610**. In an alternative embodiment, the lens may be used to obtain the image of the hologram **604** at the CCD **610** in the y-direction. Since the diffracted beam propagates through different lenses **606**, **608** in the x- and y-directions, respectively, the system provides spectral diversity in the x-direction while it maps the hologram **604** at the CCD **610** in the y-direction. It should be emphasized that this enables a degree of freedom in the design of the hologram in the y-direction. It should be noted that in alternative embodiments, the second cylindrical lens **608** can also be placed before the first cylindrical lens **606** to obtain similar results. It should be further noted that the functionality of the first cylindrical lens **606** can be further integrated into the volume hologram if the CBVH is recorded using two cylindrical beams. In this regard, for the recording arrangement shown in FIG. **1**, the plane wave should be replaced by a converging cylindrical beam focused after the hologram. The interface of a diverging cylindrical beam with a converging cylindrical beam is recorded inside the hologram. Therefore, it should be appreciated that the spectrometer arrangement becomes even more compact for such embodiments. Furthermore, the functionalities of the first lens **606** and the second lens **608** might be integrated into the CBVH if the recording plane wave of the arrangement in FIG. **1** is replaced by a beam that is converging in both x- and y-directions. This results in further reduction of the number of elements and the size of the spectrometer.

For some embodiments, the hologram can be divided in the y-direction into several regions or segments. Within each region, a corresponding hologram may be recorded to map a certain range of wavelengths of the input beam to a specific location in the output. Reference is now made to FIG. **7**, which is a diagram of an alternative embodiment of a spectrometer incorporating the cylindrical beam volume hologram from FIG. **1** where different wavelength ranges are diffracted from different locations of the hologram and mapped to different segments on the CCD in the y-direction. FIG. **7** shows an embodiment where three different segments **703***a*, **703***b*, **703***c* are recorded in the CBVH **702**. In the arrangement shown, the top hologram **703***a* diffracts the input beam in the range of λ_1 to λ_2. The spectral range corresponding to the middle hologram **703***b* diffracts the input beam in the range of λ_2 to λ_3. Likewise, the bottom hologram **703***c* diffracts the input beam in the range of λ_3 to λ_4. Therefore, the one-dimensional spectral diversity is mapped onto two dimensions at the CCD **708**. In this regard, embodiments of the hologram **702** described in FIG. **7** is spatially multiplexed to provide two-dimensional spectral-spatial mapping (i.e. spectral wrapping).

It should be appreciated that in this respect, the use of the design flexibility in the y-direction is not limited to the cases described here. The spectral wrapping technique may also be used in conjunction with thicker recording material in order to improve both resolution and spectral range. While there are some trade-off between the ultimate resolution and operating spectral range in every spectrometer, the optimal use of the spectral wrapping property of CBVH spectrometer minimizes this trade-off. It should be noted that the "segmented" or partitioned hologram **702** may be recorded in either a single step or in sequential steps, depending on the recording setup utilized. For example, a spatial light modulator or a

mask may be incorporated into the setup. Also, since the holograms **702** are recorded onto different regions or segments **703***a-c* of the recording material, the full dynamic range of the material can be used for recording each hologram **702** to obtain high diffraction efficiency.

In other embodiments, the spectral wrapping can be obtained by angularly multiplexing a plurality of CBVHs in the y-direction. Different holograms can be multiplexed using the same cylindrical beam and several plane waves with different angles of propagation in the y-direction. The arrangement of the spectrometer for this embodiment is similar to the arrangement shown in FIG. **7**. In other embodiments, both cylindrical lenses can be used to obtain the Fourier transform of the beam in both directions. In yet other embodiments, the combination of the two lenses can be implemented using a spherical lens.

In other embodiments, multiple holograms may be multiplexed to a particular segment. Reference is now made to FIG. **8**, which is a diagram of an alternative embodiment of a spectrometer incorporating the cylindrical beam volume hologram from FIG. **1** where different segments of the hologram in the y-direction are utilized. In these segments, different holograms are angularly multiplexed in the x-direction to provide different spatial-spectral maps on different segments of the CCD in the y-direction. FIG. **8** shows the segmented CBVH **804** from FIG. **7** but where multiple holograms are angularly multiplexed in the x-direction into each segment **803***a-c*. The resulting spectral-spatial mappings which correspond to the segment **803***a*, **803***b*, and **803***c* are shown as different patterns **815***a-c*, **814***a-c*, **812***a-c* on the CCD **810**, respectively, for reading with a monochromatic beam. Therefore, each wavelength is mapped to more than one location in each segment since it is diffracted from an angularly multiplexed hologram. The maps for different wavelength may overlap in each segment, but the difference in the mappings of different segments provide enough information to obtain the correct contribution of each wavelength in the spectrum of the input beam.

To incorporate angular multiplexing, multiple holograms are recorded by varying the incident angle of the plane waves. Thus, each angle-multiplexed CBVH may be recorded using a fixed cylindrical beam and a plane wave with a different (adjustable) incident angle with respect to the other holograms. As a non-limiting example, three different incident angles would be used to record three different holograms.

In the non-limiting example shown in FIG. **8**, three different holograms are multiplexed into a single segment **803***a*. Using one segment **803***a-c* of the hologram, the total power in the output corresponding to a monochromic input may be increased by a factor of approximately 3 times when compared to the case where a single CBVH is used, since three diffraction components will be collected at the CCD **810**. Each wavelength component is mapped to three vertical strips **812***a-c*, **814***a-c*, **815***a-c*, as shown in FIG. **8**. However, it should be noted that the resolution is reduced since a larger region is assigned to one input wavelength. If the segments **803***a-c* of the hologram **804** are designed differently to provide independent mapping conditions in different segments for each input wavelength component, post processing may be used to compensate for the reduction in the resolution. In each segment **803***a-c*, the output signal **812***a-c*, **814***a-c*, **815***a-c* corresponding to different wavelength components overlap in the output plane, but the independent mapping obtained using multi-segmented hologram **804** provides enough information to solve for (or estimate) the correct spectral contents of the input beam. In this regard, coded spectroscopy is achieved using angular multiplexing in each segment and spatial multiplexing of different segments, and results in an increase in the power detected for a given wavelength without sacrificing the resolution.

Reference is made to FIG. **9**, which is a flowchart for an embodiment of a method for performing spectral analysis using the spectrometer in FIG. **6**. Beginning in step **910**, input beams are received at a cylindrical beam volume hologram (CBVH) where diffracted beams are generated in a first direction and the beam is allowed to pass through unaffected in a second (orthogonal) direction. In step **920**, a spectral-spatial mapping is performed on the input beams in a first direction. In step **930**, the input beams are focused in the second direction to generate an output. In step **940**, the output is received at a charged coupled device (CCD) where the output provides a spectrum of the input beams.

Reference is made to FIG. **10**, which is a flowchart for an alternative embodiment of a method for performing spectral analysis using the spectrometer in FIG. **6**. Beginning in step **1010**, input beams are received at a cylindrical beam volume hologram (CBVH) to generate diffracted beams and to provide spectral-spatial mapping of the input beams in a first direction and different mappings in a second direction. In step **1020**, a Fourier transform is obtained for the diffracted beams in the first direction. Next, in step **1030**, the input beams are imaged (or focused) in the second direction. In step **1040** the output is received at a charged coupled device (CCD), the output providing (with possible post-processing) a spectrum of the input beams.

Tandem Fabry-Perot CBVH Spectrometer

Embodiments described herein include systems and methods for utilizing a Fabry-Perot etalon in tandem with a cylindrical beam volume hologram (CBVH) to perform diffuse light spectroscopy. Embodiments of the tandem configuration achieve high resolution and take advantage of the large spectral operating range of CBVH-based spectrometers. Such embodiments provide a more compact and less expensive means for performing spectroscopy that is less sensitive to optical alignment than conventional spectrometers. Also, it should be appreciated that embodiments of the tandem spectrometer disclosed herein encode the spectral information of the input beam into a 2D spatial pattern at the output plane, thereby resulting in more efficient use of a CCD.

Generally, to determine the spectral characteristics of an arbitrary beam, a mapping is performed of the scalar quantity of the spectrum (i.e., light intensity vs. different wavelengths) associated with the beam onto different spatial locations in an output plane. Typically, the spectrum of the input beam is spatially mapped along a line in the output plane. This mapping can be efficiently implemented by modifying the beam only in one direction while the beam remains intact in the other direction.

As briefly described earlier, a key component in spectrometers is the wavelength sensitive (or dispersive) component that provides separation of different wavelength channels for detection purposes. Holograms (or gratings) are well-known candidates for achieving this because of their wavelength selectivity, which results in non-uniform diffraction of different wavelength channels of a collimated optical beam. Most of the optical spectrometers built based on this phenomenon exploit surface relief or thin film gratings, which primarily have single grating vectors. Exemplary embodiments of CBVHs are recorded using either a plane wave and a single cylindrical beam formed by a cylindrical lens or two cylindrical beams formed by two cylindrical lenses. The CBVHs are then further utilized to derive a compact, slitless, diffuse light spectrometer. For embodiments of the spectrometer systems described herein, CBVHs are utilized in tandem with a

Fabry-Perot etalon to achieve 2D spectral-spatial mapping for spectroscopy. The functions of the Fabry-Perot etalon and the CBVH within a spectrometer are now discussed.

Reference is made to FIG. **11**A, which shows an embodiment of a Fabry-Perot spectrometer. Generally, the Fabry-Perot etalon **1103** is a basic example of an inteferometric device, or a device that superposes two or more waves and creates an output wave different from the input waves. The output is utilized to analyze the differences in wavelength characteristics of the input waves. The Fabry-Perot spectrometer shown in FIG. **11**A is composed of two dielectric mirrors **1104**, **1106**, each with a reflectivity R. Furthermore, the two dielectric mirrors **1104**, **1106** are arranged such that there is a fixed air gap, denoted by a thickness d, between the mirrors **1104**, **1106**. A CCD **1110** is used to detect the output and is placed at the focal plane of a spherical lens **1108** with a focal length f, as shown in FIG. **11**A. In this respect, Fabry-Perot etalon **1103** contains planar surfaces that are all partially reflecting so that multiple rays of light are responsible for the generation of interference patterns. Fabry-Perot etalon **1103** causes multiple reflections that reinforce the areas where constructive and destructive effects occur, thereby making the resulting fringes much more clearly defined. Constructive interference occurs if the transmitted beams are in phase, and this corresponds to a high-transmission peak of the etalon. If the transmitted beams are out of phase, destructive interference occurs and this corresponds to a transmission minimum. As such, this effect provides for much more precise measurements of wavelength and free spectral range (FSR).

FIG. **11**B shows the transmission response as a function of frequency for the Fabry-Perot spectrometer in FIG. **11**A. Specifically, FIG. **11**B shows simulation results corresponding to wavelengths λ=550 nm and λ=570 nm based on the following parameters: a mirror reflectivity set to (R=0.8), the air gap thickness (d=50 μm), and the focal length of the lens set to (f=5 cm). Furthermore, for this non-limiting example, the input beam **1102** is diffuse or spatially incoherent in nature. As seen in FIG. **11**B, for a diffuse source **1102** composed of all possible wavevectors in the air and for each input wavelength, the output spectrum of the Fabry-Perot etalon has a circularly symmetric spectral-spatial pattern at the Fourier plane of the lens. That is, when focused by a lens (such as a spherical lens), the interference fringes form concentric circles at the output plane. As such, one should note that all the spectral information is encoded in only one direction within a single line along the radii of the fringes with no spectral information encoded in the other direction (i.e., the azimuthal direction along the perimeter of the circles).

The scalar nature of the output spectrum thus requires separation of the individual wavelength components in only one direction in the spatial domain. However, it should also be noted that one apparent shortcoming of the Fabry-Perot spectrometer in FIG. **11**A is that the spectrometer fails to take advantage of the 2D capability of most optical detectors. More specifically, the Fabry-Perot spectrometer shown in FIG. **11**A fails to provide a true 2D spectral-spatial mapping at the output plane captured by the CCD **1110**.

Furthermore, another perceived shortcoming of the Fabry-Perot spectrometer shown in FIG. **11**A is the periodicity of its transmission response in the frequency domain. Ultimately, the spectral operating range of the spectrometer is limited to the FSR of the Fabry-Perot etalon **1103**. The FSR is defined as the spacing between two resonance peaks in the frequency domain. By way of illustration, reference is made to FIG. **12**, which shows the periodic spectral transmission response for the Fabry-Perot spectrometer from FIG. **11**A with a 50 micron air gap where the spectrometer has a FSR of 3 nm. The transmission response is shown for wavelengths λ=550, λ=551, λ=552, and λ=553 nm. It should be noted that the spectrum of the Fabry-Perot etalon is degenerate when its FSR is exceeded as evidenced by the overlapping of the transmission response for certain wavelengths. As clearly seen in FIG. **12**, the output pattern which corresponds to λ=553 nm overlaps with the output pattern corresponding to λ=550 nm. This coincides with an FSR of 3 nm for the Fabry-Perot etalon in the non-limiting example. As known by those skilled in the art, the FSR is dependent on the wavelength. Thus, the overlapping of these outputs (at λ=550 nm and λ=553 nm) illustrates that the output spectrum of the Fabry-Perot spectrometer shown in FIG. **11**A is degenerate for wavelengths spaced by 3 nm, the FSR value. Because of this characteristic, a Fabry-Perot etalon **1103** can be practically used as a high resolution spectrometer but with only a small spectral operating range for diffuse source spectroscopy. However, it should be noted that this unique property of Fabry-Perot etalons may be utilized in combination with diffuse source spectrometers which have large spectral ranges of operation, as will now be discussed.

One class of diffuse source spectrometers may be implemented by incorporating volume holograms such as spherical beam volume holograms and cylindrical beam volume holograms. Reference is now made to FIG. **13**, which is a diagram of an exemplary setup for recording a CBVH. As described earlier, the CBVH **1306** can be recorded using a plane wave **1302** and a cylindrical beam **1308** formed by a cylindrical lens **1304**. As illustrated in FIG. **13**, the focal plane of the cylindrical beam occurs at a distance d_1 behind the lens **1304** and at a distance d_2 in front of the hologram **1306**. Furthermore, as depicted in FIG. **13**, the hologram **1306** has a thickness L. Depending on the application, the exemplary setup shown in FIG. **13** may be modified by adjusting the incident angles of the plane wave **1302** and the cylindrical beam **1308**. It should be noted that beyond the cylindrical lens **1304**, the beam **1308** is focused in the x-direction while it remains unmodified in the y-direction. The interference pattern between the signal beam and the reference beam is recorded onto the hologram **1306**.

FIG. **14**A is a diagram of an embodiment of a spectrometer incorporating the CBVH recorded from FIG. **13**. It should be noted that for exemplary embodiments, a cylindrical lens **1406** may also be used to perform a Fourier transform in the x-direction. As described above, the beam profile in the y-direction can be easily obtained by considering the propagation from the input plane to the output. The CBVH **1404** in FIG. **14**A diffracts different wavelengths of the input diffuse beam **1401***a*, **1402***a*, **1403***a* along the x-direction and does not modify them in the y-direction. Different holograms can be spatially multiplexed in different segments of the hologram **1404** in the y-direction. It should be noted that a "segmented" or partitioned hologram **1404** may be recorded in either a single step or in sequential steps, depending on the recording setup utilized. For example, a spatial light modulator or a mask may be incorporated into the setup. Also, since the holograms **1404** are recorded onto different regions or segments of the recording material, the full dynamic range of the material can be used for recording each hologram **1404**. Using such a segmented hologram, the spectral operating range of the spectrometer can be further increased.

In this respect, it should be appreciated that for certain embodiments, it is possible to form the CBVH by utilizing two cylindrical beams to remove the lens **1406** in order to form a more compact lensless structure. Reference is now made to FIG. **14**B, which illustrates the output **1401***b*, **1402***b*, **1403***b* detected by a CCD **1408** in the CBVH spectrometer in

FIG. **14**A. While the spectral properties of the input beam are detected in a specific direction in the output plane (i.e., along the x-axis in FIG. **14**B), an orthogonal direction (i.e., along the y-axis in FIG. **14**B) may be utilized to independently modify the beam through the system as the CBVH does not affect the beam in this direction. The light distribution at the Fourier plane of the cylindrical lens is degenerate along the y-direction.

As described in detail earlier, it should be further noted that this attribute of CBVHs distinguishes CBVHs from other types of volume holograms used for the formation of 2D spatial-spectral maps. Based on the independent functionality of the spectrometer in two orthogonal directions, unique applications can be realized by using CBVHs. Furthermore, unlike simple gratings, CBVHs are not sensitive to the incident angles of the input beams, thus making the CBVH highly suitable for diffuse light spectroscopy. As such, the CBVH practically acts as a low resolution, large spectral operating range spectrometer capable of dispersing diffuse light with no input slit.

Exemplary embodiments of tandem spectrometers utilize the properties of this class of diffuse source spectrometers in combination with those of the Fabry-Perot etalon to achieve high resolution diffuse light spectroscopy over a large spectral range. Reference is now made to FIG. **15**A, which is a diagram of an exemplary embodiment of a spectrometer incorporating a Fabry-Perot etalon in tandem with a CBVH. By cascading a Fabry-Perot etalon **1503** with a CBVH **1504**, a high resolution spectrometer with a large spectral operating range can be derived. As shown in the exemplary setup in FIG. **15**A, the Fabry-Perot etalon **1503** is placed in front of the CBVH **1504**. It should be further noted that for exemplary embodiments, a cylindrical lens **1508** may be used to perform a Fourier transform in the x-direction. Using a cylindrical lens **1506** perpendicular to the cylindrical lens **1508** used for performing the Fourier transform, the input beam **1501***a*, **1502***a*, **1503***a* can be modified in the y-direction independently. The lens **1506** can be used to provide a higher degree of focusing in the y-direction. As discussed earlier, the input beam is unaffected by the hologram in the y-direction. Therefore, if the input beam is diverging in nature, the output at the CCD **1510** will also be diverging in nature after the beam passes through the hologram. Thus, the cylindrical lens **1506** is placed before the cylindrical lens **1508** such that the lens **1506** is orthogonal with respect to the cylindrical lens **1508** in order to focus (or Fourier transform) the output in the y-direction such that different wavelengths are mapped to different spatial locations at the CCD **1510**. The first cylindrical lens **1506** has a focal length f_1 and the second cylindrical lens **1508** has a focal length f_2, as illustrated in FIG. **15**A.

FIG. **15**B illustrates the output detected by a CCD **1510** in the exemplary spectrometer in FIG. **15**A. It should be noted that the components in the drawings are not necessarily drawn to scale, and emphasis is placed upon clearly illustrating the principles described herein. As seen in FIG. **15**B, the CBVH **1504** simply breaks the circular symmetry of the Fabry-Perot interference fringes and the Fabry-Perot simply removes the y-degeneracy from the CBVH **1504** spectrum to form a 2D spatial-spectral pattern in the co-Fourier plane of the two cylindrical lenses **1506**, **1508**. Since the x- and the y-directions are independently used in this configuration, a Fabry-Perot etalon **1503** can be designed to encode high resolution spectral information in the y-direction, and the CBVH can be designed to expand the spectral operating range in the x-direction.

In this respect, exemplary embodiments of spectrometers provide both high resolution and high bandwidth spectral-spatial mapping through the CBVH and Fabry-Perot etalon working in tandem, as illustrated in FIG. **15**B. First, the CBVH provides coarse resolution but over a large spectral range. This is complemented by the Fabry-Perot etalon, which provides fine resolution within the spectral-spatial mapping generated by the CBVH. Referring to FIG. **15**B, the Δy value (corresponding to wavelengths) may be very small and in some cases, may be several orders of magnitude smaller than the Δx between adjacent lines in the x-direction. In this respect, the Fabry-Perot etalon provides high resolution spectral mapping. Furthermore, the CBVH provides high bandwidth spectral mapping by providing the capability of mapping a large number of frequencies at the output in the x-direction.

For exemplary embodiments of the tandem spectrometer shown in FIG. **15**A, the resolution of the CBVH is equal to the FSR of the Fabry-Perot structure such that the fine resolution of the tandem spectrometer is defined by the Fabry-Perot resolution while its spectral operating bandwidth is defined by the CBVH. In this exemplary embodiment, high performance is achieved in a very compact structure. It should be noted that in instances where the FSR of the Fabry-Perot etalon is smaller than the resolution of the CBVH, spectral ambiguity exists in the y-direction (i.e., the direction of fine resolution due to the Fabry-Perot etalon). Therefore, to remove this degree of ambiguity in resolving the spectrum of the unknown source, the maximum resolution of the CBVH should optimally be set equal to the FSR of the Fabry-Perot etalon for exemplary embodiments of the tandem spectrometer. This in turn guarantees that the 2D spectral-spatial mapping is invertible and there is no singularity in the spectrum estimation process. For instances where the FSR of the Fabry-Perot is larger than the resolution of the CBVH (for spatial coding in the x-direction), the vertical dimension (i.e., y-direction) is not optimally used for coding using the Fabry-Perot. That is, only the spatial range or the detector pixels corresponding to the wavelength range equal to the CBVH resolution are used, thereby resulting in reduction in the resolution.

In addition to the exemplary embodiments described above, alternative embodiments of the tandem spectrometer may be derived through various modifications. As a non-limiting example, the two cylindrical lenses in FIG. **15**A can be replaced by a specially designed spherical lens. Furthermore, embodiments of spectrometers may be more compactly implemented by integrating the Fabry-Perot etalon and the two lenses into the CBVH to realize even more low-cost, compact slitless spectrometers.

Other embodiments provide for recording multiplexed volume holograms onto different segments of the hologram to achieve even greater density levels of 2D spectral-spatial encoding. For some embodiments, this may be achieved by performing angular multiplexing. To incorporate angular multiplexing, multiple holograms are recorded by varying the incident angle of the plane waves during the recording phase. Thus, each angle-multiplexed volume hologram may be recorded using a fixed cylindrical beam and a plane wave with a different (adjustable) incident angle with respect to the other holograms.

For other embodiments, fully-optimized volume holograms are derived by incorporating multiple grating vectors into the holograms. For such embodiments, each grating vector within the volume hologram is optimized by taking into account such parameters as the properties of the Fabry-Perot etalon, the requirements of the spectrometer, the material thickness available for recording the hologram, and the spectral operating range. Exemplary setups for recording such

volume holograms are configured to pass a plane wave through a diffractive optical element designed to generate an optical pattern at the recording material in order to record the desired volume hologram. As such, embodiments of spectrometers incorporating these volume holograms are fully optimized to analyze diffuse light sources without the use of input slits and collimating lenses. This results in a more compact spectrometer with fewer alignment requirements compared to conventional spectrometers.

Reference is now made to FIG. **16**, which is a flowchart for an embodiment of a method for performing spectral analysis using the tandem spectrometer in FIG. **15**A. Beginning with step **1610**, input beams are received at a Fabry-Perot component configured to provide a high resolution spectral-spatial mapping of the input beam in a first direction. Next, in step **1620**, the spectral operating range is increased by using a volume hologram. The volume hologram is configured to perform spectral mapping in a second direction orthogonal to the first direction. In step **1630**, an output pattern is received at the CCD configured to provide spectral analysis of the input beams.

It should be emphasized that the above-described embodiments are merely examples of possible implementations. Many variations and modifications may be made to the above-described embodiments without departing from the principles of the present disclosure. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.

The invention claimed is:

1. A spectrometer for performing two-dimensional (2D) high resolution spectral-spatial mapping comprising:

a Fabry-Perot etalon configured to receive a diffuse input beam and provide a high resolution spectral mapping of the diffuse input beam in a first direction;

a volume hologram for increasing a spectral operating range, the volume hologram configured to perform spectral mapping in a second direction orthogonal to the first direction to increase the spectral operating range; and

a charged coupled device (CCD) configured to receive output beams, the output beams being used to provide spectral analysis of the input beams.

2. The spectrometer of claim **1**, further comprising a first cylindrical lens configured to receive beams from the volume hologram and Fourier transform the received beams in the first direction, the first cylindrical lens having a first focal length; and

a second cylindrical lens configured to receive the beams from the first cylindrical lens and Fourier transform the beams in the second direction to generate the output beams, the second cylindrical lens having a second focal length.

3. The spectrometer of claim **1**, the spectrometer further comprising a spherical lens.

4. The spectrometer of claim **1**, wherein the volume hologram is a cylindrical beam volume hologram (CBVH).

5. The spectrometer of claim **1**, wherein the volume hologram is a spherical beam volume hologram (SBVH).

6. The spectrometer of claim **1**, wherein a free spectral range (FSR) of the Fabry-Perot etalon is equal to a resolution of the volume hologram.

7. The spectrometer of claim **1**, wherein the spectral-spatial mapping provided by the Fabry-Perot etalon comprises a circularly symmetric spatial-spectral pattern at the CCD.

8. The spectrometer of claim **7**, wherein the Fabry-Perot etalon is configured to encode the high resolution spectral pattern in a y-direction and the CBVH is configured to expand the spectral operating range in an x-direction.

9. The spectrometer of claim **8**, wherein a resolution of the Fabry-Perot etalon defines a resolution of the spectrometer.

10. The spectrometer of claim **1**, wherein the CBVH is partitioned into a plurality of segments spanning the y-direction.

11. The spectrometer of claim **10**, wherein a plurality of holograms are multiplexed into each of the plurality of segments to provide spectral coding, the spectral coding providing an additional order of spectral-spatial mapping.

12. The spectrometer of claim **11**, wherein multiplexing the plurality of holograms is performed using angular multiplexing.

13. A spectrometer for performing two-dimensional (2D) high resolution spatial-spectral mapping comprising:

a volume hologram for increasing a spectral operating range, the volume hologram configured to perform spectral mapping in a second direction orthogonal to a first direction to increase a spectral operating range, the CBVH comprising:

an integrated Fabry-Perot etalon configured to receive a diffuse input beam and provide a high resolution spectral mapping of the diffuse input beam in the first direction; and

a cylindrical lens; and

a charged coupled device (CCD) configured to receive the outputs beams, the output beams being used to provide spectral analysis of the input beams.

14. The spectrometer of claim **13**, wherein a free spectral range (FSR) of the Fabry-Perot etalon is equal to resolution of the volume hologram.

15. The spectrometer of claim **13**, further comprising a second cylindrical lens.

16. The spectrometer of claim **15**, wherein the two cylindrical lenses are integrated into the volume hologram.

17. A method for performing two-dimensional (2D) high resolution spectral-spatial spectroscopy comprising:

receiving input beams at a Fabry-Perot etalon configured to provide a high resolution spectral-spatial mapping of the input beam in a first direction;

increasing a spectral operating range for spectral-spatial mapping using a volume hologram, the volume hologram configured to perform spectral mapping in a second direction orthogonal to the first direction to increase a spectral operating range; and

receiving an output pattern at a charged coupled device (CCD) configured to provide spectral analysis of the input beams.

18. The method of claim **17**, further comprising:

receiving beams from the volume hologram at a first cylindrical lens and focusing the received beams in the first direction, the first cylindrical lens having a first focal length; and

receiving beams from the first cylindrical lens and focusing the beams in the second direction to generate the output pattern, the second cylindrical lens having a second focal length.

19. The method of claim **18**, further comprising:

receiving beams from the volume hologram at a first cylindrical lens and Fourier transforming the received beams in the first direction, the first cylindrical lens having a first focal length; and

receiving beams from the first cylindrical lens at a second cylindrical lens and Fourier transforming the beams in the second direction to generate the output pattern, the second cylindrical lens having a second focal length.

20. The method of claim **18**, wherein the two cylindrical lenses are integrated into the volume hologram.

21. The method of claim 17, wherein a free spectral range (FSR) of the Fabry-Perot etalon is equal to a resolution of the CBVH.

22. The method of claim 17, wherein the volume hologram is a cylindrical beam volume hologram (CBVH).

23. The method of claim 17, further comprising receiving beams at a spherical lens to generate the output pattern.

24. The method of claim 17, wherein the volume hologram is a spherical beam volume hologram (SBVH).

25. An apparatus for performing two-dimensional (2D) high resolution spectral-spatial mapping comprising:

means for receiving a diffuse input beam and providing a high resolution spectral mapping of the diffuse input beam in a first direction;

means for increasing a spectral operating range by performing spectral mapping in a second direction orthogonal to the first direction;

means for receiving beams at a first cylindrical lens and performing a Fourier transform on the received beams in the first direction;

means for performing a Fourier transform on the beams in the second direction to generate an output pattern; and

means for receiving the output pattern, the output pattern used to provide spectral analysis of the input beams.

26. The apparatus of claim 25, wherein a free spectral range (FSR) of a Fabry-Perot etalon is equal to a resolution of the means for increasing the spectral operating range.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 8,203,716 B2
APPLICATION NO. : 12/447992
DATED : June 19, 2012
INVENTOR(S) : Badleirostami et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

Column 2, lines 36-37: replace "out-puts beams" with -- out-put beams --

In the Claims

Column 15, line 40, Claim 1: replace "output beams, the output beams" with -- an output beam, the output beams --

Column 15, line 41, Claim 1: replace "the input beams" with -- the diffuse input beam --

Column 15, line 47, Claim 2: replace "receive the beams" with -- receive a beam --

Column 15, line 49, Claim 2: replace "beams in the second direction" with -- beam from the first cylindrical lens in the second direction --

Column 15, line 61, Claim 7: replace "The spectrometer of claim 1" with -- The spectrometer of claim 4 --

Column 15, line 61, Claim 7: replace "the spectral spatial-mapping" with -- the high resolution spectral-spatial mapping" --

Column 16, line 3, Claim 10: replace "The spectrometer of claim 1" with -- The spectrometer of claim 4 --

Column 16, line 9, Claim 11: replace "spectral-spatial mapping" with -- high resolution spectral-spatial mapping --

Signed and Sealed this
Eighteenth Day of February, 2014

Michelle K. Lee

Michelle K. Lee
Deputy Director of the United States Patent and Trademark Office

Column 16, lines 16-17, Claim 13: replace "perform spectral mapping" with -- perform high resolution spectral-spatial mapping --

Column 16, line 19, Claim 13: replace "CBVH" with -- volume hologram --

Column 16, lines 21-22, Claim 13: replace "high resolution spectral mapping" with -- high resolution spectral-spatial mapping --

Column 16, lines 25-26, Claim 13: replace "receive the outputs beams, the output beams" with -- receive an output beam, the output beam --

Column 16, line 29, Claim 14: replace "equal to resolution" with -- equal to a resolution --

Column 16, line 33, Claim 16: replace "wherein the two" with -- wherein the first and second --

Column 16, line 37, Claim 17: replace "receiving input beams" with -- receiving an input beam --

Column 16, line 40, Claim 17: replace "range for spectral-spatial" with -- range for high resolution spectral-spatial --

Column 16, line 42, Claim 17: replace "perform spectral mapping" with -- perform high resolution spectral-spatial mapping --

Column 16, line 47, Claim 17: replace "input beams" with -- input beam --

Column 16, line 49, Claim 18: replace "receiving beams" with -- receiving a beam --

Column 16, line 50, Claim 18: replace "received beams" with -- received beam from the volume hologram --

Column 16, line 53, Claim 18: replace "receiving beams" with -- receiving a beam --

Column 16, line 54, Claim 18: replace "the beams in" with -- the beam from the first cylindrical lens --

Column 16, line 58, Claim 19: replace "receiving beams" with -- receiving a beam --

Column 16, line 59, Claim 19: replace "the received beams" with -- the beam received from the volume hologram --

Column 16, line 63, Claim 19: replace "transforming the beams" with -- transforming the beams received from the first cylindrical lens --

Column 16, line 66, Claim 20: replace "wherein the two" with -- wherein the first and second --

Column 17, line 3, Claim 21: replace "CBVH" with -- "volume hologram" --

Column 17, line 13, Claim 25: replace "high resolution spectral mapping" with -- high resolution spectral-spatial mapping --

Column 18, lines 1-2, Claim 25: replace "per-forming spectral mapping" with -- forming high resolution spectral-spatial mapping --

Column 18, line 7, Claim 25: replace "on the beams" with -- on the received beams --

Column 18, line 10, Claim 25: replace "the input beams" with -- the diffuse input beam --