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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
13 September 2007 (13.09.2007)

PCT

(10) International Publication Number
WO 2007/102801 A1

(51) International Patent Classification:
G01J 3/28 (2006.01) *G01J 3/18* (2006.01)

(21) International Application Number:
PCT/US2006/006765

(22) International Filing Date:
23 February 2006 (23.02.2006)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
11/066,370 25 February 2005 (25.02.2005) US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:
US 10/920,880 (CIP)
Filed on 17 August 2004 (17.08.2004)

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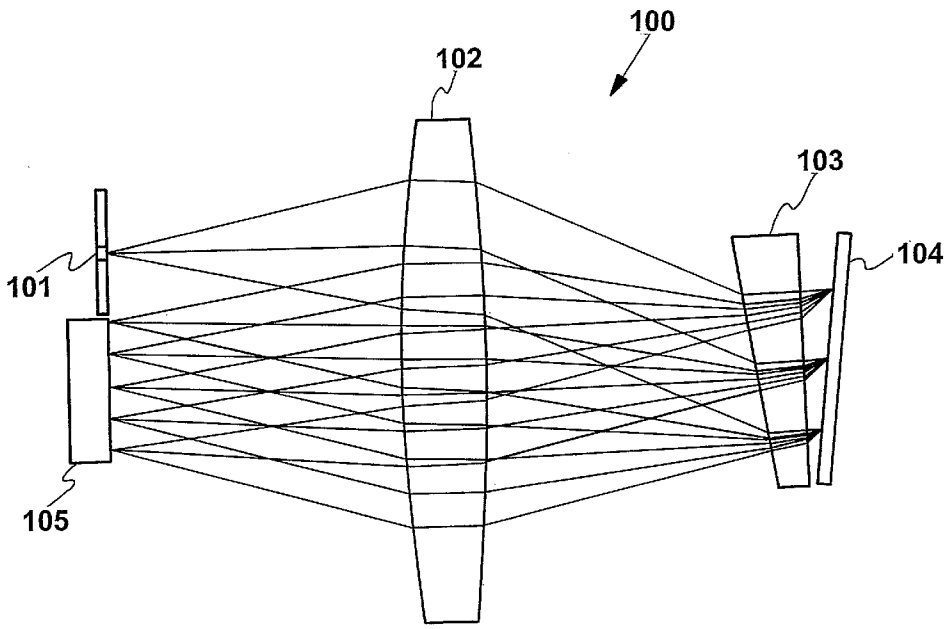
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US (patent), UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: COMPACT IMAGING SPECTROMETER



(57) Abstract: A compact imaging spectrometer comprises an entrance slit for transmitting light, a system for receiving the light and directing the light, a grating, and a detector array. The entrance slit, the system for receiving the light, the grating, and the detector array are positioned wherein the entrance slit transmits light to the system for receiving the light and the system for receiving the light directs the light to the grating and the grating receives the light and directs the light to the detector array.

WO 2007/102801 A1

Published:
— *with international search report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

COMPACT IMAGING SPECTROMETER

[0001] The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California for the operation of Lawrence Livermore National Laboratory.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] This application is a Continuation-in-Part of U.S. Patent Application No. 10/920,880 filed August 17, 2004 and titled, "Compact Imaging Spectrometer Utilizing Immersed Gratings." U.S. Patent Application No. 10/920,880 filed August 17, 2004, titled "Compact Imaging Spectrometer Utilizing Immersed Gratings," is incorporated herein by this reference.

BACKGROUND

Field of Endeavor

[0003] The present invention relates to a spectrometer and more particularly to a compact imaging spectrometer.

State of Technology

[0004] United States Patent No. 5,717,487 provides the following state of technology information: "A spectrometer is a known instrument for examining the spectral characteristics of light. Light emitted from or reflected by an object is received within the spectrometer and separated into its spectral components, such as the red, green and blue colored spectra as occurs in equal intensity when standard white light is so analyzed. The intensity of each such spectral component of that received light may be readily observed and measured. Each element of nature, molecular components, organic and inorganic compounds,

living plants, man, animal and other substances is known to emit a unique spectrum that may be used as an indicium to identify the emitter."

[0005] *United States Patent Application No. 20020135770* published September 26, 2003 provides the following state of technology information: "Imaging spectrometers have been applied to a variety of disciplines, such as the detection of defects in industrial processes, satellite imaging, and laboratory research. These instruments detect radiation from a sample and process the resulting signal to obtain and present an image of the sample that includes spectral and chemical information about the sample."

[0006] United States Patent No. 6,078,048 provides the following state of technology information: "In recent years substantial effort has been directed to the problem of detection of airborne chemicals. The remote detection of airborne chemicals issuing from exhaust stacks, vehicle exhaust, and various exhaust flumes or plumes, offers a non-intrusive means for detecting, monitoring, and attributing pollution source terms. To detect, identify, and quantify a chemical effluent, it is highly desirable to operate at the limiting spectral resolution set by atmospheric pressure broadening at approximately 0.1 cm^{-1}. This provides for maximum sensitivity to simple molecules with the narrowest spectral features, allows for corrections for the presence of atmospheric constituents, maximizing species selectivity, and provides greater opportunity to detect unanticipated species."

[0007] United States Patent No. 5,880,834 provides the following state of technology information: "There are three problems in designing an imaging spectrometer where light in a slice of an image field passing through an entrance slit is to be diffracted by a grating parallel to the slit and imaged onto

a focal plane for display or recording with good spatial resolution parallel to the slit and good spectral resolution perpendicular to the slit: 1. Eliminating astigmatism over the spectrum on the image plane. 2. Removing field curvature from the spectrum focused onto the image plane. 3. Obtaining good spatial resolution of the entrance slit which involves eliminating astigmatism at different field angles from points on the entrance slit."

SUMMARY

[0008] Features and advantages of the present invention will become apparent from the following description. Applicants are providing this description, which includes drawings and examples of specific embodiments, to give a broad representation of the invention. Various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this description and by practice of the invention. The scope of the invention is not intended to be limited to the particular forms disclosed and the invention covers all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

[0009] The present invention provides a compact imaging spectrometer with an immersive or reflective diffraction grating that compensates optical distortions. The imaging spectrometer comprises an entrance slit for transmitting light, a system for receiving the light and directing the light, an immersion grating, and a detector array. The entrance slit, the system for receiving the light, the immersion grating, and the detector array are positioned wherein the entrance slit transmits light to the system for receiving the light and the system for receiving the light directs the light to the immersion grating

and the immersion grating receives the light and directs the light through an optical element to the detector array.

[0010] The compact imaging spectrometer uses smaller cryogenic coolers facilitating its using in portable (man carried) gas detection systems and in small unmanned aerial vehicles for remote gas detection. These instruments have application for Homeland Defense to check for the presence of biological or chemical weapons without entering the contaminated areas. These instruments can be used for pollution detection, and remote sensing of agricultural crops, and geological identification. They can also be used for the remote monitoring of industrial processes.

[0011] The invention is susceptible to modifications and alternative forms. Specific embodiments are shown by way of example. It is to be understood that the invention is not limited to the particular forms disclosed. The invention covers all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The accompanying drawings, which are incorporated into and constitute a part of the specification, illustrate specific embodiments of the invention and, together with the general description of the invention given above, and the detailed description of the specific embodiments, serve to explain the principles of the invention.

FIG. 1 illustrates an embodiment of a compact imaging spectrometer constructed in accordance with the present invention utilizing a reflective grating with a prism to provide the distortion correction.

FIG. 2 illustrates another embodiment of a compact imaging spectrometer constructed in accordance with the present invention. In this design a reflective grating is utilized in conjunction with a catadioptric lens. The optical surfaces of the catadioptric lens have been tilted and decentered to provide the distortion correction.

DETAILED DESCRIPTION OF THE INVENTION

[0013] Referring now to the drawings, to the following detailed description, and to incorporated materials, detailed information about the invention is provided including the description of specific embodiments. The detailed description serves to explain the principles of the invention. The invention is susceptible to modifications and alternative forms. The invention is not limited to the particular forms disclosed. The invention covers all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

[0014] Referring now to FIG. 1 of the drawings, an embodiment of a compact imaging spectrometer constructed in accordance with the present invention is illustrated. This embodiment of the present invention is designated generally by the reference numeral 100. FIG. 1 is a raytrace of the imaging spectrometer 100. The structural elements of the compact imaging spectrometer 100 include an entrance slit 101, a dioptric lens 102, a prism 103, a reflective grating 104, and a detector 105.

[0015] The light passes from the entrance slit 101 to the dioptric lens 102 which collimates the light and sends it through the prism 103 to the reflective grating 104. The grating 104 disperses the light and sends it back through the prism 103 and on to the dioptric lens 102. The light is focused by the dioptric

lens 102 to the detector 105. The advantage of this design is that a conventional reflective grating 104 can be used, with the prism 103 providing the distortion correction. The grating can be generated by a ruling engine, replication, holographically, or by e-beam lithography. The prism 103 is tilted with respect to the grating to ensure that the ghost reflections from the additional optical surfaces do not fall on the detector. The imaging spectrometer 100 has been designed to the requirements in Table 1 and is diffraction limited over the wavelength range with excellent spatial and spectral resolutions.

Table 1

Spectral Range	7.5 – 13.5 microns
F-number (round or square)	4
Detector array	256 spatial x 256 spectral
Pixel Size	40 microns
Entrance Slit Length	10.24 mm
Spatial Distortion:	< 0.1 pixel (< ±2 microns)
Change in Spatial Mapping with Wavelength	
Spectral Distortion: Spectral Smile	*< 0.1 pixel (< ±2 microns)*
Optical Performance	Diffraction Limited
Ghosting	< 0.1% of the primary image

[0016] The spectral slit curvature has been corrected to less than one tenth of a pixel over the detector arrays. This is the curvature of slit image on the detector 105 at a single wavelength, which is a common problem with imaging spectrometer designs. The spatial mapping distortion has also been corrected to less than one tenth of a pixel over the full wavelength range. This means that the spectrum from a single point in the entrance slit will not wander from the center of a row of pixels by less than ± 2 microns. Correcting the spectral slit curvature and the spatial mapping distortion with wavelength to less than one

tenth of a pixel ensures that the images do not have to be resampled to correct for these effects.

[0017] The imaging spectrometer 100 has use for Homeland Defense to check for the presence of biological or chemical weapons without entering the contaminated areas. The imaging spectrometer 100 also has use for commercial remote sensing where portability is important. The imaging spectrometer 100 can be used for pollution detection, and remote sensing of agricultural crops, and geological identification among the various potential applications. The imaging spectrometer 100 can be used for the remote monitoring of industrial processes.

[0018] Small size for an imaging spectrometer is extremely important because it determines the requirements for the cryogenic cooling. For example, if the spectrometer is small it can fly in a small UAV. Also, if the spectrometer is small it is person portable. The imaging spectrometer 100 has a size envelope that is smaller than spectrometers currently in use. The entrance slit 101, dioptric lens 102, prism 103, reflective grating 104, and detector 105 fit within the envelope. The X axis and the Y axis are shown in the plane of the paper. The Z axis extends perpendicular to both the X axis and the Y axis. The envelope is 3.2 cm by 2.0 cm by 1.5 cm or smaller. As shown in FIG. 1, the X axis is 3.2 cm, the Y axis is 2.0 cm, and the Z axis is 1.5 cm. The compact imaging spectrometer 100 has a front and a back. The entrance slit 101 is located at or near the font and the grating 103 is located at or near the back.

[0019] Referring now to FIG. 1 of the drawings, an embodiment of a compact imaging spectrometer constructed in accordance with the present invention is illustrated. This embodiment of the present invention is designated

generally by the reference numeral 200. FIG. 2 is a raytrace of the imaging spectrometer 200. The structural elements of the compact imaging spectrometer 200 include an entrance slit 201, a catadioptric lens 204, a reflective grating 203, and a detector 205.

[0020] The light passes from the entrance slit 201 to the catadioptric lens 204. The light passes through the catadioptric lens 204 and is reflected back through the lens by the immersed mirror surface 202. The light from the catadioptric lens is received by the reflective grating 103. The reflective grating 203 disperses the light and sends it back through the catadioptric lens 204. which focuses the light onto the detector 205.

[0021] The advantage of this design is that a conventional reflective grating 203 can be used, with the catadioptric lens 204 providing distortion correction from its tilted and decentered surfaces. The lens 204 can be generated by diamond turning, in the current design the full aperture surface is a rotational asphere, the immersed mirror surface is spherical and tilted, and the final surface is a tilted and decentered rotational asphere. The grating 203 can be generated by a ruling engine, replication, holographically, or by e-beam lithography. The imaging spectrometer 200 has been designed to the requirements in Table 1 and is diffraction limited over the wavelength range with excellent spatial and spectral resolutions.

[0022] The spectral slit curvature has been corrected to less than one tenth of a pixel over the detector arrays. This is the curvature of slit image on the detector 105 at a single wavelength, which is a common problem with imaging spectrometer designs. The spatial mapping distortion has also been corrected to less than one tenth of a pixel over the full wavelength range. This means that

the spectrum from a single point in the entrance slit will not wander from the center of a row of pixels by less than ± 2 microns. Correcting the spectral slit curvature and the spatial mapping distortion with wavelength to less than one tenth of a pixel ensures that the images do not have to be resampled to correct for these effects.

[0023] Small size for an imaging spectrometer is extremely important because it determines the requirements for the cryogenic cooling. For example, if the spectrometer is small it can fly in a small UAV. Also, if the spectrometer is small it is person portable. The imaging spectrometer 200 has a size envelope that is smaller than spectrometers currently in use. The entrance slit 201, catadioptric lens 204, reflective grating 203, and detector 204 fit within the envelope. The X axis and the Y axis are shown in the plane of the paper. The Z axis extends perpendicular to both the X axis and the Y axis. The envelope is 6.1 cm by 5.0 cm by 2.5 cm or smaller. As shown in FIG. 1, the X axis is 5.0 cm, the Y axis is 6.1 cm, and the Z axis is 2.5 cm.

[0024] The imaging spectrometer of the present invention has many uses. Examples of its use include use in Homeland Defense to check for the presence of biological or chemical weapons without entering the contaminated areas. The imaging spectrometer also has use for commercial remote sensing where portability is important. The imaging spectrometer can be used for pollution detection and remote sensing of agricultural crops. It can be used for geological identification and for the remote monitoring of industrial processes. These are examples of the various potential applications of the imaging spectrometer of the present invention.

[0025] While the invention may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the following appended claims.

THE INVENTION CLAIMED IS

1. A compact imaging spectrometer apparatus, comprising:

an entrance slit for transmitting light,

a spherical surface,

a reflective grating, and

a detector array,

said entrance slit, said spherical surface, said reflective grating, and said detector array positioned are wherein

said entrance slit transmits light to said to said spherical surface, said spherical surface directs said light to said reflective grating, and said reflective grating directs said light to said detector array.

2. A compact imaging spectrometer apparatus, comprising:

entrance slit means for transmitting light,

spherical surface means for directing light,

reflective grating means for directing light, and

detector array means,

said entrance slit means, said spherical surface means, said reflective grating means, and said detector array means are positioned wherein

said entrance slit means transmits light to said to said spherical surface means, said spherical surface means directs said light to said reflective grating means, and said reflective grating means directs said light to said detector array means.

3. A compact imaging spectrometer apparatus, comprising:

an entrance slit for transmitting light,

a dioptric lens,

a prism,

a reflective grating, and

a detector array,

said entrance slit, said dioptric lens, said prism, said reflective grating, and said a detector array positioned wherein

said entrance slit transmits light to said to said dioptric lens and

said dioptric lens directs said light to said prism and

said prism receives the light and directs to said reflective grating ,

said reflective grating directs said light to said dioptric lens, prism, and detector array.

4. The compact imaging spectrometer apparatus of claim 3 wherein said reflective grating is fabricated by conventional ruling, by holographic means, or by e-beam lithography.

5. A compact imaging spectrometer apparatus, comprising:

an entrance slit for transmitting light,

a catadioptric lens for directing light,

a reflective grating for directing light, and

a detector array,

said entrance slit, said catadioptric lens, said reflective grating, said rotational asphere, and said detector array are positioned wherein

said entrance slit transmits light to said to said catadioptric lens, the said light is transmitted through the front rotationally aspheric surface to the immersed mirror surface, which is a spherical surface, said immersed mirror surface reflects the said light out through the said rotational aspheric surface to the said reflective grating, said reflective grating directs and disperses said

light back to said catadioptric lens and the light enters the lens through the said front rotational aspheric surface and exits the said lens through the back surface which has a rotational aspheric form, and said catadioptric lens focuses and directs the said light to said detector array means.

6. The compact imaging spectrometer apparatus of claim 5 wherein the said spherical mirror surface of the said catadioptric lens is tilted.

7. The compact imaging spectrometer apparatus of claim 5 wherein said rotational asphere back surface of said catadioptric lens is tilted and decentered.

8. The compact imaging spectrometer apparatus of claim 5 wherein said surfaces of the said catadioptric lens have their forms changed to spherical, conic or general aspheric surfaces to improve the imaging properties.

9. The compact imaging spectrometer apparatus of claim 5 wherein said surfaces of the said catadioptric lens are tilted and decentered to correct the spectral and spatial distortion and to improve the imaging properties.

10. The compact imaging spectrometer apparatus of claim 5 wherein said reflective grating is ruled on a rotational aspheric surface or generalized aspheric surface.

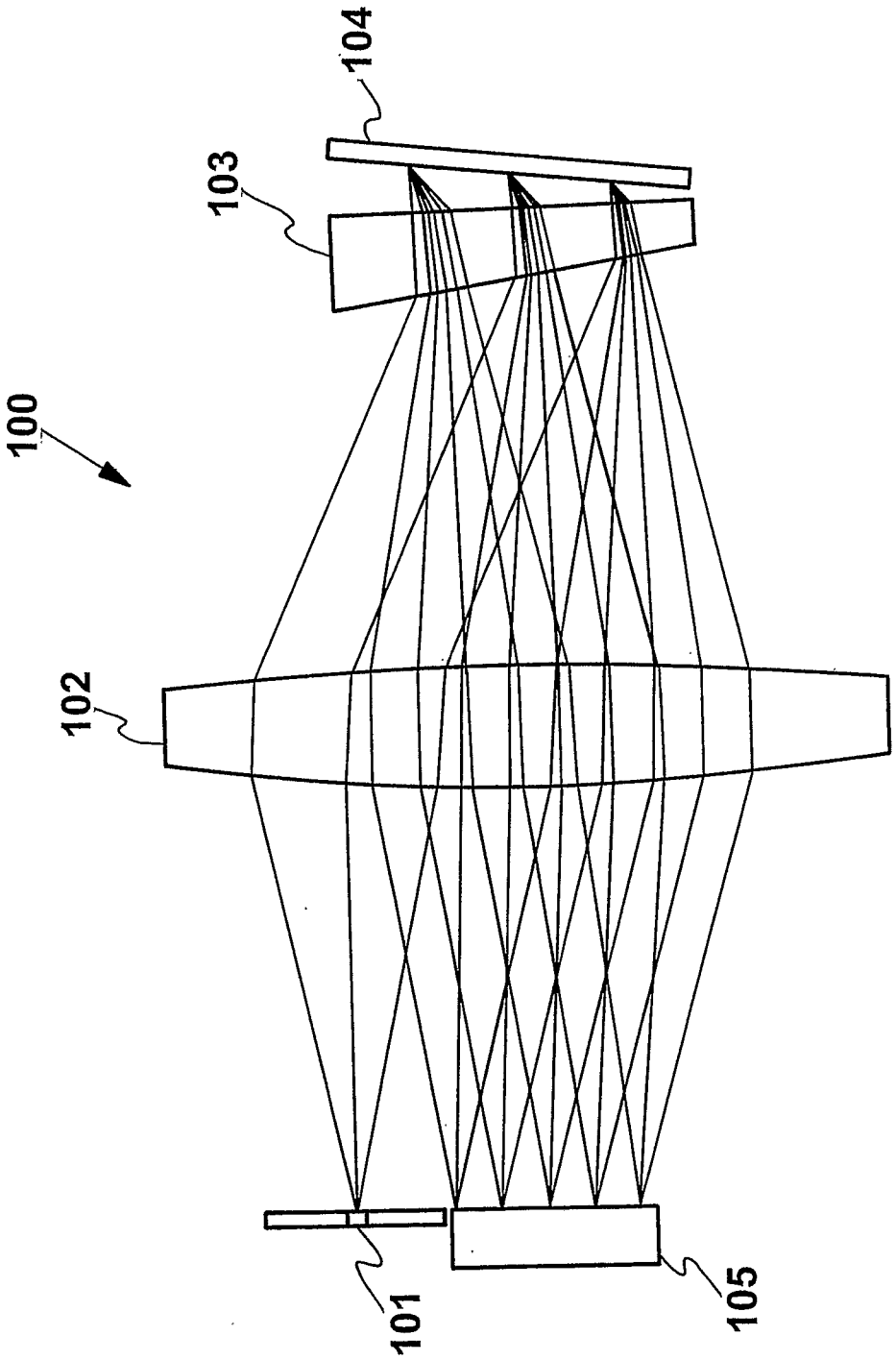


FIG. 1

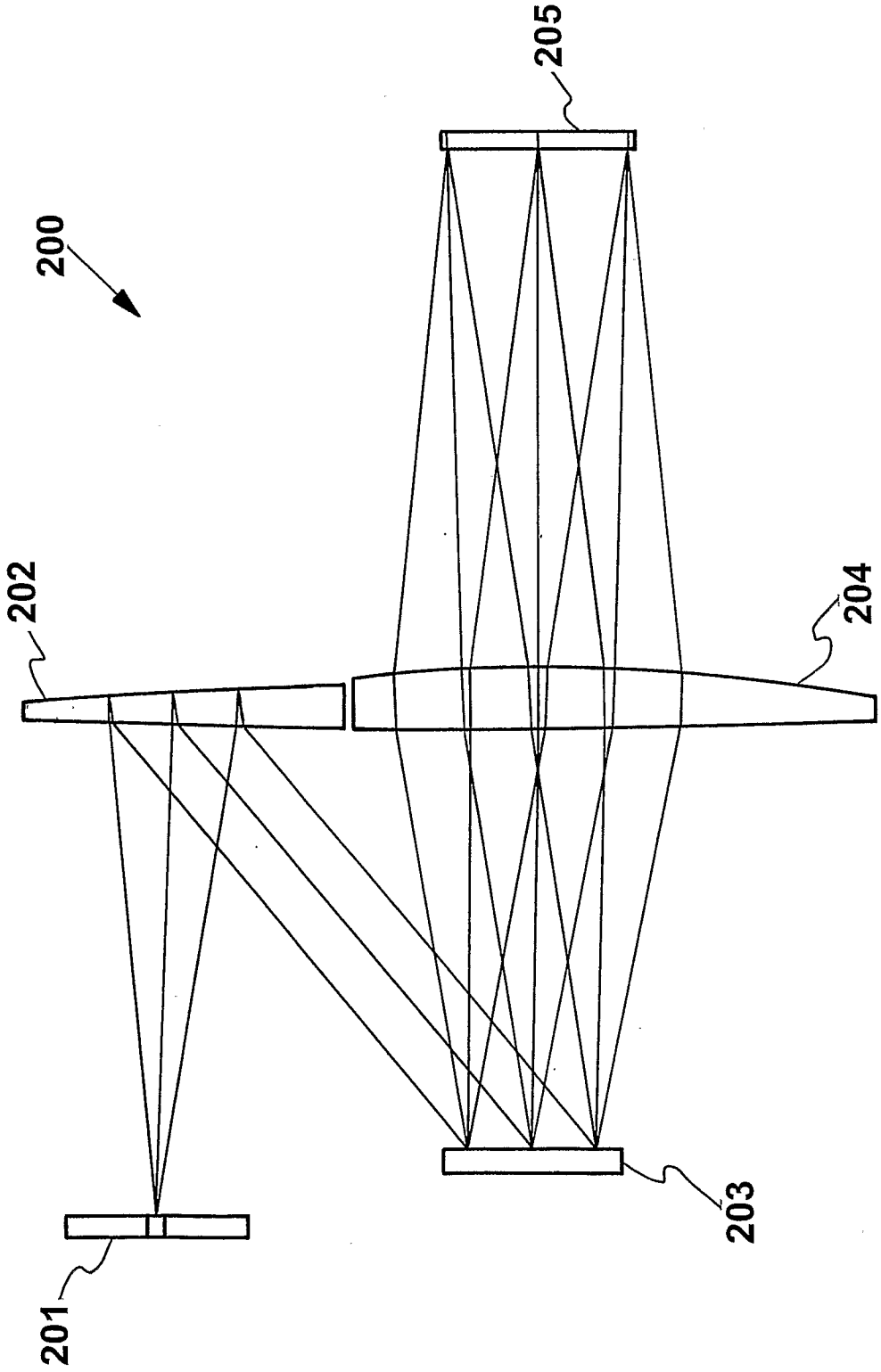


FIG. 2

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2006/006765

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01J3/28 G01J3/18

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)
G01J

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

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, WPI Data, PAJ, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 880 834 A (CHRISP ET AL) 9 March 1999 (1999-03-09) cited in the application	1,2
A	figure 1b column 3, line 60 - column 4, line 12	3-10
P,X	US 2005/073680 A1 (CHRISP MICHAEL P ET AL) 7 April 2005 (2005-04-07) figure 5 paragraph [0055] - paragraph [0056]	1,2
A	US 6 078 048 A (STEVENS ET AL) 20 June 2000 (2000-06-20) cited in the application figure 1 column 4, line 41 - column 5, line 14	3,4

☐ 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 document 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
24 May 2006	06/06/2006

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2006/006765

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5880834 A	09-03-1999	NONE	
US 2005073680 A1	07-04-2005	US 2005259253 A1	24-11-2005
US 6078048 A	20-06-2000	NONE	