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(54) **METHOD AND APPARATUS FOR MANUFACTURING PURELY REFRACTIVE OPTICAL STRUCTURES**

(57) The present invention proposes a method for the manufacture of refractive optical elements in a simple and economical manner. This method includes the following steps: (a) placing a substrate close to a white material, both arranged inside a chamber; (b) vaporizing or subliming the white material by light means; and (c) depositing this vapour phase on the substrate. The coating deposited has a refractive optical functionality on account of its composition and profile and also presents an increase in the threshold of damage at high light intensities.

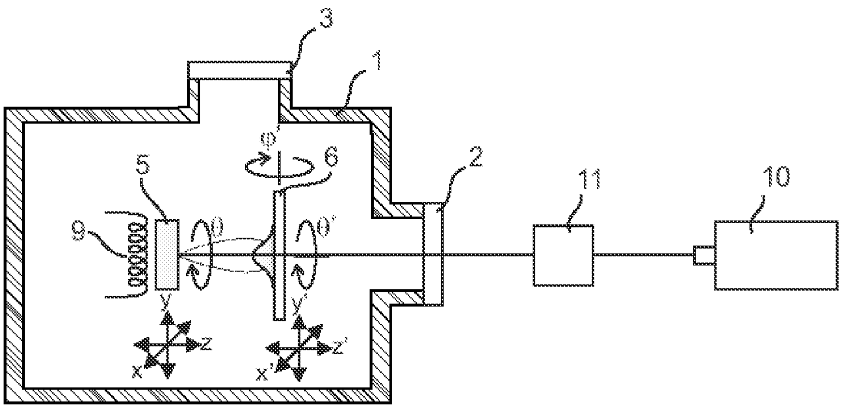

Fig. 4

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Description

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[0001]

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US 5345336	9/1994	Aoyama et al.
US 5737126	4/1998	Lawandy
US 6110291	8/2000	Haruta et al.
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[0003] A. Zakery, Y. Ruan, A. V. Rode, M. Samoc and B. Luther-Davies, "Low-loss waveguides in ultrafast laser-deposited As2S3 chalcogenide films", J. Opt. Soc. Am. B 20 (2003) 1844.

FIELD OF THE INVENTION

[0004] The present invention lies within the field of optical elements with refractive functions, and methods of manufacturing them.

PRIOR ART

[0005] Optical elements are very important in all technological fields where it is necessary to modulate the spatial distribution of light. Bearing in mind this requirement, it is necessary to optimise techniques of manufacturing simple optical structures and producing optical structures with new functions. Most of the methods used to manufacture refractive optical elements on a medium-sized scale use repeated cutting and polishing processes, or heated moulding processes [US 6668588 B1], prior to more complex subsequent treatments. Alternatively, different processes have been developed to manufacture elements on a small scale, based on complex multiple surface micromachining, or photolithography steps [US 5345336], and more recent methods that propose the ablation of plastic or glass surfaces [US 5053171], or the heat-assisted structural modification of semiconductor doped glass surfaces [US 5737126] using lasers. Furthermore, due to their connection with the invention disclosed and claimed herein, it is also important to mention methods of light-assisted deposits that are used in planar technology production processes [US 6110291], the aim of which is to create a uniform layer of conductor, semiconductor or superconductor compounds on a substrate to form active and passive optical devices [US 6924457 B2] and/or planar electronic devices.

[0006] The present invention discloses a simple method of manufacturing refractive optical elements, which is based on the light-assisted control of the profile of a semiconductor material that will be deposited on a substrate that is transparent to the working radiation for which the optical element to be manufactured is designed. The method makes it possible to extend the functions of the optical elements that are manufactured so that they may be used at high light intensities.

To the applicants' understanding, the patents cited in this section are, within the scope of our search, those that cover the most relevant inventive activities within the context of that disclosed herein, and the inventive activity claimed by the applicants for the present invention can be demonstrated on the basis of these patents.

BASIS OF THE INVENTION

[0007] The present invention discloses a simple, although not obvious, method for the light-assisted manufacturing of optical elements, which is based on the following physical facts:

1. Structural fragments of the constituent elements of semiconductor compounds can be ejected from a solid when they are irradiated with light whose photon energy is comparable (in the order of magnitude) to its optical gap, with a high enough intensity. This intensity depends on the type of semiconductor material.
2. The vapour phase, or plasma plume, that is generated condenses on a substrate located in the proximity of the starting material, causing this material to be deposited on the substrate.
3. The morphology of the deposit is related to the characteristics of the plume or vapour phase, which depend on the spatial light intensity distribution on the target material, the spectral radiance of the light source, the distance between the target material and the substrate, the pressure and the atmosphere in the chamber, the temperature of the starting material, the temperature of the substrate, and the irradiation time.
4. Concurrent illumination of the deposit during its growth may affect the physicochemical properties of the material that forms said deposit, as a consequence of its effect on the structure being formed.

[0008] On the basis of the aforementioned facts, the applicants of the present patent propose a simple but not obvious method of manufacturing refractive optical structures.

[0009] In a preferred embodiment of the invention, which is not limiting in terms of the material used or the configuration of the manufacturing system, a continuous laser beam, with a wavelength of 532 nm and a Gaussian light intensity distribution, perpendicularly crosses a transparent substrate with planoparallel sides before reaching a target material situated a few millimetres from the substrate. Said target material is a disc (wafer) with a diameter of around 1 cm and a thickness of 2 mm, made from compacted powder of an amorphous V-VI semiconductor alloy (e.g. an alloy of As and S), which is sensitive to the photon energy of light radiation from a Nd:YAG laser (2.33 eV). The sides of the substrate and the wafer that face each other are parallel.

[0010] The above-described configuration produces a deposit with an aspheric profile that generates an optical function as shown in Figure 1, which is characteristic of optical elements called axicons [McLeod]. Axicons, as shown in Figure 2, unlike lenses with conventional spherical profiles, are characterised in that they concentrate light energy along a focal segment that extends along the optical axis, and their lateral resolution remains constant to propagation on this focal segment.

[0011] The transparency of V-VI semiconductors in the infrared (IR) spectral region [Kolobov and Tanaka] guarantees the stability of the optical elements manufactured in this spectral window, therefore making it the preferred working spectral region.

[0012] However, the applicants of the present patent have observed that the optical elements produced according to the above-described preferred embodiment present a greater optical transparency and a higher damage threshold to the laser radiation used in the manufacturing process compared to that of the starting material, possibly due to concurrent uniform illumination of the material being deposited. In experiments, an increase of more than one order of magnitude has been observed in the damage intensity in alloys with a composition of $As_{20}S_{80}$, in relation to the intensity supported by the starting material.

[0013] Furthermore, due to its relevance to the present invention, it has been shown [Zakery et al.] that coating an amorphous chalcogenide deposit with a layer of polymethyl methacrylate (PMMA) increases by several orders of magnitude the damage threshold to radiation for which the chalcogenide alloy would be sensitive without any coating.

[0014] In view of such facts, both of our own and reported in the literature, it can be inferred that although the IR region is the preferred window, it should not be considered the only one.

DESCRIPTION OF THE FIGURES

[0015]

FIGURE 1. Light intensity distribution along the focal axis corresponding to an axicon manufactured according to the present invention, using an amorphous alloy with a composition of $As_{20}S_{80}$. The distances are measured in relation to the position of the axicon. A lateral resolution of ~ 60 μm is achieved at a distance of 35 mm from the axicon, and is maintained up to 45 mm, the position from which the energy begins to couple to higher modes than the zero order mode. The wavelength of the laser radiation used in these measurements was 532 nm.

FIGURE 2. Diagram showing how an extended focal lens (axicon) works. This spherical optical element presents a focal region on the optical axis with a high lateral resolution (of the order of microns) and a long depth of focus, Δf, from an initial focusing distance f_0. The light intensity distribution at different distances along the optical axis is also shown.

FIGURE 3. Cross-sectional diagram of the system for producing refractive optical elements according to the present invention, in a basic configuration wherein a light beam falls on the starting material at oblique incidence.

It shows:

1.- Chamber.
2 and 3.- Transparent windows in the chamber.
4.- Source of light radiation.
5.- Starting material.
6.- Substrate.
7.- Combination of optical and/or mechanical elements.
8.- Mirror.
9.- Heater.

FIGURE 4. Cross-sectional diagram of the system for producing refractive optical elements according to the present invention, in a basic configuration wherein a light beam falls on the starting material at normal incidence, after crossing a transparent substrate.

It shows:

1.- Chamber.
2 and 3.- Transparent windows in the chamber.
5.- Starting material.
6.- Substrate.
9.- Heater.
10.- Source of light radiation.
11.- Combination of optical and/or mechanical elements.

FIGURE 5. Cross-sectional diagram of the system for producing refractive optical elements according to the present invention, in a basic configuration wherein two light beams fall on the starting material, one with normal incidence to the starting material, which crosses the substrate, and a second light beam that falls obliquely on the material without crossing the substrate.

It shows:

1.- Chamber.
2 and 3.- Transparent windows in the chamber.
4.- Source of light radiation.
5.- Starting material.
6.- Substrate.
7.- Combination of optical and/or mechanical elements.
8.- Mirror.
9.- Heater.
10.- Source of light radiation.
11.- Combination of optical and/or mechanical elements.

DESCRIPTION OF THE INVENTION

[0016] The present invention proposes a method for manufacturing refractive optical elements in a simple and economical way. This method includes the following steps: (a) situating a substrate close to a target material, both of which are situated inside a chamber, (b) using a light source to bring about the vaporisation or sublimation of the target material and (c) depositing this vapour phase on the substrate. The deposit presents a refractive optical function due to its composition and profile, as well as an increase in the damage threshold at high light intensities.

[0017] The objects of the present invention are as follows:

- to provide a simple method of manufacturing optical elements with a refractive function,
- to provide a method of manufacturing refractive optical elements using light radiation,
- to provide a method of manufacturing aspheric refractive optical elements,
- to provide a method of manufacturing optical elements with a refractive function, without revolution symmetry,
- to provide a method of manufacturing refractive optical elements with extended functions at high light intensities.

[0018] Figure 3 shows a first preferred embodiment according to the proposed method for manufacturing optical elements with a refractive function. With reference to this figure, the system consists of a chamber 1 with transparent windows 2 and 3, and a source of continuous or pulsed light radiation 4, a starting material 5, and a substrate 6 which is transparent to the working radiation for which the optical element to be manufactured is designed. The spatial intensity distribution on the starting material is controlled by a combination of optical (lenses, mirrors, filters, masks, spatial light, phase and amplitude modulators, etc.) and/or mechanical (linear positioning stages, angular positioning stages, mechanical spatial light modulators, etc.) elements 7. The light beam from 4 enters the chamber through the window 3, after falling on the mirror 8. The mirror 8 is mounted on translation and rotary positioning stages that give it degrees of freedom to control, in combination with 7, the light intensity distribution on the starting material. The ejection of the starting material is induced by the light radiation from 4, via the mirror 8, and it can be assisted by heat from a heater 9. The deposition can also be thermally assisted by supplying heat to the substrate, in a similar way to 9 (not shown in Figure 3). The deposition is carried out at a controlled pressure and atmosphere.

[0019] The starting material 5, which is situated inside the chamber, can be an ingot of a semiconductor alloy, or a wafer made from the alloy to be deposited in powder form. The wafer can be a heterogeneous mixture of semiconductor alloys and other reactants, which act as both passive and active elements for a determined light radiation. The starting material is supported by a combination of mechanical elements that give it freedom to move in the three Cartesian directions, x, y, z, and to rotate around an axis that is perpendicular to its surface, θ.

[0020] The substrate 6 is supported by a combination of mechanical elements. The substrate is thus free to move in the three Cartesian directions, x', y', z', as well as to rotate around an axis that is perpendicular to its surface, θ', and around an axis that is parallel to its surface, φ', in a way that is not integral to the starting material.

[0021] Figure 4 shows a second preferred embodiment according to the proposed method for manufacturing optical elements with a refractive function. With reference to this figure, and similarly to that described for Figure 3, the system consists of a chamber 1 with transparent windows 2 and 3, and a source of continuous or pulsed light radiation 10, a starting material 5, and a substrate 6 which is transparent to the radiation from 10, and also transparent to the working radiation for which the optical element to be manufactured is designed. The spatial intensity distribution on the starting material is controlled by a combination of optical (lenses, mirrors, filters, masks, spatial light, phase and amplitude modulators, etc.) and/or mechanical (linear positioning stages, angular positioning stages, mechanical spatial light modulators, etc.) elements 11. The light beam from 10 enters the chamber through the window 2, and crosses the substrate 6 before falling on the starting material 5, causing its ejection. The generation of this plume can be assisted by heat from a heater 9. The deposition can also be thermally assisted by supplying heat to the substrate, in a similar way to 9 (not shown in Figure 4). The deposition is carried out at a controlled pressure and atmosphere.

[0022] Figure 5 shows a third preferred embodiment according to the proposed method for manufacturing optical elements with a refractive function. With reference to this figure, and similarly to that described for Figures 3 and 4, the system consists of a chamber 1 with transparent windows 2 and 3, two sources of continuous or pulsed light radiation 4 and 10, a starting material 5, and a substrate 6 which is transparent to the radiation from 10, and also transparent to the working radiation for which the optical element to be manufactured is designed. The spatial intensity distribution on the starting material is controlled by a combination of optical (lenses, mirrors, filters, masks, spatial light, phase and amplitude modulators, etc.) and/or mechanical (linear positioning stages, angular positioning stages, mechanical spatial light modulators, etc.) elements 7, and a combination of optical (lenses, mirrors, filters, masks, spatial light, phase and amplitude modulators, etc.) and/or mechanical (linear positioning stages, angular positioning stages, mechanical spatial light modulators, etc.) elements 11. The light beam from 4 enters the chamber through the window 3, after falling on the mirror 8. The mirror 8 is mounted on translation and rotary positioning stages that give it degrees of freedom to control, in combination with 7, the light intensity distribution on the starting material. The light beam from 10 enters the chamber through the window 2, and crosses the substrate 6 before falling on the starting material 5. The beam from 4 and the beam from 10 do not necessarily fall on the same area of the starting material. The generation of the plume can be assisted by heat from a heater 9. The deposition can also be thermally assisted by supplying heat to the substrate, in a similar way to 9 (not shown in Figure 4). The deposition is carried out at a controlled pressure and atmosphere.

[0023] The systems shown in Figures 4 and 5 involve the uniform illumination of the deposit during its growth. This concurrent uniform irradiation may modify the properties of the material being deposited, depending on its nature and the characteristics of the light radiation that falls on it. This may produce, for instance, a more stable material, with a higher damage threshold, and it may therefore extend its functions at high light intensities, as has been described above on the basis of experimental results.

[0024] A real embodiment is described below to illustrate the use of the present invention for manufacturing a refractive axicon that is stable and highly transparent in the IR region. The starting material, in this case, is a circular wafer with a 13 mm diameter, made from 125 mg of powder, compacted for 10 minutes with a 10-tonne load, of an amorphous chalcogenide alloy with a composition of $As_{20}S_{80}$, which presents an optical gap of 2.1 eV. The pressure in the chamber is reduced to below 10^{-4} mbar. The light radiation comes from a Nd:YAG continuous laser generator emitting at 532 nm (2.33 eV), with a power of 400 mW. The laser beam induces the ejection of the starting material by ablating the surface of the wafer, generating a distribution of the vapour phase in the form of a spindle (plume), which is perpendicular to the irradiated surface of the wafer. The transparent substrate is situated inside the chamber, in the path of the light beam, at 2 mm from the starting material, so that the beam crosses both sides of the substrate before falling on the starting material. The vapour phase of the starting material condenses on the side of the substrate that faces this material, presenting an aspheric spatial distribution on its surface, which has an optical function as shown in Figure 1.

[0025] The conditions of the system may be adjusted to deposit a uniform profile or a profile of a variable thickness, concentrated on a localised region of the substrate or extended across it arbitrarily. The area covered by the deposit and the thickness profiles may be controlled by moving the light beam over the surface of the starting material and/or the substrate by means of the positioning stages that give the starting material and the substrate the degrees of freedom x, y, z, θ, x', y', z', θ'', φ'', respectively, which are shown in the diagrams in Figures 3, 4 and 5.

Claims

1. Method and apparatus for manufacturing optical elements with a purely refractive function due to their composition and non-uniform profile, **characterised by**: (a) situating a substrate, which is transparent to the working radiation for which the optical element to be manufactured is designed, close to a starting material, both of which are situated inside a chamber, (b) using a light source to bring about the vaporisation or sublimation of the starting material and (c) depositing this vapour phase on the substrate.

2. Method and apparatus for manufacturing optical structures with a purely refractive function by means of a light-assisted structured deposition, according to claim 1, **characterised in that** the light radiation involved in the process is continuous or pulsed.

3. Method and apparatus for manufacturing optical structures with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 and 2, **characterised in that** the light radiation involved in the process is monochromatic or polychromatic.

4. Method and apparatus for manufacturing optical structures with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 to 3, **characterised in that** the light radiation involved in the process is coherent or incoherent.

5. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 to 4, **characterised in that** the starting material can be an ingot or a wafer made from the pressed powder of the material to be deposited.

6. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 to 5, **characterised in that** the starting material can be a homogeneous or heterogeneous mixture of semiconductor alloys containing a chalcogen element (O, S, Se and/or Te) and other reactants (e.g. Ge, Ga, Si, P, As, Sb, I, Pm, Sm, Eu, Er, etc.), which act as both passive and active elements for a determined light radiation.

7. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 to 6, **characterised in that** the process is carried out with a controlled pressure and atmosphere.

8. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 to 7, **characterised in that** the vapour or plasma phase present in the process may result from the evaporation and/or sublimation of the starting material by means of the joint action of heating and light radiation.

9. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 to 8, **characterised in that** the temperature of the substrate may be different from room temperature.

10. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 to 9, **characterised in that** a light beam uniformly irradiates the deposit during its growth in order to increase the stability of the optical device at high working light intensities.

11. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 to 10, **characterised in that** the light radiation involved in the process and the plume of the starting material that is ejected may be collinear.

12. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 to 11, **characterised in that** the refractive optical element that is manufactured may present an optical function corresponding to an axicon-type aspheric lens.

13. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 1 to 7, which comprises:

a) a chamber with transparent windows,
b) a vacuum system,
c) a source of light radiation,
d) a combination of mechanical elements, situated inside the chamber, which support the starting material and which give it the freedom to move in the three Cartesian directions, x, y, z, as well as to rotate around an axis that is perpendicular to its surface, θ.
e) a combination of mechanical elements, situated inside the chamber, which support the substrate and give it the freedom to move in the three Cartesian directions, x', y', z', as well as to rotate around an axis that is perpendicular to its surface, θ', and around an axis that is parallel to its surface, φ', in a way that is not integral to the starting material,
f) a combination of optical (lenses, mirrors, filters, beam splitters, masks, spatial light, phase and amplitude modulators, etc.) and/or mechanical (linear positioning stages, angular positioning stages, mechanical spatial light modulators, etc.) elements, situated inside the chamber, which control the spatial light intensity distribution on the starting material.

14. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 7 and 13, **characterised in that** it has a system of injecting gases (e.g. He, Ne, Ar, H_3As, H_2S, H_2Se, etc.).

15. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 8 and 13, **characterised in that** it has a heat source for the starting material.

16. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 9 and 13, **characterised in that** it has a heat source for the substrate.

17. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a light-assisted structured deposition, according to claims 10 to 13, **characterised in that** it has an additional source of light radiation that uniformly irradiates the deposit during its growth.

18. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a structured light-assisted deposition, according to claim 17, **characterised in that** the light radiations present in the process are the same in terms of their coherence, chromaticity and time regime (pulsed or continuous).

19. Method and apparatus for manufacturing optical elements with a purely refractive function by means of a structured light-assisted deposition, according to claim 17, **characterised in that** the light radiations present in the process are different in terms of their direction of propagation, intensity, coherence, chromaticity and time regime (pulsed or continuous).

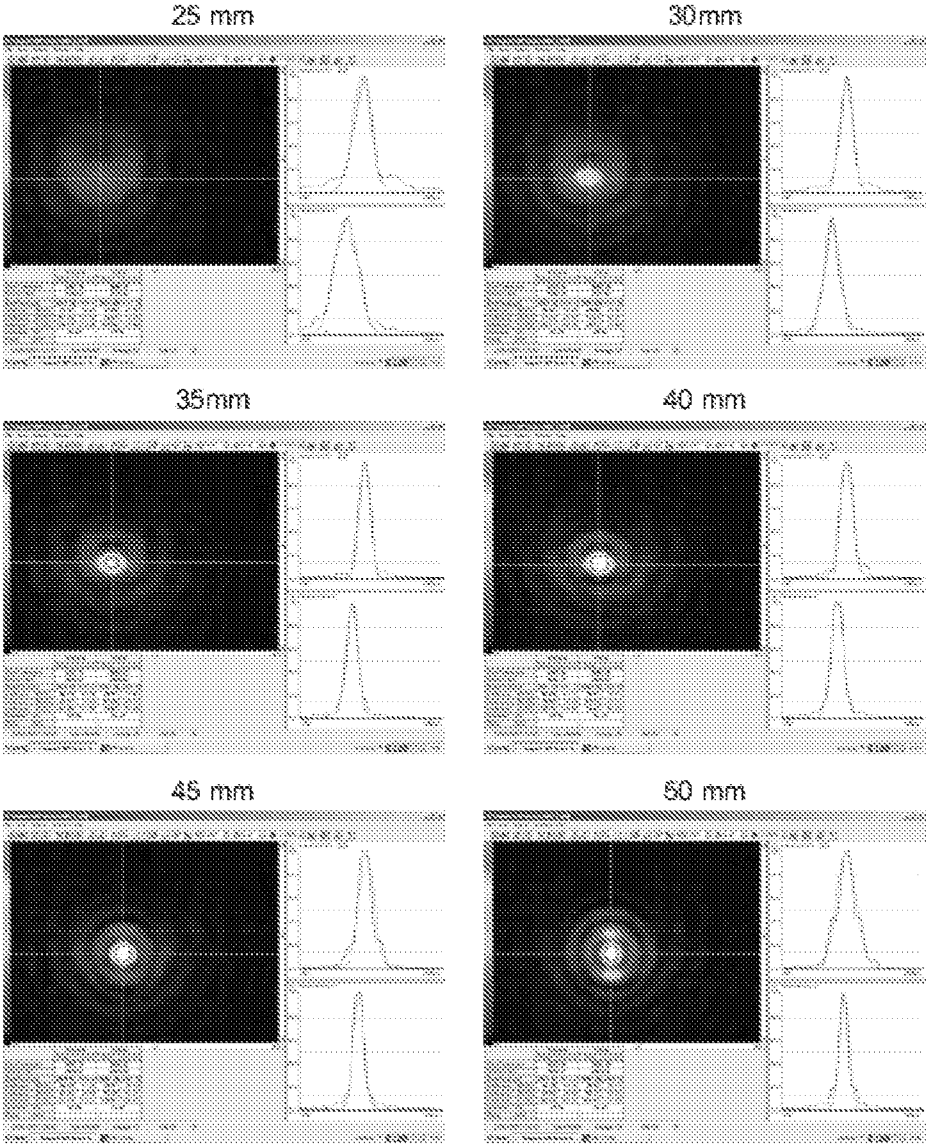

Fig. 1

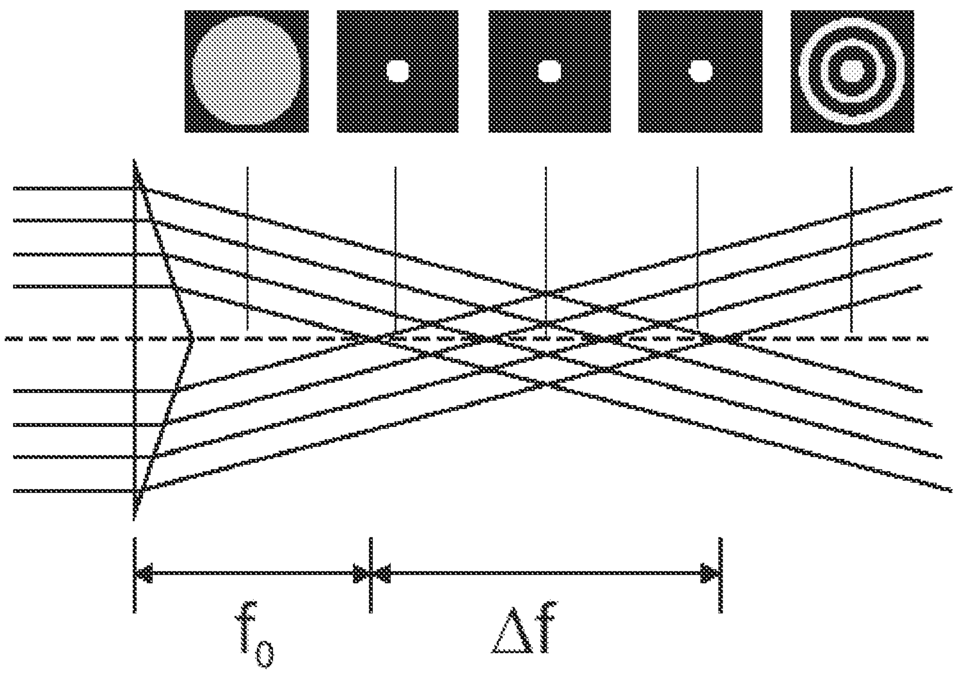

Fig. 2

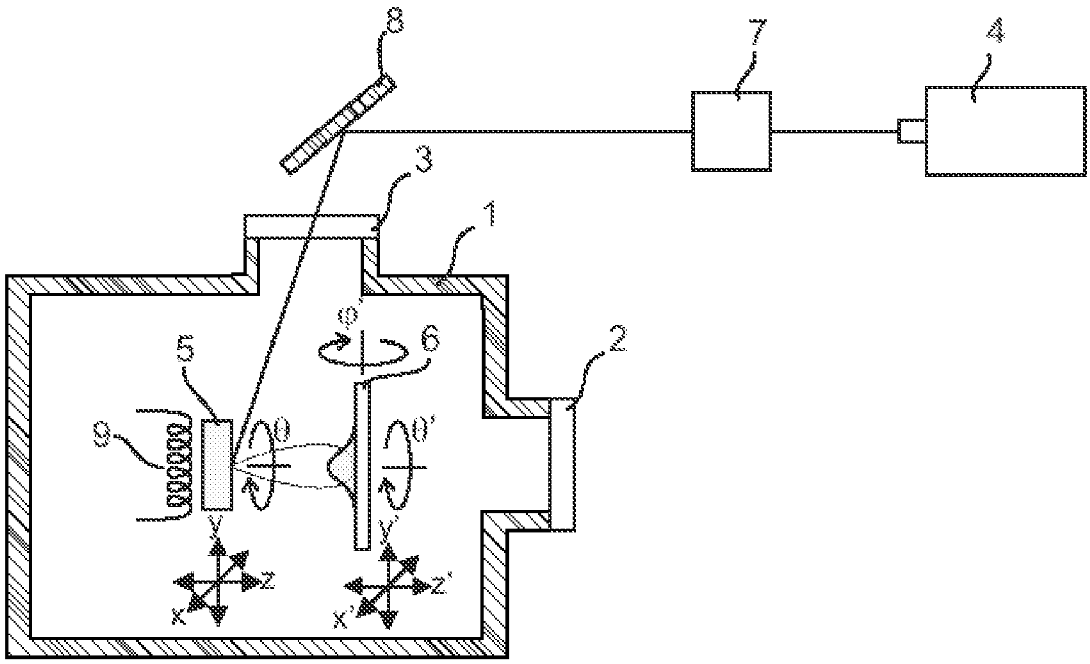

Fig. 3

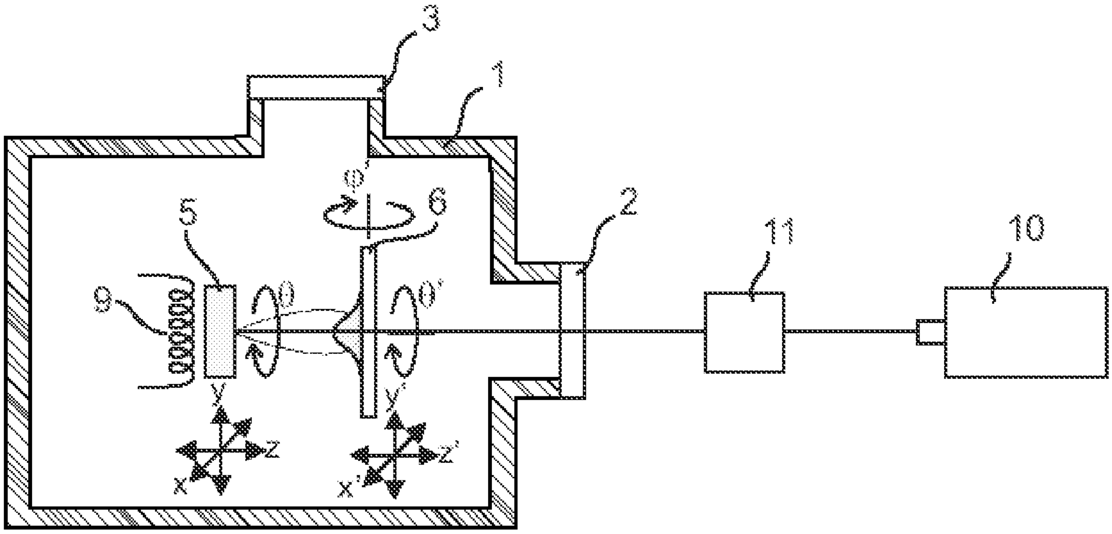

Fig. 4

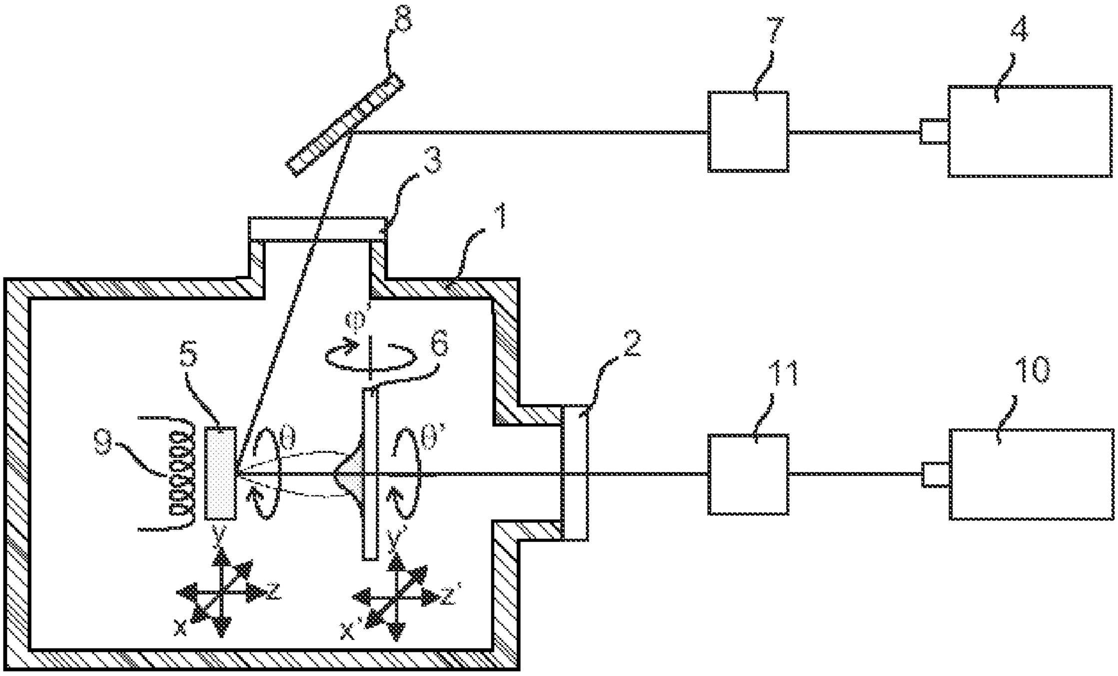

Fig. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/ ES 2007/000053

A. CLASSIFICATION OF SUBJECT MATTER

see extra sheet

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)
C23C

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 practicable, search terms used)

OEPMPAT, EPODOC, WPI

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X	US 5760366 A (HARUTA et al.) 02.06.1998, column 1, line 1 - column 4, line 48; column 10, lines 20-63; column 12, lines 55-67;column 23, line 25 - column 25, line 22;column 28, line 54 - column 31, line 57;column 33, line 18 - column 34, line 11;column 74, line 43 - column 75, line 20; figures 1-14. figures 20-28. figure 32, figure 44, abstract;	1-4,7-9, 13-19
X	BASE DE DATOS WPIL in QUESTEL, JP 4045263 A 14.02.1992; abstract; figures.	1,3,7,13-16
A	WO 0044960 A (CHRISEY et al.) 03.08.2000, the whole the document.	1-8
A	US 5737123 A (LAWANDY) 07.04.1998, the whole the document.	1-6,10-16

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

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Date of the actual completion of the international search	Date of mailing of the international search report
30 May 2007 (30.05.2007)	(04/06/2007)
Name and mailing address of the ISA/ O.E.P.M. Paseo de la Castellana, 75 28071 Madrid, España. Facsimile No. 34 91 3495304	Authorized officer A. Navarro Farell Telephone No. +34 91 349 53 94

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/ES 2007/000053

C (continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US 6924457 A (KOYAMA et al) 02.08.2005,	-

Form PCT/ISA/210 (continuation of second sheet) (April 2007)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/ ES 2007/000053

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CLASSIFICATION OF SUBJECT MATTER

C23C 14/02 (2006.01)
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