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(54) **TRANSMISSIVE OPTICAL DEVICE, LASER CHAMBER, AMPLIFIER STAGE LASER DEVICE, OSCILLATION STAGE LASER DEVICE AND LASER APPARATUS**

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(52) **U.S. Cl.**
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USPC **372/55**; 423/490

(57) **ABSTRACT**

A transmissive optical device includes a crystal part including a c-axis in a crystal structure. The crystal part is configured to include a surface to receive a laser beam. The c-axis is arranged to be inclined relative to an incident direction of the laser beam in a plane of incidence of the laser beam.

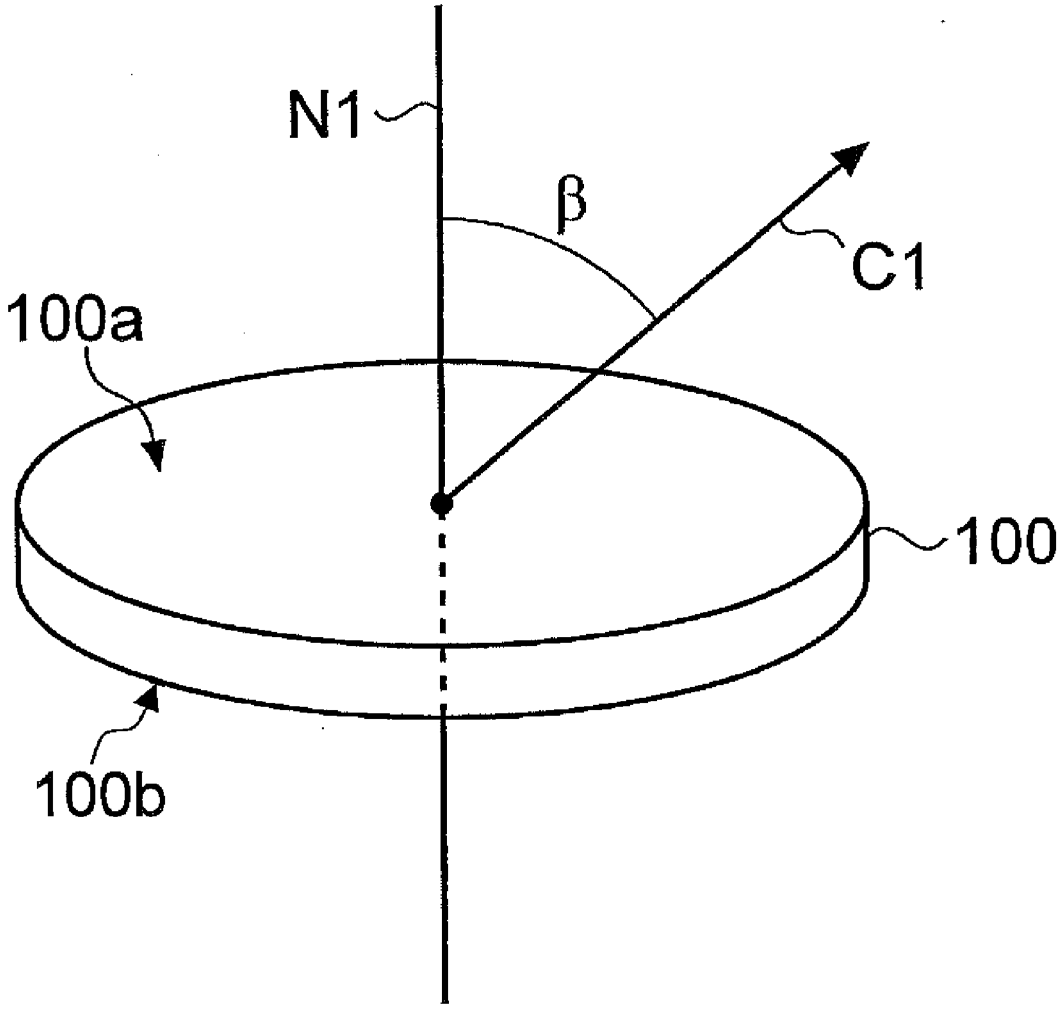


FIG.1

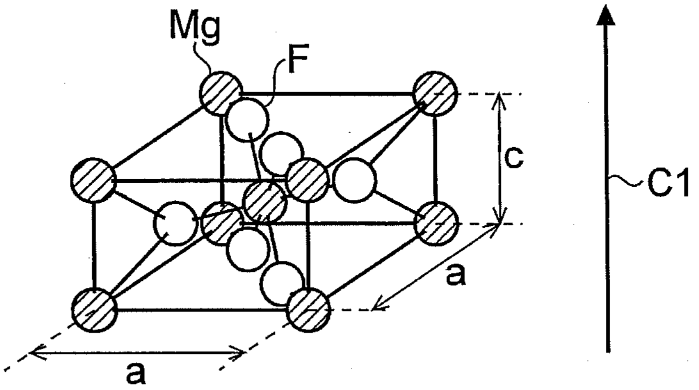


FIG.2

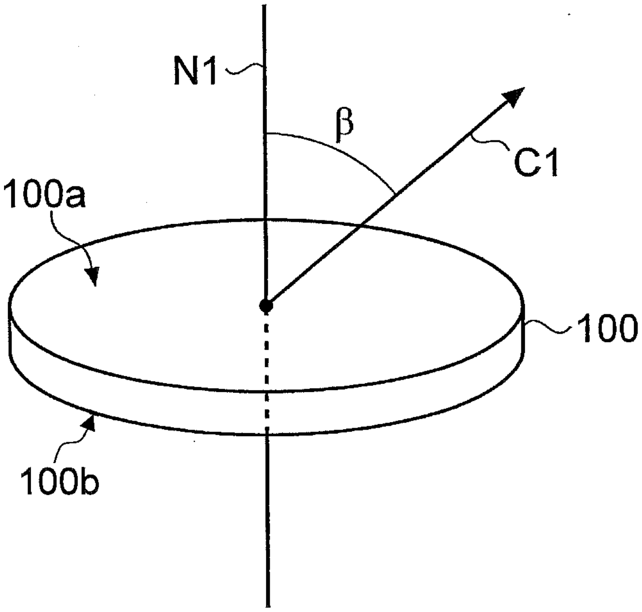


FIG.3

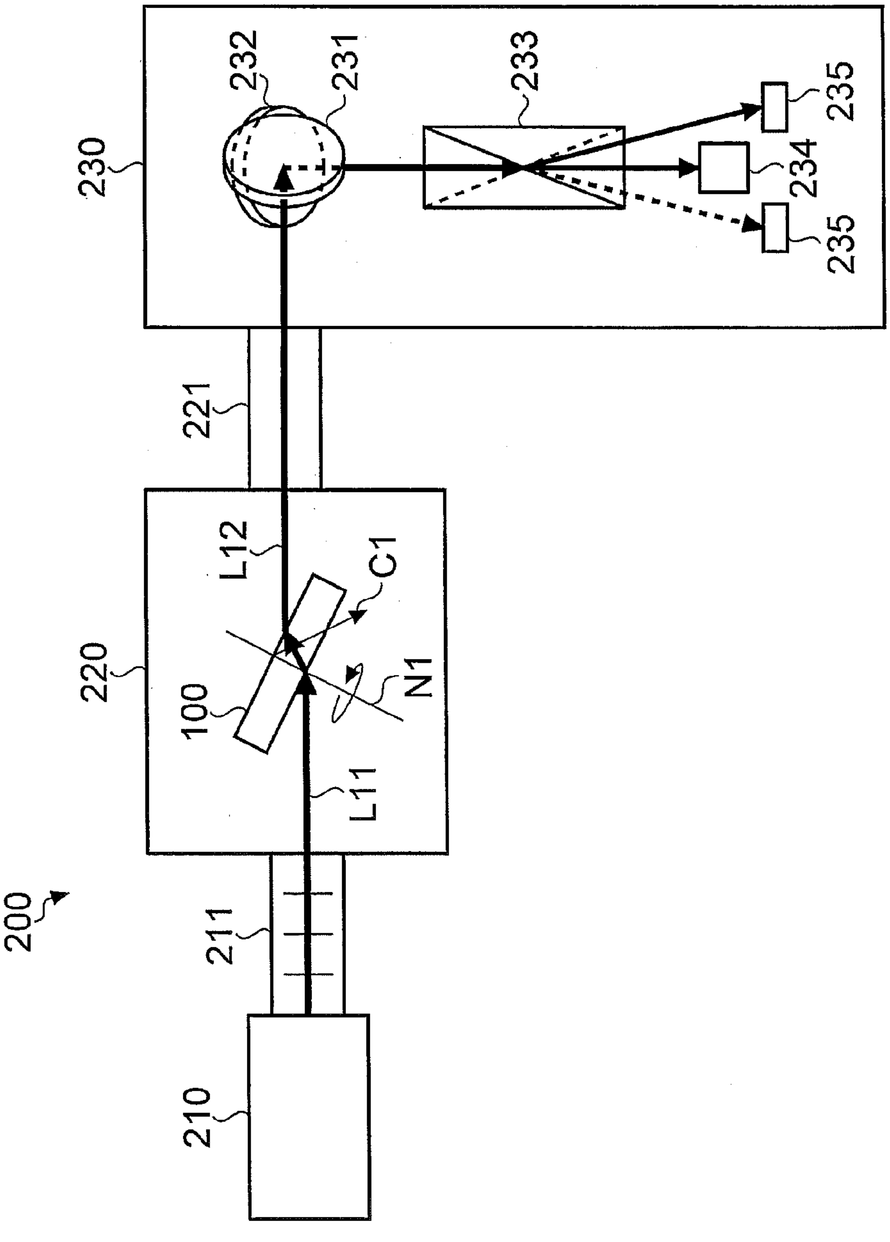


FIG.4

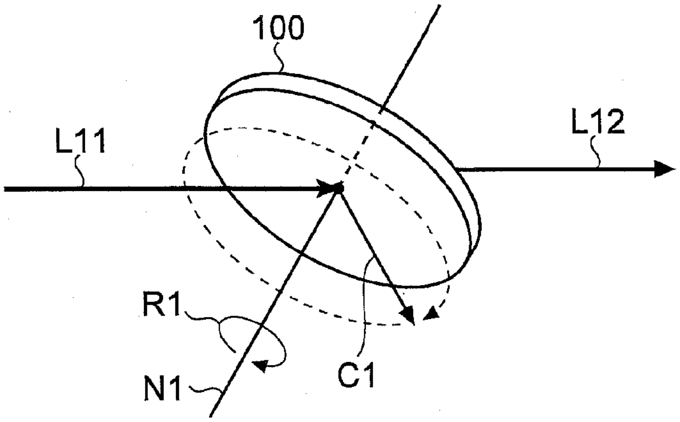


FIG.5

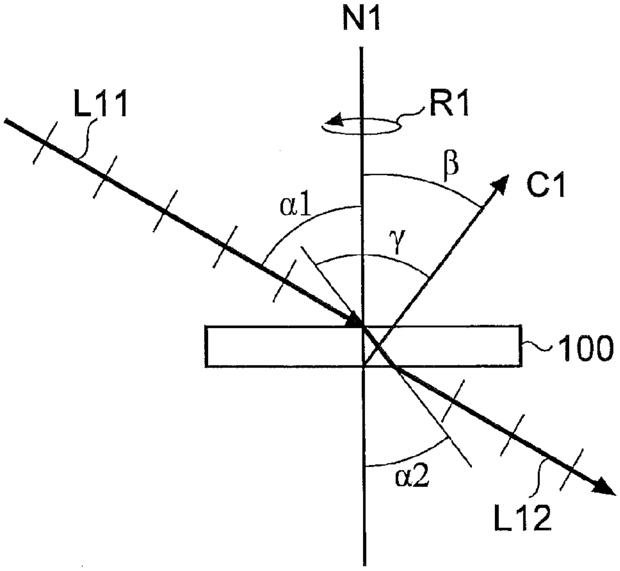


FIG.6

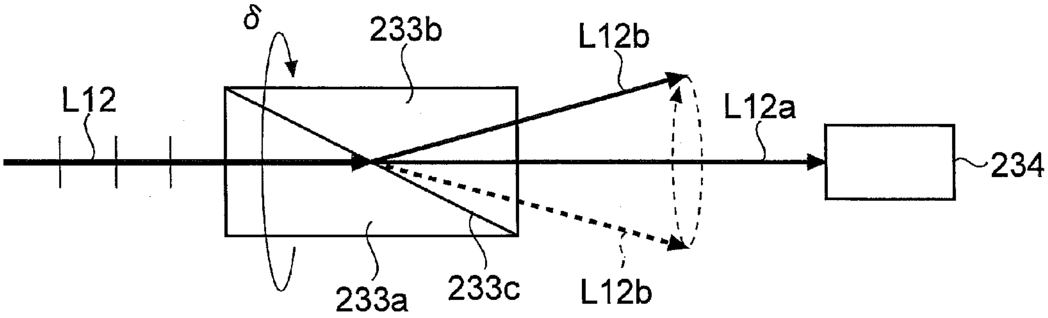

δ
233b
L12b
L12
L12a
234
233a
233c
L12b

FIG.7

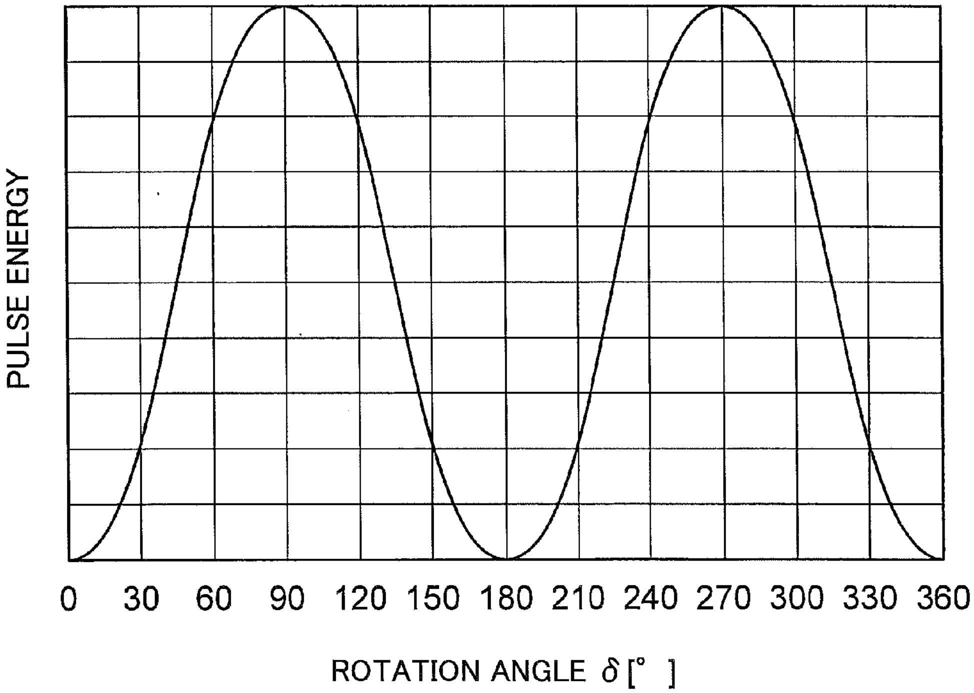

PULSE ENERGY
0
30
60
90
120
150
180
210
240
270
300
330
360
ROTATION ANGLE δ [°]

FIG.8

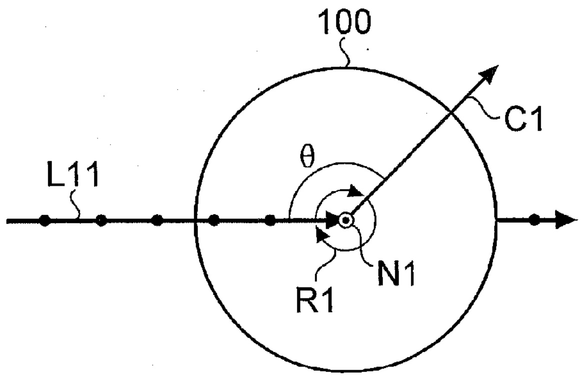

100
C1
θ
L11
N1
R1

FIG.9

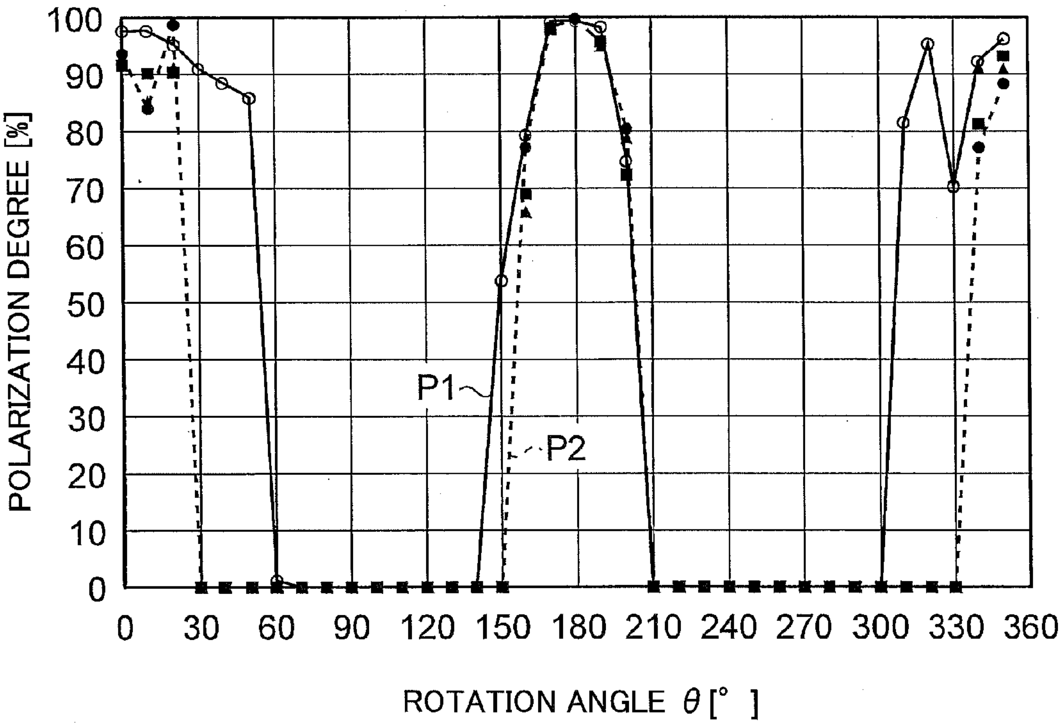

POLARIZATION DEGREE [%]
100
90
80
70
60
50
40
30
20
10
0
P1
P2
0
30
60
90
120
150
180
210
240
270
300
330
360
ROTATION ANGLE θ [°]

FIG.10

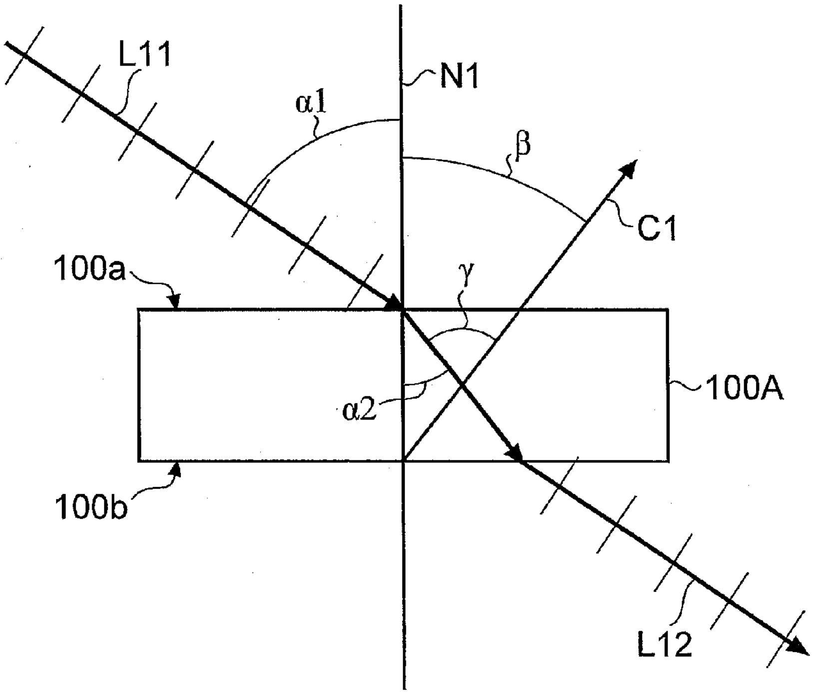


FIG.11

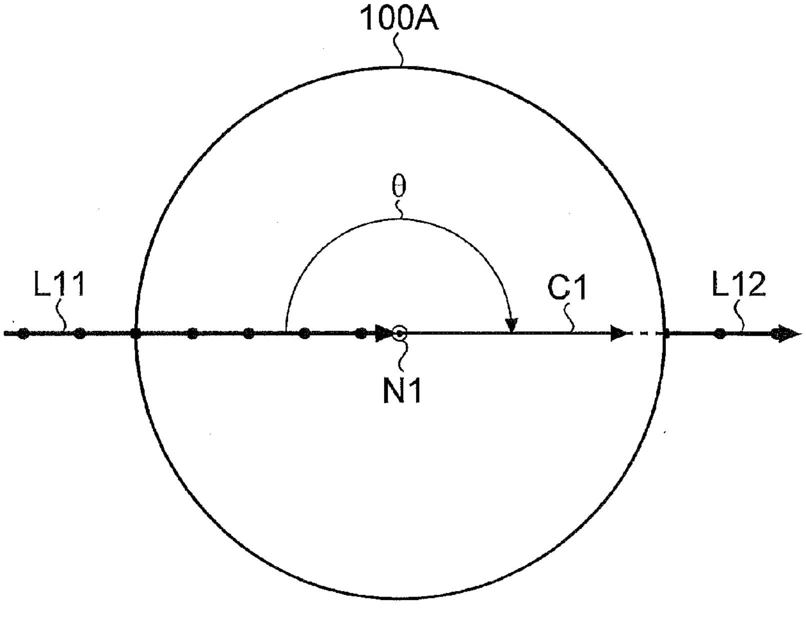


FIG.12

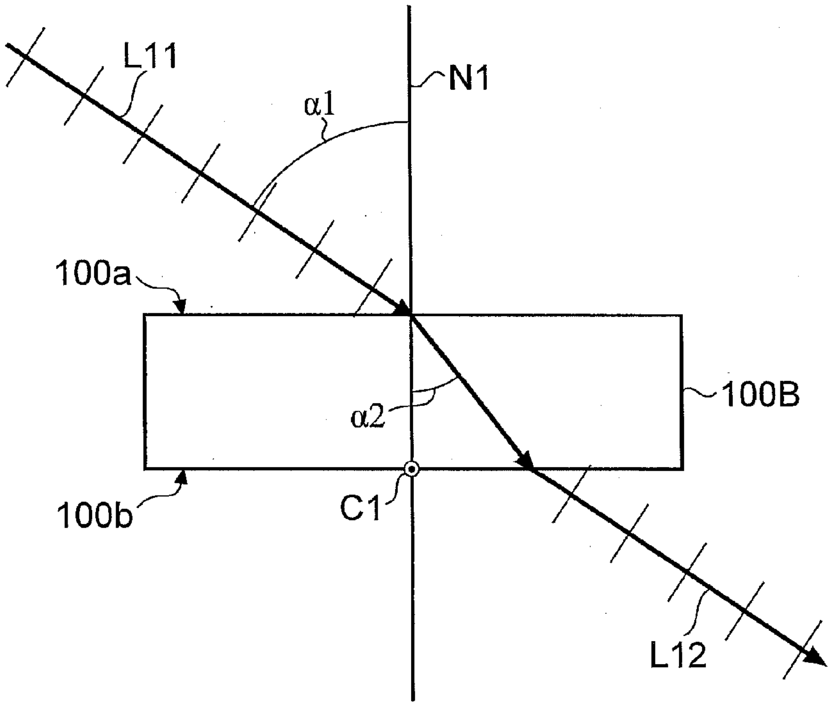


FIG.13

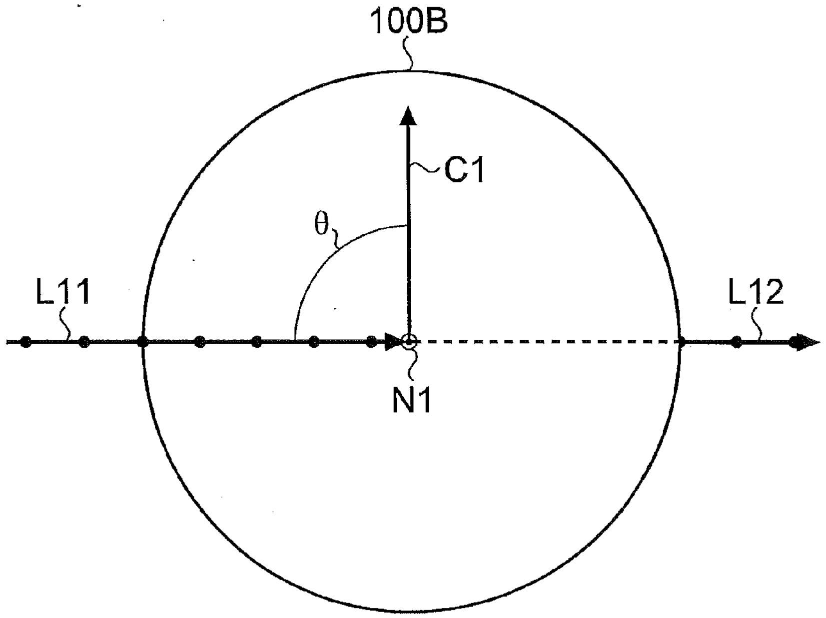


FIG.14

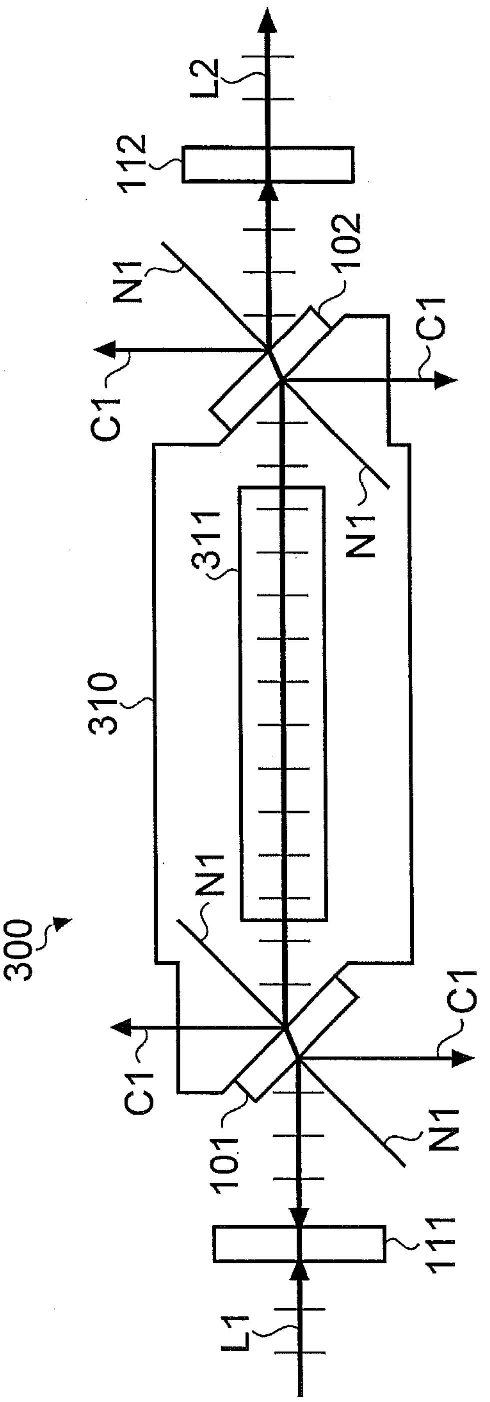
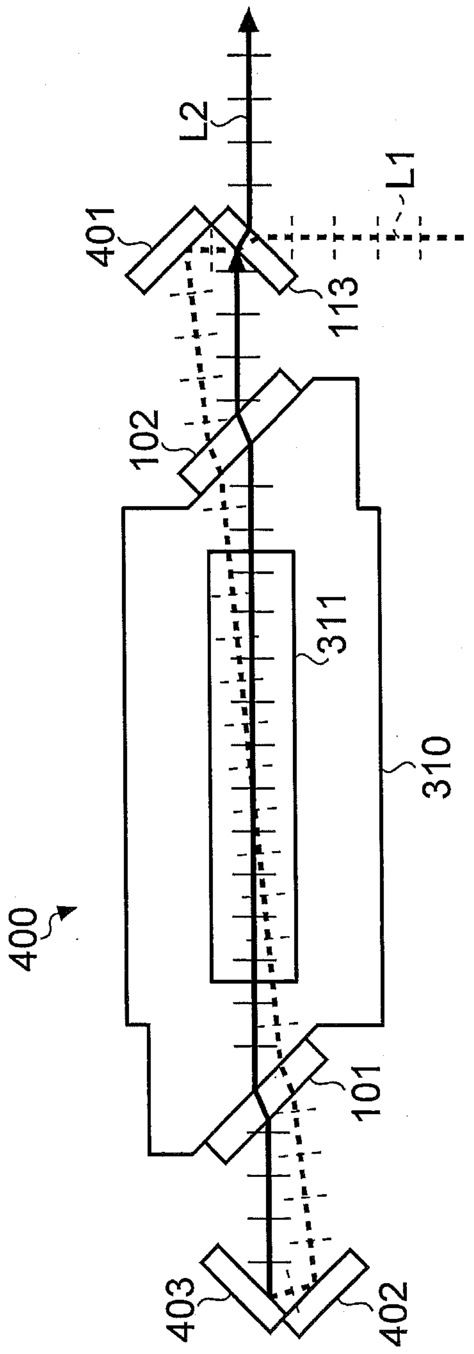


FIG.15



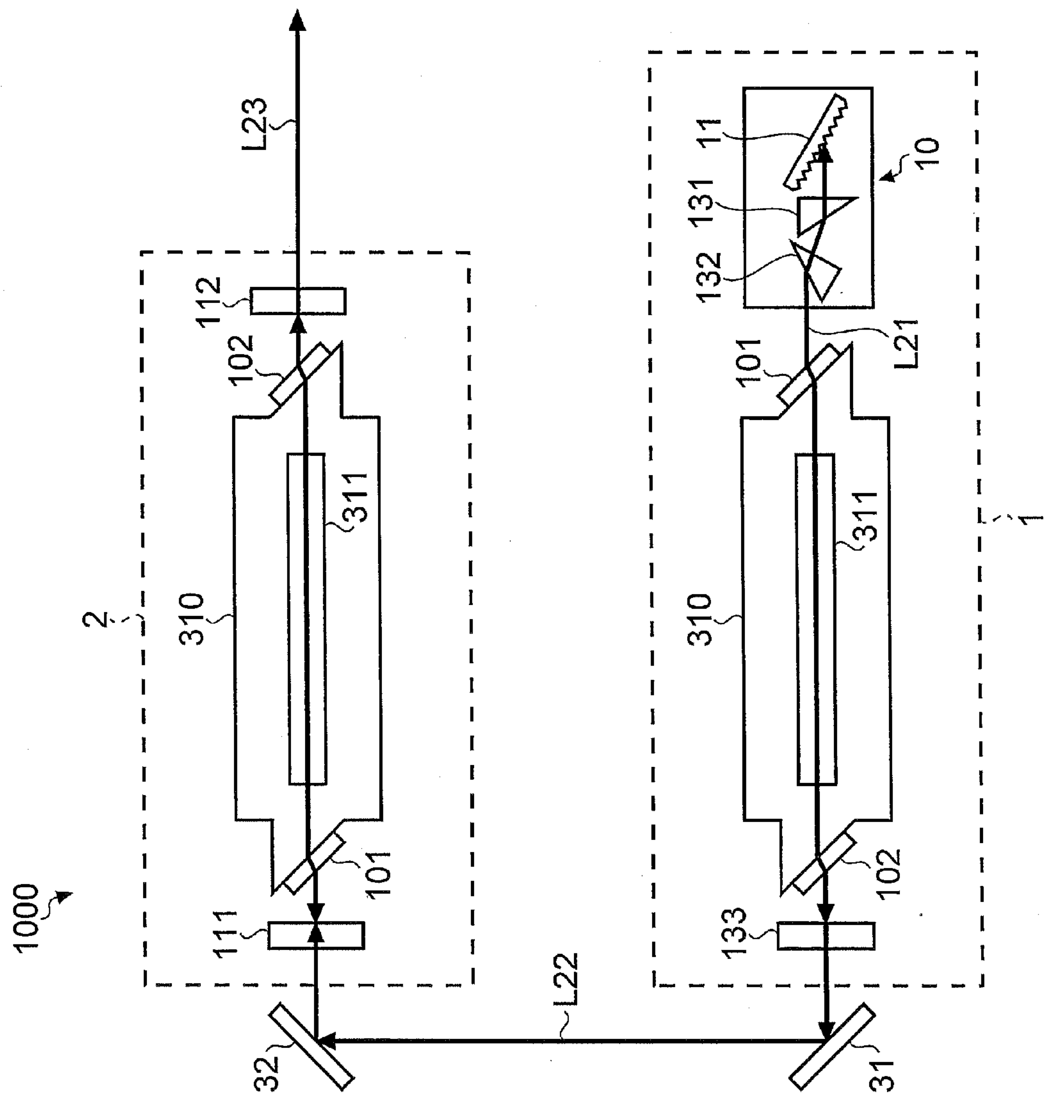

1000
2
310
311
101
111
102
112
L23
32
L22
31
133
102
311
310
1
101
L21
132
131
11
10

FIG.16

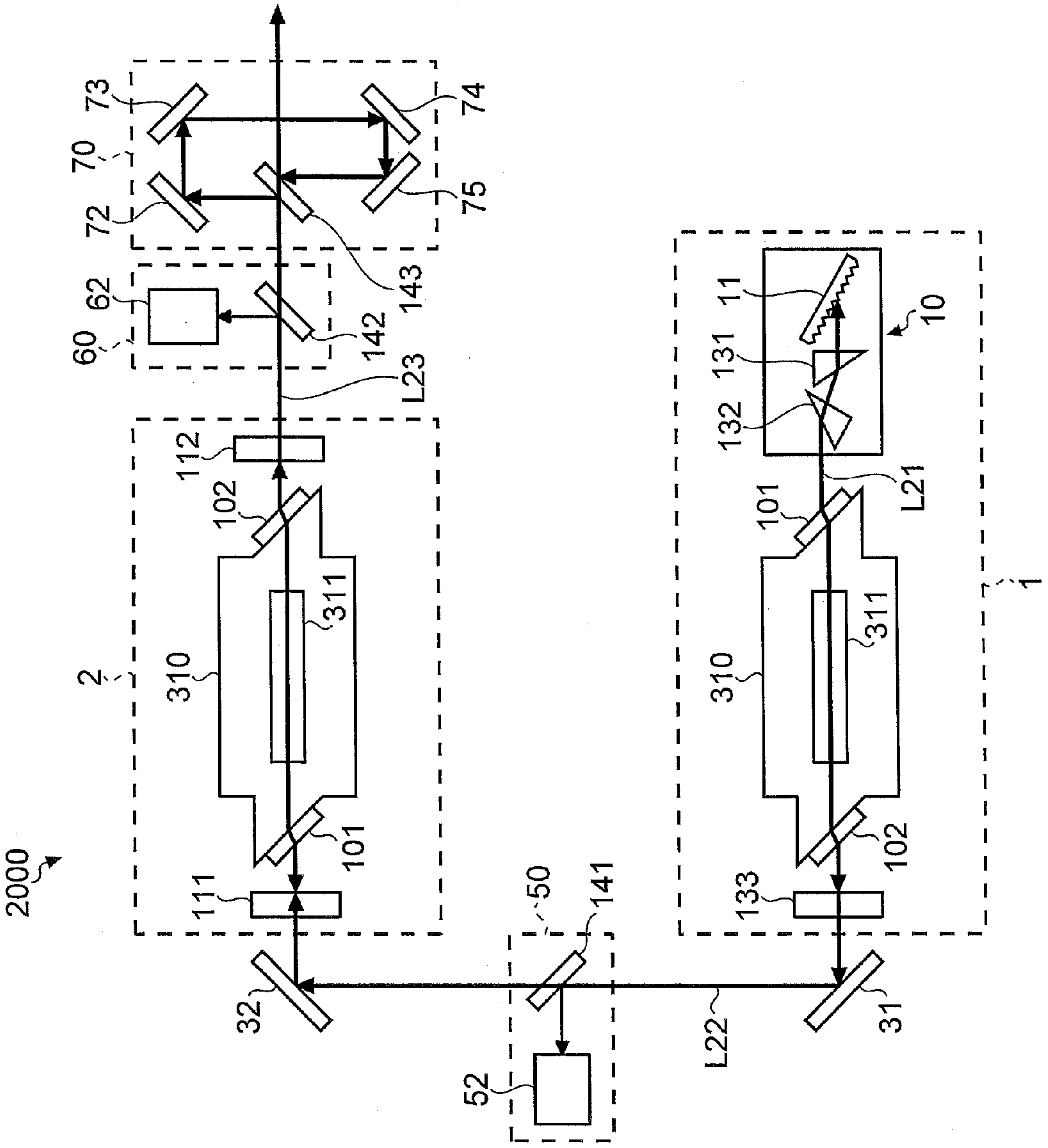

2000
2
310
311
101
102
111
112
L23
60
62
142
70
72
73
74
75
143
50
141
52
32
31
L22
1
310
311
101
102
133
L21
10
11
131
132

FIG.17

TRANSMISSIVE OPTICAL DEVICE, LASER CHAMBER, AMPLIFIER STAGE LASER DEVICE, OSCILLATION STAGE LASER DEVICE AND LASER APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This patent application is based upon and claims the benefit of priorities of Japanese Patent Application No. 2012-49121, filed on Mar. 6, 2012, and Japanese Patent Application No. 2012-270932, filed on Dec. 12, 2012, the entire contents of which are incorporated herein by reference.

BACKGROUND

[0002] 1. Technical Field

[0003] The disclosure relates to a transmissive optical device, a laser chamber, an amplifier stage laser device, an oscillation stage laser device and a laser apparatus.

[0004] 2. Description of the Related Art

[0005] The shrinkage and higher integration of a semiconductor integrated circuit have led to demands to improve the resolving power of a semiconductor lithography apparatus (which is hereinafter called "a lithography apparatus"). Because of this, advances are being made in shortening a wavelength of light emitted from a light source for lithography. A gas laser apparatus is used as the lithography light source instead of a conventional mercury lamp. At present, as the gas laser apparatus for lithography, a KrF excimer laser apparatus that emits ultraviolet light with a wavelength of 248 nm and an ArF excimer laser apparatus that emits ultraviolet light with a wavelength of 193 nm are used.

[0006] As the next-generation lithography technology, immersion lithography is being studied that shortens an apparent wavelength of a beam from the lithography light source by filling a space between a lithographic lens on the lithography apparatus side and a wafer with a liquid and by changing a refractive index. When the immersion lithography is performed by using the ArF excimer laser apparatus as the lithography light source, the wafer is irradiated with ultraviolet light with a wavelength of 134 nm under water. This technology is called an ArF immersion lithographic exposure (or ArF immersion lithography).

[0007] A natural oscillation width of the KrF excimer laser apparatus or the ArF excimer laser apparatus is broad, which is about from 350 to 400 pm. Accordingly, if a projection lens in the lithography apparatus is used, chromatic aberration occurs and the resolving power decreases. Therefore, a spectral line width (spectral width) of a laser beam emitted from a gas laser apparatus needs to be made narrower to such a degree that the chromatic aberration can be ignored. Due to this, a line narrowing module including a line narrowing device (e.g., an etalon or a grating) is provided in a laser resonator of the gas laser apparatus, and narrowing the spectral width is implemented. The laser apparatus in which the spectral width is narrowed in this manner is called a narrow band laser apparatus.

SUMMARY

[0008] According to one aspect of the present disclosure, there is provided a transmissive optical device that includes a crystal part including a c-axis in a crystal structure. The crystal part is configured to include a surface to receive a laser beam. The c-axis is arranged to be inclined relative to an incident direction of the laser beam in a plane of incidence of the laser beam.

[0009] According to another aspect of the present disclosure, there is provided a transmissive optical device that includes a crystal part including a c-axis in a crystal structure. The crystal part is configured to include a surface to receive a laser beam. The c-axis is arranged to be substantially parallel to the surface and substantially perpendicular to a plane of incidence of the laser beam.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Exemplary embodiments of the present disclosure will be described hereinafter with reference to the appended drawings.

[0011] FIG. **1** schematically shows a single crystal structure of MgF_2 crystal;

[0012] FIG. **2** schematically shows an example of a window using MgF_2 crystal;

[0013] FIG. **3** shows an example of an evaluation device that evaluates a polarization property of the window shown in FIG. **2**;

[0014] FIG. **4** shows an arrangement example of the window in the evaluation device shown in FIG. **3**;

[0015] FIG. **5** roughly shows a configuration of the window shown in FIG. **4** when cut by a plane of incidence of a laser beam;

[0016] FIG. **6** shows an arrangement example of a rochon prism and an energy sensor in the evaluation device shown in FIG. **3**;

[0017] FIG. **7** shows a pulse energy value of a laser beam measured by the energy sensor when the rochon prism shown in FIG. **6** is rotated;

[0018] FIG. **8** roughly shows a configuration of the window shown in FIG. **3** when seen from and on a normal line;

[0019] FIG. **9** shows a polarization degree property obtained in the process of rotating the window 360 degrees in a rotational direction in the evaluation device shown in FIG. **3**;

[0020] FIG. **10** shows a cross-sectional structure of a window of a first embodiment when cut by a plane including a plane of incidence of a laser beam;

[0021] FIG. **11** shows a configuration of the window shown in FIG. **10** when seen from and on a normal line;

[0022] FIG. **12** shows a cross-sectional structure of a window of a second embodiment when cut by a plane including a plane of incidence of a laser beam;

[0023] FIG. **13** shows a configuration of the window shown in FIG. **12** when seen from and on a normal line;

[0024] FIG. **14** roughly shows a configuration of an amplifier stage laser device including a stable resonator of a third embodiment;

[0025] FIG. **15** roughly shows a configuration of an amplifier stage laser device including a ring resonator of a fourth embodiment;

[0026] FIG. **16** roughly shows a configuration of a two-stage type laser apparatus of a fifth embodiment; and

[0027] FIG. **17** roughly shows a configuration of a laser apparatus including a detector and a pulse stretcher of a sixth embodiment.

DETAILED DESCRIPTION

[0028] Hereinafter, selected embodiments of the present disclosure will be described in detail with reference to the accompanying drawings. The embodiments described hereinafter indicate examples of the present disclosure, and are not intended to limit the contents of the present disclosure. Furthermore, not all of the configurations and operations described in the respective embodiments are essential to configurations and operations in the present disclosure. Note that identical constituent elements will be given identical reference numerals and characters, and redundant descriptions thereof will be omitted.

[0029] The description is given below in line with the following contents.

[0030] Contents

1. Outline

[0046] A description is given below about an outline of embodiments.

[0047] In a conventional excimer laser, a window of a CaF_2 crystal (which is hereinafter called a “CaF_2 window”) has been used as a material of an optical window installed in a laser chamber. However, the CaF_2 window readily deteriorates under a high-power ultraviolet laser beam. The deteriorated CaF_2 window absorbs heat, and generates birefringence. This sometimes causes a change of a polarization degree, a power decline or the like in an excimer laser using the CaF_2 window.

[0048] On the other hand, MgF_2 crystal has a greater band gap than that of the CaF_2 crystal in principle. Because of this, an optical window using the MgF_2 crystal (which is hereinafter called a “MgF_2 window”) has higher resistance to an ArF laser than the CaF_2 window. Moreover, because the MgF_2 crystal has a tetragonal system crystal structure in which crystal lattice lengths of an a-axis and a c-axis are different from each other, the MgF_2 crystal has birefringence. Such MgF_2 crystal is used for the optical window of the laser chamber or other transmissive optical devices in the following embodiments.

2. Explanation of Terms

[0049] Next, terms used in the present disclosure are defined as follows.

[0050] “Beam path” means a path through which a laser beam passes. “Beam path length” may be the product of a distance at which light actually passes and a refractive index of a medium through which the light has passed. “Beam cross-section” may be an area in a plane perpendicular to a traveling direction of a laser beam and having a light intensity equal to or more than a certain value. “Beam axis” may be an axis that passes through an approximate center of a beam cross-section of a laser beam along the traveling direction of the laser beam.

[0051] In a beam path of a laser beam, a generation source side of the laser beam is assumed as “upstream”, and a destination side of the laser beam is assumed as “downstream”. “Beam expansion” means that a beam cross-section gradually broadens as the laser beam travels downstream along a beam path. The laser beam that is subjected to beam expansion this way is also referred to as an “expanded beam”. “Beam reduction” means that a beam cross-section gradually narrows as the laser beam travels downstream along a beam path. The laser beam that is subjected to beam reduction this way is also referred to as a “reduced beam”.

[0052] “Predetermined repetition rate” may be allowed to be an approximate predetermined repetition rate, and is not necessarily required to be a constant repetition rate. “Burst operation” may be an operation that alternately repeats a period when a pulsed laser beam is output at a predetermined repetition rate and a period when the laser beam is not output.

[0053] Excimer laser gas is a mixed gas to be a medium of an excimer laser when excited, and may include, for example, either Kr gas or Ar gas, as well as F_2 gas and Ne gas, and may further include Xe gas if desired.

[0054] “Prism” refers to an element, having a triangular column shape or a shape similar thereto, through which light including a laser beam can pass. The base surface and the top surface of the prism may have a triangular shape or a shape similar thereto. The three surfaces of the prism that intersect with the base surface and the top surface at approximately 90 degrees are referred to as side surfaces. In the case of a right-angle prism, among these side surfaces, the one side surface that does not intersect with the other two at 90 degrees is referred to as a slope surface. Here, a prism whose shape has been changed by, for example, shaving the apex of the prism can also be included as a prism in the present descriptions.

[0055] “Plane of incidence” of a reflection-type optical device is defined as a plane including both of a beam axis of a laser beam incident on the optical device and a beam axis of a laser beam reflected by the optical device. “Plane of incidence” of a transmission-type optical device is defined as a plane including both of a beam axis of a laser beam incident on the optical device and a beam axis of a laser beam having transmitted through the optical device. “S polarization” refers to a linear polarization state in a direction perpendicular to the plane of incidence defined as the above. On the other hand, “P polarization" refers to a linear polarization state in a direction perpendicular to a beam axis and parallel to the plane of incidence.

3. Transmissive Optical Device Using MgF_2 Crystal

[0056] A description is given about the MgF_2 crystal first before a description is given about the transmissive optical device using the MgF_2 crystal.

[0057] 3.1 Structure and Physical Properties of MgF_2 Crystal

[0058] A description is given about a crystal structure and physical properties of MgF_2 crystal. FIG. **1** schematically shows a single crystal structure of the MgF_2 crystal. Table 1 lists physical properties of the MgF_2 crystal. As shown in FIG. **1** and Table 1, the MgF_2 crystal may have a tetragonal system crystal structure in which two sides with an equal lattice constant (i.e., lattice constant a=4.60 angstrom) form a square, and sides with a different lattice constant (i.e., lattice constant c=3.06 angstrom) perpendicularly intersect with the sides that form the square. In the present description, an extending direction of the side with lattice constant c is assumed as a c-axis. When the c-axis of the transmissive optical device using the MgF_2 crystal is arranged to be inclined relative to the incident axis of light, such a transmissive optical crystal can act as an optical device having birefringence depending on a polarization direction. In other words, the transmissive optical device can have a crystal part configured of the MgF_2 crystal.

TABLE 1

DENSITY	3.18
REFRACTIVE INDEX	no = 1.43
(λ = 193 nm)	ne = 1.45
CRYSTAL STRUCTURE	TETRAGONAL SYSTEM
LATTICE CONSTANT[Å]	a = 4.60
	c = 3.06
BAND GAP[eV]	11.8

[0059] As shown in Table 1, the MgF_2 crystal has a band gap of 11.8 eV (electron volt), which is, for example, higher than a band gap of a CaF_2 crystal (i.e., 10.0 eV).

[0060] By using the MgF_2 crystal that has the crystal structure and the physical properties as mentioned above, a transmissive optical device having relatively high resistance to a laser beam with a high power and a high repetition rate can be implemented.

[0061] 3.2 Example of Transmissive Optical Device Using MgF_2 Crystal (Optical Window)

[0062] Next, a description is given about a transmissive optical device using the MgF_2 crystal, with an example. In the following, a description is given by citing an optical window installed in a laser chamber and the like (which is just called a window hereinafter) as an example.

[0063] FIG. **2** schematically shows an example of a window **100** using the MgF_2 crystal. As shown in FIG. **2**, the window **100** may include a first principal surface **100*a*** and a second principal surface **100*b*** where the laser beam enters and exits. In other words, the first principal surface **100*a*** and the second principal surface **100*b*** can receive and/or emits the laser beam. The first principal surface **100*a*** and the second principal surface **100*b*** may be parallel to each other. However, the first principal surface **100*a*** and the second principal surface **100*b*** are not limited to the above-mentioned configuration, and may be inclined to each other, as in a wedge substrate and a prism, for example.

[0064] When the first principal surface **100*a*** and the second principal surface **100*b*** are parallel to each other, their normal lines may be a common normal line N**1**. A c-axis C**1** of the MgF_2 crystal that constitutes the window **100** may be inclined relative to the normal line N**1**. In the following example, an inclination angle between the normal line N**1** and the c-axis C**1** is assumed as an angle β.

[0065] 3.3 Evaluation of Polarization Property of MgF_2 Window

[0066] Next, a description is given about an evaluation of the polarization property of the window **100** shown in FIG. **2**.

[0067] 3.3.1 Evaluation Device

[0068] FIG. **3** shows an example of an evaluation device **200** that evaluates the polarization property of the window **100**. FIG. **4** shows an arrangement example of the window **100** in the evaluation device **200** shown in FIG. **3**. FIG. **5** roughly shows a configuration of the window **100** shown in FIG. **4** when cut by a plane of incidence of a laser beam L**11**. FIG. **6** shows an arrangement example of a rochon prism **233** and an energy sensor **234** in the evaluation device **200** shown in FIG. **3**.

[0069] As shown in FIG. **3**, the evaluation device **200** may include an ArF excimer laser apparatus **210**, an optical waveguide **211**, a measurement chamber **220**, an optical waveguide **221**, and a polarization degree measurement system **230**.

[0070] The ArF excimer laser apparatus **210** may output the pulsed laser beam L**11**, for example, with a pulse energy of 10 mJ (millijoule). The laser beam L**11** may be linearly-polarized light parallel to a plane of paper of FIG. **3**. The laser beam L**11** may enter the measurement chamber **220** through the optical waveguide **211**. The inside of the measurement chamber **220** may be filled with nitrogen (N_2) gas. The optical waveguide **211** may connect the ArF excimer laser apparatus **210** and the measurement chamber **220**, while shielding a beam path of the laser beam L**11** from the atmosphere.

[0071] The window **100** may be a MgF_2 crystal substrate cut by a (1 1 1) plane. Here, the (1 1 1) is a Miller index to express a crystal plane. The window **100** may be arranged in the measurement chamber **220** that is filled with the N_2 gas. As shown in FIGS. **4** and **5**, the window **100** may be arranged to be inclined at an incidence angle to be inclined when actually installed in a laser chamber relative to the incident direction of the laser beam L**11** (which is hereinafter also called a beam path). Here, the incidence angle may be set at, for example, Brewster's angle. An inclination angle of an beam axis of the laser beam L**11** relative to the normal line N**1** is assumed as an incidence angle $\alpha 1$. Moreover, the window **100** may be held to be rotatable in a rotational direction R**1** around the normal line N**1**, which is assumed as the central axis.

[0072] As shown in FIG. **3**, the laser beam L**12** having transmitted through the window **100** may enter the polarization degree measurement system **230** through the optical waveguide **221**. The optical waveguide **221** may connect the measurement chamber **220** and the polarization degree measurement system **230**, while shielding a beam path of the laser beam L**12** from the atmosphere.

[0073] The polarization degree measurement system **230** may include the rochon prism **233** and the energy sensor **234**. The polarization degree measurement system **230** may include an optical system that folds the beam path of the laser beam L**12** having transmitted through the window **100**. Preferably, this optical system may be configured to ensure that there is no change in the polarization degree of the laser beam L**12** between before and after the passing of the laser beam L**12**. In the present example, the optical system includes two folding mirrors **231** and **232**. In this case, respective inclining directions may preferably have a difference of 90 degrees relative to the beam axis of the laser beam L**12**, for example, in a way that the laser beam L**12** incident on one folding mirror **231** as P polarization light enters the other folding mirror **232** as S polarization light.

[0074] The laser beam L**12** having passed through the optical system configured of the folding mirrors **231** and **232** may enter the rochon prism **233**. As shown in FIG. **6**, the rochon prism **233** may have a configuration in which two prisms **233***a* and **233***b* are bonded. The bonded surface between the two prisms **233***a* and **233***b* may be an optical contact surface **233***c*. The rochon prism **233** may be rotatable around the beam axis of the incident laser beam L**12**, which is assumed as the rotational axis.

[0075] A laser beam L**12***a* of P polarization light among the laser beams L**12** incident on the optical contact surface **233***c* can be emitted on an extended line of the beam path of the laser beam L**12** on the incidence side. Therefore, the energy sensor **234** may be preferably arranged on the extended line of the beam path of the laser beam L**12** on the incidence side. On the other hand, a laser beam L**12***b* of S polarization light among the laser beams L**12** incident on the optical contact surface **233***c* can be emitted at an angle relative to the extended line of the beam path of the laser beam L**12** on the incidence side. Therefore, a ring-shaped beam dumper **235** for absorbing the laser beam Ll**2***b* may be arranged on the extended line of the laser beam L**12***b*.

[0076] 3.3.2 Method of Measuring Polarization Degree

[0077] FIG. **7** shows a pulse energy value of the laser beam L**12***b* measured by the energy sensor **234** relative to a rotation angle δ of the rochon prism **233** shown in FIG. **6**. FIG. **8** roughly shows a configuration of the window **100** shown in FIG. **3** when seen from and on the normal line N**1**.

[0078] In the configuration shown in FIG. **6**, the rochon prism **233** may be rotated around the beam axis of the laser beam L**12**, which is assumed as the rotation axis, while ensuring that there is no change in the polarization state of the laser beam L**12** incident thereon. In this case, as shown in FIG. **7**, the pulse energy detected by the energy sensor **234** changes with respect to the rotation angle δ in cycles of 180 degrees. Here, when the polarization state of the laser beam L**12** is a complete linear polarization, the minimum value Imin of the pulse energy detected by the energy sensor **234** may be zero. In FIG. **7**, a case is illustrated in which the laser beam L**12** enters the optical contact surface **233***c* as complete S polarization light when the angle of the c-axis C**1** relative to the beam axis of the laser beam L**11** is a standard angle in the window **100** in FIG. **8**. Furthermore, in the present description, an angle formed by the beam axis of the laser beam L**11** projected on the first principal surface **100***a* when the first principal surface **100***a* of the window **100** is seen from and on the normal line N**1** and the c-axis C**1** projected on the first principal surface **100***a* is made an angle θ. A definition of the angle θ may be similarly applied to the relationship between the beam axis of the laser beam L**11** and the c-axis C**1** with respect to the second principal surface **100***b* of the window **100**. The case of the angle θ being 0 degrees is assumed to be the standard angle of the c-axis (see FIG. **8**).

[0079] Then, as shown in FIG. **8**, the window **100** shown in FIGS. **4** and **5** is rotated a certain angle from the standard angle in a rotational direction R**1**. At this time, a polarization degree P of the laser beam L**12** is measured in the process of rotating the rochon prism **233** shown in FIG. **6** from 0 degrees to 180 degrees (or 360 degrees), while the window **100** is maintained at the rotation angle. The polarization P can be calculated by using the following formula (1) from the maximum value Imax and the minimum value Imin of the pulse energy value detected in the process. In the present description, the rotational direction R**1** may be a rotational direction in a plane parallel to the first principal surface **100***a* and the second principal surface **100***b*.

$$P = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

[0080] 3.3.3 Polarization Property Evaluation Results

[0081] FIG. **9** shows a polarization degree property obtained in the process of rotating the window **100** three hundred sixty degrees in the rotational direction R**1** in the evaluation device **200** shown in FIG. **3**. FIG. **9** shows a polarization degree obtained at each rotation angle θ when the rotation angle θ of the window **100** is rotated at 10-degree increments. In measuring the polarization degree shown in FIG. **9**, the incidence angle α**1** shown in FIG. **5** was set to 60.5 degrees, which is close to the Brewster's angle, and the angle β was set to 37.38 degrees. In this case, an angle α**2** formed by the beam axis of the laser beam L**11** that travels through the window **100** and the normal line N**1** becomes 37.38 degrees from Snell's law shown in the following formula (2) (see FIG. **5**). Accordingly, an angle γ (=α2+β) formed by the beam axis of the laser beam L**11** traveling through the window **100** and the c-axis C**1** becomes 74.76 degrees (see FIG. **5**). Here, a refractive index of a space in which the window **100** is provided is set to 1.

$$\sin \alpha 1 = n \times \sin \alpha 2 \tag{2}$$

[0082] n: a refractive index of MgF_2 crystal relative to a wavelength of the laser beam L**11**

[0083] In FIG. **9**, white circles and a solid line P**1** show a polarization property when an irradiation power of the laser beam L**11** output from the ArF excimer laser apparatus **210** is set to 2 W (watt) (pulse energy 10 mJ, repetition rate 200 Hz). Also, black circles and a dashed line P**2** show a polarization property when the irradiation power of the laser beam L**11** is set to 10 W (pulse energy 10 mJ, repetition rate 1000 Hz). Black squares show a polarization property when the irradiation power of the laser beam L**11** is set to 30 W (pulse energy 10 mJ, repetition rate 3000 Hz). Black triangles show a polarization property when the irradiation power of the laser beam L**11** is set to 60 W (pulse energy 10 mJ, repetition rate 6000 Hz).

[0084] As shown in FIG. **9**, when the rotation angle θ is around 0 degrees (and 360 degrees equal to 0 degrees), the polarization degree P is equal to or more than 90% if the irradiation power of the laser beam L**11** is 2 W (watt) (which is shown by white circles and solid line P**1**), but the polarization degree P is decreased as the irradiation power of the laser beam L**11** is increased.

[0085] In addition, when the rotation angle θ is in a range from 170 degrees to 190 degrees, the polarization degree P is maintained to be equal to or more than 95% for an irradiation power of the laser beam L**11** from 2 W to 60 W. In particular, when the rotation angle θ is around 180 degrees, the polarization degree P is equal to or more than 98%. This is maintained even when the irradiation power of the laser beam L**11** is increased.

[0086] As discussed above, it is noted that the rotation angle θ is preferably about 180 degrees. In particular, by setting the rotation angle θ of 170 degrees to 190 degrees, the polarization degree P of substantially equal to or more than 95% can be obtained. Moreover, by setting the rotation angle θ of 175 degrees to 185 degrees, the polarization degree P of substantially equal to or more than 97.5% can be obtained. Furthermore, by setting the rotation angle θ of 179 degrees to 181 degrees, the polarization degree P of substantially equal to or more than 98% can be obtained.

[0087] When the angle β shown in FIG. **5** was set to 37.38 degrees; the rotation angle θ was set to 180 degrees; and the irradiation power of the laser beam L**11** was set to 60 W (pulse energy 15 mJ, repetition rate 4000 Hz), the polarization degree P of 98.6% was obtained. This polarization degree is a value applicable to a lithography apparatus used for general semiconductor lithography. From the above discussed results, it can be said that a new finding has been acquired that a favorable polarization degree can be obtained when MgF_2 crystal with a relative high resistance to a laser beam with a high power and a high repetition frequency is used by forming a predetermined configuration and arrangement.

4. First Example of MgF_2 Window

First Embodiment

[0088] Based on the above description, a description is given about a transmissive optical device of a first embodiment of the present disclosure. In the following description, a window **100**A is taken as an example. In the present disclosure, a semi-transmissive optical device such as a partially reflecting mirror or the like is included in the transmissive optical device.

[0089] FIGS. **10** and **11** roughly show a configuration of the window **100**A of the first embodiment. More specifically, FIG. **10** shows a cross-sectional structure of the window **100**A when cut by a plane including the plane of incidence of the laser beam L**11**. FIG. **11** shows a configuration of the window **100**A when seen from and on the normal line N**1**.

[0090] As shown in FIGS. **10** and **11**, an arrangement of the window **100**A may be similar to the arrangement of the above-mentioned window **100**. Accordingly, a c-axis C**1** of MgF_2 crystal constituting the window **100**A is inclined relative to the normal line N**1** of a first principal surface **100***a* and a second principal surface **100***b* of the MgF_2 crystal. An angle of the inclination is an angle β.

[0091] A rotation angle θ in FIG. **11** may be preferably 180 degrees. However, the rotation angle θ is not limited to this, and as described above by using FIG. **9**, by allowing the rotation angle θ to be included in a range of the following formula (3), a polarization degree equal to or more than 95% can be obtained.

$$170\text{ degrees} \leqq \theta \leqq 190\text{ degrees} \quad (3)$$

[0092] More preferably, by allowing the rotation angle θ to be included in a range of the following formula (4), a polarization degree equal to or more than 97% can be obtained.

$$175\text{ degrees} \leqq \theta \leqq 185\text{ degrees} \quad (4)$$

[0093] Much more preferably, by allowing the rotation angle θ to be included in a range of the following formula (5), a polarization degree equal to or more than 98% can be obtained.

$$179\text{ degrees} \leqq \theta \leqq 181\text{ degrees} \quad (5)$$

[0094] In addition, as discussed above, an angle of an inclination of the beam axis of the incident laser beam L**11** relative to the normal line N**1** is an incidence angle α**1**.

[0095] Moreover, with respect to the refractive index of the MgF_2 crystal, as shown in Table 1 above, the refractive index no equals 1.43, and the refractive index ne equals 1.45. Hence, the Brewster's angle θb is as shown in the following formulas (6) and (7).

$$\theta b = \tan^{-1}(\mathrm{no}) = 55.0\text{ degrees(in the case of no}=1.43) \quad (6)$$

$$\theta b = \tan^{-1}(ne) = 55.4\text{ degrees(in the case of } ne=1.45) \quad (7)$$

[0096] The angle α**1** may be preferably close to the Brewster's angle θb. Because of this, the incidence angle α**1** of the laser beam L**11** incident on the window **100**A is preferably included in a range of the following formula (8).

$$45\text{ degrees} \leqq \alpha 1 \leqq 70\text{ degrees} \quad (8)$$

[0097] More preferably, the incidence angle α**1** is included in a range of the following formula (9).

$$50\text{ degrees} \leqq \alpha 1 \leqq 65\text{ degrees} \quad (9)$$

[0098] Much more preferably, the incidence angle α**1** is included in a range of the following formula (10).

$$54\text{ degrees} \leqq \alpha 1 \leqq 56.4\text{ degrees} \quad (10)$$

[0099] Furthermore, an angle γ formed by the beam axis of the laser beam L**11** in the window **100**A and the c-axis C**1** is preferably close to 90 degrees. Due to this, the angle γ is preferably included in a range of the following formula (11).

$$60\text{ degrees} \leqq \gamma \leqq 110\text{ degrees} \quad (11)$$

[0100] More preferably, the angle γ is included in a range of the following formula (12).

$$70\text{ degrees} \leqq \gamma \leqq 100\text{ degrees} \quad (12)$$

[0101] Much more preferably, the angle γ is included in a range of the following formula (13).

$$85\text{ degrees} \leqq \gamma \leqq 95\text{ degrees} \quad (13)$$

[0102] By arranging the above-mentioned window **100**A configured of the MgF_2 crystal so as to meet the above conditions for the beam axis of the laser beam L**11**, the window **100**A having relatively high resistance to the laser beam with a high power and a high repetition rate can be implemented. In addition, it may be possible to enhance a polarization degree of the transmitted laser beam. However, among the above conditions, the conditions except for the rotation angle θ are used to obtain a better optical property, but are not essential conditions.

5. Second Example of MgF_2 Window

Second Embodiment

[0103] The transmissive optical device using the MgF_2 crystal may also be configured as illustrated in a second embodiment below. In the following description, a window **100**B is taken as an example.

[0104] FIGS. **12** and **13** roughly show a configuration of the window **100**B of the second embodiment. More specifically, FIG. **12** shows a cross-sectional structure of the window **100**B when cut by a plane including the plane of incidence of the laser beam L**11**. FIG. **13** shows a configuration of the window **100**B when seen from and on the normal line N**1**.

[0105] As shown in FIGS. **12** and **13**, in the window **100**B, a direction of a c-axis C**1** may be parallel to a first principal surface **100***a* and a second principal surface **100***b*. As long as the direction of the c-axis C**1** is parallel to the first principal surface **100***a* and/or the second principal surface **100***b*, an angle γ formed by the beam axis of the laser beam L**11** and the c-axis C**1** may become 90 degrees, which can be derived from the above finding.

[0106] A direction of the c-axis referenced to the plane of incidence of the laser beam L**11**, that is to say, a rotation angle θ in FIG. **11**, is preferably 90 degrees. However, the angle θ is not limited to this, and the rotation angle θ is preferably included in a range of the following formula (14).

$$80 \text{ degrees} \leqq \theta \leqq 100 \text{ degrees} \qquad (14)$$

[0107] More preferably, the rotation angle θ is included in a range of the following formula (15).

$$85 \text{ degrees} \leqq \theta \leqq 95 \text{ degrees} \qquad (15)$$

[0108] Much more preferably, the rotation angle θ is included in a range of the following formula (16).

$$89 \text{ degrees} \leqq \theta \leqq 91 \text{ degrees} \qquad (16)$$

[0109] Furthermore, the incidence angle α**1** of the laser beam L**11** incident on the window **100**B is preferably included in a range of the following formula (17) with respect to the relation to the Brewster's angle θb.

$$45 \text{ degrees} \leqq \alpha 1 \leqq 70 \text{ degrees} \qquad (17)$$

[0110] More preferably, the incidence angle α**1** is included in a range of the following formula (18).

$$50 \text{ degrees} \leqq \alpha 1 \leqq 65 \text{ degrees} \qquad (18)$$

[0111] Much more preferably, the incidence angle α**1** is included in a range of the following formula (19).

$$54 \text{ degrees} \leqq \alpha 1 \leqq 56.4 \text{ degrees} \qquad (19)$$

[0112] By arranging the above-mentioned window **100**B configured of the MgF_2 crystal so as to meet the above conditions for the beam axis of the laser beam L**11**, the window **100**B having relatively high resistance to the laser beam with a high power and a high repetition rate can be implemented, as in the first embodiment. In addition, it is possible to enhance a polarization degree of the transmitted laser beam. However, among the above conditions, the conditions except for the rotation angle θ are used to obtain a better optical property, but are not essential conditions.

6. First Example of Amplifier Stage Laser Device Including Transmissive Optical Device Configured of MgF_2 Crystal

Third Embodiment

[0113] Subsequently, a detailed description is given about an example of an amplifier stage laser device including the above-discussed transmissive optical device with reference to the drawings. FIG. **14** roughly shows a configuration of an amplifier stage laser device **300** including a stable resonator of the third embodiment. As shown in FIG. **14**, the amplifier stage laser device **300** may include two partially reflecting mirrors **111** and **112**, and a laser chamber **310**. The two partially reflecting mirrors **111** and **112** may constitute an optical resonator. The partially reflecting mirror **112** on the downstream side may function as an output coupler.

[0114] In the laser chamber **310**, windows **101** and **102** where a laser beam L**1** propagating through the optical resonator enters and exits may be provided. An installation angle of the windows **101** and **102** relative to the beam axis of the laser beam L**1** may be the above-mentioned incidence angle α**1**. The laser beam L**11** may enter the respective windows **101** and **102**, for example, as P polarization light.

[0115] The inside of the laser chamber **310** may be filled with excimer laser gas. Inside the laser chamber **310**, a pair of discharge electrodes **311** connected to a power source (not shown in drawings) may be arranged. A direction of discharge by the discharge electrodes **311** may be, for example, a direction perpendicular to a plane including both of the beam axis and a polarization component of the laser beam L**1**.

[0116] In the above-mentioned configuration, each of the windows **101** and **102** and the partially reflecting mirrors **111** and **112** may be a transmissive optical device using the MgF_2 crystal according to the above-mentioned first or second embodiment. For example, each of the windows **101** and **102** may be the window **100**A of the first embodiment or the window **100**B of the second embodiment. Moreover, each of the partially reflecting mirrors **111** and **112** may have a configuration in which the window **100**A of the first embodiment or the window **100**B of the second embodiment is used as a substrate. A high transmission film that provides the high transmission of the laser beam L**1** may be formed on the first principal surface **100***a* of this substrate, and a partially reflecting film that partially reflects the laser beam L**1** may be formed on the second principal surface **100***b*.

[0117] Here, the partially reflecting mirrors **111** and **112** constituting the stable resonator are, for example, arranged so that the normal line N**1** of the entrance/exit surfaces of the laser beam L**1** (corresponding to the first principal surface **100***a* and the second principal surface **100***b*) is parallel to the beam axis of the laser beam L**1**. In this case, the c-axis of each of the partially reflecting mirrors **111** and **112** may be arranged so as to be parallel to a plane including the c-axis C**1** of the window **101** or the c-axis C**1** of the window **102**, and the beam axis of the laser beam L**1**.

[0118] As discussed above, the transmissive optical device using the MgF_2 crystal of the first and second embodiments may be applied not only to the windows **101** and **102**, but also to the transmissive optical device such as the partially reflecting mirrors **111** and **112**.

7. Second Example of Amplifier Stage Laser Device Including Transmissive Optical Device Configured of MgF_2 Crystal

Fourth Embodiment

[0119] The above-mentioned transmissive optical device may be utilized for an amplifier stage laser device including a ring resonator. FIG. **15** roughly shows a configuration of an amplifier stage laser device **400** including a ring resonator of the fourth embodiment. As shown in FIG. **15**, the amplifier stage laser device **400** may include a partially reflecting mirror **113**, three high reflectivity mirrors **401** to **403**, and a laser chamber **310**. The laser chamber **310** may be similar to the laser chamber **310** shown in FIG. **14**.

[0120] The partially reflecting mirror **113** may function as an entrance optical device for a laser beam L**1** and an exit optical device for an amplified laser beam L**2**. The ring resonator may be configured with the partially reflecting mirror **113** and the high reflectivity mirrors **401** to **403** as resonator mirrors. The laser chamber **310** may be arranged on the optical path of the ring resonator. In such a configuration, the components are preferably configured and arranged so that the laser beam L**1** going through the ring resonator meets the conditions illustrated in the above-mentioned first or second embodiment of different two beam paths for each or any of the windows **101** and **102** of the laser chamber **310**.

[0121] In the above configurations, each of the windows **101** and **102** of the laser chamber **310** and the partially reflecting mirror **113** may be a transmissive optical device using the MgF_2 crystal according to the above-mentioned first or second embodiment. Moreover, the partially reflecting mirror **113** is preferably arranged so that the rotation angle θ relative to the beam axis of the laser beam L**1** meets the conditions illustrated in the first or second embodiment. In this case, the beam axis of the amplified laser beam L**2** transmitting through the partially reflecting mirror **113** is preferably included in a plane including both of the beam axis of the laser beam L**1** incident on the partially reflecting mirror **113** and the c-axis C**1** of the partially reflecting mirror **113**. Furthermore, this plane may also include the c-axis of the windows **101** and **102**. In addition, the polarization components of the laser beams L**1** and L**2** may be parallel to this plane.

[0122] As discussed above, the transmissive optical device using the MgF_2 crystal of the first and second embodiments may be applied not only to the windows **101** and **102**, but also to the transmissive optical device such as the partially reflecting mirror **113**.

8. First Example of Laser Apparatus Including Transmissive Optical Device Configured of MgF_2 Crystal

Fifth Embodiment

[0123] A detailed description is given about an example of a laser apparatus including the transmissive optical device described above with reference to the drawings. FIG. **16** roughly shows a configuration of a two-stage type laser apparatus **1000** of a fifth embodiment.

[0124] As shown in FIG. **16**, the laser apparatus **1000** may include an oscillation stage laser device **1** and an amplifier stage laser device **2**. Among these, the amplifier stage laser device **2** may be, for example, similar to the amplifier stage laser device **300** shown in FIG. **14**. However, the amplifier stage laser device **2** is not limited to the amplifier stage laser device **300** in FIG. **4**, and the amplifier stage laser device **400** shown in FIG. **15** may be used.

[0125] The oscillation stage laser device **1** may include, for example, a line narrowing module **10**, a laser chamber **310**, and an output coupler **133**. The laser chamber **310** may be similar to the laser chamber **310** shown in FIG. **14**. Also, an arrangement of the output coupler **133** may be similar to the arrangement of the partially reflecting mirror **112** shown in FIG. **14**.

[0126] The line narrowing module **10** may include a grating **11** and plural prisms **131** and **132**. The grating **11** may constitute an optical resonator with the output coupler **133**. Moreover, the grating **11** may function as a wavelength selection part that selects a wavelength of a laser beam L**21** that exists in the optical resonator. The prisms **131** and **132** may be provided for the purpose of adjusting a beam width and a beam path of the laser beam L**21** incident on the grating **11**. The number of the prisms is not limited to two.

[0127] A laser beam L**22** emitted from the oscillation stage laser device **1** may enter the amplifier stage laser device **2** by way of an optical system including the high reflectivity mirrors **31** and **32**. The amplifier stage laser device **2** may amplify the incident laser beam L**22** and emit the amplified laser beam as a laser beam L**23**.

[0128] Each of the arrangements of the windows **101** and **102** of the respective laser chambers **310** of the oscillation stage laser device **1** and the amplifier stage laser device **2**, and the partially reflecting mirrors **111**, **112** and **133** may be similar to the arrangement of the transmissive optical device of the above-mentioned first or second embodiment. Each of the arrangements of the prisms **131** and **132** may be similar to the arrangement of the window **100**A of the first embodiment or the arrangement of the window **100**B of the second embodiment. However, even when a window of either embodiment is used for the windows **101** and **102**, two respective entrance/exit surfaces of the prisms **131** and **132** corresponding to the first principal surface **100***a* and the second principal surface **100***b* are not parallel to each other. In such a case, the conditions in the above embodiments may be applied to the prisms **131** and **132**, for example, by using one of the entrance/exit surfaces as a reference. For example, the prism **132** may be arranged so that of the entrance/exit surface on the laser chamber **310** side and the entrance/exit surface on the grating **11** side, a normal line of the entrance/exit surface on the laser chamber **310** side is inclined at an incidence angle α**1** with respect to the beam axis of the laser beam L**21**. In this case, the rotation angle θ of the c-axis C**1** using the entrance/exit surface of the laser beam L**21** as a reference, an angle β formed by the normal line N**1** and the c-axis C**1**, and an angle γ formed by the beam axis of the laser beam L**21** in the prism **132** and the c-axis C**1** may be set with the entrance/exit surface on the laser chamber **310** side used as a reference. However, these angles are not limited to this example, and may be set with the entrance/exit surface on the grating **11** side used as a reference. This may be applied to a wedge substrate if the wedge substrate is used in place of the prism or the window.

[0129] As discussed above, even when the two entrance/exit surfaces of the transmissive optical device such as the partially reflecting mirrors **111**, **112** and **113**, and the prisms **131** and **132** are not parallel to each other, the configuration and arrangement of the transmissive optical device using the

MgF_2 crystal of the first and second embodiments may be applied to the transmissive optical devices.

9. Second Example of Laser Apparatus Including Transmissive Optical Device Configured of MgF_2 crystal

Sixth Embodiment

[0130] The transmissive optical device described above is not limited to the oscillation stage laser device, the amplifier stage laser device, the optical resonator and the like, and may be applied to a detector and other optical systems. FIG. **17** roughly shows a configuration of a laser apparatus **2000** including detectors **50** and **60** and a pulse stretcher **70** of a sixth embodiment.

[0131] As shown in FIG. **17**, the laser apparatus **2000**, similarly to the laser apparatus **1000** shown in FIG. **16**, may include an oscillation stage laser device **1**, an amplifier stage laser device **2**, and an optical system including two high reflectivity mirrors **31** and **32**. Moreover, the laser apparatus **2000** may further include the two detectors **50** and **60**, and the pulse stretcher **70**. The oscillation laser **1**, the amplifier stage laser device **2**, and the optical system including the two high reflectivity mirrors **31** and **32** may be similar to those shown in FIG. **16**. A polarization component of the laser beam L**22** output from the oscillation stage laser device **1** may be, for example, in a direction parallel to the drawing sheet of FIG. **17**.

[0132] The detector **50** may be arranged, for example, on a beam path between the oscillation stage laser device **1** and the amplifier stage laser device **2**. The detector **50** may include a beam splitter **141** that splits a beam path of the laser beam L**22**, and a photosensor **52** that detects various parameters of the split laser beam L**22**. The beam splitter **141** is preferably arranged so that an arrangement of a c-axis relative to the beam axis of the laser beam L**22** meets the conditions illustrated in the first or second embodiment.

[0133] Moreover, an arrangement of a beam splitter **142** on the laser output side of the amplifier stage laser device **2** may also be, for example, similar to the arrangement of the beam splitter **141** in the detector **50**. A photosensor **62** of the detector **60** may detect the various parameters of the split laser beam L**23**.

[0134] Furthermore, in the pulse stretcher **70** arranged on an beam path of the laser beam L**23** having passed through the detector **60**, an arrangement of a beam splitter **143** located at a laser input stage may also be, for example, similar to the arrangement of the beam splitter **141** in the detector **50**. The pulse stretcher **70** may include, in addition to the beam splitter **143**, plural high reflectivity mirrors **72** to **75** that form a ring-shaped optical path including the beam splitter **143**.

[0135] Moreover, the laser apparatus **2000** is not limited to the detectors **50** and **60** or the pulse stretcher **70**, and may include, for example, other optical systems such as a coherence reduction mechanism that reduces coherence of a laser beam, an optical shutter that implements burst output of the laser beam L**23** or prevents optical feedback from a target substance irradiated with a laser beam from entering the laser apparatus, and the like. On this occasion, the arrangement of the transmissive optical device using the MgF_2 crystal of the above first or second embodiment may be applied to the arrangements of the transmissive optical devices included in these optical systems.

[0136] The aforementioned descriptions are intended to be taken only as examples, and are not to be seen as limiting in any way. Accordingly, it will be clear to those skilled in the art that variations of the embodiments of the present disclosure can be made without departing from the scope of the appended claims.

[0137] The terms used in the present specification and in the entirety of the scope of the appended claims are to be interpreted as not being limiting. For example, wording such as "includes" or "is included" should be interpreted as not being limited to the item that is described to include or be included. Furthermore, "has" should be interpreted as not being limited to the item that is described to have. Furthermore, the indefinite article "a" or "an" as used in the present specification and the scope of the appended claims should be interpreted as meaning "at least one" or "one or more".

What is claimed is:

1. A transmissive optical device comprising:

a crystal part including a c-axis in a crystal structure, the crystal part being configured to include a surface to receive a laser beam,

wherein the c-axis is arranged to be inclined relative to an incident direction of the laser beam in a plane of incidence of the laser beam.

2. The transmissive optical device as claimed in claim **1**,

wherein the crystal part is configured of a MgF_2 crystal.

3. The transmissive optical device as claimed in claim **1**,

wherein a rotation angle of the c-axis relative to the plane of incidence in a plane parallel to the surface is in a range from 170 degrees to 190 degrees.

4. The transmissive optical device as claimed in claim **1**,

wherein a rotation angle of the c-axis relative to the plane of incidence in a plane parallel to the surface is in a range from 175 degrees to 185 degrees.

5. The transmissive optical device as claimed in claim **1**,

wherein a rotation angle of the c-axis relative to the plane of incidence in a plane parallel to the surface is in a range from 179 degrees to 181 degrees.

6. The transmissive optical device as claimed in claim **1**,

wherein the crystal part is arranged so that the incident direction of the laser beam is inclined at Brewster's angle to a normal line of the surface.

7. The transmissive optical device as claimed in claim **1**,

wherein the crystal part is configured to be one of a window, a beam splitter and a prism.

8. A laser chamber comprising:

a pair of electrodes to generate a discharge; and

a window configured of the transmissive optical device as claimed in claim **1**, the window being arranged on an beam path of a laser beam and outside the pair of electrodes to receive the laser beam.

9. An amplifier stage laser device comprising:

a pair of electrodes to generate a discharge;

a window to receive a laser beam arranged on an beam path of the laser beam and outside the pair of the electrodes; and

an output coupler arranged on the beam path and outside the window,

wherein at least one of the window and the output coupler is configured of the transmissive optical device as claimed in claim **1**.

10. An oscillation stage laser device comprising:
a pair of electrodes to generate a discharge;
a window to receive a laser beam arranged on an beam path of the laser beam and outside the pair of the electrodes;
an output coupler arranged on the beam path and outside the window; and
a prism arranged on the beam path and outside the window opposite to the output coupler,
wherein at least one of the window, the output coupler and the prism is configured of the transmissive optical device as claimed in claim **1**.

11. A laser apparatus comprising:
a pair of electrodes to generate a discharge;
a window to receive a laser beam arranged on an beam path of the laser beam and outside the pair of the electrodes;
an output coupler arranged on the beam path and outside the window; and
a prism arranged on the beam path and outside the window opposite to the output coupler;
a beam splitter arranged on the beam path,
wherein at least one of the window, the output coupler, the prism and the beam splitter is configured of the transmissive optical device as claimed in claim **1**.

12. A transmissive optical device comprising:
a crystal part including a c-axis in a crystal structure, the crystal part being configured to include a surface to receive a laser beam,
wherein the c-axis is arranged to be substantially parallel to the surface and substantially perpendicular to a plane of incidence of the laser beam.

13. The transmissive optical device as claimed in claim **12**, wherein the crystal part is configured of a MgF_2 crystal.

14. The transmissive optical device as claimed in claim **12**, wherein a rotation angle of the c-axis relative to the plane of incidence in a plane parallel to the surface is in a range from 80 degrees to 100 degrees.

15. The transmissive optical device as claimed in claim **12**, wherein a rotation angle of the c-axis relative to the plane of incidence in a plane parallel to the surface is in a range from 85 degrees to 95 degrees.

16. The transmissive optical device as claimed in claim **12**, wherein a rotation angle of the c-axis relative to the plane of incidence in a plane parallel to the surface is in a range from 89 degrees to 91 degrees.

17. The transmissive optical device as claimed in claim **12**, wherein the crystal part is arranged so that the incident direction of the laser beam is inclined at Brewster's angle to a normal line of the surface.

18. The transmissive optical device as claimed in claim **12**, wherein the crystal part is configured to be one of a window, a beam splitter and a prism.

19. A laser chamber comprising:
a pair of electrodes to generate a discharge;
a window configured of the transmissive optical device as claimed in claim **12**, the window being arranged on an beam path of a laser beam and outside the pair of electrodes to receive the laser beam.

20. An amplifier stage laser device comprising:
a pair of electrodes to generate a discharge;
a window to receive a laser beam arranged on an beam path of the laser beam and outside the pair of the electrodes; and
an output coupler arranged on the beam path and outside the window,
wherein at least one of the window and the output coupler is configured of the transmissive optical device as claimed in claim **12**.

21. An oscillation stage laser device comprising:
a pair of electrodes to generate a discharge;
a window to receive a laser beam arranged on an beam path of the laser beam and outside the pair of the electrodes;
an output coupler arranged on the beam path and outside the window; and
a prism arranged on the beam path and outside the window opposite to the output coupler,
wherein at least one of the window, the output coupler and the prism is configured of the transmissive optical device as claimed in claim **12**.

22. A laser apparatus comprising:
a pair of electrodes to generate a discharge;
a window to receive a laser beam arranged on an beam path of the laser beam and outside the pair of the electrodes;
an output coupler arranged on the beam path and outside the window;
a prism arranged on the beam path and outside the window opposite to the output coupler; and
a beam splitter arranged on the beam path,
wherein at least one of the window, the output coupler, the prism and the beam splitter is configured of the transmissive optical device as claimed in claim **12**.

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