US008120842B2

(12) United States Patent
Higashi et al.

(10) **Patent No.: US 8,120,842 B2**

(45) **Date of Patent: Feb. 21, 2012**

(54) **WAVELENGTH CONVERSION DEVICE, LASER APPARATUS, IMAGE FORMING APPARATUS, AND DISPLAY APPARATUS**

(75) Inventors: **Yasuhiro Higashi**, Miyagi (JP); **Yasuhiro Satoh**, Miyagi (JP)

(73) Assignee: **Ricoh Company, Ltd.**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 201 days.

(21) Appl. No.: **12/532,851**

(22) PCT Filed: **Feb. 6, 2008**

(86) PCT No.: **PCT/JP2008/052390**

§ 371 (c)(1),
(2), (4) Date: **Sep. 24, 2009**

(87) PCT Pub. No.: **WO2008/117578**

PCT Pub. Date: **Oct. 2, 2008**

(65) **Prior Publication Data**

US 2010/0073755 A1 Mar. 25, 2010

(30) **Foreign Application Priority Data**

Mar. 26, 2007 (JP) 2007-078233

(51) **Int. Cl.**
G02F 1/23 (2006.01)
G02F 1/35 (2006.01)
G02F 2/02 (2006.01)

(52) **U.S. Cl.** **359/328**; 359/278; 359/326; 372/22

(58) **Field of Classification Search** 359/278, 359/326–332; 385/122; 372/21–22

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,875,053	A *	2/1999	Webjorn et al.	359/326
5,880,871	A *	3/1999	Cooke et al.	359/254
5,986,798	A *	11/1999	Karlsson et al.	359/326
6,411,420	B1 *	6/2002	Yamada et al.	359/247
7,230,753	B2 *	6/2007	Mizuuchi et al.	359/321
7,403,327	B2 *	7/2008	Kitamura et al.	359/328
7,693,194	B2 *	4/2010	Sakai et al.	372/29.022

FOREIGN PATENT DOCUMENTS

JP	4-3128	1/1992
JP	6-138506	5/1994
JP	2003 312064	11/2003

(Continued)

OTHER PUBLICATIONS

Office Action issued Feb. 17, 2011 in European Patent Application No. 08 720 727.0-2205.

Louchev, O. A. et al., "Thermal Inhibition of High-Power Second-Harmonic generation in Periodically poled $LiNbO_3$ and $LiTaO_3$ Crystals", Applied Physics Letters, vol. 87, pp. 131101-1-131101-3, 2005.

(Continued)

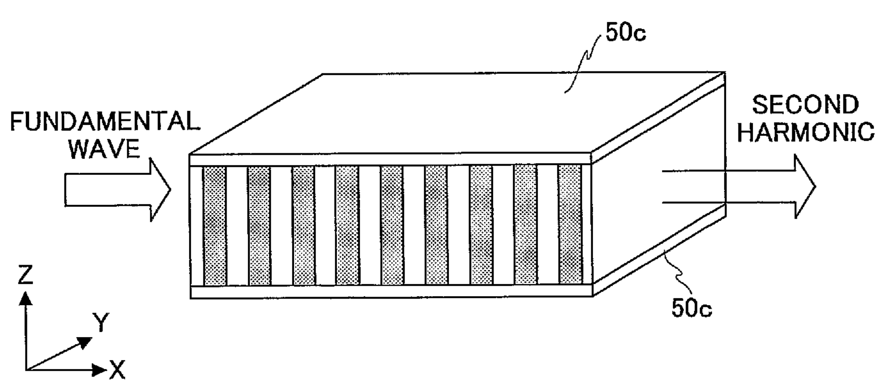
Primary Examiner — Daniel Petkovsek

(74) *Attorney, Agent, or Firm* — Oblon, Spivak, McClelland, Maier & Neustadt, L.L.P.

(57) **ABSTRACT**

A wavelength conversion device enabling the stable output of high-power harmonic light is disclosed. The wavelength conversion device includes MgO:$LiNbO_3$ (PPMgLN) having a periodic polarization reversed structure, and the +Z and −Z surfaces of the PPMgLN are covered with thin chrome (Cr) film. In the PPMgLN, the incident surface and output surface are disposed on the −X side and +X side, respectively, in the longitudinal direction. Because of this structure, even when a high-power laser fundamental wave is incident, the PPMgLN can avoid destruction and damage due to the electric field, thereby enabling the stable output of high-power harmonic.

13 Claims, 12 Drawing Sheets



FOREIGN PATENT DOCUMENTS

JP	2005 156634	6/2005
JP	2006 106804	4/2006
JP	2006 259338	9/2006
JP	2006 276326	10/2006
JP	2006 308731	11/2006
JP	2006 343397	12/2006
JP	2007 121515	5/2007
JP	2007 156177	6/2007
JP	2008 158017	7/2008
JP	2008 170582	7/2008
JP	2008 241785	10/2008
WO	WO 97/43684	11/1997

OTHER PUBLICATIONS

Ishizuki, H., "Periodical Poling Characteristics of Congruent MgO:$LiNbO_3$ Crystals At Elevated Temperature", Applied Physics Letters, vol. 82, No. 23, pp. 4062-4064 (Jun. 9, 2003).

Brief Communication issued on Sep. 16, 2011 in the corresponding European Application No. 08720727.0.

H. Ishizuki, et al., "Fabrication and Characterization of 5-mm-thick periodically poled MgO:$LiNbO_3$ device", Lasers and Electro-Optics, 2005, (CLEO), Conference on Baltimore, vol. 3, XP010877071, May 22, 2005, pp. 2108-2110.

* cited by examiner

FIG.1

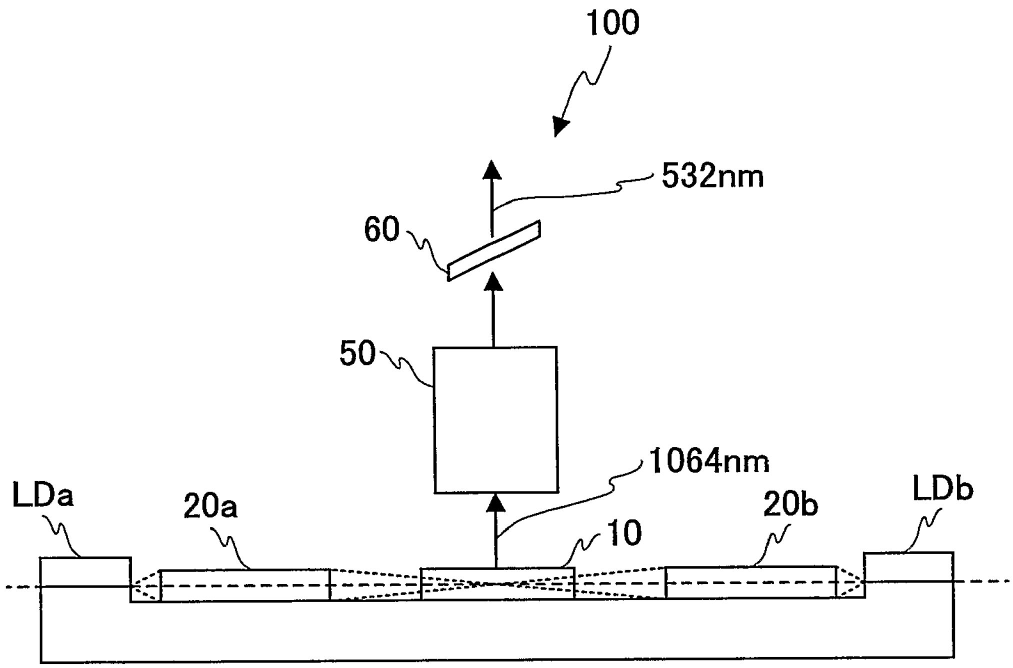

100
532nm
60
50
1064nm
LDa
20a
10
20b
LDb

FIG.2

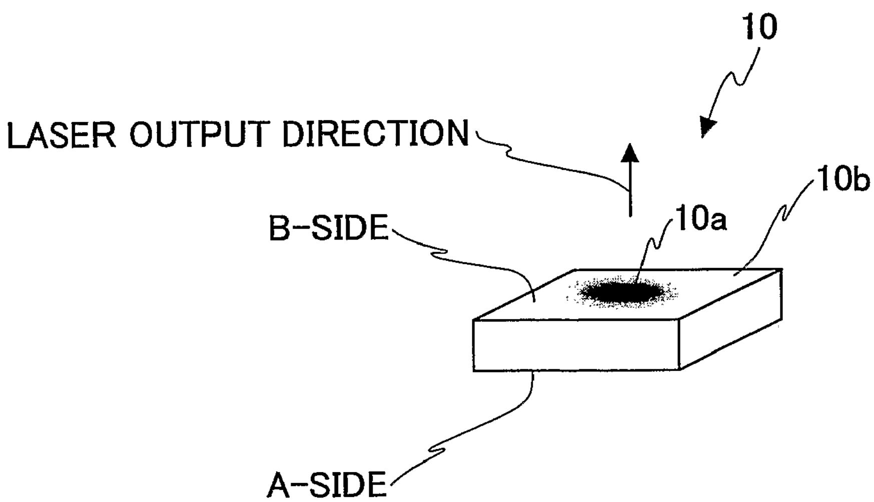

10
LASER OUTPUT DIRECTION
10b
B-SIDE
10a
A-SIDE

FIG.3A

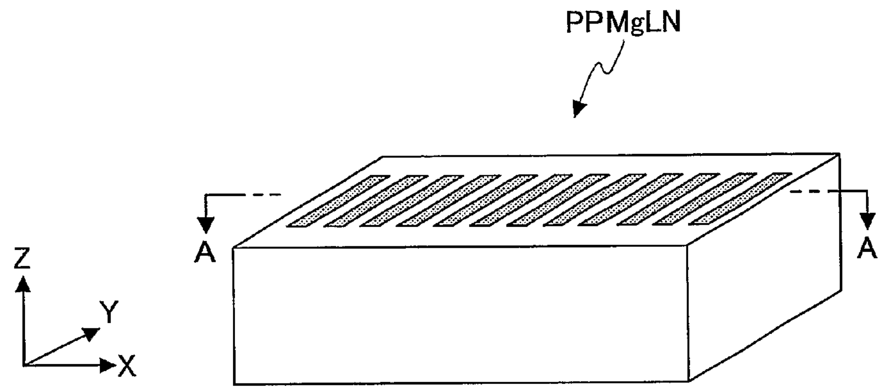


FIG.3B

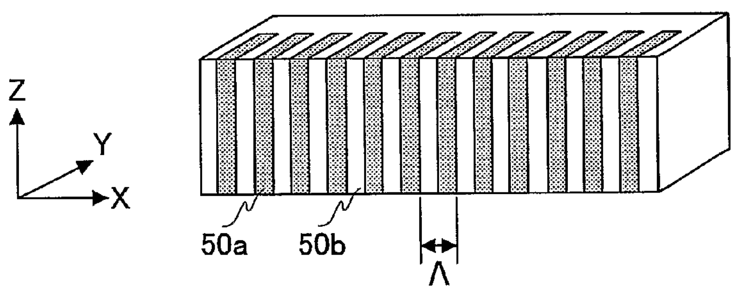


FIG.3C

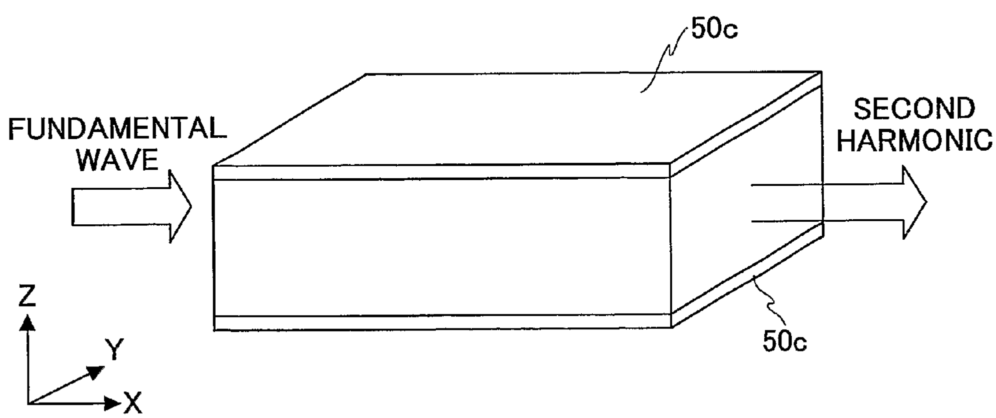


FIG.4

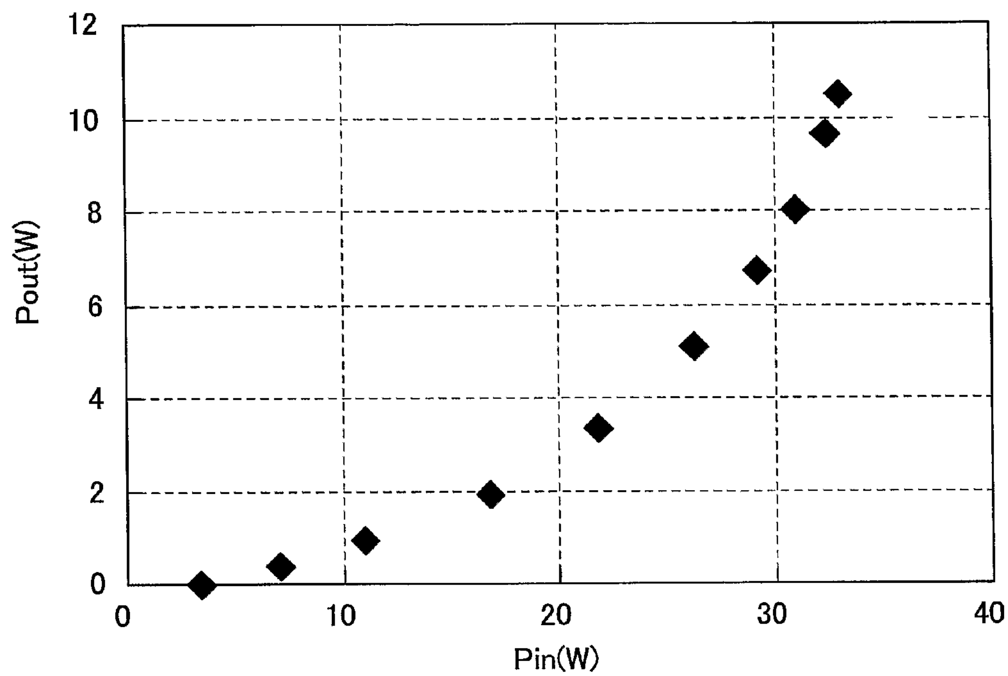

Pout(W)
Pin(W)
0
2
4
6
8
10
12
0
10
20
30
40

FIG.5

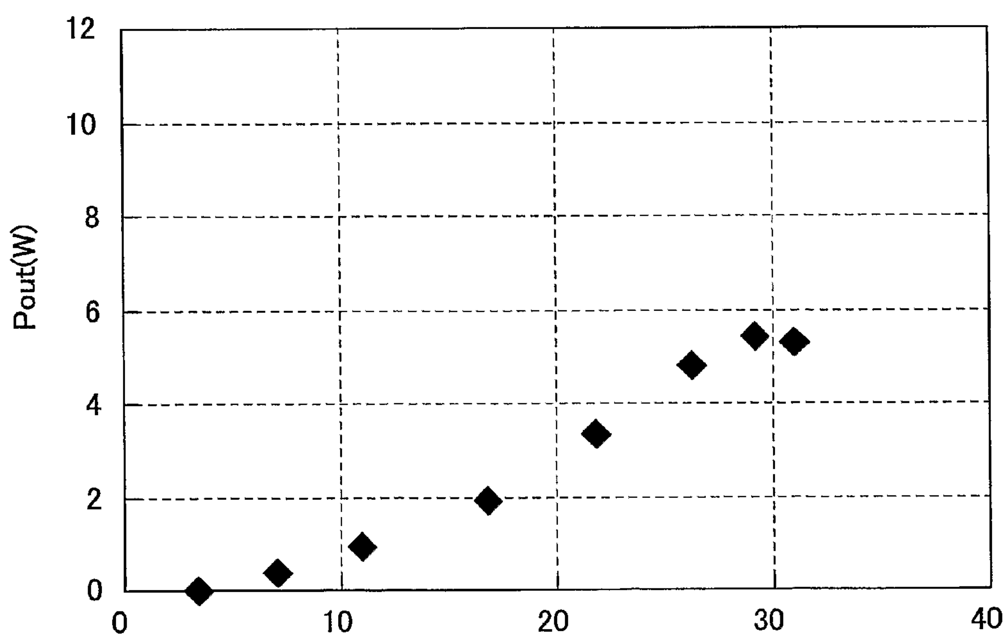

Pout(W)
0
2
4
6
8
10
12
0
10
20
30
40

FIG.6

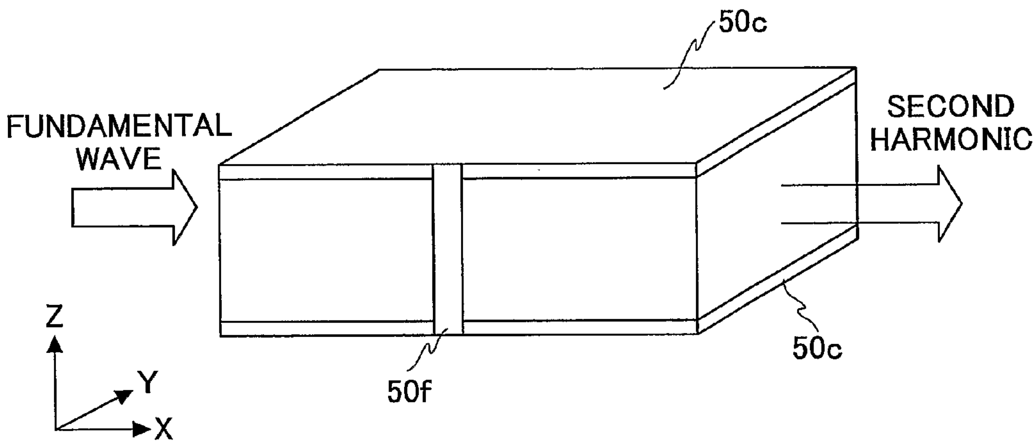


FIG.7A

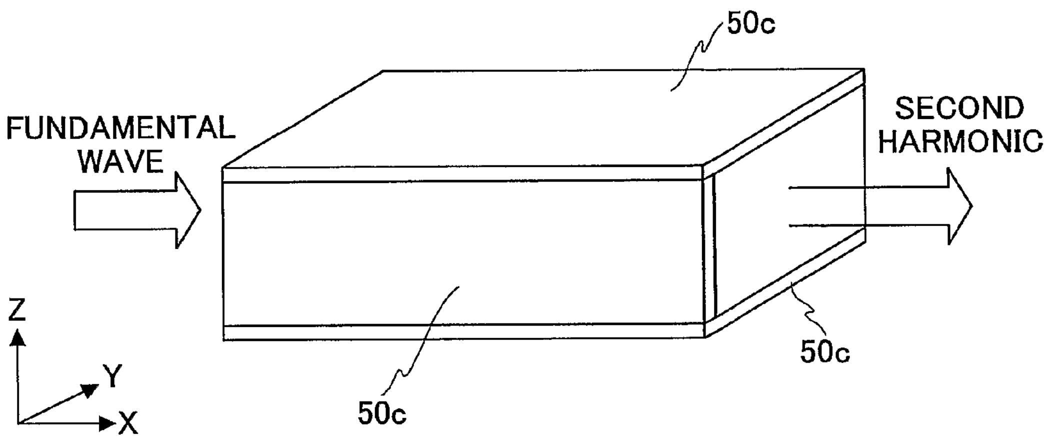

50c
FUNDAMENTAL WAVE
SECOND HARMONIC
Z
Y
X
50c
50c

FIG.7B

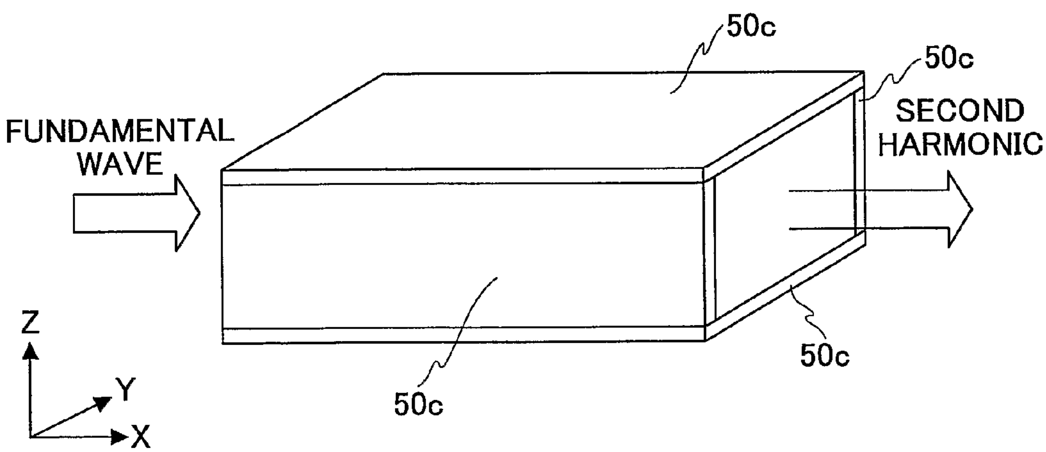

50c
50c
FUNDAMENTAL WAVE
SECOND HARMONIC
Z
Y
X
50c
50c

FIG.8

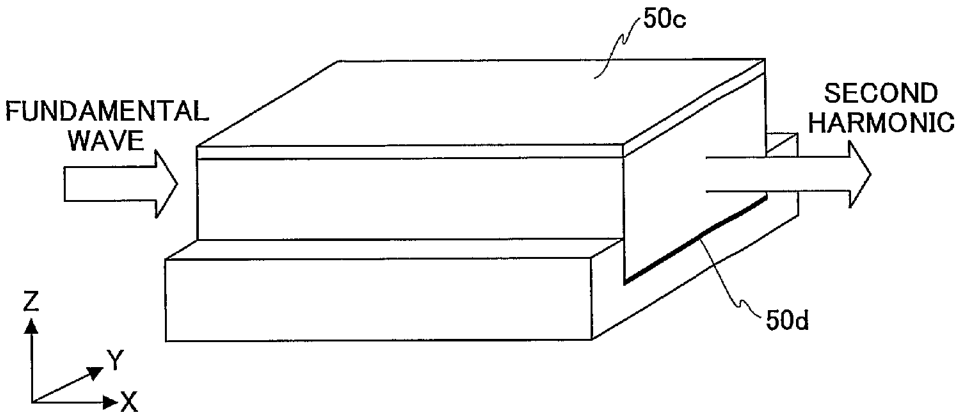

50c
FUNDAMENTAL WAVE
SECOND HARMONIC
50d
Z
Y
X

FIG.9

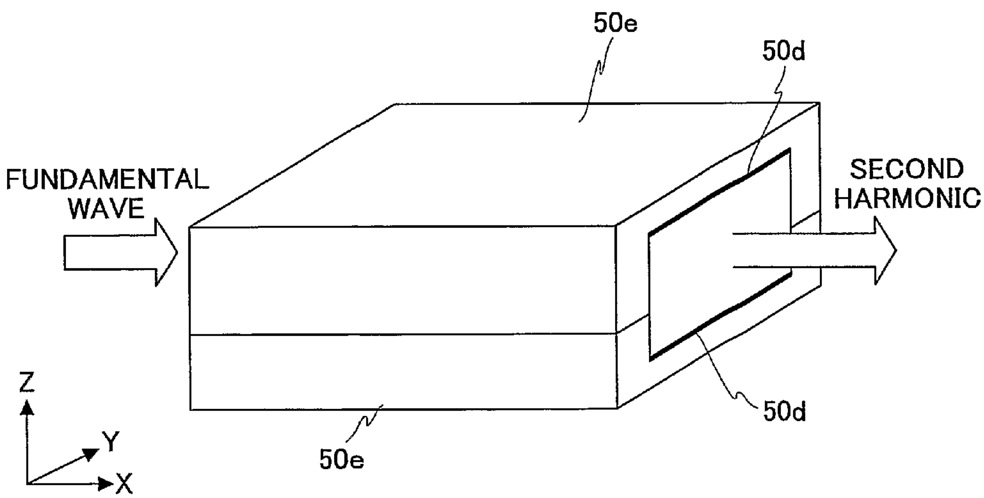

50e
50d
FUNDAMENTAL WAVE
SECOND HARMONIC
50d
Z
Y
X
50e

FIG.10A

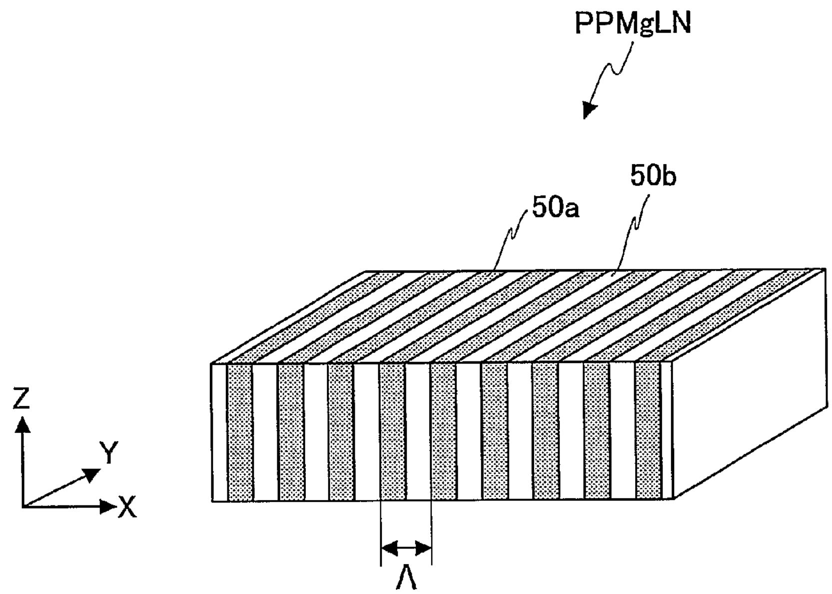


FIG.10B

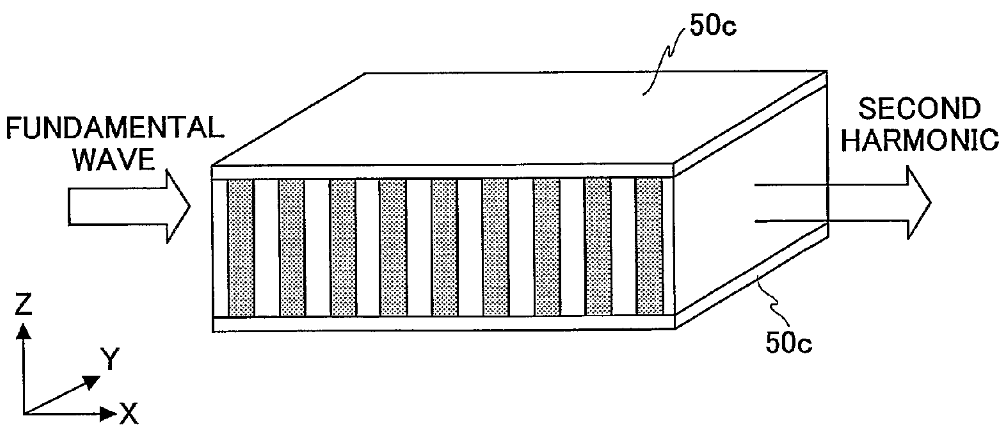


FIG.11A

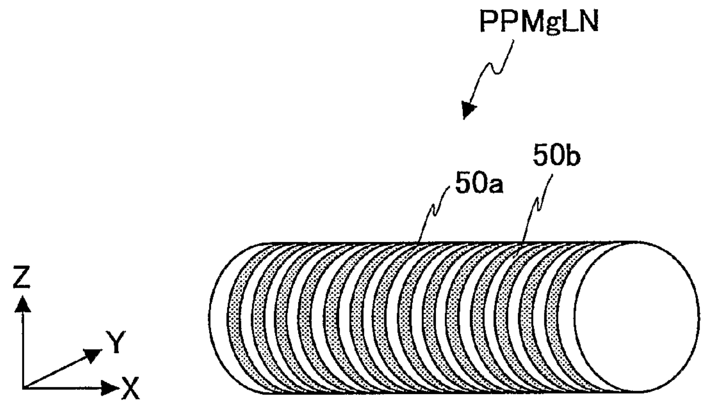


FIG.11B

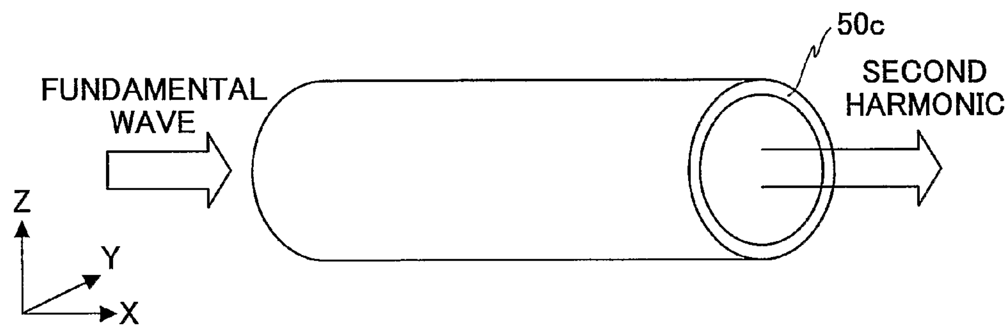


FIG.11C

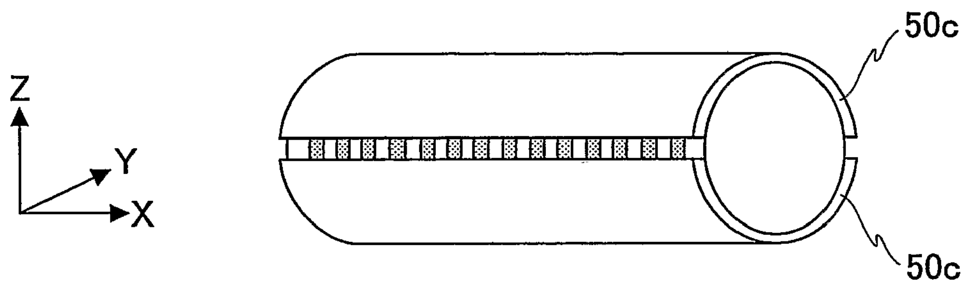


FIG.11D

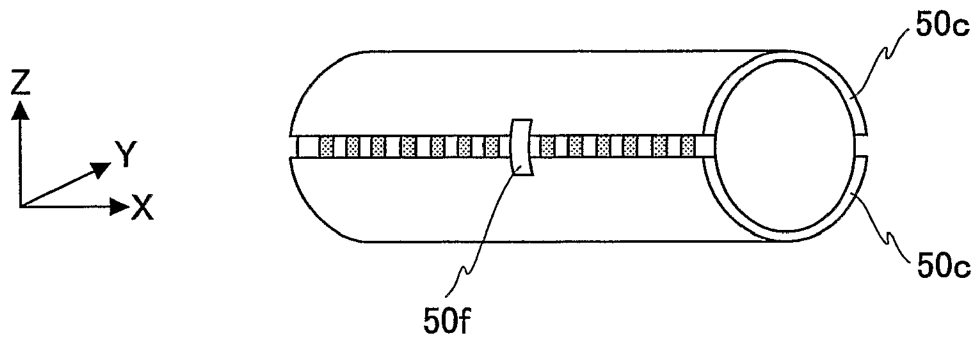


FIG.12

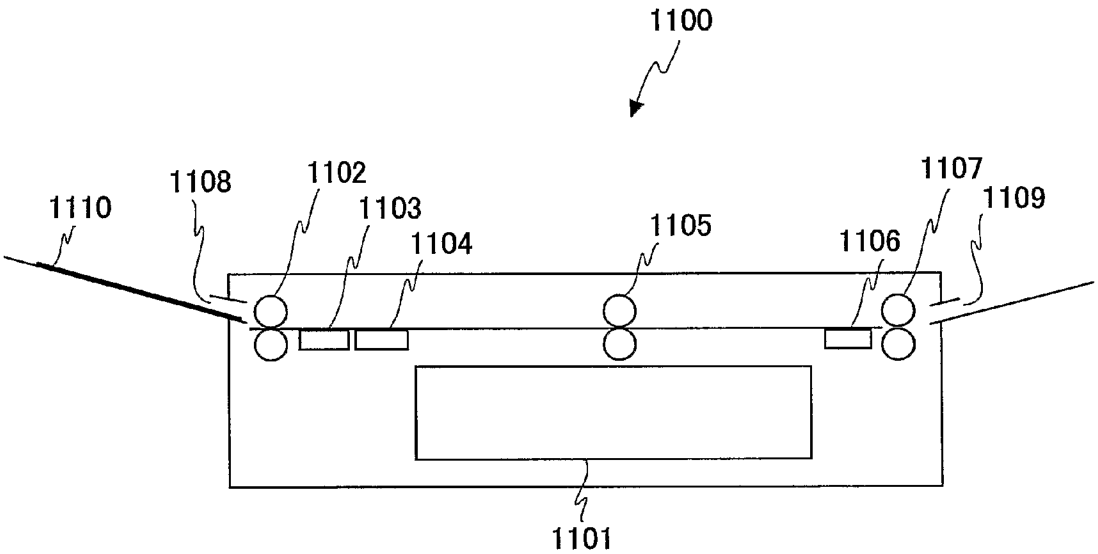


FIG.13

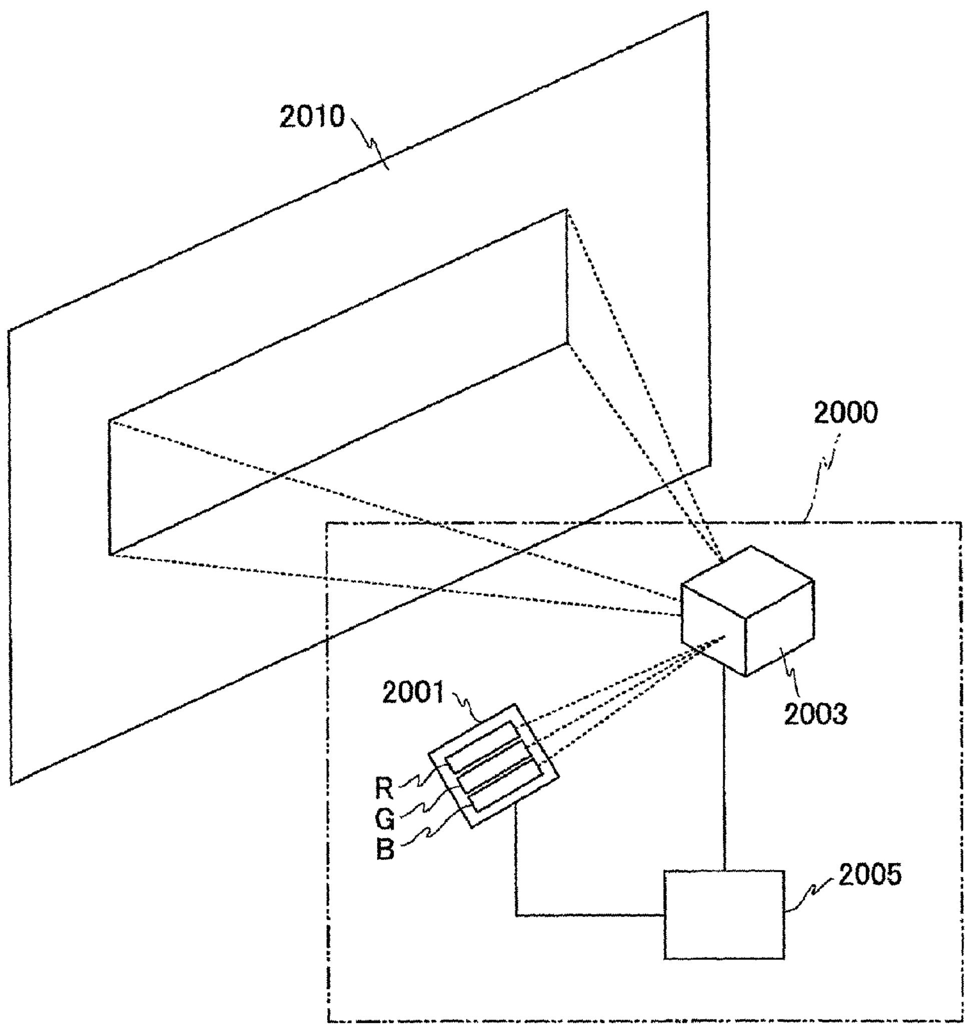
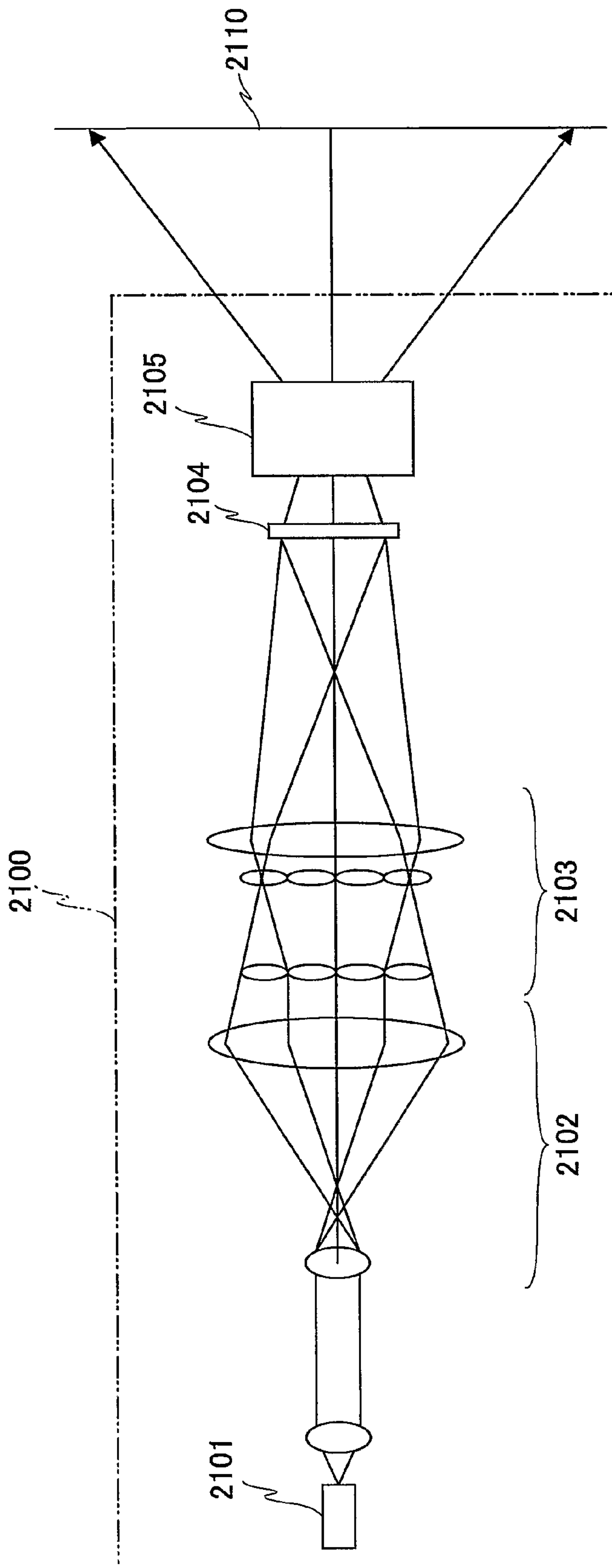


FIG.14



WAVELENGTH CONVERSION DEVICE, LASER APPARATUS, IMAGE FORMING APPARATUS, AND DISPLAY APPARATUS

TECHNICAL FIELD

The present invention relates to a wavelength conversion device, a laser apparatus, an image forming apparatus, and a display apparatus, and more specifically to a wavelength conversion device including a nonlinear optical crystal having a periodic polarization reversed structure, a laser apparatus including the wavelength conversion device, and an image forming apparatus including the laser apparatus.

BACKGROUND ART

A ferroelectric crystal such as $LiNbO_3$ and $LiRaO_3$ is called a nonlinear optical crystal due to its nonlinear optical characteristics, and is used as a wavelength conversion device for converting the wavelength of light. Especially, the nonlinear optical crystal having a polarization reversed structure where polarization directions are periodically reversed and meeting the Quasi-Phase-Matching (QPM) condition has a large nonlinear coefficient and therefore has high wavelength conversion efficiency. Further, the nonlinear optical crystal can be applied to a wide wavelength range by changing the period of the polarization reversed structure.

As the types of the nonlinear optical crystal having the polarization reversed structure, the waveguide type in which a waveguide having the width of about several μm and having the polarization reversed structure is fabricated on the surface of a crystal, and the bulk type using the entire crystal and polarization reversion structure is formed in the entire thickness of the crystal have been studied.

The bulk-type nonlinear optical crystal can convert the wavelength of a beam having a larger diameter than that of the waveguide-type. Therefore, the bulk-type nonlinear optical crystal can receive laser light having higher energy and emit light having higher power. Further, the bulk-type nonlinear optical crystal can be aligned easily.

As one of the promising bulk-type nonlinear optical crystals capable of generating a visible light of a Continuous Wave (CW) having watt-level high power obtained based on a single path conversion of the fundamental wave, $LiNbO_3$ (Periodically Poled $LiNbO_3$: PPLN) having a periodic polarization reversed structure has attracted the attention. However, the $LiNbO_3$ has a problem that the output becomes unstable due to the influences of, for example, optical damage and Green Induced Infrared Absorption (GRIIRA). Also, it is necessary to be heated to a high temperature to stabilize the operations.

Because of the disadvantages, MgO doped $LiNbO_3$, namely, MgO:$LiNbO_3$ has been studied. The MgO:$LiNbO_3$ is expected to be used as the nonlinear optical crystal capable of outputting a watt-level CW light at room temperature with a single path configuration because of its better optical damage resistivity compared with that of $LiNbO_3$.

For example, Patent Document 1 discloses a short-wavelength light source including an optical device having a single-polarized ferroelectric substrate, polarization reversed domains formed on the ferroelectric substrate, and grooves formed on the surface of the ferroelectric substrate. This short-wavelength light source may control the heat generated by the absorption of the harmonic wave generated when a fundamental wave is converted into a watt-level high-power harmonic wave.

Further, Patent Document 2 discloses an optical wavelength conversion device including a crystal having a nonlinear optical effect, periodic polarization reversed layers formed on the crystal, an incident surface formed on the end surface of the crystal, a radiating surface formed on the other surface of the crystal, and a metal film formed on at least a part of the surface or the rear surface of the crystal. This optical wavelength conversion device may control the change of the second harmonic output caused by the alternation of the refractive index due to the pyroelectric effect by the temperature change.

Patent Document 1: Japanese Patent Application Publication No. 2006-308731

Patent Document 2: Japanese Patent Application Publication No. 2006-106804

DISCLOSURE OF THE INVENTION

Problems to be Solved by the Invention

However, conventional measures for controlling heat issues are not enough to obtain a stable output of further high-power harmonics. As a matter of fact, when the input power increases, the nonlinear optical crystal may be destroyed or damaged.

The present invention is made in light of the above problems and may provide a wavelength conversion device capable of outputting stable high-power harmonic waves.

Further, the present invention may provide a laser apparatus capable of outputting a high-power stable laser light.

Still further, the present invention may provide an image forming apparatus capable of forming an image quickly.

Still further, the present invention may provide a display apparatus capable of displaying information with excellent display quality.

Means for Solving the Problems

According to a first aspect of the present invention, there is provided a first wavelength conversion device including a nonlinear optical crystal having a periodic polarization reversed structure, and conductive members covering at least two regions of the nonlinear optical crystal in which a spontaneous polarization direction of the nonlinear optical crystal crosses the region.

According to a second aspect of the present invention, there is provided a second wavelength conversion device including a nonlinear optical crystal having a periodic polarization reversed structure, a cross-sectional shape orthogonal to the periodic direction of the polarization reversed structure being substantially a circle or an ellipse, and a conductive member covering a circumferential surface of the nonlinear optical crystal.

According to the first wavelength conversion device or the second wavelength conversion device, even when the input power of a fundamental wave is high, the intensity of the electric field generated in the nonlinear optical crystal is lower than that of a conventional wavelength conversion device, thereby avoiding the destruction of or the damage to the nonlinear optical crystal. Therefore, a high-power harmonic can be stably output.

According to a third aspect of the present invention, there is provided a laser apparatus including at least one laser light source, and the wavelength conversion device according to an embodiment of the present invention disposed on an optical path of a laser light from the at least one laser light source.

According to this aspect, since the laser apparatus has the wavelength conversion device according to an embodiment of the present invention, a high-power laser light can be stably output.

According to a fourth aspect of the present invention, there is provided an image forming apparatus for forming an image on an image display medium. The image forming apparatus includes at least one laser apparatus according to an embodiment of the present invention, and an exposure apparatus for exposing the image display medium based on image information.

According to this aspect, since the image forming apparatus includes at least one laser apparatus according to an embodiment of the present invention, an image can be formed quickly.

According to a fifth aspect of the present invention, there is provided a display apparatus for displaying information on a screen using a light. The display apparatus includes a light source unit having at least one laser apparatus according to an embodiment of the present invention, and an optical system for transmitting a light from the light source unit to the screen.

According to this aspect, since the display apparatus includes at least one laser apparatus according to an embodiment of the present invention, information can be displayed with excellent display quality.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a drawing illustrating a laser apparatus according to one embodiment of the present invention;

FIG. **2** is a drawing illustrating a solid-state laser crystal **10** in FIG. **1**;

FIGS. **3**A through **3**C are drawings each illustrating the wavelength conversion device **50** in FIG. **1**;

FIG. **4** is a graph showing a relationship between the power of the incident laser fundamental wave (Pin) and the power of the output second harmonic (Pout) in the wavelength conversion device **50**;

FIG. **5** is a graph showing a relationship between the power of the incident laser fundamental wave (Pin) and the power of the output second harmonic (Pout) in a conventional wavelength conversion device;

FIG. **6** is a drawing showing a first modification of the wavelength conversion device **50** in FIG. **1**;

FIGS. **7**A and **7**B are drawings showing a second modification and a third modification, respectively, of the wavelength conversion device **50** in FIG. **1**;

FIG. **8** is a drawing showing a fourth modification of the wavelength conversion device **50** in FIG. **1**;

FIG. **9** is a drawing showing a fifth modification of the wavelength conversion device **50** in FIG. **1**;

FIGS. **10**A and **10**B are drawings each showing a sixth modification of the wavelength conversion device **50** in FIG. **1**;

FIGS. **11**A though **11**D are drawings each illustrating a case where the shape of PPMgLN is cylindrical;

FIG. **12** is a drawing schematically showing a multicolor image forming apparatus corresponding to a rewritable recording sheet according to one embodiment of the present invention;

FIG. **13** is a drawing showing a laser display apparatus according to one embodiment of the present invention; and

FIG. **14** is a drawing showing a projector according to one embodiment of the present invention.

DESCRIPTION OF THE REFERENCE NUMERALS

50 wavelength conversion device
50*c* thin chrome (Cr) film (conductive member)
100 laser apparatus
1100 multicolor image forming apparatus (image forming apparatus)
1101 exposure apparatus
2000 laser display apparatus (display apparatus)
2001 light source unit
2100 projector (display apparatus)
2101 light source device (light source unit)

BEST MODE FOR CARRYING OUT THE INVENTION

<<Laser Apparatus>>

In the following, a laser apparatus according to one embodiment of the present invention is described with reference to FIGS. **1** through **5**. FIG. **1** schematically shows the configuration of a semiconductor laser excitation solid-state laser apparatus **100** capable of efficiently exciting a laser crystal by applying exciting rays to its side surfaces according to one embodiment of the present invention.

The solid-state laser apparatus **100** includes two semiconductor laser arrays (LDa and LDb) each for excitation, two convergence optical systems (**20***a* and **20***b*), a solid-state laser crystal **10**, a wavelength conversion device **50**, and a mirror **60**.

The semiconductor laser array LDa and the semiconductor laser array LDb are equivalent to each other, each capable of outputting a 50 W laser light having wavelength of 808 nm for excitation.

The convergence optical system **20***a* converges the laser light for excitation from the semiconductor laser array LDa.

The convergence optical system **20***b* converges the laser light for excitation from the semiconductor laser array LDb.

The solid-state laser crystal **10** is, for example, a uniaxial crystal of yttrium vanadate (YVO_4) having a rectangular plate shape (a chip shape). For example, as shown in FIG. **2**, the solid-state laser crystal **10** includes a core section **10***a* where neodymium (Nd) is doped as additive (luminescent center) to be excited by the laser light for excitation, and a cladding section **10***b* that is hardly contributing to the laser excitation and that surrounds the core section **10***a* in a surface orthogonal to the outputting direction of the laser light (hereinafter abbreviated as "laser output direction").

It should be noted that a larger amount of Nd is doped in the center of the core section **10***a*. In this case, the maximum value of the doped Nd amount is 0.5 at. %.

The solid-state laser crystal **10** has a length in the laser output direction (thickness) of 0.5 nm, and has 5 mm by 5 mm cross-sectional dimensions orthogonal to the laser output direction.

Dielectric material is coated on the side surfaces of the solid-state laser crystal **10** so as to increase the transmittance of the laser light for excitation (to, for example, 99.5%).

Dielectric material is coated on an end surface (hereinafter may be referred to as "A-side" for simplicity purposes) opposite to an end surface in the laser output direction of the solid-state laser crystal **10** so as to increase the reflectance with respect to the laser light having wavelength of 1064 nm (hereinafter may be referred to as "laser fundamental wave" for simplicity purposes) (to, for example, 99.5%).

Dielectric material is coated on the end surface in the laser output direction of the solid-state laser crystal **10** (hereinafter may be referred to as "B-side" for simplicity purposes) so that the reflectance is slightly lower than that of the A-side (for example 95%).

Namely, a laser oscillator is formed between those two end surfaces of the solid-state laser crystal **10**, constituting a microchip-type laser.

The wavelength conversion device **50** is disposed on the optical path of the laser fundamental wave output from the solid-state laser crystal **10**, and converts the wavelength of the laser fundamental wave. The wavelength conversion device **50** includes $MgO:LiNbO_3$ (Periodically Poled $MgO:LiNbO_3$, hereinafter may be referred to as "PPMgLN") having a periodic polarization reversed structure as a nonlinear optical crystal.

In this embodiment, as an example, the PPMgLN has a rectangular cylinder shape with the dimensions of 20 mm (length), 3 mm (width), and 1 mm (height), and has a periodic polarization reversed structure formed in the length direction.

A z-cut 5 mol % MgO-doped $LiNbO_3$ substrate with 1-mm thickness is used for the PPMgLN. The polarization reversed structure is formed by applying an electric field between the +Z surface and the −Z surface with respect to the crystal orientation. (refer to "H. Ishizuki, I. Shoji, and T. Taira, "Periodical poling characteristics of congruent $MgO:LiNbO_3$ crystals at elevated temperature", Appl. Phys. Lett. Vol. 82, p 4062, 2003")

In the PPMgLN fabricated as described above, as representatively shown in FIG. **3**A and FIG. **3**B showing a cut-open view taken along line A-A in FIGS. **3**A, X, Y, and Z directions with respect to the crystal orientation represent the longitudinal, the width, and the height directions, respectively. Also, Z direction with respect to the crystal orientation represents the polarization direction, and X direction with respect to the crystal orientation represents the periodic direction of the polarization reversed structure. It should be noted that a symbol **50***a* in FIG. **3**B represents a domain where the direction of spontaneous polarization is reversed. Namely, the directions of spontaneous polarization in domains **50***a* and **50***b* are opposite to each other. Further, each domain **50***a* is not exposed on the surfaces of the PPMgLN in the width direction.

In this case, as an example, the polarization reversed period (polarization reversed pitch) "Λ "in the periodic polarization reversed structure is about 7 μm. Namely, the PPMgLN is arranged so that when a light having wavelength of 1064 nm is incident, the second harmonic (a green light having wavelength of 532 nm) is generated with high conversion efficiency.

As an example shown in FIG. **3**C, the PPMgLN is disposed so that an end surface on the −X side in the longitudinal direction is an incident surface of the laser fundamental wave from the solid-state laser crystal **10** and an end surface on the +X side in the longitudinal direction is an output surface. Dielectric material is coated on the incident surface so as to reduce the reflectance with respect to the laser fundamental wave (to, for example, about 0.5%).

Further, as an example shown in FIG. **3**C, thin chrome (Cr) films **50***c* with 0.2 μm thickness are coated on the +Z and −Z surfaces of the PPMgLN by sputtering. Namely, two end surfaces where a spontaneous polarization direction is crossed are covered with a conductive member.

Referring back to FIG. **1**, the mirror **60** transmits the second harmonic as it is, and separates the laser fundamental wave included in the output from the wavelength conversion device **50**. The light transmitted though the mirror **60** becomes the output from the solid-state laser apparatus **100**.

Next, the operations of the laser apparatus **100** configured as described above are briefly described.

The laser light for excitation from the semiconductor laser array LDa is transmitted through the convergence optical system **20***a* and is incident into the side surface of the solid-state laser crystal **10**. Similarly, the laser light for excitation from the semiconductor laser array LDb is transmitted through the convergence optical system **20***b* and is incident into the side surface of the solid-state laser crystal **10**.

The Nd in the core section **10***a* of the solid-state laser crystal **10** is excited by the laser light for excitation, thereby causing laser oscillation of the laser fundamental wave by a resonator formed between both end surfaces of the solid-state laser crystal **10**. As a result, the laser fundamental wave transmitted through the B-side of the solid-state laser crystal **10** is output.

The wavelength of the laser fundamental wave is converted by the wavelength conversion device **50**, and the second harmonic generated by the wavelength conversion is transmitted through the mirror **60**. It should be noted that the laser fundamental wave whose wavelength is not converted may also be output from the wavelength conversion device **50**, but the output laser fundamental wave is separated by the mirror **60**. Namely, only the second harmonic is obtained by the mirror **60**.

In this case, as an example shown in FIG. **4**, as the power of laser fundamental wave (Pin) increases, the power of the second harmonic (Pout) output from the wavelength conversion device **50** increases in proportion to nearly the square of the "Pin". Therefore, for example, when the power of the laser fundamental wave is 33 W, 10.5 W of second harmonic are stably obtained.

As a comparison, FIG. **5** shows the relationship between the "Pin" and the "Pout" in a case where a thin chrome (Cr) film **50***c* is coated only on the −Z surface of the PPMgLN. In this case, when the "Pin" exceeds 26 W, the "Pout" becomes unstable, and when the "Pin" exceeds 30 W, the PPMgLN is destroyed.

As described above, the wavelength conversion device **50** according to the embodiment of the present invention includes the PPMgLN whose +Z and −Z surfaces are covered with thin chrome (Cr) films **50***c*. Because of this structure, even when a high-power laser fundamental wave is incident, the PPMgLN can avoid the destruction and damage due to the electric field. Therefore, it is possible to output a high-power harmonic wave stably.

Further, the laser apparatus **100** according to the embodiment of the present invention includes two semiconductor laser arrays (LDa and LDb) each for excitation, a solid-state laser crystal **10** excited by each semiconductor laser arrays and for oscillating the laser fundamental wave, and a wavelength conversion device **50** disposed on the optical path of the laser fundamental wave output from the solid-state laser crystal **10** and capable of outputting the 10 W-level second harmonic stably. Therefore, it is possible to output a high-power laser light stably.

It should be noted that, in the above embodiment, a single lens or plural lenses may be used as the convergence optical system. Especially, when a micro lens is used, the size can be reduced.

Further, in the above embodiment, a case where the thickness of the thin chrome (Cr) film **50***c* is 0.2 μm is described. However, the thickness is not limited to this size.

Still further, in the above embodiment, as an example shown in FIG. **6**, the thin chrome (Cr) film **50***c* covering +Z surface of the PPMgLN and the thin chrome (Cr) film **50***c* covering −Z surface of the PPMgLN may be shorted with a conductive member **50***f*. By doing this, it is possible to reduce the voltage potential difference between the +Z and −Z surfaces of the PPMgLN to zero.

Still further, in the above embodiment, as examples shown in FIGS. **7**A and **7**B, at least one of the +Y and −Y surfaces with respect to the crystal orientation is additionally covered with the thin chrome (Cr) film **50***c*.

Still further, in the above embodiment, a case where chrome (Cr) is used as the conductive member covering the PPMgLN is described. However, the material is not limited to chrome (Cr), and, for example, aluminum (Al), silver (Ag), gold (Au), titanium (Ti) and alloys of these metals may be used.

Still further, in the above embodiment, a case is described where the conductive member covering the PPMgLN is a single layer. However, the embodiment of the present invention is not limited to this case, and a conductive member having a multilayer structure may be used. By doing this, the service life can be extended.

Still further, in the above embodiment, a case where sputtering method is used to cover the PPMgLN with the conductive member is described. However the method is not limited to sputtering, and, for example, as shown in FIGS. **8** and **9**, a conductive paste **50***d* may be used instead of the thin chrome (Cr) film **50***c*. In this case, the PPMgLN may be adhered tightly to a supporting member **50***e* made of copper (Cu) with the conductive paste **50***d*.

It should be noted that silver paste in which silver particles are scattered in resin is typically used as the conductive paste **50***d*. However, conductive paste including metal particles of, for example, gold and copper, and particles of carbon, carbon nanotube (CNT) and indium tin oxide (ITO) may be used.

Still further, in the above embodiment, the conductive member covering the PPMgLN may be transparent like, for example, ITO, tin oxide (SnO_2), zinc oxide (ZnO), and indium zinc oxide (IZO). Thin films of any of these materials can be formed on the surface of the PPMgLN by, for example, the vacuum evaporation method and the sputtering method. In this case, an antireflection film made of the same material as that of the conductive member may be coated onto the incident surface of the PPMgLN instead of the dielectric material. By doing this, a coating process of the dielectric material onto the incident surface can be abbreviated so as to simplify the processes and lower the cost.

Still further, in the above embodiment, a case where the domain **50***a* is not exposed on the surface in the width direction of the PPMgLN is described. However, the embodiment is not limited to this structure, and as examples shown in FIGS. **10**A and **10**B, the domain **50***a* may be exposed on the surface in the width direction of the PPMgLN.

Still further, in the above embodiment, a case where the shape of the PPMgLN is a rectangular cylinder is described. However, the embodiment is not limited to this, and, for example, a circular or an elliptical shape with respect to a cross section orthogonal to the periodic direction of the polarization reversed structure may also be applicable. In this case, the circumference surface of the PPMgLN may be covered with the conductive member **50***c* (see FIG. **11**B), or at least two domains where a spontaneous polarization direction is crossed may be covered with the conductive members **50***c* (see FIG. **11**C). Further, the conductive members **50***c* covering at least two domains may be shorted with the conductive member **50***f* (see FIG. **11**D).

Still further, in the above embodiment, a case where Nd:YVO_4 crystal is used as the solid-state laser crystal is described. However, the embodiment of the present invention is not limited to this, and, for example, Nd:$GdVO_4$, a Nd:YAG crystal, a Yb:YAG crystal, a Nd: Strontium-Lanthanum-Aluminate (ASL) crystal, and a Nd:Lanthanum-Scandium-Borate (LSB) crystal may be used as the solid-state laser crystal.

Still further, in the above embodiment, a semiconductor laser excitation solid-state laser apparatus capable of efficiently exciting a laser crystal by applying exciting rays to its side surfaces is described as the laser apparatus. However, the embodiment of the present invention is not limited to this, and a semiconductor laser excitation solid-state laser apparatus capable of efficiently exciting a laser crystal by applying exciting rays to its end faces may be used. Namely, the incident surface of the laser light for excitation in the solid-state laser crystal may be the A-side or the B-side of the solid-state laser crystal **10**.

Still further, in the above embodiment, sizes of the solid-state laser crystal **10** and the PPMgLN are not limited to the sizes described above.

Still further, in the above embodiment, a case where the wavelength of the light incident into the PPMgLN is 1064 nm is described. However, the embodiment of the present invention is not limited to this, and, for example, a light having wavelength of 914 nm or 1340 nm may be incident into the PPMgLN. When the wavelength of the incident light is 914 nm, a high-power blue light having wavelength of 457 nm is output from the PPMgLN, and when the wavelength of the incident light is 1340 nm, a high-power red light having wavelength of 670 nm is output from the PPMgLN.

<<Image Forming Apparatus>>

FIG. **12** schematically shows a configuration of a multicolor image forming apparatus **1100** as an image forming apparatus according to an embodiment of the present invention. The multicolor image forming apparatus **1100** is capable of corresponding to a rewritable recording sheet and includes an exposure apparatus **1101**, plural feed rollers (**1102**, **1105**, and **1107**), an ultraviolet curing unit **1103**, a heating device **1104**, and a heating device **1106**.

The exposure apparatus **1101** includes a laser apparatus corresponding to a red color, a laser apparatus corresponding to a green color, and a laser apparatus corresponding to a blue color. Each laser apparatus includes a wavelength conversion device having a nonlinear optical crystal whose at least +Z and −z surfaces are covered with conductive members similar to the wavelength conversion device **50**.

It should be noted that the exposure apparatus **1101** may be used in scanning lights from each laser apparatus onto a rewritable recording sheet or in scanning lights of each laser apparatus onto a rewritable recording paper via, for example, a liquid crystal panel.

General matters on the multicolor image forming apparatus **1100** are disclosed in, for example, Japanese Patent Application Publication No. 2003-312064.

Because of the configuration, in the multicolor image forming apparatus **1100**, each laser apparatus can output a 10 W-level laser light stably. Therefore, it is possible to form an image quickly.

<<Display Apparatus>>

FIG. **13** schematically shows a configuration of a laser display apparatus **2000** as a display apparatus according to an embodiment of the present invention.

The laser display apparatus **2000** includes a light source unit **2001**, an optical system **2003** having a mirror for reflecting the laser lights from the light source unit **2001** toward the screen **2010**, and a control unit **2005** for controlling the light source unit **2001** and the optical system **2003**.

The light source unit **2001** includes a laser apparatus “R” outputting a red light, a laser apparatus “G” outputting a green light, and a laser apparatus “B” outputting a blue light. Each laser apparatus includes a wavelength conversion device having a nonlinear optical crystal whose at least +Z and −z surfaces are covered with conductive members similar to the wavelength conversion device **50**.

Because of the configuration, in the laser display apparatus **2000** according to the embodiment of the present invention, each laser apparatus of the light source unit **2001** can output a 10 W-level laser light stably. Therefore, it is possible to display a picture and characters on the screen **2010** with excellent display quality.

It should be noted that even if a laser display apparatus that displays images by irradiating laser lights toward the space, when the laser display apparatus includes the light source unit **2001**, it is possible to perform a desired display quickly.

Further, FIG. **14** schematically shows a configuration of a projector **2100** using a transmissive liquid crystal panel.

This projector **2100** includes a light source device **2101**, a collimated optical system **2102**, an integrated optical system **2103**, a liquid crystal panel **2104**, and a projector lens **2105**.

The light source device **2101** includes a laser light source, and a wavelength conversion device having a nonlinear optical crystal whose at least +Z and −Z surfaces are covered with conductive members similar to the wavelength conversion device **50**, and outputs a green light whose wavelength is converted.

The light output from the liquid crystal panel **2104** is incident into the liquid crystal panel **2104** via the collimated optical system **2102** and the integrated optical system **2103**.

The light incident into the liquid crystal panel **2104** is modulated based on display information and is enlarged and projected on the screen **2110** by the projector lens **2105**.

In this case as well, a high-power light is output from the light source device **2101**. Therefore, it is possible to display information on the screen **2110** with excellent display quality.

It should be noted that a projector using a reflective liquid crystal panel may also be used.

The present invention is not limited to the above-mentioned embodiments, and variations and modifications may be made without departing from the scope of the present invention.

The present application is based on and claims the benefit of priority of Japanese Patent Application No. 2007-078233 filed on Mar. 26, 2007, the entire contents of which are hereby incorporated by reference.

INDUSTRIAL APPLICABILITY

As described above, the wavelength conversion device according to an embodiment of the present invention is suitable to output a high-power harmonic stably. Further, the laser apparatus according to an embodiment of the present invention is suitable to output a high-power laser light stably. Still further, the image forming apparatus according an embodiment of the present invention is suitable to form an image quickly. Still further, the display apparatus according to an embodiment of the present invention is suitable to display information with excellent display quality.

The invention claimed is:

1. A wavelength conversion device comprising:

a nonlinear optical crystal having a periodic polarization reversed structure; and

transparent conductive members covering at least two regions of the nonlinear optical crystal, wherein

a spontaneous polarization direction of the nonlinear optical crystal crosses the at least two regions, and

an incident surface of the nonlinear optical crystal is covered with an antireflection film made of a same material as that of the transparent conductive members.

2. The wavelength conversion device according to claim **1**, wherein

the conductive members covering the at least two regions are shorted to each other.

3. The wavelength conversion device according to claim **1**, wherein

the at least two regions includes a +z surface and a −z surface of the crystal surfaces.

4. The wavelength conversion device according to claim **3**, wherein the at least two regions further include either a +Y surface or a −Y surface of the crystal surfaces.

5. A laser apparatus comprising:

at least one laser light source; and

the wavelength conversion device according to claim **1** disposed on an optical path of a laser light from the at least one laser light source.

6. An image forming apparatus for forming an image on an image display medium, the image forming apparatus comprising:

at least one laser apparatus according to claim **5**; and

an exposure apparatus for exposing the image display medium based on image information.

7. A display apparatus for displaying information on a screen using a light, the display apparatus comprising:

a light source unit having at least one laser apparatus according to claim **5**; and

an optical system for transmitting the light from the light source unit to the screen.

8. The wavelength conversion device according to claim **1**, wherein the transparent conductive members have a multi-layered structure.

9. The wavelength conversion device according to claim **1**, wherein the transparent conductive members include one of ITO, tin oxide, zinc oxide, or indium oxide.

10. A wavelength conversion device comprising:

a nonlinear optical crystal having a periodic polarization reversed structure, a cross sectional shape orthogonal to the periodic direction of the polarization reversed structure being substantially a circle or an ellipse; and

a transparent conductive member covering a circumferential surface of the nonlinear optical crystal,

wherein an incident surface of the nonlinear optical crystal is covered with an antireflection film made of a same material as that of the transparent conductive member.

11. The wavelength conversion device according to claim **1**, wherein

the nonlinear optical crystal is an Mg-doped lithium niobate crystal.

12. The wavelength conversion device according to claim **1**, wherein

at least a part of the conductive member is a metal.

13. The wavelength conversion device according to claim **1**, wherein

at least a part of the conductive member is a conductive paste.

* * * * *