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(54) **TITANIUM-SAPPHIRE LASER APPARATUS, LASER APPARATUS USED FOR EXPOSURE APPARATUS, AND TITANIUM-SAPPHIRE AMPLIFIER**

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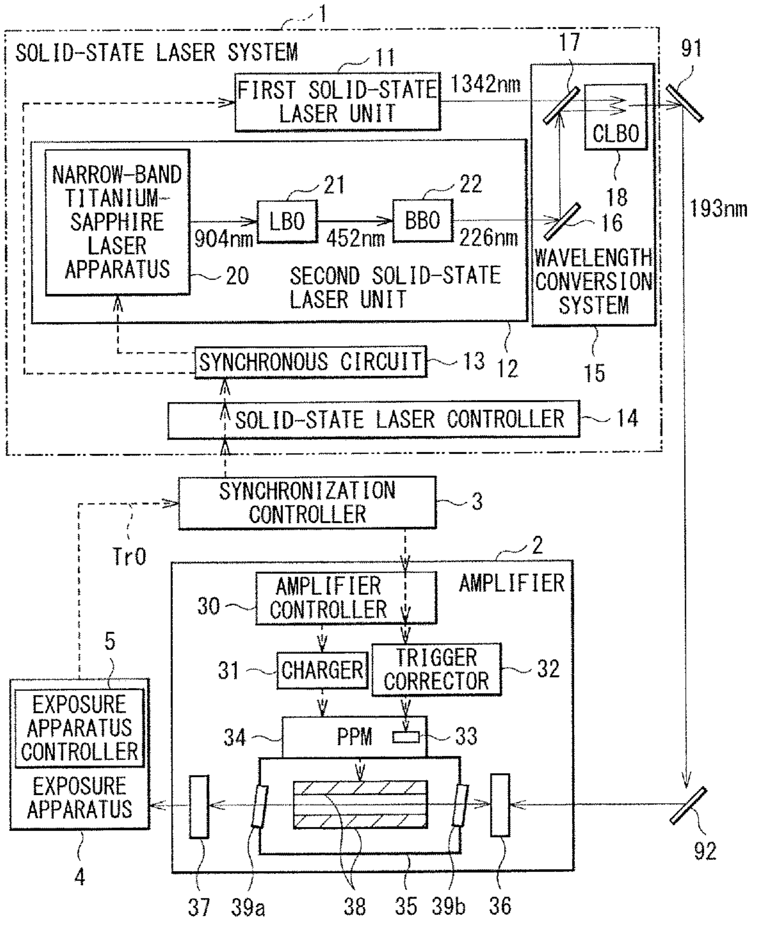
CPC ***H01S 3/1625*** (2013.01); ***H01S 3/1636*** (2013.01); *H01S 3/23* (2013.01)

(57) **ABSTRACT**

A titanium-sapphire laser apparatus may include a continuous wave oscillation laser unit, an amplification oscillator, a pulsed laser unit, an error detector, an error controller, and an optical path length corrector. The amplification oscillator may include an optical resonator and a titanium-sapphire crystal that is provided in an optical path in the optical resonator. The error detector may be provided in an optical path of leak light of seed light from the optical resonator, and may detect an optical path length error between an optical path length in the optical resonator and a positive integer multiple of a wavelength of the seed light and output an optical path length error signal. The optical path length corrector may vary the optical path length in the optical resonator on a basis of a signal resulting from adding a correction value to the optical path error signal.



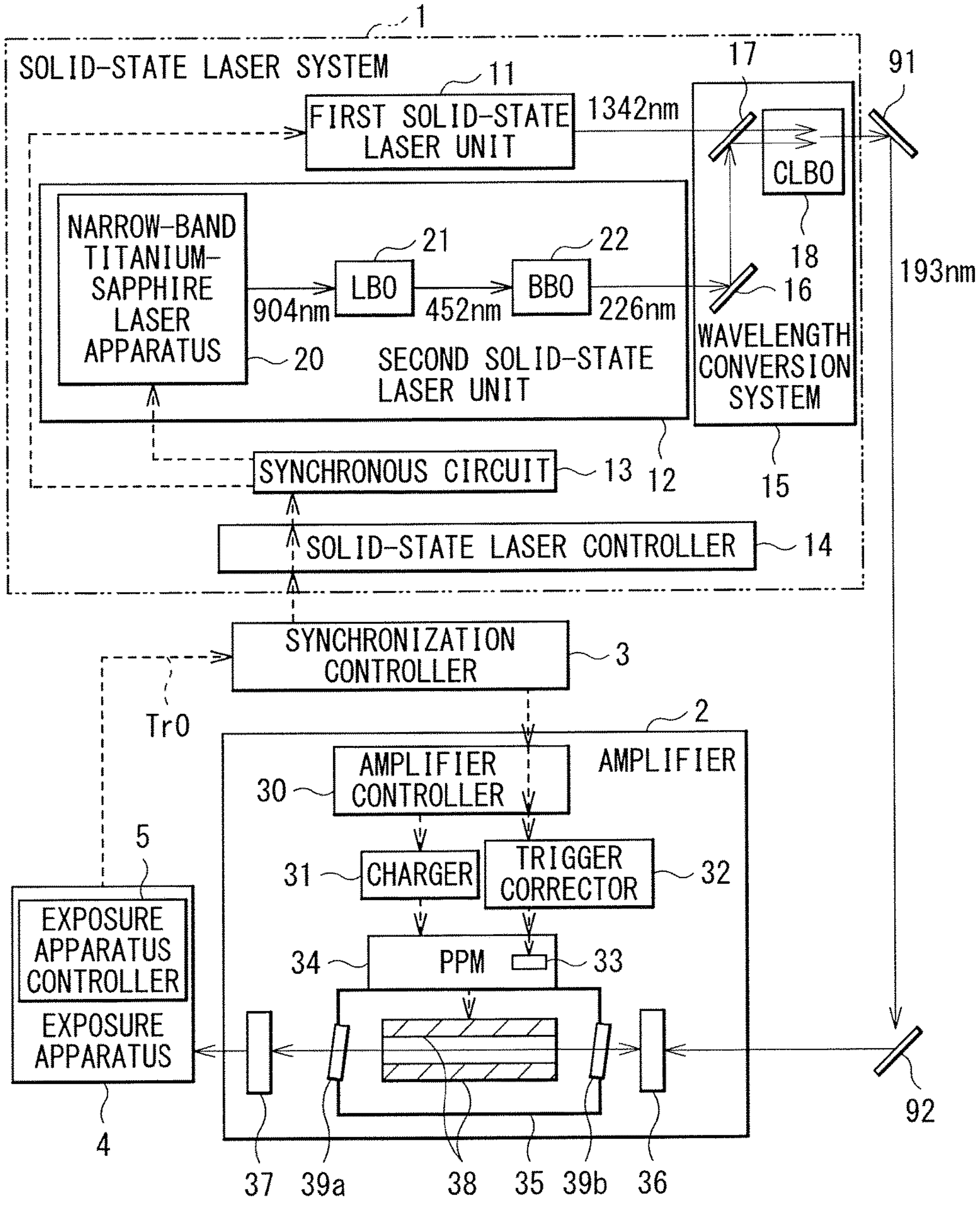

1
SOLID-STATE LASER SYSTEM
11
FIRST SOLID-STATE LASER UNIT
1342nm
17
CLBO
91
18
16
193nm
NARROW-BAND TITANIUM-SAPPHIRE LASER APPARATUS
21
LBO
22
BBO
904nm
452nm
226nm
20
SECOND SOLID-STATE LASER UNIT
WAVELENGTH CONVERSION SYSTEM
SYNCHRONOUS CIRCUIT
13
12
15
SOLID-STATE LASER CONTROLLER
14
SYNCHRONIZATION CONTROLLER
3
Tr0
2
AMPLIFIER
AMPLIFIER CONTROLLER
30
5
CHARGER
31
TRIGGER CORRECTOR
32
EXPOSURE APPARATUS CONTROLLER
34
PPM
33
EXPOSURE APPARATUS
92
4
37
39a
38
35
39b
36

FIG. 1

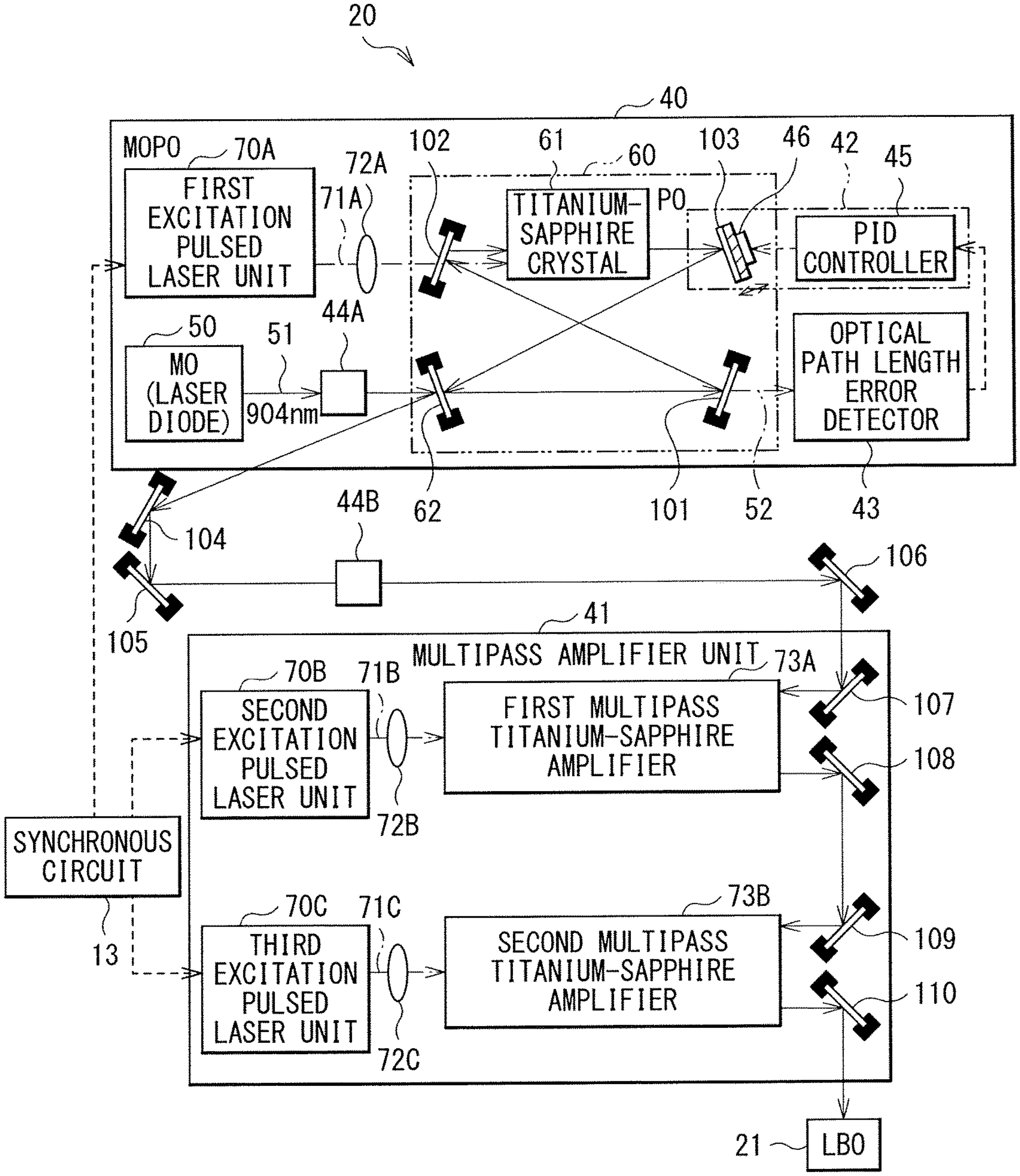

20
40
MOPO
70A
FIRST EXCITATION PULSED LASER UNIT
72A
71A
102
61
60
TITANIUM-SAPPHIRE CRYSTAL
PO
103
46
42
45
PID CONTROLLER
50
MO (LASER DIODE)
51
904nm
44A
OPTICAL PATH LENGTH ERROR DETECTOR
62
101
52
43
104
44B
105
106
41
MULTIPASS AMPLIFIER UNIT
73A
70B
SECOND EXCITATION PULSED LASER UNIT
71B
72B
FIRST MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER
107
108
SYNCHRONOUS CIRCUIT
13
70C
THIRD EXCITATION PULSED LASER UNIT
71C
72C
73B
SECOND MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER
109
110
21
LBO

FIG. 2

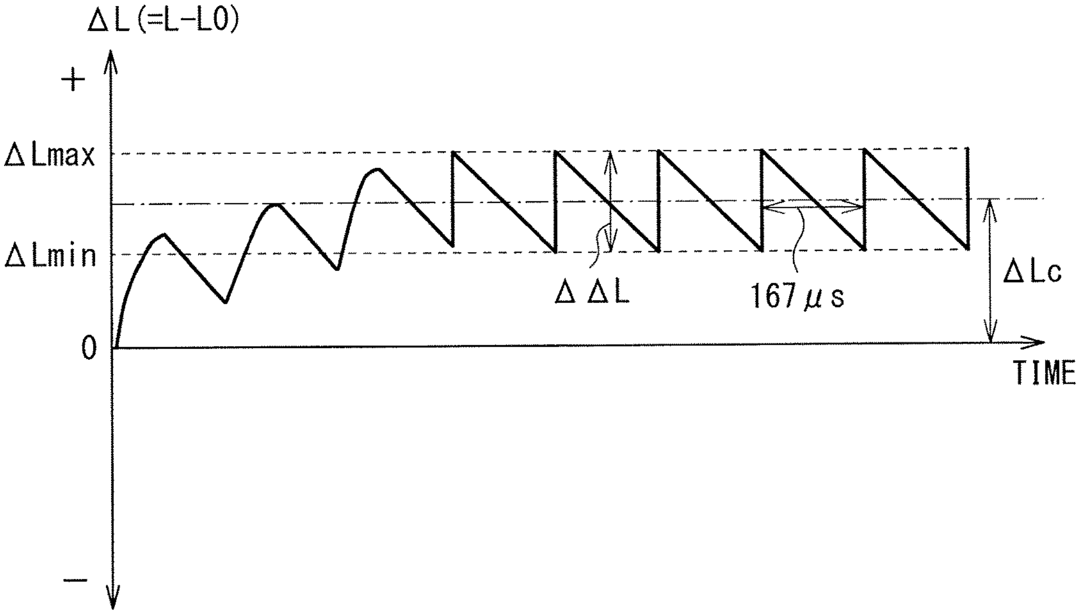

ΔL (=L−L0)
+
ΔLmax
ΔLmin
0
−
ΔΔL
167 μs
ΔLc
TIME

FIG. 3

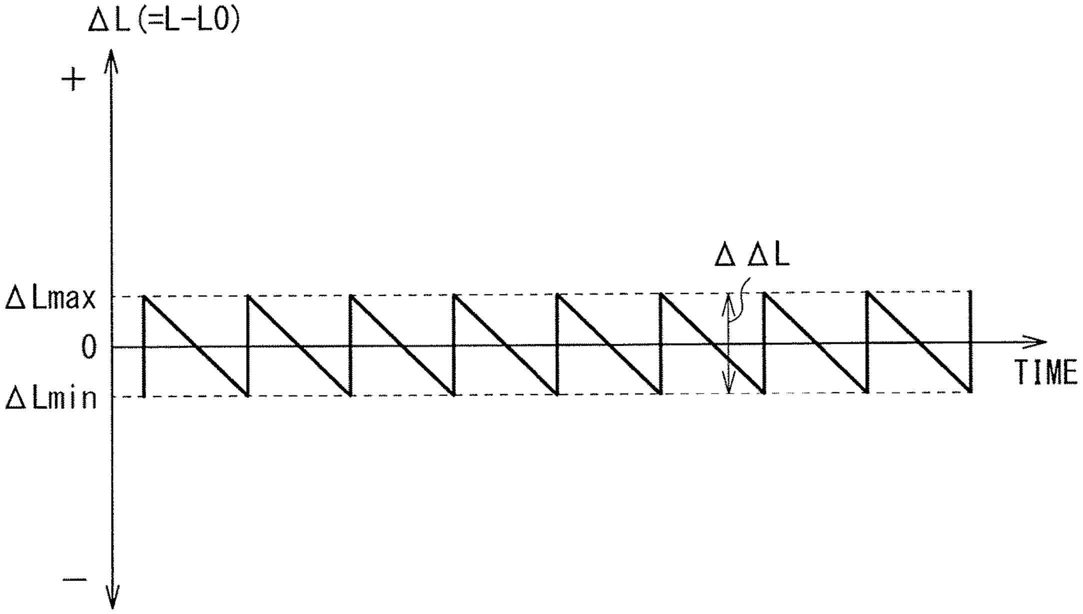

ΔL (=L−L0)
+
ΔΔL
ΔLmax
0
ΔLmin
TIME
−

FIG. 4

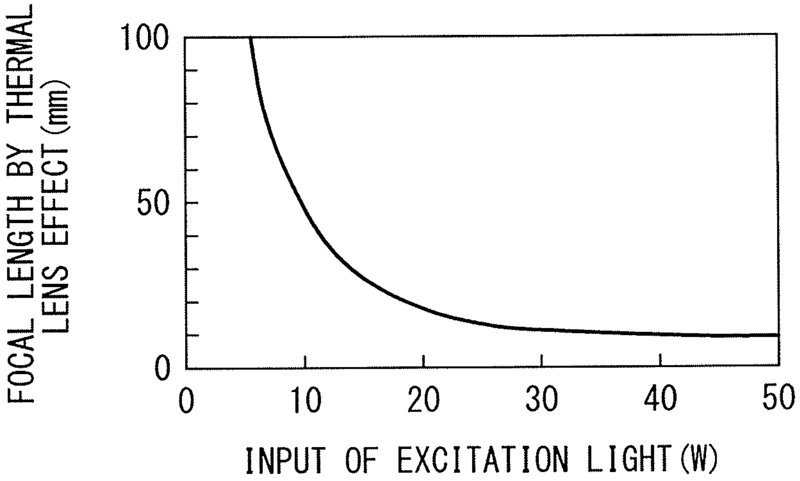

FOCAL LENGTH BY THERMAL LENS EFFECT (mm)
100
50
0
0
10
20
30
40
50
INPUT OF EXCITATION LIGHT (W)

FIG. 5

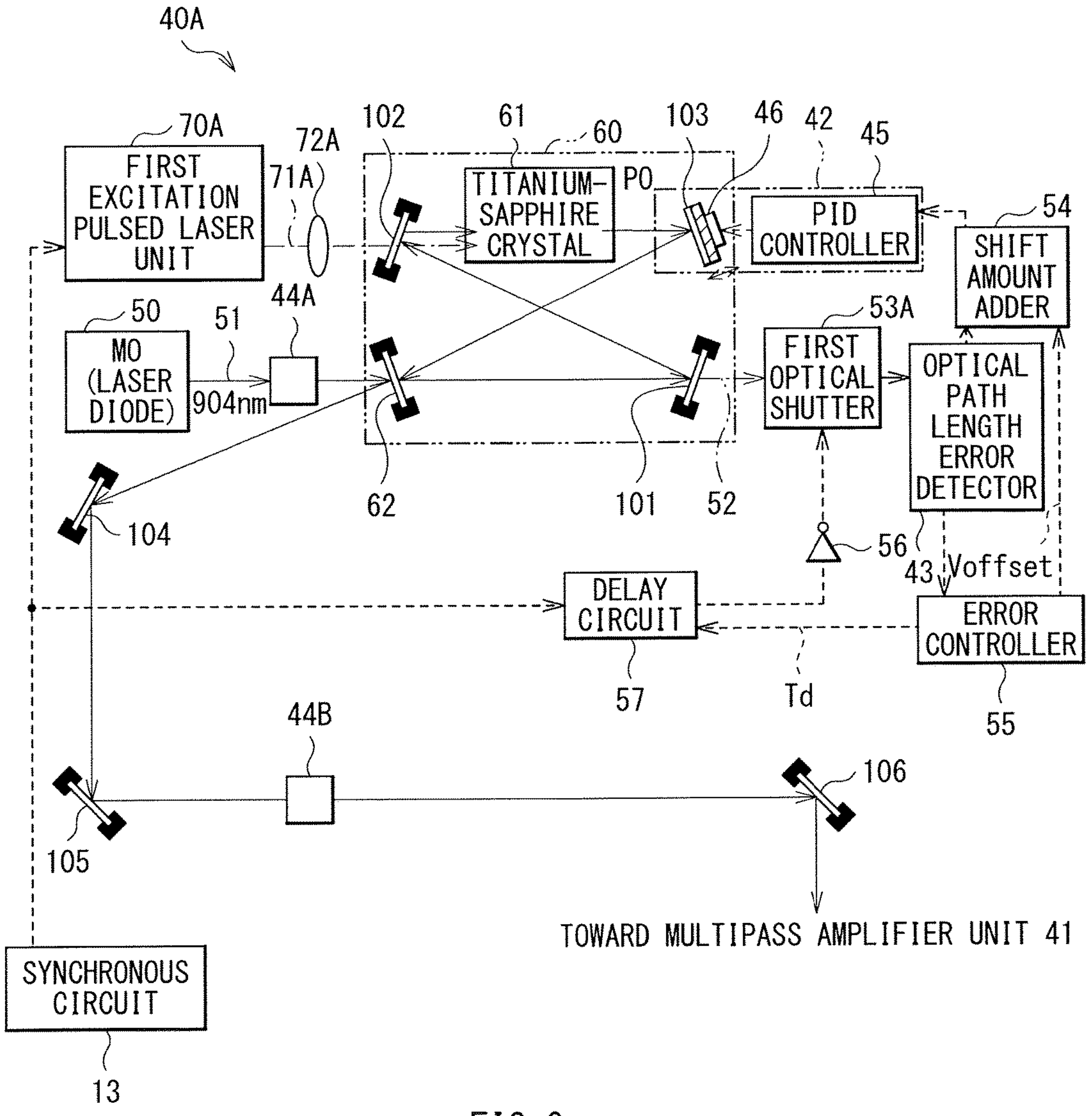

40A
70A
FIRST EXCITATION PULSED LASER UNIT
71A
72A
102
61
60
TITANIUM-SAPPHIRE CRYSTAL
P0
103
46
42
45
PID CONTROLLER
54
SHIFT AMOUNT ADDER
50
MO (LASER DIODE)
51
904nm
44A
53A
FIRST OPTICAL SHUTTER
OPTICAL PATH LENGTH ERROR DETECTOR
62
101
52
104
56
43
Voffset
DELAY CIRCUIT
ERROR CONTROLLER
57
Td
55
44B
106
105
TOWARD MULTIPASS AMPLIFIER UNIT 41
SYNCHRONOUS CIRCUIT
13

FIG. 6

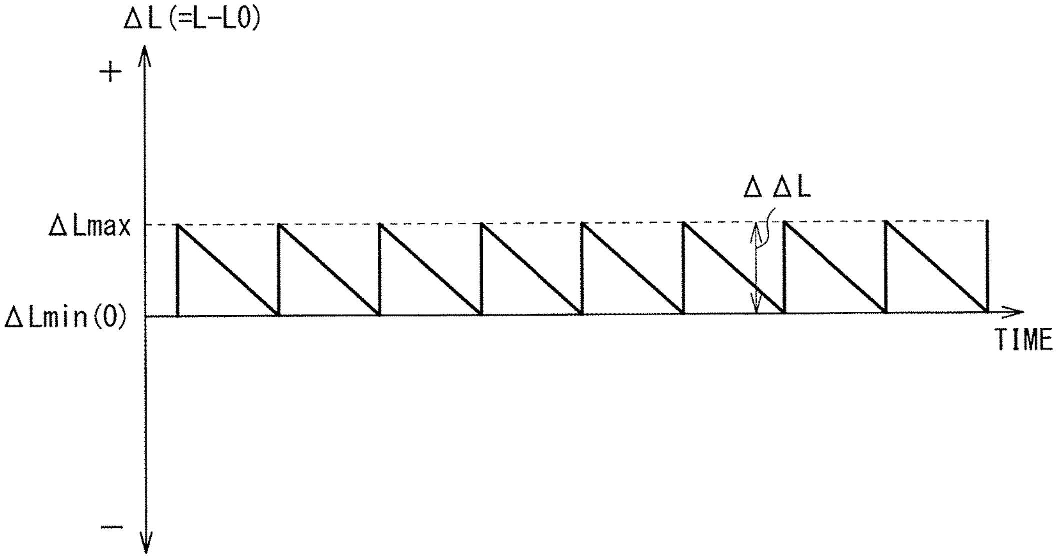


FIG. 7

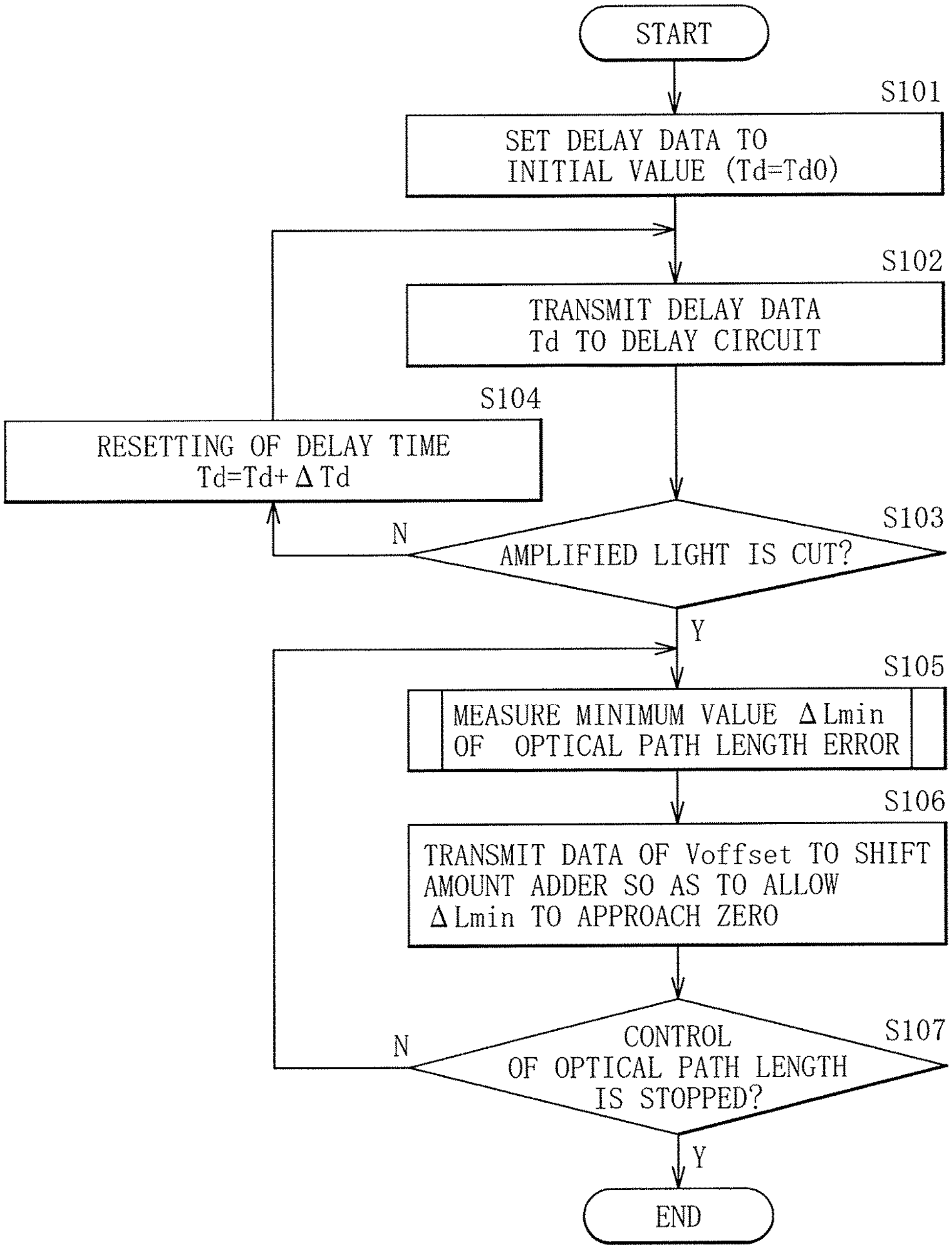

START
S101
SET DELAY DATA TO INITIAL VALUE (Td=Td0)
S102
TRANSMIT DELAY DATA Td TO DELAY CIRCUIT
S104
RESETTING OF DELAY TIME Td=Td+ΔTd
S103
AMPLIFIED LIGHT IS CUT?
N
Y
S105
MEASURE MINIMUM VALUE ΔLmin OF OPTICAL PATH LENGTH ERROR
S106
TRANSMIT DATA OF Voffset TO SHIFT AMOUNT ADDER SO AS TO ALLOW ΔLmin TO APPROACH ZERO
S107
CONTROL OF OPTICAL PATH LENGTH IS STOPPED?
N
Y
END

FIG. 8

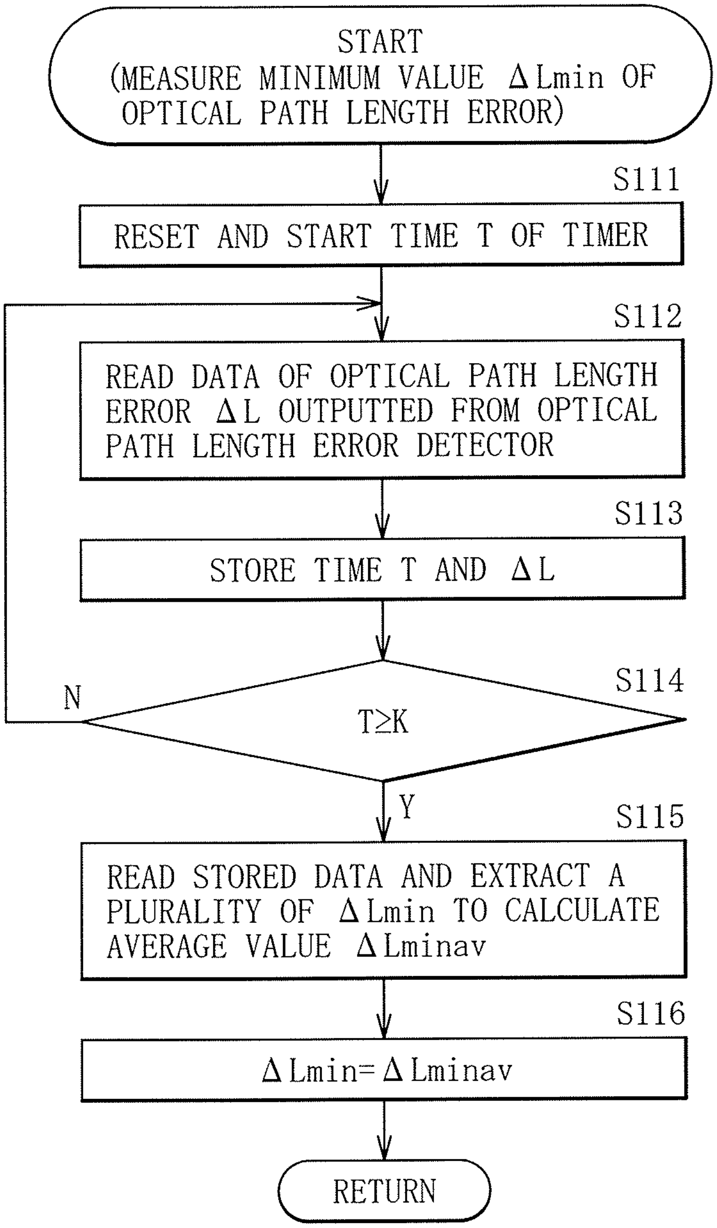
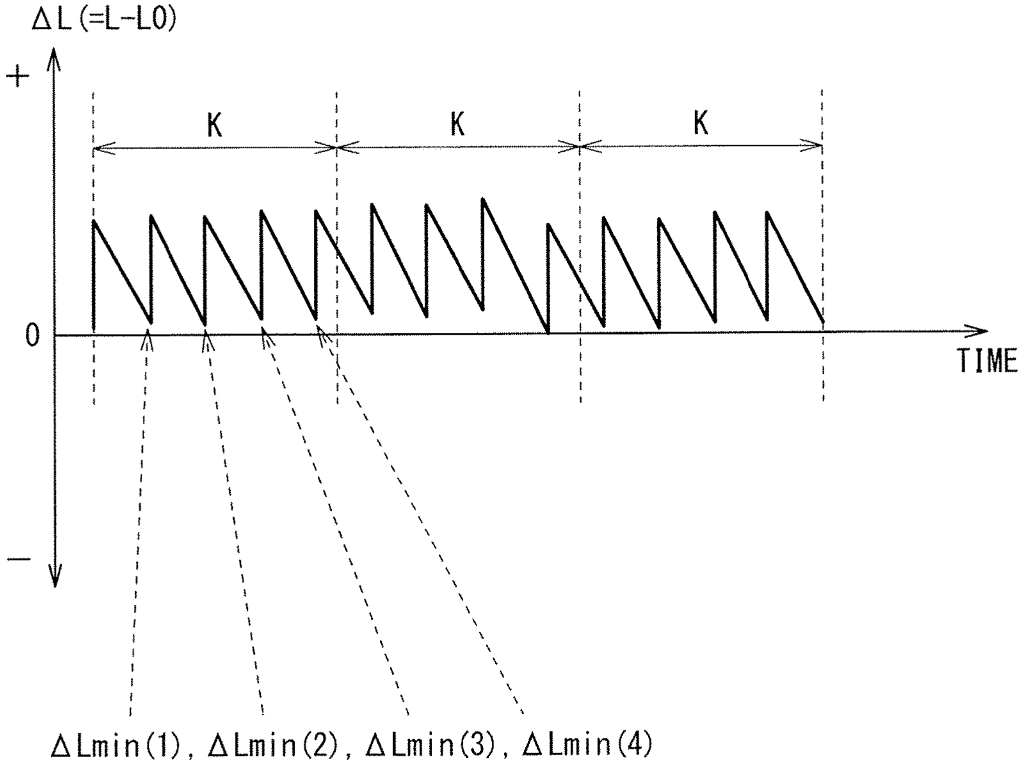

START
(MEASURE MINIMUM VALUE ΔLmin OF OPTICAL PATH LENGTH ERROR)
S111
RESET AND START TIME T OF TIMER
S112
READ DATA OF OPTICAL PATH LENGTH ERROR ΔL OUTPUTTED FROM OPTICAL PATH LENGTH ERROR DETECTOR
S113
STORE TIME T AND ΔL
S114
T≥K
N
Y
S115
READ STORED DATA AND EXTRACT A PLURALITY OF ΔLmin TO CALCULATE AVERAGE VALUE ΔLminav
S116
ΔLmin=ΔLminav
RETURN

FIG. 9



$\Delta Lminav=\{\Delta Lmin(1)+\Delta Lmin(2)+\Delta Lmin(3)+\Delta Lmin(4)\}/4$

FIG. 10

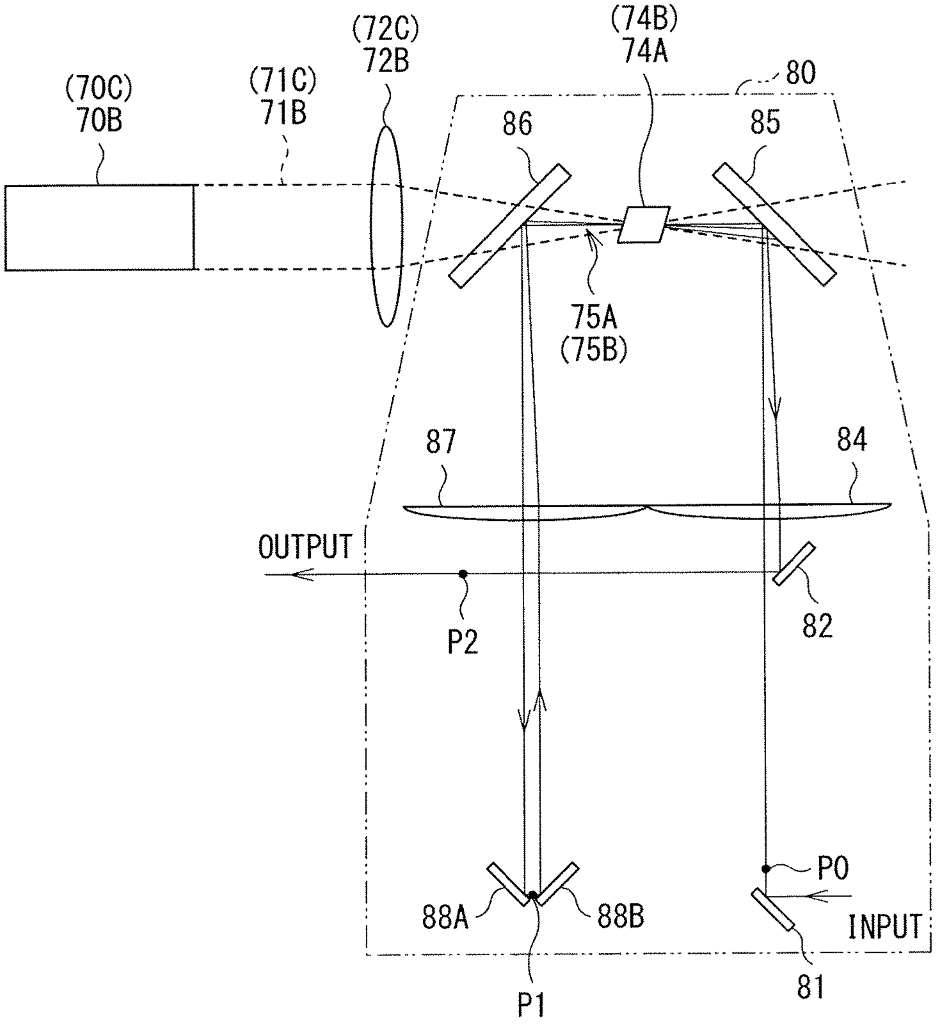

(70C)
70B
(71C)
71B
(72C)
72B
(74B)
74A
80
86
85
75A
(75B)
87
84
OUTPUT
P2
82
P0
88A
88B
INPUT
P1
81

FIG. 11

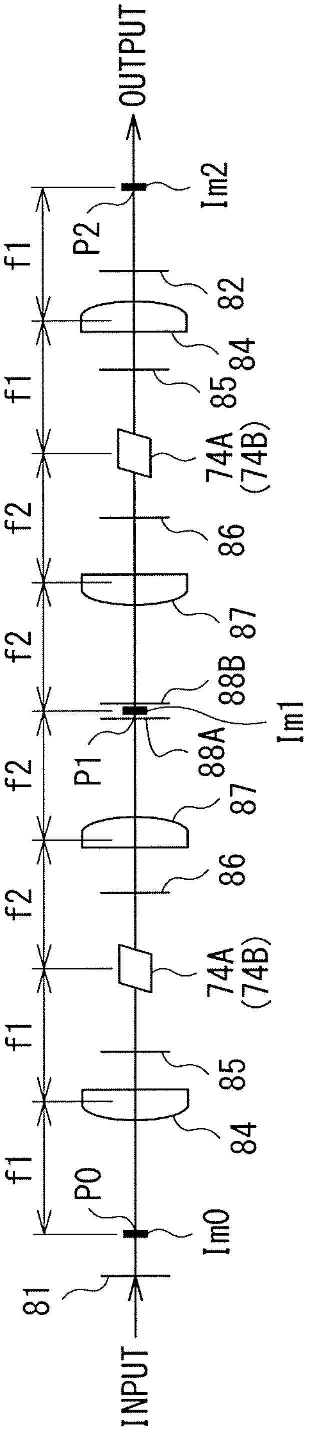

INPUT
81
Im0
P0
f1
84
85
f1
74A
(74B)
f2
86
87
f2
P1
88A
Im1
88B
f2
87
86
f2
74A
(74B)
f1
85
84
f1
82
P2
Im2
OUTPUT

FIG. 12

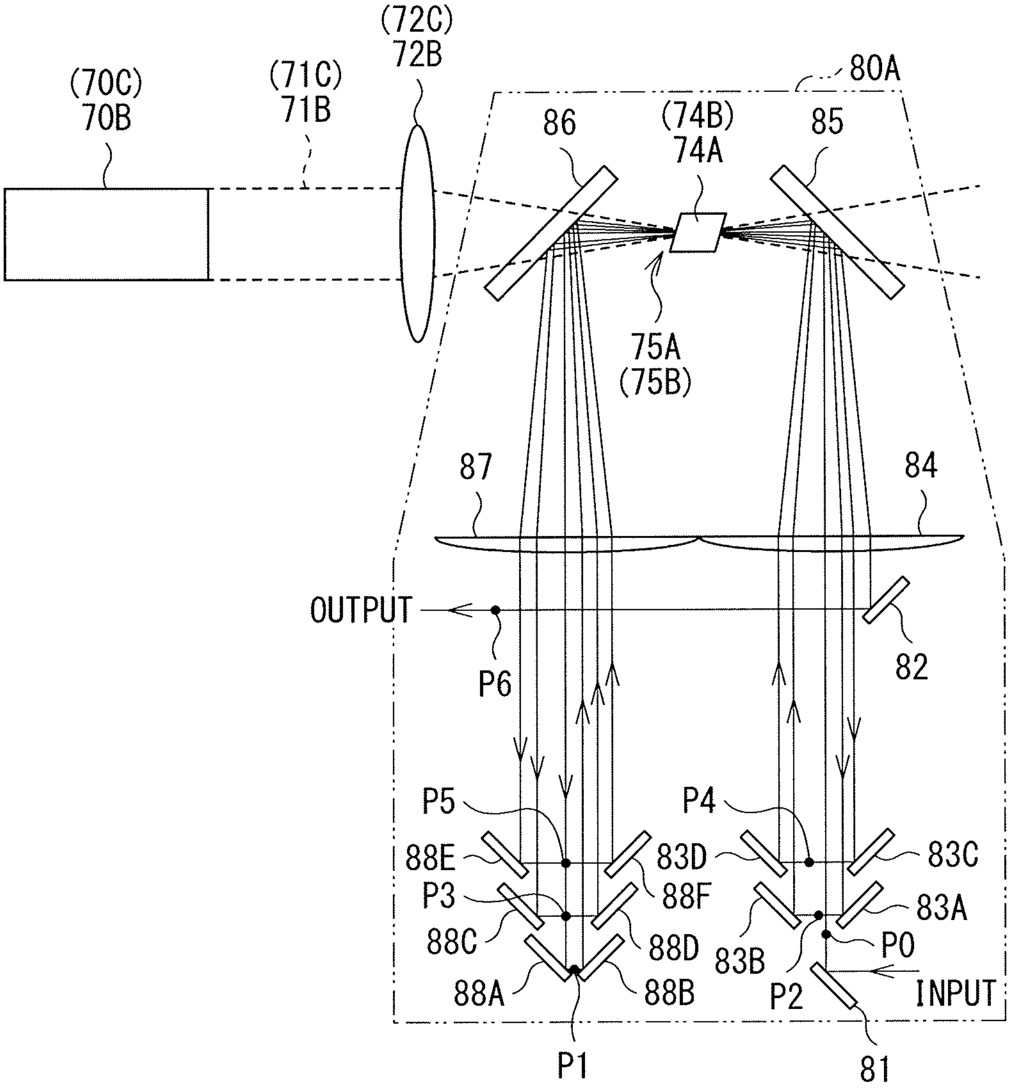

(72C)
72B
(71C)
71B
(70C)
70B
80A
86
(74B)
74A
85
75A
(75B)
87
84
OUTPUT
P6
82
P5
P4
88E
83D
83C
P3
88F
83A
88C
88D
83B
P0
88A
88B
P2
INPUT
P1
81

FIG. 13

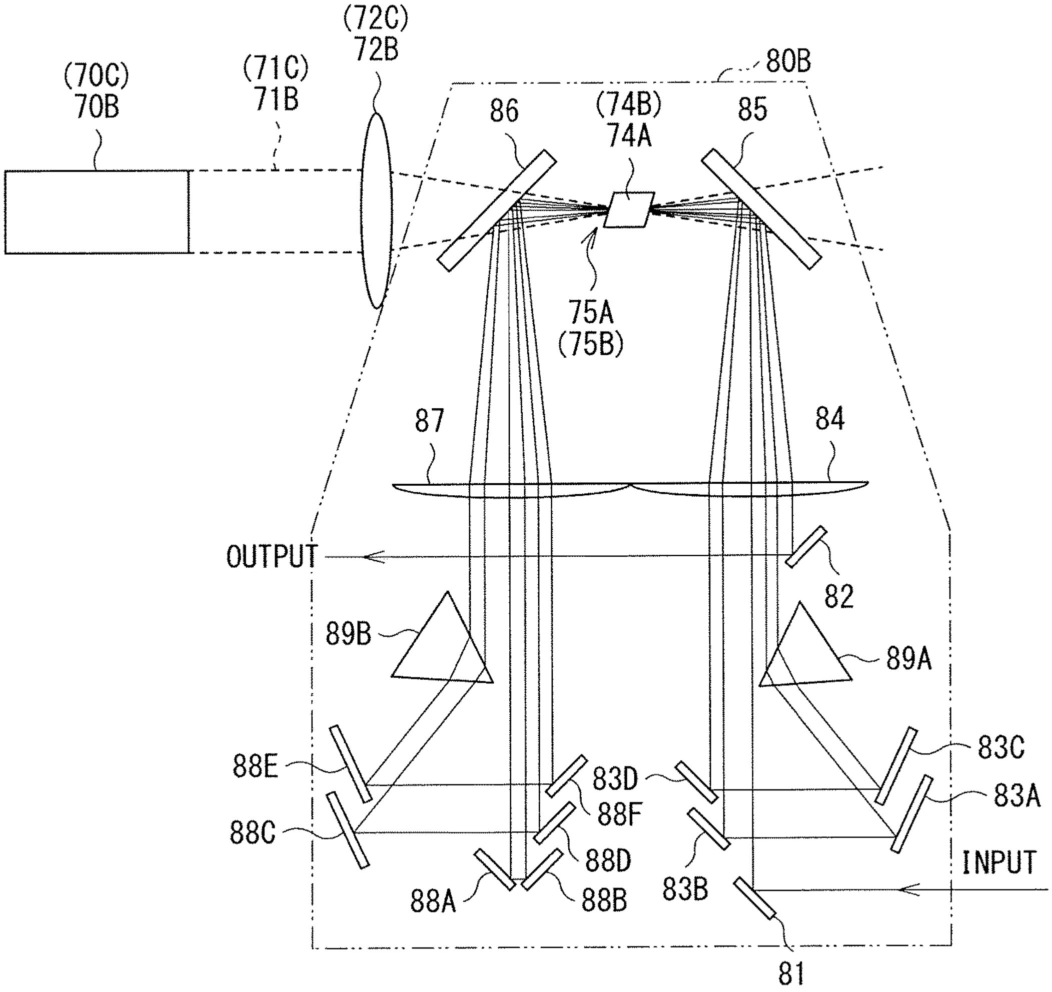

(72C)
72B
80B
(70C)
70B
(71C)
71B
86
(74B)
74A
85
75A
(75B)
87
84
OUTPUT
82
89B
89A
88E
83D
83C
83A
88F
88C
88D
INPUT
83B
88A
88B
81

FIG. 14

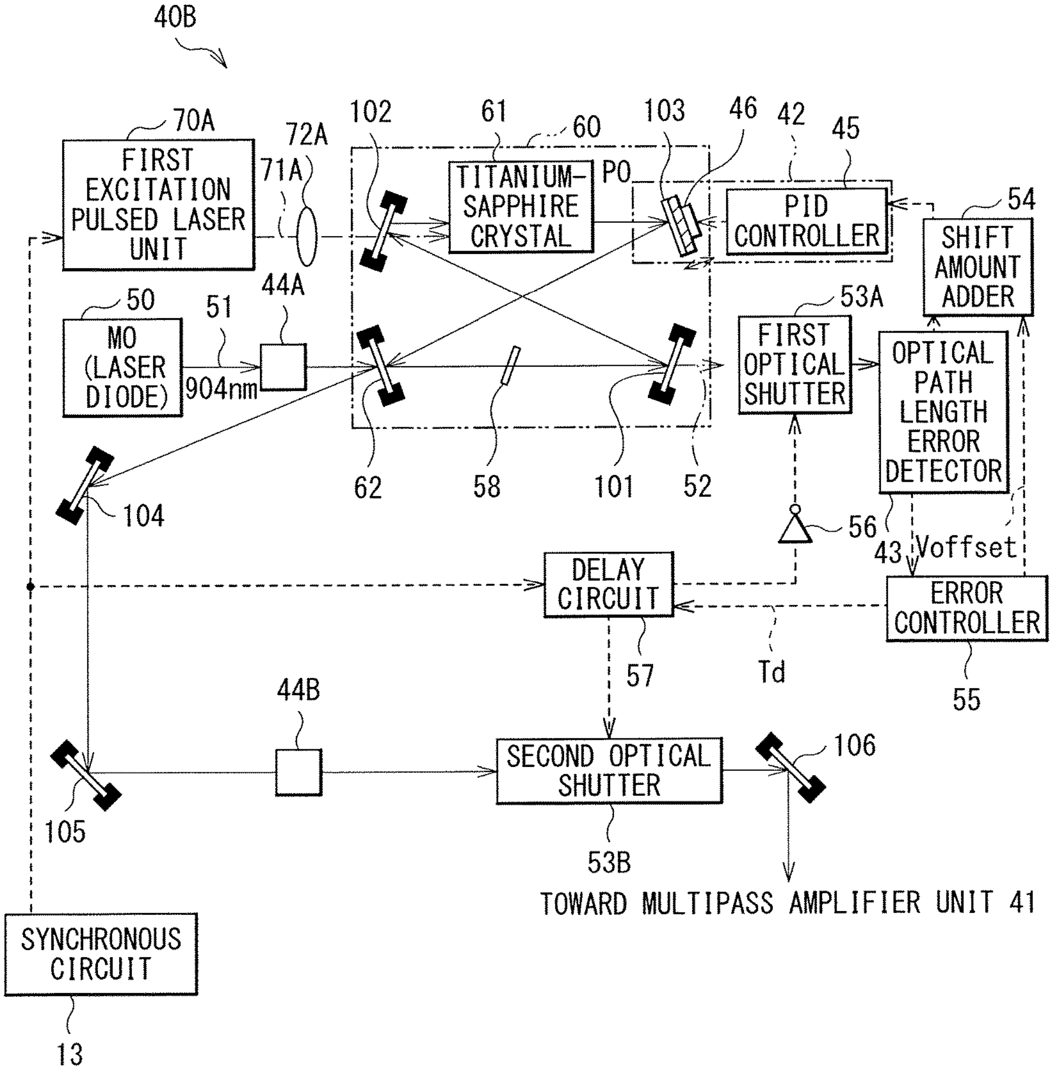

40B
70A
FIRST EXCITATION PULSED LASER UNIT
72A
71A
102
61
60
TITANIUM-SAPPHIRE CRYSTAL
P0
103
46
42
45
PID CONTROLLER
54
SHIFT AMOUNT ADDER
50
MO (LASER DIODE)
51
904nm
44A
53A
FIRST OPTICAL SHUTTER
OPTICAL PATH LENGTH ERROR DETECTOR
62
58
101
52
104
56
43
Voffset
DELAY CIRCUIT
ERROR CONTROLLER
57
Td
55
44B
SECOND OPTICAL SHUTTER
106
105
53B
TOWARD MULTIPASS AMPLIFIER UNIT 41
SYNCHRONOUS CIRCUIT
13

FIG. 15

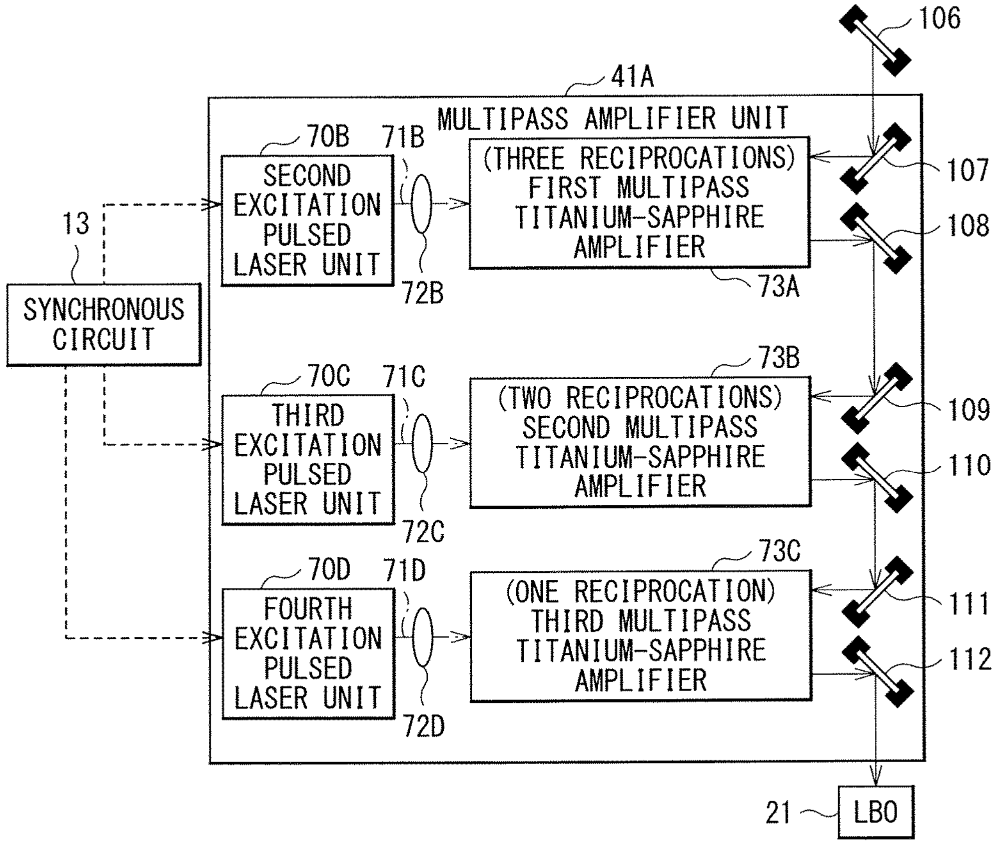

106
41A
MULTIPASS AMPLIFIER UNIT
70B
71B
SECOND EXCITATION PULSED LASER UNIT
(THREE RECIPROCATIONS) FIRST MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER
107
108
13
72B
73A
SYNCHRONOUS CIRCUIT
73B
70C
71C
THIRD EXCITATION PULSED LASER UNIT
(TWO RECIPROCATIONS) SECOND MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER
109
110
72C
73C
70D
71D
FOURTH EXCITATION PULSED LASER UNIT
(ONE RECIPROCATION) THIRD MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER
111
112
72D
21
LBO

FIG. 16

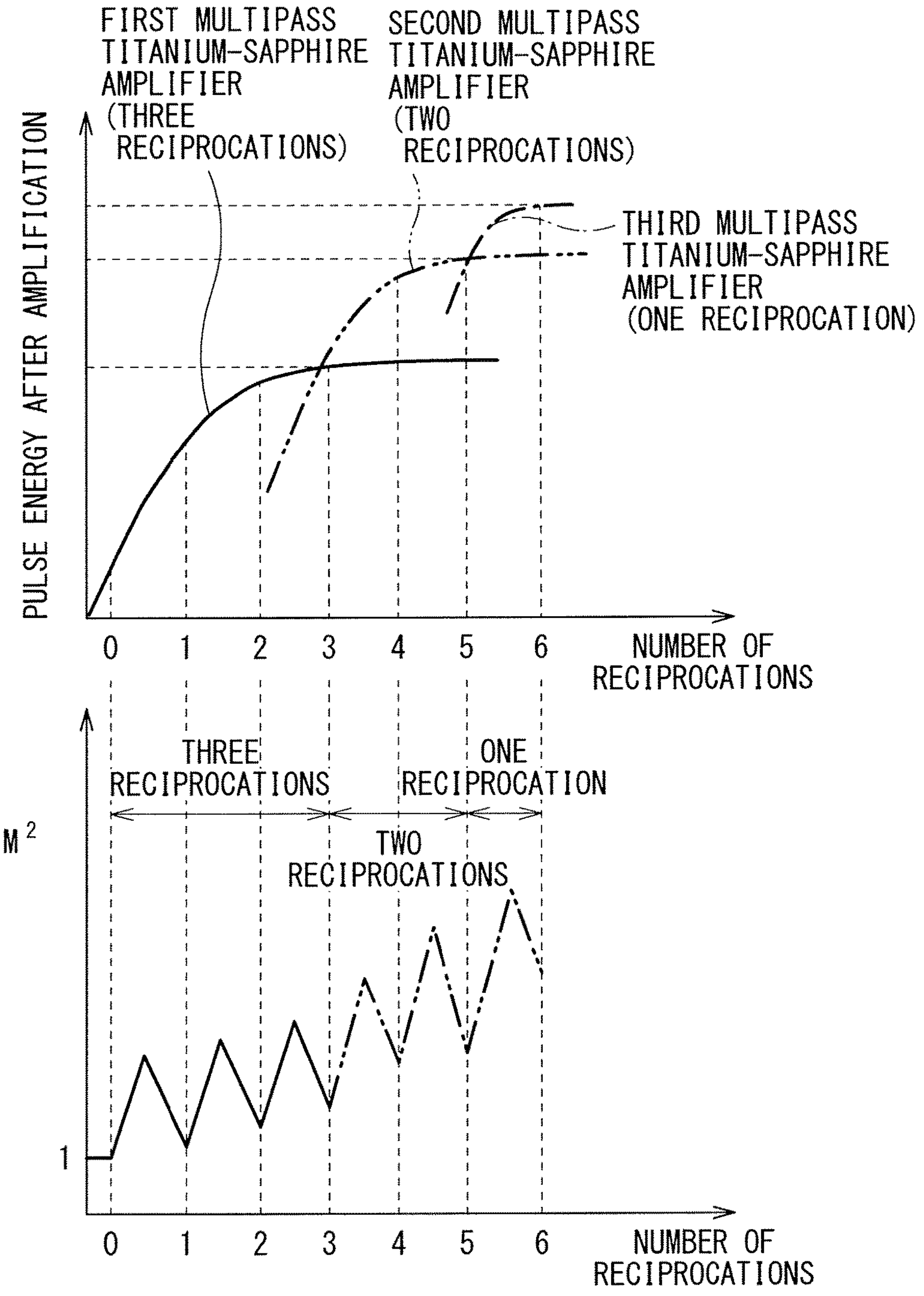

FIRST MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER (THREE RECIPROCATIONS)
SECOND MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER (TWO RECIPROCATIONS)
THIRD MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER (ONE RECIPROCATION)
PULSE ENERGY AFTER AMPLIFICATION
0
1
2
3
4
5
6
NUMBER OF RECIPROCATIONS
THREE RECIPROCATIONS
TWO RECIPROCATIONS
ONE RECIPROCATION
M^2
1
0
1
2
3
4
5
6
NUMBER OF RECIPROCATIONS

FIG. 17

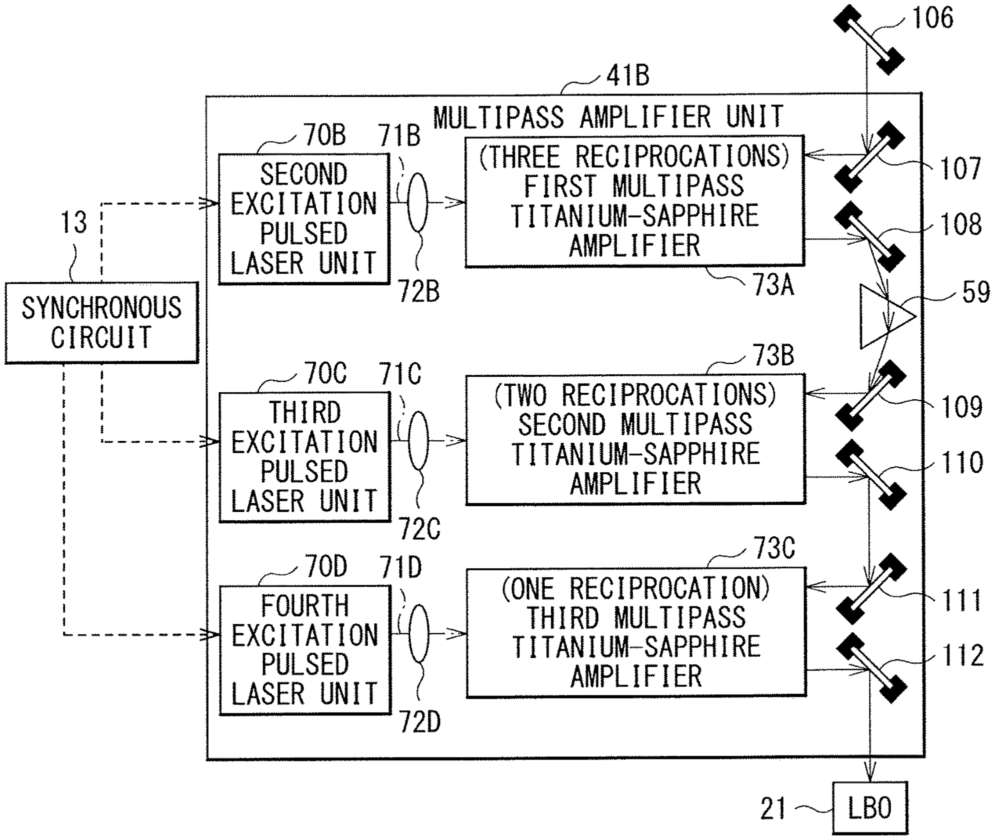

106
41B
MULTIPASS AMPLIFIER UNIT
70B
71B
SECOND EXCITATION PULSED LASER UNIT
(THREE RECIPROCATIONS) FIRST MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER
107
108
13
72B
73A
SYNCHRONOUS CIRCUIT
59
73B
70C
71C
THIRD EXCITATION PULSED LASER UNIT
(TWO RECIPROCATIONS) SECOND MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER
109
110
72C
73C
70D
71D
FOURTH EXCITATION PULSED LASER UNIT
(ONE RECIPROCATION) THIRD MULTIPASS TITANIUM-SAPPHIRE AMPLIFIER
111
112
72D
21
LBO

FIG. 18

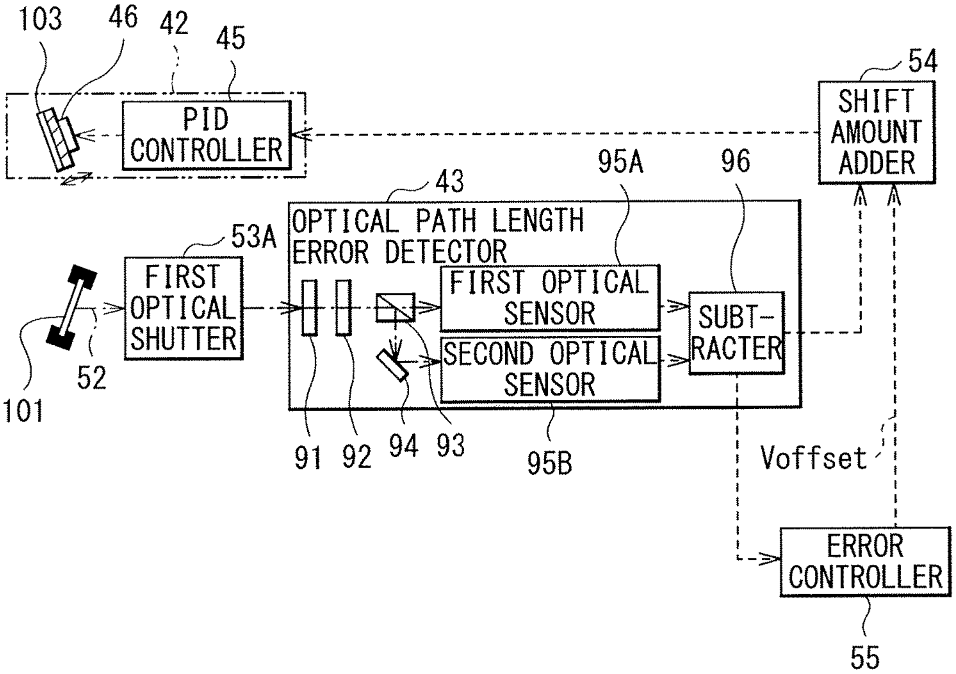

103
46
42
45
PID CONTROLLER
54
SHIFT AMOUNT ADDER
43
95A
96
OPTICAL PATH LENGTH ERROR DETECTOR
53A
FIRST OPTICAL SHUTTER
FIRST OPTICAL SENSOR
SECOND OPTICAL SENSOR
SUBT-RACTER
101
52
91
92
94
93
95B
Voffset
ERROR CONTROLLER
55

FIG. 19

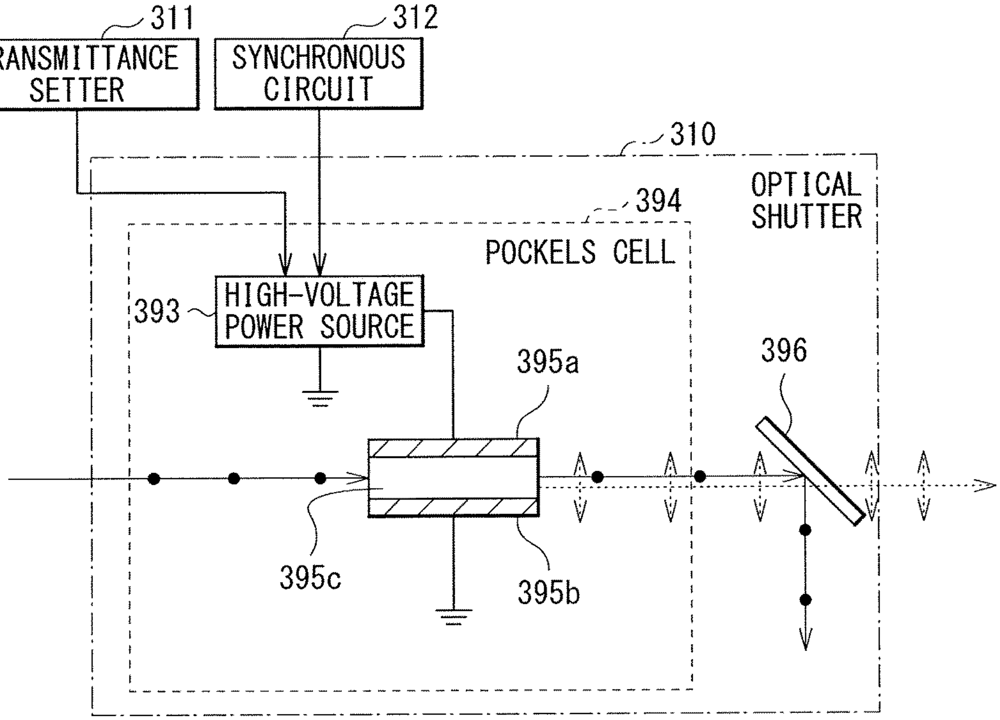

311
TRANSMITTANCE SETTER
312
SYNCHRONOUS CIRCUIT
310
OPTICAL SHUTTER
394
POCKELS CELL
393
HIGH-VOLTAGE POWER SOURCE
395a
396
395c
395b

FIG. 20

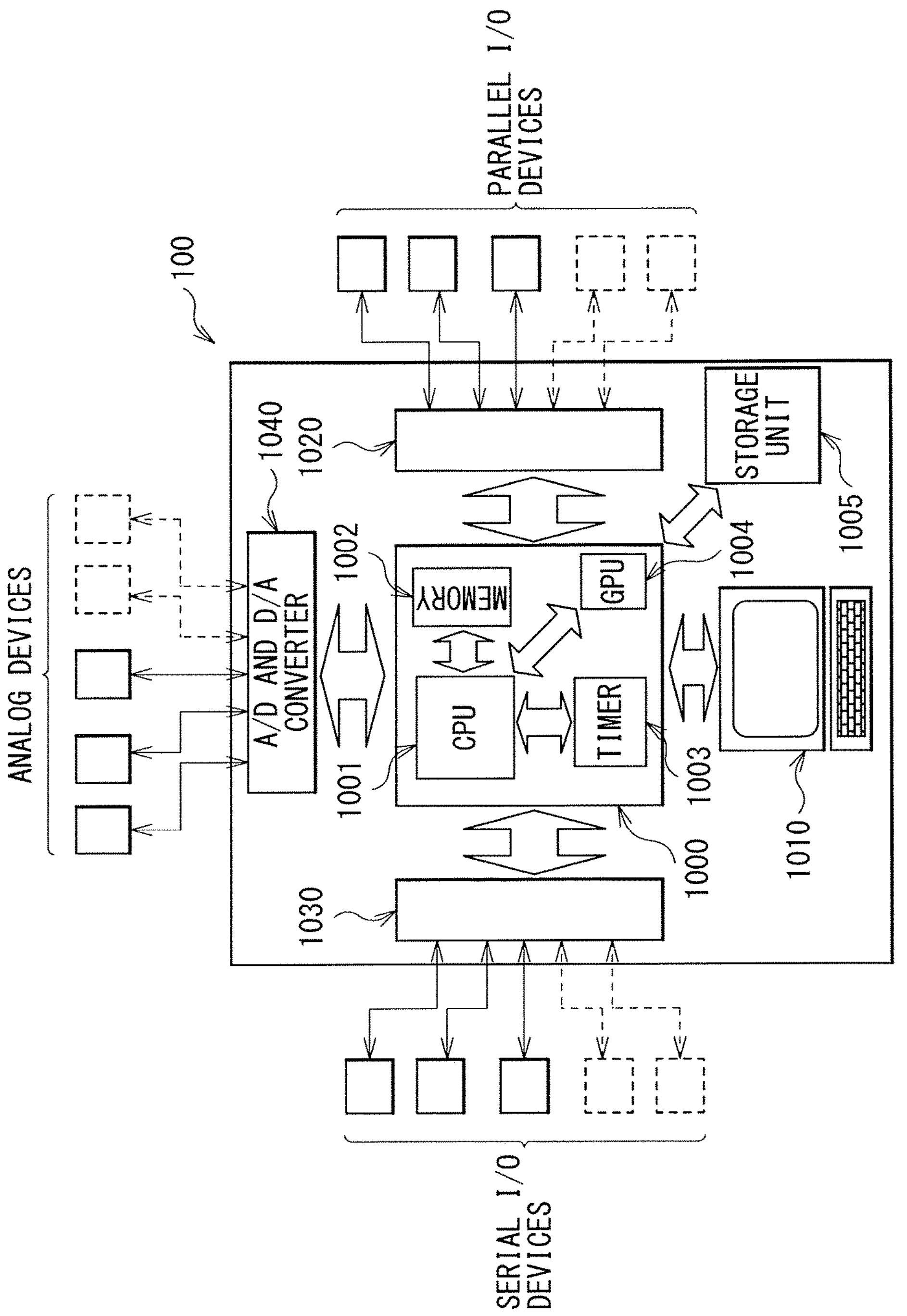

100
PARALLEL I/O DEVICES
1040
1020
STORAGE UNIT
1005
1002
MEMORY
GPU
1004
A/D AND D/A CONVERTER
CPU
TIMER
1001
1003
1000
1010
1030
ANALOG DEVICES
SERIAL I/O DEVICES

FIG. 21

TITANIUM-SAPPHIRE LASER APPARATUS, LASER APPARATUS USED FOR EXPOSURE APPARATUS, AND TITANIUM-SAPPHIRE AMPLIFIER

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a continuation application of International Application No. PCT/JP2014/084618 filed on Dec. 26, 2014. The content of the application is incorporated herein by reference in its entirety.

BACKGROUND

[0002] 1. Technical Field

[0003] The present disclosure relates to a titanium-sapphire laser apparatus using a titanium-sapphire crystal, a laser apparatus used for an exposure apparatus, and a titanium-sapphire amplifier.

[0004] 2. Related Art

[0005] With miniaturization and high integration of a semiconductor integrated circuit, an improvement in resolution has been demanded for a semiconductor exposure apparatus. Hereinafter, the semiconductor exposure apparatus is simply referred to as an "exposure apparatus". Shortening in a wavelength of light to be outputted from an exposure light source has been in progress accordingly. A gas laser unit is used in place of an existing mercury lamp for the exposure light source. Currently, a KrF excimer laser unit and an ArF excimer laser unit may be used as gas laser units for exposure. The KrF excimer laser unit may output ultraviolet light of a wavelength of 248 nm, and the ArF excimer laser unit may output ultraviolet light of a wavelength of 193 nm.

[0006] As current exposure technology, liquid immersion exposure is practically used. In the liquid immersion exposure, a clearance between a projection lens on exposure apparatus side and a wafer is filled with a liquid to change a refractive index of the clearance, thereby shortening an apparent wavelength of light from the exposure light source. When the liquid immersion exposure is performed with use of the ArF excimer laser unit as the exposure light source, ultraviolet light of a wavelength of 134 nm in water is applied to the wafer. This technology is referred to as ArF liquid immersion exposure. The ArF liquid immersion exposure is also referred to as ArF liquid immersion lithography.

[0007] Since a spectral line width in free oscillation of each of the KrF excimer laser unit and the ArF excimer laser unit is wide, e.g., in a range from about 350 pm to about 400 pm, color aberration of laser light (ultraviolet light) that is reduced and projected on the wafer by the projection lens on the exposure apparatus side occurs, which results in decrease in resolution. It is therefore necessary to narrow a spectral line width of laser light to be outputted from the gas laser unit to an extent in which the color aberration is negligible. The spectral line width is also referred to as a spectral width. Accordingly, a line narrow module including a line narrowing device is provided in a laser resonator of the gas laser unit, which achieves narrowing of the spectral width. Non-limiting examples of the line narrowing device may include an etalon and a grating. The laser unit narrowed in spectral width in this way is referred to as a line narrowing laser unit. For example, reference is made to Japanese Unexamined Patent Application Publication No. 2013-135075, Japanese Unexamined Patent Application Publication No. 2013-222173, U.S. Patent Application Publication No. 2013/0163073, and U.S. Patent Application Publication No. 2013/0279526.

SUMMARY

[0008] A titanium-sapphire laser apparatus according to one aspect of the present disclosure may include: a continuous wave oscillation laser unit, an amplification oscillator, a pulsed laser unit, an error detector, an error controller, and an optical path length corrector. The continuous wave oscillation laser unit may be configured to perform continuous wave oscillation in a single longitudinal mode to output seed light. The seed light may enter the amplified oscillator. The amplification oscillator may include an optical resonator and a titanium-sapphire crystal. The titanium-sapphire crystal may be provided in an optical path in the optical resonator. The pulsed laser unit may be configured to output pulsed laser light toward the titanium-sapphire crystal. The error detector may be provided in an optical path of leak light of the seed light from the optical resonator, and may be configured to detect an optical path length error between an optical path length in the optical resonator and a positive integer multiple of a wavelength of the seed light and output an optical path length error signal. The error controller may be configured to output a correction value of the optical path length error signal. The optical path length corrector may be configured to vary the optical path length in the optical resonator on a basis of a signal. The signal may result adding the correction value to the optical path error signal.

[0009] A laser apparatus according to one aspect of the present disclosure may be used for an exposure apparatus. The laser apparatus may include a master oscillator power oscillator, a first multipass amplifier, and a second multipass amplifier. The master oscillator power oscillator may include a continuous wave oscillation laser unit. The continuous wave oscillation laser unit may be configured to perform continuous wave oscillation in a single longitudinal mode to output seed light. The first multipass amplifier may include a first multipass optical system and a first titanium-sapphire crystal. The first multipass optical system may allow the seed light outputted from the master oscillator power oscillator to reciprocate therethrough, and the first titanium-sapphire crystal may be provided in a first multiple optical path in the first multipass optical system. The second multipass amplifier may include a second multipass optical system and a second titanium-sapphire crystal. The second multipass optical system may allow the seed light outputted from the first multipass amplifier to reciprocate therethrough, and the second titanium-sapphire crystal may be provided in a second multiple optical path in the second multipass optical system. The number of reciprocations of the seed light in the second multipass amplifier may be equal to or smaller than the number of reciprocations of the seed light in the first multipass amplifier.

[0010] A titanium-sapphire amplifier according to one aspect of the present disclosure may include a titanium-sapphire crystal, a multipass optical system, a first dichroic mirror, and a second dichroic mirror. The multipass optical system may include a plurality of light condensing optical devices. The multipass optical system may be configured to allow seed light having entered via a predetermined entry position to pass through the titanium-sapphire crystal an even number of times and may be configured to allow an incident beam image at the predetermined entry position to be transferred by the plurality of light condensing optical devices an even number of times to form an image of the incident beam image. The first dichroic mirror may be provided in an optical path of the seed light in the multipass optical system and may be provided to allow excitation light to enter the titanium-sapphire crystal. The second dichroic mirror may be provided in the optical path of the seed light in the multipass optical system and may be provided to allow the excitation light outputted from the titanium-sapphire crystal to be outputted to outside of the multipass optical system.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Some example embodiments of the present disclosure are described below as mere examples with reference to the accompanying drawings.

[0012] FIG. **1** schematically illustrates a configuration example of a laser apparatus used for an exposure apparatus according to a comparative example.

[0013] FIG. **2** schematically illustrates a configuration example of a narrow-band titanium-sapphire laser apparatus according to the comparative example.

[0014] FIG. **3** illustrates an example of variation with time in an optical path length error in an optical resonator in the narrow-band titanium-sapphire laser apparatus illustrated in FIG. **2** in a case in which the optical path length error is not corrected.

[0015] FIG. **4** illustrates an example of variation with time in the optical path length error in the optical resonator in the narrow-band titanium-sapphire laser apparatus illustrated in FIG. **2** in a case in which the optical path length error is corrected.

[0016] FIG. **5** illustrates an example of variation in focal length by a thermal lens effect in a titanium-sapphire crystal.

[0017] FIG. **6** schematically illustrates a configuration example of a master oscillator power oscillator (MOPO) in a narrow-band titanium-sapphire laser apparatus according to a first embodiment.

[0018] FIG. **7** illustrates an example of variation with time in an optical path length error in an optical resonator in the narrow-band titanium-sapphire laser apparatus illustrated in FIG. **6** in a case in which the optical path length error is corrected.

[0019] FIG. **8** is a main flow chart schematically illustrating an example of a flow of control of an optical path length in the optical resonator in the narrow-band titanium-sapphire laser apparatus illustrated in FIG. **6**.

[0020] FIG. **9** is a sub-flow chart illustrating details of a process in step S**105** of the main flow chart illustrated in FIG. **8**.

[0021] FIG. **10** schematically illustrates an example of a method of measuring a minimum value of an optical path length error.

[0022] FIG. **11** schematically illustrates a configuration example of a multipass titanium-sapphire amplifier in the narrow-band titanium-sapphire laser apparatus according to the first embodiment.

[0023] FIG. **12** schematically illustrates an optical equivalent diagram of a multipass optical system in the multipass titanium-sapphire amplifier illustrated in FIG. **11**.

[0024] FIG. **13** schematically illustrates a first modification example of the multipass titanium-sapphire amplifier illustrated in FIG. **11**.

[0025] FIG. **14** schematically illustrates a second modification example of the multipass titanium-sapphire amplifier illustrated in FIG. **11**.

[0026] FIG. **15** schematically illustrates a configuration example of an MOPO in a narrow-band titanium-sapphire laser apparatus according to a second embodiment.

[0027] FIG. **16** schematically illustrates a configuration example of a multipass amplifier unit in the narrow-band titanium-sapphire laser apparatus according to the second embodiment.

[0028] FIG. **17** illustrates an example of amplification characteristics of the multipass amplifier unit illustrated in FIG. **16**.

[0029] FIG. **18** schematically illustrates a modification example of the multipass amplifier unit illustrated in FIG. **16**.

[0030] FIG. **19** schematically illustrates a configuration example of an optical path length error detector.

[0031] FIG. **20** schematically illustrates a configuration example of an optical shutter.

[0032] FIG. **21** illustrates an example of a hardware environment of a controller.

DETAILED DESCRIPTION

<Contents>

[5. Configuration Example of Optical Path Length Error Detector] (FIG. **19**)

[0058] 5.1 Configuration

[0059] 5.2 Operation

[0060] 5.3 Modification Examples

[6. Configuration Example of Optical Shutter] (FIG. **20**)

[0061] 6.1 Configuration

[0062] 6.2 Operation

[7. Hardware Environment of Controller] (FIG. **21**)

[8. Et Cetera]

[0063] In the following, some example embodiments of the present disclosure are described in detail with reference to the drawings. Example embodiments described below each illustrate one example of the present disclosure and are not intended to limit the contents of the present disclosure. Further, all of the configurations and operations described in each example embodiment are not necessarily essential for the configurations and operations of the present disclosure. Note that like components are denoted by like reference numerals, and redundant description thereof is omitted.

1. Overview

[0064] The present disclosure relates to a titanium-sapphire laser apparatus using a titanium-sapphire crystal and a laser apparatus used for an exposure apparatus, for example.

2. Comparative Examples

[0065] First, description is given of a titanium-sapphire laser apparatus and a laser apparatus used for an exposure apparatus according to a comparative example with respect to example embodiments of the present disclosure.

(2.1 Laser Apparatus Used For Exposure Apparatus)

[0066] (2.1.1 Configuration)

[0067] FIG. **1** schematically illustrates a configuration example of the laser apparatus used for the exposure apparatus according to the comparative example with respect to example embodiments of the present disclosure.

[0068] The laser apparatus used for the exposure apparatus may include a solid-state laser system **1**, an amplifier **2**, a synchronization controller **3**, and high reflection mirrors **91** and **92**.

[0069] The solid-state laser system **1** may include a first solid-state laser unit **11**, a second solid-state laser unit **12**, a synchronous circuit **13**, a solid-state laser controller **14**, and a wavelength conversion system **15**.

[0070] The first solid-state laser unit **11** may be a Nd:YVO_4 pulsed laser unit, and may perform oscillation in a single longitudinal mode. The Nd:YVO_4 pulsed laser unit may output pulsed laser light of a wavelength of 1342 nm. The second solid-state laser unit **12** may include a narrow-band titanium-sapphire laser apparatus **20**, an LBO (LIB_3O_5) crystal **21**, and a BBO (β-BaB_2O_4) crystal **22**. The narrow-band titanium-sapphire laser apparatus **20** may perform oscillation at a wavelength of 904 nm.

[0071] The wavelength conversion system **15** may include a high reflection mirror **16**, a beam splitter **17**, and a CLBO ($CsLiB_6O_{10}$) crystal **18**.

[0072] For example, the solid-state laser controller **14** may be configured to enable transmission and startup of data and transmission of a stop signal to the first solid-state laser unit **11** and the second solid-state laser unit **12** in accordance with an unillustrated control signal.

[0073] The synchronous circuit **13** may be configured to allow first pulsed laser light outputted from the first solid-state laser unit **11** and second pulsed laser light outputted from the second solid-state laser unit **12** to enter the CLBO crystal **18** of the wavelength conversion system **15** substantially simultaneously.

[0074] The amplifier **2** may include an amplifier controller **30**, a charger **31**, a trigger corrector **32**, a pulsed power module (PPM **34** including a switch **33**, a chamber **35**, a partial reflection mirror **36**, and an output coupling mirror **37**.

[0075] The chamber **35** may be provided with windows **39***a* and **39***b*. The chamber **35** may contain, for example, a laser gas containing an Ar gas, a F_2 gas, and a Ne gas. A pair of discharge electrodes **38** may be provided inside the chamber **35**. The pair of discharge electrodes **38** may be coupled to an output terminal of the PPM **34**.

[0076] In the amplifier **2**, an optical resonator including the partial reflection mirror **36** and the output coupling mirror **37** may be configured. The partial reflection mirror **36** may be configured of, for example, a substrate made of a CaF_2 crystal coated with a partial reflection film having reflectivity from 70% to 90% both inclusive. The substrate may allow, for example, light of a wavelength of 193 nm to pass therethrough. The output coupling mirror **37** may be configured of, for example, a substrate made of a CaF_2 crystal coated with a partial reflection film having reflectivity from 10% to 20% both inclusive. The substrate may allow, for example, light of a wavelength of 193 nm to pass therethrough.

[0077] An oscillation trigger Tr**0** may be inputted from an exposure apparatus controller **5** of an exposure apparatus **4**. The synchronization controller **3** may be configured to output an oscillation trigger to the trigger corrector **32** via amplifier controller **30** so as to cause the pair of discharge electrodes **38** to perform discharge in synchronization with injection of pulsed laser light of a wavelength of 193 nm from the solid-state laser system **1** into the optical resonator of the amplifier **2**.

(2.1.2 Operation)

[0078] The solid-state laser controller **14** may prepare for operations of the first solid-state laser unit **11** and the second solid-state laser unit **12** so as to allow for output of pulsed laser light from the first solid-state laser unit **11** and the second solid-state laser unit **12**. The synchronization controller **3** may output an oscillation trigger to the synchronous circuit **13** via the solid-state laser controller **14** of the solid-state laser system **1** at a predetermined timing upon reception of the oscillation trigger Tr**0** from the exposure apparatus controller **5** of the exposure apparatus **4**. The synchronization controller **3** may also output an oscillation trigger to the trigger corrector **32** via the amplifier controller **30** of the amplifier **2** at a predetermined timing upon reception of the oscillation trigger Tr**0** from the exposure apparatus controller **5** of the exposure apparatus **4**.

[0079] The synchronous circuit **13** may output an oscillation trigger to each of the first solid-state laser unit **11** and the narrow-band titanium-sapphire laser apparatus of the second solid-state laser unit **12** at a predetermined timing. The first solid-state laser unit **11** may output the first pulsed laser light of a wavelength of 1342 nm.

[0080] In the second solid-state laser unit **12**, when the oscillation trigger is inputted to the narrow-band titanium-sapphire laser apparatus **20**, the narrow-band titanium-sapphire laser apparatus **20** may output pulsed laser light of a wavelength of 904 nm. Thereafter, the LBO crystal **21** and the BBO crystal **22** may generate the second pulsed laser light that is a fourth harmonic of a wavelength of 226 nm. The first pulsed laser light of a wavelength of 1342 nm outputted from the first solid-state laser unit **11** and the second pulsed laser light of a wavelength of 226 nm outputted from the second solid-state laser unit **12** may enter the wavelength conversion system **15**.

[0081] In the wavelength conversion system **15**, the high reflection mirror **16** and the beam splitter **17** may cause the first pulsed laser light and the second pulsed laser light to enter the CLBO crystal **18** substantially simultaneously and be superimposed on each other on the CLBO crystal **18**. The CLBO crystal **18** may generate pulsed laser light of a wavelength of 193 nm as a sum frequency of a wavelength of 226 nm and a wavelength of 1342 nm. The pulsed laser light may enter the partial reflection mirror **36** of the amplifier **2** via the high reflection mirrors **91** and **92**.

[0082] The pulsed laser light may be injected as seed light into the optical resonator including the output coupling mirror **37** and the partial reflection mirror **36** of the amplifier **2**. Discharge by the pair of discharge electrodes **38** may produce a population inversion in the chamber **35** of the amplifier **2** in synchronization with such injection. At this occasion, the trigger corrector **32** may adjust a timing of the switch **33** of the PPM **34** so as to efficiently amplify, in the amplifier **2**, the pulsed laser light of a wavelength of 193 nm from the solid-state laser system **1**. As a result, pulsed laser light may be amplified and oscillated by the optical resonator of the amplifier **2**, and the thus-amplified pulsed laser light may be outputted from the output coupling mirror **37**.

(2.2 Narrow-Band Titanium-Sapphire Laser Apparatus)

[0083] (2.2.1 Configuration)

[0084] FIG. **2** schematically illustrates a configuration example of a narrow-band titanium-sapphire laser apparatus **20** according to the comparative example with respect to example embodiments of the present disclosure.

[0085] The narrow-hand titanium-sapphire laser apparatus **20** may include a master oscillator power oscillator (MOPO) **40**, a fourth high reflection mirror **104**, a fifth high reflection mirror **105**, a second optical isolator **44**B, a sixth high reflection mirror **106**, and a multipass amplifier unit **41**.

[0086] The MOPO **40** may include a master oscillator (MO) **50** and a power oscillator (PO: amplifier oscillator) **60**. The MOPO **40** may further include a first optical isolator **44**A, a first excitation pulsed laser unit **70**A, a first condenser lens **72**A, an optical path length corrector **42**, and an optical path length error detector **43**.

[0087] The MO **50** may be a continuous wave (CW) oscillation laser unit configured to perform CW oscillation in a single longitudinal mode. The MO **50** may be, for example, a distributed-feedback laser diode. The distributed-feedback laser diode may perform CW oscillation in the single longitudinal mode to output seed light **51** of a wavelength of 904 nm. The first optical isolator **44**A may be provided in an optical path between the MO **50** and the PO **60**. The first optical isolator **44** may be adopted to suppress transmission of return light.

[0088] The first excitation pulsed laser unit **70**A may be a pulsed laser unit configured to output first pulsed laser light **71**A of a wavelength of 523 nm. The first pulsed laser light **71**A may be used for excitation. The first pulsed laser light **71**A may be a second harmonic of Nd:YLF pulsed laser light.

[0089] The PO **60** may include an optical resonator and a titanium-sapphire crystal **61**. The titanium-sapphire crystal **61** may be provided in an optical path in the optical resonator. Both end surfaces of the titanium-sapphire crystal **61** may be cut so as to allow light to enter the end surfaces at a Brewster's angle. The seed light **51** and the first pulsed laser light **71**A used for excitation may enter the PO **60**. The optical resonator of the PO **60** may be a Z-type ring optical resonator, and may include an output coupling mirror **62**, a first high reflection mirror **101**, a second high reflection mirror **102**, and a third high reflection mirror **103**.

[0090] The first high reflection mirror **101** may be configured of a substrate coated with a film. The substrate may allow light of a wavelength of 904 nm to pass therethrough, and the film may reflect light of a wavelength of 904 nm at high reflectivity, but may allow part of the light to pass therethrough. The optical path length error detector **43** may be provided in an optical path of leak light **52** of seed light **51** from the first high reflection mirror **101** so as to allow the leak light **52** to enter the optical path length error detector **43**.

[0091] The second high reflection mirror **102** may be a dichroic mirror that allows the first pulsed laser light **71**A serving as excitation light to pass therethrough at high transmittance and reflects the seed light **51** of a wavelength of 904 nm at high reflectivity.

[0092] The third high reflection mirror **103** may be a mirror that reflects light of a wavelength of 904 nm at high reflectivity. The third high reflection mirror **103** may be fixed to a piezoelectric-device-equipped mirror holder **46** including a piezoelectric device. A direction of mirror movement by the piezoelectric device may be substantially coincident with a direction of a normal to a mirror surface.

[0093] The first excitation pulsed laser unit **70**A and the first condenser lens **72**A may be provided so as to allow the first pulsed laser light **71**A used for excitation to be condensed on the titanium-sapphire crystal **61** via the first high reflection mirror **101**.

[0094] The optical path length corrector **42** may include the piezoelectric-device-equipped mirror holder **46**, the third high reflection mirror **103**, and a proportional integral derivative (RID) controller **45**.

[0095] The PID controller **45** may be configured to control a position of the third high reflection mirror **103**. An output signal of the optical path length error detector **43** may be inputted to the PID controller **45**.

[0096] The seed light **51** amplified by the PO **60** may be outputted via the output coupling mirror **62**. The fourth high reflection mirror **104**, the fifth high reflection mirror **105**, the second optical isolator **44**B, and the sixth high reflection mirror **106** may be provided so as to allow the amplified seed light **51** to enter the multipass amplifier unit **41** via the fourth high reflection mirror **104**, the fifth high reflection mirror **105**, the second optical isolator **44**B, and the sixth high reflection mirror **106**. The second optical isolator **44**B may be provided to suppress transmission of return light.

[0097] The multi pass amplifier unit **41** may include a second excitation pulsed laser unit **70**B, a third excitation pulsed laser unit **70**C, a second condenser lens **72**B, and a third condenser lens **72**C. The multipass amplifier unit **41** may further include a first multipass titanium-sapphire amplifier **73**A, a second multipass titanium-sapphire amplifier **73**B, and seventh to tenth high reflection mirrors **107** to **110**.

[0098] The second excitation pulsed laser unit **70**B may be a pulsed laser unit configured to output second pulsed laser light **71**B of a wavelength of 523 nm. The second pulsed laser light **71**B may be used for excitation. The second pulsed laser light **71**B may be a second harmonic of Nd:YLF pulsed laser light. The third excitation pulsed laser unit **70**C may be a pulsed laser unit configured to output third pulsed laser light **71**C of a wavelength of 523 nm. The third pulsed laser light **71**C may be used for excitation. The third pulsed laser light **71**C may be a second harmonic of Nd:YLF pulsed laser light.

[0099] The first multipass titanium-sapphire amplifier **73**A may include a first titanium-sapphire crystal **74**A as with an after-mentioned embodiment illustrated in FIG. **11**. The first titanium-sapphire crystal **74**A may be different from the titanium-sapphire crystal **61**. The second multipass titanium-sapphire amplifier **73**B may include a second titanium-sapphire crystal **74**B as with the after-mentioned embodiment illustrated in FIG. **11**. The second titanium-sapphire crystal **74**B may be different from the titanium-sapphire crystal **61**.

[0100] The first, second, and third excitation pulsed laser units **70**A, **70**B, and **70**C may be configured so as to receive an oscillation trigger from the synchronous circuit **13**.

(2.2.2 Operation)

[0101] The MO **50** may perform CW oscillation in the single longitudinal mode to output the seed light **51**. The seed light **51** may be inputted to the output coupling mirror **62** to the optical resonator of the PO **60** via the first optical isolator **44**A. The seed light **51** may travel around an optical path of the optical resonator of the PO **60**. This may cause leak light **52** of the seed light **51** to be outputted from the first high reflection mirror **101**.

[0102] The leak light **52** may be inputted to the optical path length error detector **43**, and the optical path length error detector **43** may output an optical path length error signal. The optical path length error signal may be a signal indicating an optical path length error ΔL (=L−L0) between a positive integer multiple L0 of a wavelength of the seed light **51** and an actual optical path length L in the optical resonator. The optical path length error detector **43** may output, for example, a voltage V as the optical path length error signal. The voltage V may be equal to K·ΔL, where K may be a proportional constant. The optical path length may be an optical length that also takes account of a refractive index.

[0103] The PID controller **45** may receive the voltage V indicating the optical path length error ΔL and may perform PID control of a position of the third high reflection mirror **103** so as to allow the voltage V, i.e., the optical path length error ΔL, to approach zero.

[0104] Thereafter, when an oscillation trigger is inputted from the synchronous circuit **13** to the first excitation pulsed laser unit **70**A, the first pulsed laser light **71**A used for excitation may be outputted to excite the titanium-sapphire crystal **61** of the PO **60** in a form of pulse. Since the seed light **51** has been already injected into the titanium-sapphire crystal **61**, the seed light **51** may be amplified in the form of pulse. As a result, the seed light **51** may be subjected to laser oscillation in the optical resonator to be modified in the form of pulse, and the modified seed light **51** may be outputted from the output coupling mirror **62**.

[0105] The seed light **51** amplified in the form of pulse may enter the multipass amplifier unit **41** via the fourth high reflection mirror **104**, the fifth high reflection mirror **105**, the second optical isolator **44**B, and the sixth high reflection mirror **106**.

[0106] The seed light **51** of a wavelength of 904 nm amplified in the form of pulse may enter the after-mentioned first titanium-sapphire crystal **74**A illustrated in FIG. **11** in the first multipass titanium-sapphire amplifier **73**A via the seventh high reflection mirror **107**. In synchronization with a timing of entry of the seed light **51**, the second pulsed laser light **71**B serving as excitation light may enter the after-mentioned first titanium-sapphire crystal **74**A from the second excitation pulsed laser unit **70**B to excite the seed light **51** in the form of pulse. In the first multipass titanium-sapphire amplifier **73**A, multiple passing of pulsed laser light of a wavelength of 904 nm through the after-mentioned first titanium-sapphire crystal **74**A may amplify the seed light **51** a plurality of times.

[0107] The seed light **51** amplified in the form of pulse by the first multipass titanium-sapphire amplifier **73**A may enter the second multipass titanium-sapphire amplifier **73**B via the eighth high reflection mirror **108** and the ninth high reflection mirror **109**. In the second multipass titanium-sapphire amplifier **73**B, the seed light **51** of a wavelength of 904 nm amplified in the form of pulse may enter the after-mentioned second titanium-sapphire crystal **74**B illustrated in FIG. **11**. In synchronization with a timing of entry of the seed light **51**, the third pulsed laser light **71**C serving as excitation light may enter the after-mentioned second titanium-sapphire crystal **74**B from the third excitation pulsed laser unit **70**C to excite the seed light **51** in the form of pulse. In the second multipass titanium-sapphire amplifier **73**B, multiple passing of pulsed laser light of a wavelength of 904 nm through the after-mentioned second titanium-sapphire crystal **74**B may amplify the seed light **51** a plurality of times.

[0108] The seed light **51** amplified by the second multipass titanium-sapphire amplifier **73**B may enter the LBO crystal **21** via the tenth high reflection mirror **110**.

(2.2.3 Issues)

[0109] (Issues of Control of Optical Path Length in Optical Resonator of PO **60**)

[0110] FIG. **3** illustrates an example of variation with time in the optical path length error ΔL in the optical resonator of the PO **60** in the narrow-band titanium-sapphire laser apparatus **20** illustrated in FIG. **2** in a case in which the optical path length error ΔL is not corrected. FIG. **3** illustrates variation with time immediately after start of excitation in the PO **60**. A horizontal axis and a vertical axis in FIG. **3** indicate time and the optical path length error ΔL, respectively.

[0111] In a state before the start of excitation, variation in temperature of the titanium-sapphire crystal **61** is small.

Hence, the optical path length error ΔL (=L−L0) is close to 0. However, when excitation starts at 6 kHz, the optical path length error ΔL may vary while being gradually drifted by ΔLc toward "+" side, and a maximum value Lmax and a minimum value Lmin may be alternately repeated for each excitation pulse.

[0112] FIG. **4** illustrates an example of variation with time in the optical path length error ΔL in the optical resonator of the PO **60** in the narrow-hand titanium-sapphire laser apparatus **20** illustrated in FIG. **2** in a case in which the optical path length error ΔL is corrected. FIG. **4** illustrates variation with time immediately after start of excitation in the PO **60**. A horizontal axis and a vertical axis in FIG. **4** indicate time and the optical path length error ΔL, respectively,

[0113] In order to suppress divergence of control, the PID controller **45** of the optical path length corrector **42** may perform control so as to allow an integral of an error signal to approach zero. Hence, while it may be possible to perform control to allow a ΔLC component to approach zero, it may be difficult to suppress variation ΔΔL (=ΔLmax−ΔLmin) for each excitation pulse. A reason for this is that it may not be possible for speed of variation in the optical path length to follow response speed of the optical path length corrector **42** in some cases. As a result, the refractive index varies by variation in the temperature of the titanium-sapphire crystal **61** every time the first pulsed laser light **71**A used for excitation is inputted to the titanium-sapphire crystal **61**, which may make it difficult for the optical path length in the optical resonator to be coincident with an optical path length of a positive integer multiple of the wavelength of the seed light **51**. Accordingly, an output timing and a pulse waveform of the seed light **51** amplified in the form of pulse and outputted from the output coupling mirror **62** may become unstable.

(Issues of Multipass Amplifier Unit **41**)

[0114] In the first and second multipass titanium-sapphire amplifiers **73**A and **73**B, gains of the after-mentioned first and second titanium-sapphire crystals **74**A and **74**B illustrated in FIG. **11** are small at a wavelength of 904 nm; therefore, in order to increase the gains; it may be necessary to condense excitation light. When an attempt to increase output is made under such a condition, a refractive index distribution may be created by a temperature distribution in the after-mentioned first and second titanium-sapphire crystals **74**A and **74**B, and the refractive index distribution may serve as a thermal lens. As output of the excitation light entering each of the first and second titanium-sapphire crystals **74**A and **74**B increases, the focal length by a thermal lens effect may be shortened.

[0115] FIG. **5** illustrates an example of a focal length by the thermal lens effect in the titanium-sapphire crystal. A horizontal axis and a vertical axis in FIG. **5** indicate input of excitation light (W) and the focal length by the thermal lens effect (mm), respectively.

[0116] In order to increase gains of the after-mentioned first and second titanium-sapphire crystals **74**A and **74**B, it may be necessary to condense high-output excitation light on a small region of each of the first and second titanium-sapphire crystals **74**A and **74**B. For example, a condensing diameter from 100 μm to 200 μm both inclusive may be necessary. In this case, the focal length of the thermal lens by the thermal lens effect created in each of the first and second titanium-sapphire crystals **74**A and **74**B may be shortened. As illustrated in FIG. **5**, as input of the excitation light increases, the focal length by the thermal lens effect may be shortened.

[0117] When the focal length of the thermal lens by the thermal lens effect is about 10 mm or less, it may not be possible to suppress deterioration in beam characteristics after amplification even though a position of an optical device of an optical system for multiple passing through the first and second titanium-sapphire crystals **74**A and **74**B is adjusted. In particular, when the number of times of multiple passing of the seed light **51** in the first and second multipass titanium-sapphire amplifiers **73**A and **73**B increases, deterioration in beam characteristics may be pronounced by the thermal lens effect.

3. First Embodiment

[0118] Next, description is given of a titanium-sapphire laser apparatus and a laser apparatus used for an exposure apparatus according to a first embodiment of the present disclosure. Note that substantially same components as the components of the foregoing titanium-sapphire laser apparatus and the foregoing laser apparatus used for the exposure apparatus according to the comparative example illustrated in FIGS. **1** and **2** are denoted by same reference numerals, and redundant description thereof is omitted.

[0119] A basic configuration of the laser apparatus used for the exposure apparatus according to the present embodiment may be substantially similar to that of the laser apparatus used for the exposure apparatus illustrated in FIG. **1**.

(3.1 MOPO)

[0120] (3.1.1 Configuration)

[0121] FIG. **6** schematically illustrates a configuration example of an MOPO **40**A as a configuration of a main part of the narrow-band titanium-sapphire laser apparatus **20** according to the first embodiment of the present disclosure.

[0122] The narrow-band titanium-sapphire laser apparatus **20** according to the present embodiment may include the MOPO **40**A in place of the MOPO **40** in the configuration of the comparative example illustrated in FIG. **2**. The MOPO **40**A may include a first optical shutter **53**A and a shift amount adder **54**. The narrow-band titanium-sapphire laser apparatus **20** according to the present embodiment may further include an inverter **56**, a delay circuit **57**, and an error controller **55** in addition to the configuration of the comparative example illustrated in FIG. **2**.

[0123] The first optical shutter **53**A may be provided in an optical path of leak light **52** between the first high reflection mirror **101** and the optical path length error detector **43**. The first optical shutter **53**A may be subjected to shutter control in which the first optical shutter **53**A is closed during entry of the first pulsed laser light **71**A into the titanium-sapphire crystal **61** and the first optical shutter **53**A is opened during non-entry of the first pulsed laser light **71**A into the titanium-sapphire crystal **61**.

[0124] The shift amount adder **54** may be provided in a signal line between the optical path length error detector **43** and the PID controller **45**.

[0125] The error controller **55** may transmit data of a correction value Voffset to the shift amount adder **54** on a basis of an optical path length error signal outputted from the optical path length error detector **43**.

[0126] The delay circuit **57** may receive an oscillation trigger of the synchronous circuit **13** and output a signal for control of opening and closing of the first optical shutter **54**A via the inverter **56** after a predetermined delay time. Delay data Td that sets a delay time may be inputted from the error controller **55** to the delay circuit **57**.

[0127] The optical path length corrector **42** may vary the optical path length in the optical resonator of the PO **60** to allow the optical path length error ΔL to approach zero at a timing immediately before entry of the first pulsed laser light **71** used for excitation into the titanium-sapphire crystal **61**.

(3.1.2 Operation)

[0128] The error controller **55** may transmit the delay data Td to the delay circuit **57** to delay an opening-closing timing of the first optical shutter **53**A with respect to an oscillation trigger from the synchronous circuit **13**. The delay data Td may set the delay time. The error controller **55** may control the first optical shutter **53**A so as to prevent the leak light **52** of the seed light **51** amplified in the form of pulse from being detected by the optical path length error detector **43** in synchronization with the first pulsed laser light **71**A used for excitation. In this case, the error controller **55** may control the delay circuit **57** so as to close the first optical shutter **53**A during entry of the first pulsed laser light **71**A into the titanium-sapphire crystal **61**. The error controller **55** may further control the delay circuit **57** so as to open the first optical shutter **53**A during non-entry of the first pulsed laser light **71**A into the titanium-sapphire crystal **61**. As described above, the first optical shutter **53**A may be controlled so as to be closed during entry of the seed light **51** amplified in the form of pulse and to be opened during non-entry of the seed light **51** amplified in the form of pulse.

[0129] The error controller **55** may read data of variation with time in the optical path length error ΔL from the optical path length error detector **43**, and may transmit data of the correction value Voffset to the shift amount adder **54** so as to allow the minimum value ΔLmin of the optical path length error ΔL to approach zero. Thus, a voltage value resulting from adding the correction value Voffset from the shift amount adder **54** to the voltage V serving as the optical path length error signal from the optical path length error detector **43** may be inputted to the PID controller **45**. Repeating such control may allow the minimum value ΔLmin of the optical path length error ΔL to approach zero.

[0130] FIG. **7** illustrates an example of variation with time in the optical path length error ΔL in the MOPO **40**A illustrated in FIG. **6** in a case in which the optical path length error ΔL in the optical resonator of the PO **60** is corrected. In the present embodiment, in the optical resonator of the PO **60**, the seed light **51** may be amplified in the form of pulse while the minimum value ΔLmin of the optical path length error ΔL approaches zero; as illustrated in FIG. **7**

[0131] FIG. **8** schematically illustrates an example of a flow of control of the optical path length in the optical resonator in the narrow-band titanium-sapphire laser apparatus **20** illustrated in FIG. **6**.

[0132] The error controller **55** may set the delay data Id to initial delay data Td=Td**0** (step S**101**). Subsequently, the delay data Td may be transmitted to the delay circuit **57** (step S**102**). Thereafter, the error controller **55** may determine whether amplified light of the seed light **51** is cut by the first optical shutter **53**A so as not to allow the amplified light to enter the optical path length error detector **43** (step S**103**). When the error controller **55** determines that the amplified light is not cut (step S**103**; N), the error controller **55** may perform resetting of the delay time (step S**104**) and may return to a process in the step S**102**. It is to be noted that the delay time may be reset to Td=Td+ΔTd. In other words, the reset value may result from adding a predetermined time ΔTd to the delay data Td before being reset.

[0133] In contrast, when the error controller **55** determines that the amplified light is cut (step S**103**; Y), the error controller **55** may then measure the minimum value ΔLmin of the optical path length error ΔL (step S**105**). Subsequently, the error controller **55** may transmit data of the correction value Voffset to the shift amount adder **54** so as to allow the minimum value ΔLmin of the optical path length error ΔL to approach zero (step S**106**). Thereafter, the error controller **55** may determine whether the control of the optical path length is stopped (step S**107**). When the control of the optical path length is not stopped (step S**107**; N), the error controller **55** may return to a process in the step S**105**. When the control of the optical path length is stopped (step S**107**; Y), the error controller **55** may end the process.

[0134] FIG. **9** is a sub-flow chart illustrating details of the process in the step S**105**.

[0135] The error controller **55** may reset a time T of an unillustrated timer and start the time T (step S**111**). Subsequently, the error controller **55** may read data of the optical path length error ΔL outputted from the optical path length error detector **43** (step S**112**). Next, the error controller **55** may store data of the time T and data of the optical path length error ΔL (step S**113**). Thereafter, the error controller **55** may determine whether or not the time T is equal to or longer than a predetermined time K, i.e., T≥K (step S**114**). When the error controller **55** determines that the time T is not equal to or longer than the predetermined time K (step S**114**; N), the error controller **55** may return to a process in the step S**112**. In contrast, when the error controller **55** determines that the time T is equal to or longer than the predetermined time K (step S**104**; Y), the error controller **55** may read stored data and extract data of a plurality of minimum values ΔLmin to calculate an average value ΔLminav (step S**115**).

[0136] Here, FIG. **10** schematically illustrates an example of a method of measuring the minimum value ΔLmin of the optical path length error ΔL. A horizontal axis and a vertical axis in FIG. **10** may indicate time and the optical path length error ΔL, respectively. For example, minimum values ΔLmin(1), ΔLmin(2), ΔLmin(3), and ΔLmin(4) may be detected as data of the minimum value ΔLmin of the optical path length error ΔL in the predetermined time K, as illustrated in FIG. **10**. In this case, the error controller **55** may calculate the average value ΔLminav of the minimum values ΔLmin as follows.

$$\Delta L\mathrm{min}av=\{\Delta L\mathrm{min}(1)+\Delta L\mathrm{min}(2)+\Delta L\mathrm{min}(3)+\Delta L\mathrm{min}(4)\}/4$$

[0137] Next, the error controller **55** may use the determined average value ΔLminav as the minimum value ΔLmin of the optical path length error ΔL (step S**116**), and thereafter may return to the main flow in FIG. **8**.

(3.1.3 Effect)

[0138] According to the MOPO **40**A in the present embodiment, control is performed so as to allow the minimum value ΔLmin of the optical path length error ΔL to approach zero immediately before the seed light **51** is amplified in the form of pulse in the optical resonator of the PO **60**. This makes it possible to enhance efficiency of pulse amplification of the seed light **51**. This also makes it possible to stabilize an output timing and a pulse waveform of the seed light **51** amplified in the form of pulse.

(3.2 Multipass Amplifier Unit)

[0139] (3.2.1 Configuration)

[0140] FIG. **11** schematically illustrates a configuration example of the multipass titanium-sapphire amplifier in the multipass amplifier unit **41** as a configuration of a main part of the narrow-band titanium-sapphire laser apparatus **20** according to the first embodiment of the present disclosure. FIG. **12** schematically illustrates an optically equivalent diagram of a multipass optical system in the multipass titanium-sapphire amplifier illustrated in FIG. **11**.

[0141] FIG. **11** collectively illustrates configurations of the first multipass titanium-sapphire amplifier **73**A and the second multipass titanium-sapphire amplifier **73**B.

[0142] The first multipass titanium-sapphire amplifier **73**A may include a multipass optical system **80** as a first multipass optical system. The second multipass titanium-sapphire amplifier **73**B may include the multipass optical system **80** as a second multipass optical system. The multipass optical system **80** may include an input mirror **81** and an output mirror **82**. The multipass optical system **80** may further include a condenser lens **84**, a dichroic mirror **85**, a dichroic mirror **86**, a condenser lens **87**, and turning back mirrors **88**A and **88**B.

[0143] The first multipass titanium-sapphire amplifier **73**A may include a first multiple optical path **75**A configured by the multipass optical system **80** and the first titanium-sapphire crystal **74**A provided in the first multiple optical path **75**A. The seed light **51** amplified by the PO **60** may pass through components such as the fourth high reflection mirror **104** to be inputted to the first multipass titanium-sapphire amplifier **73**A via the input mirror **81**.

[0144] The second multipass titanium-sapphire amplifier **73**B may include a second multiple optical path **75**B configured by the multipass optical system **80** and the second titanium-sapphire crystal **74**B provided in the second multiple optical path **75**B. The seed light **51** amplified by the first multipass titanium-sapphire amplifier **73**A may pass through the eighth high reflection mirror **108** and the ninth high reflection mirror **109** to be inputted to the second multipass titanium-sapphire amplifier **73**B via the input mirror **81**.

[0145] In the first multipass titanium-sapphire amplifier **73**A, the second condenser lens **72**B may be provided so as to allow the second pulsed laser light **71**B to be condensed on the first titanium-sapphire crystal **74**A via the dichroic mirror **86**. The second pulsed laser light **71**B may be excitation light that is used for amplification and is outputted from the second excitation pulsed laser unit **70**B. In the first multipass titanium-sapphire amplifier **73**A, the dichroic mirror **85** and the dichroic mirror **86** may be provided so as to allow the seed light **51** to reciprocate through the first titanium-sapphire crystal **74**A. In the first multipass titanium-sapphire amplifier **73**A, the output mirror **82** may be provided so as to allow the seed light **51** having reciprocated through the first titanium-sapphire crystal **74**A to be outputted toward the eighth high reflection mirror **108**.

[0146] In the second multipass titanium-sapphire amplifier **73**B, the third condenser lens **72**C may be provided so as to allow the third pulsed laser light **71**C to be condensed on the second titanium-sapphire crystal **74**B via the dichroic mirror **86**. The third pulsed laser light **71**C may be excitation light that is used for amplification and is outputted from the third excitation pulsed laser unit **70**C. In the second multipass titanium-sapphire amplifier **73**B, the dichroic mirror **85** and the dichroic mirror **86** may be provided so as to allow the seed light **51** to reciprocate through the second titanium-sapphire crystal **74**B. In the second multipass titanium-sapphire amplifier **73**B, the output mirror **82** may be provided so as to allo the seed light **51** having reciprocated through the second titanium-sapphire crystal **74**B to be outputted toward the tenth high reflection mirror **10**.

[0147] A focal length f1 of the condenser lens **84** and a focal length f2 of the condenser lens **87** each may be substantially equal to a predetermined focal length f. The condenser lens **84** and the condenser lens **87** may be provided so as to have a focal length substantially equal to the predetermined focal length f and so as to allow an optical path length between the condenser lens **84** and the condenser lens **87** to be substantially twice the predetermined focal length f, as illustrated in FIG. **12**. The first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B each may be provided in an optical path at a substantially middle point between the condenser lens **84** and the condenser lens **87**.

[0148] The dichroic mirror **85** may be provided in an optical path between the condenser lens **84** and one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B so as to reflect the seed light **51** at substantially 45 degrees. A surface of the dichroic mirror **85** may be coated with a film that allows excitation light to pass therethrough at high transmittance and reflects the seed light **51** at high reflectivity.

[0149] The dichroic mirror **86** may be provided in an optical path between the condenser lens **87** and the one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B so as to reflect the seed light **51** at substantially 45 degrees. A surface of the dichroic mirror **86** may be coated with a film that allows excitation light to pass therethrough at high transmittance and reflects the seed light **51** at high reflectivity.

[0150] The input mirror **81** may be provided to allow the seed light **51** to pass through substantially a center of the condenser lens **84**. The turning back mirrors **88**A and **88**B may configure a pair of turning back mirrors, and may be provided so as to turn back, to the condenser lens **87**, the seed light **51** having entered the pair of turning back mirrors via the condenser lens **87**. The turning back mirrors **88**A and **88**B may be provided so as to allow an optical path length of an optical path from the condenser lens **87** via the turning back mirrors **88**A and **88**B to the condenser lens **87** to be substantially twice the predetermined focal length f.

(3.2.2 Operation)

[0151] The seed light **51** having entered the multipass optical system **80** may be reflected by the input mirror **81** to enter substantially the center of the condenser lens **84** through a front-side focal position of the condenser lens **84**. An incident beam position PO where an incident beam image Im**0** of the seed light **51** is formed may be substantially the same as the front-side focal position of the condenser lens **84**, as illustrated in FIG. **12**. Thereafter, the seed light **51** may pass through one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B via the dichroic mirror **85** to be amplified.

[0152] The amplified seed light **51** may be reflected by the turning back mirror **88**A provided at a predetermined entry position via the dichroic mirror **86** and the condenser lens **87** to pass through a first transfer position P**1**, and thereafter may be reflected by the turning back mirror **88**B to enter the condenser lens **87** again. A first transfer image Im**1** of the incident beam image IM**0** may be transferred and formed at the first transfer position P**1**, as illustrated in FIG. **12**. Thereafter, the seed light **51** may pass through the one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B via the dichroic mirror **86** again to be further amplified. The amplified seed light **51** may be reflected by the output mirror **82** via the diachronic mirror **85** and the condenser lens **84** to be outputted through a second transfer position P**2**. A second transfer image Im**2** of the incident beam image Im**0** may be transferred and formed at the second transfer position P**2**.

[0153] As described above, the multipass optical system **80** may allow the seed light **51** to reciprocate through one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B. At this occasion, the first transfer image Im**1** of the incident beam image Im**0** may be transferred and formed at the first transfer position P**1**. Moreover, the second transfer image Im**2** of the incident beam image Im**0** may be transferred and formed at the second transfer position P**2**.

[0154] Here, in a comparison between a beam profile of the first transfer image Im**1** and a beam profile of the second transfer image Im**2**, the beam profile of the first transfer image Im**1** may be deteriorated, whereas deterioration of the beam profile of the second transfer image Im**2** may be suppressed.

(3.2.3 Effect)

[0155] As described above, according to the multipass amplifier unit **41** in the present embodiment, while the multipass optical system **80** allows the incident beam image Im**0** to be transferred and formed an even number of times, the seed light **51** may reciprocate through one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B to be amplified. Accordingly, distortion of a beam of amplified light by the thermal lens effect may be suppressed.

(3.2.4 Modification Examples)

[0156] The above description involves an example in a case in which the focal length f**1** of the condenser lens **84** and the focal length f**2** of the condenser lens **87** each are substantially equal to the predetermined focal length f; however, the present embodiment is not limited to the example. The focal lengths f**1** and F**2** may be different from each other. Even in this case, a multipass optical system that allows the incident beam image Im**0** to reciprocate through one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B a plurality of times while the incident beam image Im**0** is transferred and formed a plurality of times may be configured. In a case in which the focal length f**1** of the condenser lens **84** and the focal length f**2** of the condenser lens **87** are different from each other, for example, the condenser lens **84** and the condenser lens **87** may be provided so as to allow a rear-side focal position of the condenser lens **84** to be substantially coincident with a front-side focal position of the condenser lens **87**, as illustrated in FIG. **12**. At this occasion, the optical path length between the condenser lens **84** and the condenser lens **87** may be substantially equal to a sum (f**1**+f**2**) of the focal length f**1** of the condenser lens **84** and the focal length f**2** of the condenser lens **87**. Moreover, the turning back mirrors **88**A and **88**B may be provided so as to allow the optical path length of the optical path from the condenser lens **87** via the turning back mirrors **88**A and **88**B to the condenser lens **87** to be substantially twice the focal length **12** of the condenser lens **87**.

[0157] Moreover, in the first and second multipass titanium-sapphire amplifiers **73**A and **73**B, the number of reciprocations of the seed light **51** is not limited to one reciprocation illustrated in FIG. **11**. A multipass optical system that allows the incident beam image Im**0** to reciprocate one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B a plurality of times while the incident beam image Im**0** is transferred and formed a plurality of times may be adopted. Further, the number of reciprocations of the seed light **51** may differ for first multipass titanium-sapphire amplifier **73**A and the second multipass titanium-sapphire amplifier **73**B. Furthermore, the number of reciprocations of the seed light **51** in the second multipass titanium-sapphire amplifier **73**B may be equal to or smaller than the number of reciprocations of the seed light **51** in the first multipass titanium-sapphire amplifier **73**A.

[0158] Hereinafter, an example in which three reciprocations of the seed light **51** are performed is described as a modification example of the foregoing embodiment. It is to be noted that in the following modification example, substantially same components as the components of the foregoing multipass optical system **80** illustrated in FIGS. **11** and **12** are denoted by same reference numerals, and redundant description thereof is omitted.

3.2.4.1 First Modification Example

[0159] FIG. **13** illustrates a first modification example of the multipass titanium-sapphire amplifier illustrated in FIG. **11**. FIG. **13** collectively illustrates configurations of the first multipass titanium-sapphire amplifier **73**A and the second multipass titanium-sapphire amplifier **73**B.

(Configuration)

[0160] The first multipass titanium-sapphire amplifier **73**A may include a multipass optical system **80**A as the first multipass optical system, in place of the foregoing multipass optical system **80** illustrated in FIGS. **11** and **12**. The second multipass titanium-sapphire amplifier **73**B may include the multipass optical system **80**A as the second multipass optical system, in place of the foregoing multipass optical system **80** illustrated in FIGS. **11** and **12**.

[0161] The multipass optical system **80**A may include turning back mirrors **83**A and **83**B, turning back mirrors **83**C and **83**D, the turning back mirrors **88**A and **88**B, turning back mirrors **88**C and **881**), and turning back mirrors **88**E and **88**F.

[0162] The turning back mirrors **88**A and **88**B may configure a pair of turning back mirrors, and may be provided so as to turn back, to the condenser lens **87**, the seed light **51** having entered the turning back mirrors **88**A and **88**B via the condenser lens **87**. The turning back mirrors **88**A and **88**B may be provided so as to allow an optical path length of an optical path from the condenser lens **87** via the turning back mirrors **88**A and **88**B to the condenser lens **87** to be substantially twice the predetermined focal length f.

[0163] The turning back mirrors **83**A and **83**B may configure a pair of turning back mirrors, and may be provided so as to turn back, to the condense lens **84**, the seed light **51** having entered the turning back mirrors **83**A and **83**B via the condenser lens **84**. The turning back mirrors **83**A and **83**B may be provided so as to allow an optical path length of an optical path from the condenser lens **84** via the turning back mirrors **83**A and **83**B to the condenser lens **84** to be substantially twice the predetermined focal length f.

[0164] The turning back mirrors **88**C and **88**D may configure a pair of turning back mirrors, and may be provided so as to turn back, to the condenser lens **87**, the seed light having entered the turning back mirrors **88**C and **88**D via the condenser lens **87**. The turning back mirrors **88**C and **88**D may be provided so as to allow an optical path length of an optical path from the condenser lens **87** via the turning back mirrors **88**C and **88**D to the condenser lens **87** to be substantially twice the predetermined focal length f.

[0165] The turning back mirrors **83**C and **83**D may configure a pair of turning back mirrors, and may be provided so as to turn back, to the condenser lens **84**, the seed light having entered the turning back mirrors **83**C and **83**D via the condenser lens **84**. The turning back mirrors **83**C and **83**D may be provided so as to allow an optical path length of an optical path from the condenser lens **84** via the turning back mirrors **83**C and **83**D to the condenser lens **84** to be substantially twice the predetermined focal length f.

[0166] The turning back mirrors **88**E and **88**F may configure a pair of turning back mirrors, and may be provided so as to turn back, to the condenser lens **87**, the seed light having entered the turning back mirrors **88**E and **88**F via the condenser lens **87**. The turning back mirrors **88**E and **88**F may be provided so as to allow an optical path length of an optical path from the condenser lens **87** via the turning back mirrors **88**E and **88**F to the condenser lens **87** to be substantially twice the predetermined focal length f.

(Operation)

[0167] The seed light **51** having entered the multipass optical system **80**A may be reflected by the input mirror **81** to enter substantially the center of the condenser lens **84** through the front-side focal position of the condenser lens **84** that is the predetermined entry position. At this occasion, as with the embodiment in FIG. **12**, the incident beam position PO where the incident beam image Im**0** of the seed light **51** is formed may be substantially the same as the front-side focal position of the condenser lens **84**. Thereafter, the seed light **51** may pass through one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B via the dichroic mirror **85** to be amplified.

[0168] The amplified seed light **51** may be reflected by the turning back mirror **88**A via the dichroic mirror **86** and the condenser lens **87** to pass through the first transfer position P**1**, and thereafter may be reflected by the turning back mirror **88**B to enter the condenser lens **87** again. The transfer image Im**1** of the incident beam image Im**0** may be transferred and formed at the first transfer position P**1**. Thereafter, the seed light **51** may pass through the one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B via the dichroic mirror **86** again to be further amplified.

[0169] The amplified seed light **51** may be reflected by the turning back mirror **83**A via the dichroic mirror **85** and the condenser lens **84** to pass through the second transfer position P**2**, and thereafter may be reflected by the turning back mirror **83**B to enter the condenser lens **84** again. The second transfer image Im**2** of the incident beam image Im**0** may be transferred and formed at the second transfer position P**2**. Thereafter, the seed light **51** may pass through the one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B via the dichroic mirror **85** again to be further amplified.

[0170] The amplified seed light **51** may be reflected by the turning back mirror **88**C via the dichroic mirror **86** and the condenser lens **87** to pass through a third transfer position P**3**, and thereafter may be reflected by the turning back mirror **88**D to enter the condenser lens **87** again. A third transfer image Im**3** of the incident beam image Im**0** may be transferred and formed at the third transfer position P**3**. Thereafter, the seed light **51** may pass through the one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B via the dichroic mirror **86** again to be further amplified,

[0171] The amplified seed light **51** may be reflected by the turning back mirror **83**C via the dichroic mirror **85** and the condenser lens **84** to pass through a fourth transfer position P**4**, and thereafter may be reflected by the turning back mirror **83**D to enter the condenser lens **84** again. A fourth transfer image Im**4** of the incident beam image Im**0** may be transferred and formed at the fourth transfer position P**4**. Thereafter, the seed light **51** may pass through the one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B via the dichroic mirror **85** again to be further amplified.

[0172] The amplified seed light **51** may be reflected by the turning back mirror **88**E via the dichroic mirror **86** and the condenser lens **87** to pass through a fifth transfer position P**5**, and thereafter may be reflected by the turning back mirror **88**E to enter the condenser lens **87** again. A fifth transfer image Im**5** of the incident beam image Im**0** may be transferred and formed at the fifth transfer position P**5**. Thereafter, the seed light **51** may pass through the one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B via the dichroic mirror **86** again to be further amplified.

[0173] The amplified seed light **51** may be reflected by the output mirror **82** via the dichroic mirror **85** and the condenser lens **84** to be outputted through a sixth transfer position P**6**. A sixth transfer image Im**6** of the incident beam image Im**0** may be transferred and formed at the sixth transfer position P**6**.

[0174] As described above, in the multipass optical system **80**A, the seed light **51** may reciprocate through one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B. At this occasion, the incident beam image Im**0** may be transferred and formed six times in total as first to sixth transfer images. Here, beam profiles of the first, third, and fifth transfer images out of the first to sixth transfer images may be deteriorated, whereas deterioration of beam profiles of the second, fourth, and sixth transfer images may be suppressed.

(Effect)

[0175] As described above, while the multipass optical system **80**A allows the incident beam image Im**0** to be transferred and formed an even number of times, the seed light **51** may reciprocate through one of the first titanium-sapphire crystal **74**A and the second titanium-sapphire crystal **74**B to be amplified. Accordingly, distortion of a beam of amplified light by the thermal lens effect may be suppressed.

3.2.4.2 Second Modification Example

[0176] FIG. **14** illustrates a second modification example of the multipass titanium-sapphire amplifier illustrated in FIG. **11**. FIG. **14** collectively illustrates configurations of the first multipass titanium-sapphire amplifier **73**A and the second multipass titanium-sapphire amplifier **73**B.

[0177] The first and second multipass titanium-sapphire amplifiers **73**A and **73**B each may include a multipass optical system **8013** in place of the foregoing multipass optical system **80**A illustrated in FIG. **13**. The multipass optical system **8013** may include dispersing prisms **89**A and **89**B.

[0178] A gain is small in a wavelength region of a wavelength of 904 nm, which easily causes amplified spontaneous emission (ASE). In order to suppress ASE, the dispersing prisms **89**A and **89**B may be inserted in an optical path in each of the first and second titanium-sapphire amplifiers **73**A and **73**B, as illustrated in FIG. **14**. Alternatively, only one of the dispersing prisms **89**A and **89**B may be inserted. The dispersing prism **89**A may be provided between the condenser lens **84** and both the turning back mirrors **83**A and **83**C. The dispersing prism **89**B may be provided between the condenser lens **87** and both the turning back mirrors **88**C and **88**E,

4. Second Embodiment

[0179] Next, description is given of a titanium-sapphire laser apparatus and a laser apparatus used for an exposure apparatus according to a second embodiment of the present disclosure. Note that substantially same components as the components of the titanium-sapphire laser apparatus and the laser apparatus used for the exposure apparatus according to the foregoing comparative example or the foregoing first embodiment are denoted by same reference numerals, and redundant description thereof is omitted.

[0180] A basic configuration of the laser apparatus used for the exposure apparatus according to the present embodiment may be substantially similar to that of the laser apparatus used for the exposure apparatus illustrated in FIG. **1**.

(4.1 MOPO)

[0181] (4.1.1 Configuration)

[0182] FIG. **15** schematically illustrates a configuration example of an MOPO **40**B as a configuration of a main part of the narrow-band titanium-sapphire laser apparatus **20** according to the second embodiment of the present disclosure.

[0183] The narrow-band titanium-sapphire laser apparatus **20** according to the present embodiment may include the MOPO **40**B including a band pass filter **58**, in place of the MOPO **40**A in the configuration of the foregoing first embodiment illustrated in FIG. **6**. The narrow-band titanium-sapphire laser apparatus **20** according to the present embodiment may further include a second optical shutter **53**B in addition to the configuration of the foregoing first embodiment illustrated in FIG. **6**.

[0184] The band pass filter **58** may be provided in an optical path in the optical resonator of the PO **60**. The band pass filter **58** may allow light in a wavelength region around a wavelength of 904 nm that is the wavelength of the seed light **51** to selectively pass therethrough.

[0185] The second optical shutter **53**B may be provided in an optical path between the PO **60** and the multipass amplifier unit **41**. The delay circuit **57** may receive an oscillation trigger of the synchronous circuit **13** and may output a signal for control of opening and closing of the second optical shutter **54**B after a predetermined delay time.

(4.1.2 Effect)

[0186] According to the MOPO **40**B in the present embodiment, the band pass filter **58** is provided in the optical path in the optical resonator of the PO **60**, which makes it possible to suppress oscillation of a wavelength component other than the seed light **51**. A gain is small wavelength region of a wavelength of 904 nm, which easily causes oscillation of laser light of the wavelength component other than the seed light **51**. Accordingly, providing the band pass filter **58** that allows light in a wavelength region of the seed light **51** to pass therethrough at high transmittance makes it possible to suppress oscillation of the wavelength component other than the seed light **51**. This makes it possible for the PO **60** to amplify and oscillate even weak CW seed light Si to produce laser light of the same wavelength as that of a laser diode.

[0187] Moreover, according to the narrow-band titanium-sapphire laser apparatus **20** in the present embodiment, the second optical shutter **53**B is provided between the PO **60** and the multipass amplifier unit **41**, which makes it possible to suppress variation in a pulsed width of the seed light **51** amplified in the form of pulse after having passed through the second optical shutter **53**B and fluctuation of a pulse rising time of the amplified seed light **51**. In an injection locking method for the PO **60**, the pulse rising time and a pulse waveform may vary to some extent by a slight optical path length error in the optical resonator. In other words, even if the pulse of the seed light **51** entering the second optical shutter **53**B varies to some extent, trimming the pulse of the seed light **51** by the second optical shutter **53**B makes it possible to stabilize the pulse rising time and the pulse waveform of the seed light **51** outputted from the second optical shutter **53**B. Moreover, when the optical resonator is designed suitably for a thermal lens of the titanium-sapphire crystal **61** of the PO **60**, the optical path length in the optical resonator may increase. Therefore, the second optical shutter **53**B that operates at high speed may be introduced to perform opening and closing at predetermined timings, thereby trimming the seed light **51** amplified in the form of pulse. This makes it possible to suppress variation in the pulse width and fluctuation of the pulse rising time. Since final output from the narrow-band titanium-sapphire laser apparatus **20** is determined by the multipass amplifier unit **41**, it is possible to reduce an influence of loss due to trimming by the second optical shutter **53**B.

(4.2 Multipass Amplifier Unit)

4.2.1 Configuration

[0188] FIG. **16** schematically illustrates a configuration example of a multipass amplifier unit **41**A as a configuration of a main part of the narrow-band titanium-sapphire laser apparatus **20** according to the second embodiment of the present disclosure.

[0189] The narrow-band titanium-sapphire laser apparatus **20** according to the present embodiment may include the multipass amplifier unit **41**A in place of the multipass amplifier unit **41** in the configuration of the comparative example illustrated in FIG. **2**. The multipass amplifier unit **41**A may include a third multipass titanium-sapphire amplifier **73**C. The third multipass titanium-sapphire amplifier **73**C may include a third titanium-sapphire crystal that is different from the titanium-sapphire crystal **61**. The third multipass titanium-sapphire amplifier **73**C may be configured to allow the seed light **51** to reciprocate through the third titanium-sapphire crystal in a manner substantially similar to that in the first and second multipass titanium-sapphire amplifiers **73**A and **73**B illustrated in FIG. **11**.

[0190] The multipass amplifier unit **41**A may further include a fourth excitation pulsed laser unit **70**D, a fourth condenser lens **72**D, an eleventh high reflection mirror **111**, and a twelfth high reflection mirror **112**. The fourth excitation pulsed laser unit **70**D may be a pulsed laser unit that outputs fourth pulsed laser light **71**D used for excitation.

[0191] An oscillation trigger may be inputted from the synchronous circuit **13** to each of the first, second, and third excitation pulsed laser units **70**A, **70**B, and **70**C and the fourth excitation pulsed laser unit **70**D,

4.2.2 Operation and Effect

[0192] In the multipass amplifier unit **41**A, the seed light **51** amplified by the second multipass titanium-sapphire amplifier **73**B may enter the third multipass titanium-sapphire amplifier **73**C via the tenth high reflection mirror **110** and the eleventh high reflection mirror **111**. In the third multipass titanium-sapphire amplifier **73**C, the seed light **51** of a wavelength of 904 nm amplified in the form of pulse may enter the third titanium-sapphire crystal. The fourth pulsed laser light **71**D serving as excitation light from the fourth excitation pulsed laser unit **70**D may enter the third titanium-sapphire crystal in synchronization with an entry timing of the seed light **51** to excite the seed light **51** in the form of pulse. In the third multipass titanium-sapphire amplifier **73**C, multiple passing of pulsed laser light of a wavelength of 904 nm through the third titanium-sapphire crystal may amplify the seed light **51** a plurality of times.

[0193] The seed light **51** amplified by the third multipass titanium-sapphire amplifier **73**C may enter the LBO crystal **1** via the twelfth high reflection mirror **112**.

[0194] At this occasion, the multipass amplifier unit **41**A for further amplification of the seed light **51** of a wavelength of 904 nm amplified in the form of pulse has a small amplification gain at this wavelength. In order to have a sufficiently long focal length of the thermal lens in the titanium-sapphire crystal with respect to a crystal length, it is necessary to optimize the number of times of multiple passing in the multipass amplifier unit **41**A and the number of multipass titanium-sapphire amplifiers.

[0195] In the multipass amplifier unit **41**A in the present embodiment, the number of times of multiple passing in the first multipass titanium-sapphire amplifier **73**A may be three reciprocations. Moreover, the number of times of multiple passing in the second multipass titanium-sapphire amplifier **73**B may be two reciprocations. Further, the number of times of multiple passing in the third multipass titanium-sapphire amplifier **73**C may be one reciprocation.

[0196] Incidentally, as illustrated in FIG. **5** mentioned above, as input of the excitation light increases, the focal length by the thermal lens effect in the titanium-sapphire crystal may be shortened. When the focal length of the thermal lens by the thermal lens effect is about 10 mm or less, even if a position of an optical device of an optical system for multiple passing through the titanium-sapphire crystal is adjusted in an optical path axis direction, deterioration in beam characteristics after amplification may not suppressed. Examples of the optical device may include the condenser lenses **84** and **87** illustrated in FIG. **11**. In particular, when the number of reciprocations increases, deterioration in beam characteristics may be pronounced by the thermal lens effect in the titanium-sapphire crystal.

[0197] FIG. **17** illustrates an example of amplification characteristics of the multipass amplifier unit **41**A illustrated in FIG. **16**.

[0198] An upper portion of FIG. **17** illustrates a relationship between the total number of reciprocations of the seed light **51** in the first, second, and third multipass titanium-sapphire amplifiers **73**A, **73**B, and **73**C and pulse energy of amplified light of the seed light **51**. As illustrated in the upper portion of FIG. **17**, in the first multipass titanium-sapphire amplifier **73**A, first amplified light of the seed light **51** having small pulse energy outputted from the PO **60** may reciprocate three times to be amplified until a gain is saturated, and the thus-amplified seed light **51** may be outputted as second amplified light.

[0199] In the second multipass titanium-sapphire amplifier **73**B, the second amplified light of the seed light **51** may reciprocate twice to be amplified until a gain is saturated, and the thus-amplified light may be outputted as third amplified light.

[0200] In the third multipass titanium-sapphire amplifier **73**C, the third amplified light of the seed light **51** may reciprocate once to be amplified until a gain is saturated, and the thus-amplified light may be outputted as fourth amplified light.

[0201] A lower portion of FIG. **17** illustrates a relationship between the total number of reciprocations of the seed light **51** in the first, second, and third multipass titanium-sapphire amplifiers **73**A, **73**B, and **73**C and M^2 of amplified light of the seed light **51**, where M^2 may indicate light condensing performance of laser beam characteristics. $M^2=1$ may indicate single transverse mode laser beam condensing performance. It may be indicated that the condensing performance of laser light deteriorates as M^2 that is larger than 1 increases.

[0202] In the first, second, and third multipass titanium-sapphire amplifiers **73**A, **73**B, and **73**C, M^2 may increase in an odd number of times of multiple passing, and M^2 may be improved by an even number of times of multiple passing. Performing the even number of times of multiple passing may mean multiple passing so as to cause reciprocation through the titanium-sapphire crystal. Energy of excitation light of each of the first, second, and third multipass titanium-sapphire amplifiers **73**A, **73**B, and **73**C may have the following relationship of input of excitation light in order to sequentially increase a gain to be saturated.

[0203] (Input of excitation light to the first multipass titanium-sapphire amplifier **73**A)<(input of excitation light to the second multipass titanium-sapphire amplifier **73**B)<(input of excitation light to the third multipass titanium-sapphire amplifier **73**C)

[0204] The more the input of the excitation light increases, the more M^2 of the amplified light after one reciprocation may increase, as illustrated in the lower portion of FIG. **17**.

[0205] As described above, in terms of a relationship between saturation of the gain and an increase in M^2, the number of reciprocations in first multipass titanium-sapphire amplifier **73**A may be three. The number of reciprocations in the second multipass titanium-sapphire amplifier **73**B may be two. The number of reciprocations in the third multipass titanium-sapphire amplifier **73**C may be one. This makes it possible to improve amplification efficiency and to suppress an increase in M^2.

4.2.3 Modification Example

[0206] FIG. **18** schematically illustrates a configuration example of a multipass amplifier unit **41**B according to a modification example of the present embodiment. A dispersing prism **59** may be provided in an optical path between the first multipass titanium-sapphire amplifier **73**A and the second multipass titanium-sapphire amplifier **73**B, as with the multipass amplifier unit **41**B illustrated in FIG. **18**. The dispersing prism **59** makes it possible to suppress entry of ASE light generated in the first titanium-sapphire crystal **74**A of the first multipass titanium-sapphire amplifier **73**A into the second multipass titanium-sapphire amplifier **73**B.

(Another Configuration)

[0207] In the modification example in FIG. **18**, the dispersing prism **59** may be provided in the optical path between the first multipass titanium-sapphire amplifier **73**A and the second multipass titanium-sapphire amplifier **73**B. Alternatively, the dispersing prism **59** may be provided in an optical path of the seed light **51** other than the foregoing optical path, as necessary. This makes it possible to suppress ASE of a wavelength other than a wavelength around 904 nm and to suppress deterioration in beam characteristics of amplified pulsed laser light by the thermal lens effect.

5. Configuration Example of Optical Path Length Error Detector

[0208] Next, description is given of a specific configuration example of the optical path length error detector **43** with reference to FIG. **19**. Note that substantially same components as the components of the titanium-sapphire laser apparatus and the laser apparatus used for the exposure apparatus according to any of the foregoing comparative example and the foregoing first and second embodiments are denoted by same reference numerals, and redundant description thereof is omitted.

5.1 Configuration

[0209] The optical path length error detector **43** may be a detector by a Hansch-Couillaud method. The Hansch-Couillaud method may be a method of detecting the optical path length error ΔL between a positive integer multiple of the wavelength of the seed light **51** and the optical path length in the optical resonator by measuring polarization characteristics of the leak light **52** of the seed light **51** from the optical resonator.

[0210] The optical path length error detector **43** may include a λ/2 plate **91**, a λ/4 plate **92**, a polarizer **93**, a high reflection mirror **94**, a first optical sensor **95**A, a second optical sensor **95**B, and a subtracter **96**.

5.2 Operation

[0211] In order to analyze a polarization state of the leak light **52**, the leak light **52** may pass through the λ/2 plate **91** and the λ/4 plate **92**, and may be separated by the polarizer **93** into a P-polarized component and an S-polarized component Thereafter, light intensities of the respective polarized components may be detected by the first optical sensor **95**A and the second optical sensor **95**B.

[0212] The subtractor **96** may subtract signals of light intensity of the first optical sensor **95**A and the second optical sensor **95**B from each other, and when a value of the subtractor **96** is zero, the positive integer multiple of the wavelength of the seed light **51** may be equal to the optical path length in the optical resonator. A subtracted voltage value may be outputted from the subtractor **96** in accordance with the optical path length error ΔL. The voltage value outputted from the substractor **96** may be read by the error controller **55** to measure a state of the optical path length error ΔL.

5.3 Modification Examples

[0213] In the configuration example in FIG. **19**, the method of measuring the optical path length error ΔL is the Hansch-Couillaud method, but is not limited thereto. Alternatively, any other method such as a Pound-Derever-Hall method and a phase sensitive detection method may be adopted.

6. Configuration Example of Optical Shutter

[0214] Next, description is given of a specific configuration example of an optical shutter **310** applicable as the first optical shutter **53**A and the second optical shutter **53**B mentioned above with reference to FIG. **20**. It is to be noted that substantially same components as the components of the titanium-sapphire laser apparatus and the laser apparatus used for the exposure apparatus according to any of the foregoing comparative example and the foregoing first and second embodiments are denoted by same reference numerals, and redundant description thereof is omitted.

(6.1 Configuration)

[0215] FIG. **20** illustrates a configuration example of the optical shutter **310**. The optical shutter **310** may include a Pockets cell **394** and a polarizer **396**. The pockets cell **394** may include a high-voltage power source **393**, a first electrode **395***a*, a second electrode **395***b*, and an electro-optic crystal **395***c*. The first electrode **395***a* and the second electrode **395***b* may be provided to face each other, and the electro-optic crystal **395***c* may be provided between the first electrode **395***a* and the second electrode **395***b*. The high-voltage power source **393** may be controlled by a transmittance setter **311** and a synchronous circuit **312**.

(6.2 Operation)

[0216] The high-voltage power source **393** may receive a control signal of the optical shutter **310** from the transmittance setter **311** or the synchronous circuit **312**. The high-voltage power source **393** may generate a predetermined high voltage that is not 0 V upon reception of an open signal as the control signal of the optical shutter **310**, and may apply the generated voltage between the first electrode **395***a* and the second electrode **395***b*. The open signal r ray allow the optical shutter **310** to be opened. The high-voltage power source **393** may change the voltage to be applied between the first electrode **395***a* and the second electrode **39***b* to 0 V upon reception of a close signal as the control signal of the optical shutter **310**. The close signal may allow the optical shutter to be closed.

[0217] The Pockets cell **394** may have a function equivalent to a λ/2 plate when a predetermined high voltage is applied between the first electrode **395***a* and the second electrode **395***b*. When the predetermined high voltage is not applied between the first electrode **395***a* and the second electrode **395***b*, light linearly polarized in a direction perpendicular to a paper plane may pass through the electro-optic crystal **39***c* without changing its polarization state, and may be reflected by the polarizer **396**. In FIG. **20**, light linearly polarized in the direction perpendicular to the paper plane may be indicated by a black circle drawn in a laser optical path. At this occasion, upon application of the predetermined high voltage, a phase of the light linearly polarized in the direction perpendicular to the paper plane may be shifted by **212** to cause the light linearly polarized in the direction perpendicular to the paper plane to be converted into light linearly polarized in a direction including the paper plane. In FIG. **20**, the light linearly polarized in the direction including the paper plane may be indicated by an arrow perpendicular to an optical path drawn in the laser optical path. This light may pass through the polarizer **396**. As described above, the optical shutter **310** may allow light to pass therethrough during application of the high voltage to the electro-optic crystal **395***c*.

[0218] The Pockets cell **394** has responsivity of about 1 ns, and is applicable as a high-speed optical shutter. Moreover, for example, an acousto-optical (AO) device may be used as the optical shutter **310**. In this case, the AO device has responsivity of about several hundreds of ns; therefore, the AO device is applicable. Moreover, changing the voltage to be applied between the first electrode **395***a* and the second electrode **395***b* in response to control from the transmittance setter **311** makes it possible to vary transmittance.

[0219] It is to be noted that a polarizer and a λ/2 plate may be further included in an upstream-side optical path in addition to the configuration of the optical shutter **310** in FIG. **20** to serve as an optical isolator. Note that left side and right side of FIG. **20** may indicate upstream side and downstream side, respectively. In this case, when the predetermined high voltage is applied between the first electrode **395***a* and the second electrode **395***b* in the Pockels cell **394**, the optical isolator may allow both light from the upstream side and light from downstream side to pass therethrough at high transmittance. In other words, the optical isolator may be opened. When the predetermined high voltage is not applied between the first electrode **395***a* and the second electrode **395***b*, the optical isolator may prevent both the light from the upstream side and the light from the downstream side from passing therethrough. In other words, the optical isolator may be closed.

7. Hardware Environment of Controller

[0220] A person skilled in the art will appreciate that a general-purpose computer or a programmable controller may be combined with a program module or a software application to execute any subject matter disclosed herein. The program module, in general, may include one or more of a routine, a program, a component, a data structure, and so forth that each causes any process described in any example embodiment of the present disclosure to be executed.

[0221] FIG. **21** is a block diagram illustrating an exemplary hardware environment in which various aspects of any subject matter disclosed therein may be executed. An exemplary hardware environment **100** in FIG. **21** may include a processing unit **1000**, a storage unit **1005**, a user interface **1010**, a parallel input/output (PO) controller **1020**, a serial I/O controller **1030**, and an analog-to-digital (A/D) and digital-to-analog (D/A) converter **1040**. Note that the configuration of the hardware environment **100** is not limited thereto.

[0222] The processing unit **1000** may include a central processing unit (CPU) **1001**, a memory **1002**, a timer **1003**, and a graphics processing unit (GPU) **1004**. The memory **1002** may include a random access memory (RAM) and a read only memory (ROM). The CPU **1001** may be any commercially-available processor. A dual microprocessor or any other multi-processor architecture may be used as the CPU **1001**.

[0223] The components illustrated in FIG. **21** may be coupled to one another to execute any process described in any example embodiment of the present disclosure.

[0224] Upon operation, the processing unit **1000** may load programs stored in the storage unit **1005** to execute the loaded programs. The processing unit **1000** may read data from the storage unit **1005** together with the programs, and may write data in the storage unit **1005**. The CPU **1001** may execute the programs loaded from the storage unit **1005**. The memory **1002** may be a work area in which programs to be executed by the CPU **1001** and data to be used for operation of the CPU **1001** are held temporarily. The timer **1003** may measure time intervals to output a result of the measurement to the CPU **1001** in accordance with the execution of the programs. The GPU **1004** may process image data in accordance with the programs loaded from the storage unit **1005**, and may output the processed image data to the CPU **1001**.

[0225] The parallel I/O controller **1020** may be coupled to parallel I/O devices operable to perform communication with the processing unit **1000**, and may control the communication performed between the processing unit **1000** and the parallel I/O devices. Non-limiting examples of the parallel I/O devices may include the synchronization controller **3**, the exposure apparatus controller **5**, the synchronous circuit **13**, the amplifier controller **30**, the charger **31**, the shift amount adder **54**, and the error controller **55**. The serial I/O controller **1030** may be coupled to a plurality of serial I/O devices operable to perform communication with the processing unit **1000**, and may control the communication performed between the processing unit **1000** and the serial I/O devices. Non-limiting examples of serial I/O devices may include the delay circuit **57** and the error controller **55**. The A/D and D/A converter **1040** may be coupled to analog devices such as various kinds of sensors through respective analog ports. Non-limiting examples of the sensors may include the optical path length error detector **43**. The A/D and D/A converter **1040** may control communication performed between the processing unit **1000** and the analog devices, and may perform analog-to-digital conversion and digital-to-analog conversion of contents of the communication.

[0226] The user interface **1010** may provide an operator with display showing a progress of the execution of the programs executed by the processing unit **1000**, such that the operator is able to instruct the processing unit **1000** to stop execution of the programs or to execute an interruption routine.

[0227] The exemplary hardware environment **100** may be applied to one or more of configurations of the solid-state laser controller **14** and other controllers according to any example embodiment of the present disclosure. A person skilled in the art will appreciate that such controllers may be executed in a distributed computing environment, namely, in an environment where tasks may be performed by processing units linked through any communication network. In any example embodiment of the present disclosure, controllers such as an unillustrated controller for an exposure apparatus that integrally controls the solid-state laser controller **14**, the synchronization controller **3**, and the amplifier controller **30** may be coupled to one another through a communication network such as Ethernet (Registered Trademark) or the Internet. In the distributed computing environment, the program module may be stored in each of local and remote memory storage devices.

8. Et Cetera

[0228] The foregoing description is intended to be merely illustrative rather than limiting. It should therefore be appreciated that variations may be made in example embodiments of the present disclosure by persons skilled in the art without departing from the scope as defined by the appended claims.

[0229] The terms used throughout the specification and the appended claims are to be construed as "open-ended" terms. For example, the term "include" and its grammatical variants are intended to be non-limiting, such that recitation of items in a list is not to the exclusion of other like items that can be substituted or added to the listed items. The term "have" and its grammatical variants are intended to be non-limiting, such that recitation of items in a list is not to the exclusion of other like items that can be substituted or added to the listed items. Also, the singular forms "a", "an", and "the" used in the specification and the appended claims include plural references unless expressly and unequivocally limited to one referent.

What is claimed is:

1. A titanium-sapphire laser apparatus, comprising:

a continuous wave oscillation laser unit configured to perform continuous wave oscillation in a single longitudinal mode to output seed light;

an amplification oscillator where the seed light enters, and including an optical resonator and a titanium-sapphire crystal, the titanium-sapphire crystal being provided in an optical path in the optical resonator;

a pulsed laser unit configured to output pulsed laser light toward the titanium-sapphire crystal;

an error detector provided in an optical path of leak light of the seed light from the optical resonator, and configured to detect an optical path length error between an optical path length in the optical resonator and a positive integer multiple of a wavelength of the seed light and output an optical path length error signal;

an error controller configured to output a correction value of the optical path length error signal; and

an optical path length corrector configured to vary the optical path length in the optical resonator on a basis of a signal, the signal resulting from adding the correction value to the optical path error signal.

2. The titanium-sapphire laser apparatus according to claim **1**, wherein the error controller calculates the correction value on a basis of the optical path length error signal inputted from the error detector within a predetermined period.

3. The titanium-sapphire laser apparatus according to claim **2**, wherein the error controller calculates the correction value to allow the optical path length error to approach zero at a timing immediately before entry of the pulsed laser light into the titanium-sapphire crystal.

4. The titanium-sapphire laser apparatus according to claim **2**, further comprising:

a synchronous circuit configured to output an oscillation trigger to the pulsed laser unit, the oscillation trigger controlling an output timing of the pulsed laser light;

an optical shutter provided in the optical path of the leak light between the optical resonator and the error detector; and

an optical shutter controller configured to perform, on a basis of the oscillation trigger, control in which the optical shutter is closed during entry of the seed light amplified in a form of pulse by the amplification oscillator into the optical shutter and the optical shutter is opened during non-entry of the seed light amplified in the form of pulse by the amplification oscillator into the optical shutter.

5. The titanium-sapphire laser apparatus according to claim **1**, further comprising a band pass filter provided in the optical path in the optical resonator and configured to allow the seed light to selectively pass therethrough.

6. The titanium-sapphire laser apparatus according to claim **1**, wherein the wavelength of the seed light is about 904 nm.

7. The titanium-sapphire laser apparatus according to claim **1**, wherein the optical resonator is a ring optical resonator.

8. The titanium-sapphire laser apparatus according to claim **1**, further comprising a first multipass amplifier including a first multipass optical system and a first titanium-sapphire crystal, the first multipass optical system allowing the seed light outputted from the amplification oscillator to reciprocate therethrough, and the first titanium-sapphire crystal being provided in a first multiple optical path in the first multipass optical system and being different from the titanium-sapphire crystal.

9. The titanium-sapphire laser apparatus according to claim **8**, further comprising a second multipass amplifier including a second multipass optical system and a second titanium-sapphire crystal, the second multipass optical system allowing the seed light outputted from the first multipass amplifier to reciprocate therethrough, and the second titanium-sapphire crystal being provided in a second multiple optical path in the second multipass optical system and being different from the titanium-sapphire crystal, wherein the number of reciprocations of the seed light in the second multipass amplifier is equal to or smaller than the number of reciprocations of the seed light in the first multipass amplifier.

10. The titanium-sapphire laser apparatus according to claim **9**, further comprising a dispersing prism provided in an optical path between the first multipass amplifier and the second multipass amplifier.

11. The titanium-sapphire laser apparatus according to claim **8**, wherein the first multipass optical system allows an incident beam image at a predetermined entry position in an optical path of the seed light in the first multipass optical system to be transferred onto the optical path of the seed light an even number of times to form an image of the incident beam image.

12. The titanium-sapphire laser apparatus according to claim **8**, wherein

the first multipass optical system includes a first condenser lens and a second condenser lens,

an optical path length between the first condenser lens and the second condenser lens is substantially a sum of a focal length of the first condenser length and a focal length of the second condenser lens, and

the first titanium-sapphire crystal is provided substantially at a rear-side focal position of the first condenser lens between the first condenser lens and the second condenser lens.

13. The titanium-sapphire laser apparatus according to claim **12**, wherein the focal length of the first condenser lens is substantially equal to the focal length of the second condenser lens.

14. The titanium-sapphire laser apparatus according to claim **12**, wherein

the first multipass optical system includes a pair of turning back mirrors provided in an optical path of the seed light that has passed through one of the first condenser lens and the second condenser lens, the pair of turning back mirrors being configured to turn back the optical path of the seed light to the one of the first condenser lens and the second condenser lens, and

an optical path length of an optical path from the one of the first condenser lens and the second condenser lens via the pair of turning back mirrors to the one of the first condenser lens and the second condenser lens is substantially twice the focal length of the one of the first condenser lens and the second condenser lens.

15. The titanium-sapphire laser apparatus according to claim **14**, wherein the focal length of the first condenser lens is substantially equal to the focal length of the second condenser lens.

16. A laser apparatus used for an exposure apparatus, the laser apparatus comprising:

a master oscillator power oscillator including a continuous wave oscillation laser unit, the continuous wave oscillation laser unit being configured to perform continuous wave oscillation in a single longitudinal mode to output seed light;

a first multipass amplifier including a first multipass optical system and a first titanium-sapphire crystal, the first multipass optical system allowing the seed light outputted from the master oscillator power oscillator to reciprocate therethrough, and the first titanium-sapphire crystal being provided in a first multiple optical path in the first multipass optical system; and

a second multipass amplifier including a second multipass optical system and a second titanium-sapphire crystal, the second multipass optical system allowing the seed light outputted from the first multipass amplifier to reciprocate therethrough, and the second titanium-sapphire crystal being provided in a second multiple optical path in the second multipass optical system,

the number of reciprocations of the seed light in the second multipass amplifier being equal to or smaller than the number of reciprocations of the seed light in the first multipass amplifier.

17. A titanium-sapphire amplifier, comprising:

a titanium-sapphire crystal;

a multipass optical system including a plurality of light condensing optical devices, and configured to allow seed light having entered via a predetermined entry position to pass through the titanium-sapphire crystal an even number of times and configured to allow an incident beam image at the predetermined entry position to be transferred by the plurality of light condensing optical devices an even number of times to form an image of the incident beam image;

a first dichroic mirror provided in an optical path of the seed light in the multipass optical system and provided to allow excitation light to enter the titanium-sapphire crystal; and

a second dichroic mirror provided in the optical path of the seed light in the multipass optical system and provided to allow the excitation light outputted from the titanium-sapphire crystal to be outputted to outside of the multipass optical system.

18. The titanium-sapphire amplifier according to claim **17**, wherein

the plurality of light condensing optical devices each include a first condenser lens and a second condenser lens,

an optical path length between the first condenser lens and the second condenser lens is substantially a sum of a focal length of the first condenser lens and a focal length of the second condenser lens, and

the titanium-sapphire crystal is provided substantially at a rear-side focal position of the first condenser lens between the first condenser lens and the second condenser lens.

19. The titanium-sapphire laser amplifier according to claim **18**, wherein the focal length of the first condenser lens is substantially equal to the focal length of the second condenser lens.

20. The titanium-sapphire amplifier according to claim **19**, wherein

the multipass optical system includes a pair of turning back mirrors provided in an optical path of the seed light that has passed through one of the first condenser lens and the second condenser lens, the pair of turning back mirrors being configured to turn back the optical path of the seed light to the one of the first condenser lens and the second condenser lens, and

an optical path length of an optical path from the one of the first condenser lens and the second condenser lens via the pair of turning back mirrors to the one of the first condenser lens and the second condenser lens is substantially twice the focal length of the one of the first condenser lens and the second condenser lens.

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