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(54) LIGHT MODULATION CONTROL METHOD, CONTROL PROGRAM, CONTROL DEVICE AND LASER BEAM IRRADIATION DEVICE

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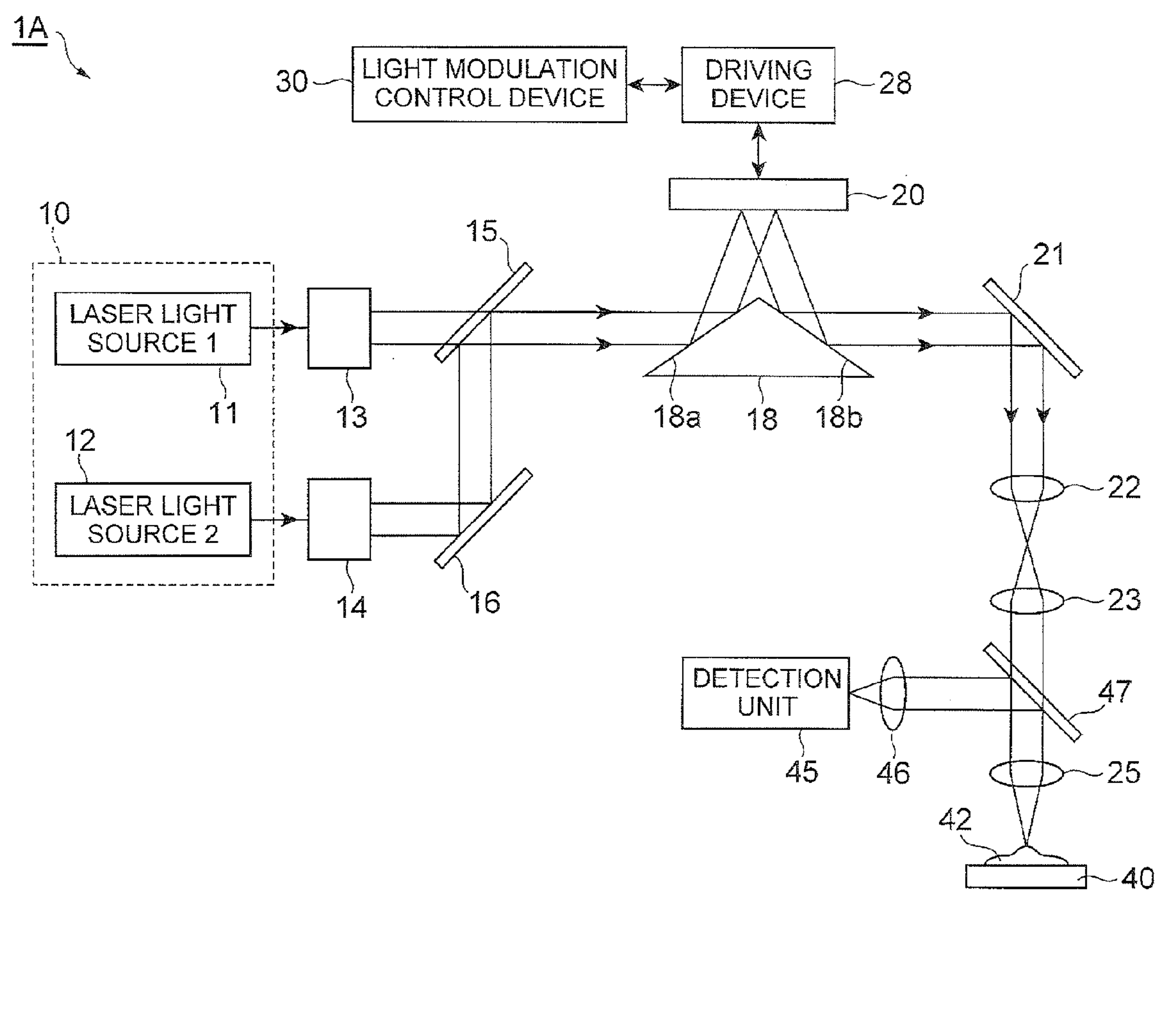
(57) **ABSTRACT**

In the control of light condensing irradiation of laser light using a spatial light modulator, the number of wavelengths, a value of each wavelength, and incident conditions of the laser light are acquired, the number of light condensing points, and a light condensing position, a wavelength, and a light condensing intensity on each light condensing point are set, and a distortion phase pattern provided in an optical system including the spatial light modulator to the laser light is derived. Then, a modulation pattern presented in the spatial light modulator is designed in consideration of the distortion phase pattern. Further, in the design of a modulation pattern, a design method focusing on an effect by a phase value of one pixel is used, and when evaluating a light condensing state, a propagation function to which a distortion phase pattern is added is used.



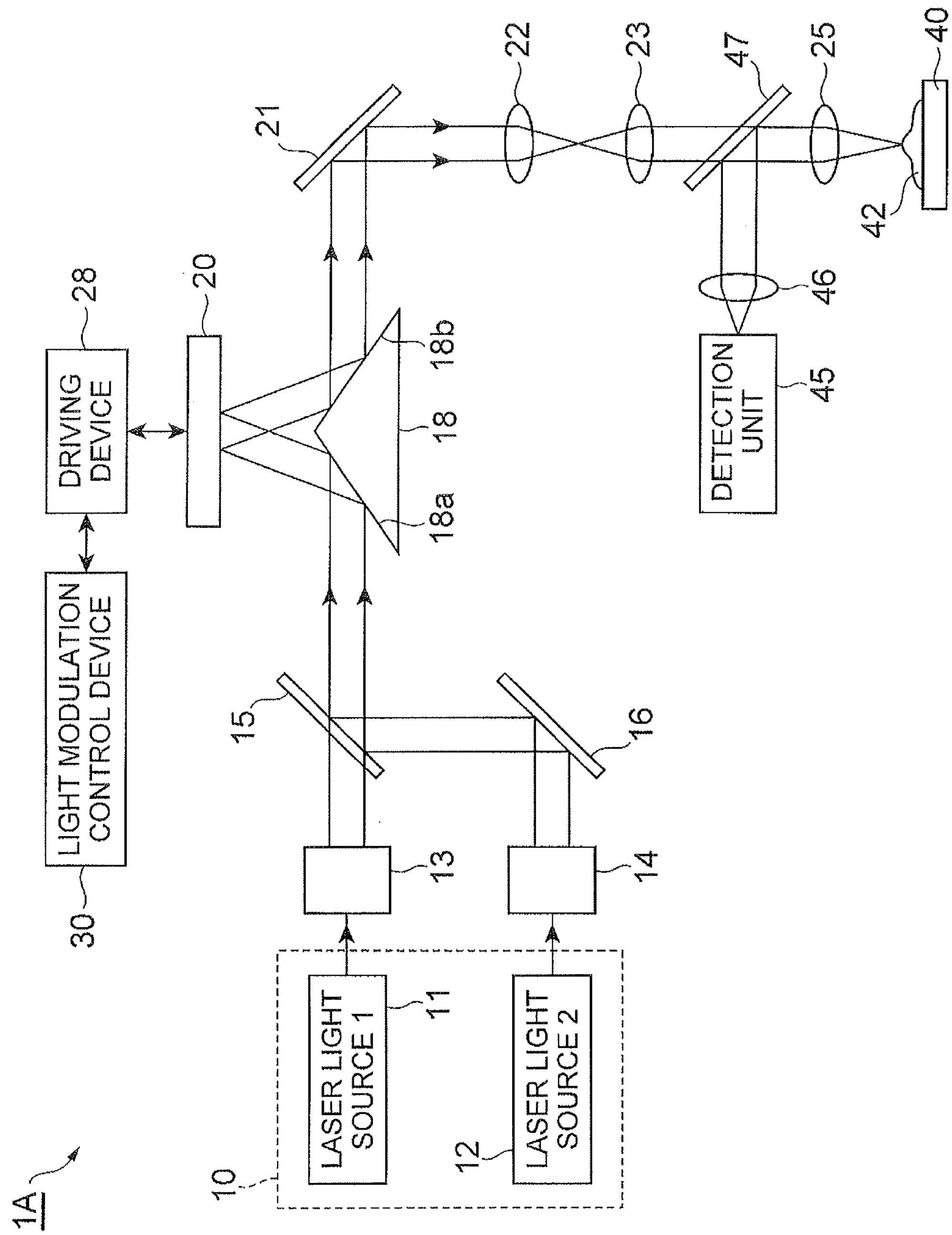

LIGHT MODULATION CONTROL DEVICE
DRIVING DEVICE
LASER LIGHT SOURCE 1
LASER LIGHT SOURCE 2
DETECTION UNIT
1A
10
11
12
13
14
15
16
18
18a
18b
20
21
22
23
25
28
30
40
42
45
46
47

Fig.1

Fig.2

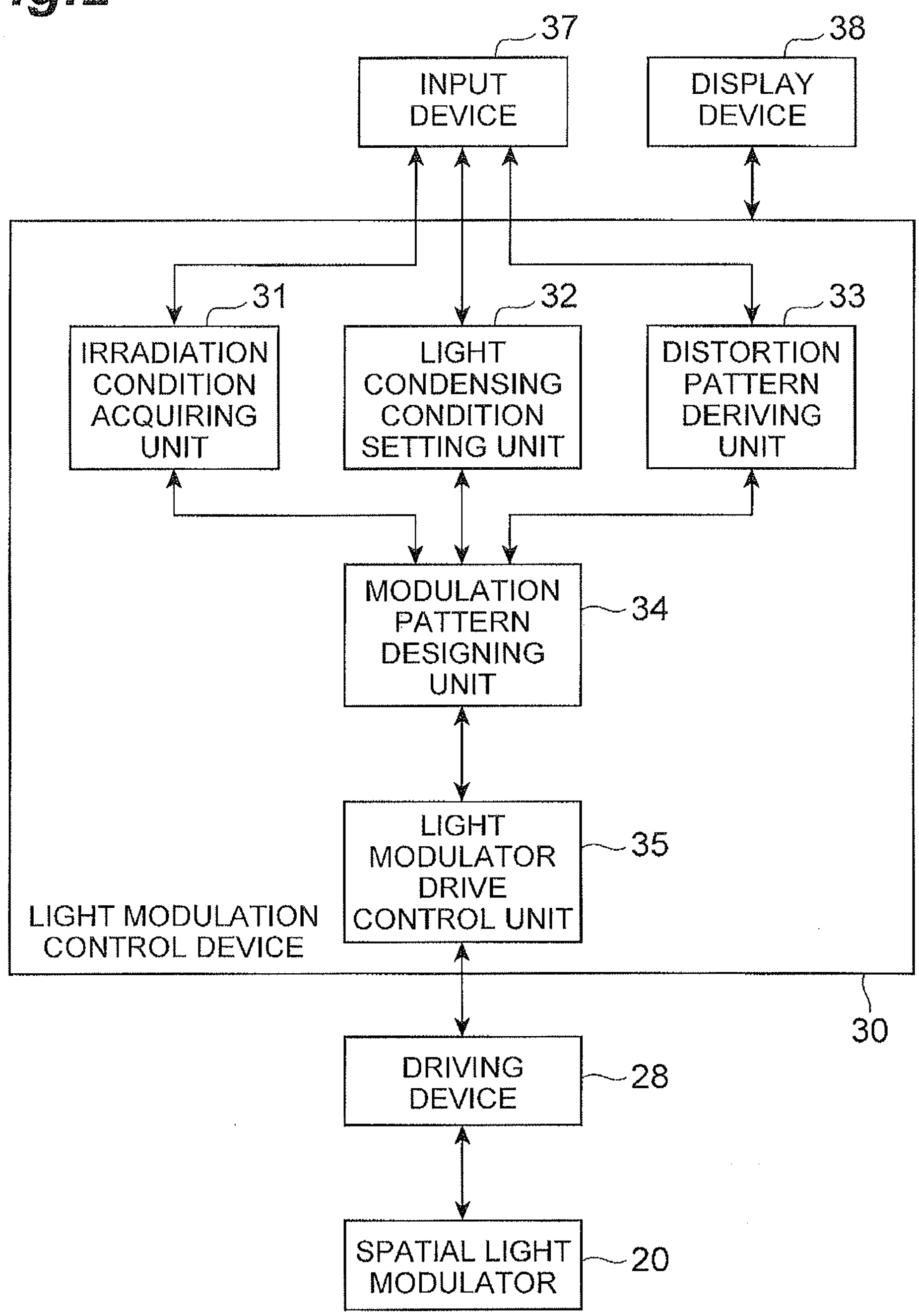

37
INPUT DEVICE
38
DISPLAY DEVICE
31
IRRADIATION CONDITION ACQUIRING UNIT
32
LIGHT CONDENSING CONDITION SETTING UNIT
33
DISTORTION PATTERN DERIVING UNIT
MODULATION PATTERN DESIGNING UNIT
34
LIGHT MODULATOR DRIVE CONTROL UNIT
35
LIGHT MODULATION CONTROL DEVICE
30
DRIVING DEVICE
28
SPATIAL LIGHT MODULATOR
20

Fig.3

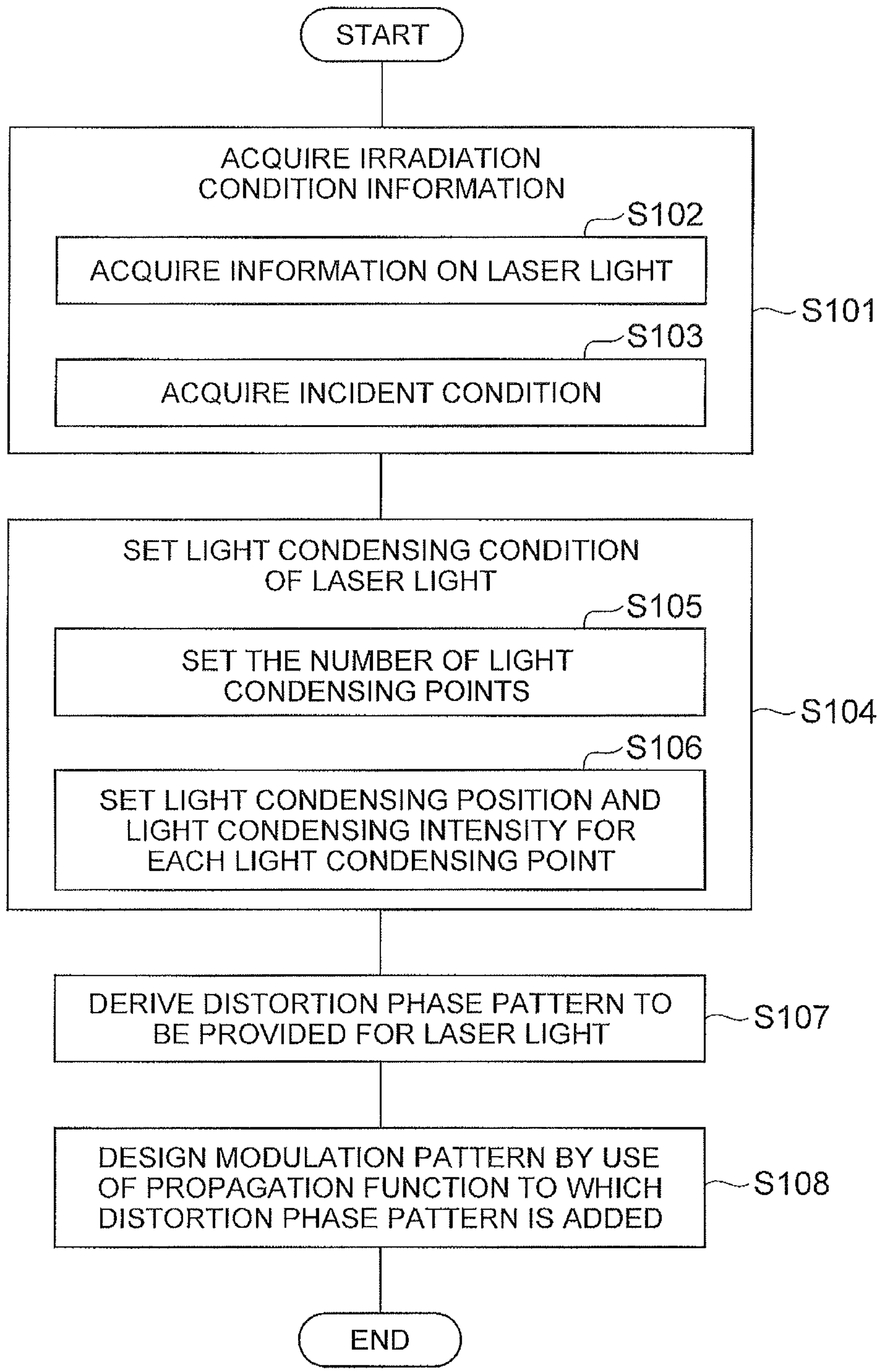

START
ACQUIRE IRRADIATION CONDITION INFORMATION
S102
ACQUIRE INFORMATION ON LASER LIGHT
S101
S103
ACQUIRE INCIDENT CONDITION
SET LIGHT CONDENSING CONDITION OF LASER LIGHT
S105
SET THE NUMBER OF LIGHT CONDENSING POINTS
S104
S106
SET LIGHT CONDENSING POSITION AND LIGHT CONDENSING INTENSITY FOR EACH LIGHT CONDENSING POINT
DERIVE DISTORTION PHASE PATTERN TO BE PROVIDED FOR LASER LIGHT
S107
DESIGN MODULATION PATTERN BY USE OF PROPAGATION FUNCTION TO WHICH DISTORTION PHASE PATTERN IS ADDED
S108
END

Fig.4

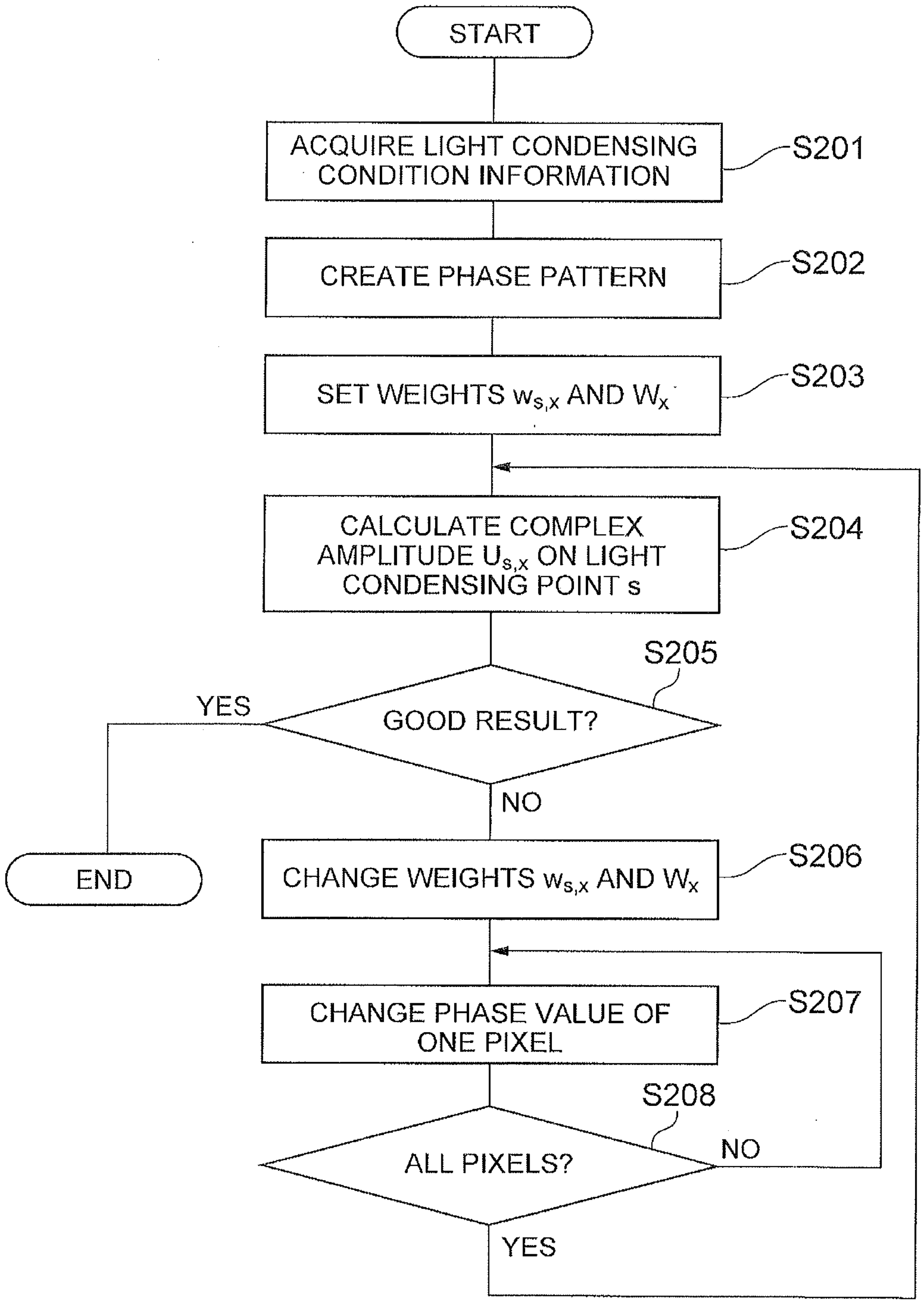

START
ACQUIRE LIGHT CONDENSING CONDITION INFORMATION
S201
CREATE PHASE PATTERN
S202
SET WEIGHTS $w_{s,x}$ AND W_x
S203
CALCULATE COMPLEX AMPLITUDE $U_{s,x}$ ON LIGHT CONDENSING POINT s
S204
S205
GOOD RESULT?
YES
NO
END
CHANGE WEIGHTS $w_{s,x}$ AND W_x
S206
CHANGE PHASE VALUE OF ONE PIXEL
S207
S208
ALL PIXELS?
NO
YES

Fig.5

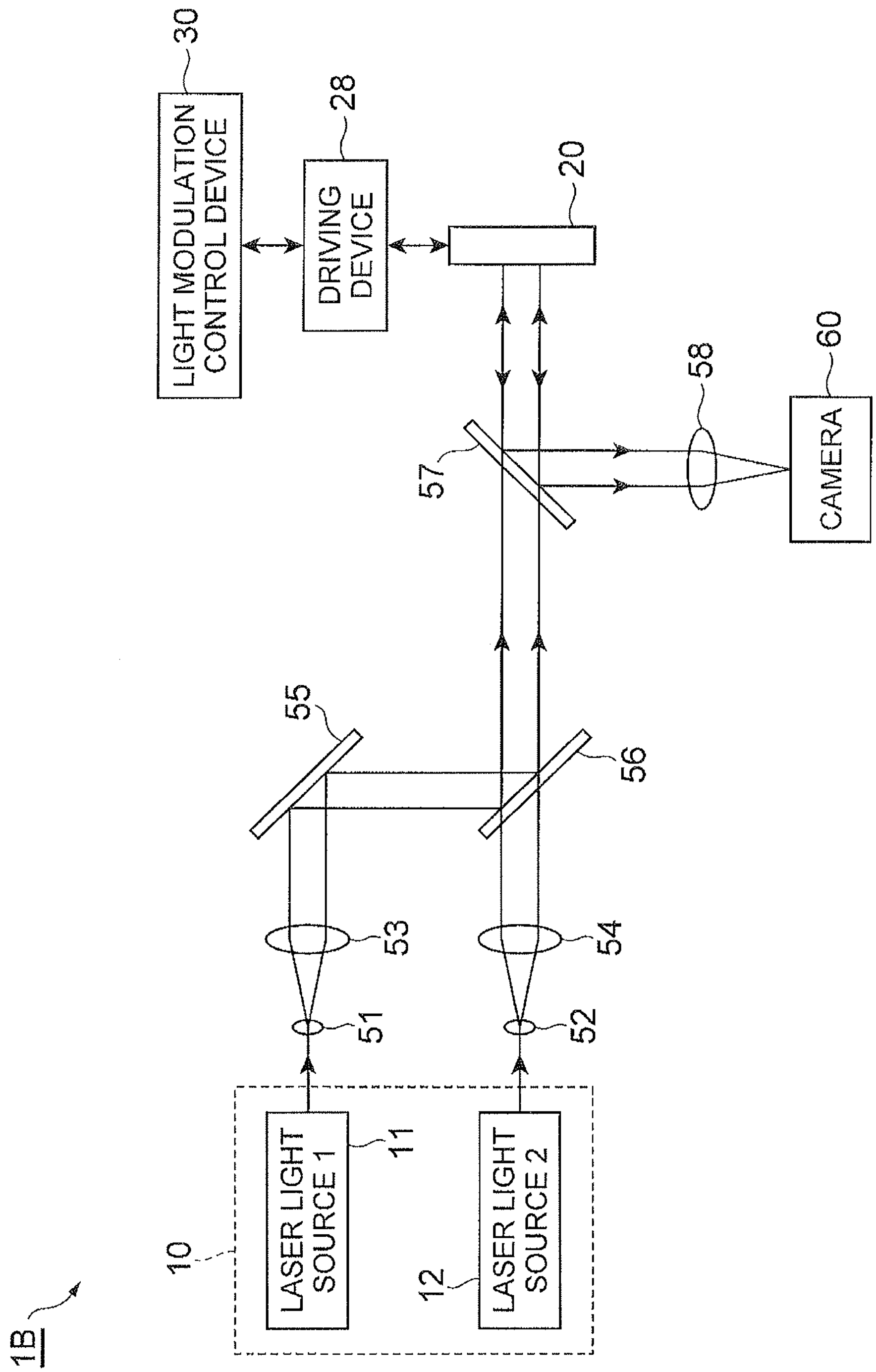

1B
10
LASER LIGHT SOURCE 1
11
LASER LIGHT SOURCE 2
12
51
52
53
54
55
56
57
58
CAMERA
60
20
DRIVING DEVICE
28
LIGHT MODULATION CONTROL DEVICE
30

Fig.6

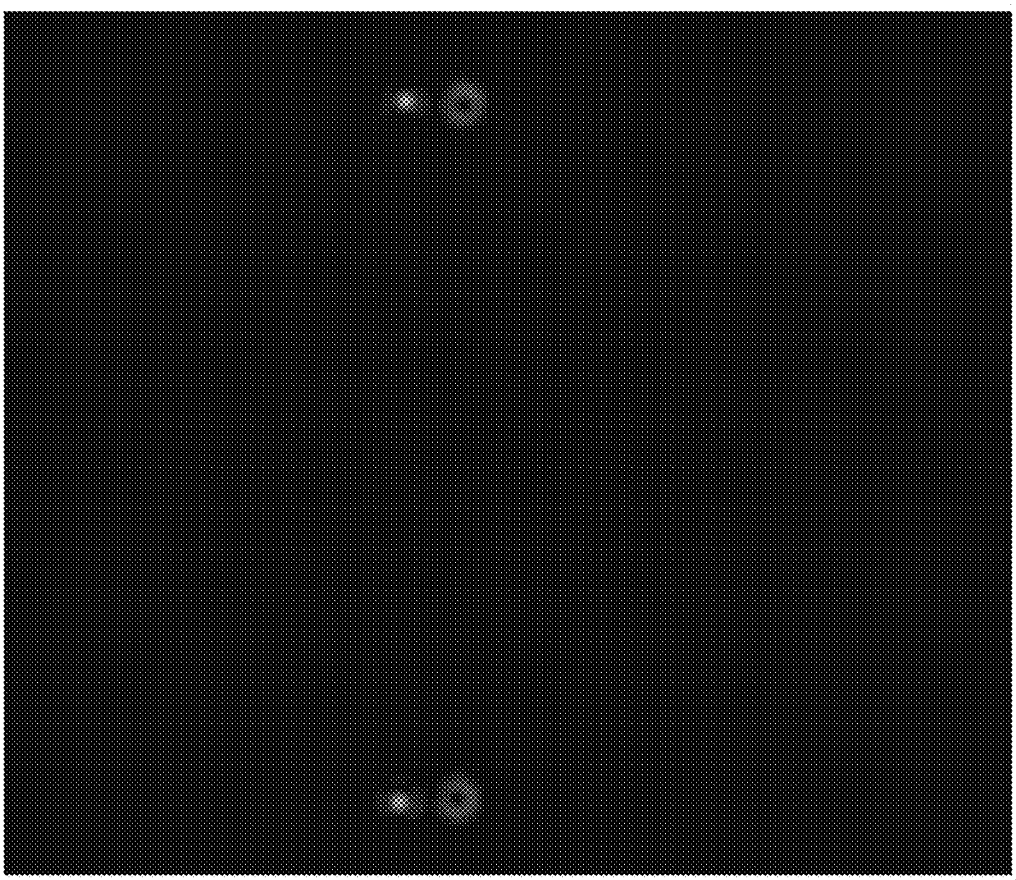
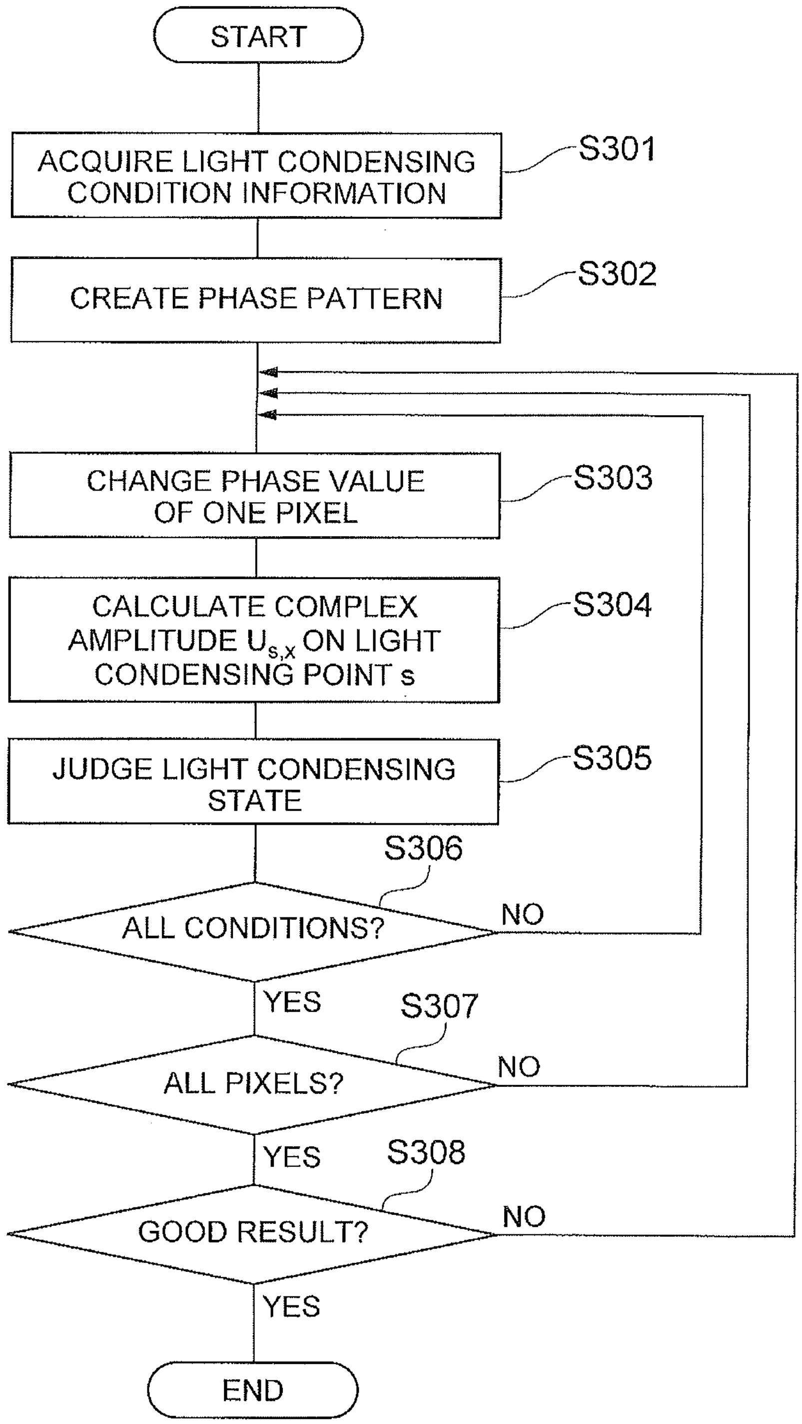


Fig.7


START
ACQUIRE LIGHT CONDENSING CONDITION INFORMATION
S301
CREATE PHASE PATTERN
S302
CHANGE PHASE VALUE OF ONE PIXEL
S303
CALCULATE COMPLEX AMPLITUDE $U_{s,x}$ ON LIGHT CONDENSING POINT s
S304
JUDGE LIGHT CONDENSING STATE
S305
S306
ALL CONDITIONS?
NO
YES
S307
ALL PIXELS?
NO
YES
S308
GOOD RESULT?
NO
YES
END

LIGHT MODULATION CONTROL METHOD, CONTROL PROGRAM, CONTROL DEVICE AND LASER BEAM IRRADIATION DEVICE

TECHNICAL FIELD

[0001] The present invention relates to a light modulation control method, a control program, and a control device which control light condensing irradiation of laser light onto a light condensing point by a modulation pattern to be presented in a spatial light modulator, and a laser light irradiation device using the same.

BACKGROUND ART

[0002] Laser light irradiation devices which irradiate an object with laser light under predetermined light condensing conditions have been used as various optical devices such as a laser processing device, a laser microscope for observing scattering and reflection of laser light. Further, in such a laser light irradiation device, there is a configuration in which light condensing irradiation conditions of laser light for an object are set and controlled by use of a phase-modulation type spatial light modulator (SLM: Spatial Light Modulator).

[0003] In a laser light irradiation device using a spatial light modulator, for example, a hologram (CGH: Computer Generated Hologram) set by a numerical calculation is presented in the modulator, thereby it is possible to control the light condensing irradiation conditions such as a light condensing position, a light condensing intensity, and a light condensing shape of laser light on an irradiation object (refer to, for example, Patent Documents 1 to 5, Non-Patent Documents 1 to 7).

CITATION LIST

Patent Literature

[0004] Patent Document 1: Japanese Patent Application Laid-Open No. 2010-58128

[0005] Patent Document 2: Japanese Patent Application Laid-Open No. 2010-75997

[0006] Patent Document 3: Japanese Patent Publication No. 4300101

[0007] Patent Document 4: Japanese Patent Publication No. 4420672

[0008] Patent Document 5: Japanese Patent Application Laid-Open No. 2005-84266

Non Patent Literature

[0009] Non-Patent Document 1: J. Bengtsson, "Kinoforms designed to produce different fan-out patterns for two wavelengths," Appl. Opt. Vol, 37 No, 11 (1998) pp. 2011-2020

[0010] Non-Patent Document 2: Y. Ogura et al., "Wavelength-multiplexing diffractive phase elements: design, fabrication, and performance evaluation," J. Opt. Soc. Am. A Vol. 18 No. 5 (2001) pp. 1082-1092

[0011] Non-Patent Document 3: J. Bengtsson, "Kinoform design with an optimal-rotation-angle method," Appl. Opt. Vol. 33 No. 29 (1994) pp. 6879-6884

[0012] Non-Patent Document 4: J. Bengtsson, "Design of fan-out kinoforms in the entire scalar diffraction regime with an optimal-rotation-angle method," Appl. Opt. Vol. 36 No. 32 (1997) pp. 8435-8444

[0013] Non-Patent Document 5: N. Yoshikawa et al., "Phase optimization of a kinoform by simulated annealing," Appl. Opt. Vol. 33 No. 5 (1994) pp. 863-868

[0014] Non-Patent Document 6: N. Yoshikawa et al., "Quantized phase optimization of two-dimensional Fourier kinoforms by a genetic algorithm," Opt. Lett. Vol. 20 No. 7 (1995) pp. 752-754

[0015] Non-Patent Document 7: J. Leach et al., "Observation of chromatic effects near a white-light vortex," New Journal of Physics Vol. 5 (2003) pp. 154.1-154.7

[0016] Non-Patent Document 8: S. W. Hell et al., "Breaking the diffraction resolution limit by stimulated emission: stimulated-emission-depletion fluorescence microscopy," Opt. Lett. Vol. 19 No. 11 (1994) pp. 780-782

[0017] Non-Patent Document 9: D. Wildanger et al., "A STED microscope aligned by design," Opt. Express Vol. 17 No. 18 (2009) pp. 16100-16110

SUMMARY OF INVENTION

Technical Problem

[0018] As described above, in light condensing irradiation of laser light utilizing a phase-modulation type spatial light modulator, it is possible to irradiate an arbitrary light condensing position with laser light in an arbitrary light condensing shape by a phase pattern to be presented in the spatial light modulator. Further, in the case where an SLM such as an LCOS (Liquid Crystal on Silicon)-SLM which is capable of dynamically switching a phase pattern for modulation to be presented is used as a spatial light modulator, it is possible to increase the degree of freedom of light condensing control of laser light, to achieve setting and control of the light condensing irradiation conditions in various modes.

[0019] On the other hand, in some cases, a phase shift caused by distortion of a substrate composing the spatial light modulator and the like becomes a problem in a spatial light modulator such as the LCOS-SLM described above. Further, a phase shift may be caused in the same way in a laser light guiding optical system as well other than a spatial light modulator. In the case where such a phase shift becomes a problem in light condensing control, as a method of solving that effect, a method in which a phase pattern ϕ_{SLM}

$$\phi_{SLM}=\phi_{CGH}+\phi_{cor}$$

that is, a distortion correction pattern ϕ_{cor} for correcting a phase shift is added to a CGH pattern ϕ_{CGH} to be presented in an SLM is presented in a spatial light modulator, has been proposed (refer to Patent Document 4). In such a method, given that a distortion phase pattern due to a phase shift or the like provided in an optical system is ϕ_{dis}, a distortion correction pattern cor ideally becomes a phase pattern opposite to the distortion phase pattern.

$$\phi_{cor}=\phi_{dis}$$

[0020] However, in such a method, in some cases, it is not possible to obtain sufficient accuracy of distortion correction in light condensing control of laser light. As such an example, in the case where light condensing control of laser light containing light components of plural wavelengths is performed by a single spatial light modulator, in the above-described method, the same distortion correction pattern acts on the laser light components of the respective wavelengths, however, because a phase shift to be provided for laser light differs at each wavelength, it is not possible to perform distortion correction with sufficient accuracy by such a method. Such a problem of the accuracy of distortion correction in light condensing control may be caused in the same way in a configuration other than the configuration of light condensing irradiation of the laser light at the plural wavelengths.

[0021] The present invention has been achieved in order to solve the above-described problem, and an object thereof is to provide a light modulation control method, a light modulation control program, and a light modulation control device by which it is possible to preferably achieve distortion correction in light condensing control of laser light using a spatial light modulator with sufficient accuracy, and a laser light irradiation device using the same.

Solution to Problem

[0022] In order to achieve such an object, a light modulation control method according to the present invention (1) which controls light condensing irradiation of laser light onto a set light condensing point by a modulation pattern to be presented in a spatial light modulator by use of the phase-modulation type spatial light modulator that inputs laser light thereto, to modulate a phase of the laser light, and that outputs the phase-modulated laser light, the method includes (2) an irradiation condition acquiring step of acquiring the number of wavelengths x_t (x_t is an integer of 1 or more) of the laser light to be input to the spatial light modulator, x_t wavelengths λ_x (x=1, . . . , and x), and incident conditions of the laser light at each wavelength to the spatial light modulator, as irradiation conditions of the laser light, (3) a light condensing condition setting step of setting the number of the light condensing points s_t (s_t is an integer of 1 or more) on which light condensing irradiation of the laser light from the spatial light modulator is performed, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity for each of the s_t light condensing points s (s=1, . . . , and s_t), as light condensing conditions of the laser light, (4) a distortion pattern deriving step of deriving a distortion phase pattern containing a phase shift due to distortion in the spatial light modulator to be provided in an optical system to the laser light at the wavelength for the s_t light condensing points s, and (5) a modulation pattern designing step of designing the modulation pattern to be presented in the spatial light modulator in consideration of the distortion phase pattern derived in the distortion pattern deriving step, and in the method, (6) the modulation pattern designing step assumes a plurality of two-dimensionally arrayed pixels in the spatial light modulator, changes a phase value so as to bring a light condensing state closer to a desired state by focusing on an effect on the light condensing state of the laser light on the light condensing point by changing the phase value of one pixel in the modulation pattern to be presented in the plurality of pixels, and performs such phase value changing operations for all the pixels in the modulation pattern, thereby designing the modulation pattern, and when evaluating the light condensing state on the light condensing point, a propagation function $\phi_{js,x}'$

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

that is, the distortion phase pattern $\phi_{js\text{-}dis,x}$ which is derived in the distortion pattern deriving step is added to a wave propagation function $\phi_{js,x}$ is used for propagation of light at a wavelength λ_x from a pixel j in the spatial light modulator to the light condensing point s.

[0023] Further, a light modulation control program according to the present invention (1) which is for causing a computer to execute light modulation control that controls light condensing irradiation of the laser light onto a set light condensing point by a modulation pattern to be presented in a spatial light modulator by use of the phase-modulation type spatial light modulator that inputs the laser light thereto, to modulate a phase of the laser light, and that outputs the phase-modulated laser light, the program causes the computer to execute (2) irradiation condition acquiring processing of acquiring the number of wavelengths x_t (x_t is an integer of 1 or more) of the laser light to be input to the spatial light modulator, x_t wavelengths λ_x (x=1, . . . , and x_t), and incident conditions of the laser light at each wavelength λ_x to the spatial light modulator, as irradiation conditions of the laser light, (3) light condensing condition setting processing of setting the number of light condensing points s_t (s_t is an integer of 1 or more) on which light condensing irradiation of the laser light from the spatial light modulator is performed, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity for each of the s_t light condensing points s (s=1, . . . , and s_t), as light condensing conditions of the laser light, (4) distortion pattern deriving processing of deriving a distortion phase pattern containing a phase shift due to distortion in the spatial light modulator to be provided in an optical system to the laser light at the wavelength λ_x for the s_t light condensing points s, and (5) modulation pattern designing processing of designing the modulation pattern to be presented in the spatial light modulator in consideration of the distortion phase pattern derived in the distortion pattern deriving processing, and in the program (6) the modulation pattern designing processing assumes a plurality of two-dimensionally arrayed pixels in the spatial light modulator, changes a phase value so as to bring a light condensing state closer to a desired state by focusing on an effect on the light condensing state of the laser light on the light condensing point by changing the phase value of one pixel in the modulation pattern to be presented in the plurality of pixels, and performs such phase value changing operations for all the pixels in the modulation pattern, thereby designing the modulation pattern, and when evaluating the light condensing state on the light condensing point, a propagation function $\phi_{js,x}'$

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

that is, the distortion phase pattern $\phi_{js\text{-}dis,x}$ which is derived in the distortion pattern deriving processing is added to a wave propagation function $\phi_{js,x}$ is used for propagation of light at a wavelength λ_x from a pixel j in the modulation pattern of the spatial light modulator to the light condensing point s.

[0024] Further, a light modulation control device according to the present invention (1) which controls light condensing irradiation of laser light onto a set light condensing point by a modulation pattern to be presented in a spatial light modulator by use of the phase-modulation type spatial light modulator that inputs the laser light thereto, to modulate a phase of the laser light, and that outputs the phase-modulated laser light, the device includes (2) irradiation condition acquiring means acquiring the number of wavelengths x_t (x_t is an integer of 1 or more) of the laser light to be input to the spatial light modulator, x_t wavelengths λ_x (x=1, . . . , and x_t), and incident conditions of the laser light at each wavelength λ_x to the spatial light modulator, as irradiation conditions of the laser light, (3) light condensing condition setting means setting the number of light condensing points s_t (s_t is an integer of 1 or more) on which light condensing irradiation of the laser light from the spatial light modulator is performed, and a light condensing position, a wavelength λ of the laser light to be condensed, and a light condensing intensity for each of the s_t light condensing points s (s=1, . . . , and s_t), as light condensing conditions of the laser light, (4) distortion pattern deriving means deriving a distortion phase pattern containing a phase shift due to distortion in the spatial light modulator to be provided in an optical system to the laser light at the wavelength λ_x for the s_t light condensing points s, and (5) modulation pattern designing means designing the modulation pattern to be presented in the spatial light modulator in consideration of the distortion phase pattern derived in the distortion pattern deriving means, and in the device, (6) the modulation pattern designing means assumes a plurality of two-dimensionally arrayed pixels in the spatial light modulator, changes a phase value so as to bring a light condensing state closer to a desired state by focusing on an effect on the light condensing state of the laser light on the light condensing point by changing the phase value of one pixel in the modulation pattern to be presented in the plurality of pixels, and performs such phase value changing operations for all the pixels in the modulation pattern, thereby designing the modulation pattern, and when evaluating the light condensing state on the light condensing point, a propagation function $\phi_{js,x}'$

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

that is, the distortion phase pattern $\phi_{js\text{-}dis,x}$ which is derived in the distortion pattern deriving means is added to a wave propagation function $\phi_{js,x}$ is used for propagation of light at a wavelength λ_x from a pixel j in the modulation pattern of the spatial light modulator to the light condensing point s.

[0025] In the above-described light modulation control method, control program, and control device, for light condensing irradiation with the laser light onto the light condensing point by use of a spatial light modulator, the information on the number of wavelengths x_t of the laser light, a value of a wavelength λ_x, and incident conditions (for example, an incident amplitude, an incident phase) of the laser light at each wavelength λ_x to the spatial light modulator is acquired, and the light condensing conditions including the number of light condensing points s_t of the laser light, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity on each light condensing point s are set. Then, a distortion phase pattern to be provided in the optical system to the laser light at the wavelength λ_x, which is specifically a distortion phase pattern containing at least a phase shift due to distortion in the spatial light modulator is derived for each light condensing point s, and a modulation pattern is designed in consideration of the distortion phase pattern. Thereby, it is possible to preferably execute distortion correction for the laser light at the wavelength λ_x condensed on each light condensing point s.

[0026] Moreover, for the design of a modulation pattern, specifically, a pixel structure of a plurality of pixels is assumed in the spatial light modulator. Then, a design method focusing on an effect on a light condensing state of the laser light on the light condensing point s by changing a phase value of one pixel in the modulation pattern is used, and in an evaluation of the light condensing state of the laser light at the wavelength λ_x, a propagation function $\phi_{js,x}$ from a pixel j in the spatial light modulator to the light condensing point s is not used directly, but a propagation function $\phi_{js,x}'$ to which the derived distortion phase pattern $\phi_{js\text{-}dis,x}$ is added is used, so as to evaluate the light condensing state.

[0027] In accordance with such a configuration, for light condensing control of the laser light at the wavelength λ_x on the light condensing point s, a phase pattern for distortion correction for resolving an effect by a distortion phase pattern to be provided in the optical system including the spatial light modulator is reliably incorporated in a modulation pattern to be finally obtained, and therefore, it is possible to preferably achieve distortion correction in light condensing control of the laser light by use of the spatial light modulator with sufficient accuracy.

[0028] In addition, in the case where a spatial light modulator which has a plurality of two-dimensionally arrayed pixels, and which is configured to modulate a phase of laser light at each of the plurality of pixels is used as the spatial light modulator, the pixel structure thereof may be directly applied to the design of a modulation pattern. Further, in the case where the distortion phase pattern is determined depending only on a wavelength λ_x independently of a light condensing point s on which light condensing irradiation of laser light is performed, a distortion phase pattern may be derived for each wavelength λ_x.

[0029] A laser light irradiation device according to the present invention includes (a) a laser light source which supplies laser light with x_t (x_t is an integer of 1 or more) wavelengths λ_x, (b) a phase-modulation type spatial light modulator which inputs the laser light thereto, to modulate a phase of the laser light, and which outputs the phase-modulated laser light, and (c) the light modulation control device having the above-described configuration which controls light condensing irradiation of the laser light at each wavelength λ_x onto set s_t (s_t is an integer of 1 or more) light condensing points s by a modulation pattern to be presented in the spatial light modulator.

[0030] In accordance with such a configuration, by the light modulation control device, a distortion correction pattern for canceling an effect by a distortion phase pattern to be provided in the optical system including the spatial light modulator is reliably incorporated in a modulation pattern to be finally obtained, thereby, it is possible to preferably achieve distortion correction in light condensing control of the laser light, and it is possible to preferably achieve light condensing irradiation of the laser light on the light condensing point s set on an irradiation object, and operations such as processing, observations, and the like of the object thereby. Such a laser light irradiation device may be used as, for example, a laser processing device, a laser microscope, or the like. In addition, as a spatial light modulator, a spatial light modulator which has a plurality of two-dimensionally arrayed pixels, and which is configured to modulate a phase of laser light for each of the plurality of pixels is preferably used.

Advantageous Effects of Invention

[0031] In accordance with the light modulation control method, the control program, the control device, and the laser light irradiation device using the same of the present invention, for light condensing irradiation with laser light onto a light condensing point by use of a spatial light modulator, the number of wavelengths of the laser light, a value of a wavelength, and incident conditions of the laser light to the spatial light modulator at each wavelength are acquired, the number of the light condensing points of the laser light, and a light condensing position, a wavelength of the laser light to be condensed, and a light condensing intensity on each light condensing point are set, a distortion phase pattern to be provided in the optical system including the spatial light modulator for the laser light at the wavelength to be condensed is derived for each light condensing point, and further, a modulation pattern is designed in consideration of the distortion phase pattern, and in the design of a modulation pattern, a design method focusing on an effect on a light condensing state of the laser light on the light condensing point by changing a phase value of one pixel in the modulation pattern is used, and in an evaluation of the light condensing state of the laser light, a propagation function to which a distortion phase pattern is added is used, thereby, it is possible to preferably achieve distortion correction in light condensing control of the laser light with sufficient accuracy.

BRIEF DESCRIPTION OF DRAWINGS

[0032] FIG. **1** is a diagram showing a configuration of an embodiment of a laser light irradiation device.

[0033] FIG. **2** is a block diagram showing an example of a configuration of a light modulation control device.

[0034] FIG. **3** is a flowchart showing an example of a light modulation control method.

[0035] FIG. **4** is a flowchart showing an example of a modulation pattern design method.

[0036] FIG. **5** is a diagram showing a configuration of a laser light irradiation device used for a confirmatory experiment.

[0037] FIG. **6** is a view showing an example of light condensing control of laser light by the laser light irradiation device.

[0038] FIG. **7** is a flowchart showing another example of a modulation pattern design method.

DESCRIPTION OF EMBODIMENTS

[0039] Hereinafter, an embodiment of a light modulation control method, a control program, a control device, and a laser light irradiation device according to the present invention will be described in detail with reference to the accompanying drawings. In addition, in the description of the drawings, the same components are denoted by the same reference symbols, and overlapping descriptions thereof will be omitted. Further, the dimensional ratios in the drawings are not necessarily equal to those in the descriptions.

[0040] First, a basic configuration of a laser light irradiation device including a spatial light modulator, which serves as an object for light modulation control, will be described along with its configuration example. FIG. **1** is a diagram showing a configuration of an embodiment of the laser light irradiation device including a light modulation control device. A laser light irradiation device **1**A according to the present embodiment is a device performing light condensing irradiation on an irradiation object **42** with laser light, and includes a laser light source unit **10**, a spatial light modulator **20**, and a movable stage **40**.

[0041] In the configuration shown in FIG. **1**, the irradiation object **42** is placed on the movable stage **40** which is configured to be movable in an X direction, a Y direction (horizontal direction), and a Z direction (vertical direction). Further, in the device **1**A, a light condensing point for carrying out observations, processing, and the like for the irradiation object **42** is set to a predetermined position, and light condensing irradiation is performed on the light condensing point with laser light.

[0042] The laser light source unit **10** functions as a laser light source which supplies laser light with x_t (x_t is an integer of 1 or more) wavelengths λ_x ($\lambda_x=\lambda_1, \ldots,$ and λ_{xt}). In the present embodiment, the number of wavelengths of the laser light is set to $x_t=2$. Further, in response to this number of wavelengths, the laser light source unit **10** is composed of a first laser light source **11** which supplies laser light at a wavelength λ_1 and a second laser light source **12** which supplies laser light at a wavelength λ_2.

[0043] The laser light at a wavelength λ_1 from the laser light source **11** is expanded by a beam expander **13**, to thereafter pass through a dichroic mirror **15**. Further, the laser light at a wavelength λ_2 from the laser light source **12** is expanded by a beam expander **14**, to be reflected by a mirror **16**, and is thereafter reflected by the dichroic mirror **15**. Thereby, the light beams from the laser light sources **11** and **12** are multiplexed in the dichroic mirror **15**, to be laser light containing the wavelength components of the wavelengths λ_1 and λ_2. The laser light from the dichroic mirror **15** is input to the spatial light modulator (SUM) **20** via a first reflective surface **18***a* of a prism **18**.

[0044] The spatial light modulator **20** is a phase-modulation type spatial light modulator, and, for example, modulates a phase of laser light at each portion on its two-dimensional modulation surface, to output a phase-modulated laser light. Here, given that a phase of laser light to be input to the spatial light modulator **20** is ϕ_{in}, and a phase value to be provided in the spatial light modulator **20** is ϕ_{SLM}, a phase ϕ_{out} of the laser light to be output is as follows.

$$\phi_{out}=\phi_{SLM}+\phi_{in}$$

[0045] As the spatial light modulator **20**, preferably, a spatial light modulator having a plurality of two-dimensionally arrayed pixels, that modulates a phase of the laser light at each of the plurality of pixels is used. In such a configuration, a modulation pattern such as a CGH is to be presented in the spatial light modulator **20**, and light condensing irradiation of the laser light onto a set light condensing point is controlled by this modulation pattern. Further, the spatial light modulator **20** is drive-controlled by a light modulation control device **30** via a light modulator driving device **28**. The specific configuration of the light modulation control device **30** will be described later. Further, as the spatial light modulator **20**, a spatial light modulator without the above-described pixel structure may be used.

[0046] The spatial light modulator **20** may be a reflective type, or a transmissive type. In FIG. **1**, a reflective type is shown as the spatial light modulator **20**. Further, as the spatial light modulator **20**, a refractive-index changing material type SLM (for example, as an SLM using a liquid crystal, an LCOS (Liquid Crystal on Silicon) type, an LCD (Liquid Crystal Display)), a Segment Mirror type SLM, a Continuous Deformable Mirror type SLM, or the like is exemplified. These SLMs are configured to be capable of dynamically switching a modulation pattern to be presented. Further, as the spatial light modulator **20** which statically presents a modulation pattern, a DOE (Diffractive Optical Element) or the like may be exemplified. In addition, as a DOE, a DOE whose phase is discretely expressed, or a DOE that a pattern is designed by use of a method which will be described later, to convert it into a continuous pattern by smoothing or the like is included.

[0047] A CGH designed as a modulation pattern is, for example, expressed in a DOE by use of electron beam exposure and etching, or its phase pattern is converted into a voltage distribution to be displayed on an SLM having a pixel structure, according to a configuration of the spatial light modulator **20**. Further, in the case where laser light at plural wavelengths is modulated by a single SLM, a DOE available as a fixed pattern has mainly been used in a conventional example.

[0048] The laser light containing the wavelength components of the wavelengths λ_1 and λ_2, which is phase-modulated into a predetermined pattern in the spatial light modulator **20**, to be output, is reflected by a second reflective surface **18***b* of the prism **18**, and is propagated to an objective lens **25** composed of a single lens or a plurality of lenses by a mirror **21** and a **4***f* optical system composed of lenses **22** and **23**. Then, with this objective lens **25**, light condensing irradiation of the laser light is performed on a single or a plurality of light condensing points set on the surface or the inside of the irradiation object **42** on the stage **40**.

[0049] Further, the laser light irradiation device **1**A according to the present embodiment further includes a detection unit **45**, a lens **46**, and a dichroic mirror **47** in addition to the above-described configuration. The dichroic mirror **47** is provided between the lens **23** composing the 4f optical system and the objective lens **25** in the laser light irradiation optical system. Further, it is configured such that light from the irradiation object **42** reflected by the dichroic mirror **47** is to be incident to the detection unit **45** via the lens **46**.

[0050] In accordance with this, the laser light irradiation device **1**A of FIG. **1** is configured as a laser scanning microscope which irradiates an observation sample which is the irradiation object **42** with laser light, and makes observations for a reflected light, a scattering light, fluorescence, or the like from the sample with the detection unit **45**. In addition, with respect to laser scanning of a sample, it is configured to move the irradiation object **42** by the movable stage **40** in FIG. **1**, however, for example, it may also be configured such that this stage is fixed, and a movable mechanism, a galvano mirror, or the like may be provided on the optical system side. Further, as the laser light sources **11** and **12**, pulsed laser light sources such as femtosecond laser light sources, which supply pulsed laser light are preferably used. Further, as the laser light sources **11** and **12**, CW (Continuous Wave) laser light sources may be used.

[0051] Further, the configuration of the optical system in the laser light irradiation device **1**A is not specifically limited to the configuration shown in FIG. **1**, and various configurations may be used. For example, in FIG. **1**, the optical system is configured to expand laser light with the beam expanders **13** and **14**, however, the optical system may also be configured to use a combination of a spatial filter and a collimator lens. Further, the driving device **28** may also be integrally provided with the spatial light modulator **20**. Further, as the 4f optical system by the lenses **22** and **23**, in general, a both-side telecentric optical system composed of a plurality of lenses is preferably used.

[0052] Further, for the laser light source unit **10** used for supplying laser light, the configuration by the laser light sources **11** and **12** which respectively output the laser light beams at the wavelengths λ_1 and λ_2 is exemplified, however, as a configuration of a laser light source, specifically, various configurations may be used. For example, the number of wavelengths x_t of laser light may be set to 3 or more. Further, laser light may be set to have a single wavelength ($x_t=1$), and a single laser light source may be used.

[0053] Further, in the present embodiment, the configuration of the laser scanning microscope used for cell observation or the like is exemplified, however, this laser light irradiation device may be applicable to, not only a laser microscope such as a laser scanning microscope, but also various devices such as a laser processing device which performs laser processing on the inside of the object **42** by light condensing irradiation on the irradiation object **42** with laser light. Further, in the case where the object **42** is processed by light condensing irradiation of laser light, examples thereof include preparation of an optical integrated circuit by an internal processing of glass or the like, however, a material of the object **42** is not limited to a glass medium, for example, various materials such as a silicon inside, SiC, and the like may serve as objects to be processed. In the above-described configuration, it is possible to achieve laser processing at a single wavelength, simultaneous laser processing at plural wavelengths, or the like.

[0054] In the laser light irradiation device **1**A using the spatial light modulator **20** as shown in FIG. **1**, in some cases, a phase shift (aberration) from a desired phase pattern may be caused in laser light of which light condensing irradiation is performed on the object **42** due to distortion of the substrate or the like composing the spatial light modulator **20**. Such an effect by a phase shift is likely increased, in particular, in the case where a configuration by which it is possible to dynamically switch a modulation pattern to be presented in the spatial light modulator **20** is used.

[0055] With respect to such an effect by a phase shift, a case where an LCOS-SLM is used as the spatial light modulator **20** will be described as an example. An LCOS-SLM has a structure in which a liquid crystal is enclosed between a silicon substrate and a glass substrate on which ITO is evaporated. The silicon substrate has a pixel structure, and when a voltage is applied to the pixels, the liquid crystal on the pixels rotates according to the voltage. In such a configuration, when a voltage v to be applied to the pixels is changed at each position, it is possible to provide a phase distribution ϕ_{SLM} as shown in the following formula (1).

[Formula 1]

$$\phi_{SLM}(x_j, y_j, \lambda) = \frac{2 \times n_{LC}(v(x_j, y_j)) \times d}{\lambda} \times 2\pi \ \text{[rad]} \tag{1}$$

Here, (x_j, y_j) is a position of a pixel j, λ is a wavelength, n_{LC} is a refractive index of the liquid crystal, and d is a thickness of a liquid crystal layer.

[0056] In the LCOS-SLM, the silicon substrate functions as a mirror reflecting light as well. Further, because this silicon substrate is thin, that is, for example, the substrate itself is about 600 μm, this substrate may be distorted to a maximum of approximately several μm at the time of manufacturing. In the case where the substrate is distorted in this way, for example, even if a constant voltage v is applied to all the pixels in the SLM, and the refractive index n_{LC} is uniformed all over the pixels, because the thickness d of the liquid crystal layer is different depending on a position by an effect by the distortion, a phase distribution (phase pattern) due to distortion as shown in the following formula (2)

[Formula 2]

$$\phi_{SLM-dis}(x_j, y_j, \lambda) = \frac{2 \times n_{LC} \times d(x_j, y_j)}{\lambda} \times 2\pi \ \text{[rad]} \quad (2)$$

is generated. When there is such a distortion phase pattern, it is not possible to provide a desired phase pattern to laser light serving as an object for light condensing control with the SLM. Further, such a distortion phase pattern may be provided for laser light in the same way in an optical system portion other than the SLM in a laser light guiding optical system in some cases.

[0057] As a method of canceling such an effect by a distortion phase pattern $\phi_{SLM-dis}$, there is a method in which a distortion correction pattern $\phi_{SLM-cor}$ is added to a desired phase pattern ϕ_{CGH} to be presented in the SLM. In this case, a phase pattern ϕ_{SLM} to be presented in the SLM is as follows.

[Formula 3]

$$\phi_{SLM}=\phi_{CGH}+\phi_{SLM-cor} \quad (3)$$

Further, the distortion correction pattern $\phi_{SLM-cor}$ is ideally as follows.

[Formula 4]

$$\phi_{SLM-cor}=-\phi_{SLM-dis}+\alpha \quad (4)$$

In addition, α is an error value or the like contained in measurement, and is taken into account as necessary.

[0058] Here, in the laser light irradiation device **1**A shown in FIG. **1**, the configuration in which light condensing irradiation is performed on the object **42** with the laser light containing light components of the two wavelengths λ_1 and λ_2 via the single spatial light modulator **20** is exemplified. In such a configuration, as is clear from the above-described formula, a distortion phase pattern $\phi_{SLM-dis}$ provided in the optical system to the laser light is different at each wavelength, accordingly, a distortion correction pattern $\phi_{SLM-cor}$ as well is different at each wavelength.

[0059] On the other hand, in the conventional distortion correction method described above, the same distortion correction pattern acts on the respective wavelength components of the laser light at plural wavelengths. Therefore, in some cases, it is not possible to obtain sufficient accuracy of distortion correction, such as, it is not possible to appropriately perform distortion correction for each of the laser light components at plural wavelengths. Further, in some cases, such a problem of the accuracy of distortion correction may be caused in a configuration other than the configuration of light condensing irradiation of the laser light at the plural wavelengths.

[0060] In response to this, the laser light irradiation device **1**A of FIG. **1** appropriately sets a CGH of a modulation pattern to be presented in the spatial light modulator **20** via the driving device **28** in the light modulation control device **30**, thereby improving the accuracy of distortion correction, to preferably control the light condensing irradiation conditions of the laser light on a light condensing point. Further, in accordance with the laser light irradiation device **1**A and the light modulation control device **30** according to the present embodiment, as will be described later, even in the case where light condensing irradiation of laser light at plural wavelengths is performed, it is possible to preferably achieve the light condensing control including distortion correction of the laser light at each wavelength.

[0061] FIG. **2** is a block diagram showing an example of a configuration of the light modulation control device **30** which is applied to the laser light irradiation device **1**A shown in FIG. **1**. The light modulation control device **30** according to the present configuration example includes an irradiation condition acquiring unit **31**, a light condensing condition setting unit **32**, a distortion phase pattern deriving unit **33**, a modulation pattern designing unit **34**, and a light modulator drive control unit **35**. In addition, such a light modulation control device **30** may be composed of, for example, a computer. Further, an input device **37** used for inputting information, instructions, and the like necessary for light modulation control, and a display device **38** used for displaying information for an operator are connected to this control device **30**.

[0062] The irradiation condition acquiring unit **31** is irradiation condition acquiring means for acquiring information on irradiation conditions of laser light on the irradiation object **42**. Specifically, the irradiation condition acquiring unit **31** acquires the number of wavelengths x_t (x_t=2 in the example shown in FIG. **1**) of laser light to be input to the spatial light modulator **20**, respective values of the x_t wavelengths λ_x (x=1, . . . , and x_t), and incident conditions (for example, an incident intensity distribution, an incident phase distribution) of the laser light at each wavelength λ_x to the spatial light modulator **20**, as irradiation conditions of the laser light (an irradiation condition acquiring step). The number of wavelengths x_t is set as an integer of 1 or more, and is set as an integer of 2 or more in the case of simultaneous irradiation at plural wavelengths.

[0063] The light condensing condition setting unit **32** is light condensing condition setting means for setting light condensing conditions of laser light on the irradiation object **42**. Specifically, the light condensing condition setting unit **32** sets the number of light condensing points s_t on which light condensing irradiation of the laser light output from the spatial light modulator **20** is performed, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity for each of the s_t light condensing points (s=1, . . . , and s_t), as light condensing conditions of the laser light (a light condensing condition setting step). The number of light condensing points s_t is set as an integer of 1 or more, and is set as an integer of 2 or more in the case of simultaneous irradiation on multiple points.

[0064] The distortion pattern deriving unit **33** is distortion pattern deriving means for deriving a distortion phase pattern to be provided in the laser light guiding optical system to the laser light at the wavelength λ_x for the set s_t light condensing points s. Here, specifically, a distortion phase pattern containing at least a phase shift (aberration) due to distortion in the spatial light modulator **20**, which is provided in the optical system to the laser light at the wavelength λ_x is derived (a distortion pattern deriving step).

[0065] In this deriving unit **33**, in the case where the phase shift caused in the optical system portion other than the spatial light modulator **20** in the laser light guiding optical system is small, which does not become a problem in light condensing control, only a distortion phase pattern corresponding to a phase shift due to distortion in the spatial light modulator **20** may be derived. This derivation of a distortion phase pattern is performed as necessary for each light condensing point and each wavelength. Further, in the case where a distortion phase pattern is determined depending only on a wavelength λ_x independently of a light condensing point s on which light condensing irradiation of laser light is performed, a distortion phase pattern may be derived for each wavelength λ_x independently of the light condensing point s.

[0066] In addition, acquisition of irradiation conditions by the acquiring unit **31**, setting of light condensing conditions by the setting unit **32**, and derivation of a distortion phase pattern by the deriving unit **33** are performed automatically or manually by an operator based on information prepared in advance in the light modulation control device **30**, information input from the input device **37**, information supplied from an external device, and the like.

[0067] The modulation pattern designing unit **34** is modulation pattern designing means for designing a CGH to be a modulation pattern to be presented in the spatial light modulator **20** in consideration of the distortion phase pattern derived in the distortion pattern deriving unit **33**. Specifically, the modulation pattern designing unit **34** refers to the irradiation conditions acquired in the acquiring unit **31**, the light condensing conditions set in the setting unit **32**, and the distortion phase pattern derived in the deriving unit **33**, and designs a modulation pattern for performing light condensing irradiation on a desired light condensing point with laser light at a desired wavelength based on those conditions (a modulation pattern designing step).

[0068] In particular, in the modulation pattern designing unit **34** in the present embodiment, in the design of a modulation pattern to be presented in the spatial light modulator **20**, a design method in which a plurality of two-dimensionally arrayed pixels in the spatial light modulator **20** is assumed, and which focuses on an effect on a light condensing state of the laser light on the light condensing point s by changing a phase value of one pixel (corresponding to one pixel assumed in the spatial light modulator **20**, and in the case where the spatial light modulator **20** has a pixel structure composed of a plurality of two-dimensionally arrayed pixels, one pixel thereof) in a modulation pattern to be presented in the plurality of pixels is used. Then, the phase value of the one pixel is changed so as to bring its light condensing state closer to a desired state, and such phase value changing operations are performed for all the pixels (at least all the pixels to which the light is incident) in the modulation pattern, thereby designing an optimum modulation pattern.

[0069] Further, in this modulation pattern designing unit **34**, in the above-described phase value changing operations for the respective pixels, when evaluating the light condensing state of the laser light on the light condensing point, for propagation of light at a wavelength λ_x from a pixel j in the modulation pattern of the spatial light modulator **20** to the light condensing point s, a wave propagation function $\phi_{js,x}$ is not directly used, but a propagation function $\phi_{js,x}'$

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

that is, the distortion phase pattern $\phi_{js\text{-}dis,x}$ derived in the distortion pattern deriving unit **33** is added to the propagation function $\phi_{js,x}$ is used. Thereby, the distortion correction pattern $\phi_{js\text{-}cor,x}$, which is for performing correction for the distortion phase pattern derived for each light condensing point and each wavelength is incorporated in the modulation pattern, to be reflected into the light condensing control of the laser light by the modulation pattern.

[0070] The light modulator drive control unit **35** is drive control means for drive-controlling the spatial light modulator **20** via the driving device **28**, to present the modulation pattern designed by the modulation pattern designing unit **34** to the plurality of pixels in the spatial light modulator **20**. Such a drive control unit **35** is provided as necessary in the case where the light modulation control device **30** is included in the laser light irradiation device **1**A.

[0071] It is possible to achieve processing corresponding to the control method executed in the light modulation control device **30** shown in FIG. **2** by a light modulation control program for causing a computer to execute light modulation control. For example, the light modulation control device **30** may be composed of a CPU for operating the respective software programs necessary for the processing of light modulation control, a ROM in which the above-described software programs and the like are stored, and a RAM in which data is temporarily stored during program execution. In such a configuration, by executing a predetermined control program by the CPU, it is possible to achieve the light modulation control device **30** described above.

[0072] Further, the above-described program for causing the CPU to execute light modulation control by use of the spatial light modulator **20**, in particular, each processing for designing a modulation pattern to be presented in the spatial light modulator **20**, may be recorded in a computer readable recording medium, so as to be distributed. As such a recording medium, for example, a magnetic medium such as a hard disk or a flexible disk, an optical medium such as a CD-ROM or a DVD-ROM, a magnetooptic medium such as a floptical disk, or a hardware device such as a RAM, a ROM, and a semiconductor nonvolatile memory, which are specially arranged so as to execute or store program instructions, and the like are included.

[0073] The effects of the light modulation control method, the light modulation control program, the light modulation control device **30**, and the laser light irradiation device **1**A according to the present embodiment will be described.

[0074] In the light modulation control method, the control program, and the control device **30** shown in FIG. **1** and FIG. **2**, for light condensing irradiation with laser light by use of the spatial light modulator **20**, information on the number of wavelengths x_t of the laser light, respective values of the x_t wavelengths λ_x, and incident conditions (for example, an incident amplitude, an incident phase) of the laser light at each wavelength λ_x to the spatial light modulator **20** is acquired, and light condensing conditions including the number of light condensing points s_t of the laser light, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity on each light condensing point s are set. Then, in the distortion pattern deriving unit **33**, a distortion phase pattern to be provided in the light guiding optical system including the spatial light modulator **20** to the laser light at the wavelength λ_x is derived for each light condensing point s, and in the modulation pattern designing unit **34**, a modulation pattern is designed in consideration of the distortion phase pattern. Thereby, it is possible to preferably execute distortion correction for the laser light at the wavelength λ_x to be condensed on each light condensing point s.

[0075] Moreover, for the design of a modulation pattern in such a configuration, specifically, a pixel structure of a plurality of two-dimensionally arrayed pixels is assumed in the spatial light modulator **20**. Then, a design method focusing on an effect on a light condensing state of the laser light on the light condensing point s by changing the phase value of one pixel in the modulation pattern is used, and in an evaluation of the light condensing state of the laser light at a wavelength λ_x, a propagation function $\phi_{js,x}$ from a pixel j in the spatial light modulator to the light condensing point s is not used directly, but a propagation function $\phi_{js,x}'$ to which the derived distortion phase pattern $\phi_{js\text{-}dis,x}$ is added is used, so as to evaluate the light condensing state.

[0076] In accordance with such a configuration, for light condensing control of the laser light at the wavelength λ_x onto the light condensing point s, a phase pattern for distortion correction for resolving an effect by a distortion phase pattern to be provided in the optical system including the spatial light modulator **20** is reliably incorporated in a modulation pattern to be finally obtained as an appropriate distortion correction pattern different at each wavelength. Thereby, it is possible to preferably achieve distortion correction in light condensing control of the laser light by use of the spatial light modulator **20** with sufficient accuracy.

[0077] In addition, with respect to the pixel structure assumed in the spatial light modulator **20**, in the case where a spatial light modulator which has a plurality of two-dimensionally arrayed pixels, and modulates a phase of the laser light at each of the plurality of pixels, is used as the spatial light modulator **20**, the pixel structure may be directly applied to the design of a modulation pattern.

[0078] Further, in the laser light irradiation device **1**A shown in FIG. **1**, the laser light irradiation device **1**A includes the laser light source unit **10** functioning as a laser light source for supplying laser light with x_t wavelengths λ_x, the phase-modulation type spatial light modulator **20**, and the light modulation control device **30** having the above-described configuration. In accordance with such a configuration, the correction pattern for canceling the distortion phase pattern derived for each light condensing point s and wavelength λ_x is reliably incorporated in a modulation pattern to be finally obtained by the control device **30**, which makes it possible to preferably achieve distortion control in light condensing control of the laser light with sufficient accuracy, and it is possible to preferably achieve light condensing irradiation of the laser light on the light condensing point s set on the irradiation object **42**, and operations such as processing, observations, and the like of the object **42** thereby. Further, as described above, such a laser light irradiation device may be used as, for example, a laser processing device, a laser microscope, or the like.

[0079] In the light modulation control device **30** and the laser light irradiation device **1**A having the above-described configuration, a configuration in which the number of wavelengths x_t of the laser light is set to a plural number may be used for acquisition of irradiation conditions in the acquiring unit **31**. As described above, a method of designing a modulation pattern by use of a propagation function $\phi_{js,x}'$ to which a distortion phase pattern provided in the optical system is added, is particularly effective in the point that it is possible to appropriately perform distortion correction at each wavelength in the control of the light condensing irradiation conditions of laser light containing the light components of the plural wavelengths $\lambda_1, \lambda_2, \ldots$, and λ_{xt} in this way.

[0080] Further, in the case where light condensing irradiation of laser light containing plural wavelength components as described above is performed, the configuration in which the modulation pattern is designed in consideration of wavelength dispersion of a refractive index in the spatial light modulator **20** may be used in the design of a modulation pattern in the designing unit **34**. Thereby, it is possible to more accurately control the light condensing irradiation conditions of the laser light at the wavelength λ_x on each light condensing point s for the respective wavelengths λ_x different from each other.

[0081] Further, in the above-described configuration, as the spatial light modulator **20** used for light condensing control of the laser light, a spatial light modulator which is configured to be capable of dynamically switching a modulation pattern to be presented may be used. Usually, such a spatial light modulator structurally has, as described above for an LCOS-SLM, a larger effect by a phase shift or the like due to distortion as compared with a modulator which statically presents a modulation pattern, and accordingly, distortion correction by the above-described method is particularly effective therefor. Further, the light condensing control described above may also be, as necessary, applicable to a spatial light modulator such as a DOE which statically presents a modulation pattern. Here, a DOE may be created by use of electron exposure, meanwhile, in a raster scanning method exposure device, independent distortion is caused in each axis of electron beam deflection, and as a result, astigmatism may be caused in some cases.

[0082] Further, with respect to the design of a modulation pattern in the designing unit **34**, it is preferable that, given that an incident amplitude of the laser light at the wavelength **2** to the pixel j in the spatial light modulator **20** is $A_{j\text{-}in,x}$, a phase is $\phi_{j\text{-}in,x}$, and a phase value for the laser light at the wavelength λ_x in the pixel j is $\phi_{j,x}$, a complex amplitude $U_{s,x}$ indicating the light condensing state of the laser light at the wavelength λ_x on the light condensing point s is determined by the following formula.

$$\begin{aligned} U_{s,x} &= A_{s,x}\exp(i\phi_{s,x}) \\ &= \sum_j A_{j\text{-}in,x}\exp(i\phi'_{js,x})\times\exp\bigl(i(\phi_{j,x}+\phi_{j\text{-}in,x})\bigr). \end{aligned}$$

Thereby, it is possible to preferably evaluate a light condensing state of the laser light at each wavelength λ_x on the light condensing point s.

[0083] Here, the incident amplitude $A_{j\text{-}in,x}$ of the laser light at the wavelength λ_x to the pixel j is in the relationship of

$$I_{j\text{-}in,x}=|A_{j\text{-}in,x}|^2$$

for an incident intensity $I_{j\text{-}in,x}$. Further, in the complex amplitude $U_{s,x}$, $A_{s,x}$ is an amplitude, and $\phi_{s,x}$ is a phase. Further, in the case where the laser light incident to the spatial light modulator **20** is a plane wave, the incident phase $\phi_{j\text{-}in,x}$ can be disregarded.

[0084] Further, from the above-described formula, it is considered that the complex amplitude $U_{s,x}$ on the light condensing point s after propagation is the sum of the complex amplitudes of the respective pixels j multiplied by the propagation functions, and its amplitude $A_{s,x}$ is affected independently at each pixel in the modulation pattern. That is, by changing a phase value of each pixel in the modulation pattern to be presented in the SLM, it is possible to change the amplitude $A_{s,x}$. With use of this, it is possible to preferably design a CUR used for a modulation pattern by a design method focusing on an effect by changing the phase value of one pixel described above.

[0085] As a specific configuration in the design of a modulation pattern, a configuration in which a phase value is changed according to a value analytically determined based on a phase $\phi_{s,x}$ of a complex amplitude indicating the light condensing state of the laser light at the wavelength λ_x on the light condensing point s, the propagation function $\phi_{s,x}'$, a phase value $\phi_{j,x}$ of the pixel j before change, and an incident phase $\phi_{j\text{-}in,x}$ of the laser light may be used for changing the phase value of the pixel j in the modulation pattern. As a design method of analytically updating a phase value in this way, there is, for example, an ORA (Optimal Rotation Angle) method.

[0086] Or, for the design of a modulation pattern, a configuration in which a phase value is changed according to a value determined by searching by use of any method of a hill-climbing method, a simulated annealing method, and a genetic algorithm may be used for changing the phase value of the pixel j in the modulation pattern. Here, in the genetic algorithm, operations such as a mutation that a certain pixel is selected to change its pixel value, and a crossover that two pixels are selected to exchange their pixel values are performed, and the above-described design method focusing on an effect on a light condensing state of laser light at a light condensing point by changing the phase value of one pixel in the modulation pattern includes a method of performing such operations. In addition, the modulation pattern design method will be described in detail later.

[0087] Further, in the light modulation control device **30** shown in FIG. **2**, in addition to the configuration for designing a modulation pattern, the light modulator drive control unit **35** which drive-controls the spatial light modulator **20**, and presents a modulation pattern designed by the designing unit **34** to the spatial light modulator **20** is provided. Such a configuration is effective in the case where the control device **30** is used in a manner incorporated in the laser light irradiation device **1**A as shown in FIG. **1**. Further, such a drive control unit **35** may also be provided as a separate device from the light modulation control device **30**.

[0088] Further, for example, in the case where a glass medium is processed by laser light irradiation to prepare an optical integrated circuit, one or a plurality of new CGHs may be designed after one or several laser light irradiations, to switch a modulation pattern to be presented in the spatial light modulator **20**. Or, in the case where the processing content has been determined, a plurality of modulation patterns necessary for laser processing may be designed in advance. Further, in the case where a DOE is singularly used, there is no need to have a driving device because a DOE is a static pattern. Further, in the case where a pattern is dynamically switched by use of a plurality of DOEs, a switching device is used in place of a driving device.

[0089] In addition, in the laser light irradiation device **1**A shown in FIG. **1**, the configuration of the laser scanning microscope is exemplified as described above. Such a laser microscope is preferably applicable to a super-resolution microscope which is considered to go beyond the diffraction limit, such as an STED (stimulated emission depletion) microscope using laser light sources at two or more wavelengths, or a PALM (photoactivated localization microscopy) microscope.

[0090] For example, in an STED microscope, light sources at two wavelengths of an excitation light source which transfers fluorescent molecules from the ground state to a specific excitation state, and a control light source which transfers fluorescent molecules from the specific excitation state to another level are used (refer to Patent Document 5, and Non-Patent Documents 8 and 9). Further, in this case, light condensing irradiation of control laser light from the control light source is performed so as to be a ring-shaped light condensing shape such that a diameter of a shadow inside the condensed light is smaller than the diffraction limit of the excitation light. In such a configuration, only the excitation light inside the ring-shaped light condensing shape of the control light is to contribute to fluorescent observation, and the fluorescing region is limited, and as a result, it is possible to obtain a super-resolution lower than the diffraction limit.

[0091] As problems in such an STED microscope, there may be cited an alignment of excitation light and control light including an optical axis direction under a high NA objective lens, a long measurement time, phase modulations for respectively generating ring-shaped control light beams for various wavelengths output from a wavelength variable laser or the like, an increase in size of the optical system due to its complicated configuration, and the like. Meanwhile, in accordance with the laser light irradiation device **1**A having the above-described configuration which is capable of separately achieving light condensing control of laser light and distortion correction for each light condensing point and wavelength, it is possible to construct the optical system by use of SLMs which are less than the number of light sources, which brings about the effects of simplification of a configuration and an improvement in operability of the super-resolution microscope, and the like. Further, it is possible to obtain such effects in the same way in a laser processing device and the like.

[0092] The light modulation control method and the modulation pattern design method executed in the laser light irradiation device **1**A and the light modulation control device **30** shown in FIG. **1** and FIG. **2** will be further described along with their specific examples. FIG. **3** is a flowchart showing an example of the light modulation control method executed in the light modulation control device **30** shown in FIG. **2**.

[0093] In the control method shown in FIG. **3**, first, information on the irradiation conditions of laser light supplied from the laser light source unit **10** to the object **42** is acquired (step S**101**). Specifically, information on the laser light including the number of wavelengths x_t of the laser light, and respective values of the x_t wavelengths $\lambda_x=\lambda_1, \ldots,$ and λ_{xt} is obtained (S **102**). The number of wavelengths x_t is the number of the laser light sources in the case where individual laser light sources are used at each wavelength. Further, when there is information necessary for derivation of a CGH, such as an NA and a focal point distance f of the objective lens **25**, information on distortion of the substrate in the spatial light modulator **20** used for deriving a distortion phase pattern, and the like other than the above-described information, these are acquired in addition to the information on the laser light.

[0094] Further, incident conditions of the laser light supplied from the laser light source unit **10** to the spatial light modulator **20** are acquired for each wavelength λ_x (step S **103**). As incident conditions in this case, for example, there is an incident pattern of the laser light at the wavelength λ_x to the spatial light modulator **20**. An incident pattern is provided as an incident light intensity distribution by an incident laser light intensity

$$I_{in}(x_j,y_3,\lambda_x)=I_{j\text{-}in,x}$$

for a pixel j at a position (x_j, y_j) among the plurality of two-dimensionally arrayed pixels in the spatial light modulator **20**. Or, an incident pattern of the laser light may be acquired as an incident light amplitude distribution by an amplitude $A_{j\text{-}in,x}$. Further, in case of necessity, an incident phase $\phi_{j\text{-}in,x}$ of the laser light as well is acquired in the same way.

[0095] Next, light condensing conditions of the laser light on the irradiation object **42** are set (S**104**). First, the number of a single or a plurality of light condensing points s_t at which light condensing irradiation of the laser light phase-modulated in the spatial light modulator **20** is performed on the irradiation object **42** is set (S**105**). Here, in the laser light irradiation device **1**A according to the above-described configuration, it is possible to obtain a plurality of light condensing points as necessary according to a modulation pattern to be presented in the spatial light modulator **20**.

[0096] Further, a light condensing position γ_s=(u_s, v_s, z_s) of the laser light, a single or plural wavelengths λ_x of the laser light to be condensed, and a desired light condensing intensity $I_{s\text{-}des,x}$ are set for each of the s_t light condensing points s=1, . . . , and s_t on the object **42** (S**106**). In addition, with respect to the wavelength of the laser light to be condensed, in the case where a single wavelength is made to correspond to each light condensing point s, given that the wavelength is λ_s, a light condensing parameter γ_s=(u_s, v_s, λ_s) may be set. Further, a light condensing intensity of the laser light on each light condensing point is not limited to the setting according to an absolute value of an intensity, and may be set according to, for example, a relative ratio of the intensity.

[0097] Next, a distortion phase pattern provided in the optical system for the laser light at the wavelength λ_x is derived with reference to the information on the configuration, performance and the like of the spatial light modulator **20**, or further the information on the configuration of the laser light guiding optical system including the spatial light modulator **20**, for the set s_t light condensing points s (S**107**). Then, in consideration of the distortion phase pattern derived in step S**107**, with reference to the irradiation conditions and the light condensing conditions of the laser light which are acquired and set in steps S**101** and S**104**, a CGH serving as a modulation pattern to be presented in the spatial light modulator (SLM) **20** is designed by use of a propagation function to which the distortion phase pattern is added (S**108**).

[0098] In addition, with respect to the information necessary for the derivation of the distortion phase pattern in step S**107**, a method in which a phase shift (aberration) due to distortion in the SLM is measured in advance by use of a separate optical system of, for example, a Michelson interferometer or a Mach-Zehnder interferometer may be used. Or, a method in which a phase shift is measured by applying a wavefront measuring device such as a Shack-Hartmann sensor to an appropriate position of the optical system, which is scheduled to be used for the laser light irradiation device may be used. In the case where a Shack-Hartmann sensor is used, it is possible to measure distortion in, not only the SLM, but also the light guiding optical system including the SLM depending on a position of the sensor. In this way, a phase shift due to distortion used for derivation of a distortion phase pattern may be measured over the entire optical system including the SLM.

[0099] The modulation pattern design method executed in step S**108** in the flowchart of FIG. **3** will be described in detail. Hereinafter, as an example of the design method focusing on an effect by a phase value of one pixel in the modulation pattern to be presented in the plurality of pixels in the SLM **20**, a design method by use of an ORA method will be described (refer to Patent Document 3, and Non-Patent Documents 1 to 4).

[0100] Here, in general, there are a plurality of design methods of a CGH used as a modulation pattern in the SLM, and for example, an iterative Fourier method and the like may be cited. First, an iterative Fourier transform method is a method in which, two surfaces of an SLM surface and a diffractive surface are prepared, to propagate light between the respective surfaces by a Fourier transform and an inverse Fourier transform. Then, the amplitude information of the respective surfaces is replaced in each propagation, to finally acquire a phase distribution.

[0101] Further, as another CGH design method, two methods of a ray tracing method and a design method focusing on an effect by one pixel may be cited. As a ray tracing method, there is a superposition-of-lens method (S method: Superposition of Lens). This method is effective in the case where there is not much overlapping of wave fronts from a light condensing point, meanwhile, when overlapping of wave fronts is increased, the intensity of light propagating to a light condensing point among the laser light intensities incident to the SLM is drastically reduced, or it is not possible to control the intensity in some cases. Therefore, there is an iterative S method which improved the S method.

[0102] On the other hand, the design method focusing on an effect by one pixel in a CGH is a method of appropriately selecting one pixel in a CGH, and changing a phase value of each pixel, to perform designing the CGH, and there are a search type method and an analysis type method according to a method of determining a phase of one pixel.

[0103] In this design method, a phase value of a certain pixel in a CGH is changed as a parameter, and a modulation laser light is propagated by use of a wave propagation function by the Fresnel diffraction or the like, to examine how values (for example, values of an amplitude, an intensity, and a complex amplitude) indicating a light condensing state at a desired light condensing point change. Then, a phase value by which the light condensing state on the light condensing point is brought closer to a desired result is adopted. Such an operation is performed on one pixel by one pixel on at least all the pixels to which light is incident.

[0104] After the operations are completed on all the pixels, in an analysis type method, after it is confirmed how a phase at a desired position changes based on the results of the phase-modulations of all the pixels, the process returns to the first pixel, to change a phase one pixel by one pixel by use of the phase at the desired position. Further, in a search type method, the process returns to the first pixel without performing confirmation. As a search type method, for example, there are a hill-climbing method, a simulated annealing method (SA: Simulated Annealing), and a genetic algorithm (GA: Genetic Algorithm), and the like (refer to Non-Patent Documents 5 and 6).

[0105] An ORA (Optimal Rotation Angle) method which will be hereinafter described is an optimization algorithm using an analysis type method. In this method, a change and an adjustment in a phase value of each pixel in a modulation pattern are carried out according to a value analytically determined based on a phase $\phi_{s,x}$ of a complex amplitude indicating a light condensing state on the light condensing point s, a phase $\phi_{js,x}$ of the propagation function, a phase value $\phi_{j,x}$ of the pixel j before change, and an incident phase $\phi_{j\text{-}in,x}$ of the laser light. In particular, in the design method in the present embodiment, as a wave propagation function, in place of the usual $\phi_{js,x}$, a propagation function $\phi_{js,x}'$ to which a distortion phase pattern is added is used.

[0106] FIG. **4** is a flowchart showing an example of a modulation pattern design method executed in the light modulation control device **30** shown in FIG. **2**. First, information on the set light condensing conditions for light condensing irradiation of laser light on the irradiation object **42** performed via the spatial light modulator **20** is acquired (step S**201**). As the light condensing conditions acquired here, there are the number of light condensing points s_t, a light condensing position $\gamma_s=(u_s, v_s, z_s)$ of each light condensing point s, a wavelength λ_x of the laser light to be condensed, and a desired light condensing intensity $I_{s\text{-}des,x}$.

[0107] Next, a phase pattern serving as an initial condition for the design of a CGH used as a modulation pattern to be presented in the SLM **20** is created (S**202**). This phase pattern is created by, for example, a method in which a phase value ϕ_j of a pixel j in the CGH is made into a random phase pattern. Because the design of a CGH by an ORA is an optimization technique, this method is used for the purpose of preventing from leading to a specific minimum solution due to a random phase. In addition, in the case where the possibility of leading to a specific minimum solution can be disregarded, for example, it may be set to a uniform phase pattern or the like. Further, in the case where light condensing irradiation of laser light at plural wavelengths is performed, a predetermined wavelength λ_a among the wavelengths λ_1 to λ_{xt} of the laser light is set to a reference wavelength, and a phase value $\phi_{j,a}$ for this reference wavelength λ_a is set.

[0108] Next, in the case where the number of light condensing points is set to a plural number ($s_t \geq 2$), a weight $w_{s,x}$ which is a parameter for adjusting a light condensing intensity ratio among those light condensing points s=1 to s_t is set to $w_{s,x}=1$ as its initial condition (S**203**). In addition, this weight exists by the number of wavelengths x_t (by the number of laser light sources), which are respectively arrayed in $1\times s_t$. Further, in the case of a single light condensing point ($s_t=1$), it is not necessary to set a weight $w_{s,x}$. Further, in the case where the number of wavelengths is set as a plural number ($x_t \geq 2$), a weight W_x which is a parameter for adjusting a light quantity ratio among the plural wavelengths is set to $W_x=1$ as its initial condition.

[0109] When the settings of the phase pattern $\phi_{j,a}$ of the CGH and the weights $w_{s,x}$ and W_x are completed, a complex amplitude $U_{s,x}$ indicating a light condensing state of the laser light on the light condensing point s is calculated (S**204**). Specifically, for the laser light at the wavelength λ_x, a complex amplitude $U_{s,x}=A_{s,x}\exp(i\phi_{s,x})$ which the laser light at the wavelength λ_x applies on the light condensing point s is determined by the following formula (5) representing lightwave propagation.

[Formula 5]

$$\begin{aligned} U_{s,x} &= A_{s,x}\exp(i\phi_{s,x}) \\ &= \sum_j A_{j\text{-}in,x}\exp(i\phi'_{js,x})\exp\left(i\left(\phi_{j,x}+\phi_{j\text{-}in,x}\right)\right) \end{aligned} \tag{5}$$

[0110] Here, $A_{j\text{-}in,x}$ is an incident amplitude of the laser light at the wavelength λ_x onto the pixel j in the SLM **20**, $\phi_{j\text{-}in,x}$ is an initial phase when the laser light at the wavelength λ_x is incident to the pixel j. Further, $\phi_{j,x}$ is a phase value for the laser light at the wavelength λ_x of the pixel j. This phase value $\phi_{j,x}$ is determined by the following formula (6)

[Formula 6]

$$\phi_{j,x}=\tau(\lambda_a,\lambda_x)\times\phi_{j,a} \tag{6}$$

according to the phase value $\phi_{j,a}$ for the reference wavelength λ_a described above.

[0111] In addition, in this formula (6), $\tau(\lambda_a, \lambda_x)$ is a correction formula (correction coefficient) in consideration of wavelength dispersion and the like. For example, in the case where the SLM **20** is an LCOS-SLM using a liquid crystal, modulation of a phase of laser light is performed by use of the birefringence characteristics of the liquid crystal, meanwhile, the birefringence of the liquid crystal is not linear with respect to a wavelength λ. Then, in conversion of a phase value, as a correction formula in consideration of the birefringence characteristics of the liquid crystal and the like, the above-described $\tau(\lambda_a, \lambda_x)$ is used.

[0112] Further, in the formula (5), $\phi_{js,x}'$ is a propagation function to which a distortion phase pattern $\phi_{js\text{-}dis,x}$ derived for the laser light at the wavelength λ_x is added, and is determined as follows.

[Formula 7]

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x} \tag{7}$$

In addition, as the distortion phase pattern $\phi_{js\text{-}dis,x}$, for example, a phase of the aberration conditions due to distortion in the SLM shown in the formula (2) is used in the case where the SLM **20** is an LCOM-SLM.

[0113] In this way, by use of the propagation function $\phi_{js,x}'$ to which the distortion phase pattern is added, it is possible to reliably reflect a distortion correction pattern for canceling the distortion phase pattern for the laser light at each light condensing point s and wavelength λ_x, into a modulation pattern to be finally obtained. In this case, for example, even if the SLM has distortion, it is possible to obtain a CGH capable of providing a desired light condensing result at each wavelength. Further, $\phi_{js,x}$ is a propagation function in a finite distance region in the case of assuming a free propagation. As this propagation function $\phi_{js,x}$, for example, the Fresnel diffraction which is an approximation formula of a wave propagation function which is provided by the following formula (8)

[Formula 8]

$$\phi_{js,x} = \frac{n_1\times\pi}{\lambda_x f}\left[(u_s-x_j)^2+(v_s-y_j)^2\right] \tag{8}$$

may be used. Here, in the above-described formula (8), n_1 is a refractive index of an ambient medium such as air, water, or oil, and f is a focal point distance. Further, it is clear from this formula (8) that an ideal propagation function $\phi_{js,x}$ differs according to a wavelength λ_x. Further, a distortion phase pattern $\phi_{js\text{-}dis,x}$ differs according to a wavelength λ_x in the same way.

[0114] In addition, as a propagation function $\phi_{js,x}$ of free propagation, for example, various expression formulas such as an approximation formula of the Fresnel diffraction described above, an approximation formula of the Fraunhofer diffraction, or a solution of the Helmholtz equation may be used. Further, in the formula (5) of a complex amplitude and the formula (7) of a propagation function described above, given that a distortion phase pattern to be added to a wave propagation function is $\phi_{js\text{-}dis,x}=0$, the propagation function becomes $\phi_{js,x}'=\phi_{js,x}$, which brings about a normal calculation formula of a complex amplitude which has been used for a conventional ORA method.

[0115] Next, it is judged whether or not a desired result has been obtained in the design of a CGH by the above-described method (S**205**). As a judgment method in this case, for example, a method in which a light condensing intensity $I_{s,x}=|A_{s,x}|^2$ obtained by the light at the wavelength λ_x on each light condensing point s and a desired intensity $I_{s\text{-}des,x}$ are compared by the following formula (9)

[Formula 9]

$$\max\left(\frac{I_{s\text{-}des,x}}{I_{s,x}}\right) \leq \varepsilon \tag{9}$$

and it is judged by whether or not an intensity ratio is less than or equal to a predetermined value c for all the light condensing points s and the wavelengths λ_x, may be used. Further, a judgment may be made by, not the light condensing intensity $I_{s,x}$, but an amplitude $A_{s,x}$, a complex amplitude $U_{s,x}$, and the like.

[0116] Or, in the flowchart of FIG. **4**, a method in which it is judged by conditions of, such as, whether or not a specified number of loops of changing a phase value and calculating a complex amplitude, and the like are performed, may be used. In the case where it is judged that the designed CGH satisfies the necessary conditions for the set light condensing conditions, the design algorithm for a CGH by an ORA is completed. Further, in the case where the conditions are not satisfied, the process proceeds to the following step S**206**.

[0117] In the case where it is judged that the conditions necessary for the completion of the design are not satisfied, first, the values of a weight $w_{s,x}$ for adjusting a light condensing intensity ratio among the light condensing points s, and a weight W_x for adjusting a light quantity ratio among the plural wavelengths λ_x are changed by the following formulas (10), (11), and (12) (S**206**).

[Formula 10]

$$w_{s,x} = w_{s,x}\left(\frac{I_{s-des,x}}{I_{s,x}}\right)^{\eta} \tag{10}$$

[Formula 11]

$$W_a = 1 \tag{11}$$

[0118] Here, W_a in the formula (11) is a weight at a reference wavelength λ_a. Further, for a parameter n used for updating the weight $w_{s,x}$ in the formula (10), and a parameter q used for updating the weight W_x in the formula (12), usually, values of η=approximately 0.25 to 0.35, and q=approximately 0.25 to 0.35 are customarily used in order to prevent the ORA algorithm from becoming unstable. Further, in the formula (12), I_x^{ave} is an average of the intensities on all the points at the wavelength λ_x.

[0119] Next, a phase value changing operation is performed for each pixel of the CGH such that the light condensing state of the laser light on the light condensing point s is brought closer to a desired state (S**207**). In an analysis type ORA method, in order to bring a light condensing state closer to a desired state, an amount of phase change $\Delta\phi_{j,a}$ to be added to the phase value $\phi_{j,a}$ of the pixel j is, by use of the phase $\phi_{s,x}$ of a complex amplitude obtained in the formula (5), the phase $\phi_{js,x}'$ of the propagation function, the phase value $\phi_{j,x}$ before updating, and the incident phase $\phi_{j\text{-}in,x}$ of the laser light, analytically determined by the following formula (13)

[Formula 13]

$$\Delta\phi_{j,a} = \arctan\left(\frac{P_2}{P_1}\right) \tag{13}$$

and judgment is made. Here, the following formulas

[Formula 14]

$$P_1 = \sum_x \sum_s W_x w_{s,x} A_{j\text{-}in,x} \cos\Phi_{js,x} \tag{14}$$

[Formula 15]

$$P_2 = \sum_x \sum_s W_x w_{s,x} A_{j\text{-}in,x} \sin\Phi_{js,x} \tag{15}$$

[Formula 16]

$$\begin{aligned}\Phi_{js,x} &= \phi_{s,x} - (\phi'_{js,x} + \phi_{j,x} + \phi_{j\text{-}in,x}) \\ &= \phi_{s,x} - (\phi_{js,x} + \phi_{js\text{-}dis,x} + \tau(\lambda_a, \lambda_x) \times \phi_{j,a} + \phi_{j\text{-}in,x})\end{aligned} \tag{16}$$

are held. A method of analytically determining a phase value in this way has an advantage that a time required for computation is shortened as compared with a method such as the hill-climbing method which determines a phase value by searching.

[0120] In addition, with respect to $\Phi_{js,x}$ used for determining an amount of phase change $\Delta\phi_{j,a}$, in a usual ORA method, the following formula (17)

[Formula 17]

$$\Phi_{js,x}=\phi_{s,x}-(\phi_{js,x}+\phi_{j,x}+\phi_{j\text{-}in,x}) \tag{17}$$

is used, meanwhile, in an improved ORA method which is described here, in addition to the change in the propagation function described above, in a calculation of this $\Phi_{js,x}$ in the update of a phase value as well, the formula (16) to which the distortion phase pattern $\phi_{js\text{-}dis,x}$ is provided is used.

[0121] As described above, when an amount of phase change $\Delta\phi_{j,a}$ is determined, a phase value $\phi_{j,a}$ at a j-th pixel in the CGH is changed and updated by the following formula (18).

[Formula 18]

$$\phi_{j,a}=\phi_{j,a}+\Delta\phi_{j,a} \tag{18}$$

Further, at this time, a phase value $\phi_{j,x}$ for each wavelength λ_x is determined by the formula (6).

[0122] Then, it is confirmed whether or not a phase value changing operation is performed on all the pixels (S**208**), and when the changing operation has not been completed, it is assumed that j=j+1, a phase value changing operation is performed on the next pixel. On the other hand, when the changing operation for all the pixels has been completed, the process returns to step S**204**, and a calculation of a complex amplitude $U_{s,x}$ and an evaluation of a light condensing state of the laser light thereby are carried out. Such operations are repeatedly executed, a CGH of a modulation pattern corresponding to the set light condensing conditions is thereby created.

[0123] As described above, provided that a CGH is designed by use of a propagation function to which a distortion phase pattern caused by a phase shift or the like due to distortion in the SLM **20** is added, it is possible to apply a distortion phase pattern corresponding to each wavelength, or further, as necessary, each light condensing point, which makes it possible to perform distortion correction at a high accuracy under appropriate correction conditions different from each other.

[0124] Further, in the case where a spatial light modulator which is capable of dynamically switching a modulation pattern to be presented is used, it is easy to perform an alignment of a position in the depth direction of a light condensing point or the like by performing feedback control or the like. Further, for example, a plurality of light condensing points are created from a single light source by use of a spatial light modulator, and a plurality of detectors are prepared so as to correspond to those, thereby it is possible to shorten a measurement time. Moreover, provided that it is configured to measure aberration in the optical system in measurement for deriving a distortion phase pattern, it is possible to entirely reduce the effect by the aberration, to obtain a favorable light condensing shape of laser light by achieving aberration correction in the SLM.

[0125] In addition, in the specific example described above, an amount of change $\Delta\phi_{j,a}$ to be added to a phase value of the pixel j is analytically determined by the formulas (13) to (16), however, for the calculation of an amount of phase change, specifically, a method other than the above-described method may be used. For example, a method of determining an amount of phase change $\Delta\phi_{j,x}$ at each wavelength λ_x may be used by the following formula (19).

[Formula 19]

$$\Delta\phi_{j,x} = \arctan\left(\frac{P_2}{P_1}\right) \tag{19}$$

Here, the following formulas

[Formula 20]

$$P_1 = \sum_s W_x w_{s,x} A_{j\text{-}in,x} \cos\Phi_{js,x} \tag{20}$$

[Formula 21]

$$P_2 = \sum_s W_x w_{s,x} A_{j\text{-}in,x} \sin\Phi_{js,x} \tag{21}$$

are held. Further, with respect to $\Phi_{js,x}$, $\Phi_{js,x}$ shown in the formula (16) is used.

[0126] Further, in this case, the phase value $\phi_{j,a}$ is changed and updated by the following formula (22).

[Formula 22]

$$\phi_{j,a} = \phi_{j,a} + \kappa(\lambda_a, \lambda_x)\sum_x \Delta\phi_{j,x} \tag{22}$$

In addition, in this formula (22), $\kappa(\lambda_a, \lambda_x)$ is a parameter for adjusting an amount of phase change $\Delta\phi_{j,x}$ which differs at each wavelength. This parameter may be omitted if not necessary.

[0127] The effects of light condensing control of laser light by the light modulation control device **30** and the laser light irradiation device **1**A according to the above-described embodiment will be described along with the specific example. Here, a laser light irradiation device **1**B is configured by an optical system shown in FIG. **5**, and a confirmatory experiment on light condensing control has been carried out by use of this laser light irradiation device **1**B.

[0128] In the configuration shown in FIG. **5**, the laser light source unit **10** is composed of the laser light source **11** which supplies laser light at a wavelength of 532 nm, and the laser light source **12** which supplies laser light at a wavelength of 633 nm. The laser light from the laser light source **11** is expanded by a spatial filter **51** and a collimator lens **53**, and reflected by a mirror **55**, to be thereafter reflected by a dichroic mirror **56**. Further, the laser light from the laser light source **12** is expanded by a spatial filter **52** and a collimator lens **54**, to thereafter pass through the dichroic mirror **56**. Thereby, the laser light beams from the laser light sources **11** and **12** are multiplexed on the dichroic mirror **56**.

[0129] The laser light from the dichroic mirror **56** passes through a half mirror **57**, to be phase-modulated by the reflective type spatial light modulator **20**. Then, the reflected laser light from the spatial light modulator **20** is reflected by the half mirror **57**, and its condensed light image is imaged by a camera **60** via a lens **58**. With this condensed light image of the laser light, it is possible to confirm light condensing control by the spatial light modulator **20**.

[0130] Further, with respect to light condensing control conditions by a phase pattern to be provided for the laser light in the spatial light modulator **20**, the light condensing positions (regeneration positions) of the laser light at a wavelength of 532 nm and the laser light at a wavelength of 633 nm are shifted in order to increase visibility, and conditions for condensing the laser light at a wavelength of 532 nm into a Gaussian shape, and condensing the laser light at a wavelength of 633 nm into a ring shape are used. In addition, as a phase pattern for light condensing control to be displayed on the SLM for condensing laser light into a ring shape, for example, a phase pattern of a Laguerre-Gaussian (LG) beam may be used.

[0131] FIG. **6** shows a condensed light image of laser light obtained by such a configuration and setting. As shown in this FIG. **6**, according to a modulation pattern designed by the method described above, it is possible to preferably regenerate a condensed light spot of a Gaussian shape of laser light at a wavelength of 532 nm, and a condensed light spot of a ring shape of laser light at a wavelength of 633 nm, respectively. Further, it is possible to apply such light condensing control conditions to an STED microscope by matching the light condensing positions.

[0132] The modulation pattern design method executed in step S**108** in the flowchart of FIG. **3** will be further described. In the flowchart of FIG. **4**, as an example of the design method focusing on an effect by one pixel in a CGH, a design method using an analysis type ORA method is shown. Meanwhile, as a modulation pattern design method, a search type design method such as a hill-climbing method, a simulated annealing method, or a genetic algorithm may be used as described above.

[0133] FIG. **7** is a flowchart showing another example of a modulation pattern design method executed in the light modulation control device **30** shown in FIG. **2**. In this flowchart, a design method in the case where the hill-climbing method is used is shown as an example of a search type design method. In this method, first, information on set light condensing conditions for light condensing irradiation of laser light onto the irradiation object **42** performed via the SLM **20** is acquired, in the same way as in the case of an ORA method described above (step S**301**). Next, a phase pattern serving as an initial condition for the design of a CGH to be presented in the SLM **20** is created as, for example, a random phase pattern (S**302**).

[0134] Next, a phase value changing operation of one pixel in the CGH is performed (S**303**). Moreover, a complex amplitude $U_{s,x}=A_{s,x}\exp(i\phi_{s,x})$ indicating a light condensing state of the laser light on the light condensing point s is calculated by use of the formula (5) including the wave propagation function $\phi_{js,x}'$ to which the distortion phase pattern $\phi_{js\text{-}dis,x}$ is added (S**304**). After calculating the complex amplitude $U_{s,x}$, a judgment of the obtained light condensing state is made (S**305**).

[0135] Here, when the amplitude $A_{s,x}$, the intensity $I_{s,x}=|A_{s,x}|^2$, or the complex amplitude $U_{s,x}$ are brought closer to a desired value by switching a phase value of one pixel in the modulation pattern, a phase value at that time is adopted. In the hill-climbing method, for example, a phase value of each pixel in the CGH is switched every 0.1π (rad) from 0π (rad) to a predetermined phase value, for example, switched to 2π (rad), and a propagation is carried out by use of the formula (5) for every switching. Then, a phase value by which an intensity on the light condensing point s is maximized is determined by searching.

[0136] Next, it is determined whether or not switching of a phase value of one pixel has been confirmed under all the conditions (S**306**), and when it has not been confirmed, the process returns to step S**303**. Moreover, it is judged whether or not the phase value changing operations of one pixel, judging a light condensing state and the like have been performed on all the pixels (S**307**), and when it has not been performed, it is assumed that the pixel number is j=j+1, the process returns to step S**303**, and a necessary operation is performed on the next pixel.

[0137] When the necessary operations have been performed on all the pixels, it is judged whether or not a desired result has been obtained in the design of the CGH (S**308**). As a judgment method in this case, in the same way as the case of an ORA method, for example, a method of judging by whether or not the values of a light condensing intensity, an amplitude, a complex amplitude, and the like obtained on each light condensing point are within the allowable ranges may be used. Or, in the flowchart of FIG. **7**, a method in which it is judged by conditions of, such as, whether or not a specified number of loops of changing a phase value, judging a light condensing state, and the like is performed, may be used. In the case where the necessary conditions are satisfied, the design algorithm for a CGH is completed. In the case where the conditions are not satisfied, the process returns to step S**303**, to repeat searches from the first pixel.

[0138] The light modulation control method, the control program, the control device, and the laser light irradiation device according to the present invention are not limited to the above-described embodiment and the configuration examples, and various modifications thereof are possible. For example, a configuration of an optical system including laser light sources and a spatial light modulator is not limited to the configuration example shown in FIG. **1**, and specifically, various configurations may be used.

[0139] Further, in the above-described embodiment, the case where the number of wavelengths of laser light with which light condensing control is performed is plural, has been mainly described, however, in the case where light condensing irradiation of laser light at a single wavelength is performed, it is also possible to preferably apply a light modulation control method according to the above-described configuration. In this case, for example, in the above-described ORA method, a parameter W_x for adjusting a light quantity ratio among plural wavelengths is not updated as $W_x=1$. Further, with respect to the number of laser light sources, for example, specifically, various specific configurations such as a configuration in which laser light at plural wavelengths is supplied from a single laser light source may be used.

[0140] Further, with respect to the design of a modulation pattern (CGH) to be presented in a spatial light modulator as well, specifically, various methods other than the examples described above may be used. In general, it suffices that, in the design of a modulation pattern, by focusing on an effect on a light condensing state of laser light on a light condensing point by changing a phase value of one pixel in a modulation pattern, the phase value is changed such that its light condensing state is brought closer to a desired state, and such phase value changing operations are performed for all the pixels in the modulation pattern, thereby designing a modulation pattern, and, when evaluating the light condensing state on the light condensing point, a propagation function to which a distortion phase pattern is added may be used for propagation of light at a wavelength λ_x from the pixel j in the modulation pattern of the spatial light modulator to the light condensing point s.

[0141] Further, in derivation of the complex amplitude $U_{s,x}$, when a propagation function

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

is substituted for the formula,

$$U_{s,x} = \sum_j A_{j\text{-}in,x}\exp\{i(\phi_{js,x} + \phi_{js\text{-}dis,x} + \phi_{j,x} + \phi_{j\text{-}in,x})\}$$

$$= \sum_j A_{j\text{-}in,x}\exp\{i(\phi_{js,x} + \phi_{j,x} + \phi_{j\text{-}in,x} + \phi_{js\text{-}dis,x})\}$$

is derived. As is clear from this formula, the same result is obtained by adding ($+\phi_{js\text{-}dis,x}$) to an incident phase $\phi_{j\text{-}in,x}$ for the purpose of calculation. Such a method is equivalent to a method of adding ($+\phi_{js\text{-}dis,x}$) to the propagation function $\phi_{s,x}$, and accordingly, the present invention also includes such a configuration.

[0142] The light modulation control method according to the above-described embodiment (1) which controls light condensing irradiation of laser light onto a set light condensing point by a modulation pattern to be presented in a spatial light modulator by use of the phase-modulation type spatial light modulator that inputs the laser light thereto, to modulate a phase of the laser light, and that outputs the phase-modulated laser light, the method includes (2) an irradiation condition acquiring step of acquiring the number of wavelengths x_t (x_t is an integer of 1 or more) of the laser light to be input to the spatial light modulator, x_t wavelengths λ_x (x=1, . . . , and x_t), and incident conditions of the laser light at each wavelength to the spatial light modulator, as irradiation conditions of the laser light, (3) a light condensing condition setting step of setting the number of the light condensing points s_t (s_t is an integer of 1 or more) on which light condensing irradiation of the laser light from the spatial light modulator is perfoinied, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity for each of the s_t light condensing points s (s=1, . . . , and s_t), as light condensing conditions of the laser light, (4) a distortion pattern deriving step of deriving a distortion phase pattern containing a phase shift due to distortion in the spatial light modulator to be provided in an optical system to the laser light at the wavelength λ_x for the s_t light condensing points s, and (5) a modulation pattern designing step of designing the modulation pattern to be presented in the spatial light modulator in consideration of the distortion phase pattern derived in the distortion pattern deriving step, and in the method, (6) the modulation pattern designing step assumes a plurality of two-dimensionally arrayed pixels in the spatial light modulator, changes a phase value so as to bring a light condensing state closer to a desired state by focusing on an effect on the light condensing state of the laser light on the light condensing point by changing the phase value of one pixel in the modulation pattern to be presented in the plurality of pixels, and performs such phase value changing operations for all the pixels in the modulation pattern, thereby designing the modulation pattern, and when evaluating the light condensing state on the light condensing point, a propagation function $\phi_{js,x}'$

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

that is, the distortion phase pattern $\phi_{js\text{-}dis,x}$ which is derived in the distortion pattern deriving step is added to a wave propagation function $\phi_{js,x}$ is used for propagation of light at a wavelength λ_x from a pixel j in the modulation pattern of the spatial light modulator to the light condensing point s.

[0143] Further, the light modulation control program according to the present embodiment (1) which is for causing a computer to execute light modulation control that controls light condensing irradiation of the laser light onto a set light condensing point by a modulation pattern to be presented in a spatial light modulator by use of the phase-modulation type spatial light modulator that inputs the laser light thereto, to modulate a phase of the laser light, and that outputs the phase-modulated laser light, the program causes the computer to execute (2) irradiation condition acquiring processing of acquiring the number of wavelengths x_t (x_t is an integer of 1 or more) of the laser light to be input to the spatial light modulator, x_t wavelengths λ_x (x=1, . . . , and x_t), and incident conditions of the laser light at each wavelength λ_x to the spatial light modulator, as irradiation conditions of the laser light, (3) light condensing condition setting processing of setting the number of light condensing points s_t (s_t is an integer of 1 or more) on which light condensing irradiation of the laser light from the spatial light modulator is performed, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity for each of the s_t light condensing points s (s=1, . . . , and s_t), as light condensing conditions of the laser light, (4) distortion pattern deriving processing of deriving a distortion phase pattern containing a phase shift due to distortion in the spatial light modulator to be provided in an optical system to the laser light at the wavelength λ_x for the s_t light condensing points s, and (5) modulation pattern designing processing of designing the modulation pattern to be presented in the spatial light modulator in consideration of the distortion phase pattern derived in the distortion pattern deriving step, and in the program, (6) the modulation pattern designing processing assumes a plurality of two-dimensionally arrayed pixels in the spatial light modulator, changes a phase value so as to bring a light condensing state closer to a desired state by focusing on an effect on the light condensing state of the laser light on the light condensing point by changing the phase value of one pixel in the modulation pattern to be presented in the plurality of pixels, and performs such phase value changing operations for all the pixels in the modulation pattern, thereby designing the modulation pattern, and when evaluating the light condensing state on the light condensing point, a propagation function $\phi_{js,x}'$

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

that is, the distortion phase pattern $\phi_{js\text{-}dis,x}$ which is derived in the distortion pattern deriving processing is added to a wave propagation function $\phi_{js,x}$ is used for propagation of light at a wavelength λ_x from a pixel j in the modulation pattern of the spatial light modulator to the light condensing point s.

[0144] Further, the light modulation control device according to the present embodiment (1) which controls light condensing irradiation of laser light onto a set light condensing point by a modulation pattern to be presented in a spatial light modulator by use of the phase-modulation type spatial light modulator that inputs the laser light thereto, to modulate a phase of the laser light, and that outputs the phase-modulated laser light, the device includes (2) irradiation condition acquiring means for acquiring the number of wavelengths x_t (x_t is an integer of 1 or more) of the laser light to be input to the spatial light modulator, x_t wavelengths λ_x (x=1, . . . , and x_t), and incident conditions of the laser light at each wavelength λ_x to the spatial light modulator, as irradiation conditions of the laser light, (3) light condensing condition setting means for setting the number of light condensing points s_t (s_t is an integer of 1 or more) on which light condensing irradiation of the laser light from the spatial light modulator is performed, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity for each of the s_t light condensing points s (s=1, . . . , and s_t), as light condensing conditions of the laser light, (4) distortion pattern deriving means for deriving a distortion phase pattern containing a phase shift due to distortion in the spatial light modulator to be provided in an optical system to the laser light at the wavelength λ_x for the s_t light condensing points s, and (5) modulation pattern designing means for designing the modulation pattern to be presented in the spatial light modulator in consideration of the distortion phase pattern derived in the distortion pattern deriving means, and in the device, (6) the modulation pattern designing means assumes a plurality of two-dimensionally arrayed pixels in the spatial light modulator, changes a phase value so as to bring a light condensing state closer to a desired state by focusing on an effect on the light condensing state of the laser light on the light condensing point by changing the phase value of one pixel in the modulation pattern to be presented in the plurality of pixels, and performs such phase value changing operations for all the pixels in the modulation pattern, thereby designing the modulation pattern, and when evaluating the light condensing state on the light condensing point, a propagation function $\phi_{js,x}'$

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

that is, the distortion phase pattern $\phi_{js\text{-}dis,x}$ which is derived in the distortion pattern deriving means is added to a wave propagation function $\phi_{js,x}$ is used for propagation of light at a wavelength λ_x from a pixel j in the modulation pattern of the spatial light modulator to the light condensing point s.

[0145] Here, in the light modulation control method, the control program, and the control device described above, a configuration in which the number of wavelengths x_t of the laser light is set to a plural number may be used for acquisition of irradiation conditions. As described above, a method of designing a modulation pattern by use of a propagation function to which a distortion phase pattern to be provided in an optical system is added, is particularly effective for the control of light condensing irradiation conditions of laser light containing the plural wavelength components in this way.

[0146] Further, in the case where light condensing irradiation of laser light containing plural wavelength components is performed as described above, the light modulation control method, the control program, and the control device may use a configuration in which the modulation pattern is designed in consideration of wavelength dispersion of a refractive index in the spatial light modulator in the design of a modulation pattern. Thereby, it is possible to more accurately control the light condensing irradiation conditions of the laser light at the wavelength λ_x on each light condensing point s for the respective wavelengths λ_x different from each other.

[0147] Further, in the above-described configuration, as the spatial light modulator used for light condensing control of the laser light, a spatial light modulator which is configured to be capable of dynamically switching a modulation pattern to be presented may be used. Usually, such a spatial light modulator structurally has a larger effect by a phase shift or the like due to distortion as compared with a modulator which statically presents a modulation pattern, and accordingly, distortion correction by the above-described method is particularly effective therefor.

[0148] Further, the light modulation control method, the control program, and the control device may use a configuration in which, in the design of a modulation pattern, given that an incident amplitude of the laser light at the wavelength λ_x to the pixel j in the spatial light modulator is $A_{j\text{-}in,x}$, its phase is $\phi_{j\text{-}in,x}$, and a phase value for the laser light at the wavelength λ_x of the pixel j is $\phi_{j,x}$, a complex amplitude indicating a light condensing state of the laser light at the wavelength λ_x on the light condensing point s is determined by the following formula.

$$\begin{aligned} U_{s,x} &= A_{s,x}\exp(i\phi_{s,x}) \\ &= \sum_j A_{j\text{-}in,x}\exp(i\phi'_{js,x})\times\exp\big(i(\phi_{j,x}+\phi_{j\text{-}in,x})\big) \end{aligned}$$

Thereby, it is possible to preferably evaluate a light condensing state of the laser light on the light condensing point s.

[0149] As a specific configuration in the design of a modulation pattern, a configuration in which a phase value is changed according to a value analytically determined based on a phase $\phi_{s,x}$ of a complex amplitude indicating the light condensing state of the laser light at the wavelength λ_x on the light condensing point s, the propagation function $\phi_{js,x}'$, a phase value $\phi_{j,x}$ of the pixel j before change, and an incident phase $\phi_{j\text{-}in,x}$ of the laser light may be used for changing the phase value of the pixel j in the modulation pattern. As a design method of analytically updating a phase value in this way, there is, for example, an ORA (Optimal Rotation Angle) method.

[0150] Or, with respect to the design of a modulation pattern, a configuration in which a phase value is changed according to a value determined by searching by use of any method of a hill-climbing method, a simulated annealing method, and a genetic algorithm may be used for changing the phase value of the pixel j in the modulation pattern.

[0151] Further, the light modulation control device may also be configured to include light modulator drive control means for drive-controlling the spatial light modulator, to present the modulation pattern designed by the modulation pattern designing means in the spatial light modulator. Further, such light modulator drive control means may also be configured to be provided as a separate device from the light modulation control device which performs the design of a modulation pattern.

[0152] The laser light irradiation device according to the present embodiment includes (a) a laser light source which supplies laser light with x_t (x, is an integer of 1 or more) wavelengths λ_x, (b) a phase-modulation type spatial light modulator which inputs the laser light thereto, to modulate a phase of the laser light, and which outputs the phase-modulated laser light, and (c) the light modulation control device having the above-described configuration, which controls light condensing irradiation of the laser light at each wavelength λ, onto set s_t (s_t is an integer of 1 or more) light condensing points s by a modulation pattern to be presented in the spatial light modulator.

[0153] In accordance with such a configuration, a distortion correction pattern for canceling an effect by a distortion phase pattern to be provided in the optical system including the spatial light modulator is reliably incorporated in a modulation pattern to be finally obtained by the light modulation control device, thereby, it is possible to preferably achieve distortion correction in light condensing control of the laser light with sufficient accuracy, and it is possible to preferably achieve light condensing irradiation of the laser light on the light condensing point s set on an irradiation object, and operations such as processing, observations, and the like of the object thereby. Such a laser light irradiation device may be used as, for example, a laser processing device, a laser microscope, or the like. In addition, as a spatial light modulator, it is preferable to use a spatial light modulator having a plurality of two-dimensionally arrayed pixels, which is configured to modulate a phase of the laser light for each of the plurality of pixels.

INDUSTRIAL APPLICABILITY

[0154] The present invention is applicable as a light modulation control method, a control program, a control device, and a laser light irradiation device by which it is possible to preferably achieve distortion correction in light condensing control of laser light using a spatial light modulator with sufficient accuracy.

REFERENCE SIGNS LIST

[0155] **1**A, **1**B—laser light irradiation device, **10**—laser light source unit, **11**—laser light source, **12**—laser light source, **13**, **14**—beam expander, **15**—dichroic mirror, **16**—mirror, **18**—prism, **20**—spatial light modulator, **21**—mirror, **22**, **23**—4f optical system lens, **25**—objective lens, **28**—light modulator driving device, **40**—movable stage, **42**-irradiation object, **45**—detection unit, **46**—lens, **47**—dichroic mirror,

[0156] **51**, **52**—spatial filter, **53**, **54**—collimator lens, **55**—mirror, **56**—dichroic mirror, **57**—half mirror, **58**—lens, **60**—camera,

[0157] **30**—light modulation control device, **31**—irradiation condition acquiring unit, **32**—light condensing condition setting unit, **33**—distortion phase pattern deriving unit, **34**—modulation pattern designing unit, **35**—light modulator drive control unit, **37**—input device, **38**—display device.

1. A light modulation control method which controls light condensing irradiation of laser light onto a set light condensing point by a modulation pattern to be presented in a spatial light modulator by use of the phase-modulation type spatial light modulator that inputs the laser light thereto, to modulate a phase of the laser light, and that outputs the phase-modulated laser light, the method comprising:

an irradiation condition acquiring step of acquiring the number of wavelengths x_t (x_t is an integer of 1 or more) of the laser light to be input to the spatial light modulator, x_t wavelengths λ_x, and incident conditions of the laser light at each wavelength to the spatial light modulator, as irradiation conditions of the laser light;

a light condensing condition setting step of setting the number of the light condensing points s_t (s_t is an integer of 1 or more) on which light condensing irradiation of the laser light from the spatial light modulator is performed, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity for each of the s_t light condensing points s, as light condensing conditions of the laser light;

a distortion pattern deriving step of deriving a distortion phase pattern containing a phase shift due to distortion in the spatial light modulator to be provided in an optical system to the laser light at the wavelength λ_x for the s_t light condensing points s; and

a modulation pattern designing step of designing the modulation pattern to be presented in the spatial light modulator in consideration of the distortion phase pattern derived in the distortion pattern deriving step, the method wherein

the modulation pattern designing step assumes a plurality of two-dimensionally arrayed pixels in the spatial light modulator, changes a phase value so as to bring a light condensing state closer to a desired state by focusing on an effect on the light condensing state of the laser light on the light condensing point by changing the phase value of one pixel in the modulation pattern to be presented in the plurality of pixels, and performs such phase value changing operations for all the pixels in the modulation pattern, thereby designing the modulation pattern, and

when evaluating the light condensing state on the light condensing point, a propagation function $\phi_{js,x}'$

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

that is, the distortion phase pattern $\phi_{js\text{-}dis,x}$ which is derived in the distortion pattern deriving step is added to a wave propagation function $\phi_{js,x}$ is used for propagation of light at a wavelength λ_x from a pixel j in the modulation pattern of the spatial light modulator to the light condensing point s.

2. The light modulation control method according to claim **1**, wherein the irradiation condition acquiring step sets the number of wavelengths x_t of the laser light to a plural number.

3. The light modulation control method according to claim **1**, wherein the spatial light modulator is configured to be capable of dynamically switching the modulation pattern to be presented.

4. The light modulation control method according to claim **1**, wherein the modulation pattern designing step determines a complex amplitude indicating the light condensing state of the laser light at the wavelength λ_x on the light condensing point s, given that an incident amplitude of the laser light at the wavelength λ_x to the pixel j in the spatial light modulator is $A_{j\text{-}in,x}$, its phase is $\phi_{j\text{-}in,x}$, and a phase value for the laser light at the wavelength λ_x of the pixel j is $\phi_{j,x}$, by the following formula.

$$\begin{aligned} U_{s,x} &= A_{s,x}\exp(i\phi_{s,x}) \\ &= \sum_j A_{j\text{-}in,x}\exp(i\phi'_{js,x})\times\exp\left(i\left(\phi_{j,x}+\phi_{j\text{-}in,x}\right)\right) \end{aligned}$$

5. The light modulation control method according to claim **1**, wherein the modulation pattern designing step changes a phase value according to a value analytically determined based on a phase $\phi_{s,x}$ of a complex amplitude indicating the light condensing state of the laser light at the wavelength λ_x on the light condensing point s, the propagation function $\phi_{js,x}'$, a phase value $\phi_{j,x}$ of the pixel j before change, and an incident phase $\phi_{j\text{-}in,x}$ of the laser light in changing of the phase value of the pixel j in the modulation pattern.

6. The light modulation control method according to claim **1**, wherein the modulation pattern designing step changes a phase value according to a value determined by searching by use of any method of a hill-climbing method, a simulated annealing method, and a genetic algorithm in changing of the phase value of the pixel j in the modulation pattern.

7. A light modulation control program which is for causing a computer to execute light modulation control which controls light condensing irradiation of laser light onto a set light condensing point by a modulation pattern to be presented in a spatial light modulator by use of the phase-modulation type spatial light modulator that inputs the laser light thereto, to modulate a phase of the laser light, and that outputs the phase-modulated laser light, the program causes the computer to execute:

irradiation condition acquiring processing of acquiring the number of wavelengths x_t (x_t is an integer of 1 or more) of the laser light to be input to the spatial light modulator, x_t wavelengths λ_x, and incident conditions of the laser light at each wavelength to the spatial light modulator, as irradiation conditions of the laser light;

light condensing condition setting processing of setting the number of light condensing points s_t (s_t is an integer of 1 or more) on which light condensing irradiation of the laser light from the spatial light modulator is performed, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity for each of the s_t light condensing points s, as light condensing conditions of the laser light;

distortion pattern deriving processing of deriving a distortion phase pattern containing a phase shift due to distortion in the spatial light modulator to be provided in an optical system to the laser light at the wavelength λ_x for the s_t light condensing points s; and

modulation pattern designing processing of designing the modulation pattern to be presented in the spatial light modulator in consideration of the distortion phase pattern derived in the distortion pattern deriving processing, the program wherein

the modulation pattern designing processing assumes a plurality of two-dimensionally arrayed pixels in the spatial light modulator, changes a phase value so as to bring a light condensing state closer to a desired state by focusing on an effect on the light condensing state of the laser light on the light condensing point by changing the phase value of one pixel in the modulation pattern to be presented in the plurality of pixels, and performs such phase value changing operations for all the pixels in the modulation pattern, thereby designing the modulation pattern, and

when evaluating the light condensing state on the light condensing point, a propagation function $_{js,x}'$

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

that is, the distortion phase pattern $\phi_{js\text{-}dis,x}$ which is derived in the distortion pattern deriving processing is added to a wave propagation function $\phi_{js,x}$ is used for propagation of light at a wavelength λ_x from a pixel j in the modulation pattern of the spatial light modulator to the light condensing point s.

8. The light modulation control program according to claim **7**, wherein the irradiation condition acquiring processing sets the number of wavelengths x_t of the laser light to a plural number.

9. The light modulation control program according to claim **7**, wherein the spatial light modulator is configured to be capable of dynamically switching the modulation pattern to be presented.

10. The light modulation control program according to claim **7**, wherein the modulation pattern designing processing determines a complex amplitude indicating the light condensing state of the laser light at the wavelength λ_x on the light condensing point s, given that an incident amplitude of the laser light at the wavelength λ_x to the pixel j in the spatial light modulator is $A_{j\text{-}in,x}$, its phase is $\phi_{j\text{-}in,x}$, and a phase value for the laser light at the wavelength λ_x of the pixel j is $\phi_{j,x}$, by the following formula.

$$U_{s,x} = A_{s,x}\exp(i\phi_{s,x}) = \sum_j A_{j\text{-}in,x}\exp(i\phi'_{js,x})\times\exp\left(i\left(\phi_{j,x}+\phi_{j\text{-}in,x}\right)\right)$$

11. The light modulation control program according to claim **7**, wherein the modulation pattern designing processing changes a phase value according to a value analytically determined based on a phase $\phi_{s,x}$ of a complex amplitude indicating the light condensing state of the laser light at the wavelength λ_x on the light condensing point s, the propagation function $\phi_{js,x}'$, a phase value $\phi_{j,x}$ of the pixel j before change, and an incident phase $\phi_{j\text{-}in,x}$ of the laser light in changing of the phase value of the pixel j in the modulation pattern.

12. The light modulation control program according to claim **7**, wherein the modulation pattern designing processing changes a phase value according to a value determined by searching by use of any method of a hill-climbing method, a simulated annealing method, and a genetic algorithm in changing of the phase value of the pixel j in the modulation pattern.

13. A light modulation control device which controls light condensing irradiation of laser light onto a set light condensing point by a modulation pattern to be presented in a spatial light modulator by use of the phase-modulation type spatial light modulator that inputs the laser light thereto, to modulate a phase of the laser light, and that outputs the phase-modulated laser light, the device comprising:

irradiation condition acquiring means acquiring the number of wavelengths x_t (x_t is an integer of 1 or more) of the laser light to be input to the spatial light modulator, x_t wavelengths λ_x, and incident conditions of the laser light at each wavelength to the spatial light modulator, as irradiation conditions of the laser light;

light condensing condition setting means setting the number of light condensing points s_t (s_t is an integer of 1 or more) on which light condensing irradiation of the laser light from the spatial light modulator is performed, and a light condensing position, a wavelength λ_x of the laser light to be condensed, and a light condensing intensity for each of the s_t light condensing points s, as light condensing conditions of the laser light;

distortion pattern deriving means deriving a distortion phase pattern containing a phase shift due to distortion in the spatial light modulator to be provided in an optical system to the laser light at the wavelength λ_x for the s_t light condensing points s; and

modulation pattern designing means designing the modulation pattern to be presented in the spatial light modulator in consideration of the distortion phase pattern derived in the distortion pattern deriving means, the device wherein the modulation pattern designing means assumes a plurality of two-dimensionally arrayed pixels in the spatial light modulator, changes a phase value so as to bring a light condensing state closer to a desired state by focusing on an effect on the light condensing state of the laser light on the light condensing point by changing the phase value of one pixel in the modulation pattern to be presented in the plurality of pixels, and performs such phase value changing operations for all the pixels in the modulation pattern, thereby designing the modulation pattern, and

when evaluating the light condensing state on the light condensing point, a propagation function $\phi_{js,x}'$

$$\phi_{js,x}'=\phi_{js,x}+\phi_{js\text{-}dis,x}$$

that is, the distortion phase pattern $\phi_{js\text{-}dis,x}$ which is derived in the distortion pattern deriving means is added to a wave propagation function $\phi_{js,x}$ is used for propagation of light at a wavelength λ_x from a pixel j in the modulation pattern of the spatial light modulator to the light condensing point s.

14. The light modulation control device according to claim **13**, wherein the irradiation condition acquiring means sets the number of wavelengths x_t of the laser light to a plural number.

15. The light modulation control device according to claim **13**, wherein the spatial light modulator is configured to be capable of dynamically switching the modulation pattern to be presented.

16. The light modulation control device according to claim **13**, wherein the modulation pattern designing means determines a complex amplitude indicating the light condensing state of the laser light at the wavelength λ_x on the light condensing point s, given that an incident amplitude of the laser light at the wavelength λ_x to the pixel j in the spatial light modulator is $A_{j\text{-}in,x}$, its phase is $\phi_{j\text{-}in,x}$, and a phase value for the laser light at the wavelength λ_x of the pixel j is $\phi_{j,x}$, by the following formula.

$$U_{s,x} = A_{s,x}\exp(i\phi_{s,x}) = \sum_j A_{j\text{-}in,x}\exp(i\phi'_{js,x})\times\exp(i(\phi_{j,x}+\phi_{j\text{-}in,x}))$$

17. The light modulation control device according to claim **13**, wherein the modulation pattern designing means changes a phase value according to a value analytically determined based on a phase $\phi_{s,x}$ of a complex amplitude indicating the light condensing state of the laser light at the wavelength λ_x on the light condensing point s, the propagation function $\phi_{js,x}'$, a phase value $\phi_{j,x}$ of the pixel j before change, and an incident phase $\phi_{j\text{-}in,x}$ of the laser light in changing of the phase value of the pixel j in the modulation pattern.

18. The light modulation control device according to claim **13**, wherein the modulation pattern designing means changes a phase value according to a value determined by searching by use of any method of a hill-climbing method, a simulated annealing method, and a genetic algorithm in changing of the phase value of the pixel j in the modulation pattern.

19. The light modulation control device according to claim **13**, further comprising light modulator drive control means for drive-controlling the spatial light modulator, to present the modulation pattern designed by the modulation pattern designing means in the spatial light modulator.

20. A laser light irradiation device comprising:

a laser light source which supplies laser light with x_t (x_t is an integer of 1 or more) wavelengths λ_x;

a phase-modulation type spatial light modulator which inputs the laser light thereto, to modulate a phase of the laser light, and which outputs the phase-modulated laser light; and

the light modulation control device according to claim **13**, which controls light condensing irradiation of the laser light at each wavelength λ_x onto set s_t (s_t is an integer of 1 or more) light condensing points s by a modulation pattern to be presented in the spatial light modulator.

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