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Optical apparatus

Abstract

An optical apparatus includes a display that displays an image, and an optical system that includes a filter (a reflective polarizing plate) and a lens (a half mirror surface) arranged on a downstream side and an upstream side, respectively, on an optical axis L of a display and magnifies the image by at least the lens (half mirror surface). The optical apparatus drives the lens along the optical axis L with respect to the filter by a mobile device, or changes the surface shape or the lens power of the lens having a variable surface shape or variable lens power. Thus, the optical path is folded back twice between the filter and the lens of the optical system, and the image is magnified by the lens (the half mirror surface), so that the position of the magnified virtual image can be adjusted according to the diopter of the user.

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References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
5479224	12/1994	Yasugaki	N/A	N/A
6421183	12/2001	Ophey	N/A	N/A
2001/0050758	12/2000	Suzuki	348/E5.142	G02B 13/16
2015/0212326	12/2014	Kress	N/A	N/A
2016/0274336	12/2015	Kawamura	N/A	N/A
2017/0336637	12/2016	Van Heugten	N/A	N/A
2017/0358136	12/2016	Gollier	N/A	N/A
2018/0031947	12/2017	Shibuya	N/A	N/A
2018/0239146	12/2017	Bierhuizen	N/A	N/A
2019/0018248	12/2018	Nishiyama	N/A	N/A
2019/0265494	12/2018	Takagi	N/A	N/A
2020/0096817	12/2019	Richards	N/A	N/A
2022/0350121	12/2021	Nishiyama	N/A	N/A

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
1316063	12/2000	CN	N/A
107024773	12/2016	CN	N/A
108227209	12/2017	CN	N/A
110196492	12/2018	CN	N/A
H06194598	12/1993	JP	N/A
H06258561	12/1993	JP	N/A
2000298237	12/1999	JP	N/A
2001305475	12/2000	JP	N/A
2016173398	12/2015	JP	N/A
2016188969	12/2015	JP	N/A
2016194731	12/2015	JP	N/A
6414998	12/2017	JP	N/A
2019507367	12/2018	JP	N/A
2019207342	12/2018	JP	N/A
7103566	12/2021	JP	N/A

2018150773	12/2017	WO	N/A
2019013864	12/2018	WO	N/A

OTHER PUBLICATIONS

Office Action issued for counterpart Chinese Application 201980094743.0, issued by The State Intellectual Property Office of People's Republic of China on Apr. 11, 2024. cited by applicant
International Preliminary Report on Patentability for International Application No. PCT/JP2019/046018, issued by the International Bureau of WIPO on May 12, 2021. cited by applicant
International Search Report and Written Opinion (ISA/237) of the International Search Authority for International Patent Application No. PCT/JP2021/008527, mailed by the Japan Patent Office on May 18, 2021. cited by applicant
Office Action issued for related Japanese Application No. 2021-566311, transmitted from the Japanese Patent Office on Aug. 9, 2022 (drafted on Aug. 3, 2022). cited by applicant
Office Action issued for related Chinese Application 202180004847.5, issued by the State Intellectual Property Office of People's Republic of China on May 24, 2025. cited by applicant

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS
(1) The contents of the following international patent application(s) are incorporated herein by reference: PCT/JP2019/046018 filed on Nov. 25, 2019
BACKGROUND
1. Technical Field
(2) The present invention relates to an optical apparatus that generates a magnified virtual image of an image.
2. Related Art
(3) There is known an optical apparatus adopting an immersive virtual reality (VR) technology in which an image displayed on a display panel is magnified by a thinned triple-pass optical module by folding back two optical paths by two reflection surfaces, and the magnified virtual image is projected (see, for example, Patent Document 1). Patent Document 1: International Publication No. 2018/150773
(4) However, an optical apparatus capable of adjusting the position of the magnified virtual image according to the diopter of a user is not known.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** schematically illustrates a configuration of an optical apparatus according to the present embodiment.
(2) FIG. **2**A illustrates an example of a surface shape of a half mirror surface (HM) of a lens.
(3) FIG. **2**B illustrates an example of a light flux cone angle characteristic after reflection on the half mirror surface (HM) of the lens.
(4) FIG. **3**A illustrates an overall configuration of a mobile device.
(5) FIG. **3**B illustrates an exploded configuration of the mobile device.

(6) FIG. **4**A illustrates the principle (minimum separation state) of lens movement by the mobile device.
(7) FIG. **4**B illustrates the principle (unreeled state) of lens movement by the mobile device.
(8) FIG. **4**C illustrates the principle (maximum separation state) of lens movement by the mobile device.
(9) FIG. **5**A illustrates an overall configuration of a mobile device according to a first modification.
(10) FIG. **5**B illustrates an exploded configuration of the mobile device according to the first modification.
(11) FIG. **6**A illustrates the principle (minimum separation state) of lens movement by the mobile device according to the first modification.
(12) FIG. **6**B illustrates the principle (unreeled state) of lens movement by the mobile device according to the first modification.
(13) FIG. **6**C illustrates the principle (maximum separation state) of lens movement by the mobile device according to the first modification.
(14) FIG. **7**A illustrates an overall configuration of a mobile device according to a second modification.
(15) FIG. **7**B illustrates an exploded configuration of the mobile device according to the second modification.
(16) FIG. **8**A illustrates the principle (minimum separation state) of lens movement by the mobile device according to the second modification.
(17) FIG. **8**B illustrates the principle (unreeled state) of lens movement by the mobile device according to the second modification.
(18) FIG. **8**C illustrates the principle (maximum separation state) of lens movement by the mobile device according to the second modification.
(19) FIG. **9**A illustrates a change in field curvature when a distance (air distance) between a reflective polarizing plate and a half mirror surface is changed (air distance: small).
(20) FIG. **9**B illustrates a field curvature when the distance (air distance) between the reflective polarizing plate and the half mirror surface is changed (air distance: intermedium).
(21) FIG. **9**C illustrates a field curvature when the distance (air distance) between the reflective polarizing plate and the half mirror surface is changed (air distance: large).
(22) FIG. **10**A illustrates a definition of a light beam section in the optical apparatus.
(23) FIG. **10**B illustrates a cone angle of a light beam in each light beam section illustrated in FIG. **10**A.
(24) FIG. **11** illustrates a change in field curvature with respect to air distance in each diopter.
(25) FIG. **12**A illustrates detailed configurations of a diffractive optical element, a lens, and a filter included in the optical apparatuses according to Models **1** to **3**.
(26) FIG. **12**B illustrates detailed configurations of filters A to C.
(27) FIG. **13**A illustrates a detailed design of an optical apparatus according to Example 1.
(28) FIG. **13**B illustrates a lateral aberration detected with respect to +2 diopter in the optical apparatus according to Example 1.
(29) FIG. **13**C illustrates a lateral aberration detected with respect to −1 diopter in the optical apparatus according to Example 1.
(30) FIG. **13**D illustrates a lateral aberration detected with respect to −5 diopter in the optical apparatus according to Example 1.
(31) FIG. **13**E illustrates a spherical aberration detected with respect to +2 diopter in the optical apparatus according to Example 1.
(32) FIG. **13**F illustrates a spherical aberration detected with respect to −1 diopter in the optical apparatus according to Example 1.
(33) FIG. **13**G illustrates a detected spherical aberration with respect to −5 diopter in the optical apparatus according to Example 1.

(34) FIG. **13**H illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to +2 diopter in the optical apparatus according to Example 1.
(35) FIG. **13**I illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −1 diopter in the optical apparatus according to Example 1.
(36) FIG. **13**J illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −5 diopter in the optical apparatus according to Example 1.
(37) FIG. **14**A illustrates a detailed design of an optical apparatus according to Example 2.
(38) FIG. **14**B illustrates a lateral aberration detected with respect to +2 diopter in the optical apparatus according to Example 2.
(39) FIG. **14**C illustrates a lateral aberration detected with respect to −1 diopter in the optical apparatus according to Example 2.
(40) FIG. **14**D illustrates a lateral aberration detected with respect to −5 diopter in the optical apparatus according to Example 2.
(41) FIG. **14**E illustrates a spherical aberration detected with respect to +2 diopter in the optical apparatus according to Example 2.
(42) FIG. **14**F illustrates a spherical aberration detected with respect to −1 diopter in the optical apparatus according to Example 2.
(43) FIG. **14**G illustrates a spherical aberration detected with respect to −5 diopter in the optical apparatus according to Example 2.
(44) FIG. **14**H illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to +2 diopter in the optical apparatus according to Example 2.
(45) FIG. **14**I illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −1 diopter in the optical apparatus according to Example 2.
(46) FIG. **14**J illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −5 diopter in the optical apparatus according to Example 2.
(47) FIG. **15**A illustrates a detailed design of an optical apparatus according to Example 3.
(48) FIG. **15**B illustrates a lateral aberration detected with respect to +2 diopter in the optical apparatus according to Example 3.
(49) FIG. **15**C illustrates a lateral aberration detected with respect to −1 diopter in the optical apparatus according to Example 3.
(50) FIG. **15**D illustrates a lateral aberration detected with respect to −5 diopter in the optical apparatus according to Example 3.
(51) FIG. **15**E illustrates a spherical aberration detected with respect to +2 diopter in the optical apparatus according to Example 3.
(52) FIG. **15**F illustrates a spherical aberration detected with respect to −1 diopter in the optical apparatus according to Example 3.
(53) FIG. **15**G illustrates a spherical aberration detected with respect to −5 diopter in the optical apparatus according to Example 3.
(54) FIG. **15**H illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to +2 diopter in the optical apparatus according to Example 3.
(55) FIG. **15**I illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −1 diopter in the optical apparatus according to Example 3.
(56) FIG. **15**J illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −5 diopter in the optical apparatus according to Example 3.
(57) FIG. **16**A illustrates a detailed design of an optical apparatus according to Example 4.
(58) FIG. **16**B illustrates a lateral aberration detected with respect to +2 diopter in the optical apparatus according to Example 4.
(59) FIG. **16**C illustrates a lateral aberration detected with respect to −1 diopter in the optical apparatus according to Example 4.
(60) FIG. **16**D illustrates a lateral aberration detected with respect to −5 diopter in the optical

apparatus according to Example 4.
(61) FIG. **16**E illustrates a spherical aberration detected with respect to +2 diopter in the optical apparatus according to Example 4.
(62) FIG. **16**F illustrates a spherical aberration detected with respect to −1 diopter in the optical apparatus according to Example 4.
(63) FIG. **16**G illustrates a spherical aberration detected with respect to −5 diopter in the optical apparatus according to Example 4.
(64) FIG. **16**H illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to +2 diopter in the optical apparatus according to Example 4.
(65) FIG. **16**I illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −1 diopter in the optical apparatus according to Example 4.
(66) FIG. **16**J illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −5 diopter in the optical apparatus according to Example 4.
(67) FIG. **17**A illustrates a detailed design of an optical apparatus according to Example 5.
(68) FIG. **17**B illustrates a lateral aberration detected with respect to +2 diopter in the optical apparatus according to Example 5.
(69) FIG. **17**C illustrates a lateral aberration detected with respect to −1 diopter in the optical apparatus according to Example 5.
(70) FIG. **17**D illustrates a lateral aberration detected with respect to −5 diopter in the optical apparatus according to Example 5.
(71) FIG. **17**E illustrates a spherical aberration detected with respect to +2 diopter in the optical apparatus according to Example 5.
(72) FIG. **17**F illustrates a spherical aberration detected with respect to −1 diopter in the optical apparatus according to Example 5.
(73) FIG. **17**G illustrates a spherical aberration detected with respect to −5 diopter in the optical apparatus according to Example 5.
(74) FIG. **17**H illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to +2 diopter in the optical apparatus according to Example 5.
(75) FIG. **17**I illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −1 diopter in the optical apparatus according to Example 5.
(76) FIG. **17**J illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −5 diopter in the optical apparatus according to Example 5.
(77) FIG. **18**A illustrates a detailed design of an optical apparatus according to Example 6.
(78) FIG. **18**B illustrates a lateral aberration detected with respect to +2 diopter in the optical apparatus according to Example 6.
(79) FIG. **18**C illustrates a lateral aberrations detected with respect to −1 diopter in the optical apparatus according to Example 6.
(80) FIG. **18**D illustrates a lateral aberration detected with respect to −5 diopter in the optical apparatus according to Example 6.
(81) FIG. **18**E illustrates a spherical aberration detected with respect to +2 diopter in the optical apparatus according to Example 6.
(82) FIG. **18**F illustrates a spherical aberration detected with respect to −1 diopter in the optical apparatus according to Example 6.
(83) FIG. **18**G illustrates a spherical aberration detected with respect to −5 diopter in the optical apparatus according to Example 6.
(84) FIG. **18**H illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to +2 diopter in the optical apparatus according to Example 6.
(85) FIG. **18**I illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −1 diopter in the optical apparatus according to Example 6.
(86) FIG. **18**J illustrates a field curvature (left diagram) and an image distortion (right diagram)

detected with respect to −5 diopter in the optical apparatus according to Example 6.
(87) FIG. **19**A illustrates a detailed design of an optical apparatus according to Example 7.
(88) FIG. **19**B illustrates a lateral aberration detected with respect to +2 diopter in the optical apparatus according to Example 7.
(89) FIG. **19**C illustrates a lateral aberration detected with respect to −1 diopter in the optical apparatus according to Example 7.
(90) FIG. **19**D illustrates a lateral aberration detected with respect to −5 diopter in the optical apparatus according to Example 7.
(91) FIG. **19**E illustrates a spherical aberration detected with respect to +2 diopter in the optical apparatus according to Example 7.
(92) FIG. **19**F illustrates a spherical aberration detected with respect to −1 diopter in the optical apparatus according to Example 7.
(93) FIG. **19**G illustrates a spherical aberration detected with respect to −5 diopter in the optical apparatus according to Example 7.
(94) FIG. **19**H illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to +2 diopter in the optical apparatus according to Example 7.
(95) FIG. **19**I illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −1 diopter in the optical apparatus according to Example 7.
(96) FIG. **19**J illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −5 diopter in the optical apparatus according to Example 7.
(97) FIG. **20**A illustrates a detailed design of an optical apparatus according to Example 8.
(98) FIG. **20**B illustrates a lateral aberration detected with respect to +2 diopter in the optical apparatus according to Example 8.
(99) FIG. **20**C illustrates a lateral aberration detected with respect to −1 diopter in the optical apparatus according to Example 8.
(100) FIG. **20**D illustrates a lateral aberration detected with respect to −5 diopter in the optical apparatus according to Example 8.
(101) FIG. **20**E illustrates a spherical aberration detected with respect to +2 diopter in the optical apparatus according to Example 8.
(102) FIG. **20**F illustrates a spherical aberration detected with respect to −1 diopter in the optical apparatus according to Example 8.
(103) FIG. **20**G illustrates a spherical aberration detected with respect to −5 diopter in the optical apparatus according to Example 8.
(104) FIG. **20**H illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to +2 diopter in the optical apparatus according to Example 8.
(105) FIG. **20**I illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −1 diopter in the optical apparatus according to Example 8.
(106) FIG. **20**J illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −5 diopter in the optical apparatus according to Example 8.
(107) FIG. **21**A illustrates a detailed design of an optical apparatus according to Example 9.
(108) FIG. **21**B illustrates a lateral aberration detected with respect to +2 diopter in the optical apparatus according to Example 9.
(109) FIG. **21**C illustrates a lateral aberration detected with respect to −1 diopter in the optical apparatus according to Example 9.
(110) FIG. **21**D illustrates a lateral aberration detected with respect to −5 diopter in the optical apparatus according to Example 9.
(111) FIG. **21**E illustrates a spherical aberration detected with respect to +2 diopter in the optical apparatus according to Example 9.
(112) FIG. **21**F illustrates a spherical aberration detected with respect to −1 diopter in the optical apparatus according to Example 9.

(113) FIG. **21**G illustrates a spherical aberration detected with respect to −5 diopter in the optical apparatus according to Example 9.
(114) FIG. **21**H illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to +2 diopter in the optical apparatus according to Example 9.
(115) FIG. **21**I illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −1 diopter in the optical apparatus according to Example 9.
(116) FIG. **21**J illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −5 diopter in the optical apparatus according to Example 9.
(117) FIG. **22**A illustrates a detailed design of an optical apparatus according to Example 10.
(118) FIG. **22**B illustrates the lateral aberrations detected with respect to +2 diopter in the optical apparatus according to Example 10.
(119) FIG. **22**C illustrates a lateral aberration detected with respect to −1 diopter in the optical apparatus according to Example 10.
(120) FIG. **22**D illustrates a lateral aberration detected with respect to −5 diopter in the optical apparatus according to Example 10.
(121) FIG. **22**E illustrates a spherical aberration detected with respect to +2 diopter in the optical apparatus according to Example 10.
(122) FIG. **22**F illustrates a spherical aberration detected with respect to −1 diopter in the optical apparatus according to Example 10.
(123) FIG. **22**G illustrates a spherical aberration detected with respect to −5 diopter in the optical apparatus according to Example 10.
(124) FIG. **22**H illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to +2 diopter in the optical apparatus according to Example 10.
(125) FIG. **22**I illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −1 diopter in the optical apparatus according to Example 10.
(126) FIG. **22**J illustrates a field curvature (left diagram) and an image distortion (right diagram) detected with respect to −5 diopter in the optical apparatus according to Example 10.
(127) FIG. **23** schematically illustrates a configuration of an optical apparatus according to a modification.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

(128) Hereinafter, the present invention will be described through embodiments of the invention, but the following embodiments do not limit the invention according to the claims. In addition, not all combinations of features described in the embodiments are essential to the solution of the invention.
(129) FIG. **1** schematically illustrates a configuration of an optical apparatus **100** according to the present embodiment. The optical apparatus **100** is an apparatus that generates a magnified virtual image of an image, and is used for an immersive virtual reality (VR) technology, for example. The optical apparatus **100** includes a display **110**, a diffractive optical element **200**, an optical system **300**, a control device **390**, and a housing **400**. Note that an image light **50** emitted from the display **110** is guided to an eye (one eye) **30** of a user via the diffractive optical element **200** and the optical system **300**. Here, on an optical axis L of the image light **50**, the display **110** side is referred to as an upstream side, and the user eye **30** side is referred to as a downstream side. The polarized light of the image light **50** is distinguished into a linearly polarized light in the horizontal direction, a linearly polarized light in the vertical direction, a left-turning (also referred to as counterclockwise-turning) circularly polarized light, and a right-turning (also referred to as clockwise-turning) circularly polarized light from the trajectory of the vibration of the electric field when the upstream side is viewed from the downstream side.
(130) The display **110** is a device that displays an image. As the display **110**, for example, a display device including an organic light emitting diode (OLED), a liquid crystal display device including a light source and a liquid crystal panel, or the like can be adopted. The image may be one or more

images forming a still image, a moving image, or the like, or may be a color image including three colors of red, green, and blue. The display **110** emits the image light **50** forming an image from the display surface. In the case of a color image, each color may be emitted in a time-division manner, or may be simultaneously emitted in a manner superimposed on each other or spatially divided in units of pixels.
(131) The diffractive optical element **200** includes a plurality of elements that process the image light **50**. The diffractive optical element **200** is disposed on the downstream side of the display **110** and includes a first GPH element, a first λ/4 plate, a CSF element, a second λ/4 plate, a second GPH element, a third λ/4 plate, a first polarizing plate, and a fourth λ/4 plate (all not illustrated) stacked in order from the upstream side to the downstream side.
(132) The first and second GPH (geometric phase hologram) elements are elements formed by distributing polymerizable liquid crystals in a specific pattern, and exert a lens action (diffusion or light condensing action) by a diffraction phenomenon while changing a polarization direction of incident light to output first-order diffracted light. The first and second GPH elements diffuse and output a light flux of the left-turning circularly polarized light, and condense and output a light flux of the right-turning circularly polarized light when unpolarized light is incident, diffuse and output a light flux while inverting the polarization direction to the left-turning circularly polarized light when the right-turning circularly polarized light is incident, and condense and output a light flux while inverting to the right-turning circularly polarized light when the left-turning circularly polarized light is incident. By using the first and second GPH elements, it is possible to compensate for a wavelength dispersion of a refraction angle with respect to the image light **50** and a chromatic aberration associated therewith.
(133) The first to fourth λ/4 plates are elements that give a phase difference of ¼ wavelength to two polarized components of the image light **50** and modulate the two polarized components. The λ/4 plate modulates a linearly polarized light into a circularly polarized light and a circularly polarized light into a linearly polarized light.
(134) A wavelength-selective polarization conversion (CSF) element is an element that rotates the polarization direction by 90 degrees only in a specific wavelength region. For example, the CSF element modulates a linearly polarized light in the vertical direction to a linearly polarized light in the horizontal direction, and a linearly polarized light in the horizontal direction to a linearly polarized light in the vertical direction.
(135) The first polarizing plate is an element (so-called linearly polarizing plate) that absorbs one of the linearly polarized lights orthogonal to each other and transmits the other. As an example, the first polarizing plate transmits the linearly polarized light in the vertical direction and absorbs the linearly polarized light in the horizontal direction.
(136) The optical system **300** is a triple-pass type optical system which is thinned by folding back the optical path twice by two reflection surfaces, and includes a filter **320** and a lens **310** arranged on the downstream side and the upstream side on the optical axis L, respectively. The optical system **300** diffuses the image light **50** by the lens **310** to magnify the image.
(137) The filter **320** includes a plurality of elements that process the image light **50**. The filter **320** is disposed on the downstream side of the lens **310** and includes a fifth λ/4 plate (not illustrated), a reflective polarizing plate **321**, and a second polarizing plate (not illustrated) stacked in order from the upstream side to the downstream side.
(138) The fifth λ/4 plate is an element that modulates the image light **50** through the lens **310** by giving a phase difference of ¼ wavelength to the two polarized components.
(139) The reflective polarizing plate **321** is an example of a first transmissive/reflective surface, and is an element that reflects one of linearly polarized light orthogonal to each other and transmits the other linearly polarized light. As an example, the reflective polarizing plate **321** transmits the linearly polarized light in the vertical direction and reflects the linearly polarized light in the horizontal direction.

(140) The second polarizing plate **320** is an element that absorbs one of the linearly polarized lights orthogonal to each other and transmits the other. As an example, the second polarizing plate **320** transmits the linearly polarized light in the vertical direction and absorbs the linearly polarized light in the horizontal direction.
(141) The lens **310** is an element that diffuses the image light **50** to magnify an image. The lens **310** is designed to have a diopter (inverse of a focal length value in units of meters) of any value, for example, in a range from −5 to +2. The lens **310** has a half mirror surface **311**, which is an example of a second transmissive/reflective surface, on one surface on the upstream side thereof. The half mirror surface **311** is a curved surface, in particular, an aspherical surface whose curved surface angle increases or decreases according to the distance from the center.
(142) FIG. **2**A illustrates an example of a surface shape of the half mirror surface (HM) **311** of the lens **310**. Here, the solid line indicates the aspherical shape of the half mirror surface (HM) **311** by a surface position Z with respect to the surface radius. The broken line indicates a change amount Δθ of the curved surface angle of the half mirror surface (HM) **311** with respect to the surface radius. In the surface shape of the half mirror surface **311**, the surface position Z is shifted with increasing distance from the center to the outside, but the change amount Δθ of the curved surface angle tends to decrease with increasing distance from the center to the outside.
(143) FIG. **2**B illustrates an example of light flux cone angle characteristics after reflection on the half mirror surface (HM) **311** of the lens **310**. Here, the solid line indicates the light flux cone angle after being reflected on the half mirror surface (HM) **311** with respect to the reflection position. However, the width of the light flux before reflection has been set to 5 mm, and the cone angle has been set to an infinite distance condition (parallel). The broken line indicates the transition of the change amount of the light flux cone angle after being reflected on the half mirror surface (HM) **311** with respect to the reflection position. The light flux cone angle decreases as it goes away from the center of the half mirror surface **311** toward the outside, and the change amount tends to increase.
(144) Since the change amount Δθ of the curved surface angle of the half mirror surface **311** tends to decrease as it goes away from the center toward the outside, the change amount of the light flux cone angle after being reflected on the half mirror surface **311** tends to increase as it goes away from the center toward the outside. As a result, the field curvature can be corrected by moving the half mirror surface **311** in the optical axis direction and changing the reflection position of the image light **50** on the half mirror surface **311** in the surface radial direction.
(145) Note that, instead of the lens **310**, a lens element that exerts a lens action on the image light **50** by combining optical elements including a plurality of lenses may be adopted.
(146) The control device **390** is a device that controls each component of the optical apparatus **100**. The control device **390** may drive the lens **310** in the optical axis L direction by rotating a guide ring **430** of a mobile device **410** to be described later by, for example, a rotary motor, an actuator, or the like (not illustrated) included in the housing **400**.
(147) The control device **390** changes a distortion correction value of the image according to the state of the optical system **300**, for example, the diopter of the optical system **300**. For example, in the triple-pass optical system **300**, a virtual image tends to be distorted in a pincushion shape. Therefore, the control device **390** corrects distortion by causing the display **110** to display a barrel-shaped distortion image by an amount that cancels the pincushion-shaped distortion by the optical system **300**. Here, the distortion of the optical system **300** is measured in advance using a camera or the like, and a distortion amount for generating a barrel-shaped distortion image that cancels the distortion is stored in the control device **390** as a distortion correction value. When the degree of distortion by the optical system **300** is different for each diopter, the distortion is measured for each diopter, and the distortion correction value is stored in the control device **390**. The control device **390** inputs the distortion correction value according to the diopter of the optical system **300** to the display **110**, and causes the display **110** to display the barrel-shaped distortion image according to

the distortion correction value, thereby correcting distortion of the diopter selected by the user.
(148) The housing **400** accommodates the display **110**, the diffractive optical element **200**, and the optical system **300**. The housing **400** holds the mobile device **410** that moves the lens **310** (particularly, the half mirror surface **311**) along the optical axis L with respect to the filter **320** (particularly, the reflective polarizing plate **321**). The position of the magnified virtual image can be changed by moving the lens **310** with respect to the filter **320** to change the folded length of the optical path of the image light **50** therebetween. The configuration of the mobile device **410** will be further described later.
(149) The principle in which the optical apparatus **100** guides the image light **50** of the display **110** to the eye **30** of the user will be described.
(150) The display **110** generates and outputs an unpolarized image light **50**. By making the image light **50** unpolarized, luminance unevenness can be prevented when the image light **50** passes through the first GPH element for correcting the chromatic aberration.
(151) The image light **50** output from the display **110** is incident on the diffractive optical element **200**. In the diffractive optical element **200**, the image light **50** first enters the first GPH element. As a result, one of the ±first-order diffracted lights of the unpolarized image light **50** is diffused and output as a left-turning circularly polarized light, and the other is condensed and output as a right-turning circularly polarized light. Next, the image light **50** enters the first λ/4 plate. As a result, the image light **50** of the left-turning circularly polarized light is modulated into a linearly polarized light in the horizontal direction, and the image light **50** of the right-turning circularly polarized light is modulated into a linearly polarized light in the vertical direction. Next, the image light **50** enters the CSF. As a result, the image light **50** of the linearly polarized light in the horizontal direction in the specific wavelength region is modulated into the linearly polarized light in the vertical direction, and is output together with the image light **50** of the linearly polarized light in the vertical direction outside the specific wavelength region. The image light **50** of the linearly polarized light in the vertical direction in the specific wavelength region is modulated into the linearly polarized light in the horizontal direction, and then removed by the first polarizing plate. Thereby, one of the diffused light and the focused light output from the first GPH element is output from the diffractive optical element **200** according to the wavelength region, that is, the optical path is changed according to the wavelength region, whereby the chromatic aberration is corrected. Hereinafter, only the image light **50** of the linearly polarized light in the vertical direction output from the CSF will be described.
(152) Next, the image light **50** enters the second λ/4 plate. As a result, the image light **50** of the linearly polarized light in the vertical direction is modulated into a left-turning circularly polarized light. Next, the image light **50** enters the second GPH element. As a result, the image light **50** of the left-turning circularly polarized light is modulated into a right-turning circularly polarized light while receiving a light condensing action. Next, the image light **50** enters the third λ/4 plate. As a result, the image light **50** of the right-turning circularly polarized light is modulated into a linearly polarized light in the vertical direction. Next, the image light **50** enters the first polarizing plate. The image light **50** of linearly polarized light in the vertical direction is transmitted through the first polarizing plate, and unnecessary light of the linearly polarized light in the horizontal direction is absorbed by the first polarizing plate. Next, the image light **50** enters the fourth λ/4 plate. As a result, the image light **50** of the linearly polarized light in the vertical direction is modulated into a left-turning circularly polarized light. In this way, the image light **50** is modulated into the left-turning circularly polarized light and the chromatic aberration is compensated, and is output from the diffractive optical element **200** to the downstream side.
(153) Note that, in the optical apparatus **100** according to the present embodiment, the image light **50** modulated into the linearly polarized light in the vertical direction by the first λ/4 plate and the CSF element in the diffractive optical element **200** is used, and the image light **50** modulated into the linearly polarized light in the horizontal direction is removed by the first polarizing plate as

unnecessary light. However, instead of this, the image light **50** modulated into the linearly polarized light in the horizontal direction by the first λ/4 plate and the CSF element in the diffractive optical element **200** may be used, and the image light **50** modulated into the linearly polarized light in the vertical direction may be removed by the first polarizing plate as unnecessary light.
(154) The image light **50** output from the diffractive optical element **200** enters the optical system **300**. In the optical system **300**, the image light **50** is first incident on the lens **310**. As a result, the image light **50** having half the intensity is transmitted through the half mirror surface **311** without depending on the polarization state, is magnified by the lens action and is output to the downstream side, and the image light **50** having the remaining half the intensity is reflected on the half mirror surface **311**.
(155) Next, the image light **50** is incident on the filter **320**. Within the filter **320**, the image light **50** first enters the fifth λ/4 plate. As a result, the image light **50** of the left-turning circularly polarized light is modulated into the linearly polarized light in the horizontal direction. Next, the image light **50** enters the reflective polarizing plate. As a result, the image light **50** of the linearly polarized light in the horizontal direction is reflected. The image light **50** enters the fifth λ/4 plate again. As a result, the image light **50** of the linearly polarized light in the horizontal direction is modulated into the right-turning circularly polarized light. The image light **50** is thus reflected on the filter **320** and output to the upstream side.
(156) The image light **50** is incident on the lens **310** from the downstream side. As a result, the image light **50** is magnified by the lens action, the image light **50** having half the intensity is reflected on the half mirror surface **311** to be further magnified by the lens action, and is output to the downstream side, and the image light **50** having the remaining half intensity is transmitted through the half mirror surface **311**.
(157) The image light **50** is incident on the filter **320** again. Within the filter **320**, the image light **50** first enters the fifth λ/4 plate. As a result, the image light **50** of the right-turning circularly polarized light is modulated into a linearly polarized light in the vertical direction. Next, the image light **50** enters the reflective polarizing plate. The image light **50** of the linearly polarized light in the vertical direction is transmitted through the reflective polarizing plate. Next, the image light **50** enters the second polarizing plate. The image light **50** of linearly polarized light in the vertical direction is transmitted through the second polarizing plate, and unnecessary light of the linearly polarized light in the horizontal direction is absorbed by the second polarizing plate. The diffused image light **50** is output from the filter **320** to the downstream side.
(158) In this way, the image light **50** once passes through the lens **310** in the optical system **300**, is reflected on the filter **320** and reciprocates through the lens **310**, is further subjected to the lens action by the lens **310** to be magnified, is output to the downstream side, and is guided to the eye **30** of the user.
(159) FIG. **3**A and FIG. **3**B illustrate an overall configuration and an exploded configuration of the mobile device **410**, respectively. The mobile device **410** includes a first case **420**, a second case **440**, and a guide ring **430**.
(160) The first case **420** is a housing that accommodates the second case **440** in an internal space **420***a* so as to be unreeled. The first case **420** includes a body portion **421** and first and second flange portions **422** and **423**. The body portion **421** has a cylindrical shape including the internal space **420***a*, and is provided with a slit **421***a* on the side surface to be extended in the axial direction. The first flange portion **422** is formed to protrude outward from one end of the body portion **421**, and extends inward to form a circular opening **422***a* smaller than the inner diameter of the body portion **421**. The second flange portion **423** is formed to protrude outward from the other end of the body portion **421**.
(161) The second case **440** is a housing that accommodates the lens **310** and the like. In the present embodiment, the second case **440** accommodates the display **110**, the diffractive optical element

200, and the lens **310** in order from the near side to the far side in the drawing. The second case **440** is molded in a bottomed cylindrical shape having an outer diameter equal to or slightly smaller than the inner diameter of the body portion **421**, and a guide pin **441** is provided on the side surface.

(162) The guide ring **430** is a member that guides the movement of the second case **440** in the first case **420**. The guide ring **430** has a cylindrical shape having an inner diameter equal to or slightly larger than the outer diameter of the body portion **421**, and a slit **430***a* extending in a spiral shape is provided on the side surface.

(163) The mobile device **410** is assembled as follows. First, while the guide pin **441** of the second case **440** enters the slit **421***a* of the body portion **421**, the second case **440** is inserted into the internal space **420***a* of the first case **420**. The second case **440** is positioned in contact with the inner edge of the first flange portion **422** in the first case **420**. Then, while the guide pin **441** protruding upward from the slit **421***a* of the body portion **421** enters the slit **430***a* of the guide ring **430**, the guide ring **430** is fitted to the outer periphery of the body portion **421** between the first and second flange portions **422** and **423**.

(164) Note that the filter **320** is fixed to the downstream side of the mobile device **410** in the housing **400**.

(165) FIG. **4**A to FIG. **4**C illustrate the principle of lens movement by the mobile device **410**. First, in the state illustrated in FIG. **4**A (minimum separation state), the guide pin **441** is located on one side of the slit **430***a* of the guide ring **430**. At this time, the second case **440** is retracted into the first case **420**. That is, the lens **310** is closest to the filter **320**. Next, as illustrated in FIG. **4**B (unreeled state), by rotating the side surface of the guide ring **430** on the near side in the drawing upward, the guide pin **441** is guided by the spiral slit **430***a* and moves in the slit **421***a* of the body portion **421** to the right side in the drawing, and accordingly, the second case **440** is unreeled from the first case **420** to the right side in the drawing. As illustrated in FIG. **4**C (maximum separation state), the guide pin **441** reaches the other side of the slit **430***a* of the guide ring **430**, so that the second case **440** is most unreeled from the first case **420**. That is, the lens **310** is most separated from the filter **320**. Conversely, by rotating the side surface of the guide ring **430** on the near side in the drawing downward, the guide pin **441** is guided by the spiral slit **430***a* and moves in the slit **421***a* of the body portion **421** to the left side in the drawing, and accordingly, as illustrated in FIG. **4**A (minimum separation state), the second case **440** is retracted into the first case **420**.

(166) Therefore, the mobile device **410** maintains the relative positional relationship among the display **110**, the diffractive optical element **200**, and the lens **310** (the half mirror surface **311**), and relatively moves the display **110**, the diffractive optical element **200**, and the lens **310** with respect to the filter **320** (the reflective polarizing plate **321**).

(167) FIG. **5**A and FIG. **5**B illustrate an overall configuration and an exploded configuration of a mobile device **411** according to a first modification, respectively. The mobile device **411** includes the first case **420**, the second case **440**, a guide ring **431**, and the second flange portion **423**.

(168) The first case **420** includes the body portion **421** and the first flange portion **422** described above.

(169) The second case **440** is configured in a similar manner as described above.

(170) The guide ring **431** has a cylindrical shape having an inner diameter equal to or slightly larger than the outer diameter of the body portion **421**, and is provided, on a side surface, with a slit **431***a* extending in a spiral shape and having one side opening toward one end of the cylinder. Note that one side of the slit **431***a* that opens toward one end of the cylinder is referred to as an opening end, and a portion of the slit **431***a* that extends in a spiral shape is referred to as a spiral portion.

(171) The second flange portion **423** is molded in a ring shape as a member independent from the first case **420** described above. The inner diameter of the second flange portion **423** is equal to the inner diameter of the body portion **421**, and the outer diameter thereof is larger than the outer diameter of the body portion **421**.

(172) The mobile device **411** is assembled as follows. First, while the guide pin **441** of the second case **440** enters the slit **421***a* of the body portion **421**, the second case **440** is inserted into the internal space **420***a* of the first case **420**. The second case **440** is positioned in contact with the inner edge of the first flange portion **422** in the first case **420**. Next, the guide pin **441** protruding upward from the slit **421***a* of the body portion **421** enters the slit **431***a* of the guide ring **431** from the opening end, and the guide ring **431** is rotated with respect to the first case **420** so that the guide pin **441** enters the spiral portion of the slit **431***a*. Finally, the second flange portion **423** is fixed to the end portion of the body portion **421** by adhesion, welding, screwing, or the like. As a result, the guide ring **431** is fitted into the outer periphery of the body portion **421** between the first and second flange portions **422** and **423**.
(173) FIG. **6**A to FIG. **6**C illustrate the principle of lens movement by the mobile device **411**. First, in the state (minimum separation state) illustrated in FIG. **6**A, the guide pin **441** is located on one side of the slit **431***a* of the guide ring **431**. At this time, the second case **440** is retracted into the first case **420**. That is, the lens **310** is closest to the filter **320**. Next, as illustrated in FIG. **6**B (unreeled state), by rotating the side surface of the guide ring **431** on the near side in the drawing upward, the guide pin **441** is guided by the spiral portion of the slit **431***a* and moves in the slit **421***a* of the body portion **421** to the right side in the drawing, and accordingly, the second case **440** is unreeled from the first case **420** to the right side in the drawing. As illustrated in FIG. **6**C (maximum separation state), the guide pin **441** reaches the other side of the slit **431***a* of the guide ring **431**, so that the second case **440** is most unreeled from the first case **420**. That is, the lens **310** is most separated from the filter **320**. Conversely, by rotating the side surface of the guide ring **431** on the near side in the drawing downward, the guide pin **441** is guided by the spiral portion of the slit **431***a* and moves in the slit **421***a* of the body portion **421** to the left side in the drawing, and accordingly, as illustrated in FIG. **6**A (minimum separation state), the second case **440** is retracted into the first case **420**.
(174) Therefore, similarly to the mobile device **410**, the mobile device **411** maintains the relative positional relationship among the display **110**, the diffractive optical element **200**, and the lens **310** (the half mirror surface **311**), and relatively moves the display **110**, the diffractive optical element **200**, and the lens **310** with respect to the filter **320** (the reflective polarizing plate **321**).
(175) FIG. **7**A and FIG. **7**B illustrate an overall configuration and an exploded configuration of a mobile device **412** according to a second modification, respectively. The mobile device **412** includes the first case **420**, the second case **440**, a guide ring **432**, and the second flange portion **423**.
(176) The first case **420**, the second case **440**, and the second flange portion **423** are configured similarly to those in the mobile device **411** according to the first modification described above. However, the guide pin **441** of the second case **440** is formed slightly lower than that of the first modification.
(177) The guide ring **432** has a cylindrical shape having an inner diameter equal to or slightly larger than the outer diameter of the body portion **421**, and a slit **432***a* extending in a spiral shape and a tunnel portion **432***b* having a groove shape provided on the inner surface from one side of the slit **432***a* toward one end of the cylinder are provided on the side surface. The thickness of the tunnel portion **432***b* is thinner than the other portions.
(178) Instead of the slit **432***a*, a spiral groove portion may be formed on the inner surface of the guide ring **432**. The groove portion is connected to the tunnel portion **432***b* on one side thereof. As a result, the second case **440** is sealed in the first case **420** by the guide ring **432**, and mixing of foreign matter such as dust can be prevented.
(179) The mobile device **412** is assembled as follows. First, while the guide pin **441** of the second case **440** enters the slit **421***a* of the body portion **421**, the second case **440** is inserted into the internal space **420***a* of the first case **420**. The second case **440** is positioned in contact with the inner edge of the first flange portion **422** in the first case **420**. Next, the guide pin **441** protruding

upward from the slit **421***a* of the body portion **421** enters the slit **432***a* through the tunnel portion **432***b* of the guide ring **432**, and the guide ring **432** is rotated with respect to the first case **420** to move the guide pin **441** to the back side of the slit **432***a*. Finally, the second flange portion **423** is fixed to the end portion of the body portion **421** by adhesion, welding, screwing, or the like. As a result, the guide ring **432** is fitted into the outer periphery of the body portion **421** between the first and second flange portions **422** and **423**.

(180) FIG. **8**A to FIG. **8**C illustrate the principle of lens movement by the mobile device **412**. First, in the state (minimum separation state) illustrated in FIG. **8**A, the guide pin **441** is located on one side of the slit **432***a* of the guide ring **432**. At this time, the second case **440** is retracted into the first case **420**. That is, the lens **310** is closest to the filter **320**. Next, as illustrated in FIG. **8**B (unreeled state), by rotating the side surface of the guide ring **432** on the near side in the drawing upward, the guide pin **441** is guided by the slit **432***a* and moves in the slit **421***a* of the body portion **421** to the right side in the drawing, and accordingly, the second case **440** is unreeled from the first case **420** to the right side in the drawing. As illustrated in FIG. **8**C (maximum separation state), the guide pin **441** reaches the other side of the slit **432***a* of the guide ring **432**, so that the second case **440** is most unreeled from the first case **420**. That is, the lens **310** is most separated from the filter **320**. Conversely, by rotating the side surface of the guide ring **432** on the near side in the drawing downward, the guide pin **441** is guided by the slit **432***a* and moves in the slit **421***a* of the body portion **421** to the left side in the drawing, and accordingly, as illustrated in FIG. **8**A (minimum separation state), the second case **440** is retracted into the first case **420**.

(181) Therefore, similarly to the mobile device **410**, the mobile device **412** maintains the relative positional relationship among the display **110**, the diffractive optical element **200**, and the lens **310** (the half mirror surface **311**), and relatively moves the display **110**, the diffractive optical element **200**, and the lens **310** with respect to the filter **320** (the reflective polarizing plate **321**).

(182) In the optical apparatus **100**, it is necessary to keep the field curvature of the virtual image displayed at the virtual image position within the focal depth of the optical system **300**. However, in the case of the triple-pass optical system **300**, since the focal depth is shallow, there is a problem that the field curvature does not fall within the focal depth as the diopter of the optical system **300** is changed. Therefore, in the optical apparatus **100** according to the present embodiment, the lens **310** (the half mirror surface **311**) is moved along the optical axis L with respect to the filter **320** (the reflective polarizing plate **321**) by the mobile device **410**, and the field curvature is adjusted by changing the distance between the reflective polarizing plate **321** and the half mirror surface **311**, and it is possible to keep the field curvature within the focal depth for each diopter.

(183) FIG. **9**A to FIG. **9**C illustrate changes in the trajectory of the light beam and the field curvature in a case where the diopter of the optical system **300** is uniquely set, and a distance a (referred to as a spatial distance or an air distance) between the reflective polarizing plate **321** and the half mirror surface **311** is changed by moving the lens **310** (the half mirror surface **311**) along the optical axis L with respect to the filter **320** (the reflective polarizing plate **321**). However, in a light beam reverse tracking simulation, a light beam is drawn from the virtual image position toward the eye box, and retroreflected on the eye box to follow the trajectory of the light beam toward the display **110**, and the curvature of the image plane imaged on the display is analyzed. Note that, in the present example, the diopter of the optical system **300** is set to −3. Each drawing illustrates a light beam (referred to as center light **51**) horizontally reflected from the eye box to the upstream side to reach the center of the display surface of the display **110** and a light beam (referred to as ambient light **52**) reflected obliquely upward from the eye box to the upstream side to reach the upper end of the display **110**.

(184) FIG. **9**A illustrates the trajectory of the light beam and the field curvature on the display surface of the display **110** in the case of the air distance a=1.5 mm. Note that the field curvature is indicated at a position in the optical axis L direction where the light beam is most focused. Here, the solid line indicates the field curvature on the tangential plane, and the broken line indicates the

field curvature on the sagittal plane. The hatched region represents the range of the focal diopter of the optical system **300**, and the field curvature needs to fall within this range. The center light **51** horizontally reflected from the eye box to the upstream side is transmitted through the filter **320**, enters the lens **310**, is reflected at the center of the half mirror surface **311**, is condensed and transmitted to the downstream side, is reflected on the reflective polarizing plate **321** in the filter **320**, is transmitted through the lens **310**, is further condensed, and reaches the center of the display **110** via the diffractive optical element **200**. The ambient light **52** reflected obliquely upward from the eye box to the upstream side passes through the filter **320**, enters the lens **310**, is reflected on the upper side of the half mirror surface **311**, is condensed and transmitted obliquely downward to the downstream side, is reflected on the reflective polarizing plate **321** in the filter **320**, is transmitted through the lens **310**, is further condensed, and reaches the upper end of the display **110** via the diffractive optical element **200**. The image plane tends to be imaged on the downstream side in the periphery relative to the center of the display **110** and somewhat beyond the range of the focal depth.

(185) FIG. **9**B illustrates the trajectory of the light beam and the field curvature on the display surface of the display **110** in the case of the air distance a=1.7 mm. The center light **51** horizontally reflected from the eye box to the upstream side is condensed similarly to the case of the air distance a=1.5 mm, and reaches the center of the display **110** following the same optical path. The ambient light **52** reflected obliquely upward from the eye box to the upstream side passes through the filter **320**, enters the lens **310**, is further reflected on the upper side of the half mirror surface **311**, is condensed and transmitted obliquely downward to the downstream side, is reflected on the reflective polarizing plate **321** in the filter **320**, is transmitted through the lens **310**, is further condensed, and reaches the upper side of the display **110** via the diffractive optical element **200**. The field curvature is small and is within the focal depth.

(186) FIG. **9**C illustrates the trajectory of the light beam and the field curvature on the display surface of the display **110** in the case of the air distance a=1.9 mm. The center light **51** horizontally reflected from the eye box to the upstream side is condensed similarly to the case of the air distance a=1.5 mm, and reaches the center of the display **110** following the same optical path. The ambient light **52** reflected obliquely upward from the eye box to the upstream side passes through the filter **320**, enters the lens **310**, is further reflected on the upper side of the half mirror surface **311**, is condensed and transmitted obliquely downward to the downstream side, is reflected on the reflective polarizing plate **321** in the filter **320**, is transmitted through the lens **310**, is further condensed, and reaches the upper side of the display **110** via the diffractive optical element **200**. The image plane tends to be imaged on the upstream side in the periphery relative to the center of the display **110** and somewhat beyond the range of the focal depth.

(187) FIG. **10**A illustrates a definition of a light beam section in the optical apparatus **100**. Here, a light beam section **1** represents a section from the eye box to the emission surface of the filter **320**, a light beam section **2** represents a section from the incident surface of the filter **320** to the emission surface of the lens **310**, a light beam section **3** represents a section from the emission surface of the lens **310** to the incident surface (the half mirror surface **311**) of the lens **310**, a light beam section **4** represents a section from the incident surface (the half mirror surface **311**) of the lens **310** to the emission surface of the lens **310**, a light beam section **5** represents a section from the emission surface of the lens **310** to the incident surface of the filter **320**, a light beam section **6** represents a section from the incident surface of the filter **320** to the emission surface of the lens **310**, a light beam section **7** represents a section from the emission surface of the lens **310** to the incident surface of the lens **310**, a light beam section **8** represents a section from the incident surface of the lens **310** to the emission surface of the diffractive optical element **200**, and a light beam section **9** represents a section from the incident surface of the diffractive optical element **200** to the emission surface of the display **110**. Note that, although the light beam sections are defined for the ambient light **52** in FIG. **10**A, the center light **51** is also defined in a similar manner.

(188) FIG. **10**B illustrates cone angles of the center light **51** and the ambient light **52** in each of the light beam sections **1** to **9** in the optical apparatus **100** defined in FIG. **10**A. The cone angle of the center light **51** is equal for each of the air distances a=1.5, 1.7, and 1.9 mm, is zero in the light beam sections **1** and **2**, increases in the sections **3** and **4**, that is, is expanded by entering the lens **310**, becomes constant in the sections **5** and **6**, decreases in the section **7**, increases again in the section **8**, and reaches the display **110** at the maximum angle in the section **9**. The behavior of the cone angle of the ambient light **52** is the same as the cone angle of the center light **51**. However, the cone angle of the ambient light **52** varies depending on the air distance after the section **4** in which the ambient light **52** enters the lens **310**. That is, as the air distance increases, the ambient light **52** enters the upper side of the half mirror surface **311**, so that the cone angle decreases, and the ambient light **52** is condensed far. As the air distance decreases, the ambient light **52** enters the lower side of the half mirror surface **311**, so that the cone angle increases, and the ambient light **52** is condensed near.
(189) By changing the air distance, the light flux condensed position around the screen can be changed back and forth with respect to the light flux condensed position at the screen center, thereby adjusting the field curvature. Note that, as illustrated in FIG. **2**B, the change amount of the cone angle increases toward the periphery of the half mirror surface **311**, so that the field curvature can be corrected by changing the air distance.
(190) FIG. **11** illustrates a change in field curvature with respect to the air distance for each of the diopters −5, −3, −1, and +2. The field curvature decreases as the air distance increases, exhibiting a minimum at some air distance, and exhibits behavior that increases as the air distance further increases. For each diopter, there is an air distance at which the field curvature is minimized. Therefore, it can be seen that the field curvature can be minimized more precisely according to the diopter by roughly selecting the diopter according to the diopter of the user, designing the optical system **300**, and moving the optical system **300** with respect to the filter **320**.
(191) FIG. **12**A illustrates detailed configurations of the diffractive optical element **200**, the lens **310**, and the filter **320** included in the optical apparatus **100** according to Models **1** to **3**. In Model **1**, the diffractive optical element **200** is configured by stacking a GPL (GPH lens) element, a filter A, a GPL element, and a filter B in order from the upstream side to the downstream side. The lens **310** is configured by stacking a half mirror and a biconvex lens in order from the upstream side to the downstream side. The filter **320** is configured by stacking a λ/4 plate, a reflective polarizing plate, and a polarizing plate in order from the upstream side to the downstream side. In the optical apparatus **100** according to Model **1**, the diffractive optical element **200** is configured similarly to the diffractive optical element **200** according to the above-described embodiment, and chromatic aberration is suppressed by two GPH elements (GPL elements) and the CSF element. In Model **2**, the diffractive optical element **200** includes a filter C. The lens **310** is configured by stacking a half mirror, a biconvex lens, and a concave meniscus lens in order from the upstream side to the downstream side. The filter **320** is configured similarly to Model **1**. In the optical apparatus **100** according to Model **2**, the diffractive optical element **200** does not include the GPH element (GPL element) and the CSF element, and chromatic aberration is suppressed only by the configuration of the lens **310**. In Model **3**, the diffractive optical element **200** is configured by stacking the GPL element and a filter B in order from the upstream side to the downstream side. The lens **310** is configured similarly to Model **2**. The filter **320** is configured similarly to Model **1**. In the optical apparatus **100** according to Model **3**, the diffractive optical element **200** does not include the CSF element, and chromatic aberration is suppressed only by the GPH element (GPL element).
(192) FIG. **12**B illustrates a detailed configuration of the filters A to C. Each filter is configured by stacking the elements listed in the right column in order from the upstream side to the downstream side.
(193) FIG. **13**A illustrates a detailed design of the optical apparatus **100** according to Example 1. In Example 1, Model **1** of FIG. **12**A is adopted, and the optical apparatus **100** is designed according to

various parameters given to the lens specification, the aspheric coefficient, the GPL data, and the variable interval data. In the optical apparatus **100**, a focal length B is uniquely determined by designing the lens **310** by applying the lens parameter to the lens configuration of Model **1**, and the position of the magnified virtual image can be adjusted according to the diopter of the user by determining a focal length A of the entire optical system **300** by adjusting the air distance or the like. Therefore, it is considered that the detailed configuration of the optical apparatus **100** can be summarized by the ratio A/B of the focal length A of the entire optical system **300** to the focal length B of the lens **310**. In the present example, the ratios A/B are given as 0.183, 0.176, and 0.168 with respect to +2, −1, and −5 diopters, respectively. Note that X diopter indicates a state in which the magnified virtual image by the optical system can be located at a position of 1/X [m] on the optical axis from the eye box. However, the sign is positive when the image is formed on the downstream side of the optical system.

(194) FIG. **13**B, FIG. **13**C, and FIG. **13**D illustrate lateral aberrations detected with respect to +2, −1, and −5 diopters (ratios A/B=0.183, 0.176, and 0.168), respectively, in the optical apparatus **100** according to Example 1. Here, the upper left set of diagrams illustrates the center of the image, the upper right set of diagrams illustrates the center of the upper and lower ends of the image, the lower left set of diagrams illustrates the center of the left and right ends, and the lower right set of diagrams illustrates the aberration at the diagonal. Py and Px are coordinates (full scale: 4 mm) on the aperture plane (at the position of the eye box), and ey and ex are the aberration amount of the tangential plane and the aberration amount of the sagittal plane (full scale is shown in each drawing), respectively. The solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.

(195) FIG. **13**E, FIG. **13**F, and FIG. **13**G illustrate spherical aberrations on the optical axis detected with respect to +2, −1, and −5 diopters (ratios A/B=0.183, 0.176, and 0.168), respectively, in the optical apparatus **100** according to Example 1. Here, the vertical axis represents normalized pupil coordinates (full scale: 4 mm) at the position of the eye box, and the horizontal axis represents the aberration amount. In each drawing, the solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.

(196) FIG. **13**H, FIG. **13**I, and FIG. **13**J illustrate field curvatures (left diagram) and image distortion (right diagram) detected with respect to +2, −1, and −5 diopters (ratios A/B=0.183, 0.176, and 0.168), respectively, in the optical apparatus **100** according to Example 1. Similarly to the field curvature illustrated in FIG. **9**A to FIG. **9**C, the field curvature is illustrated on the horizontal axis with respect to the position (the outermost position is 1.0) to the center on the display surface [**110**] of the vertical axis. The field curvature on the tangential plane and the field curvature on the sagittal plane are shown, respectively. The image distortion is shown on the horizontal axis with respect to the position on the diagonal to the center on the display surface of the vertical axis. In each drawing, the solid line indicates a wavelength of 0.515 μm, the dotted line indicates a wavelength of 0.528 μm, and the alternate long and short dash line indicates the field curvature and the image distortion with respect to a wavelength of 0.544 μm.

(197) In FIG. **13**H (+2 diopter, ratio A/B=0.183), the image plane is imaged on the downstream side in the periphery with respect to the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center of the display **110** on the sagittal plane. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(198) In FIG. **13**I (−1 diopter, ratio A/B=0.176), the image plane is imaged on the somewhat upstream side in the periphery with respect to the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center of the display **110** on

the sagittal plane. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(199) In FIG. **13**J (−5 diopter, ratio A/B=0.168), the image plane is imaged on the downstream side in the periphery with respect to the center of the display **110** on the tangential plane and the sagittal plane. Note that the wavelength dependency of the field curvature is very small. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(200) In the optical apparatus **100** according to Example 1, the field curvature has been within a range of ±0.2 mm with respect to +2, −1, and −5 diopters (ratios A/B=0.183, 0.176, and 0.168), and the image distortion has been about −3% at maximum.

(201) FIG. **14**A illustrates a detailed design of the optical apparatus **100** according to Example 2. In Example 2, Model **1** of FIG. **12**A is adopted, and the optical apparatus **100** is designed according to various parameters given to the lens specification, the aspheric coefficient, the GPL data, and the variable interval data. In the present example, the ratios A/B are given as 0.210, 0.202, and 0.193 with respect to +2, −1, and −5 diopters, respectively.

(202) FIG. **14**B, FIG. **14**C, and FIG. **14**D illustrate lateral aberrations detected with respect to +2, −1, and −5 diopters (ratios A/B=0.210, 0.202, and 0.193), respectively, in the optical apparatus **100** according to Example 2. Here, the upper left set of diagrams illustrates the center of the image, the upper right set of diagrams illustrates the center of the upper and lower ends of the image, the lower left set of diagrams illustrates the center of the left and right ends, and the lower right set of diagrams illustrates the aberration at the diagonal. Py and Px are coordinates (full scale: 4 mm) on the aperture plane (at the position of the eye box), and ey and ex are the aberration amount of the tangential plane and the aberration amount of the sagittal plane (full scale is shown in each drawing), respectively. The solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.

(203) FIG. **14**E, FIG. **14**F, and FIG. **14**G illustrate spherical aberrations on the optical axis detected with respect to +2, −1, and −5 diopters (ratios A/B=0.210, 0.202, and 0.193), respectively, in the optical apparatus **100** according to Example 2. Here, the vertical axis represents normalized pupil coordinates (full scale: 4 mm) at the position of the eye box, and the horizontal axis represents the aberration amount. In each drawing, the solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.

(204) FIG. **14**H, FIG. **14**I, and FIG. **14**J illustrate the field curvature (left diagram) and the image distortion (right diagram) detected with respect to +2, −1, and −5 diopters (ratios A/B=0.210, 0.202, and 0.193), respectively, in the optical apparatus **100** according to Example 2. Similarly to the field curvature illustrated in FIG. **9**A to FIG. **9**C, the field curvature is illustrated on the horizontal axis with respect to the position (the outermost position is 1.0) to the center on the display surface of the vertical axis. The field curvature on the tangential plane and the field curvature on the sagittal plane are shown, respectively. The image distortion is shown on the horizontal axis with respect to the position on the diagonal to the center on the display surface [**110**] of the vertical axis. In each drawing, the solid line indicates a wavelength of 0.515 μm, the dotted line indicates a wavelength of 0.528 μm, and the alternate long and short dash line indicates the field curvature and the image distortion with respect to a wavelength of 0.544 μm.

(205) In FIG. **14**H (+2 diopter, ratio A/B=0.210), the image plane is imaged on the downstream side in the periphery with respect to the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center of the display **110** on the sagittal plane. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(206) In FIG. **14**I (−1 diopter, ratio A/B=0.202), the image plane is imaged on the somewhat upstream side in the periphery with respect to the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center of the display **110** on the sagittal plane. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(207) In FIG. **14**J (−5 diopter, ratio A/B=0.193), the image plane is imaged on the upstream side in the periphery with respect to the center of the display **110** on the tangential plane and the sagittal plane. Note that the wavelength dependency of the field curvature is hardly observed. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(208) In the optical apparatus **100** according to Example 2, the field curvature has been within a range of ±0.2 mm with respect to +2, −1, and −5 diopters (ratios A/B=0.210, 0.202, and 0.193), and the image distortion has been about −3% at maximum.
(209) FIG. **15**A illustrates a detailed design of the optical apparatus **100** according to Example 3. In Example 3, Model **1** of FIG. **12**A is adopted, and the optical apparatus **100** is designed according to various parameters given to the lens specification, the aspheric coefficient, the GPL data, and the variable interval data. In the present example, the ratios A/B are given as 0.283, 0.270, and 0.254 with respect to +2, −1, and −5 diopters, respectively.
(210) FIG. **15**B, FIG. **15**C, and FIG. **15**D illustrate lateral aberrations detected with respect to +2, −1, and −5 diopters (ratios A/B=0.283, 0.270, and 0.254), respectively, in the optical apparatus **100** according to Example 3. Here, the upper left set of diagrams illustrates the center of the image, the upper right set of diagrams illustrates the center of the upper and lower ends of the image, the lower left set of diagrams illustrates the center of the left and right ends, and the lower right set of diagrams illustrates the aberration at the diagonal. Py and Px are coordinates (full scale: 4 mm) on the aperture plane (at the position of the eye box), and ey and ex are the aberration amount of the tangential plane and the aberration amount of the sagittal plane (full scale is shown in each drawing), respectively. The solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(211) FIG. **15**E, FIG. **15**F, and FIG. **15**G illustrate spherical aberrations on the optical axis detected with respect to +2, −1, and −5 diopters (ratios A/B=0.283, 0.270, and 0.254), respectively, in the optical apparatus **100** according to Example 3. Here, the vertical axis represents normalized pupil coordinates (full scale: 4 mm) at the position of the eye box, and the horizontal axis represents the aberration amount. In each drawing, the solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(212) FIG. **15**H, FIG. **15**I, and FIG. **15**J illustrate the field curvature (left diagram) and the image distortion (right diagram) detected with respect to +2, −1, and −5 diopters (ratios A/B=0.283, 0.270, and 0.254), respectively, in the optical apparatus **100** according to Example 3. Similarly to the field curvature illustrated in FIG. **9**A to FIG. **9**C, the field curvature is illustrated on the horizontal axis with respect to the position (the outermost position is 1.0) to the center on the display surface of the vertical axis. The field curvature on the tangential plane and the field curvature on the sagittal plane are shown, respectively. The image distortion is shown on the horizontal axis with respect to the position on the diagonal to the center on the display surface of the vertical axis. In each drawing, the solid line indicates a wavelength of 0.515 μm, the dotted line indicates a wavelength of 0.528 μm, and the alternate long and short dash line indicates the field curvature and the image distortion with respect to a wavelength of 0.544 μm.
(213) In FIG. **15**H (2 diopter, ratio A/B=0.283), the image plane is imaged on the downstream side in the periphery with respect to the center of the display **110** on the tangential plane and the sagittal

plane. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(214) In FIG. **15**I (−1 diopter, ratio A/B=0.270), the image plane is imaged on the somewhat downstream side in the periphery with respect to the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center of the display **110** on the sagittal plane. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(215) In FIG. **15**J (−5 diopter, ratio A/B=0.254), the image plane is imaged on the upstream side in the periphery with respect to the center of the display **110** on the tangential plane, and is hardly distorted on the sagittal plane. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(216) In the optical apparatus **100** according to Example 3, the field curvature has been within a range of ±0.2 mm with respect to +2, −1, and −5 diopters (ratios A/B=0.283, 0.270, and 0.254), and the image distortion has been about −3% at maximum.
(217) FIG. **16**A illustrates a detailed design of the optical apparatus **100** according to Example 4. In Example 4, Model **1** of FIG. **12**A is adopted, and the optical apparatus **100** is designed according to various parameters given to the lens specification, the aspheric coefficient, the GPL data, and the variable interval data. In the present example, the ratios A/B are given as 0.317, 0.299, and 0.279 with respect to +2, −1, and −5 diopters, respectively.
(218) FIG. **16**B, FIG. **16**C, and FIG. **16**D illustrate lateral aberrations detected with respect to +2, −1, and −5 diopters (ratios A/B=0.317, 0.299, and 0.279), respectively, in the optical apparatus **100** according to Example 4. Here, the upper left set of diagrams illustrates the center of the image, the upper right set of diagrams illustrates the center of the upper and lower ends of the image, the lower left set of diagrams illustrates the center of the left and right ends, and the lower right set of diagrams illustrates the aberration at the diagonal. Py and Px are coordinates (full scale: 4 mm) on the aperture plane (at the position of the eye box), and ey and ex are the aberration amount of the tangential plane and the aberration amount of the sagittal plane (full scale is shown in each drawing), respectively. The solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(219) FIG. **16**E, FIG. **16**F, and FIG. **16**G illustrate spherical aberrations on the optical axis detected with respect to +2, −1, and −5 diopters (ratios A/B=0.317, 0.299, and 0.279), respectively, in the optical apparatus **100** according to Example 4. Here, the vertical axis represents normalized pupil coordinates (full scale: 4 mm) at the position of the eye box, and the horizontal axis represents the aberration amount. In each drawing, the solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(220) FIG. **16**H, FIG. **16**I, and FIG. **16**J illustrate the field curvature (left diagram) and the image distortion (right diagram) detected with respect to +2, −1, and −5 diopters (ratios A/B=0.317, 0.299, and 0.279), respectively, in the optical apparatus **100** according to Example 4. Similarly to the field curvature illustrated in FIG. **9**A to FIG. **9**C, the field curvature is illustrated on the horizontal axis with respect to the position (the outermost position is 1.0) to the center on the display surface of the vertical axis. The field curvature on the tangential plane and the field curvature on the sagittal plane are shown, respectively. The image distortion is shown on the horizontal axis with respect to the position on the diagonal to the center on the display surface of the vertical axis. In each drawing, the solid line indicates a wavelength of 0.515 μm, the dotted line indicates a wavelength of 0.528 μm, and the alternate long and short dash line indicates the field curvature and the image distortion with respect to a wavelength of 0.544 μm.
(221) In FIG. **16**H (2 diopter, ratio A/B=0.317), the image plane is imaged on the downstream side

in the periphery with respect to the center of the display **110** on the tangential plane and the sagittal plane. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(222) In FIG. **16**I (−1 diopter, ratio A/B=0.299), the image plane is imaged on the somewhat downstream side in the periphery with respect to the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center of the display **110** on the sagittal plane. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(223) In FIG. **16**J (−5 diopter, ratio A/B=0.279), the image plane is imaged on the upstream side in the periphery with respect to the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center of the display **110** on the sagittal plane. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(224) In the optical apparatus **100** according to Example 4, the field curvature has been within a range of ±0.2 mm with respect to +2, −1, and −5 diopters (ratios A/B=0.317, 0.299, and 0.279), and the image distortion has been about −3% at maximum.

(225) FIG. **17**A illustrates a detailed design of the optical apparatus **100** according to Example 5. In Example 5, Model **2** of FIG. **12**A is adopted, and the optical apparatus **100** is designed according to various parameters given to the lens specification, the aspheric coefficient, the GPL data, and the variable interval data. In the present example, the ratios A/B are given as 0.179, 0.175, and 0.171 with respect to +2, −1, and −5 diopters, respectively.

(226) FIG. **17**B, FIG. **17**C, and FIG. **17**D illustrate lateral aberrations detected with respect to +2, −1, and −5 diopters (ratios A/B=0.179, 0.175, and 0.171), respectively, in the optical apparatus **100** according to Example 5. Here, the upper left set of diagrams illustrates the center of the image, the upper right set of diagrams illustrates the center of the upper and lower ends of the image, the lower left set of diagrams illustrates the center of the left and right ends, and the lower right set of diagrams illustrates the aberration at the diagonal. Py and Px are coordinates (full scale: 4 mm) on the aperture plane (at the position of the eye box), and ey and ex are the aberration amount of the tangential plane and the aberration amount of the sagittal plane (full scale is shown in each drawing), respectively. The solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.

(227) FIG. **17**E, FIG. **17**F, and FIG. **17**G illustrate spherical aberrations on the optical axis detected with respect to +2, −1, and −5 diopters (ratios A/B=0.179, 0.175, and 0.171), respectively, in the optical apparatus **100** according to Example 5. Here, the vertical axis represents normalized pupil coordinates (full scale: 4 mm) at the position of the eye box, and the horizontal axis represents the aberration amount. In each drawing, the solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.

(228) FIG. **17**H, FIG. **17**I, and FIG. **17**J illustrate the field curvature (left diagram) and the image distortion (right diagram) detected with respect to +2, −1, and −5 diopters (ratios A/B=0.179, 0.175, and 0.171), respectively, in the optical apparatus **100** according to Example 5. Similarly to the field curvature illustrated in FIG. **9**A to FIG. **9**C, the field curvature is illustrated on the horizontal axis with respect to the position (the outermost position is 1.0) to the center on the display surface of the vertical axis. The field curvature on the tangential plane and the field curvature on the sagittal plane are shown, respectively. The image distortion is shown on the horizontal axis with respect to the position on the diagonal to the center on the display surface of the vertical axis. In each drawing, the solid line indicates a wavelength of 0.515 μm, the dotted line indicates a wavelength of 0.528 μm, and the alternate long and short dash line indicates the field

curvature and the image distortion with respect to a wavelength of 0.544 μm.
(229) In FIG. **17**H (+2 diopter, ratio A/B=0.179), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently vibrates according to the position from the center of the display **110**, and is imaged on the somewhat upstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(230) In FIG. **17**I (−1 diopter, ratio A/B=0.175), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently vibrates according to the position from the center of the display **110**, and is imaged on the upstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(231) In FIG. **17**J (−5 diopter, ratio A/B=0.171), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the upstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(232) In the optical apparatus **100** according to Example 5, the field curvature has been within a range of ±0.2 mm with respect to +2, −1, and −5 diopters (ratios A/B=0.179, 0.175, and 0.171), and the image distortion has been about −2% at maximum.
(233) FIG. **18**A illustrates a detailed design of the optical apparatus **100** according to Example 6. In Example 6, Model **2** of FIG. **12**A is adopted, and the optical apparatus **100** is designed according to various parameters given to the lens specification, the aspheric coefficient, the GPL data, and the variable interval data. In the present example, the ratios A/B are given as 0.204, 0.201, and 0.196 with respect to +2, −1, and −5 diopters, respectively.
(234) FIG. **18**B, FIG. **18**C, and FIG. **18**D illustrate lateral aberrations detected with respect to +2, −1, and −5 diopters (ratios A/B=0.204, 0.201, and 0.196), respectively, in the optical apparatus **100** according to Example 6. Here, the upper left set of diagrams illustrates the center of the image, the upper right set of diagrams illustrates the center of the upper and lower ends of the image, the lower left set of diagrams illustrates the center of the left and right ends, and the lower right set of diagrams illustrates the aberration at the diagonal. Py and Px are coordinates (full scale: 4 mm) on the aperture plane (at the position of the eye box), and ey and ex are the aberration amount of the tangential plane and the aberration amount of the sagittal plane (full scale is shown in each drawing), respectively. The solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(235) FIG. **18**E, FIG. **18**F, and FIG. **18**G illustrate spherical aberrations on the optical axis detected with respect to +2, −1, and −5 diopters (ratios A/B=0.204, 0.201, and 0.196), respectively, in the optical apparatus **100** according to Example 6. Here, the vertical axis represents normalized pupil coordinates (full scale: 4 mm) at the position of the eye box, and the horizontal axis represents the aberration amount. In each drawing, the solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(236) FIG. **18**H, FIG. **18**I, and FIG. **18**J illustrate the field curvature (left diagram) and the image distortion (right diagram) detected with respect to +2, −1, and −5 diopters (ratios A/B=0.204,

0.201, and 0.196), respectively, in the optical apparatus **100** according to Example 6. Similarly to the field curvature illustrated in FIG. **9**A to FIG. **9**C, the field curvature is illustrated on the horizontal axis with respect to the position (the outermost position is 1.0) to the center on the display surface of the vertical axis. The field curvature on the tangential plane and the field curvature on the sagittal plane are shown, respectively. The image distortion is shown on the horizontal axis with respect to the position on the diagonal to the center on the display surface of the vertical axis. In each drawing, the solid line indicates a wavelength of 0.515 μm, the dotted line indicates a wavelength of 0.528 μm, and the alternate long and short dash line indicates the field curvature and the image distortion with respect to a wavelength of 0.544 μm.
(237) In FIG. **18**H (+2 diopter, ratio A/B=0.204), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the somewhat downstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(238) In FIG. **18**I (−1 diopter, ratio A/B=0.201), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the upstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(239) In FIG. **18**J (−5 diopter, ratio A/B=0.196), the image plane gently varies according to the position from the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the upstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(240) In the optical apparatus **100** according to Example 6, the field curvature has been within a range of ±0.2 mm with respect to +2, −1, and −5 diopters (ratios A/B=0.204, 0.201, and 0.196), and the image distortion has been about −3% at maximum.
(241) FIG. **19**A illustrates a detailed design of the optical apparatus **100** according to Example 7. In Example 7, Model **2** of FIG. **12**A is adopted, and the optical apparatus **100** is designed according to various parameters given to the lens specification, the aspheric coefficient, the GPL data, and the variable interval data. In the present example, the ratios A/B are given as 0.289, 0.280, and 0.269 with respect to +2, −1, and −5 diopters, respectively.
(242) FIG. **19**B, FIG. **19**C, and FIG. **19**D illustrate lateral aberrations detected with respect to +2, −1, and −5 diopters (ratios A/B=0.289, 0.280, and 0.269), respectively, in the optical apparatus **100** according to Example 7. Here, the upper left set of diagrams illustrates the center of the image, the upper right set of diagrams illustrates the center of the upper and lower ends of the image, the lower left set of diagrams illustrates the center of the left and right ends, and the lower right set of diagrams illustrates the aberration at the diagonal. Py and Px are coordinates (full scale: 4 mm) on the aperture plane (at the position of the eye box), and ey and ex are the aberration amount of the tangential plane and the aberration amount of the sagittal plane (full scale is shown in each drawing), respectively. The solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(243) FIG. **19**E, FIG. **19**F, and FIG. **19**G illustrate spherical aberrations on the optical axis detected with respect to +2, −1, and −5 diopters (ratios A/B=0.289, 0.280, and 0.269), respectively, in the

optical apparatus **100** according to Example 7. Here, the vertical axis represents normalized pupil coordinates (full scale: 4 mm) at the position of the eye box, and the horizontal axis represents the aberration amount. In each drawing, the solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.

(244) FIG. **19**H, FIG. **19**I, and FIG. **19**J illustrate the field curvature (left diagram) and the image distortion (right diagram) detected with respect to +2, −1, and −5 diopters (ratios A/B=0.289, 0.280, and 0.269), respectively, in the optical apparatus **100** according to Example 7. Similarly to the field curvature illustrated in FIG. **9**A to FIG. **9**C, the field curvature is illustrated on the horizontal axis with respect to the position (the outermost position is 1.0) to the center on the display surface of the vertical axis. The field curvature on the tangential plane and the field curvature on the sagittal plane are shown, respectively. The image distortion is shown on the horizontal axis with respect to the position on the diagonal to the center on the display surface of the vertical axis. In each drawing, the solid line indicates a wavelength of 0.515 μm, the dotted line indicates a wavelength of 0.528 μm, and the alternate long and short dash line indicates the field curvature and the image distortion with respect to a wavelength of 0.544 μm.

(245) In FIG. **19**H (+2 diopter, ratio A/B=0.289), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the somewhat downstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(246) In FIG. **19**I (−1 diopter, ratio A/B=0.280), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the somewhat downstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(247) In FIG. **19**J (−5 diopter, ratio A/B=0.269), the image plane gently varies according to the position from the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center. On the sagittal plane, the image plane hardly varies with respect to the position from the center of the display **110**, and is imaged at a constant position. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(248) In the optical apparatus **100** according to Example 7, the field curvature has been within a range of ±0.2 mm with respect to +2, −1, and −5 diopters (ratios A/B=0.289, 0.280, and 0.269), and the image distortion has been about −2% at maximum.

(249) FIG. **20**A illustrates a detailed design of the optical apparatus **100** according to Example 8. In Example 8, Model **3** of FIG. **12**A is adopted, and the optical apparatus **100** is designed according to various parameters given to the lens specification, the aspheric coefficient, the GPL data, and the variable interval data. In the present example, the ratios A/B are given as 0.173, 0.170, and 0.166 with respect to +2, −1, and −5 diopters, respectively.

(250) FIG. **20**B, FIG. **20**C, and FIG. **20**D illustrate lateral aberrations detected with respect to +2, −1, and −5 diopters (ratios A/B=0.173, 0.170, and 0.166), respectively, in the optical apparatus **100** according to Example 8. Here, the upper left set of diagrams illustrates the center of the image, the upper right set of diagrams illustrates the center of the upper and lower ends of the image, the lower left set of diagrams illustrates the center of the left and right ends, and the lower right set of

diagrams illustrates the aberration at the diagonal. Py and Px are coordinates (full scale: 4 mm) on the aperture plane (at the position of the eye box), and ey and ex are the aberration amount of the tangential plane and the aberration amount of the sagittal plane (full scale is shown in each drawing), respectively. The solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(251) FIG. **20**E, FIG. **20**F, and FIG. **20**G illustrate spherical aberrations on the optical axis detected with respect to +2, −1, and −5 diopters (ratios A/B=0.173, 0.170, and 0.166), respectively, in the optical apparatus **100** according to Example 8. Here, the vertical axis represents normalized pupil coordinates (full scale: 4 mm) at the position of the eye box, and the horizontal axis represents the aberration amount. In each drawing, the solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(252) FIG. **20**H, FIG. **20**I, and FIG. **20**J illustrate the field curvature (left diagram) and the image distortion (right diagram) detected with respect to +2, −1, and −5 diopters (ratios A/B=0.173, 0.170, and 0.166), respectively, in the optical apparatus **100** according to Example 8. Similarly to the field curvature illustrated in FIG. **9**A to FIG. **9**C, the field curvature is illustrated on the horizontal axis with respect to the position (the outermost position is 1.0) to the center on the display surface of the vertical axis. The field curvature on the tangential plane and the field curvature on the sagittal plane are shown, respectively. The image distortion is shown on the horizontal axis with respect to the position on the diagonal to the center on the display surface [**110**] of the vertical axis. In each drawing, the solid line indicates a wavelength of 0.515 μm, the dotted line indicates a wavelength of 0.528 μm, and the alternate long and short dash line indicates the field curvature and the image distortion with respect to a wavelength of 0.544 μm.
(253) In FIG. **20**H (+2 diopter, ratio A/B=0.173), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the somewhat upstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(254) In FIG. **20**I (−1 diopter, ratio A/B=0.170), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the downstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(255) In FIG. **20**J (−5 diopter, ratio A/B=0.166), the image plane greatly varies according to the position from the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the upstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(256) In the optical apparatus **100** according to Example 8, the field curvature has been within a range of ±0.2 mm with respect to +2, −1, and −5 diopters (ratios A/B=0.173, 0.170, and 0.166), and the image distortion has been about −2% at maximum.
(257) FIG. **21**A illustrates a detailed design of the optical apparatus **100** according to Example 9. In Example 9, Model **3** of FIG. **12**A is adopted, and the optical apparatus **100** is designed according to various parameters given to the lens specification, the aspheric coefficient, the GPL data, and the

variable interval data. In the present example, the ratios A/B are given as 0.215, 0.210, and 0.203 with respect to +2, −1, and −5 diopters, respectively.
(258) FIG. **21**B, FIG. **21**C, and FIG. **21**D illustrate lateral aberrations detected with respect to +2, −1, and −5 diopters (ratios A/B=0.215, 0.210, and 0.203), respectively, in the optical apparatus **100** according to Example 9. Here, the upper left set of diagrams illustrates the center of the image, the upper right set of diagrams illustrates the center of the upper and lower ends of the image, the lower left set of diagrams illustrates the center of the left and right ends, and the lower right set of diagrams illustrates the aberration at the diagonal. Py and Px are coordinates (full scale: 4 mm) on the aperture plane (at the position of the eye box), and ey and ex are the aberration amount of the tangential plane and the aberration amount of the sagittal plane (full scale is shown in each drawing), respectively. The solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(259) FIG. **21**E, FIG. **21**F, and FIG. **21**G illustrate spherical aberrations on the optical axis detected with respect to +2, −1, and −5 diopters (ratios A/B=0.215, 0.210, and 0.203), respectively, in the optical apparatus **100** according to Example 9. Here, the vertical axis represents normalized pupil coordinates (full scale: 4 mm) at the position of the eye box, and the horizontal axis represents the aberration amount. In each drawing, the solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.
(260) FIG. **21**H, FIG. **21**I, and FIG. **21**J illustrate the field curvature (left diagram) and the image distortion (right diagram) detected with respect to +2, −1, and −5 diopters (ratios A/B=0.215, 0.210, and 0.203), respectively, in the optical apparatus **100** according to Example 9. Similarly to the field curvature illustrated in FIG. **9**A to FIG. **9**C, the field curvature is illustrated on the horizontal axis with respect to the position (the outermost position is 1.0) to the center on the display surface of the vertical axis. The field curvature on the tangential plane and the field curvature on the sagittal plane are shown, respectively. The image distortion is shown on the horizontal axis with respect to the position on the diagonal to the center on the display surface of the vertical axis. In each drawing, the solid line indicates a wavelength of 0.515 μm, the dotted line indicates a wavelength of 0.528 μm, and the alternate long and short dash line indicates the field curvature and the image distortion with respect to a wavelength of 0.544 μm.
(261) In FIG. **21**H (+2 diopter, ratio A/B=0.215), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the somewhat downstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(262) In FIG. **21**I (−1 diopter, ratio A/B=0.210), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the upstream side in the periphery with respect to the center. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.
(263) In FIG. **21**J (−5 diopter, ratio A/B=0.203), the image plane gently varies according to the position from the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the upstream side in

the periphery with respect to the center. Note that the wavelength dependency is hardly observed. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(264) In the optical apparatus **100** according to Example 9, the field curvature has been within a range of ±0.2 mm with respect to +2, −1, and −5 diopters (ratios A/B=0.215, 0.210, and 0.203), and the image distortion has been about −2% at maximum.

(265) FIG. **22**A illustrates a detailed design of the optical apparatus **100** according to Example 10. In Example 10, Model **3** of FIG. **12**A is adopted, and the optical apparatus **100** is designed according to various parameters given to the lens specification, the aspheric coefficient, the GPL data, and the variable interval data. In the present example, the ratios A/B are given as 0.301, 0.280, and 0.257 with respect to +2, −1, and −5 diopters, respectively.

(266) FIG. **22**B, FIG. **22**C, and FIG. **22**D illustrate lateral aberrations detected with respect to +2, −1, and −5 diopters (ratios A/B=0.301, 0.280, and 0.257), respectively, in the optical apparatus **100** according to Example 10. Here, the upper left set of diagrams illustrates the center of the image, the upper right set of diagrams illustrates the center of the upper and lower ends of the image, the lower left set of diagrams illustrates the center of the left and right ends, and the lower right set of diagrams illustrates the aberration at the diagonal. Py and Px are coordinates (full scale: 4 mm) on the aperture plane (at the position of the eye box), and ey and ex are the aberration amount of the tangential plane and the aberration amount of the sagittal plane (full scale is shown in each drawing), respectively. The solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.

(267) FIG. **22**E, FIG. **22**F, and FIG. **22**G illustrate spherical aberrations on the optical axis detected with respect to +2, −1, and −5 diopters (ratios A/B=0.301, 0.280, and 0.257), respectively, in the optical apparatus **100** according to Example 10. Here, the vertical axis represents normalized pupil coordinates (full scale: 4 mm) at the position of the eye box, and the horizontal axis represents the aberration amount. In each drawing, the solid line indicates an aberration with respect to a wavelength of 0.515 μm, the dotted line indicates an aberration with respect to a wavelength of 0.528 μm, and the alternate long and short dash line indicates aberration with respect to a wavelength of 0.544 μm.

(268) FIG. **22**H, FIG. **22**I, and FIG. **22**J illustrate the field curvature (left diagram) and the image distortion (right diagram) detected with respect to +2, −1, and −5 diopters (ratios A/B=0.301, 0.280, and 0.257), respectively, in the optical apparatus **100** according to Example 10. Similarly to the field curvature illustrated in FIG. **9**A to FIG. **9**C, the field curvature is illustrated on the horizontal axis with respect to the position (the outermost position is 1.0) to the center on the display surface [**110**] of the vertical axis. The field curvature on the tangential plane and the field curvature on the sagittal plane are shown, respectively. The image distortion is shown on the horizontal axis with respect to the position on the diagonal to the center on the display surface [**110**] of the vertical axis. In each drawing, the solid line indicates a wavelength of 0.515 μm, the dotted line indicates a wavelength of 0.528 μm, and the alternate long and short dash line indicates the field curvature and the image distortion with respect to a wavelength of 0.544 μm.

(269) In FIG. **22**H (+2 diopter, ratio A/B=0.301), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the downstream side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the downstream side in the periphery with respect to the center. Note that the wavelength dependency is hardly observed. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(270) In FIG. **22**I (−1 diopter, ratio A/B=0.280), the image plane greatly vibrates according to the position from the center of the display **110** on the tangential plane, and is imaged on the upstream

side in the periphery with respect to the center. On the sagittal plane, the image plane gently varies according to the position from the center of the display **110**, and is imaged on the somewhat downstream side in the periphery with respect to the center. Note that the wavelength dependency is hardly observed. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(271) In FIG. **22**J (−5 diopter, ratio A/B=0.257), the image plane gently varies according to the position from the center of the display **110** on the tangential plane, and is imaged on the upstream side in the periphery with respect to the center. On the sagittal plane, the image plane hardly varies, and is imaged at an almost constant position. Note that the wavelength dependency is hardly observed. The image distortion shows a negative distortion with respect to the center of the display **110**, that is, the image is distorted in a barrel shape.

(272) In the optical apparatus **100** according to Example 10, the field curvature has been within a range of ±0.2 mm with respect to +2, −1, and −5 diopters (ratios A/B=0.301, 0.280, and 0.257), and the image distortion has been about −2% at maximum.

(273) From the results of the field curvature and the image distortion in Examples 1 to 10, by setting the ratio A/B of the total focal length A of the optical system **300** to the focal length B of the lens **310** within the range of 0.166 to 0.317, or by setting the ratio A/B to the +2 diopter within the range of 0.173 to 0.317, the ratio A/B to the −1 diopter within the range of 0.170 to 0.299, and the ratio A/B to the −5 diopter within the range of 0.166 to 0.279, it is possible to obtain good imaging characteristics regardless of the detailed design of the lens **310** and regardless of the detailed design of the diffractive optical element **200** such as the presence or absence of chromatic aberration correction by the GPH element (GPL element) and the CSF element.

(274) Note that, regarding Examples 1 to 4 for the optical apparatus **100** designed by adopting Model **1** in FIG. **12**A, when the result of Example 2 is compared with the result of Example 1, the lateral aberration, the spherical aberration, the field curvature, and the image distortion are relatively good, and when the result of Example 3 is compared with the result of Example 4, the lateral aberration, the spherical aberration, the field curvature, and the image distortion are relatively good. Therefore, it can be seen that there is a range in which good imaging characteristics can be obtained at the ratio A/B of the total focal length A of the optical system **300** to the focal length B of the lens **310**, and relatively good imaging characteristics can be obtained with respect to the outside of the range within the above range.

(275) Note that, the optical apparatus **100** according to the present embodiment has maintained the relative positional relationship among the display **110**, the diffractive optical element **200**, and the lens **310** (the half mirror surface **311**) by the mobile device **410**, and has relatively moved the display **110**, the diffractive optical element **200**, and the lens **310** with respect to the filter **320** (the reflective polarizing plate **321**). However, a configuration in which the display **110**, the diffractive optical element **200**, the lens **310**, and the filter **320** are further moved may be adopted as long as the separation distance between at least the filter **320** (the reflective polarizing plate **321**) and the lens **310** (the half mirror surface **311**) can be changed. For example, the lens **310** may be moved with respect to the filter **320** and the display **110** may be moved with respect to the lens **310**. Not limited to this, the relative position of the filter **320** and the lens **310** may be maintained, and the display **110** may be moved with respect to these.

(276) The optical apparatus **100** according to the present embodiment includes the display **110** that displays an image, the optical system **300** that includes the filter **320** (the reflective polarizing plate **321**) and the lens **310** (the half mirror surface **311**) respectively arranged on the downstream side and the upstream side on the optical axis L of the display **110** and magnifies an image by at least the lens **310** (the half mirror surface **311**), and the mobile device **410** that moves at least one of the filter **320**, the lens **310**, and the display **110** along the optical axis L. As a result, the optical path is folded back twice between the filter **320** and the lens **310** of the optical system **300**, and the image is magnified by the lens **310** (the half mirror surface **311**), so that the position of the magnified

virtual image can be adjusted according to the diopter of the user.
(277) The optical system **300** and the mobile device **410** in the optical apparatus **100** according to the present embodiment are examples of a diopter optical system and a diopter adjustment mechanism that adjust the position of the magnified virtual image according to the eyesight of the user, and the optical apparatus **100** has high optical performance in the diopter adjustment range with a small size, a light size, and a small thickness by including the optical system and the mobile device.
(278) Note that the optical apparatus **100** according to the present embodiment moves the lens **310** (the half mirror surface **311**) relatively to the filter **320** (the reflective polarizing plate **321**), but a lens having a variable surface shape or variable lens power may be adopted instead of the movable lens **310**.
(279) FIG. **23** schematically illustrates a configuration of an optical apparatus **101** according to a modification. The optical apparatus **100** includes a display **110**, a diffractive optical element **200**, an optical system **300**, a control device **390**, and a housing **400**.
(280) The display **110** and the diffractive optical element **200** are configured in the similar manner to those according to the embodiment described above.
(281) The optical system **300** is a triple-pass type optical system which is thinned by folding back the optical path twice by two reflection surfaces, and includes the filter **320** and a lens **330** arranged on the downstream side and the upstream side on the optical axis L, respectively. The optical system **300** diffuses the image light **50** to magnify the image by changing the variable surface shape or the lens power of the lens **330**.
(282) The filter **320** is configured similarly to that according to the embodiment described above.
(283) As the lens **330**, for example, a liquid lens that realizes a variable surface shape by changing a boundary surface shape between liquids having different refractive indexes by adjusting an applied voltage can be adopted. In such a case, a half mirror surface **331**, which is an example of the second transmissive/reflective surface, is provided on the end surface on the upstream side of the lens **330**. Here, the variable surface shape is formed in an aspherical surface shape in which the curved surface angle increases or decreases according to the distance from the center. For example, as illustrated in FIG. **2**A, the surface position Z is shifted with increasing distance from the center to the outside, but the change amount $\Delta\theta$ of the curved surface angle may be formed in a surface shape that tends to decrease with increasing distance from the center to the outside.
(284) As the lens **330**, a liquid crystal lens that realizes variable lens power by controlling the orientation of the liquid crystal by adjusting the applied voltage and effectively changing the refractive index can be adopted. In such a case, a half mirror surface **331**, which is an example of the second transmissive/reflective surface, is provided on the end surface on the upstream side of the lens **330**. Here, the variable lens power is generated so as to correspond to an aspherical surface whose curved surface angle increases or decreases according to the distance from the center. For example, as illustrated in FIG. **2**A, the surface position Z is shifted with increasing distance from the center to the outside, but the change amount $\Delta\theta$ of the curved surface angle may be generated so as to correspond to a surface shape that tends to decrease with increasing distance from the center to the outside.
(285) The control device **390** is a device that controls each component of the optical apparatus **101**. The control device **390** adjusts the applied voltage of the lens **330** to control the variable surface shape or the variable lens power.
(286) The housing **400** accommodates the display **110**, the diffractive optical element **200**, and the optical system **300**.
(287) The principle in which the optical apparatus **101** guides the image light **50** of the display **110** to the eye **30** of the user will be described.
(288) The display **110** generates an unpolarized image light **50**.
(289) The image light **50** output from the display **110** is incident on the diffractive optical element

200. The image light **50** is modulated into right-turning circularly polarized light and the chromatic aberration is compensated. The light is output from the diffractive optical element **200** to the downstream side. Details are similar to those of the embodiment described above.

(290) The image light **50** output from the diffractive optical element **200** enters the optical system **300**. In the optical system **300**, the image light **50** is first incident on the lens **330**. As a result, the image light **50** having half the intensity is transmitted through the half mirror surface **331** without depending on the polarization state, is magnified by the lens action and is output to the downstream side, and the image light **50** having the remaining half the intensity is reflected on the half mirror surface **331**.

(291) Next, the image light **50** is incident on the filter **320**. The image light **50** is modulated into a left-turning circularly polarized light, reflected, and output from the filter **320** to the upstream side. Details are similar to those of the embodiment described above.

(292) The image light **50** is incident on the lens **330** from the downstream side. As a result, the image light **50** is magnified by the lens action, the image light **50** having half the intensity is reflected on the half mirror surface **331**, further magnified by the lens action, and output to the downstream side, and the image light **50** having the remaining half the intensity is transmitted through the half mirror surface **331**.

(293) The image light **50** is incident on the filter **320** again. The image light **50** is modulated into a linearly polarized light in the horizontal direction, transmitted through the filter **320**, and is output to the downstream side. Details are similar to those of the embodiment described above.

(294) After passing through the lens **330** once in the optical system **300**, the image light **50** is reflected on the filter **320** and reciprocates through the lens **330**, further subjected to a lens action by the lens **330** to be magnified, output to the downstream side, and guided to the eye **30** of the user.

(295) Note that the optical apparatus **100** according to the present embodiment magnifies the image light **50** of the display **110** and guides the image light to one eye **30** of the user to adjust the position of the magnified virtual image. That is, the optical apparatus **100** includes the diffractive optical element **200** and the optical system **300** only for one eye **30** of the left eye and the right eye. The binocular optical apparatus may be configured by providing the optical apparatus **100** having such a configuration, that is, the diffractive optical element **200** and the optical system **300** for each of the both eyes **30**.

(296) Note that the optical apparatus **100** according to the present embodiment has been configured to employ an immersive virtual reality (VR) technology to magnify the image light **50** of the display **110** and guide the image light to the user's eye **30**, but may be configured to employ an augmented reality (AR) technology to superimpose the image light **50** of the display **110** and the external light and guide the superimposed light to the user's eye **30**.

(297) While the embodiments of the present invention have been described, the technical scope of the invention is not limited to the above described embodiments. It is apparent to persons skilled in the art that various alterations and improvements can be added to the above-described embodiments. It is also apparent from the scope of the claims that the embodiments added with such alterations or improvements can be included in the technical scope of the invention.

(298) The operations, procedures, steps, and stages of each process performed by an apparatus, system, program, and method shown in the claims, embodiments, or diagrams can be performed in any order as long as the order is not indicated by “prior to,” “before,” or the like and as long as the output from a previous process is not used in a later process. Even if the process flow is described using phrases such as “first” or “next” in the claims, embodiments, or diagrams, it does not necessarily mean that the process must be performed in this order.

(299) As is clear from the above description, according to (one) embodiment of the present invention, an optical apparatus can be realized.

Claims

1. An optical apparatus that generates a magnified virtual image of an image, the optical apparatus comprising: a display configured to output an image light for forming an image; an optical system configured to magnify the image, the optical system including: a first transmissive/reflective surface and a second transmissive/reflective surface that are arranged on an eye point side and a display side, respectively, on an optical axis of the display; and a lens element in which the second transmissive/reflective surface is provided on one surface on the display side, wherein the first transmissive/reflective surface transmits or reflects at least a part of the image light, and the second transmissive/reflective surface is an aspherical curved surface in which a change amount of a curved surface angle continuously increases or decreases according to a distance from a center, and transmits or reflects at least a part of the image light; and a mobile device configured to relatively move at least the second transmissive/reflective surface along the optical axis with respect to the first transmissive/reflective surface.
2. The optical apparatus according to claim 1, wherein the mobile device is further configured to move the display while maintaining a relative positional relationship with the second transmissive/reflective surface.
3. The optical apparatus according to claim 1, wherein the first transmissive/reflective surface is configured to reflect at least a part of the image light transmitted through the second transmissive/reflective surface, and transmit at least a part of the image light reflected on the second transmissive/reflective surface.
4. The optical apparatus according to claim 3, wherein the first transmissive/reflective surface is a polarizing element that reflects one of linearly polarized lights orthogonal to each other and transmits the other.
5. The optical apparatus according to claim 4, wherein the first transmissive/reflective surface is a flat surface.
6. The optical apparatus according to claim 1, wherein the second transmissive/reflective surface transmits at least a part of the image light sent from the display, and reflects a part of the image light reflected on the first transmissive/reflective surface and returned.
7. The optical apparatus according to claim 5, wherein the second transmissive/reflective surface is a half mirror surface.
8. The optical apparatus according to claim 7, wherein the change amount of the curved surface angle of the second transmissive/reflective surface continuously decreases from 1.1 degrees to 0.4 degrees from the center to an outer edge.
9. The optical apparatus according to claim 8, wherein a ratio of a focal length of the optical system to a focal length of the lens element ranges from 0.166 to 0.317.
10. The optical apparatus according to claim 9, wherein the ratio ranges from 0.173 to 0.317 with respect to +2 diopter, from 0.170 to 0.299 with respect to −1 diopter, and from 0.166 to 0.279 with respect to −5 diopter.
11. The optical apparatus according to claim 1, further comprising: a diffractive optical element disposed between the display and the second transmissive/reflective surface.
12. The optical apparatus according to claim 11, wherein the diffractive optical element includes a GPH element that compensates for wavelength dispersibility of the optical system.
13. The optical apparatus according to claim 12, wherein the diffractive optical element includes an unnecessary light removal element that removes an unnecessary light on the eye point side of the GPH element.
14. The optical apparatus according to claim 13, wherein the unnecessary light removing element includes a $\lambda/4$ plate and a linearly polarizing plate.
15. The optical apparatus according to claim 1, further comprising: a control device configured to

change a distortion correction value of the image according to a state of the optical system.
16. The optical apparatus according to claim 1, further comprising: a housing configured to accommodate the display and the optical system, wherein the first transmissive/reflective surface is held by the housing, and the second transmissive/reflective surface moves along the optical axis in the housing.
17. The optical apparatus according to claim 2, wherein the first transmissive/reflective surface is configured to reflect at least a part of the image light transmitted through the second transmissive/reflective surface, and transmit at least a part of the image light reflected on the second transmissive/reflective surface.
18. The optical apparatus according to claim 2, wherein the second transmissive/reflective surface transmits at least a part of the image light sent from the display, and reflects a part of the image light reflected on the first transmissive/reflective surface and returned.
19. The optical apparatus according to claim 2, further comprising: a diffractive optical element disposed between the display and the second transmissive/reflective surface.
20. The optical apparatus according to claim 2, further comprising: a control device configured to change a distortion correction value of the image according to a state of the optical system.