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United States Patent Application Publication	20250258364
Kind Code	A1
Publication Date	August 14, 2025
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OPTICAL SYSTEM AND IMAGE DISPLAY APPARATUS

Abstract

An optical system is configured to guide light from a display element to an observation side, and includes a transmissive reflective surface, a polarization separation surface, a polarizing element, and a lens including a resin material. The transmissive reflective surface or the polarization separation surface and the polarizing element are integrated with each other to form an optical unit. The optical unit and the lens are cemented to each other via a first adhesive layer. The light transmits through the first adhesive layer a plurality of times. Predetermined inequalities are satisfied.

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Family ID: **1000008448664**

Appl. No.: **19/047722**

Filed: **February 07, 2025**

Foreign Application Priority Data

JP	2024-019913	Feb. 14, 2024

Publication Classification

Int. Cl.: **G02B17/08** (20060101)

U.S. Cl.:

CPC **G02B17/08** (20130101);

Background/Summary

BACKGROUND

Technical Field

[0001] The disclosure relates to an optical system suitable for an image display apparatus such as a head mount display (HMD) that displays an enlarged original image displayed on a display element.

Description of Related Art

[0002] As an example of such an optical system, Japanese Patent Laid-Open Nos. 2000-275566 and 2019-148626 disclose an optical system that folds an optical path by using polarization, and includes an optical unit adhered to a lens, in which a polarization selection element (polarization separation element), a half-mirror, a phase plate, a polarizing plate, etc. are laminated.

SUMMARY

[0003] An optical system according to one aspect of the disclosure is configured to guide light from a display element to an observation side, and includes a transmissive reflective surface, a polarization separation surface, a polarizing element, and a lens including a resin material. The transmissive reflective surface or the polarization separation surface and the polarizing element are integrated with each other to form an optical unit. The optical unit and the lens are cemented to each other via a first adhesive layer. The light transmits through the first adhesive layer a plurality of times. The following inequalities are satisfied:

[00001] $0.009 < N2 \times d1 < 0.031$ $0.95 \leq N1 / N2 \leq 1.1$

where d1 (mm) is a thickness of the first adhesive layer, N1 is a refractive index of the lens for d-line, and N2 is a refractive index of the first adhesive layer for the d-line. An image display apparatus having the above optical system also constitutes another aspect of the disclosure.

[0004] Further features of various embodiments of the disclosure will become apparent from the following description of embodiments with reference to the attached drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. **1** illustrates the configuration of an image display apparatus having an optical system according to a first embodiment.

[0006] FIG. **2** illustrates the configuration of the optical system according to the first embodiment.

[0007] FIG. **3** is an optical path diagram of the optical system according to the first embodiment.

[0008] FIG. **4** is an enlarged view illustrating the configuration of a cemented portion between an optical unit and a lens in the optical system according to the first embodiment.

[0009] FIG. **5** illustrates the configuration of an image display apparatus having an optical system according to a second embodiment.

[0010] FIG. **6** illustrates the configuration of the optical system according to the second embodiment.

[0011] FIG. **7** is an optical path diagram of the optical system according to the second embodiment.

[0012] FIG. **8** is an enlarged view illustrating the configuration of a cemented portion between an optical unit and a lens in the optical system according to the second embodiment.

[0013] FIG. **9** illustrates the configuration of an image display apparatus having an optical system according to a third embodiment.

[0014] FIG. **10** illustrates the configuration of the optical system according to the third embodiment.

[0015] FIG. **11** is an optical path diagram of the optical system according to the third embodiment.

[0016] FIG. **12** is an enlarged view illustrating the configuration of a cemented portion between an optical unit and a lens in the optical system according to the third embodiment.

[0017] FIG. **13** is an enlarged view illustrating the configuration of a PBS and a cemented portion between a phase plate and a lens in the optical system according to the third embodiment.
[0018] FIG. **14** is an external view of the image display apparatus according to FIG. **1**.
DETAILED DESCRIPTION
[0019] Referring now to the accompanying drawings, a description will be given of embodiments according to the disclosure.
First Embodiment
Image Display Apparatus
[0020] FIG. **1** illustrates a head mount display (HMD) **101** as an image display apparatus using an optical system (display optical system, observation optical system, eyepiece optical system) according to a first embodiment, viewed from above. Reference numeral **102** denotes a right eye of an observer (observer's right eye), and reference numeral **103** denotes a left eye of the observer (observer's left eye). Lenses **104** to **106** constitute a part of the right-eye optical system, and lenses **107** to **109** constitute a part of the left-eye optical system. Reference numeral **110** denotes a right-eye display element, and reference numeral **111** denotes a left-eye display element, each of which is constituted by an organic electro-luminescence (EL) element that emits unpolarized light.
[0021] The right-eye optical system enlarges light (virtual image) from an original image displayed on the right-eye display element **110** and directs it to the right eye **102**, and the left-eye optical system enlarges light from an original image displayed on the left-eye display element **111** and directs it to the left eye **103**.
[0022] Each of the right-eye optical system and the left-eye optical system has a focal length f of 17 mm, a horizontal display angle of view of 60°, a vertical display angle of view of 60°, and a diagonal display angle of view $2\times\theta 1$ of 72°. A distance (eye relief) between the HMD **101** and the observer's eyeball is 12 mm.
Optical System
[0023] The optical system according to The first embodiment is an optical system that folds the optical path utilizing polarization, and FIG. **2** illustrates an enlarged view of the right-eye optical system. In addition to the lenses **104** to **106**, the right-eye optical system further includes a first polarizing plate **112** and a first phase plate **113**, arranged in this order from the display element side between the right-eye display element **110** and the first lens **106**, and the right-eye optical system further includes a half-mirror **114** evaporated on a display-element-side surface of the second lens **105**. Each of the first polarizing plate **112** and the first phase plate **113** has a planar shape, and they are laminated and adhered to the right-eye display element **110**. The half-mirror **114** functions as a transmissive reflective surface disposed between cemented surfaces of the first lens **106** and the second lens **105**. That is, the first lens **106** and the second lens **105** are configured as a cemented lens in which the half-mirror **114** is sandwiched between the cemented surfaces. The ratio of the transmittance and reflectance of the half-mirror **114** may be 50:50, but the ratio may be changed, as necessary.
[0024] The right-eye optical system includes, in order from the display element side between the second lens **105** and the third lens **104**, a second phase plate **115**, a polarization separation element (polarization beam splitter: PBS) **116**, and a second polarizing plate **117**. Each of the second phase plate **115**, the PBS **116**, and the second polarizing plate **117** has a planar shape, and they are laminated and adhered together to form a laminated optical functional element (referred to as an optical unit hereinafter). The PBS **116** functions as a polarization separation surface.
[0025] The first polarizing plate **112**, the first phase plate **113**, the second phase plate **115**, and the second polarizing plate **117** correspond to a plurality of polarizing elements.
[0026] Each of the first phase plate **113** and the second phase plate **115** is a waveplate with a phase difference of $\lambda/4$ (quarter waveplate). The polarization direction of the polarized light that transmits through the first polarizing plate **112** and the slow axis of the first phase plate **113** are tilted by 45°, and the polarization direction of the polarized light that transmits through the first polarizing plate

112 and the slow axis of the second phase plate **115** are tilted by −45°. The polarization direction of the polarized light that transmits through the first polarizing plate **112** and the polarization direction of the polarized light that transmits through the PBS **116** are orthogonal to each other. The polarization direction of the polarized light that transmits through the second polarizing plate **117** and the polarization direction of the polarized light that transmits through the PBS **116** coincide with each other.

[0027] In the right-eye optical system, a third lens **104** is disposed between the optical unit that includes the second phase plate **115**, the PBS **116**, and the second polarizing plate **117**, and the exit pupil where the right eye **102** is disposed.

[0028] FIG. **3** illustrates the optical path of the right-eye optical system configured as described above. The unpolarized light emitted from the right-eye display element **110** transmits through the first polarizing plate **112** and becomes linearly polarized light, and the linearly polarized light transmits through the first phase plate **113** and becomes circularly polarized light. The circularly polarized light that transmits through the first lens **106** transmits through the half-mirror **114**, transmits through the second lens **105** and the second phase plate **115**, and becomes linearly polarized light. Since the polarization direction of this linearly polarized light is orthogonal to the transmission polarization direction of the PBS **116**, it is reflected by the PBS **116**, transmits through the second phase plate **115**, and becomes circularly polarized light. The circularly polarized light transmits through the second lens **105**, is reflected by the half-mirror **114**, transmits through the second lens **105** again, transmits through the second phase plate **115**, and becomes linearly polarized light. Since the polarization direction of this linearly polarized light coincides with the transmission polarization direction of the PBS **116**, it transmits through the PBS **116**, the second polarizing plate **117**, and the third lens **104**, and is guided to the right eye **102**. The second polarizing plate **117** can reduce ghost light caused by external light, and increase the contrast of the displayed image. As for the left-eye optical system, the light from the left-eye display element **111** follows a similar optical path and is guided to the left eye **103**.

[0029] An optical system that folds the optical path using polarization in this way has a reduced thickness and a reduced focal length, and enables an image to be displayed at a wide angle of view. Forming the first and second lenses **106** and **105** into a cemented lens and further cementing the optical unit to the second lens **105** can further reduce the thickness of the optical system. The third lens **104** disposed in front of the exit pupil can secure high optical performance.

[0030] FIG. **14** illustrates the external appearance of the HMD **101**. The HMD **101** is mounted on a user's head and thus may have a reduced weight. The lenses constituting the right-eye optical system can be manufactured (formed) using a resin material with a lower specific gravity than that of glass, and all the lenses **104** to **106** are made of resin in the first embodiment. The resin material referred to herein is not limited to a material consisting of resin exclusively, but may contain components other than resin, such as inorganic fine particles, as long as the main component is resin. This is similarly applied to the other embodiments described below.

[0031] The second lens **105** as a plano-convex aspherical lens improves the aberration correcting effect. The first lens **106** is also a double-sided aspherical lens. This is similarly applied to the left-eye optical system.

[0032] The characteristic configuration of the lenses in this embodiment will be described. The second lens **105** is a lens with positive refractive power, a planar lens surface on the observation side (exit pupil side), and an aspherical lens surface on the display element side (the cemented surface with the first lens **106**) that is convex toward the display element side. A half-mirror **114** is provided as a reflective surface on the display-element-side lens surface of the second lens **105**, and the half-mirror **114** has positive refractive power, so that the optical path can be folded, and the optical system has a reduced thickness and a wide angle of view. In addition, the display-element-side lens surface of the second lens **105** and the observation-side lens surface of the first lens **106** are cemented together to form a cemented surface, so that the total reflection condition can be

avoided for light incident on the cemented surface compared to when these lens surfaces are in contact with air. The first lens **106** is a double-sided aspheric lens with negative refractive power.
[0033] The following inequality (1) may be satisfied:
[00002] $0.2 \leq |\Phi 1 / \Phi 2| \leq 0.8 \quad (1)$
where Φ1 is optical power (a reciprocal of a focal length) on the optical axis of the first lens **106**, Φ2 is optical power on the optical axis of the second lens **105**.
[0034] Inequality (1) defines a proper relationship between the optical powers of the first and second lenses **106** and **105** that constitute a cemented lens. In a case where |Φ1/Φ2| becomes higher than the upper limit of inequality (1), the focal length of the optical system increases and the size of the HMD **101** finally increases. In a case where |Φ1/Φ2| becomes lower than the lower limit of inequality (1), it becomes difficult to configure an optical system with good optical performance. In The first embodiment, Φ1=−0.0045, Φ2=0.0085, and |Φ1/Φ2|=0.526. That is, the optical system according to The first embodiment satisfies inequality (1).
[0035] The third lens **104** with positive refractive power disposed on the display element side of the exit pupil can correct aberrations that could not be corrected by the first and second lenses **106** and **105**. In a case where the third lens **104** is an aspheric lens, higher optical performance can be obtained.
[0036] In a case where resin lenses are used for the lenses **104** to **106**, birefringence that occurs during molding of each lens may affect the optical performance of the right-eye optical system. Thus, an annealing process or the like may be performed to satisfy the following inequality (2):
[00003] $Re \leq 30 \quad (2)$
where Re (nm) is a phase difference amount due to the birefringence of each lens.
[0037] In this embodiment, the phase difference amount Re of the first lens **106** is 20 nm, the phase difference amount Re of the second lens **105** is 5 nm, and the phase difference amount Re of the third lens **104** is 20 nm, each of which satisfies inequality (2).
Adhesive Layer
[0038] FIG. **4** illustrates an enlarged view of adhesive layers **120** to **122** in the optical unit and an adhesive layer (first adhesive layer) **119** between the optical unit and the lens **105**. The second phase plate **115** and the PBS **116** are adhered together via the adhesive layer **120**, and the PBS **116** and the second polarizing plate **117** are adhered together via the adhesive layer **121**. In order to reduce reflection at the interface between the second polarizing plate **117** and air, an antireflection film **118** is adhered to the second polarizing plate **117** via the adhesive layer **122**. The optical unit having such a laminated structure is adhered to the second lens **105** by the adhesive layer **119**.
[0039] The adhesive layer **119** may satisfy the following inequalities (3) and (4):
[00004] $0.009 < N2 \times d1 < 0.031 \quad (3) \quad 0.95 \leq N1 / N2 \leq 1.1 \quad (4)$
where d1 (mm) is a thickness of the adhesive layer **119**, N1 is a refractive index of the second lens **105** for the d-line (587.6 nm), and N2 is a refractive index of the adhesive layer **119** for the d-line. The thickness referred to in this specification is the width in the optical axis direction.
[0040] Inequality (3) defines a proper range of the optical path length N2×d1 when light transmits through the adhesive layer **119**. In a case where N2×d1 becomes higher than the upper limit of inequality (3), the thickness of the adhesive layer **119** increases, and the quality of the displayed image deteriorates due to the influence of birefringence of the adhesive layer **119**. In a case where N2×d1 becomes lower than the lower limit of inequality (3), the thickness of the adhesive layer **119** reduces, and the adhesive layer **119** is likely to contain air bubbles due to the influence of surface shape errors of the resin lens and variations in surface shape errors due to the annealing process. As a result, the quality of the displayed image deteriorates.
[0041] Inequality (4) defines a proper relationship between the refractive indexes N1 and N2 of the second lens **105** and the adhesive layer **119**. Setting N1/N2 within the numerical range of inequality (4) can reduce a refractive index difference between the adhesive layer **119** and the second lens

105, and the influence of the refractive power difference on the optical performance.
[0042] In this embodiment, the thickness d1 of the adhesive layer **119** is 0.015 mm (tolerance±0.003 mm), the refractive index N1 of the second lens **105** is 1.54, and the refractive index of the adhesive layer **119** is 1.48. Therefore, N2×d1-0.022 and N1/N2=1.045, and thus inequalities (3) and (4) are satisfied.
[0043] d1 may be 0.020 mm or less, 0.019 mm or less, 0.018 mm or less, or 0.016 mm or less. This is also applied to the thickness d1 of the adhesive layer in other embodiments described later.
[0044] The thickness d1 of the adhesive layer **119** may satisfy the following inequality (5):
[00005] $0.0002 \leq d1/f \leq 0.002 \quad (5)$
where f (mm) is a focal length of the optical system.
[0045] Inequality (5) defines a proper relationship between the thickness d1 of the adhesive layer **119** and the focal length f of the optical system. Satisfying this condition can reduce the influence of the adhesive layer **119** on the optical performance of the optical system. In this embodiment, the focal length f is 17 mm, and the thickness d1 of the adhesive layer **119** is 0.015 mm, so d1/f=0.0009, which satisfies inequality (5).
[0046] In an optical system that folds the optical path utilizing polarization, the adhesive layer **119** significantly affects the optical performance because the light ray from the right-eye display element **110** toward the observation side transmits through the adhesive layer **119** a plurality of times (three times). Therefore, satisfying inequalities (3) to (5) can effectively suppress the deterioration of the quality of the displayed image caused by the cemented portion where the optical unit and the lens **105** are adhered together via the adhesive layer **119**.
[0047] The adhesive layers **120** to **122** in the optical unit will be described. The following inequality (6) may be satisfied:
[00006] $0.005\text{mm} \leq d2 < 0.02\text{mm} \quad (6)$
where d2 is a thickness of the adhesive layer (second adhesive layer) **120** that adheres the second phase plate **115** and the PBS **116**.
[0048] Inequality (6) defines a proper range for the thickness d2 of the adhesive layer **120**. Since the PBS **116** is a thin film-shape element (referred to as a film element hereinafter), in a case where the adhesive layer **120** has thickness variations (unevenness) in the in-plane direction, unevenness corresponding to that unevenness will also appear on the PBS **116**. In a case where the adhesive layer **120** has periodic unevenness, local optical power will be generated for the light reflected by the PBS **116**. As a result, the displayed image has a local focus shift, and the displayed image will be observed as a blurred image with reduced contrast. In particular, since the PBS **116** functions as a reflective surface, it is more likely to affect the displayed image than a transparent surface. In a case where d2 becomes higher than the upper limit of inequality (6), the unevenness of the adhesive layer **120** and accordingly the unevenness appearing on the PBS **116** increase, and the optical power for the light reflected by the PBS **116** increases. In a case where d2 becomes lower than the lower limit of inequality (6), the thickness of the adhesive layer **120** reduces, it becomes difficult to adhere the second phase plate **115** and the PBS **116**, and wrinkles and air bubbles are more likely to occur in the adhesive layer **120**.
[0049] In this embodiment, the thickness d2 of the adhesive layer **120** is 0.010 mm (±0.003 mm), which satisfies inequality (6).
[0050] d2 may be 0.019 mm or less, 0.018 mm or less, or 0.016 mm or less. This is similarly applied to the thickness d2 of the adhesive layer in the other embodiments described below.
[0051] In this embodiment, the thickness of the adhesive layer **121** that adheres the PBS **116** and the second polarizing plate **117** is 0.025 mm (±0.003 mm), and the thickness of the adhesive layer **122** that adheres the second polarizing plate **117** and the antireflection film **118** is 0.025 mm (±0.003 mm). Thereby, the influence of the unevenness of each adhesive layer on the optical performance can be suppressed.

Second Embodiment

Image Display Apparatus

[0052] FIG. **5** illustrates an HMD **201** as an image display apparatus using an optical system according to a second embodiment, viewed from above. Reference numeral **202** denotes the observer's right eye, and reference numeral **203** denotes the observer's left eye. Lenses **204** and **205** form part of the right-eye optical system, and lenses **206** and **207** form part of the left-eye optical system. Reference numeral **208** denotes a right-eye display element, and reference numeral **209** denotes a left-eye display element, each of which includes an organic EL element that emits nonpolarized light.

[0053] The right-eye optical system enlarges the light (virtual image) from the original image displayed on the right-eye display element **208** and guides it to the right eye **202**, and the left-eye optical system enlarges the light from the original image displayed on the left-eye display element **209** and guides it to the left eye **203**.

[0054] Each of the right-eye optical system and the left-eye optical system has a focal length f of 17 mm, a horizontal display angle of view of 60°, a vertical display angle of view of 60°, and a diagonal display angle of view $2\times\theta 1$ of 78°. A distance between the HMD **201** and the observer's eyeball (eye relief) is 18 mm.

Optical System

[0055] The optical system according to the second embodiment is also an optical system that folds the optical path by utilizing polarization, and an enlarged view of the right-eye optical system is illustrated in FIG. **6**. In addition to the lenses **204** and **205**, the right-eye optical system further includes a first polarizing plate **210** and a first phase plate **211**, arranged in this order from the display element side between the right-eye display element **208** and the first lens **205**, and the right-eye optical system further includes a half-mirror **212** evaporated on a display-element-side surface of the second lens **204**. Each of the first polarizing plate **210** and the first phase plate **211** has a planar shape, and they are laminated. The half-mirror **212** functions as a transmissive reflective surface disposed between cemented surfaces of the first and second lenses **205** and **204**. That is, the first and second lenses **205** and **204** are configured as a cemented lens in which the half-mirror **212** is sandwiched between the cemented surfaces. The ratio of the transmittance and reflectance of the half-mirror **212** may be 50:50, but the ratio may be changed, as necessary.

[0056] The right-eye optical system includes, in order from the display element side on the observation side of the second lens **204**, a second phase plate **213**, a PBS **214**, and a second polarizing plate **215**. Each of the second phase plate **213**, the PBS **214**, and the second polarizing plate **215** has a planar shape, and they are laminated and adhered together to form an optical unit.

[0057] Each of the first phase plate **211** and the second phase plate **213** is a waveplate with a phase difference of $\lambda/4$ (quarter waveplate). The polarization direction of the polarized light that transmits through the first polarizing plate **210** and the slow axis of the first phase plate **211** are tilted by 45°, and the polarization direction of the polarized light that transmits through the first polarizing plate **210** and the slow axis of the second phase plate **213** are tilted by −45°. The polarization direction of the polarized light that transmits through the first polarizing plate **210** and the polarization direction of the polarized light that transmits through the PBS **214** are orthogonal to each other. The polarization direction of the polarized light that transmits through the second polarizing plate **215** and the polarization direction of the polarized light that transmits through the PBS **214** coincide with each other.

[0058] FIG. **7** illustrates the optical path of the right-eye optical system configured as described above. The unpolarized light emitted from the right-eye display element **208** transmits through the first polarizing plate **210** and becomes linearly polarized light, and the linearly polarized light transmits through the first phase plate **211** and becomes circularly polarized light. The circularly polarized light that transmits through the first lens **205** transmits through the half-mirror **212**, transmits through the second lens **204** and the second phase plate **213**, and becomes linearly polarized light. Since the polarization direction of this linearly polarized light is orthogonal to the transmission polarization direction of the PBS **214**, it is reflected by the PBS **214**, transmits through the second phase plate **213**, and becomes circularly polarized light. The circularly polarized light transmits through the second lens **204**, is reflected by the half-mirror **212**, transmits through the second lens **204** again, transmits through the second phase plate **213**, and becomes linearly polarized light. Since the polarization direction of this linearly polarized light coincides with the transmission polarization direction of the PBS **214**, it transmits through the PBS **214** and the second polarizing plate **215**, and is guided to the right eye **202**. The second polarizing plate **215** can reduce ghost light caused by external light, and increase the contrast of the displayed image. As for the left-eye optical system, the light from the left-eye display element **209** follows a similar optical path and is guided to the left eye **203**.

[0059] An optical system that folds the optical path utilizing polarization in this way has a reduced thickness and a reduced focal length, and enables an image to be displayed at a wide angle of view. Forming the first and second lenses **205** and **204** into a cemented lens and further cementing the optical unit to the second lens **204** can reduce the thickness of the optical system.

[0060] The HMD **201** is mounted on a user's head and thus may have a reduced weight. Thus, the lenses constituting the right-eye optical system can be manufactured using a resin material with a lower specific gravity than that of glass, and all the lenses **204** and **205** are made of resin in the second embodiment. The second lens **204** is also a plano-convex aspherical lens to enhance the aberration correcting effect. The first lens **205** is also a double-sided aspherical lens. This is similarly applied to the left-eye optical system.

[0061] The characteristic configuration of the lenses according to this embodiment will be described. The right-eye optical system according to this example includes two lenses **204** and **205**. The second lens **204** is a lens with positive refractive power, a flat lens surface on the observation side, and an aspheric lens surface on the display element side (the cemented portion surface with the first lens **205**) that is convex toward the display element side. The half-mirror **212** is provided as a reflective surface on the display-element-side lens surface of the second lens **204**, and the half-mirror **212** has positive refractive power, so that the optical path can be folded, and the optical system has a reduced thickness and a wide angle of view.

[0062] Since the display-element-side lens surface of the second lens **204** and the observation-side lens surface of the first lens **205** are cemented together to form a cemented surface, so that the total reflection condition for light incident on the cemented surface can be avoided compared to when these lens surfaces are in contact with air. The first lens **205** is a double-sided aspheric lens with negative refractive power.

[0063] Inequality (1) described in the first embodiment may be satisfied where $\Phi1$ is the optical power on the optical axis of the first lens **205**, and $\Phi2$ is the optical power on the optical axis of the second lens **204**. In this embodiment, $\Phi1=-0.0044$, $\Phi2=0.0128$, and $|\Phi1/\Phi2|=0.346$. In other words, the optical system according to the second embodiment satisfies inequality (1).

[0064] The display-element-side surface of the first lens **205** has a convex shape toward the display element side in the central area including the optical axis, but the curvature becomes gentler as it moves away from the optical axis, and has an inflection point within an optically effective area, which is an area through which an effective light ray that contributes to imaging passes. The inflection point is a point where the shape changes from convex to concave toward the display element side. In other words, the inflection point is a point where a value obtained when the curve representing the display-element-side surface of the first lens **205** is differentiated twice becomes 0 in the section along the optical axis of the first lens **205**.

[0065] The focal length of the optical system is reduced by making the central area including the optical axis of the display-element-side surface of the first lens **205** convex toward the display element side. Making the curvature of the display-element-side surface of the first lens **205** gentler as it moves away from the optical axis can reduce the exit angle from the right-eye display element

208 at the peripheral portion. Such an aspheric shape provided to the display-element-side surface of the first lens **205** can provide an optical system with a reduced focal length and a wide angle of view, reduce the exit angle from the right-eye display element **208** at the peripheral portion, and suppress the deterioration of a field angle characteristic of the display element and a color shift. In addition, this configuration can reduce an incident angle to the first polarizing plate **210** and the first phase plate **211**, and thereby suppress factors that deteriorate image quality, such as a light amount decrease, light amount unevenness, and color unevenness.

[0066] The aspheric shape on the display element side of the first lens **205** has an inflection point in order to reduce the exit angle from the right-eye display element **208** in the peripheral portion and the focal length of the optical system. The following inequality (7) may be satisfied:

[00007] $0.2 < Yip / Yea < 0.75 \quad (7)$

where Yip is a distance from the optical axis to the inflection point, and Yea is a maximum distance (effective diameter) from the optical axis to the optically effective area on the display-element-side surface of the first lens **205**.

[0067] Inequality (7) defines a proper position of the inflection point on the display-element-side aspheric surface of the first lens **205**. In a case where Yip/Yea becomes higher than the upper limit of inequality (7), the inflection point is located at the peripheral portion of the optically effective area, and the effect of reducing the exit angle from the right-eye display element **208** at the peripheral portion is reduced. In a case where Yip/Yea becomes lower than the lower limit of inequality (7), the inflection point is close to the optical axis, and the optical power near the optical axis is reduced, and the focal length of the optical system cannot be reduced.

[0068] In this embodiment, Yip is 4 mm, Yea is 12 mm, and Yip/Yea=0.33, and thus inequality (7) is satisfied.

[0069] Inequality (7) may be replaced with inequality (7a) below:

[00008] $3 \leq Yip / Yea \leq 0.7 \quad (7a)$

[0070] The aspheric shape on the display element side of the first lens **205** changes monotonically as it moves away from the optical axis, and has no maximum or minimum values within the optically effective area other than a point on the optical axis. Such an aspheric shape can reduce the exit angle from the right-eye display element **208** at the peripheral portion and the focal length of the optical system. Reducing an aspheric shape change can reduce an optical performance change from the central portion to the peripheral portion, present a display image that is easy to observe, and improve the processing accuracy of the aspheric shape. The above description of the first lens **205** is also applicable to the first lens **207** in the left-eye optical system.

[0071] Even in this embodiment, the first and second lenses **205** and **204** are made of resin, and birefringence occurring during molding of each lens may negatively affect the optical performance of the right-eye optical system. Therefore, an annealing process or the like is performed to set the phase difference amount Re due to the birefringence of each lens so as to satisfy inequality (2) described in the first embodiment. In this embodiment, the phase difference amount Re of the first lens **205** is 18 nm, and the phase difference amount Re of the second lens **204** is 7 nm, each of which satisfies inequality (2).

Adhesive Layer

[0072] FIG. **8** illustrates an enlarged view of adhesive layers **218** to **220** in the optical unit and an adhesive layer **217** between the optical unit and the second lens **204**. The second phase plate **213** and PBS **214** are adhered together via the adhesive layer **218**, and the PBS **214** and second polarizing plate **215** are adhered together via the adhesive layer **219**. In order to reduce reflection at the interface between the second polarizing plate **215** and air, an antireflection film **216** is adhered to the second polarizing plate **215** via the adhesive layer **220**. The optical unit having such a laminated structure is adhered to the second lens **204** by the adhesive layer (first adhesive layer) **217**.

[0073] The adhesive layer **217** may satisfy inequalities (3) and (4) described in the first embodiment, where d1 is a thickness of the adhesive layer **217**, N1 is a refractive index of the second lens **204** for the d-line, and N2 is a refractive index of the adhesive layer **217** for the d-line. In this embodiment, the thickness d1 of the adhesive layer **217** is 0.015 mm (±0.003 mm), the refractive index N1 of the second lens **204** is 1.54, and the refractive index of the adhesive layer **217** is 1.46. Therefore, N2×d1=0.022 and N1/N2=1.058, each of which satisfies inequalities (3) and (4).
[0074] The thickness d1 of the adhesive layer **217** may satisfy inequality (5) described in the first embodiment, where f is the focal length of the optical system. In this embodiment, the focal length f is 13 mm, the thickness d1 of the adhesive layer **217** is 0.015 mm (±0.003 mm), and d1/f=0.0012. Therefore, inequality (5) is satisfied.
[0075] In an optical system that folds the optical path utilizing polarization, the adhesive layer **217** significantly affects the optical performance because the light ray from the right-eye display element **208** toward the observation side transmits through the adhesive layer **217** three times. Therefore, satisfying inequalities (3) to (5) can effectively suppress the deterioration of the quality of the displayed image caused by the cemented portion where the optical unit and the second lens **204** are adhered together via the adhesive layer **217**.
[0076] The adhesive layers **218** to **220** in the optical unit will be described. Inequality (6) may be satisfied as in the first embodiment, where d2 is a thickness of the adhesive layer **218** that adheres the second phase plate **213** and the PBS **214**. In this embodiment, the thickness d2 of the adhesive layer **218** is 0.015 mm (±0.003 mm), which satisfies inequality (6).
[0077] In this embodiment, the thickness of the adhesive layer **219** that adheres the PBS **214** and the second polarizing plate **215** is 0.020 mm (±0.003 mm), and the thickness of the adhesive layer **220** that adheres the second polarizing plate **215** and the antireflection film **216** is 0.025 mm (±0.003 mm). Thereby, the influence of the unevenness of each adhesive layer on the optical performance can be suppressed.

Third Embodiment

Image Display Apparatus

[0078] FIG. **9** illustrates an HMD **301** as an image display apparatus using an optical system according to a third embodiment, viewed from above. Reference numeral **302** denotes the observer's right eye, and reference numeral **303** denotes the observer's left eye. Lenses **304** and **305** form part of the right-eye optical system, and lenses **306** and **307** form part of the left-eye optical system. Reference numeral **308** denotes a right-eye display element, and reference numeral **309** denotes a left-eye display element, each of which includes an organic EL element that emits unpolarized light.
[0079] The right-eye optical system enlarges the light (virtual image) from the original image displayed on the right-eye display element **308** and guides it to the right eye **302**, while the left-eye optical system enlarges the light from the original image displayed on the left-eye display element **309** and guides it to the left eye **303**.
[0080] Each of the right-eye optical system and the left-eye optical system has a focal length f of 16 mm, a horizontal display angle of view of 65°, a vertical display angle of view of 65°, and a diagonal display angle of view 2×θ1 of 84°. A distance between the HMD **301** and the observer's eyeball (eye relief) is 20 mm.

Optical System

[0081] The optical system according to the third embodiment is also an optical system that folds the optical path by utilizing polarization, and an enlarged view of the right-eye optical system is illustrated in FIG. **10**. In addition to the lenses **304** and **305**, the right-eye optical system further includes a first polarizing plate **310** disposed between the right-eye display element **308** and the first lens **305**, and the right-eye optical system further includes a PBS **312** and a first phase plate **313**, arranged in this order from the display element side between the first and second lenses **305**

and **304**. Each of the PBS **312** and the first phase plate **313** has a curved surface shape and they are laminated and adhered together to form a first optical unit. The PBS **312** functions as a polarization separation surface disposed between cemented surfaces of the first and second lenses **305** and **304**. In other words, the first and second lenses **305** and **304** are configured as a cemented lens in which the half-mirror **314** is sandwiched between the cemented surfaces. The ratio of the transmittance and reflectance of the half-mirror **314** may be 50:50, but the ratio may be changed, as necessary.
[0082] Arranged in order from the display element side on the observation side of the second lens **304** are a half-mirror **314**, a second phase plate **315**, and a second polarizing plate **316** as film elements. Each of the half-mirror **314**, the second phase plate **315**, and the second polarizing plate **316** has a planar shape and they are laminated and adhered together to form a second optical unit. The half-mirror **314** functions as a transmissive reflective surface.
[0083] Each of the first phase plate **313** and the second phase plate **315** is a waveplate with a phase difference of λ/4 (quarter waveplate). The polarization direction of the polarized light that transmits through the first polarizing plate **310** and the slow axis of the first phase plate **313** are tilted by 45°, and the polarization direction of the polarized light that transmits through the first polarizing plate **310** and the slow axis of the second phase plate **315** are tilted by −45°. The polarization direction of the polarized light that transmits through the first polarizing plate **310** and the polarization direction of the polarized light that transmits through the PBS **312** are consistent with each other. The polarization direction of the polarized light that transmits through the second polarizing plate **316** and the polarization direction of the polarized light that transmits through the PBS **312** coincide with each other.
[0084] FIG. **11** illustrates the optical path of the right-eye optical system configured as described above. The nonpolarized light emitted from the right-eye display element **308** transmits through the first polarizing plate **310** and becomes linearly polarized light, and the linearly polarized light transmits through the first lens **305** and the PBS **312**, transmits through the first phase plate **313**, and becomes circularly polarized light. Part of the circularly polarized light that transmits through the second lens **304** is reflected by the half-mirror **314**, and transmits through the second lens **304** and the first phase plate **313**, and becomes linearly polarized light. Since the polarization direction of this linearly polarized light is orthogonal to the transmission polarization direction of the PBS **312**, it is reflected by the PBS **312**, transmits through the second lens **304**, and transmits through the first phase plate **313**, and becomes circularly polarized light. The circularly polarized light transmits through the first lens **305**, transmits through the half-mirror **314**, and transmits through the second phase plate **315**, and becomes linearly polarized light. This linearly polarized light has a polarization direction that coincides with the transmission polarization direction of the second polarizing plate **316**, and transmits through the second polarizing plate **316**, and is guided to the right eye **302**. The second polarizing plate **316** can reduce ghost light caused by external light, and increase the contrast of the displayed image. As for the left-eye optical system, the light from the left-eye display element **309** follows a similar optical path and is guided to the left eye **303**.
[0085] An optical system that folds the optical path utilizing polarization in this way has a reduced thickness and a reduced focal length, and enables an image to be displayed at a wide angle of view. Forming the first and second lenses **305** and **304** into a cemented lens, placing the first optical unit between them, and further cementing the second optical unit to the second lens **304** can reduce the thickness of the optical system.
[0086] The HMD **301** is mounted on a user's head and thus may have a reduced weight. Thus, the lenses constituting the right-eye optical system can be manufactured using resin, which has a smaller specific gravity than that of glass, and all the lenses **304** and **305** are made of resin in the third embodiment. The second lens **304** is also a plano-convex aspherical lens to enhance the aberration correcting effect. The first lens **305** is also a double-sided aspherical lens. This is similarly applied to the left-eye optical system.
[0087] The characteristic configuration of the lenses according to this embodiment will be

described. The right-eye optical system according to this example includes two lenses **304** and **305**. The second lens **304** is a lens with positive refractive power, a flat lens surface on the observation side, and an aspheric lens surface on the display element side (the cemented portion surface with the first lens **305**) that is convex toward the display element side. The PBS **312** is provided as a reflective surface on the display element side of the second lens **304**, and the PBS **312** has positive refractive power, so that the optical path to be folded, and the optical system has a reduced thickness and a wide angle of view.

[0088] Since the display-element-side lens surface of the second lens **304** and the observation-side lens surface of the first lens **305** are cemented together to form a cemented surface, the total reflection condition for light incident on the cemented surface can be avoided compared to when these lens surfaces are in contact with air. The first lens **305** is a double-sided aspheric lens with negative refractive power.

[0089] Inequality (1) described in the first embodiment may be satisfied where $\Phi1$ is the optical power on the optical axis of the first lens **305** and $\Phi2$ is the optical power on the optical axis of the second lens **304**. In this example, $\Phi1=-0.0075$, $\Phi2=0.0112$, and $|\Phi1/\Phi2|=0.673$. In other words, the optical system according to the third embodiment satisfies inequality (1).

[0090] The display-element-side surface of the first lens **305** has a convex shape toward the display element side in the central area including the optical axis, but the curvature becomes gentler as it moves away from the optical axis, and has an inflection point within an optically effective area, which is an area through which effective light ray that contribute to imaging passes.

[0091] Inequality (7) described in the second embodiment may be satisfied where Yip is a distance from the optical axis of the inflection point and Yea is a maximum distance from the optical axis (effective diameter) of the optically effective area of the display-element-side surface of the first lens **305**. In this embodiment, Yip is 6 mm, Yea is 13 mm, Yip/Yea=0.46, and thus inequality (7) is satisfied.

[0092] The aspheric shape of the display element side of the first lens **305** changes monotonically as it moves away from the optical axis, and has no maximum or minimum values within the optically effective area other than a point on the optical axis. Such an aspheric shape can reduce the exit angle from the right-eye display element **308** at the peripheral portion and the focal length of the optical system. Reducing an aspheric shape change can reduce an optical performance change from the central portion to the peripheral portion, present a display image that is easy to observe, and improve the processing accuracy of the aspheric shape. The above description of the first lens **305** is also applicable to the first lens **307** in the left-eye optical system.

[0093] Even in this embodiment, the first and second lenses **305** and **304** are made of resin, and birefringence that occurs during molding of each lens may negatively affect the optical performance of the right-eye optical system. Therefore, an annealing process or the like is performed to set the phase difference amount Re due to the birefringence of each lens so as to satisfy inequality (2) described in the first embodiment. In this embodiment, the phase difference amount Re of the first lens **305** is 20 nm, and the phase difference amount Re of the second lens **304** is 5 nm, each of which satisfies inequality (2).

Adhesive Layer

[0094] FIG. **12** illustrates an enlarged view of adhesive layers **325** to **327** in the second optical unit and an adhesive layer **324** between the second optical unit and the second lens **304**. The half-mirror **314** and the second phase plate **315** are adhered together via the adhesive layer **325**, and the second phase plate **315** and the second polarizing plate **316** are adhered together via the adhesive layer **326**. In order to reduce reflection at the interface between the second polarizing plate **316** and air, an antireflection film **317** is adhered to the second polarizing plate **316** via the adhesive layer **327**. The second optical unit having such a laminated structure is adhered to the lens **304** by the adhesive layer (first adhesive layer) **324**.

[0095] The adhesive layer **324** may satisfy inequalities (3) and (4) described in the first embodiment, where d1 is a thickness of the adhesive layer **324**, N1 is a refractive index of the second lens **304** for the d-line, and N2 is a refractive index of the adhesive layer **324** for the d-line. In this embodiment, the thickness d1 of the adhesive layer **324** is 0.020 mm (±0.003 mm), the refractive index N1 of the second lens **304** is 1.49, and the refractive index of the adhesive layer **324** is 1.478. Therefore, N2×d1=0.029 and N1/N2=1.006, which respectively satisfy inequalities (3) and (4).

[0096] The thickness d1 of the adhesive layer **324** may satisfy inequality (5) described in the first embodiment, where f is the focal length of the optical system. In this embodiment, the focal length f is 16 mm, the thickness d1 of the adhesive layer **324** is 0.020 mm (±0.003 mm), and d1/f=0.0013. Therefore, inequality (5) is satisfied.

[0097] FIG. **13** also illustrates an enlarged view of an adhesive layer **322** within the first optical unit, and adhesive layers **321** and **323** between the first optical unit and the lenses **304** and **305**. The PBS **312** and first phase plate **313** are adhered together via the adhesive layer **322**, the first phase plate **313** is adhered to second lens **304** via the adhesive layer (first adhesive layer) **321**, and the PBS **312** is adhered to the first lens **305** via the adhesive layer **323**.

[0098] Inequalities (3) and (4) described in the first embodiment may be satisfied, where d1 is a thickness of adhesive layer **321**, N1 is a refractive index of the second lens **304** for the d-line, and N2 is a refractive index of the adhesive layer **321** for the d-line. In this embodiment, the thickness d1 of the adhesive layer **324** is 0.015 mm (±0.003 mm), the refractive index N1 of the lens **304** is 1.49, and the refractive index of the adhesive layer **321** is 1.46. Therefore, N2×d1=0.022 and N1/N2=1.018, which satisfy inequalities (3) and (4), respectively.

[0099] The thickness d1 of the adhesive layer **321** may satisfy inequality (5) described in the first embodiment, where f is a focal length of the optical system. In this embodiment, the focal length f is 16 mm, the thickness d1 of the adhesive layer **321** is 0.015 mm (±0.003 mm), and d1/f=0.0009. Therefore, inequality (5) is satisfied.

[0100] In an optical system that folds the optical path utilizing polarization, the adhesive layers **321** and **324** significantly affect the optical performance because the light ray from the right-eye display element **308** toward the observation side passes through the adhesive layers **321** and **324** at least three times. Therefore, satisfying inequalities (3) to (5) can effectively suppress the degradation of the quality of the displayed image caused by the cemented portions where the optical units and the lenses are adhered together via the adhesive layers **321** and **324**.

[0101] The adhesive layers **325** to **327** in the first and second optical units will be described. d2 is each of the thickness of the adhesive layer **322** that adheres the PBS **312** and the first phase plate **313**, the thickness of the adhesive layer **325** that adheres the half-mirror **314** and the second phase plate **315**, and the thickness of the adhesive layer **326** that adheres the second phase plate **315** and the second polarizing plate **316**. Then, inequality (6) may be satisfied as in the first embodiment. In this embodiment, the thickness of adhesive layer **322** is 0.010 mm (±0.003 mm), and the thickness of adhesive layer **325** is 0.015 mm (±0.003 mm), both of which satisfy inequality (6).

[0102] In this embodiment, the thickness of adhesive layer **326** is 0.015 mm (±0.003 mm), and the thickness of adhesive layer **327** that adheres the second polarizing plate **316** and the antireflection film **317** is 0.015 mm (±0.003 mm). This reduces the influence of unevenness in each adhesive layer on the optical performance.

[0103] While the disclosure has described example embodiments, it is to be understood that the disclosure is not limited to the example embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

[0104] Each embodiment can reduce image degradation of a displayed image caused by an adhesive layer that adheres an optical unit and a lens.

[0105] This application claims priority to Japanese Patent Application No. 2024-019913, which was filed on Feb. 14, 2024, and which is hereby incorporated by reference herein in its entirety.

Claims

1. An optical system configured to guide light from a display element to an observation side, the optical system comprising: a transmissive reflective surface; a polarization separation surface; a polarizing element; and a lens including a resin material, wherein the transmissive reflective surface or the polarization separation surface and the polarizing element are integrated with each other to form an optical unit, wherein the optical unit and the lens are cemented to each other via a first adhesive layer, wherein the light transmits through the first adhesive layer a plurality of times, and wherein the following inequalities are satisfied: $0.009 < N2 \times d1 < 0.031$
$0.95 \leq N1 / N2 \leq 1.1$ where d1 (mm) is a thickness of the first adhesive layer, N1 is a refractive index of the lens for d-line, and N2 is a refractive index of the first adhesive layer for the d-line.
2. The optical system according to claim 1, wherein the following inequality is satisfied:
Re≤30 where Re (nm) a phase difference amount caused by birefringence of the lens.
3. The optical system according to claim 1, wherein the following inequality is satisfied:
$0.0002 \leq d1 / f \leq 0.002$ where f is a focal length of the optical system.
4. The optical system according to claim 1, wherein the light transmits through the first adhesive layer three times.
5. The optical system according to claim 1, wherein at least one of the transmissive reflective surface and the polarization separation surface includes a film element, and the film element is attached to one of a plurality of polarizing elements via a second adhesive layer, and wherein the following inequality is satisfied: $0.005 \leq d2 < 0.02$ where d2 (mm) is a thickness of the second adhesive layer.
6. The optical system according to claim 1, further comprising a first lens on a display element side and a second lens on the observation side, each of which is a resin lens, the first lens and the second lens being cemented together, and the transmissive reflective surface being disposed at a cemented portion between the first lens and the second lens, wherein the optical unit including the polarization separation surface is adhered to an observation-side-surface of the second lens via the first adhesive layer.
7. The optical system according to claim 1, further comprising a first lens on a display element side and a second lens on the observation side, each of which is a resin lens, the first lens and the second lens being cemented together, and a first optical unit including the polarization separation surface being adhered to a cemented surface of the second lens with the first lens via the first adhesive layer, wherein a second optical unit including the transmissive reflective surface is adhered to an observation-side surface of the second lens via the first adhesive layer.
8. The optical system according to claim 1, wherein a lens surface closest to a display element in the optical system is an aspheric surface that has a convex shape toward a display element side in a central area including an optical axis of the optical system, and an inflection point within an optically effective area.
9. The optical system according to claim 8, wherein the following inequality is satisfied:
0.2 ≤ Yip / Yea ≤ 0.75 where Yip is a distance from the optical axis to the inflection point on the aspheric surface, and Yea is a maximum distance from the optical axis to the optically effective area.
10. The optical system according to claim 1, further comprising a first lens on a display element side and a second lens on the observation side, each of which is a resin lens, the first lens and the second lens being cemented together, and the transmissive reflective surface or the polarization separation surface being disposed at a cemented portion between the first lens and the second lens, wherein the following inequalities are satisfied: 0.2 ≤ .Math. Φ1 / Φ2 .Math. ≤ 0.8 where Φ1 is optical power on an optical axis of the optical system, of the first lens, and Φ2 is optical power on the optical axis of the second lens.

11. The optical system according to claim 1, further comprising a first lens on a display element side and a second lens on the observation side, each of which is a resin lens, the first lens and the second lens being cemented together, and the transmissive reflective surface or the polarization separation surface being adhered to a cemented surface of the second lens with the first lens via an adhesive layer, wherein an observation-side-surface of the second lens is a planar surface, and wherein the cemented surface is an aspheric surface that is convex toward a display element side.

12. The optical system according to claim 1, comprising, in order from a display element side to the observation side: a first polarizing plate; a first phase plate; a first lens with negative refractive power; the transmissive reflective surface; a second lens with positive refractive power; a second phase plate; the polarization separation surface; a second polarizing plate; and a third lens with positive refractive power, wherein the second phase plate is adhered to the second lens via the first adhesive layer.

13. The optical system according to claim 1, comprising, in order from a display element side to the observation side: a first polarizing plate; a first phase plate; a first lens with negative refractive power; the transmissive reflective surface; a second lens with positive refractive power; a second phase plate; the polarization separation surface; and a second polarizing plate, wherein the second phase plate is adhered to the second lens via the first adhesive layer.

14. The optical system according to claim 1, comprising, in order from a display element side to the observation side: a first polarizing plate; a first lens with negative refractive power; the polarization separation surface; a first phase plate; a second lens with positive refractive power; the transmissive reflective surface; a second phase plate; and a second polarizing plate, wherein the first phase plate is adhered to a display-element-side surface of the second lens via the first adhesive layer, and the transmissive reflective surface is adhered to an observation-side-surface of the second lens via the first adhesive layer.

15. An image display apparatus comprising: an optical system configured to guide light from a display element to an observation side; and the display element, wherein the optical system includes: a transmissive reflective surface; a polarization separation surface; a polarizing element; and a lens including a resin material, wherein the transmissive reflective surface or the polarization separation surface and the polarizing element are integrated with each other to form an optical unit, wherein the optical unit and the lens are cemented to each other via a first adhesive layer, wherein the light transmits through the first adhesive layer a plurality of times, and wherein the following inequalities are satisfied: $0.009 < N2 \times d1 < 0.031$ $0.95 \leq N1 / N2 \leq 1.1$ where d1 (mm) is a thickness of the first adhesive layer, N1 is a refractive index of the lens for d-line, and N2 is a refractive index of the first adhesive layer for the d-line.