US 20250258365A1

(19) United States
(12) Patent Application Publication
(10) Pub. No.: US 2025/0258365 A1
(43) Pub. Date: Aug. 14, 2025
TOHARA et al.

(54) **DISPLAY OPTICAL SYSTEM AND IMAGE DISPLAY APPARATUS**

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(21) Appl. No.: **19/049,871**

(22) Filed: **Feb. 10, 2025**

(30) **Foreign Application Priority Data**

Feb. 14, 2024 (JP) 2024-019879

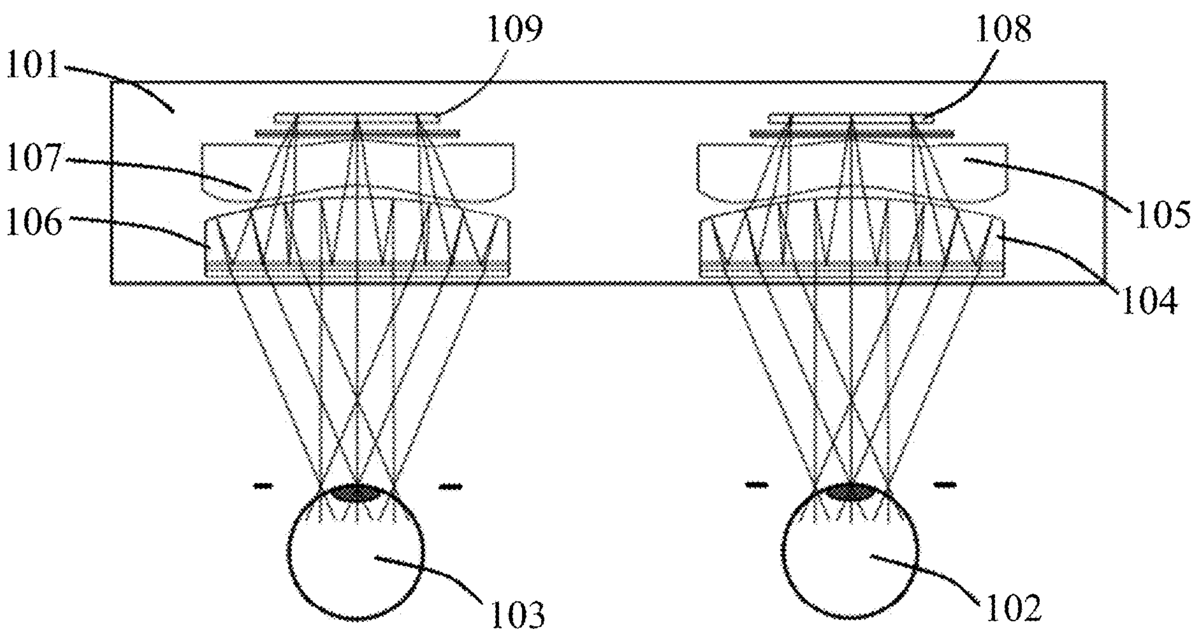
Publication Classification

(51) **Int. Cl.**
G02B 17/08 (2006.01)
G02B 5/30 (2006.01)
G02B 13/18 (2006.01)

(52) **U.S. Cl.**
CPC *G02B 17/0856* (2013.01); *G02B 5/3025* (2013.01); *G02B 13/18* (2013.01)

(57) **ABSTRACT**

A display optical system is configured to guide light from a display element to an observation side. The display optical system includes a half-transmissive reflective surface, a polarization separation surface, and a plurality of polarization elements. At least one of surfaces having refractive power in the display optical system is aspheric. At least one of the half-transmissive reflective surface or the polarization separation surface includes a film element. The film element is adhered to one of the plurality of polarization elements or a lens via a first adhesive layer on a reflection side of the film element. A predetermined inequality is satisfied.



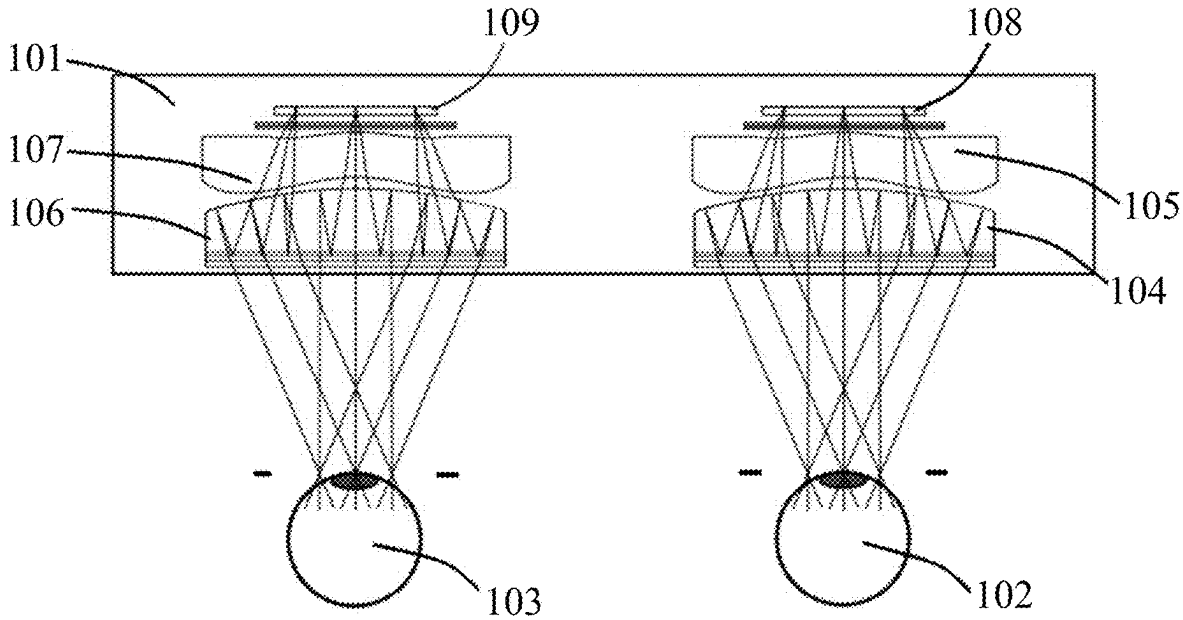

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FIG. 1

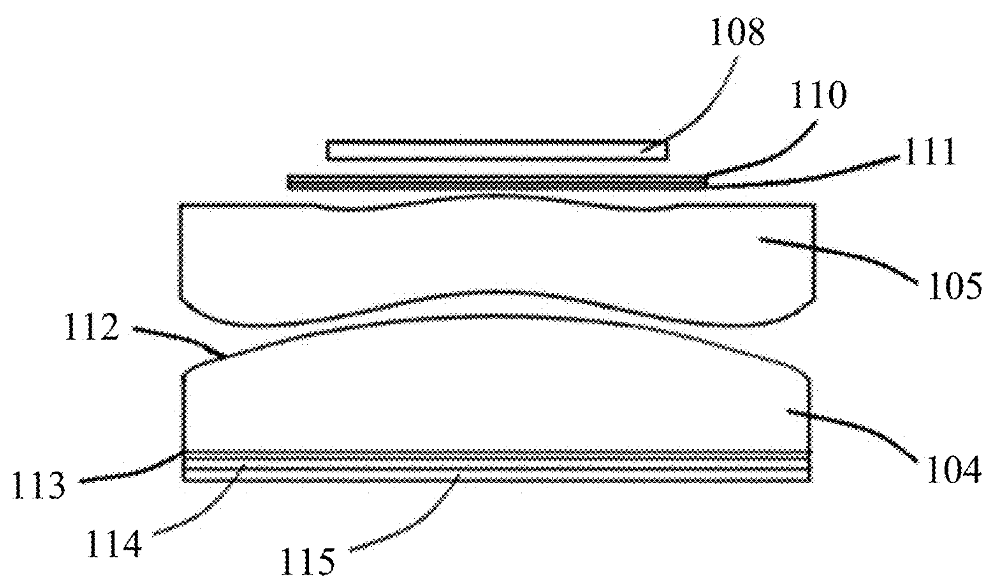
108
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FIG. 2

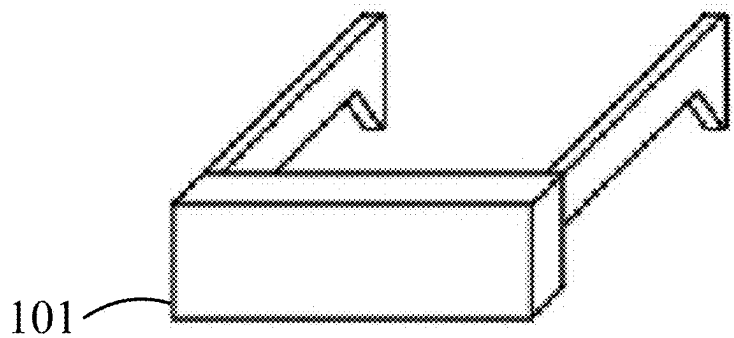

FIG. 3

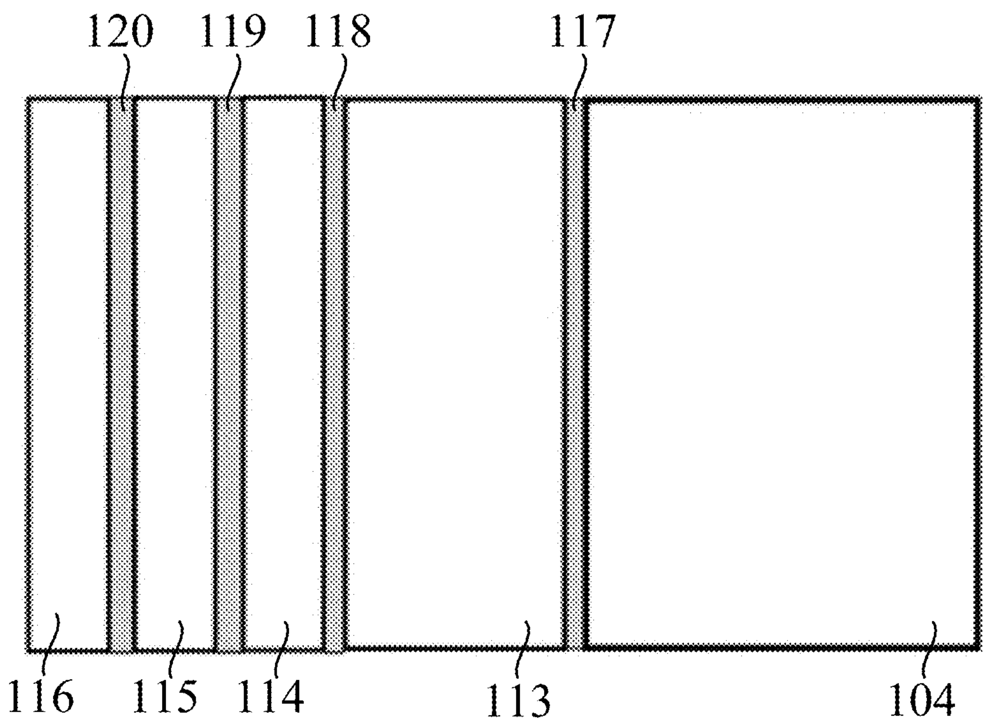

FIG. 4

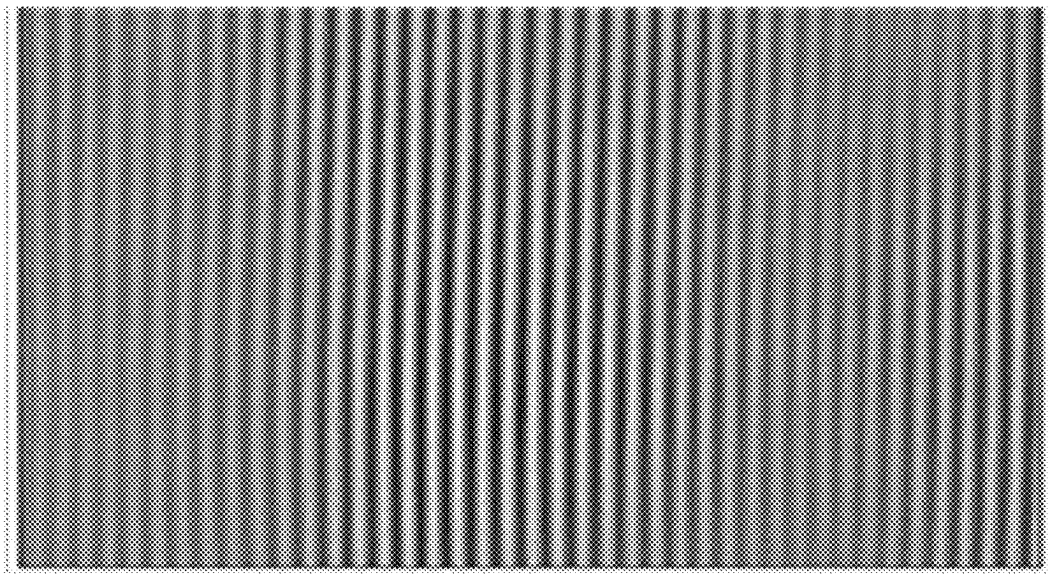

FIG. 5

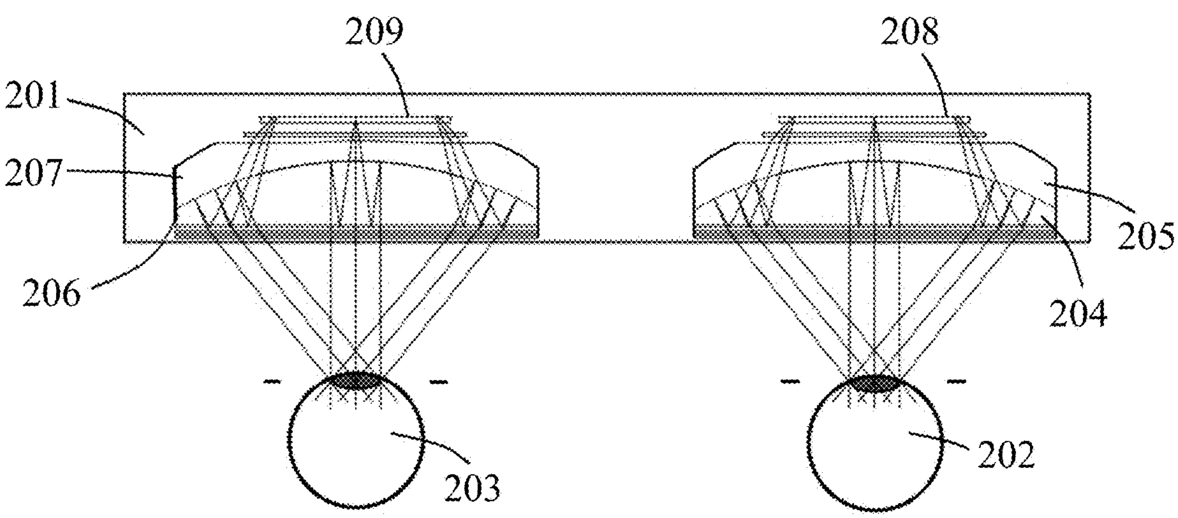

FIG. 6

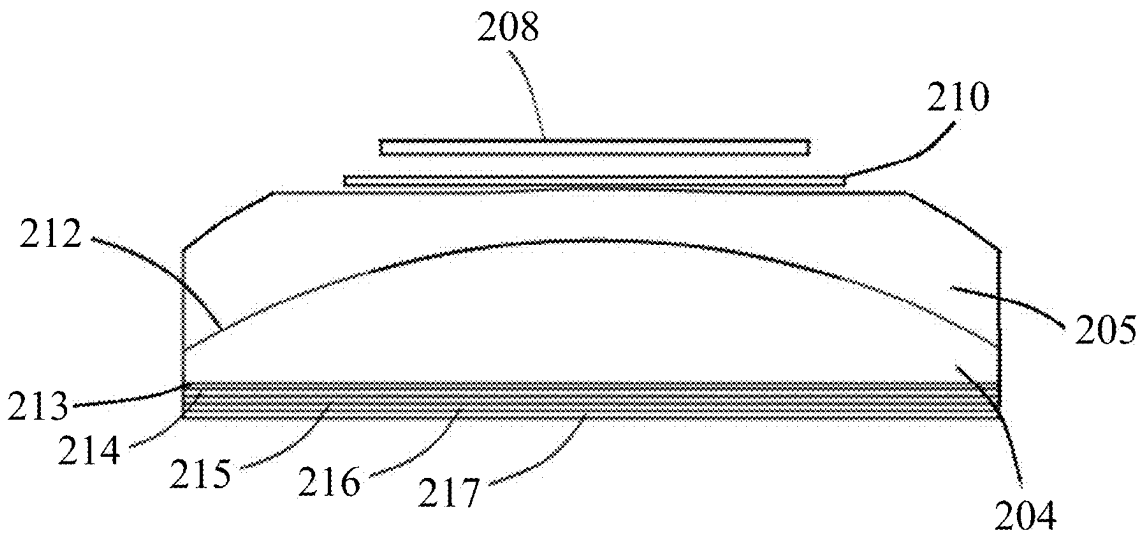
208
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FIG. 7

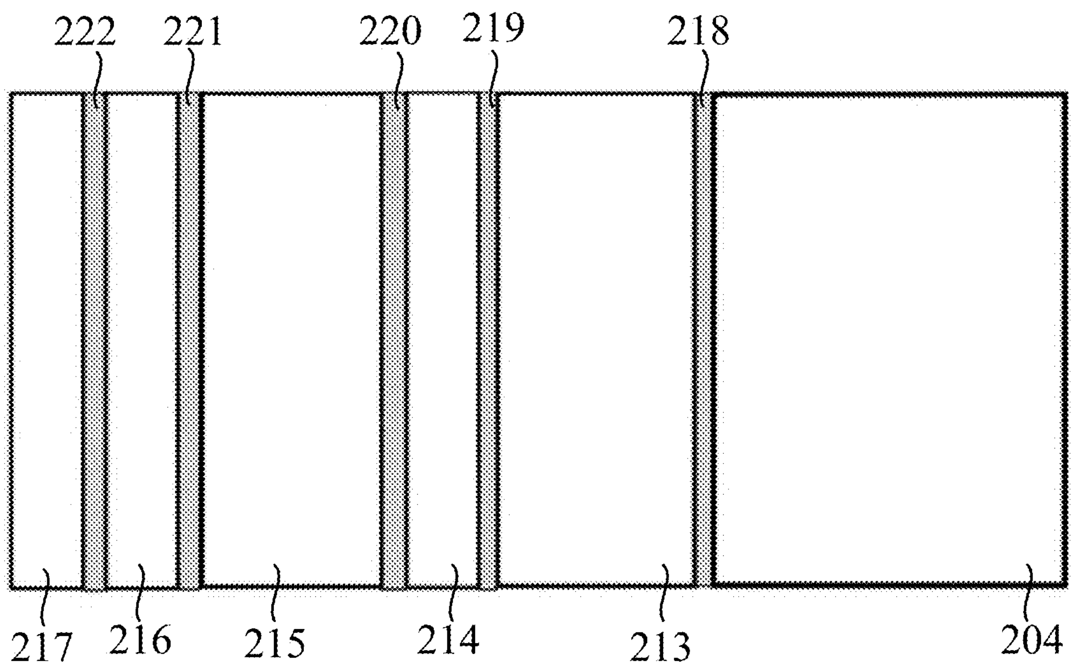
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FIG. 8

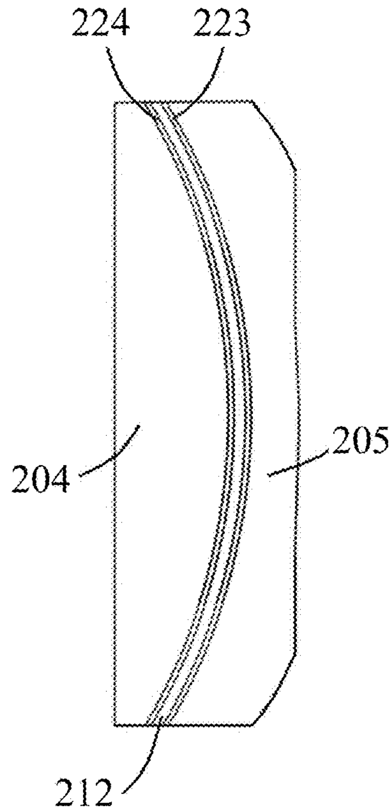

FIG. 9

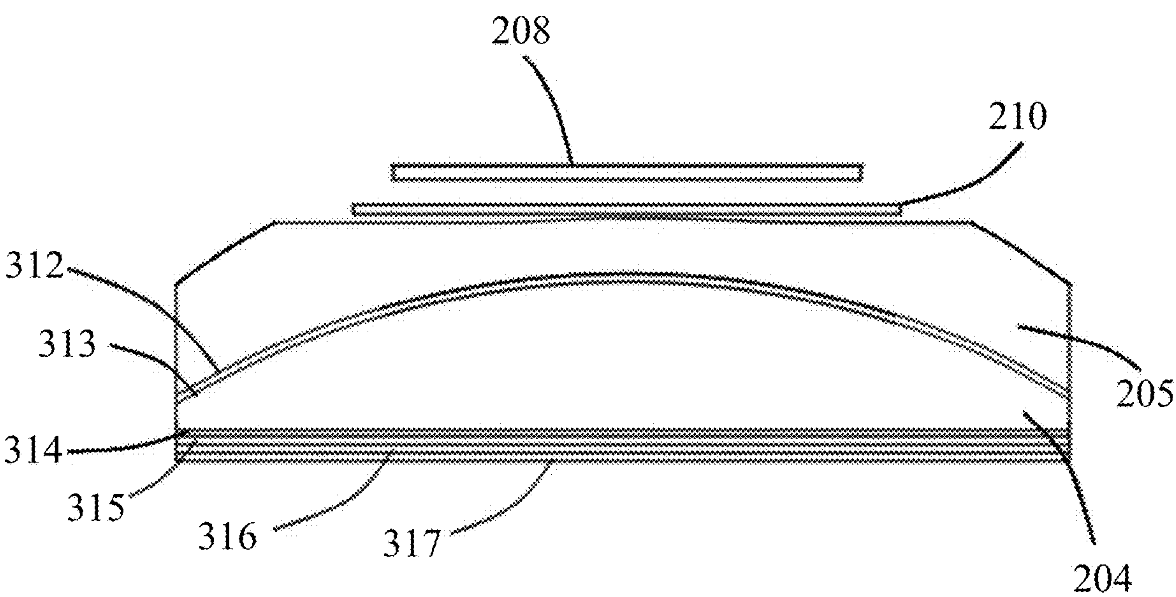

FIG. 10

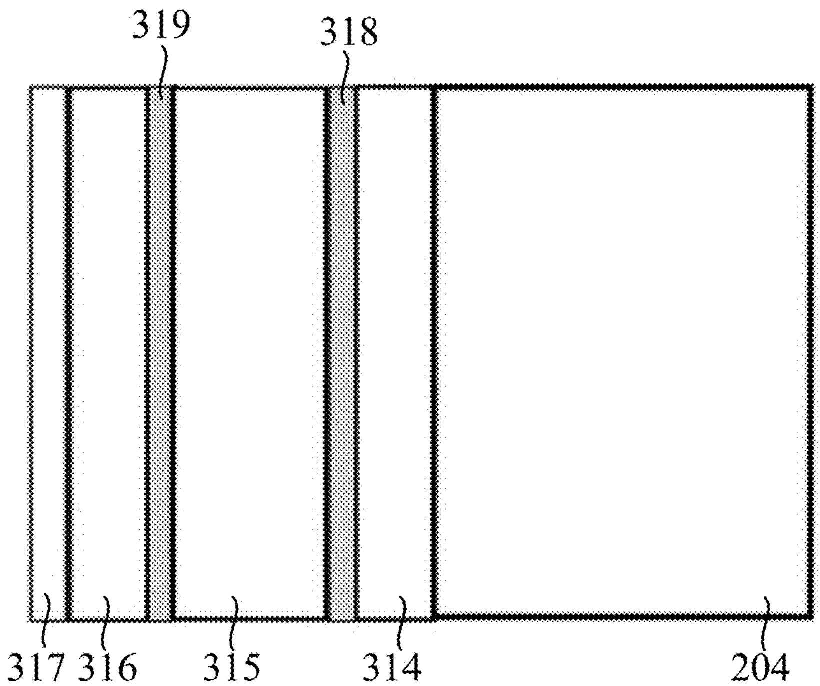

FIG. 11

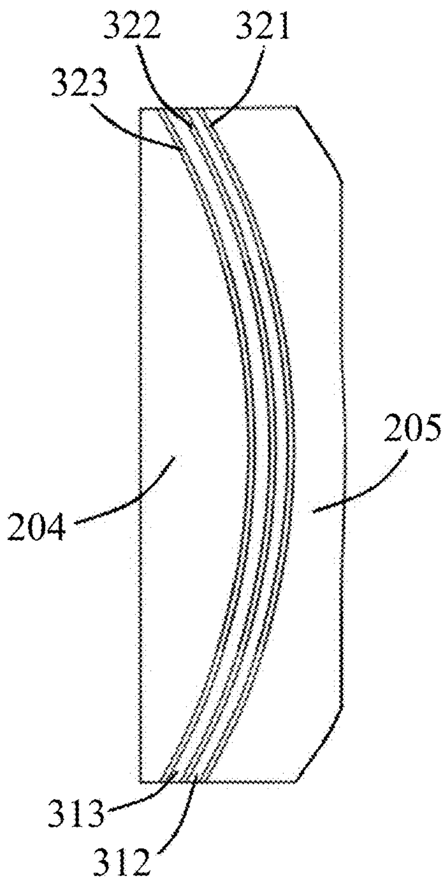

FIG. 12

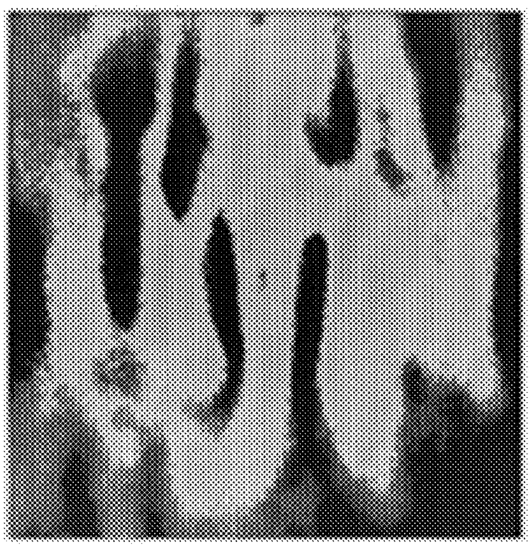

FIG. 13A

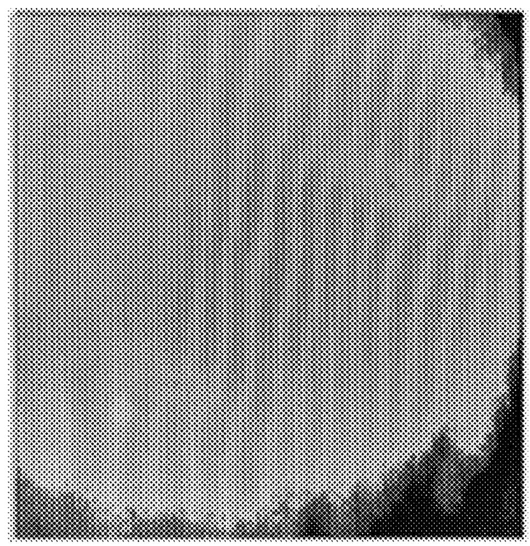

FIG. 13B

DISPLAY OPTICAL SYSTEM AND IMAGE DISPLAY APPARATUS

BACKGROUND

Technical Field

[0001] The present disclosure relates to a display 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 a display optical system, Japanese Patent Applications Laid-Open Nos. 2000-275566 and 2019-148626 disclose an optical system that folds an optical path by utilizing polarization and includes a polarization selective element (polarization separation element) and a half-mirror.

SUMMARY

[0003] A display optical system according to one aspect of the disclosure is configured to guide light from a display element to an observation side. The display optical system includes a half-transmissive reflective surface, a polarization separation surface, and a plurality of polarization elements. At least one of surfaces having refractive power in the display optical system is aspheric. At least one of the half-transmissive reflective surface or the polarization separation surface includes a film element. The film element is adhered to one of the plurality of polarization elements or a lens via a first adhesive layer on a reflection side of the film element. The following inequality is satisfied:

$$5\,\mu\text{m} \leq d1 < 20\,\mu\text{m}$$

where d1 is a thickness of the first adhesive layer. An image pickup apparatus having the above display 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.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. **1** illustrates an image observation apparatus that includes a display optical system according to a first embodiment.

[0006] FIG. **2** is a detailed diagram illustrating the configuration of the display optical system according to the first embodiment.

[0007] FIG. **3** is an external view of an image display apparatus according to FIG. **1**.

[0008] FIG. **4** is a partially enlarged view of the display optical system according to the first embodiment.

[0009] FIG. **5** illustrates local contrast decrease of a displayed image.

[0010] FIG. **6** illustrates an image observation apparatus that includes a display optical system according to a second embodiment.

[0011] FIG. **7** is a detailed diagram illustrating the configuration of the display optical system according to the second embodiment.

[0012] FIG. **8** is a partially enlarged view of the display optical system according to the second embodiment.

[0013] FIG. **9** is another partially enlarged view of the display optical system according to the second embodiment.

[0014] FIG. **10** is a detailed diagram illustrating the configuration of the display optical system according to a third embodiment.

[0015] FIG. **11** is a partially enlarged view of the display optical system according to the third embodiment.

[0016] FIG. **12** is another partially enlarged view of the display optical system according to the third embodiment.

[0017] FIGS. **13**A and **13**B illustrate an example in which local contrast decrease is improved in this embodiment.

DETAILED DESCRIPTION

[0018] Referring now to the accompanying drawings, a description will be given of embodiments according to the disclosure.

First Embodiment

[0019] FIG. **1** illustrates the configuration of an HMD **101** as an image display apparatus using a display optical system according to a first embodiment, viewed from above. Reference numeral **102** denotes a right eye of an observer, and reference numeral **103** denotes a left eye of the observer. Lenses **104** and **105** form part of a right-eye display optical system, and lenses **106** and **107** form part of a left-eye display optical system. Reference numeral **108** denotes a right-eye display element, and reference numeral **109** denotes a left-eye display element, each of which uses an organic electro-luminescence (EL) element in this embodiment.

[0020] The right-eye display optical system enlarges light (virtual image) from an original image displayed on the right-eye display element **108** and guides it to the right eye **102** disposed on the observation side, and the left-eye display optical system enlarges light from an original image displayed on the left-eye display element **109** and guides it to the left eye **103** disposed on the observation side.

[0021] Each of the right-eye display optical system and the left-eye display optical system has a focal length f1 of 12 mm, a horizontal display angle of view of 55°, a vertical display angle of view of 40°, and a diagonal display angle of view $2\times\theta 1$ of 65°. In order to enhance the immersion of the observer who observes an image, the diagonal display angle of view may be 60° or more. A distance (eye relief) **E1** between the HMD **101** and the observer's eyeball is 25 mm.

[0022] The display optical system according to this embodiment is an optical system that folds the optical path by using polarization, and its specific configuration will be described using the right-eye display optical system illustrated in FIG. **2**. The right-eye display optical system includes, in order from the display element side, a first polarizing plate **110** and a first phase plate **111** between the right-eye display element **108** and the lens **105**. Each of the first polarizing plate **110** and the first phase plate **111** has a planar shape and they are laminated.

[0023] A half-mirror **112** constituting a half-transmissive reflective surface is formed by vapor deposition on a display-element-side (lens-**105**-side) surface of the lens **104**.

The right-eye display optical system further includes, in order from the display element side (lens **104** side) between the lens **104** and the right eye **102**, a second phase plate **113**, a polarization separation element (polarization beam splitter: PBS) **114** constituting a polarization separation surface, and a second polarizing plate **115**. The polarization separation surface is an optically functional surface whose transmittance and reflectance change according to the polarization direction of the incident light. Each of the second phase plate **113**, the PBS **114**, and the second polarizing plate **115** has a planar shape and they are laminated. Each of the first phase plate **111** and the second phase plate **113** includes a quarter waveplate.

[0024] A polarization direction of polarized light that transmits through the first polarizing plate **110** and a slow axis of the first phase plate **111** are tilted by 45° to each other. The polarization direction of the polarized light that transmits through the first polarizing plate **110** and a slow axis of the second phase plate **113** are tilted by −45° to each other. The polarization direction of the polarized light that transmits through the first polarizing plate **110** and a polarization direction of polarized light that transmits through the PBS **114** are orthogonal to each other. The polarization direction of polarized light that transmits through the second polarizing plate **115** and the polarization direction of the polarized light transmitted by the PBS **114** coincide with each other.

[0025] In the above configuration, unpolarized light emitted from the right-eye display element **108** transmits through the first polarizing plate **110** and becomes linearly polarized light, and this linearly polarized light transmits through the first phase plate **111** and becomes circularly polarized light. The circularly polarized light that has transmitted through the half-mirror **112** transmits through the second phase plate **113** and becomes linearly polarized light, and since the polarization direction of this linearly polarized light is orthogonal to the polarization direction of the polarized light that transmits through the PBS **114**, it is reflected by the PBS **114**. The reflected linearly polarized light then transmits through the second phase plate **113** and becomes circularly polarized light.

[0026] The circularly polarized light that has been reflected by the half-mirror **112** transmits through the second phase plate **113** and becomes linearly polarized light. This linearly polarized light transmits through the PBS **114** because its polarization direction coincides with the polarization direction of the polarized light that transmits through the PBS **114**, and then transmits through the second polarizing plate **115** and is guided to the right eye **102**. The second polarizing plate **115** can reduce ghost light generated by external light, and increase the contrast of the displayed image. The above configuration is similarly applied to the left-eye display optical system.

[0027] Folding the optical path utilizing polarization as in this embodiment can reduce the thickness of the display optical system and the focal length, and achieve image observation at a wide angle of view.

[0028] FIG. **3** illustrates the external appearance of the HMD **101**. Since the HM **101** is worn on the observer's head, it may have a reduced weight. Thus, the lenses constituting the display optical system may be made of resin, which has a smaller specific gravity than glass, and in this embodiment, the lenses **104** and **106** are made of resin. The lenses **104** and **106** as aspherical lenses with a plano-convex shape can improve an aberration correcting effect. The lenses **105** and **107** are made of resin and have aspheric surfaces on both sides.

[0029] The exit pupil position of the display optical system in this embodiment is 35 mm, which is the sum of an eye relief of 25 mm and the eyeball's rotation radius of 10 mm, and the exit pupil diameter is 6 mm. Thereby, light in directions in which the eyeball rotates to observe up, down, left, or right can enter the eyeball. The eye relief may be 15 mm or more so that observers wearing glasses can also wear HMD **101**. Since a longer eye relief results in a larger lens outer shape and therefore a larger HMD **101**, the eye relief may be 25 mm or less.

[0030] FIG. **4** illustrates the second phase plate **113**, the PBS **114**, and the second polarizing plate **115**, which are laminated on the observation-side surface of lens **104** and adhered together by an adhesive. An adhesive layer **117** is provided between the observation-side surface of the lens **104** and the second phase plate **113**, an adhesive layer (first adhesive layer) **118** is provided between the second phase plate **113** and the PBS **114**, and an adhesive layer **119** is provided between the PBS **114** and the second polarizing plate **115**. Laminating the second phase plate **113**, the PBS **114**, and the second polarizing plate **115** in this manner can reduce the thickness of the display optical system. An antireflection (AR) film **116** for preventing reflection of external light is adhered to an observation-side surface of the second polarizing plate **115** via an adhesive layer **120**.

[0031] In this embodiment, the PBS **114** includes a thin film-like element (film element), and if the adhesive layer **118** between the PBS **114** and the second phase plate **113** has thickness variation (unevenness or irregularities) in the in-plane direction, unevenness corresponding to that unevenness will appear on the PBS **114**. In particular, if the thickness of the adhesive layer **118** between the PBS **114** and the second phase plate **113** disposed on the reflection side of the PBS **114** changes periodically, the PBS **114** with corresponding unevenness generates local optical power for the light reflected by the PBS **114**. In a case where local optical power is generated by the PBS **114**, a local focus shift occurs in the displayed image, and the displayed image is observed as a blurred image with decreased contrast.

[0032] FIG. **5** illustrates how the unevenness of the PBS **114** locally reduces the contrast in a displayed image including vertical lines. The contrast of the vertical lines is high near the center of FIG. **5**, but low in the left and right portions.

[0033] Accordingly, this embodiment reduces the thickness of the adhesive layer **118** between the PBS **114** and the second phase plate **113**, and suppresses the unevenness (particularly the periodic unevenness) of the adhesive layer **118** and thereby the generation of local optical power in the PBS **114**. More specifically, the thickness of the adhesive layer **118** is set to 15 μm, and the thickness variation is suppressed to 6 μm (tolerance±3 μm). Basically, the thickness d1 of the adhesive layer **118** between the PBS **114** having a reflecting action and the second phase plate **113** may be 5 μm or more and 20 μm or less so as to satisfy an inequality of $5\ \mu m \leq d1 \leq 20\ \mu m$. In a case where the thickness of the adhesive layer **118** is 20 μm or more, the thickness variation increases, unevenness is likely to appear on the PBS **114**, and the optical power generated by that unevenness increases. On the other hand, in a case where the thickness of the adhesive layer **118** becomes less than 5 μm, it becomes difficult to adhere the PBS **114** and the second phase plate **113**, and wrinkles and air bubbles are likely to occur during adhesion. The thickness d1 of the adhesive layer **118** may be 19 μm or less, 18 μm or less, or 16 μm or less. This is similarly applied to the thickness d1 of the adhesive layer in other embodiments described later.

[0034] A thickness variation amount Δd1 of the adhesive layer **118** may be less than 10 μm so as to satisfy an inequality of $0<\Delta d1<10$ μm. In a case where the thickness variation amount of the adhesive layer **118** is 10 μm or more, unevenness is likely to appear on the PBS **114**, and the optical power generated by the unevenness increases.

[0035] The observer is sensitive to a local contrast decrease near the center of the displayed image (for example, a range of 30° horizontally and 20° vertically, which is the effective visual field of the human eye). Therefore, the thickness variation of the adhesive layer **118** within the width of the light beam incident on the observer's eye near the optical axis of the display optical system, which corresponds to the vicinity of the center of the displayed image, may be as small as possible. More specifically, in a case where the light beam emitted from a pixel on the optical axis of the display optical system among the display elements is reflected by the PBS **114**, the ratio of the variation amount Δd1 to the light beam width Φ1 may be less than 0.002 so as to satisfy the following inequality:

$$0 < \Delta d1/\Phi 1 < 0.002$$

[0036] In this embodiment, the thickness variation amount Δd1 of the adhesive layer **118** near the center is 4 μm, and since the diameter of the pupil of the observer's eye (=Φ1) is about 4 mm, Δd1/Φ1 is 0.001.

[0037] In a case where the unevenness of the adhesive layer **118** is periodic, the period of the unevenness may be twice or more as long as the light beam width Φ1. In a case where the period of the unevenness is less than twice as long as the light beam width Φ1, the optical power of the PBS **114** caused by the unevenness of the adhesive layer **118** increases.

[0038] The thickness of the PBS **114**, 60 μm, is four times as long as the thickness of the adhesive layer **118**. As the thickness of the PBS **114** becomes large relative to the thickness of the adhesive layer **118**, the unevenness of the adhesive layer **118** will be less likely to appear on the PBS **114**, and local optical power is less likely to occur. Thus, the thickness of the PBS **114** may be three times or more as long as the thickness of the adhesive layer **118**. On the other hand, in a case where the thickness of the PBS **114** increases, it becomes difficult to reduce the thickness of the display optical system, so the thickness of the PBS **114** may be 15 times or less as long as the thickness of the adhesive layer **118**.

[0039] Thus, reducing the thickness of the adhesive layer **118** between the PBS **114** and the polarization element (second phase plate **113**) adjacent to and disposed on the reflection side of the PBS **114** and the thickness variation can reduce the unevenness generated on the PBS **114**. Since the PBS **114** has a reflecting action, the influence of local unevenness on the optical power is greater than that of a surface with a transmitting action, and local contrast decrease is likely to occur in the displayed image. Therefore, reducing the unevenness of the adhesive layer **118** between the PBS **114** and the second phase plate **113** adjacent to and disposed on the reflection side of the PBS **114** can reduce the unevenness of the PBS **114** and suppress the local contrast decrease in the displayed image.

[0040] FIG. **13**A illustrates an example of a display image different from that of FIG. **5**, in which a local contrast decrease occurs due to the unevenness of the adhesive layer **18**. Areas where the contrast is decreased are illustrated in black. In this display image, a plurality of multiple areas where the contrast is decreased, which gives an unnatural feeling. On the other hand, FIG. **13**B illustrates a display image in which the unevenness of the adhesive layer **18** is reduced as in this embodiment, and the local contrast decrease is suppressed.

[0041] While the thickness of the adhesive layer **118** between the PBS **114** and the second phase plate **113** has been described, but the thickness of the adhesive layer **119** between the PBS **114** and the second polarizing plate **115** may also be reduced to suppress the thickness variation. In this embodiment, the thickness of the adhesive layer **119** is 20 μm, and the thickness variation is 8 μm (±4 μm). The thickness variation of the adhesive layer **119** near the center is 5 μm, and a ratio of this thickness variation to the light beam width near the center is 0.00125.

[0042] In this embodiment, the AR film **116** is adhered to the observation-side surface of the second polarizing plate **115** via the adhesive layer **120**. Similarly to the PBS **114**, in a case where there is unevenness at the interface between the AR film **116** and air, local optical power is generated and the contrast decreases. Accordingly, this embodiment reduces the thickness of the adhesive layer **120** between the AR film **116** and the second polarizing plate **115** to suppress the unevenness of the adhesive layer **120**.

[0043] More specifically, the thickness d2 of the adhesive layer **120** is 14 μm, and the thickness variation Δd2 is 10 μm (±5 μm). Basically, the thickness d2 of the adhesive layer **120** between the AR film **116**, which has a transmitting effect, and the second polarizing plate **115** may be 5 μm or more and less than 20 μm so as to satisfy an inequality 5 μm≤d2<20 μm. In a case where the thickness of the adhesive layer **120** becomes 20 μm or more, the unevenness of the adhesive layer **120** increases, and unevenness corresponding to that unevenness will appear in the AR film **116**. In a case where the thickness of the adhesive layer **120** is less than 5 μm, the adhesive layer **120** reduces, it becomes difficult to attach the AR film **116** to the second polarizing plate **115**, and wrinkles and air bubbles are likely to occur during attachment.

[0044] The thickness d2 of the adhesive layer **120** may be 19 μm or less, 18 μm or less, or 16 μm or less. This is similarly applied to the thickness d2 of the adhesive layer in other examples described later.

[0045] The thickness variation Δd2 of the adhesive layer **120** may be less than 20 μm so as to satisfy the inequality $0<\Delta d2<20$ μm. In a case where the thickness variation is 20 μm or more, the unevenness of the adhesive layer **120** generates optical power in the AR film **116**.

[0046] Near the center, the thickness variation Δd2 of the adhesive layer **120** is 8 μm. Where Φ2 is a light beam width of a light beam emitted from the pixel on the optical axis of the display element in a case where the light beam transmits through the adhesive layer **120**, $\Delta d2/\Phi 2$ is 0.002. $\Delta d2/\Phi 2$ may be less than 0.005 so as to satisfy an inequality of $0<\Delta d2/\Phi 2<0.005$.

[0047] The focal length of the display optical system according to this embodiment is 12 mm, and in a case where the focal length of the display optical system is short and the optical power is large, optical power differences from the PBS **114** and the AR film **116** increase, and the influence is less likely. Thus, the focal length of the display optical system may be 20 mm or less, or 16 mm or less. In a case where the focal length is too short, the optical performance decreases and high-quality image observation becomes impossible, so the focal length f may be 10 mm or more, or 12 mm or more. That is, the following inequality may be satisfied:

$$10\ \text{mm} \leq f \leq 20\ \text{mm or } 12\ \text{mm} \leq f \leq 16\ \text{mm}$$

[0048] In this embodiment, the surface of the lens **104** on which the half-mirror **112** is vapor-deposited has a convex shape on the display element side. Vapor-depositing the half-mirror on this convex surface can achieve a wide angle of view and reduces the thickness of the display optical system. Making the convex surface on which the half-mirror **112** is vapor-deposited aspheric can improve the aberration correcting effect.

[0049] In this embodiment, the observation-side surface of the lens **104** on which the second phase plate **113** and the PBS **114** are laminated has a planar shape. This configuration can secure a sufficient eye relief and reduce the thickness of the display optical system. In a case where this surface is concave on the observation side, the thickness of the lens increases in order to secure the eye relief in the peripheral portion. Moreover, in a case where it is convex on the observation side, the thickness of the lens increases in order to secure the thickness of the edge of the lens. Therefore, in this embodiment, the lens **104** is a plano-convex lens.

[0050] In this embodiment, both the first phase plate **111** and the second phase plate **113** are quarter waveplates, but the phase difference may be shifted from $\lambda/4$ so as to cancel the birefringences of the lenses **104** and **105**. In this case, the sum of the phase differences of the lens **104** and the second phase plate **113** may be $3\lambda/20$ or more and $7\lambda/20$ or less. The sum of the phase differences of the lens **105** and the first phase plate **111** may be $3\lambda/20$ or more and $7\lambda/20$ or less. In a case where it becomes outside this range, the intensity of the ghost light increases and natural image observation becomes impossible.

[0051] This embodiment uses an organic EL element that emits unpolarized light as the display element, but may use a liquid crystal display that emits linearly polarized light as the display element to eliminate the first polarizing plate **110** and reduce the thickness of the display optical system.

Second Embodiment

[0052] FIG. **6** illustrates the configuration of an HMD **201** as an image display apparatus using a display optical system according to a second embodiment, viewed from above. Reference numeral **202** denotes the right eye of the observer, and reference numeral **203** denotes the left eye of the observer. Lenses **204** and **205** are cemented together and form a part of the right-eye display optical system, and lenses **206** and **207** are cemented together and form a part of the left-eye display optical system. Reference numeral **208** denotes a right-eye display element, and reference numeral **209** denotes a left-eye display element, and each of them is also made of an organic EL element in this embodiment.

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

[0054] Each of the right-eye display optical system and the left-eye display optical system has a focal length f2 of 13 mm, a horizontal display angle of view of 60°, a vertical display angle of view of 60°, and a diagonal display angle of view $2\times\theta 2$ of 78°. In order to enhance the immersion of the observer who observes an image, the diagonal display angle of view may be 75° or more. An eye relief E**2** is 18 mm.

[0055] The display optical system according to this embodiment is also an optical system that folds the optical path by utilizing polarization, and its specific configuration will be described using the right-eye display optical system illustrated in FIG. **7**. The right-eye display optical system includes, in order from the display element side, a first polarizing plate **210** disposed between the right-eye display element **208** and the lens **205**, a PBS **212** disposed between the lens **204** and the lens **205**, a first phase plate **213**, a half-mirror **214**, a second phase plate **215**, a second polarizing plate **216**, and an AR film **217** disposed between the lens **204** and the right eye **202**.

[0056] Each of the first phase plate **213**, the half-mirror **214**, the second phase plate **215**, and the second polarizing plate **216** has a planar shape and they are laminated. Each of the first phase plate **213** and the second phase plate **215** includes a quarter waveplate.

[0057] A polarization direction of polarized light that transmits through the first polarizing plate **210** and a polarization direction of polarized light that transmits through the PBS **212** coincide with each other, and the slow axis of the first phase plate **213** is tilted by 45° with respect to these polarization directions. The polarization direction of the polarized light that transmits through the first polarizing plate **210** and the slow axis of the second phase plate **215** are tilted by −45°. The polarization direction of the polarized light that transmits through the PBS **212** and the polarization direction of the polarized light that transmits through the second polarizing plate **216** coincide with each other.

[0058] In the above configuration, the unpolarized light emitted from the right-eye display element **208** transmits through the first polarizing plate **210** and becomes linearly polarized light. This linearly polarized light transmits through the PBS **212** and then through the first phase plate **213** and becomes circularly polarized light. The circularly polarized light reflected by the half-mirror **214** transmits through the first phase plate **213** and becomes linearly polarized light. Since the polarization direction of this linearly polarized light is perpendicular to the polarization direction of the polarized light that transmits through the PBS **212**, it is reflected by the PBS **212** and then transmits through the first phase plate **213** and becomes circularly polarized light. The circularly polarized light that transmits through the half-mirror **214** transmits through the second phase plate **215** and becomes linearly polarized light. Since the polarization direction of this linearly polarized light coincides with the polarization direction of the polarized light that transmits through the second polarizing plate **216**, it transmits through the second polarizing plate **216** and then through the AR film **217** and is guided to the right eye **202**.

[0059] In this embodiment, the second polarizing plate **216** is disposed to absorb the light that is emitted from the right-eye display element **208** and first transmits through the half-mirror **214**. The above configuration is similarly applied to the left-eye display optical system.

[0060] Folding the optical path utilizing polarization as in this embodiment can reduce the thickness of the display optical system and the focal length, and achieve image observation at a wide angle of view.

[0061] In this embodiment, each of the lenses **204**, **205**, **206**, and **207** is made of resin to reduce the weight of the display optical system, and aspheric lenses can enhance the aberration correcting effect. The exit pupil position of the display optical system in this embodiment is 28 mm, which is the eye relief of 18 mm plus the eyeball rotation radius of 10 mm, and the exit pupil diameter is 6 mm.

[0062] FIG. **8** illustrates the first phase plate **213**, half-mirror **214**, second phase plate **215**, and second polarizing plate **216**, which are laminated on the observation-side surface of lens **104** and adhered together by an adhesive. An adhesive layer **218** is provided between the observation-side surface of the lens **204** and the first phase plate **213**, an adhesive layer (first adhesive layer) **219** is provided between the first phase plate **213** and the half-mirror **214**, and an adhesive layer **220** is provided between the half-mirror **214** and the second phase plate **215**. An adhesive layer **221** is provided between the second phase plate **215** and the second polarizing plate **216**.

[0063] Laminating the first phase plate **213**, the half-mirror **214**, the second phase plate **215**, and the second polarizing plate **216** in this manner can reduce the thickness of the display optical system. An antireflection (AR) film **217** for preventing reflection of external light is adhered to the observation-side surface of the second polarizing plate **216** via an adhesive layer **222**.

[0064] In this embodiment, the half-mirror **214** includes a film element. If the adhesive layer **219** between the half-mirror **214** and the first phase plate **213** adjacent to and disposed on the reflection side of the half-mirror **214** has a thickness variation (unevenness or irregularities) in the in-plane direction, unevenness corresponding to that unevenness will appear on the half-mirror **214**. If the half-mirror **214** has unevenness, local optical power is generated in the half-mirror **214** for the light reflected by the half-mirror **214**, a local focus shift occurs in the displayed image, and the displayed image is observed as a blurred image with decreased contrast.

[0065] Accordingly, this embodiment reduces the thickness of the adhesive layer **219** between the half-mirror **214** and the first phase plate **213**, and suppresses the unevenness of the adhesive layer **219** and thereby the generation of local optical power in the half-mirror **214**. More specifically, similarly to the first embodiment, the thickness of the adhesive layer **219** is set to 10 μm, and the variation amount in the thickness is suppressed to 5 μm (±2.5 μm). Basically, the thickness (d1) of the adhesive layer **219** between the half-mirror **214** having a reflecting action and the first phase plate **213** may be 5 μm or more and less than 20 μm. Similarly to the first embodiment, the thickness variation (Δd1) of the adhesive layer **219** may be less than 10 μm.

[0066] Similarly to the first embodiment, the thickness variation of the adhesive layer **219** within the width of the light beam incident on the observer's eye near the optical axis of the display optical system, which corresponds to the vicinity of the center of the display image, may be as small as possible. More specifically, in a case where the light beam emitted from a pixel on the optical axis of the display optical system among the display elements is reflected by the half-mirror **214**, the ratio (Δd1/Φ1) of the thickness variation amount (Δd1) to the light beam width (Φ1) may be less than 0.002. In this embodiment, the thickness variation of the adhesive layer **219** near the center is 3 μm, and the diameter of the pupil of the observer's eye is about 4 mm, so the above ratio is 0.00075. The thickness of the half-mirror **214**, 40 μm, is four times as long as the thickness of the adhesive layer **219**. The thickness of the half-mirror **214** may be 3 times or more and 15 times or less as long as the thickness of the adhesive layer **219**.

[0067] The thickness of the adhesive layer **220** between the half-mirror **214** and the second phase plate **215** may be reduced to suppress the thickness variation. In this embodiment, the thickness of the adhesive layer **220** is 10 μm, and the thickness variation is 5 μm (±2.5 μm). The thickness variation of the adhesive layer **220** near the center is 3 μm, and the ratio to the light beam width near the center is 0.00075.

[0068] In this embodiment, as illustrated in FIG. **9**, an adhesive layer **223** is provided between the lens **205** and the PBS **212** to adhere them together, and an adhesive layer **224** is provided between the PBS **212** and the lens **204** to adhere them together. By adhering the PBS **212** having a curved surface to the lenses **204** and **205** in this manner, the design freedom of the display optical system is improved, and a thinner structure and a wider angle of view can be achieved.

[0069] In this embodiment, the PBS **212** also includes a film element. Therefore, if the adhesive layer **224** between the PBS **212** and the lens **204** adjacent to and disposed on the reflection side of the PBS **212** has unevenness, unevenness corresponding to that unevenness will appear on the PBS **212**, and the PBS **212** will generate local optical power for the light reflected by the PBS **212**. As a result, a local focus shift occurs in the displayed image, and the displayed image is observed as a blurred image with decreased contrast.

[0070] Accordingly, this embodiment also reduces the thickness of the adhesive layer (first adhesive layer) **224**, and suppresses the thickness variation and the unevenness of the adhesive layer **224**. This embodiment similarly reduces the thickness of the adhesive layer **223** between the PBS **212** and the lens **205**. More specifically, the thickness (d1) of each of the adhesive layers **223** and **224** is 15 μm, and the thickness variation amount (Δd1) is 8 μm (±4 μm). Basically, the thickness of the adhesive layer **224** between the PBS **212** having a reflecting action and the lens **204** may be 5 μm or more and less than 20 μm. The thickness variation of the adhesive layer **224** may be less than 10 μm.

[0071] The thickness variation of each of the adhesive layers **223** and **224** near the center is 3 μm, and since the size of the pupil of the observer's eye is about 4 mm, the ratio to the light beam width (Δd1/Φ1) near the center is 0.00075. This ratio may be less than 0.002. The thickness of the PBS **212** is 80 μm, which is 5.3 times as long as the thickness of each of the adhesive layers **223** and **224**. The thickness of the PBS **212** may be 3 times or more and 15 times or less as long as the thickness of the adhesive layers **223** and **224**.

[0072] Thus, this embodiment reduces the thickness of the adhesive layer between the half-mirror **214** or PBS **212** and the polarization element (first phase plate **213**) or lens **204** adjacent to and disposed on the reflection side of the half-mirror **214** or PBS **212** to suppress the thickness variation. This configuration can reduce unevenness on the half-mirror **214** or PBS **212**. Since the half-mirror **214** or PBS **212** has a reflecting action, its local unevenness more significantly affects the optical power than a surface with a transmitting action, and is more likely to cause a local contrast decrease in the displayed image. Therefore, reducing the unevenness of the adhesive layer between the half-mirror **214** or PBS **212** and the first phase plate **213** or lens **204** adjacent to and disposed on the reflection side of the half-mirror **214** or PBS **212** can reduce the unevenness of the half-mirror **214** or PBS **212** and suppress the local contrast decrease in the displayed image.

[0073] In this embodiment, the AR film **217** is adhered to the second polarizing plate **216** via the adhesive layer (second adhesive layer) **222**. Similarly to the half-mirror **214** and the PBS **212**, in a case where there is unevenness at the interface between the AR film **217** and air, local optical power is generated in the AR film **217**, and the contrast of the displayed image decreases. Accordingly, this embodiment reduces the thickness of the adhesive layer **222** between the AR film **217** and the second polarizing plate **216** to suppress the thickness variation and the unevenness of the AR film **217**.

[0074] In this embodiment, the thickness of the adhesive layer **222** is 10 μm, and the thickness variation is 10 μm (±5 μm). Basically, the thickness (d2) of the adhesive layer **222** between the AR film **217**, which has a transmitting effect, and the second polarizing plate **216** may be 5 μm or more and less than 20 μm, and the thickness variation (Δd2) may be less than 20 μm. The thickness variation of the adhesive layer **222** near the center (Δd2) is 10 μm, and the ratio (Δd2/Φ2) to the light beam width (Φ2) near the center is 0.0025. This ratio may be less than 0.005.

[0075] Each pair of the lenses **204** and **205** and the lenses **206** and **207** in this embodiment is a cemented lens. The cemented lens can be easily held in the HMD **201** in comparison with using two separate lenses. Thus, the lens surface on which the half-mirror **214** is vapor-deposited may be the observation-side surface of the lens **205**. Even in this case, the surface on which the half-mirror **214** is vapor-deposited has a convex shape toward the display element side. Vapor-depositing the half-mirror **214** on the convex surface can achieve a wide angle of view and reduce the thickness of the display optical system. Furthermore, making the convex surface on which the half-mirror **214** is vapor-deposited an aspheric shape can enhance the aberration correcting effect.

[0076] The observation-side surface of the lens **204** on which the first phase plate **213**, the PBS **212**, etc. are laminated has a planar shape. Thereby, the thickness of the display optical system can be reduced and sufficient eye relief can be secured. The lens **204** is a plano-convex lens.

[0077] In this embodiment, each of the first and second phase plates **213** and **215** is a quarter waveplate, but the phase difference may be shifted from λ/4 so as to cancel the birefringences of the lenses **204** and **205**. In this case, the sum of the phase differences of the lens **204** and the second phase plate **215** may be 3λ/20 or more and 7λ/20 or less. The sum of the phase differences of the lens **205** and the first phase plate **213** may be 3λ/20 or more and 7λ/20 or less. In a case where it becomes outside this range, the intensity of ghost light increases and natural image observation becomes impossible.

[0078] This embodiment uses an organic EL element that emits unpolarized light as the display element, but may use a liquid crystal display that emits linearly polarized light as the display element to eliminate the first polarizing plate **210** and reduce the thickness of the display optical system.

Third Embodiment

[0079] FIG. **10** illustrates a display optical system according to a third embodiment. This embodiment is a variation of the second embodiment, and those elements in this embodiment, which are corresponding elements in the second embodiment, will be designated by the same reference numerals.

[0080] In this embodiment, a PBS **312** and a first phase plate **313** are disposed between the lenses **204** and **205**, and a half-mirror **314**, a second phase plate **315**, a second polarizing plate **316**, and an AR coating **317** are laminated on the observation-side surface of the lens **204**. The half-mirror **314** is evaporated on the display-element-side surface of the lens **204**, and the AR coating **317** is evaporated on the observation-side surface of the second polarizing plate **316**.

[0081] In this configuration, as illustrated in FIG. **11**, an adhesive layer **319** is provided between the second phase plate **315** and the second polarizing plate **316** to adhere them together. An adhesive layer **318** is provided between the second phase plate **315** and the half-mirror **314** evaporated on the lens **204** to adhere them together.

[0082] As illustrated in FIG. **12**, an adhesive layer **322** is provided between the PBS **312** and the first phase plate **313** to adhere them together. An adhesive layer **321** is provided between the PBS **312** and the lens **205**, and an adhesive layer **323** is provided between the first phase plate **313** and the lens **204**.

[0083] The PBS **312** includes a film element, and if the adhesive layer **322** between the PBS **312** and the polarization element (first phase plate **313**) adjacent to and disposed on the reflection side of the PBS **312** has unevenness, unevenness corresponding to that unevenness will appear on the PBS **312**. As a result, local optical power is generated in the PBS **312** for the light reflected by the PBS **312**. As a result, a local focus shift occurs in the displayed image, and the displayed image is observed as a blurred image with decreased contrast.

[0084] Accordingly, this embodiment reduces the thickness of the adhesive layer (first adhesive layer) **322** between the PBS **312** and the first phase plate **313** to suppress the thickness variation and thereby the unevenness on the PBS **312**. In this embodiment, the thickness (d1) of the adhesive layer **322** is 10 μm, and the thickness variation (Δd1) is 8 μm (±4 μm). Basically, the thickness of the adhesive layer **322** may be 5 μm or more and less than 20 μm, and the thickness variation may be less than 10 μm.

[0085] The thickness variation of the adhesive layer **322** near the center is 4 μm, and since the size of the pupil of the observer's eye is about 4 mm, a ratio (Δd1/Φ1) to the light beam width (Φ1) near the center is 0.001. This ratio may be less than 0.002. The thickness of the PBS **312** is 45 μm, which is 4.5 times as long as the thickness of the adhesive layer **322**. The thickness of PBS **312** may be 3 times or more and 15 times or less as long as the thickness of the adhesive layer **322**.

[0086] The thickness of the adhesive layer **321** between the PBS **312** and lens **205** as well may be reduced to suppress the thickness variation. In this embodiment, the thickness of the adhesive layer **321** is 15 μm, and the thickness variation is 6 μm (±3 μm). The thickness variation of the adhesive layer **321** near the center is 4 μm, and the ratio to the light beam width near the center is 0.001.

[0087] 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.

[0088] Each embodiment can provide a display optical system in which even if an adhesive layer for attaching a film element is provided, a local contrast decrease of a displayed image is small.

[0089] This application claims priority to Japanese Patent Application No. 2024-019879, which was filed on Feb. 14, 2024, and which is hereby incorporated by reference herein in its entirety.

What is claimed is:

1. A display optical system configured to guide light from a display element to an observation side, the display optical system comprising:

a half-transmissive reflective surface;

a polarization separation surface; and

a plurality of polarization elements,

wherein at least one of surfaces having refractive power in the display optical system is aspheric,

wherein at least one of the half-transmissive reflective surface or the polarization separation surface includes a film element,

wherein the film element is adhered to one of the plurality of polarization elements or a lens via a first adhesive layer on a reflection side of the film element, and

wherein the following inequality is satisfied:

$$5\,\mu\text{m} \le d1 < 20\,\mu\text{m}$$

where d1 is a thickness of the first adhesive layer.

2. The display optical system according to claim **1**, wherein the following inequality is satisfied:

$$0<\Delta d1<10\ \mu\text{m}$$

where Δd1 is a thickness variation amount in an in-plane direction of the first adhesive layer.

3. The display optical system according to claim **1**, wherein in a case where a light beam emitted from a pixel on an optical axis of the display optical system among the plurality of display elements is reflected by the film element, the following inequality is satisfied:

$$0 < \Delta d1/\Phi1 < 0.002$$

where Δd1 is a thickness variation amount in an in-plane direction of the first adhesive layer, and Φ1 is a light beam width of the light beam.

4. The display optical system according to claim **3**, wherein in a case where the thickness variation amount changes periodically in the in-plane direction, a changing period of the thickness variation amount is twice or more as long as the light beam width Φ1.

5. The display optical system according to claim **1**, wherein the thickness of the film element is three times or more and 15 times or less as long as the thickness of the first adhesive layer.

6. The display optical system according to claim **1**, comprising, in order from a display element side:

a first polarizing plate;

a first phase plate;

the half-transmissive reflective surface;

a second phase plate;

the polarization separation surface; and

a second polarizing plate,

wherein the film element constituting the polarization separation surface is adhered to the second phase plate via the first adhesive layer.

7. The display optical system according to claim **1**, comprising, in order from a display element side:

a first polarizing plate;

the polarization separation surface;

a first phase plate;

the half-transmissive reflective surface;

a second phase plate; and

a second polarizing plate,

wherein the film element constituting the half-transmissive reflective surface is adhered to the first phase plate via the first adhesive layer.

8. The display optical system according to claim **1**, comprising, in order from a display element side:

a first polarizing plate;

the polarization separation surface;

the lens;

a first phase plate;

the half-transmissive reflective surface;

a second phase plate; and

a second polarizing plate,

wherein the film element constituting the polarization separation surface is adhered to the lens via the first adhesive layer.

9. The display optical system according to claim **1**, further comprising a polarizing plate disposed closest to the observation side, and an antireflection film is adhered to the polarizing plate via a second adhesive layer, and

wherein the following inequality is satisfied:

$$5\,\mu\text{m} \le d2 < 20\,\mu\text{m}$$

where d2 is a thickness of the second adhesive layer.

10. The display optical system according to claim **8**, wherein the following inequality is satisfied:

$$0<\Delta d2<20\ \mu m$$

where $\Delta d2$ is a thickness variation amount of the second adhesive layer in an in-plane direction of the second adhesive layer.

11. The display optical system according to claim **10**, wherein in a case where a light beam emitted from a pixel on an optical axis of the display optical system among the plurality of display elements transmits through the second adhesive layer, the following inequality is satisfied:

$$0<\Delta d2/\Phi 2<0.005$$

where $\Phi 2$ is a light beam width of the light beam that transmits through the second adhesive layer.

12. The display optical system according to claim **1**, wherein the following inequality is satisfied:

$$10\ mm \leq f \leq 20\ mm$$

where f is a focal length of the display optical system.

13. An image display apparatus comprising:

a display optical system configured to guide light from a display element to an observation side; and

a display element,

wherein the display optical system includes:

a half-transmissive reflective surface;

a polarization separation surface; and

a plurality of polarization elements,

wherein at least one of surfaces having refractive power in the display optical system is aspheric,

wherein at least one of the half-transmissive reflective surface or the polarization separation surface includes a film element,

wherein the film element is adhered to one of the plurality of polarization elements or a lens via a first adhesive layer on a reflection side of the film element, and

wherein the following inequality is satisfied:

$$5\ \mu m \leq d1 < 20\ \mu m$$

where d1 is a thickness of the first adhesive layer.

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