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Ultra-wide angle lens systems with external pupil

Abstract

Embodiments of the present disclosure generally relate to an optical system having a lens system configured to have a wide field of view and high resolution. The optical system includes three or more lens groups with ability to combat optical aberrations and produce a pupil outside of the lens group. The lens system as an image projection system projects a pattern or image rendered on a flat reticle or display of finite distance to the infinity. In an imaging system, the lens system collects light from infinity and forms an image of that object on a sensor.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application claims benefit of U.S. Provisional Patent Application No. 63/209,552, filed Jun. 11, 2021, which is herein incorporated by reference in its entirety.

BACKGROUND
Field
(1) Embodiments of the present disclosure generally relate to an optical system. More specifically, embodiments described herein provide for an optical system having a lens system configured to have a wide field of view and high resolution.
Description of the Related Art
(2) Optical systems used for imaging or used as light engines are common in the art. The optical systems have many different application, such as to take pictures or for use in augmented reality/virtual reality applications, including with cameras and scanners. The optical systems generally include imaging systems that contain multiples lenses, composite lenses, and films, in order to reduce aberrations caused by imperfections in lenses. Lenses with chromatic aberrations cause "fringes" of color along boundaries that separate dark and bright parts of images.
(3) Conventional optical systems attempting to achieve a wide field of view with a high resolution result in undesired increases in chromatic aberrations. Therefore, there is a need for an apparatus and method that can reduce chromatic aberrations while still maintaining a wide field of view with high resolution.
SUMMARY
(4) In one embodiment, an optical system is provided. The optical system includes a display configured to render an image by projecting a plurality of light waves and a lens system. The lens system includes a first lens group configured to relay the light waves to a center of the lens system, a second lens group adjacent to the first lens group and configured to flatten a field of the light waves; and a third lens group adjacent to the second lens group. The third lens group is configured to form a pupil on a pupil plane outside of the lens system. The optical system further includes a light injection port. The pupil plane is aligned with the light injection port and the light waves are projected to the light injection port.
(5) In another embodiment, a lens system is provided. The lens system includes a first lens group configured to relay a plurality of light waves to a center of the lens system. The first lens group is a double Gauss lens. The lens system includes a second lens group adjacent to the first lens group. The second lens group is a flat-field lens configured to flatten a field of the light waves. The lens system includes a third lens group adjacent to the second lens group. The third lens group includes

a bi-convex lens and a positive meniscus lens and is configured to form a pupil on a pupil plane outside of the lens system.
(6) In yet another embodiment, a method of using a lens system is provided. The method includes projecting a plurality of light waves from a display to a lens system. The lens system includes a first lens group configured to relay the light waves to a center of the lens system. The first lens group is a double Gauss lens. The lens system includes a second lens group adjacent to the first lens group. The second lens group is a flat-field lens configured to flatten a field of the light waves. The lens system includes a third lens group adjacent to the second lens group. The third lens group includes a bi-convex lens and a positive meniscus lens and is configured to form a pupil on a pupil plane outside of the lens system. The method further incudes projecting the light waves to a light injection port such that a pupil on a pupil plane is formed outside of the lens system.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.
(2) FIGS. **1**A and **1**B are a schematic, side views of an optical system, according to embodiments described herein.
(3) FIG. **2** is a flow diagram of a method of projecting light waves with an optical system, according to embodiments described herein.
(4) FIG. **3** is a flow diagram of a method of imaging light waves with an optical system, according to embodiments described herein.
(5) FIG. **4** is a schematic, cross-sectional view of an optical system, according to embodiments described herein.
(6) To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.
DETAILED DESCRIPTION
(7) Embodiments of the present disclosure generally relate to an optical system. More specifically, embodiments described herein provide for an optical system having a lens system configured to have a wide field of view and high resolution.
(8) An optical system having an external pupil is described herein. The optical system is configured to have a wide field of view with high resolution, while decreasing aberrations. The optical system includes a lens system that includes multiple lens groups that projects a pattern or image rendered on a flat reticle or display of finite distance to infinity. Alternatively, the lens system collects light from infinity and forms an image of that object on a flat surface.
(9) The combination of a large field of view, a pupil external of the lens system, and high resolution poses is challenging to fabricate. Large field of view requires high correcting power for off-axis aberrations, which include coma, field curvature, astigmatism, and lateral color. To correct the off-axis aberration, lens systems of symmetry may be implemented. However, achieving an external pupil with the symmetry in design, constitutes a challenge for obtaining wide field angle and large pupil size. As such, the optical system described below allows for large field of view, a pupil external of the lens system, and high resolution.

(10) FIG. **1**A is a schematic, side view of an optical system **100**A. The optical system **100**A is a projection system. For example, the optical system **100**A is a projection light engine for virtual reality or augmented reality related applications. In another example, the optical system **100**A is utilized as an imaging camera in a metrology system for testing image quality or optical performance of virtual reality or augmented reality display components. In other examples, the optical system **100**A is utilized in a microscope or telescope assembly. The optical system **100**A includes a display **102**, a lens system **104**, and a light injection port **106**.
(11) In one embodiment, which can be combined with other embodiments described herein, the display **102** is a display panel, micro-display, a reticle with a pattern, or other image producing device. In embodiments where the display **102** is a reticle, the size of the reticle is between about 10 mm and about 40 mm. In one embodiment, which can be combined with other embodiments described herein, an intermediate image from a primary lens of a telescope or microscope is rendered by the display **102**. The display **102** is configured to render an image that is projected to the light injection port **106**. The display **102** includes a plurality of pixels **108**R, **108**G, **108**B. The plurality of pixels **108**R, **108**G, **108**B combine to render the image. Although only three pixels are shown in FIG. **1**A for ease of explanation, a display **102** is not limited in the number of pixels that are located on the display **102**. The pixel **108**R corresponds to a red pixel, the pixel **108**G corresponds to a green pixel, and the pixel **108**B corresponds to a blue pixel. Each pixel **108**R, **108**G, **108**B emits a light wave **110**. For example, the pixel **108**R emits a light wave **110**R, the pixel **108**G emits a light wave **110**G, and the pixel **108**B emits a light wave **110**G. The light wave **110**R, **110**G, **110**B are collectively referred to as the light waves **110**.
(12) The light waves **110** are emitted from the display **102** to the lens system **104**. The lens system **104** includes three or more lens groups. For example, the lens system **104** includes a first lens group **112**, a second lens group **114**, and a third lens group **116**. The second lens group **114** is disposed between the first lens group **112** and the third lens group **116**. The multiple lens groups of the lens system **104** are configured to reduce optical aberrations in the optical system **100**A, while maintaining high imaging performance. The lens system **104** projects the pattern or image rendered from the display **102** at a finite distance to the infinity. As such, the lens system **104** is telecentric. The lens system **104** has an effective focal length of between about 10 mm and about 30 mm. The total mass of the lens system **104** is between about 50 g and about 200 g.
(13) The light injection port **106** is configured to receive the light waves **110** from the lens system **104**. For example, the light injection port **106** may be an augmented, virtual, mixed/merged reality device, or other pupil expanding device. Examples of such devices include waveguide displays or other head mounted displays used in augmented reality glasses or goggles and the like. In some examples, the light injection port **106** corresponds to a human eye for use in microscope or telescope applications. In some examples, the light injection port **106** corresponds to an effective entrance aperture to mimic a human eye location during the metrology of a virtual reality or augmented reality display. In some examples, the light injection port **106** is one of a waveguide combiner or a metasurface-based combiner.
(14) The maximum diameter of the lens system **104** is defined as maximum aperture **115**. For example, the maximum aperture **115** is between about 20 mm and about 50 mm. The lens system **104** forms a pupil outside of the lens system **104** on a pupil plane **118**. The pupil is defined as the fourier image of the image producing device. The pupil is formed where the light waves **110** intersect at the pupil plane **118** (e.g., where light waves across entire field of view intersect). As shown, the pupil plane **118** is external of the lens system **104**. In some embodiments, which can be combined with other embodiments described herein, the pupil plane **118** is aligned with the light injection port **106**. The distance between the lens system **104** and the pupil plane **118** is defined as pupil relief distance **120**. The pupil relief distance **120** is between about 1 mm and about 10 mm. The pupil has a pupil diameter **124** defined as the diameter of the pupil on the pupil plane **118**. The pupil diameter **124** is between about 1 mm and about 6 mm. A field of view **122** of the lens system

104 is defined as the angle through which the light waves **110** are incident on the light injection port **106**. The lens system **104** is a telecentric lens system, which improves uniform brightness of the image.

(15) By having the pupil plane **118** aligned with the light injection port **106**, performance of the optical system **100**A is improved. For example, when the light injection port **106** is a waveguide, the lens system **104** allows for the light waves **110** to be efficiently coupled in and out of waveguide. The lens system **104** is capable of a wide field of view **122** and has a large pupil relief distance **120** while also achieving high modulation transfer function (MTF) performance. The lens system **104** includes a field of view **122** greater than about 80 degrees, pupil diameter **124** greater than about 3 mm, and the pupil relief distance **120** is greater than about 5 mm. Additionally, the lens system **104** has a modulation transfer function (MTF) performance greater than about 0.3 at 30 cycles per degree. The MTF performance measures the loss in contrast between the display **102** and the image formed on the light injection port **106**.

(16) The lens system **104** includes a first lens group **112**, a second lens group **114**, and a third lens group **116**. The combination of the first lens group **112**, the second lens group **114**, and the third lens group **116** in combination combat optical aberrations that may occur during use of the optical system **100**A. For example, the lens system **104** reduces severe coma aberration, lateral color, field curvature, astigmatism, distortion and other optical aberrations. Each lens group of the lens system **104** includes one or more lens elements **126**. Each lens element **126** is an optical component with refractive power. For example, the lens elements **126** may be one or more of a relay lens, a positive meniscus lens, a negative meniscus lens, a convex lens, concave lens, or doublet lens. Each lens element **126** is made from optical glass, polymer, resin or any other refractive optical materials. Each lens element **126** can include a standard spherical surface, conic surface, aspherical surface, free form surface, diffractive surface or combinations thereof.

(17) The first lens group **112** is a double gaussian lens. The first lens group **112** is configured to prevent off-axis aberrations including coma, lateral color, and astigmatism which leads to high symmetry of the light waves **110** incident on the first lens group. For example, when the light waves **110** are incident on the first lens group **112** with off-axis aberrations, the first lens group **112** improves the symmetry of the light waves **110**. In one embodiment, which can be combined with other embodiments described herein, the first lens group **112** is a double Gauss lens. In another embodiment, which can be combined with other embodiments described herein, the first lens group **112** can include any number of the lens elements **126** such that the first lens group **112** is any lens stack which improves symmetry of the light waves **110**. In other words, the first lens group **112** relays an image to the center of the second lens group **114**.

(18) The second lens group **114** is a flat-field lens. The second lens group **114** is configured to handle field curvature of the light waves **110**. In one embodiment, which can be combined with other embodiments described herein, the second lens group **114** includes a meniscus lenses and a bi-convex field lens adjacent to eachother. In other words, the second lens group **114** corrects the curvature of the light waves **110**. For example, the light waves **110** become flatter after passing through the second lens group **114**.

(19) The third lens group **116** includes a bi-convex lens and a positive meniscus lens. The third lens group **116** is configured to form the pupil on the pupil plane **118** outside of the lens system **104** with large pupil relief distance **120**. The third lens group **116** is an eyepiece lens.

(20) FIG. **1**B is a schematic, side view of an optical system **100**B. The optical system **100**A is an imaging system. For example, the optical system **100**B may be used for sensing operations. In other examples, the optical system **100**B is utilized in a wide-angle camera or sensor lens. The optical system **100**B includes a virtual display **132**, a lens system **134**, and a sensor **136**.

(21) In one embodiment, which can be combined with other embodiments described herein, the virtual display **132** is a virtual display from an AR or VR device. For example, the virtual display **132** includes a virtual image from a waveguide display. The virtual display **132** is configured to

collect light from infinity and form an image from the virtual display **132** on a flat surface (e.g., the sensor **136**). The virtual display **132** emits one or more light waves **110** from infinity to the lens system **134**. For example, the virtual display **132** emits a light wave **110**R, a light wave **110**G, and a light wave **110**G. The light wave **110**R, **110**G, **110**B are collectively referred to as the light waves **110**.

(22) The light waves **110** are emitted from the virtual display **132** to the lens system **134**. The lens system **134** includes three or more lens groups. For example, the lens system **104** includes a first lens group **112**, a second lens group **114**, and a third lens group **116**. The lens system **134** is similar to the lens system **104**, however the first lens group **112** and the third lens group **116** are switched positions. The second lens group **114** is disposed between the first lens group **112** and the third lens group **116**. The multiple lens groups of the lens system **104** are configured to reduce optical aberrations in the optical system **1006**, while maintaining high imaging performance. The lens system **134** has an effective focal length of between about 10 mm and about 30 mm. The total mass of the lens system **134** is between about 50 g and about 200 g.

(23) The sensor **136** is configured to receive the light waves **110** from the lens system **134**. For example, the sensor **136** is an active-pixel sensor, which includes a plurality of pixel sensor unit cells configured to sense each light wave **110**. Examples of such devices include CMOS or CCD sensors. In some examples, the sensor **136** is included in a camera system used for capturing images.

(24) The maximum diameter of the lens system **134** is defined as maximum aperture **115**. For example, the maximum aperture **115** is between about 20 mm and about 50 mm. A pupil is formed outside of the lens system **134** on a pupil plane **118**. The pupil is defined as the fourier image of the sensor **136**. The pupil is formed between the virtual display **132** and the lens system **134**. The pupil is formed where the light waves **110** intersect at the pupil plane **118**. As shown, the pupil plane **118** is external of the lens system **134**. The distance between the lens system **134** and the pupil plane **118** is defined as pupil relief distance **120**. The pupil relief distance **120** is between about 1 mm and about 10 mm. The pupil has a pupil diameter **124** defined as the diameter of the pupil on the pupil plane **118**. The pupil diameter **124** is between about 1 mm and about 6 mm. A field of view **122** of the lens system **134** is defined as the angle through which the light waves **110** are projected from the virtual display **132**. The optical system **1006** is configured to be a wide angle system with a field of view greater than about 80 degrees.

(25) The lens system **104** is capable of a wide field of view **122** and has a large pupil relief distance **120** while also achieving high modulation transfer function (MTF) performance. The lens system **104** includes a field of view **122** greater than about 80 degrees, pupil diameter **124** greater than about 3 mm, and the pupil relief distance **120** is greater than about 5 mm. Additionally, the lens system **104** has a modulation transfer function (MTF) performance greater than about 0.3 at 30 cycles per degree. The MTF performance measures the loss in contrast between the display **102** and the image formed on the light injection port **106**.

(26) The lens system **134** includes a first lens group **112**, a second lens group **114**, and a third lens group **116**. The combination of the first lens group **112**, the second lens group **114**, and the third lens group **116** in combination combat optical aberrations that may occur during use of the optical system **1006**. For example, the lens system **134** reduces severe coma aberration, lateral color, field curvature, astigmatism, distortion and other optical aberrations. Each lens group of the lens system **134** includes one or more lens elements **126**. Each lens element **126** is an optical component with refractive power. For example, the lens elements **126** may be one or more of a relay lens, a positive meniscus lens, a negative meniscus lens, a convex lens, concave lens, or doublet lens. Each lens element **126** is made from optical glass, polymer, resin or any other refractive optical materials. Each lens element **126** can include a standard spherical surface, conic surface, aspherical surface, free form surface, diffractive surface or combinations thereof.

(27) The third lens group **116** includes a bi-convex lens and a positive meniscus lens. The third lens

group **116** is configured to form the pupil on the pupil plane **118** outside of the lens system **134** with large pupil relief distance **120**. The third lens group **116** is an eyepiece lens.
(28) The second lens group **114** is a flat-field lens. The second lens group **114** is configured to handle field curvature of the light waves **110**. In one embodiment, which can be combined with other embodiments described herein, the second lens group **114** includes a meniscus lenses and a bi-convex field lens adjacent to each other. In other words, the second lens group **114** corrects the curvature of the light waves **110**. For example, the light waves **110** become flatter after passing through the second lens group **114**.
(29) The first lens group **112** is a double gaussian lens. The first lens group **112** is configured to prevent off-axis aberrations including coma, lateral color, and astigmatism which leads to high symmetry of the light waves **110** incident on the first lens group. For example, when the light waves **110** are incident on the first lens group **112** with off-axis aberrations, the first lens group **112** improves the symmetry of the light waves **110**. In one embodiment, which can be combined with other embodiments described herein, the first lens group **112** is a double Gauss lens. In another embodiment, which can be combined with other embodiments described herein, the first lens group **112** can include any number of the lens elements **126** such that the first lens group **112** is any lens stack which improves symmetry of the light waves **110**. In other words, the first lens group **112** relays an image to the center of the second lens group **114**.
(30) FIG. **2** is a flow diagram of a method **200** of projecting light waves with an optical system **100**A. The method **200** may be utilized in operation of a projection light engine for virtual reality or augmented reality related applications. In another example, the method **200** is utilized during a metrology system for testing various metrics of different optical components. In other examples, the optical system **100**A is utilized in a microscope or telescope assembly. The method **200** is utilized in conjunction with the optical system **100**A.
(31) At operation **201**, an image or pattern is rendered on a display **102**. A light source may be included in the display **102** or adjacent to the display **102**. A plurality of light waves **110** (e.g., light waves **110**R, **110**G, **110**B) corresponding to a plurality of pixels **108**R, **108**G, **108**B render the image. The plurality of light waves **110** are projected to the lens system **104**.
(32) At operation **202**, the image is projected to the lens system **104**. The lens system **104** includes a first lens group **112**, a second lens group **114**, and a third lens group **116**. The lens system **104** is capable of producing a large field of view (e.g., greater than about 80 degrees) and has a pupil relief distance **120** greater than about 5.5 mm. The lens system **104** forms a pupil outside of the lens system **104** on a pupil plane **118**. The pupil is defined as the virtual image of the maximum aperture. The pupil is formed where the light waves **110** intersect at the pupil plane **118**. As shown, the pupil plane **118** is external of the lens system **104**. The first lens group **112** is configured to reduce off-axis symmetry. The second lens group **114** is configured for flattening of the field of the light waves **110**, and the third lens group **116** is the eyepiece group for forming the pupil outside of the lens system **104**.
(33) At operation **203**, the pupil is formed at the pupil plane **118** on the light injection port **106**. The pupil is formed between the light injection port **106** and the lens system **104**. The image rendered by the display **102** is projected to the light injection port **106**. The image is projected to infinity. In some examples, the light injection port **106** is configured to receive the light waves **110** from the lens system **104** to incouple the light waves **110** into a waveguide combiner. In another example, the light injection port **106** is a human eye for receiving the light waves **110** for telescopes or microscopes. In some examples, the light injection port **106** corresponds to an optical component that is being analyzed during a metrology operation.
(34) By having the pupil plane **118** aligned with the light injection port **106**, performance of the optical system **100**A is improved. For example, when the light injection port **106** is a waveguide, the lens system **104** allows for the light waves **110** to be efficiently coupled in and out of waveguide. The combination of the first lens group **112**, the second lens group **114**, and the third

lens group **116** in combination combat optical aberrations that may occur during use of the optical system **100**A. The lens system **104** is capable of a wide field of view **122** and has a large pupil relief distance **120** while also achieving high modulation transfer function (MTF) performance. Additionally, the pupil relief distance **120** allows for rotation of the light injection port **106**, as needed.

(35) FIG. **3** is a flow diagram of a method **300** of imaging light waves with an optical system **100**B. The method **200** may be utilized in operation of an imaging system. For example, the optical system **100**B may capture images of a virtual image from an AR or VR device, such as a waveguide combiner. The method **300** is utilized in conjunction with the optical system **100**B, shown in FIG. **1**B.

(36) At operation **301**, a virtual display **132** renders a virtual image from infinity. A plurality of light waves **110** (e.g., light waves **110**R, **110**G, **110**B) at infinity correspond to the virtual display **132**. In some examples, the virtual display **132** renders an image from an AR or VR device.

(37) At operation **302**, the light waves are collected by the lens system **134**. The lens system **134** includes a third lens group **116**, a second lens group **114**, and a first lens group **112**, in order from the virtual display **132**. The lens system **134** is capable of collecting the light waves **110** from a large field of view (e.g., greater than about 80 degrees) and has a pupil relief distance **120** greater than about 5.5 mm. A pupil outside of the lens system **134** is formed on a pupil plane **118** between the virtual display **132** and the lens system **134**. The pupil is defined as the virtual image of the maximum aperture **115**. As shown, the pupil plane **118** is external of the lens system **104**. The first lens group **112** is configured to reduce off-axis symmetry. The second lens group **114** is configured for flattening of the field of the light waves **110**, and the third lens group **116** is the eyepiece group for forming the pupil outside of the lens system **104**.

(38) At operation **303**, the lens system **134** provides the light waves **110** to a sensor **136**. The lens system **134** provides an image from the virtual display to the sensor **136**. The sensor **136** may be utilized to capture the image, for example as a camera system. The lens system **134** is capable of a wide field of view **122** and has a large pupil relief distance **120** while also achieving high modulation transfer function (MTF) performance. Additionally, the pupil relief distance **120** allows for rotation of the light injection port **106**, as needed. The combination of the first lens group **112**, the second lens group **114**, and the third lens group **116** in combination combat optical aberrations that may occur during use of the optical system **100**B. Additionally, the longer pupil relief distance **120** allows for an easier assembly process of the optical system **1006** and allows for rotation of the optical system **1006** as needed to collect the light waves **110**. For example, the optical system **100**B is able to rotate around the external pupil position.

(39) FIG. **4** is a schematic, cross-sectional view of an optical system **400**. The optical system **400** includes a substrate **402** and a waveguide structure **404**. The optical system **400** includes an input coupling region **406**, a waveguide region **408**, and an output coupling region **410**. The waveguide region **408** is located between the input coupling region **406** and the output coupling region **410**. The waveguide structure **404** is disposed on and in contact with the substrate **402**.

(40) The waveguide structure **404** is implemented in a display device, such as an augmented, virtual, or mixed/merged reality device. Examples of such devices include waveguide combiners or other head mounted displays used in augmented reality glasses or goggles and the like. Accordingly, the optical system **400** may also include an optical system **100**A which generates light waves **110** to form a virtual image at a light injection port **106** (corresponding to the input coupling region **406**). The light waves travel through a lens system **104** prior to being incident on the light injection port **106**. The lens system **104** forms an external pupil on a pupil plane **118**. The light waves **110** generated by the optical system **100**A are modulated by the waveguide structure **404** and propagates through the waveguide structure **404** and substrate **402** until the light waves **110** exits the waveguide structure **404** and is imaged (e.g. focused) on the sensor **136**. The virtual image is projected from the virtual display **132** (corresponding to the output coupling region **410**) to the lens

system **134**. The light waves **110** pass through a lens system **134** and direct the light waves to the sensor **136**.
(41) The lens systems **134** improve overall performance of incoupling the light waves **110** to the input coupling region **406** and improve mechanical set up of the optical system **400**. The pupils that are formed outside of the lens systems allow for improved field of view with high resolution with high MTF performance.
(42) In summation, an optical system having a lens system configured to have a wide field of view and high resolution is provided herein. The optical system may be an image projection system or an imaging system. The optical system includes three or more lens groups with ability to combat optical aberrations and produce a pupil outside of the lens group. The lens system as an image projection system projects a pattern or image rendered on a flat reticle or display of finite distance to the infinity. In an imaging system, the lens system collects light from infinity and forms an image of that object on a sensor. The lens system improves overall performance of the optical system.
(43) While the foregoing is directed to some embodiments, other and further embodiments may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

Claims

1. An optical system, comprising: a display configured to render an image by projecting a plurality of light waves emanating from at least two pixels spaced apart from each other; a lens system, the lens system comprising: a first lens group configured to relay the emanating light waves to a center of the lens system and focus the emanating light waves within the first lens group; a second lens group adjacent to the first lens group, the second lens group configured to flatten a field of the emanating light waves; and a third lens group adjacent to the second lens group, wherein the third lens group is configured to form a single pupil on a pupil plane outside of the lens system; and a light injection port, wherein the pupil plane is aligned with the light injection port and the emanating light waves are projected to the light injection port, wherein the light injection port is an input coupling region of a waveguide structure.
2. The optical system of claim 1, wherein a field of view of the lens system is greater than about 80 degrees.
3. The optical system of claim 1, wherein the lens system is a telecentric lens system.
4. The optical system of claim 1, wherein the lens system has a modulation transfer function (MTF) performance greater than about 0.3 at 30 cycles per degree.
5. The optical system of claim 1, wherein a pupil diameter of the pupil is between about 1 mm and about 6 mm.
6. The optical system of claim 1, wherein the first lens group is a double Gauss lens.
7. The optical system of claim 1, wherein the second lens group is a flat-field lens.
8. The optical system of claim 1, wherein the second lens group includes at least a meniscus lens and a bi-convex field lens adjacent to the meniscus lens.
9. The optical system of claim 1, wherein the third lens group includes at least a bi-convex lens and a positive meniscus lens.
10. The optical system of claim 1, wherein the second lens group is disposed between the first lens group and the third lens group.
11. The optical system of claim 1, wherein: the first lens group is a double Gauss lens; the second lens group includes at least a meniscus lens and a bi-convex field lens adjacent to the meniscus lens; and the third lens group includes at least a bi-convex lens and a positive meniscus lens.
12. A lens system, comprising: a first lens group configured to relay a plurality of light waves, the plurality of light waves comprising a first light wave and a second light wave, generated from a

display comprising at least two pixels spaced apart from each other to a center of the lens system and focus the plurality of light waves within the first lens group, the at least two pixels including a first pixel and a second pixel, the first pixel emitting the first light wave and the second pixel emitting the second light wave, wherein the first lens group is a double Gauss lens and focusing the plurality of light waves comprises intersecting the first light wave and the second light wave; a second lens group adjacent to the first lens group, wherein the second lens group is a flat-field lens configured to flatten the plurality of light waves, wherein flattening the plurality of light waves comprises converging the first light wave to a first point and converging the second light wave to a second point, wherein the first point and the second point are separated by a distance; and a third lens group adjacent to the second lens group, wherein the third lens group includes a bi-convex lens and a positive meniscus lens and is configured to form a single pupil on a pupil plane outside of the lens system.

13. The lens system of claim 12, wherein the second lens group is disposed between the first lens group and the third lens group.

14. The lens system of claim 12, wherein a field of view of the lens system is greater than about 80 degrees.

15. The lens system of claim 12, wherein the lens system is a telecentric lens system.

16. The lens system of claim 12, wherein the lens system has a modulation transfer function (MTF) performance greater than about 0.3 at 30 cycles per degree.

17. The lens system of claim 12, wherein a pupil diameter of the pupil is between about 1 mm and about 6 mm.

18. A method of using a lens system, comprising: projecting a plurality of light waves, comprising a first light wave and a second light wave, from a display comprising at least two pixels spaced apart from each other to a lens system, the at least two pixels including a first pixel and a second pixel, the first pixel projecting the first light wave and the second pixel projecting the second light wave, wherein the lens system includes: a first lens group configured to relay the first light wave and the second light wave to a center of the lens system and focus the light waves within the first lens group, wherein the first lens group is a double Gauss lens and the first light wave and the second light wave intersect one another at the center of the first lens group; a second lens group adjacent to the first lens group, wherein the second lens group is a flat-field lens configured to flatten the first light wave and the second light wave parallel to one another, wherein the first light wave and the second light wave are separated by a distance; and a third lens group adjacent to the second lens group, wherein the third lens group includes a bi-convex lens and a positive meniscus lens and is configured to form a single pupil on a pupil plane outside of the lens system; and projecting the light waves to a light injection port, wherein the formed pupil on a pupil plane is outside of the lens system.

19. The method of claim 18, wherein the third lens group is configured to prevent off-axis aberrations including coma, lateral color, and astigmatism.

20. The method of claim 18, wherein the light injection port is an input coupling region of a waveguide structure.