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DeJong et al.

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(54) **SCANNED IMAGE PROJECTION SYSTEM EMPLOYING INTERMEDIATE IMAGE PLANE**

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H04N 9/31	(2006.01)
G02B 27/01	(2006.01)

(52) **U.S. Cl.**

CPC ***H04N 9/3129*** (2013.01); ***G02B 27/017*** (2013.01)

USPC **351/158**; 359/298

(58) **Field of Classification Search**

USPC .... 351/160 R, 158, 118, 161, 177, 200; 359/629–639, 298

See application file for complete search history.

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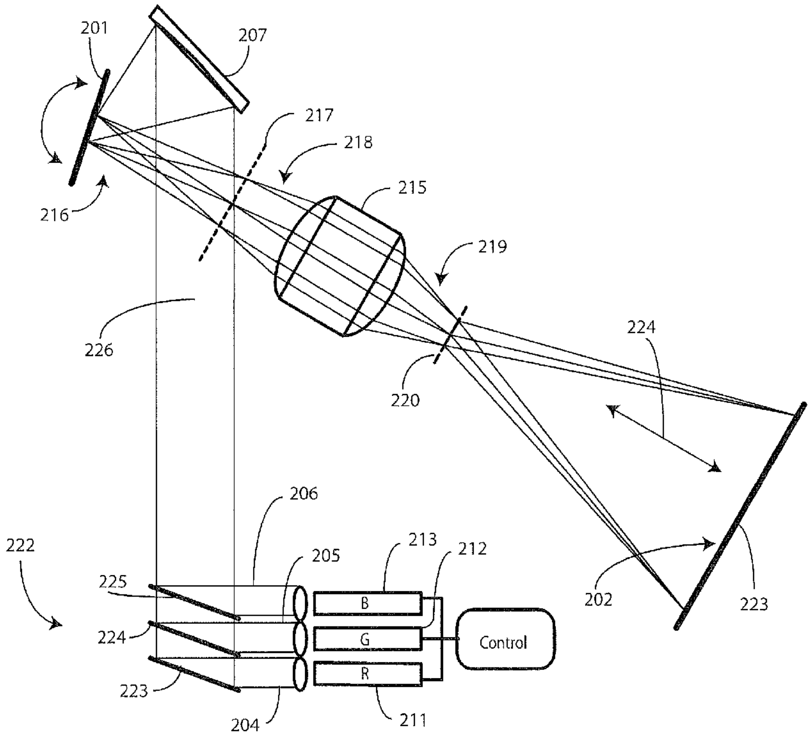
(57) **ABSTRACT**

In imaging system (**100**), a spatial light modulator (**101**) is configured to produce images (**102**) by scanning a plurality light beams (**104**,**105**,**106**). A first optical element (**107**) is configured to cause the plurality of light beams to converge along an optical path (**114**) defined between the first optical element and the spatial light modulator. A second optical element (**115**) is disposed between the spatial light modulator and a waveguide (**1401**). The first optical element and the spatial light modulator are arranged such that an image plane (**117**) is created between the spatial light modulator and the second optical element. The second optical element is configured to collect the diverging light (**118**) from the image plane and collimate it. The second optical element then delivers the collimated light to a pupil (**120**) at an input of the waveguide.

16 Claims, 13 Drawing Sheets



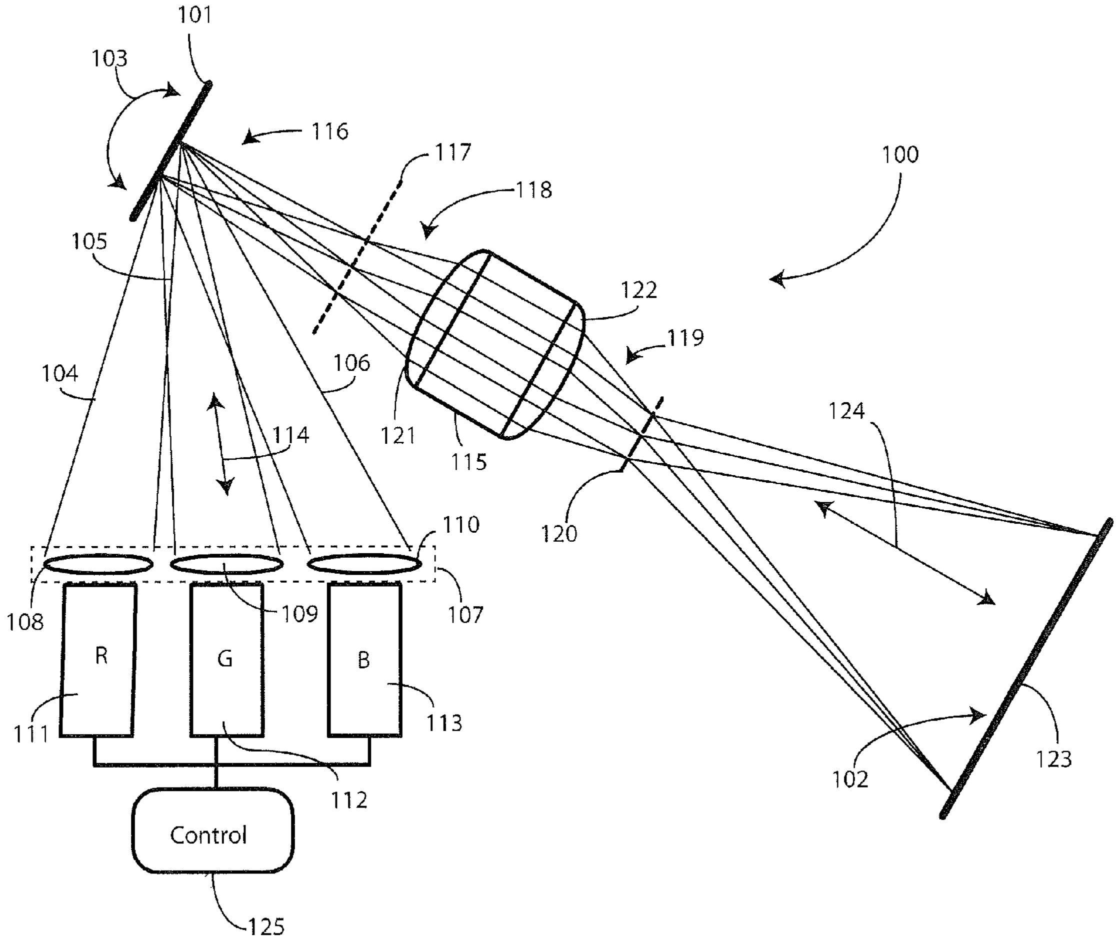
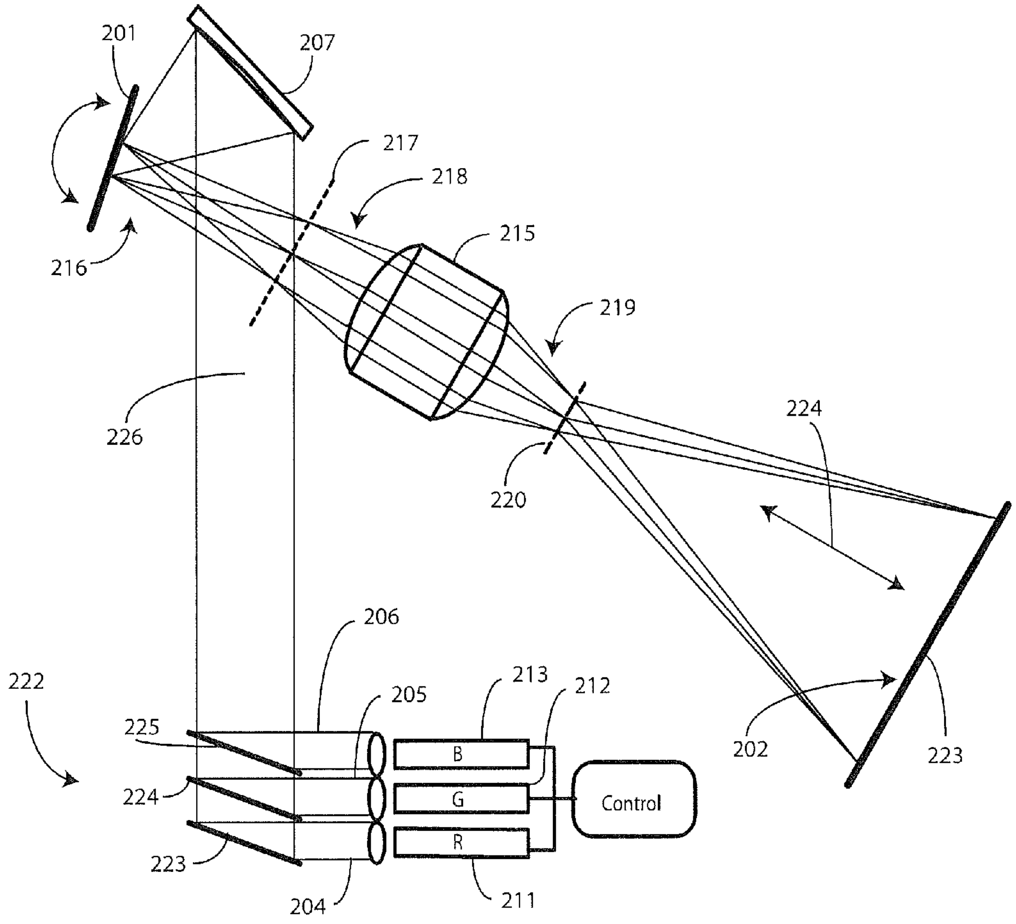

101
103
116
117
118
100
105
122
119
104
106
114
121
115
124
110
120
108
109
107
R
G
B
111
113
112
102
123
Control
125

FIG. 1


201
207
217
218
215
216
219
226
224
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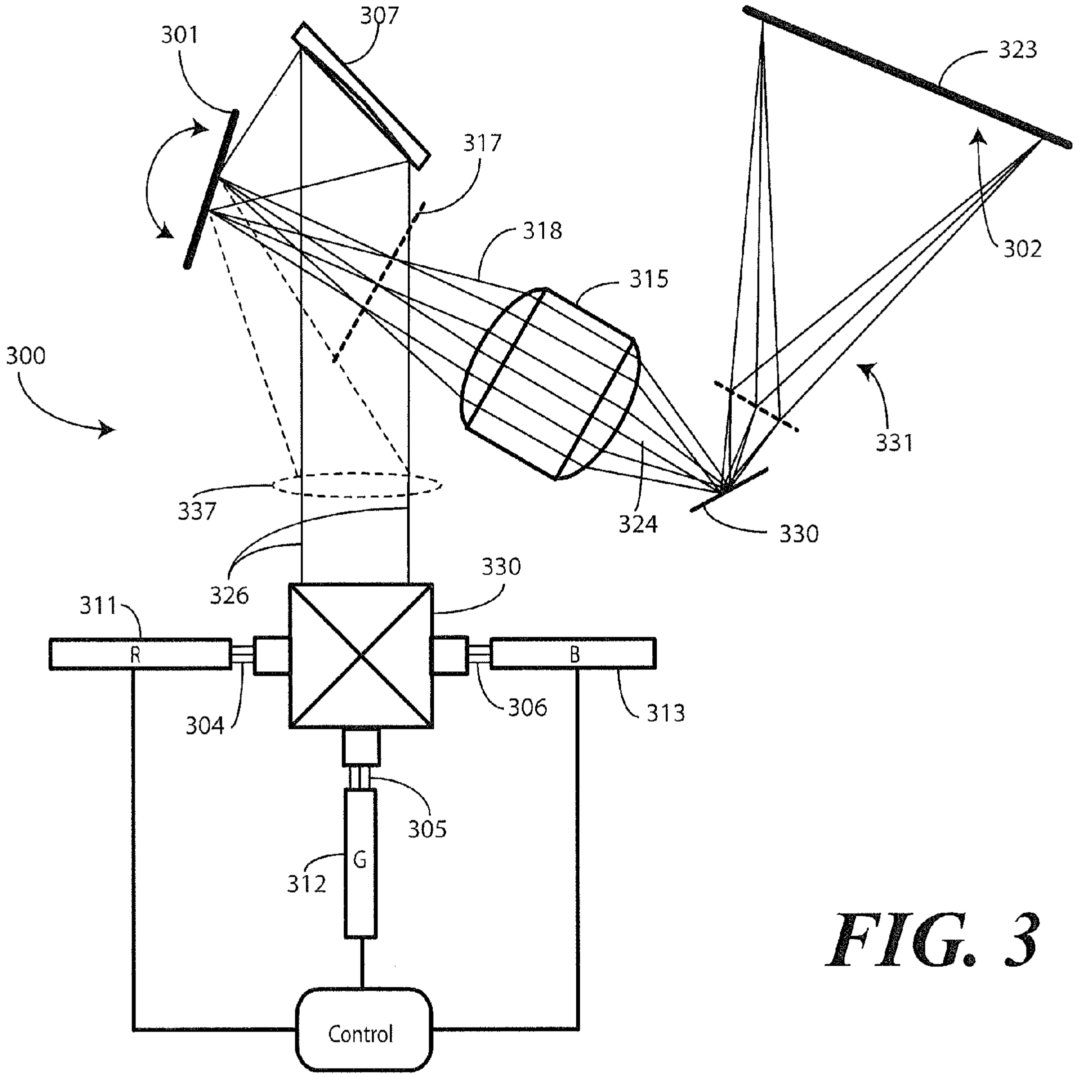
206
222
205
213
212
225
B
224
G
Control
202
223
R
223
204
211

FIG. 2


301
307
317
323
318
315
302
300
331
337
324
330
326
330
311
R
B
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306
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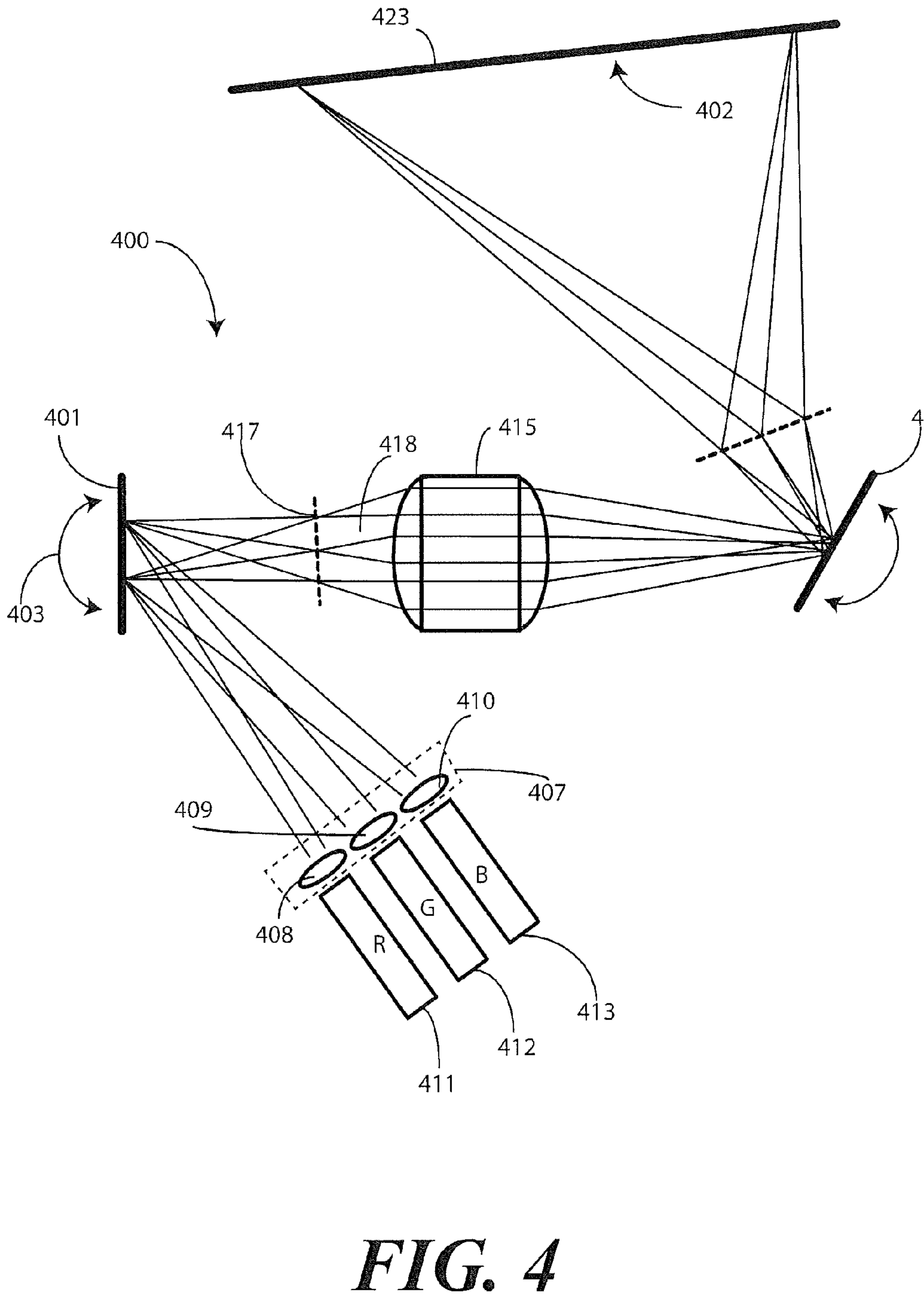
305
G
312
Control

FIG. 3


423
402
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401
417
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415
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403
410
407
409
B
G
R
408
413
412
411

FIG. 4

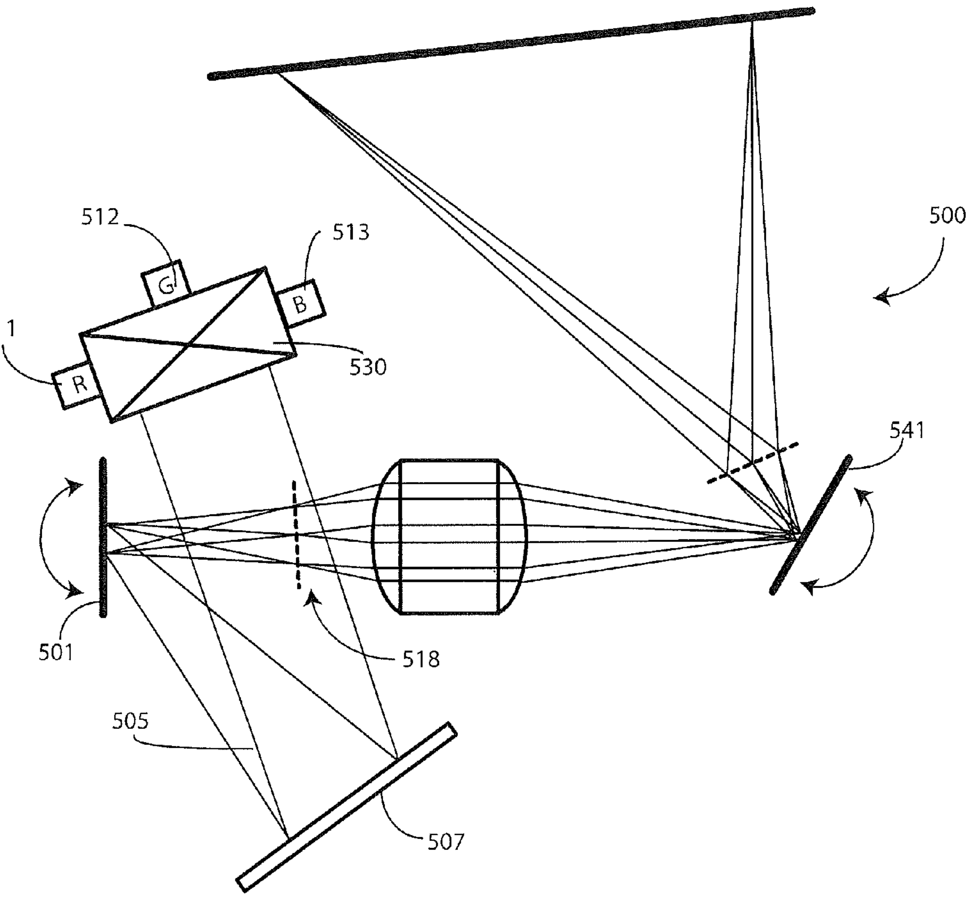

FIG. 5

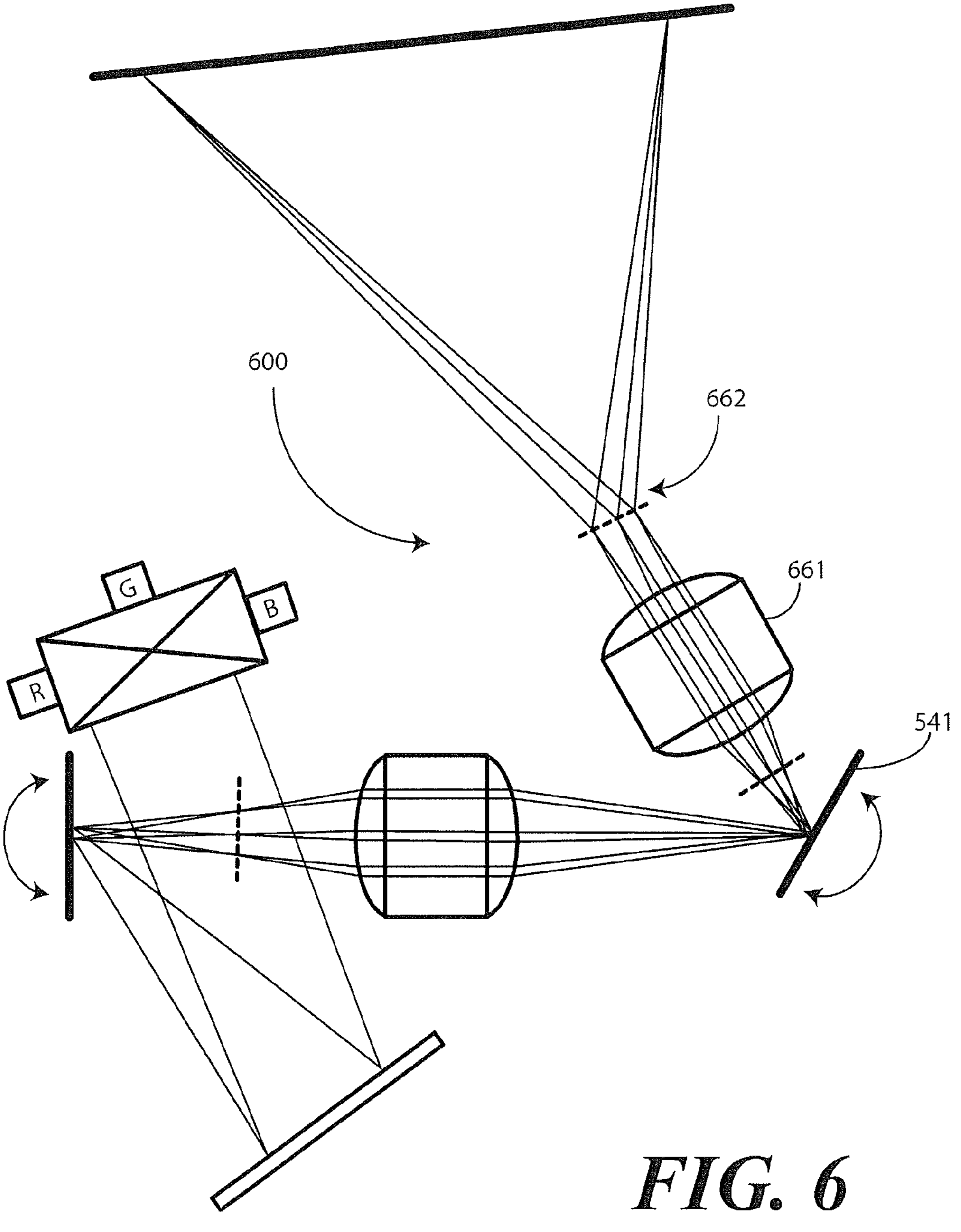

FIG. 6

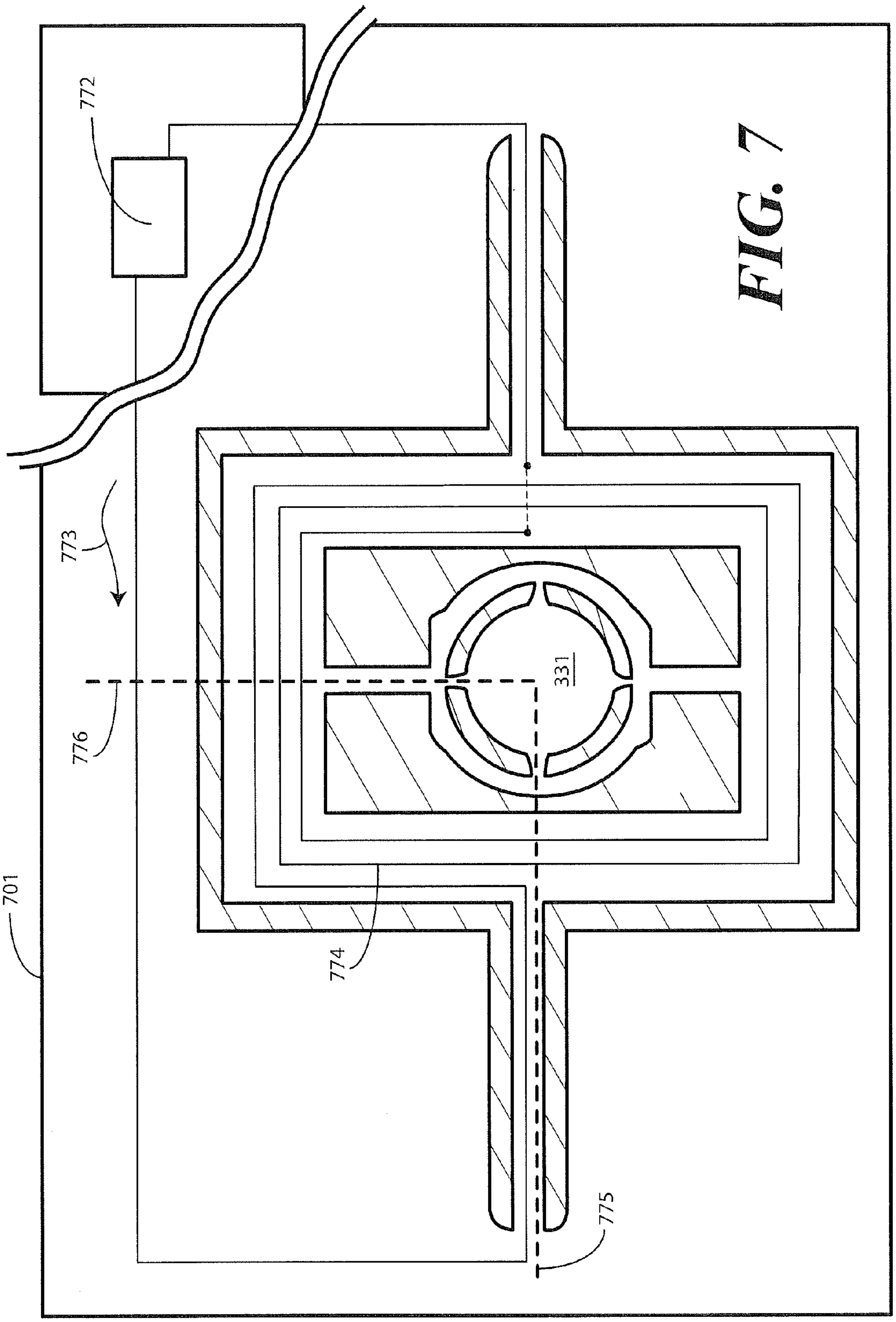

FIG. 7

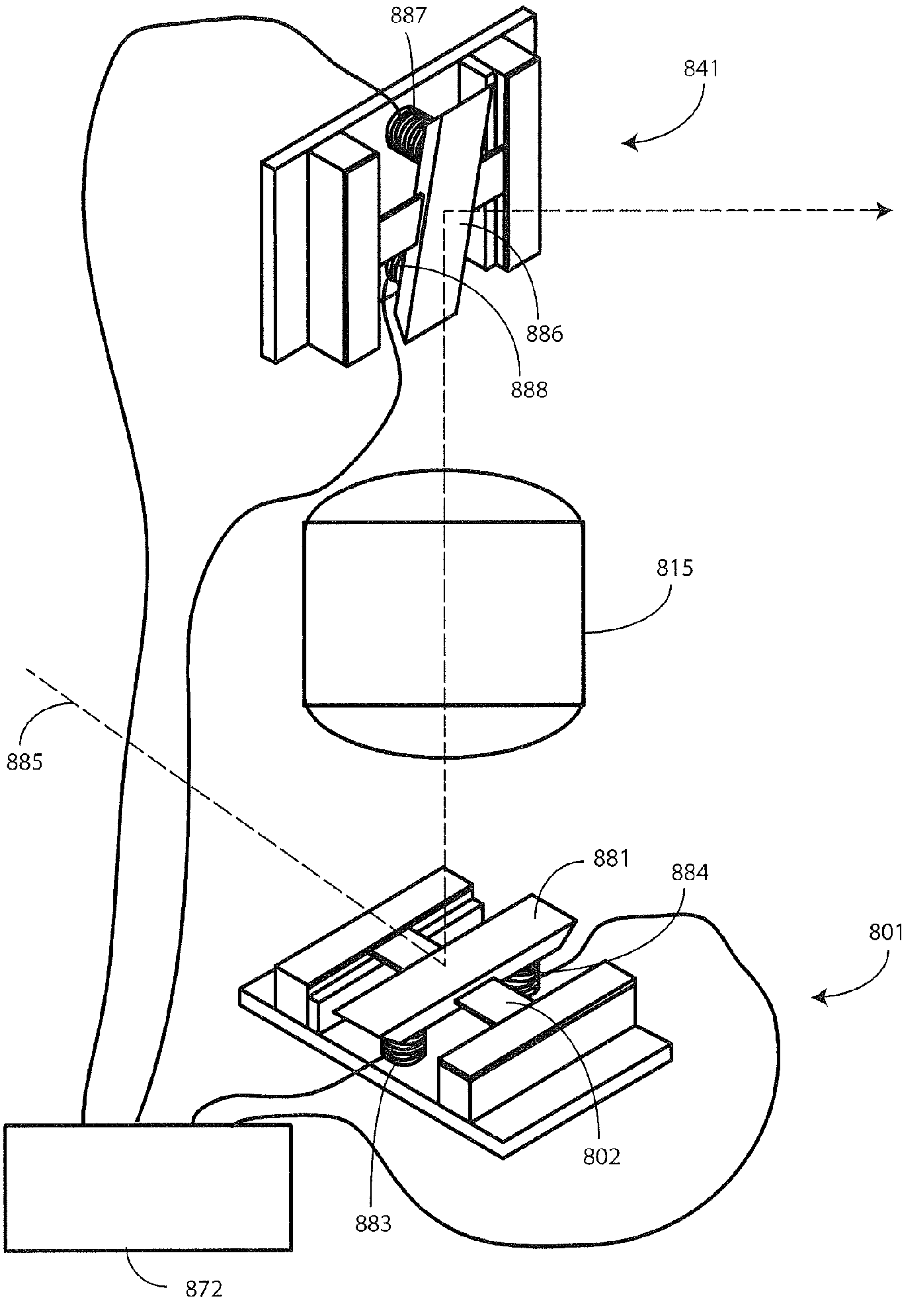

FIG. 8

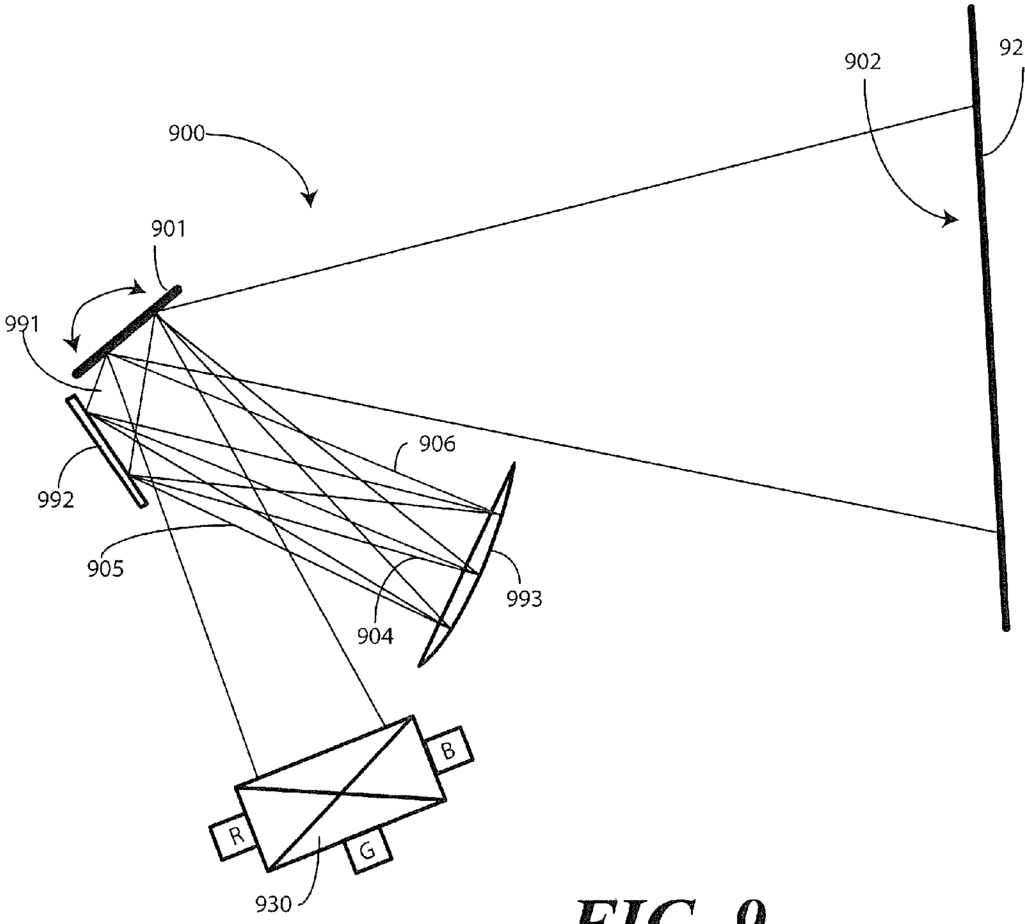

FIG. 9

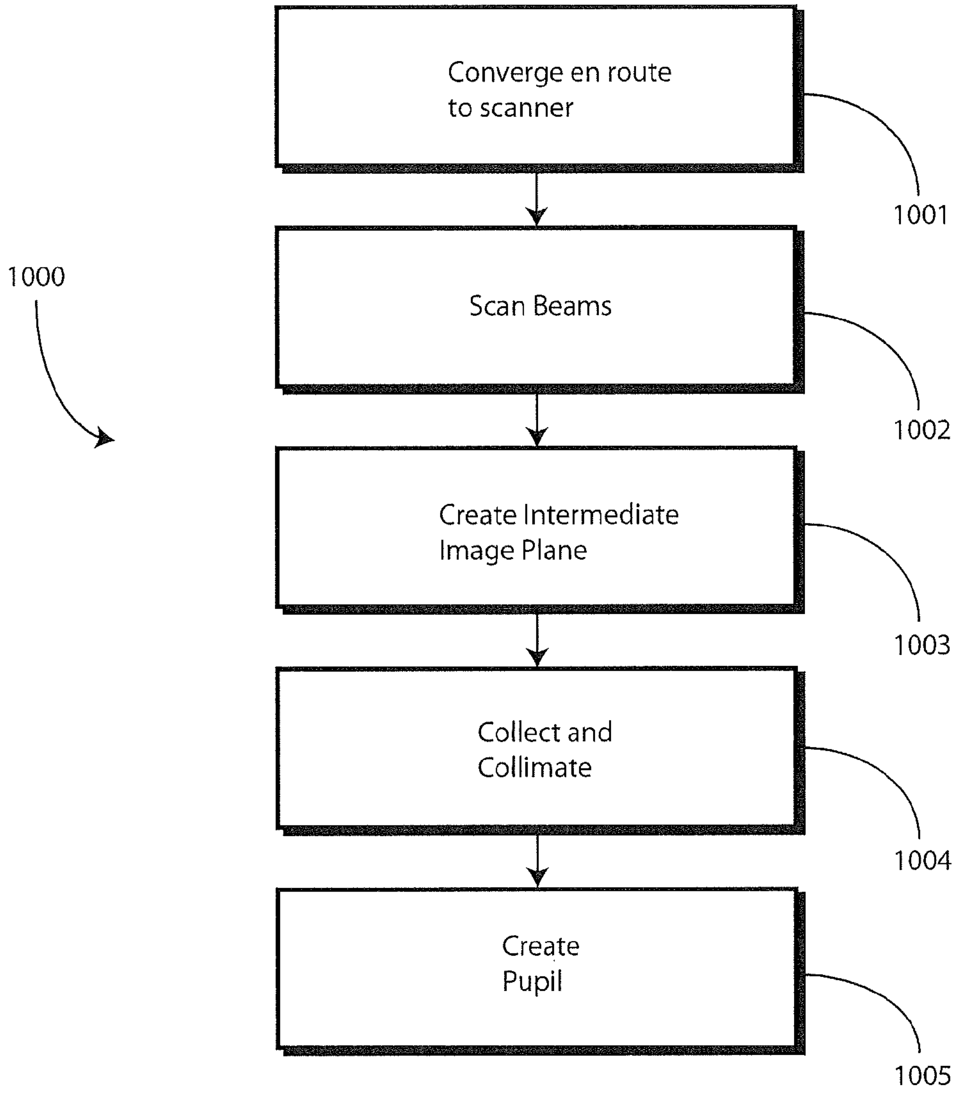
Converge en route to scanner
1001
Scan Beams
1002
1000
Create Intermediate Image Plane
1003
Collect and Collimate
1004
Create Pupil
1005

FIG. 10

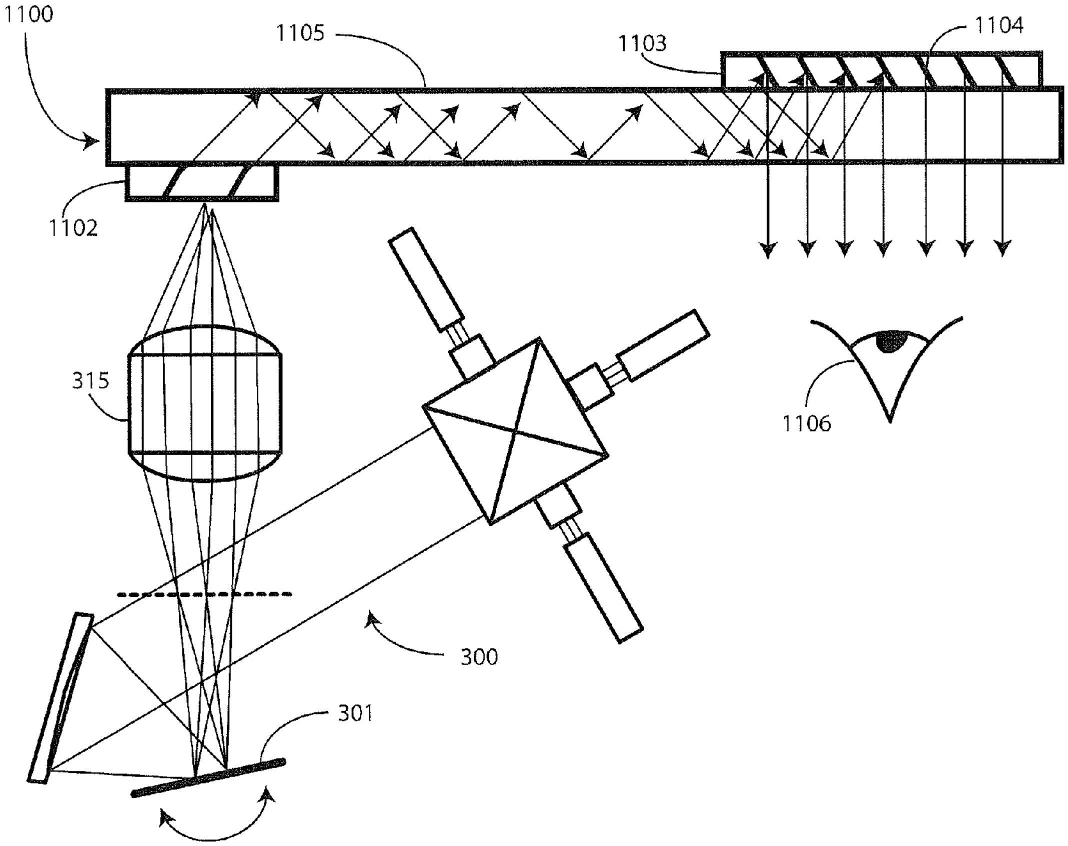

FIG. 11

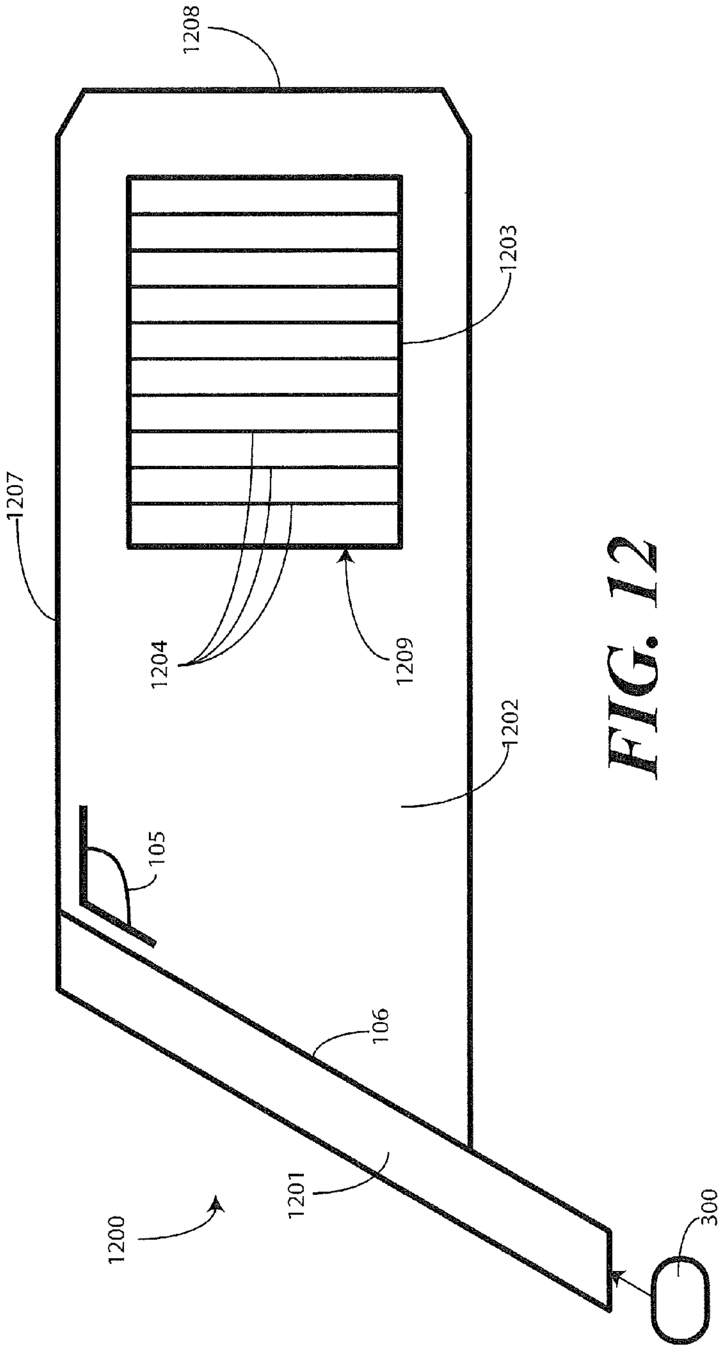
1208
1203
1207
1204
1209
1202
105
106
1201
1200
300

FIG. 12

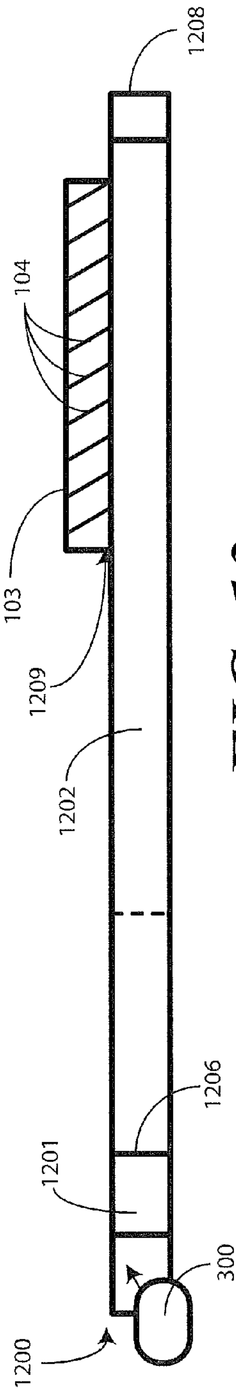
1208
104
103
1209
1202
1206
1201
300
1200

FIG. 13

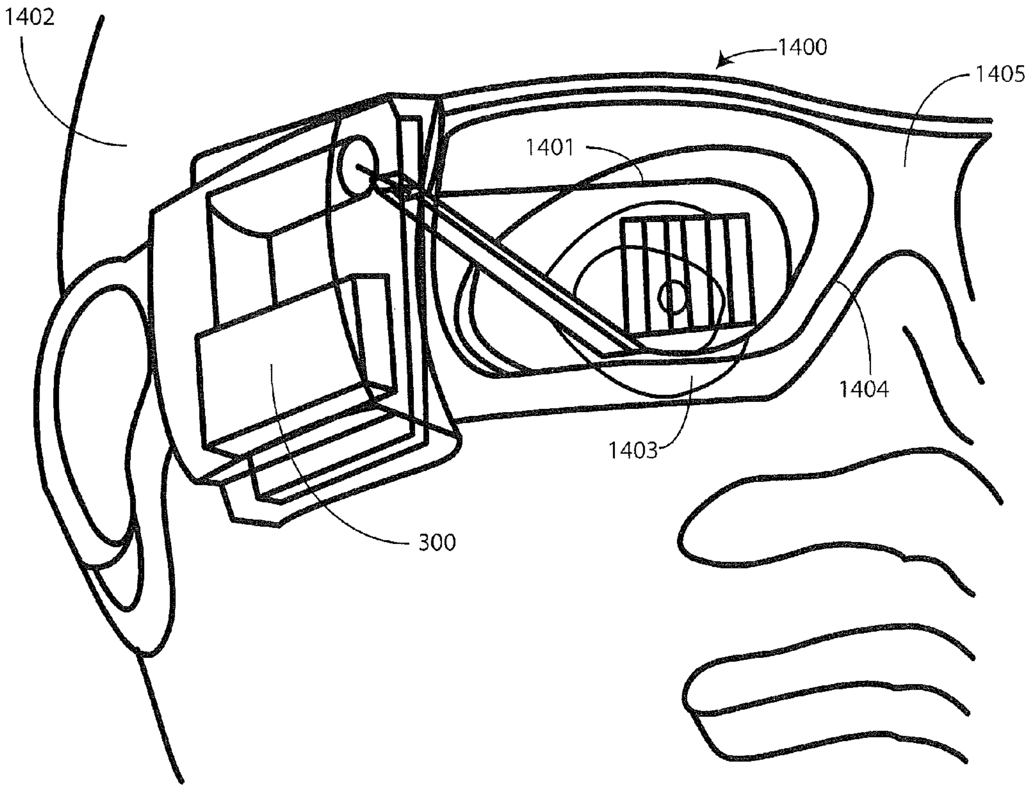

FIG. 14

SCANNED IMAGE PROJECTION SYSTEM EMPLOYING INTERMEDIATE IMAGE PLANE

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under Contract Number NNX11CG59P awarded by NASA. The government has certain rights in the invention.

BACKGROUND

1. Technical Field

This invention relates generally to image projection systems, and more particularly to scanned image projection systems.

2. Background Art

Scanned laser projection devices facilitate the production of brilliant images created with vibrant colors. Scanned systems, such as those manufactured by Microvision, Inc., are capable of creating bright, sharp images with a large depth of focus. Additionally, these scanned laser projection systems can be designed with compact form factors at a reasonable cost. These systems consume small amounts of power yet deliver vivid, complex images.

Scanned laser projection devices are frequently used in sophisticated projection systems such as head-up displays and near-to-eye displays. In such applications, lasers present information to a user, either by presenting the information on a projection surface or by delivering the information directly to the user's eye.

One challenge associated with these systems is size reduction. It can be desirable to make the systems smaller, so that the projection systems can be used in compact applications, such as with eyeglasses or goggles. However, as the optical components become smaller, design issues can arise. Distortion of images can be introduced. Similarly, optical artifacts can become a problem.

It would be advantageous to have a compact projection system that mitigates image distortion.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying figures, where like reference numerals refer to identical or functionally similar elements throughout the separate views and which together with the detailed description below are incorporated in and form part of the specification, serve to further illustrate various embodiments and to explain various principles and advantages all in accordance with the present invention.

FIG. **1** illustrates one scanning image projection system employing an intermediate image plane in accordance with one or more embodiments of the invention.

FIG. **2** illustrates another scanning image projection system employing an intermediate image plane in accordance with one or more embodiments of the invention.

FIG. **3** illustrates another scanning image projection system employing an intermediate image plane in accordance with one or more embodiments of the invention.

FIG. **4** illustrates yet another scanning image projection system employing an intermediate image plane in accordance with one or more embodiments of the invention.

FIG. **5** illustrates yet another scanning image projection system employing an intermediate image plane in accordance with one or more embodiments of the invention.

FIG. **6** illustrates yet another scanning image projection system employing an intermediate image plane in accordance with one or more embodiments of the invention.

FIG. **7** illustrates one embodiment of a spatial light modulator suitable for use with one or more embodiments of a scanned image projection system employing an intermediate image plane in accordance with embodiments of the invention.

FIG. **8** illustrates another embodiment of a spatial light modulator in use with one or more embodiments of a scanned image projection system employing an intermediate image plane in accordance with embodiments of the invention.

FIG. **9** illustrates yet another scanning image projection system employing an intermediate image plane in accordance with one or more embodiments of the invention.

FIG. **10** illustrates a method of employing an intermediate image plane in a scanned projection system configured in accordance with one or more embodiments of the invention.

FIG. **11** illustrates one explanatory imaging system delivering imaging light to a waveguide in accordance with one or more embodiments of the invention.

FIGS. **12** and **13** illustrate another suitable waveguide for use with one or more embodiments of the invention.

FIG. **14** illustrates one application suitable for one or more embodiments of the invention.

Skilled artisans will appreciate that elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale. For example, the dimensions of some of the elements in the figures may be exaggerated relative to other elements to help to improve understanding of embodiments of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

Before describing in detail embodiments that are in accordance with the present invention, it will be appreciated that embodiments of the invention described herein may be comprised of one or more conventional processors and unique stored program instructions that control the one or more processors to implement, in conjunction with certain non-processor circuits, some, most, or all of the functions of employing an intermediate image plane in a scanning projection system as described herein.

The non-processor circuits may include, but are not limited to, microprocessors, scanning mirrors, image encoding devices, memory devices, clock circuits, power circuits, and so forth. As such, these functions may be interpreted as steps of a method to use an intermediate image plane in a scanning projection system. It is expected that one of ordinary skill, notwithstanding possibly significant effort and many design choices motivated by, for example, available time, current technology, and economic considerations, when guided by the concepts and principles disclosed herein will be readily capable of generating such programs and circuits with minimal experimentation.

Embodiments of the invention are now described in detail. Referring to the drawings, like numbers indicate like parts throughout the views. As used in the description herein and throughout the claims, the following terms take the meanings explicitly associated herein, unless the context clearly dictates otherwise: the meaning of "a," "an," and "the" includes plural reference, the meaning of "in" includes "in" and "on." Relational terms such as first and second, top and bottom, and the like may be used solely to distinguish one entity or action from another entity or action without necessarily requiring or implying any actual such relationship or order between such entities or actions. Also, reference designators shown herein in parenthesis indicate components shown in a figure other than the one in discussion. For example, talking about a device (**10**) while discussing figure A would refer to an element, **10**, shown in figure other than figure A.

Embodiments of the present invention employ optical elements and a spatial light modulator to create images. In one embodiment, the optical elements are arranges such that light converges as it is delivered to the spatial light modulator. Once scanned by the spatial light modulator, the scanned light then defines an intermediate image plane within the system. Illustrating by example, a first optical element is arranged so as to cause a plurality of light beams created by a plurality of light sources to converge as they travel from the light sources to the spatial light modulator. The spatial light modulator then scans the plurality of light beams. The convergence causes an image plane to be defined between the spatial light modulator and a second optical element. The second optical element then collects diverging light from the intermediate image plane at an input side of the second optical element and reimages the light to one of a finite or infinite conjugate. In one embodiment, the reimaging includes collimation of the light. When collimated, the second optical element can cause the collimated light to define a pupil on an output side of the second optical element.

In one or more embodiments, a second reflective device, which itself may be a spatial light modulator, is disposed opposite the second optical element from the spatial light modulator. In such an embodiment, the second optical element can be configured to create an image pupil on the second reflective device. Light from the second reflective device can be output by the system to create images in one embodiment. In another embodiment, additional optical devices can be used to translate the light and create additional pupils as required by a particular application.

The use of an intermediate image plane within an imaging system offers numerous advantages over prior art designs. A first advantage is that the components of the system can be made smaller when the light is configured to define an intermediate image plane within the image projection system. This advantage is particularly applicable to scanning image systems where the spatial light modulator is configured to create images by pivoting along one or more axes, such as in a raster pattern. Illustrating again by example, when two spatial light modulators are used to create images in a raster pattern, with a first spatial light modulator scanning along a horizontal axis and the second spatial light modulator scanning along a vertical axis, the inclusion of an optical element between the modulators—combined with the creation of the intermediate image plane—allows for the second modulator to be much smaller.

If, for instance, the first spatial light modulator scans at an angle of fourteen degrees, and the second spatial light modulator is ten millimeters away, the second spatial light modulator must be large to handle the large spot defined by the scan angle of, and distance from, the first spatial light modulator. By using an intermediate image plane and an intermediate optical element disposed between the spatial light modulators, the second spatial light modulator can be very small when the optical element causes the diverging light from the image plane to become a pupil at the second light modulator.

Another advantage is that the creation and use of the intermediate image plane allows the designer to trade image spot size occurring on the spatial light modulator for field of view to both use smaller components and to tailor a particular imaging device to a specific application. Said differently, the designer can design the optical elements of the system to convert the rations of Θ and D to meet a desired Θ or D, while preserving the Θ*D product. Considering the pupil is directly related to the necessary modulator surface area, and the field of view being defined by the angle at which the modulator can scan, there is a one-to-one trade on field of view and pupil size when an intermediate image plane is employed. If a designer wants a larger field of view with a smaller pupil, this can be achieved by proper orientation and selection of the optical elements. With some technologies it can be easier to build a modulator having a surface area of one-half millimeter than it is to build one having a surface area of one millimeter, the smaller modulator can be used in accordance with embodiments described below to achieve the same field of view. Thus, instead of building a one-millimeter modulator with a twenty-degree scan angle, a designer can build a half-millimeter mirror with a forty-degree scan angle and then and scale it back to the original design due to the one-to-one trade on field of view and pupil size.

With some technologies it is easier, smaller, or more power or cost efficient to build a two-millimeter wide mirror with ten-degree scan angle than to build a one-millimeter wide mirror with a twenty-degree scan angle. Thus, in accordance with one or more embodiments of the invention, a two-millimeter mirror can be built. Then using proper selection and placement of the intermediate optics, a conversion of that mirror into a one-millimeter pupil having a twenty-degree scan angle can occur. It is also the case that one device employing embodiments of the invention may desire a one-millimeter pupil with a forty-five degree scan angle, while another device desires a 1.5 millimeter pupil with a thirty-degree scan angle, while yet another third device desires a two-millimeter pupil and a 22.5 degree field of view. Advantageously, using the pupil and field of view scaling available with the optical elements and an intermediate image plane of embodiments of the present invention, all three devices can use the same scanning engine, which results in significant cost savings.

A third advantage is relates to the C6 safety coefficient set forth in numerous laser classification standards. When using lasers as the light sources, safety ratings like the C6 measurement relate to the worst-case scenario, which occurs when the eye focused directly at the source of the image. In a scanning image projection system, the worst-case scenario occurs when the eye is focused directly on a spatial light modulator. In this scenario, the eye images the pupil defined along the surface of the spatial light modulator. If that pupil, or spot, is bigger than something upon which the eye can focus, i.e., is large enough that the eye is unable to receive all the energy and focus it in a spot on the retina, the C6 coefficient accounts for the resulting energy being spread over the retina. The larger the spot on the retina, the larger the C6 coefficient. The use of the intermediate image plane allows the locations of the various pupils of the system to be controlled, thereby allowing the designer to have more control over the C6 factor. Said differently, embodiments of the present invention allow a designer to change the "apparent" spot size on a spatial light modulator, thereby yielding a larger C6. Other advantages will be noted in the description of the figures that follows.

Turning now to FIG. **1**, illustrated therein is one embodiment of an imaging system **100** configured in accordance with one or more embodiments of the invention. As shown in FIG. **1**, a spatial light modulator **101** is configured to produce images by scanning **103** a plurality of light beams **104**,**105**, **106**. A first optical element **107** is disposed at an output of a plurality of light sources **111**,**112**,**113**. In the illustrative embodiment of FIG. **1**, the first optical element **107** is configured as three optical elements **108**,**109**,**110** disposed at the outputs of the light sources **111**,**112**,**113**. The first optical element **107** in this embodiment is configured as being a first powered optical element **108**, a second powered optical element **109**, and a third powered optical element **110**, each being disposed at an output of a first light source **112**, a second light source **113**, and a third light source **113**, respectively. The first powered optical element **108**, a second powered optical element **109**, and a third powered optical element **110** of this embodiment correspond to the plurality of light sources **111**,**112**,**113** on a one-to-one basis.

While the plurality of light sources **111**,**112**,**113** is shown for simplicity in FIG. **1** as delivering light directly to the spatial light modulator **101** through the three optical elements **108**,**109**,**110**, it will be clear to those of ordinary skill in the art having the benefit of this disclosure that additional optical elements may be disposed between the plurality of light sources **111**,**112**,**113** and the spatial light modulator **101**. To wit, FIGS. **2** and **3** illustrate two examples of the additional optical elements that may be used. FIG. **2** illustrates dichroic mirrors (**223**,**224**,**225**) being disposed between the plurality of light sources (**211**,**212**,**213**) to take light from each source and collimate it into a common beam (**226**). Similarly, FIG. **3** uses an optical combiner (**330**) to combine beams from the light sources (**311**,**312**,**313**) into a common beam (**326**). It should be understood that while such elements have been omitted from some embodiments for ease of illustration, that dichroic mirrors, beam combiners, or other optical elements can be used to combine the output of each light source in any of the embodiments described herein. Alternatively, light can be fed from the various sources to the spatial light modulator **101** without beam combination as well.

In other embodiments, the first optical element **107** may include one or more powered optical elements that do not correspond to the light sources **111**,**112**,**113** on a one-to-one basis. For example the first light source **111** may use one powered optical element, while the second light source **112** and third light source **113** share a common powered optical element, and so forth. Other combinations and arrangements will be obvious to those of ordinary skill in the art having the benefit of this disclosure.

As shown in FIG. **1**, the first optical element **107** is configured to cause the plurality of light beams **104**,**105**,**106** to converge along an optical path **114** defined between the first optical element **107** and the spatial light modulator **101**. Said differently the plurality of light beams **104**,**105**,**106** get closer together as they travel toward the spatial light modulator **101**. A second optical element **115** is then disposed between the spatial light modulator **101** and an output of the imaging system **100**.

In the illustrative embodiment of FIG. **1**, the first optical element **107** and the spatial light modulator **101** are arranged such that an intermediate image plane **117**, where each pixel of the scanned light **116** is in focus, is created, defined, and exists between the spatial light modulator **101** and the second optical element **115**. The second optical element **115** is then configured to collect diverging light **118** from the image plane **117** at an input side **121** of the second optical element **115**, shown here as a convex surface, and collimate the collected, diverging light. The second optical element **115** then causes the collimated light **119** to converge from an output side **122** of the second optical element **115** along a second optical axis **124** to a pupil **120**. By altering the geometry, material, and location of the second optical element **115**, the location of the pupil **120** can be changed as necessary in a given application. In the illustrative embodiment of FIG. **1**, the pupil **120** occurs at the output of the imaging system **100**. Accordingly, the collimated light **119** diverges again to a projection surface **123** where the image **102** is formed.

In the illustrative embodiment of FIG. **1**, the plurality of light sources **111**,**112**,**113** includes a green light source **112**, a blue light source **113**, and a red light source **111**. While the plurality of light sources can be various types of light sources, in this illustrative embodiment they are laser light sources. Accordingly, the green light source **112** comprises a green laser light source. Similarly, the blue light source **113** comprises a blue laser light source and the red light source **111** comprises a red laser light source. The red laser light source, green laser light source, and blue light source are indicated in FIG. **1** with the "R," "G," and "B." Where lasers are used as the light sources, the lasers can be any of a variety of types of lasers, including semiconductor lasers such as edge-emitting lasers or vertical cavity surface emitting lasers. Such semiconductor lasers are well known in the art and are commonly available from a variety of manufacturers.

In the illustrative embodiment of FIG. **1**, the powered optical elements **108**,**109**,**110** are configured such that light exits the plurality of light sources **111**,**112**,**113** with a particular orientation. As noted above, the light beams **104**,**105**,**106** are configured to converge as they move towards the spatial light modulator **101** at such an angle that the image plane **117** is created at a desired location between the spatial light modulator **101** and the second optical element **115**. Accordingly, the pixels created by the light beams **104**,**105**,**106** will not be focused along the surface of the spatial light modulator **101**, but will rather be focused at the image plane **117**. However, the designer can tailor the amount of convergence to fit a necessary modulator area, and thus is able to use a smaller modulator mirror by imparting more convergence on the light beams **104**,**105**,**106**.

In one embodiment, the spatial light modulator **101** can be a MEMS scanning mirror, such as those manufactured by Microvision, Inc. Examples of MEMS scanning mirrors, such as those suitable for use with embodiments of the present invention, are set forth in commonly assigned U.S. patent application Ser. No. 11/786,423, filed Apr. 10, 2007, entitled, "Integrated Photonics Module and Devices Using Integrated Photonics Module," which is incorporated herein by reference, and in U.S. Published patent application Ser. No. 10/984,327, filed Nov. 9, 2004, entitled "MEMS Device Having Simplified Drive," which is incorporated herein by reference. A MEMS light modulator is well suited to embodiments of the invention due to its compact construction, cost effectiveness, and reliability. While a MEMS device will be used herein for discussion purposes, it will be clear to those of ordinary skill in the art having the benefit of the disclosure that other modulator platforms may be used as well.

In one or more embodiments, the spatial light modulator **101** is responsive to a driver and a control circuit **125**. The control circuit **125** can comprise one or more processors that execute instructions stored in a corresponding memory. The control circuit **125** and driver, in one embodiment are configured to deliver a drive signal to the spatial light modulator **101** based upon video or image data, which may be stored in a memory that is operable with the control circuit **125**. The driver can then cause the spatial light modulator **101** to sweep the scanned light **116** to form the image **102**. In one embodiment, the spatial light modulator **101** is configured to form the image **102** by moving in a raster pattern. Each raster scan of the raster pattern can comprise a frame of image content. Each raster scan can refresh image content by redrawing it. The refresh rate is 60 Hz in one embodiment. In other embodiments, other sub-120 Hz frequencies can be used, including 75 Hz, 80 Hz, or 90 Hz. In conjunction with modulation of the light sources **111**,**112**,**113**, the driver is operative to pivot the spatial light modulator **101** of FIG. **1** about a first axis and second axis by delivering a control signal to the spatial light modulator **101**. This pivoting action causes the scanned light to move horizontally and vertically to form the image **102**.

Turning now to FIG. **2**, illustrated therein is an alternate embodiment of an imaging system **200** configured in accordance with one or more embodiments of the invention. While the imaging system (**100**) of FIG. **1** delivered light on a direct path to the spatial light modulator (**101**), the imaging system **200** of FIG. **2** delivers light along an indirect path to the spatial light modulator **201**. Specifically, a reflective optical element **207** is disposed between the light sources **211**,**212**,**213** and the spatial light modulator **201**. Additionally, as mentioned above, the embodiment of FIG. **2** illustrates the use of dichroic mirrors **223**,**224**,**225** as an intermediate optical alignment device **222** configured to collimate the light beams **204**,**205**,**206** into a common beam **226**.

As shown in FIG. **2**, light beams **204**,**205**,**206** are emitted from the light sources **211**,**212**,**213** in a substantially parallel orientation. Each light beam **204**,**205**,**206** is directed to dichroic mirrors **223**,**224**,**225**, which are used as an optical alignment device **222** that collimates the light beams **204**,**205**,**206** into a collimated beam **226**. Dichroic mirrors **223**,**224**,**225** are partially reflective mirrors that include dichroic filters that selectively pass light in a narrow wavelength bandwidth while reflecting others. In one embodiment, polarizing coatings can be incorporated into the dichroic mirrors as well. Dichroic mirrors and their use in laser-based projection systems are known in the art and, as such, will not be discussed in further detail here. Note that the location, as well as the number, of the dichroic mirrors **223**,**224**,**225** can vary based upon application. For example, as noted with reference to FIG. **1**, in some MEMS-type scanning systems the light beams **204**,**205**,**206** can be encoded directly into the scanning mirror.

The reflective optical element **207** then functions as a converging reflective element in that it causes the collimated light beam **226** to converge after reflection from the reflective optical element **207** as it travels along an optical axis **214** defined between the reflective optical element **207** and the spatial light modulator **201**.

The remainder of the imaging system **200** of FIG. **2** then functions substantially in the same fashion as the imaging system (**100**) of FIG. **1**. The reflective optical element **207** and the spatial light modulator **201** are arranged such that an intermediate image plane **217**, where each pixel of the scanned light **216** is in focus, exists between the spatial light modulator **201** and a second optical element **215**. The second optical element **215** is then configured to collect diverging light **218** from the image plane **217** and reimage it to a finite or infinite conjugate. This can include collimating the collected, diverging light.

In one or more embodiments, the second optical element **215** comprises a doublet for color correction. The second optical element **215** then causes the collimated light **219** to converge at an output side of the second optical element **215** along a second optical axis **224** to a pupil **220**. In the illustrative embodiment of FIG. **2**, the pupil **220** occurs at the output of the image projection system **200**. Accordingly, the collimated light **219** diverges again to a projection surface **223** where the image **202** is formed. The combination of the reflective optical element **207**, which delivers the converging beam cone to the spatial light modulator **201**, and the second optical element **215** that creates a subsequent pupil **220** provides the designer with the flexibility to use smaller components. This will become clearer in the discussion of FIG. **4** that follows.

Turning now to FIG. **3**, another imaging system **300** is shown. The imaging system **300** of FIG. **3** is similar to that shown in FIG. **2**. However, a beam combiner **330** is used to collimate light **304**,**305**,**306** into a collimated beam **326**. Once output from the beam combiner **330**, the collimated beam **326** can be delivered to a reflective optical element **307** to cause the collimated beam **326** to converge as described above with reference to FIG. **2**. Alternatively, an intermediate optical element **337** can be used to cause the convergence and deliver light to the spatial light modulator **301**.

Additionally, the imaging system **300** of FIG. **3** includes a reflective element **330** disposed on an opposite side of the second optical element **315** relative to the spatial light modulator **301**. The reflective element **330** can take a variety of forms. In the illustrative embodiment of FIG. **3**, the reflective element **330** is a mirror configured to redirect an output beam **331** of the imaging system **300**. Designers may employ such devices to alter the geometry of the overall imaging system **300** to fit within a predetermined housing or form factor.

In other embodiments, the reflective element **330** can be other types of devices. For example, in one embodiment the reflective element **330** comprises a second spatial light modulator configured so scan the output beam **331** along the projection surface **323**. In one embodiment, the second optical element **315** is configured to relay the image plane **317** off the reflective element **330** at an infinite conjugate to create an infinite focus image projection system. At the same time, the second optical element **315** can be configured to create a small pupil at the reflective element **330**.

As shown in FIG. **3**, the second optical element **315** is configured to cause the diverging light **318** from the intermediate image plane **317** to converge along a second optical axis **324** defined between the second optical element **315** and the reflective element **330**. In this illustrative embodiment, the second optical element **315** causes the diverging light **318** to converge to a pupil at the reflective element **330**. The reflective element **330** then redirects the diverging light **318** as an output beam **331** to the projection surface. The output beam **331** expands from the pupil at the reflective element **330** to form the image **302** on the projection surface **323**.

Turning briefly to FIG. **7**, illustrated therein is one explanatory embodiment of a spatial light modulator **701** suitable for use with embodiments of the invention shown in FIGS. **1**-**3**. This embodiment is illustrative only, as other forms of modulating and scanning devices will be obvious to those of ordinary skill in the art having the benefit of this disclosure.

As noted above, one or more embodiments can employ a MEMS scanning platform such as that described in commonly assigned U.S. patent application Ser. No. 12/496,892 to Brown et al., entitled, “Phase Locked Resonant Scanning Display Projection,” which is incorporated herein by reference. Such a spatial light modulator **701** is shown in FIG. **7**. Note that there are many different ways in which a spatial light modulator can be constructed, and the MEMS scanning platform is but one example. Further, other spatial light modulators can be substituted for the spatial light modulator **701** of FIG. **7**, which is illustrative only.

The principal scanning component of the spatial light modulator **701** is a scanning mirror **771**. A driver **772**, which may be integrated with a control circuit, delivers a drive signal **773** to a drive coil **774** disposed about the scanning mirror **771**. The drive signal **773** causes a corresponding current to pass through the windings of the drive coil **774**. An external magnetic field source disposed near the light encoder (not shown) imposes a static magnetic field on the drive coil **774**. The magnetic field has a component in the plane of the coil, and is oriented non-orthogonally with respect to the two drive axes **775**,**776**. The in-plane current in the windings of the drive coil **774** interacts with the in-plane magnetic field component to produce out-of-plane Lorentz forces on the conductors of the drive coil **774**. As the drive current forms a loop, the current reverses sign across the scan axes, which causes the Lorentz forces to also reverse sign across the scan axes, thereby causing the application of mechanical torque. This combined torque produces responses in the two scan directions, depending on the frequency content of the torque, thereby causing motion about the axes **775**,**776**. This motion permits the driver **772**, or the control circuit via the driver, to scan an image on a projection surface.

FIGS. **1** and **2** each employ a single spatial light modulator capable of scanning along two axes. However, it can be desirable to separate employ multiple spatial light modulators in some embodiments. For example, in some systems employing a two-axis spatial light modulator, image artifacts can occur due to crosstalk in the vertical and horizontal drive signals. Said differently, when a two-axis mirror is driven both in the horizontal and vertical directions, image artifacts can result when there is not strong isolation between the vertical and horizontal signals. Illustrating by example, sinusoidal image brightness variation can occur from image top to image bottom. At times this sinusoidal image brightness variation can roll. Thus, accordingly, in one or more embodiments, separating the spatial light modulation function can be advantageous. Moreover, when one splits the modulation into two devices, different technologies can be selected for different modulators—one can be a PV electric (comb drive) modulator and one can be a magnetic resonant scanning modulator. Accordingly, separation can allow a designer to use a preferred technology from a size and/or cost standpoint.

Turning now to FIG. **4**, illustrated therein is an imaging system **400** employing spilt modulating devices. As shown in FIG. **4**, a first spatial light modulator **401** is disposed on a first side of a second optical element **415**. A second spatial light modulator **441** is disposed on a second side of the second optical element **415** opposite the first side. While the first spatial light modulator **401** and the second spatial light modulator **441** can each be two-axis scanning devices, in the illustrative embodiment of FIG. **4** the first spatial light modulator **401** scans only along a single axis, while the second spatial light modulator **441** also scans only along a single axis. In one embodiment, the scanning axis of the first spatial light modulator **401** and the scanning axis of the second spatial light modulator **441** are substantially orthogonal such that the combined scanning of the first spatial light modulator **401** and the second spatial light modulator **441** can result in a raster pattern.

Turning briefly to FIG. **8**, illustrated therein is a more detailed view of one embodiment of a split scanning system. The design of FIG. **8** is but one explanatory embodiment, as others will be obvious to those of ordinary skill in the art having the benefit of this disclosure. In the illustrative embodiment of FIG. **8**, the first spatial light modulator **801** and the second spatial light modulator **841** are made from the same technology. As noted above, in some embodiments different technologies can be selected for the first spatial light modulator **801** and the second spatial light modulator **841**. Accordingly, the embodiment of FIG. **8** is illustrative only.

As shown in FIG. **8**, the first spatial light modulator **801** is disposed opposite the second optical element **815** relative to the second spatial light modulator **841**. The first spatial light modulator **801** and the second spatial light modulator **841** are both resonant scanners in this illustration. Using the first spatial light modulator **801** as an example, the principal scanning component is a moving mirror **881** mounted to a spring plate **882**. The dimensions of the mirror **881** and spring plate **882**, as well as the material properties of the spring plate **882**, can be selected so that the mirror **881** and spring plate **882** have a high Q with a natural oscillatory ("resonant") frequency on the order of 1-100 kHz. The selected resonant frequency can depend upon the application. For VGA quality output with a 60 Hz refresh rate and no interlacing, the resonant frequency is preferably about 15-20 kHz.

A ferromagnetic material mounted with the mirror **881** is driven by a pair of electromagnetic coils **883**,**884** to provide motive force to mirror **881**, thereby initiating and sustaining oscillation. The ferromagnetic material can be manufactured so as to be integral to the spring plate **882** and body of the mirror **881**. A driver **872** provides electrical signals to activate the coils **883**,**884**. Responsive to the electrical signals, the coils **883**,**884** produce periodic electromagnetic fields that apply force to the ferromagnetic material, thereby causing oscillation of the mirror **881**. If the frequency and phase of the electric signals are properly synchronized with the movement of the mirror **881**, the mirror **881** oscillates at its resonant frequency with little power consumption.

When light passes through the system, it interacts with the mirror **881** of the first spatial light modulator **801** first. It then passes through the second optical element **815** to the mirror **886** of the second spatial light modulator **841**. One of the first spatial light modulator **801** or the second spatial light modulator **841** can be configured to scan along a first axis, while another of the first spatial light modulator **801** and the second spatial light modulator can be configured to scan along a second axis. Illustrating by example, where the first spatial light modulator **801** is configured to sweep the vertical axis of a raster pattern, it will be referred to as the "slow scan" device while the second spatial light modulator **841**, configured to scan the horizontal axis of a raster pattern, will be referred to as the "fast scan" device. Either the first spatial light modulator **801** or the second spatial light modulator **841** can be the slow scan device, and vice versa.

As shown in FIG. **8**, the second spatial light modulator **841** is configured as the slow scan device. The slow scan device is structured very similarly, in this illustrative embodiment, to the fast scan device, i.e., first spatial light modulator **801**. Like the slow scan device, the fast scan device includes a mirror **886** driven by a pair of coils **887**,**888** in response to electrical signals from the driver **872**. However, because the rate of oscillation is much lower for vertical scanning, the slow scan device can be configured as a non-resonant device, or alternatively may employ another non-resonant technology. The mirror **886** receives light **885** passing through the second optical element **815** from the fast scan device and produces vertical deflection, which occurs in one embodiment at about 30-100 Hz. While in prior art designs the mirror **886** had to be significantly larger than mirror **881**, the inclusion of the second optical element **815** allows the pupil to be placed at mirror **886**, thereby allowing a smaller mirror to be used. The second optical element **815** also reduces constraints on the positioning of the slow scan device due to the fact that the pupil created by the second optical element **815** can be moved in accordance with the design of the second optical element.

The light sources (not shown) output a plurality of light beams that are modulated according to an image signal from the driver **872**. At the same time, the driver **872** activates the coils **883**,**884**,**887**,**888** to manipulate the mirrors **881**,**886**. In this illustrative embodiment, the modulated beam of light strikes mirror **881**, and is deflected horizontally by an angle corresponding to the instantaneous angle of the mirror **881**. The deflected light then forms an image plane **817** prior to reaching the second optical element **815** and passes through the second optical element **815**. The light is then caused to converge to a pupil as it strikes mirror **886**, where it is deflected at a vertical angle corresponding to the instantaneous angle of mirror **886**. The modulation of the optical beam is synchronized with the horizontal and vertical scans so that at each position of the mirrors, the beam color and intensity correspond to a desired virtual image.

It will be clear to those of ordinary skill in the art having the benefit of this disclosure that other components of the scanning system have been omitted for clarity of presentation. For example, the first spatial light modulator **801** and second spatial light modulator **841** are typically mounted in fixed relative positions within a housing. Additionally, as will be shown in FIG. **9** below, the system can include one or more turning mirrors that direct the beam such that the beam strikes each of the mirrors a plurality of times to increase the angular range of scanning.

Turning now back to FIG. **4**, a first optical element **407** is disposed at an output of the plurality of light sources **411**,**412**, **413**. As with FIG. **1** above, the first optical element **407** of FIG. **4** is configured as three optical elements **408**,**409**,**410** disposed at the outputs of the light sources **411**,**412**,**413**. The first optical element **407** is configured to cause the plurality of light beams **404**,**405**,**406** emanating from the light sources **411**,**412**,**413** to converge along an optical path defined between the first optical element **407** and the spatial light modulator **401**. The second optical element **415** is then disposed between the first spatial light modulator **401** and the second spatial light modulator **441**. Note that FIG. **4** could have employed the beam combiner (**330**) of FIG. **3** instead of the first optical element **407**, provided a reflector was included to cause the output of the beam combiner (**330**) to converge to create the intermediate image plane **417**.

Light reflected from the first spatial light modulator **401** creates an intermediate image plane **417** between the spatial light modulator **401** and the second optical element **415**. The second optical element **415** then collects diverging light **418** from the image plane **417**, collimates the light, and delivers the light to the second spatial light modulator **441**. In one embodiment, the second optical element **415** causes the light to converge to a pupil at the second spatial light modulator **441**. The second spatial light modulator **441** scans the light to form the image **402** on the projection surface **423**.

In the imaging system **400** of FIG. **4**, the arrangement of the optical elements results in zero "walk" of the pupil created on the second spatial light modulator **441** since the second spatial light modulator **441** is disposed at the pupil plane of the second optical element **415**. This allows the effective Θ*D product to be decoupled, thereby allowing for a much larger Θ*D product than if the pupil occurred on a single mirror. Moreover, experimental testing has shown that the imaging system **400** can be configured to have no vertical smile distortion despite not having an output correction optical device.

Turning now to FIG. **5**, illustrated therein is an "indirect" imaging system **500** that is analogous to that shown in FIG. **2**, but that uses two spatial light modulators **501**,**541**. As shown in FIG. **5**, light beams **504**,**505**,**505** delivered to a beam combiner **530**. The light then leaves the beam combiner **530** in a converging fashion, with convergence being responsible for the creation of the intermediate image plane **517**. The addition of the reflective optical element **507**, which in this embodiment is a flat mirror, allows for a smaller overall form factor. The beam combiner **530**, or optionally one or more intermediate optical devices, function as the converging element in that the light beams **504**,**505**,**506** converge as they travel along an optical axis defined both between the light sources **511**,**512**,**513** and the reflective optical element **507**, and between the reflective optical element **507** and the first spatial light modulator **501**.

The remainder of the imaging system **500** of FIG. **5** then functions substantially in the same fashion as the imaging system (**400**) of FIG. **4**. The reflective optical element **507** and the spatial light modulator **501** are arranged such that an intermediate image plane **517** is created between the spatial light modulator **501** and the second optical element **515**. The second optical element **515** is then configured to collect diverging light **518** from the image plane **517** and collimate the collected, diverging light. The second optical element **515** then creates a pupil at the second spatial light modulator **541** as described above.

Turning to FIG. **6**, illustrated therein is an imaging system **600** employing a third optical element **661**. The third optical element **661** can be used with any of the aforementioned embodiments, but is shown illustratively in FIG. **6** as being used with the imaging system (**500**) of FIG. **5**. In the illustrative embodiment of FIG. **6**, the third optical element **661** is disposed between the reflective element formed by the second spatial light modulator **541** and the output of the imaging system **600**. The third optical element **661** is configured to collect reflected light from the second spatial light modulator **541** and create a pupil **662** on a side of the third optical element **661** disposed opposite the second spatial light modulator **541**. The third optical element **661** can be used to relay the output image to a farther point by creating a pupil **662** at a predefined location outside the imaging system **600**.

Turning to FIG. **9**, illustrated therein is another imaging system **900** configured in accordance with one or more embodiments of the invention. As noted in the discussion of FIG. **8**, embodiments of the invention can include one or more turning mirrors that direct the beam such that the beam strikes each of the mirrors a plurality of times to increase the angular range of scanning available by a spatial light modulator. The embodiment of FIG. **9** includes such turning mirrors.

Specifically, as shown in FIG. **9**, a spatial light modulator **901** is configured to produce images **902** by scanning a plurality of light beams that have been combined by a beam combiner **930**. The beam combiner **930** also causes the combined beam to converge as it moves toward the spatial light modulator **901**. The spatial light modulator **901** takes the combined, converging beam and scans it as scanned light **991**. The imaging system **900** includes a first reflector **992** and a second reflector **993**. The second reflector **993** of this illustrative embodiment comprises a concave mirror.

As shown in FIG. **9**, the first reflector **992** is arranged so as to redirect the scanned light **991** received from the spatial light modulator **901** to the second reflector **993**. The second reflector **993** is then arranged so as to redirect the scanned light **991** again to the spatial light modulator **901**. The second reflector **993** further causes the scanned light **991** to converge along an optical axis defined between the second reflector **993** and the spatial light modulator **901**. The spatial light modulator **901**, which is a MEMS scanning device in one embodiment, then re-scans the light to form the image **902** on the projection surface **923**. Where the second reflector **993** is configured to create a pupil at the spatial light modulator **901**, a smaller mirror surface can be used.

Turning to FIG. **10**, illustrated therein is a method **1000** of producing images that occurs in one or more of the imaging systems shown above. At step **1001**, the method **1000** causes, with a first optical element, a light beam or plurality of light beams to converge as the beam(s) travel to a spatial light modulator. At step **1002**, the method **1000** scans a plurality of light beams with a spatial light modulator. At step **1003**, the convergence occurring in step **1001** creates an image plane between the spatial light modulator and an optical element disposed between the spatial light modulator and an output of the imaging system.

At step **1004**, the method **1000** collects, with a second optical element, diverging light from the image plane and collimates the diverging light. At step **1005**, the method **1000** delivers the plurality of light beams to a pupil with the second optical element. In one embodiment, step **1005** occurs such that the pupil is an image pupil placed on a reflective element or additional spatial light modulator. As shown and described, the methods and systems above allow for relaxed mirror and device requirements while still meeting high resolution and small form factor design requirements.

To this point, embodiments of the present invention have been shown as creating images on projection surfaces. However, the establishment of an intermediate image plane by a first optical element and the collection of light therefrom by a second optical element, which is then delivered to a pupil by the second optical element, offers advantages in other applications as well. For example, when delivering light to a waveguide, capturing the quickly expanding light from a scanning mirror is a very complicated task. The factors governing waveguide design are the thickness of the waveguide, the size of the pupil entering the waveguide, and the desired size of the field of view. The use if an intermediate image plane in a waveguide system allows a designer "tradability" amongst these factors. By having control over the location and size of a pupil entering a waveguide via the intermediate image plane and second optical element, the designer is no longer held hostage regarding the size of mirror manufactured in a particular factory. If the factory produces a one-millimeter mirror, the designer can create an effective two-millimeter mirror with the design and placement of the second optical element and so forth. Moreover, the placement of the second optical element allows the designer to place the pupil exactly where desired.

Another benefit of embodiments of the present invention, when used in waveguide applications, relates to pupil size. When using a waveguide, to create a uniform image, a lot of copies of the incoming pupil must be created within the waveguide. If the pupil is one millimeter across, one needs many more copies than when the pupil is three millimeters across. As substrates move into smaller form factors, embodiments of the present invention allow a designer to create a pupil of arbitrary size without increasing the size of the imaging system components. Accordingly, a near-to-eye display can be created with a very small imaging engine. This allows for a much simpler waveguide design, and results in a transition from a "dust-goggle" sized near-to-eye devices to "normal eyeglass" sized devices.

Turning now to FIG. **11**, illustrated therein is the imaging system **300** of FIG. **3** delivering imaging light to a waveguide, which in this case is a substrate guided relay **1100**. A substrate guided relay is but one type of relay suitable for use with embodiments of the present invention. Others will be readily apparent to those of ordinary skill in the art having the benefit if this disclosure. This illustrative substrate guided relay **1100** of FIG. **11** includes an exit pupil expander **1104** located in an output coupler **1103**, a substrate **1105**, and an input coupler **1102**. The illustrative substrate guided relay **1100** is suitable for use in near-to-eye applications.

As shown in FIG. **11**, the second optical element **315** creates a pupil at an input coupler **1102** of the substrate guided relay **1100**. This launches the light scanned by the spatial light modulator **301** into the relay optics of the substrate guided relay **1100**. Light then propagates through the substrate guided relay **1100** in accordance with the optical properties of the substrate to the output coupler **1103**. In this embodiment, the light then is redirected from one or more partially reflective layers of the exit pupil expander **1104** to the user's eye **1106**.

FIGS. **12** and **13** illustrate another suitable waveguide for use with embodiments of the present invention. As with FIG. **11**, the waveguide of FIGS. **12** and **13** is configured as a substrate guided relay **1200** having an optical input device **1201**, an optical substrate **1202**, and an optical output device **1203**. FIG. **12** is a top, plan view of the substrate guided relay **1200**, while FIG. **13** is a side elevation view of the substrate guided relay **1200**. Embodiments and operating characteristics of such substrate guided relays are described in commonly assigned, copending U.S. patent application Ser. No. 11/775,511, filed Jul. 10, 2007, entitled "Substrate-Guided Relays for Use with Scanned Beam Light Sources," which is incorporated herein by reference.

In the illustrative embodiment of FIG. **12**, the optical input device **1201** is coupled to the optical substrate at an angle **1205**. This angle affects how light leaves the optical input device **1201** and enters the optical substrate **1202**. While this angle **1205** can be orthogonal, and while various angles can work for angle **1205**, in one embodiment angle **1205** is between **30** and **60** degrees. Experimental testing has shown that an angle of 45 degrees is effective for many applications.

The optical input device **1201** collects and receives light from the imaging system **300**. As described with reference to FIG. **11**, in one embodiment the second optical device (**315**) of the imaging system **300** is configured to create a pupil of the designer's choice of size at the input edge of the optical input device **1201**. Light is the delivered from the imaging system **300** to the optical substrate **1202** through a first interface **1206**. The optical input source **1210** can be coupled to the optical substrate **1202** along the first interface **1206** in a variety of ways, including adhesives, glues, and epoxies. In one exemplary embodiment, the optical input source **1210** is "optically contacted" to the optical substrate **1202**. This bond can be enhanced by chemically treating the surfaces prior to contacting.

In one embodiment, the first interface **1206** includes a partially reflective coating, which can be a metallic coating, such as silver. Once light is delivered from the optical input device **1201** to the optical substrate **1202** through the first interface **1206**, the light passes along the optical substrate **1202** to the optical output device **1203**. In some embodiments, light passing along the optical substrate **1202** is confined within the optical substrate **1202** by the principles of total internal inflection. Once light as passed sufficiently along the optical substrate **1202**, distally from the optical input device **1201**, the light reaches the optical output device **1203**. The optical output device **1203** is configured to receive light from the optical substrate **1202** and to enable a viewer (not shown) to see a displayed image, whether it be projected on a projection surface or directly into the viewer's eye. In one embodiment, the optical output device **1203** directs light to the viewer through a plurality of partially reflective layers **1204**. Note that the optical output device **1203** may be disposed either on top of, or beneath, the optical substrate **1202**. In one embodiment, a second interface **1209**, which occurs between the optical substrate **1202** and the optical output device **1203**, includes a partially reflective coating. The partially reflective coating directs light toward a viewing region, which in some embodiments is a user's pupil. When the pupil created by the second optical element (**315**) of the imaging system (**300**) is sufficiently large, light from all image points (or pixels) can be delivered to a viewer as a complete image with sufficient uniformity.

FIG. **14** illustrates the imaging system **300** and one illustrative waveguide **1401** in operation. An eyewear device **1400** using the waveguide **1401** presents information directly into than eye **1403** of a user **1402**. The illustrative eyewear device **1400** includes lens assemblies **1404** that are coupled to a frame **1405**. In this illustrative embodiment, the waveguide **1401** is integrated into the lens assembly **1404**. In one embodiment, the eyewear device **1400** and waveguide **1401** are configured such that the user **1402** can see images beyond the lens assemblies **1404** at the same time the imaging system **300** is delivering information. This particular eyewear device can be configured to be substantially smaller than prior art designs thanks to the intermediate image plane (**317**) and the second optical element (**315**).

In the foregoing specification, specific embodiments of the present invention have been described. However, one of ordinary skill in the art appreciates that various modifications and changes can be made without departing from the scope of the present invention as set forth in the claims below. Thus, while preferred embodiments of the invention have been illustrated and described, it is clear that the invention is not so limited. Numerous modifications, changes, variations, substitutions, and equivalents will occur to those skilled in the art without departing from the spirit and scope of the present invention as defined by the following claims. Accordingly, the specification and figures are to be regarded in an illustrative rather than a restrictive sense, and all such modifications are intended to be included within the scope of present invention. The benefits, advantages, solutions to problems, and any element(s) that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential features or elements of any or all the claims.

What is claimed is:

1. An imaging system, comprising:

a spatial light modulator configured to produce images by scanning a plurality of light beams;

a first optical element configured to cause the plurality of light beams to converge along an optical path defined between the first optical element and the spatial light modulator;

a waveguide; and

a second optical element disposed between the spatial light modulator and an input of the waveguide;

wherein the first optical element and the spatial light modulator are arranged such that an image plane exists between the spatial light modulator and the second optical element.

2. The imaging system of claim **1**, wherein the first optical element comprises a powered optical element disposed at an output of a plurality of light sources.

3. The imaging system of claim **2**, wherein the powered optical element comprises a plurality of powered optical elements.

4. The imaging system of claim **3**, further comprising the plurality of light sources configured to produce the plurality of light beams, wherein the plurality of powered optical elements correspond to the plurality of light sources on a one to one basis.

5. The imaging system of claim **1**, wherein the first optical element comprises a converging reflective element.

6. The imaging system of claim **5**, further comprising:

a plurality of light sources configured to produce the plurality of light beams; and

one or more powered optical elements disposed at the output of the plurality of light sources.

7. The imaging system of claim **1**, wherein the second optical element is configured to collect diverging light from the image plane and collimate the diverging light.

8. The imaging system of claim **7**, wherein the second optical element is configured to cause the diverging light to converge along a second optical axis defined between the second optical element and the input of the waveguide.

9. The imaging system of claim **8**, wherein the second optical element is configured to cause the diverging light to converge to a pupil at the input of the waveguide.

10. The imaging system of claim **9**, wherein the waveguide comprises a substrate guided relay.

11. The imaging system of claim **10**, wherein the substrate guided relay comprises an input coupler, a substrate, and an output coupler.

12. The imaging system of claim **1**, further comprising a third optical element disposed between the second optical element and the input of the waveguide, wherein the third optical element is configured to collect reflected light from the second optical element and create a pupil on the input of the waveguide.

13. The imaging system of claim **12**, further comprising a reflective element disposed between the second optical element and the third optical element.

14. The imaging system of claim **1**, wherein the second optical element comprises a doublet.

15. The imaging system of claim **1**, wherein the waveguide is integrated into an eyeglass lens.

16. The imaging system of claim **1**, wherein the spatial light modulator comprises a MEMS scanning mirror.

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