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(54) **FULL-FIELD METROLOGY TOOL FOR WAVEGUIDE COMBINERS AND META-SURFACES**

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G02B 27/01 (2006.01)

(52) **U.S. Cl.**
CPC ***G02B 27/0172*** (2013.01); ***G02B 27/0176*** (2013.01)

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CPC G02B 27/0172; G02B 27/0176
See application file for complete search history.

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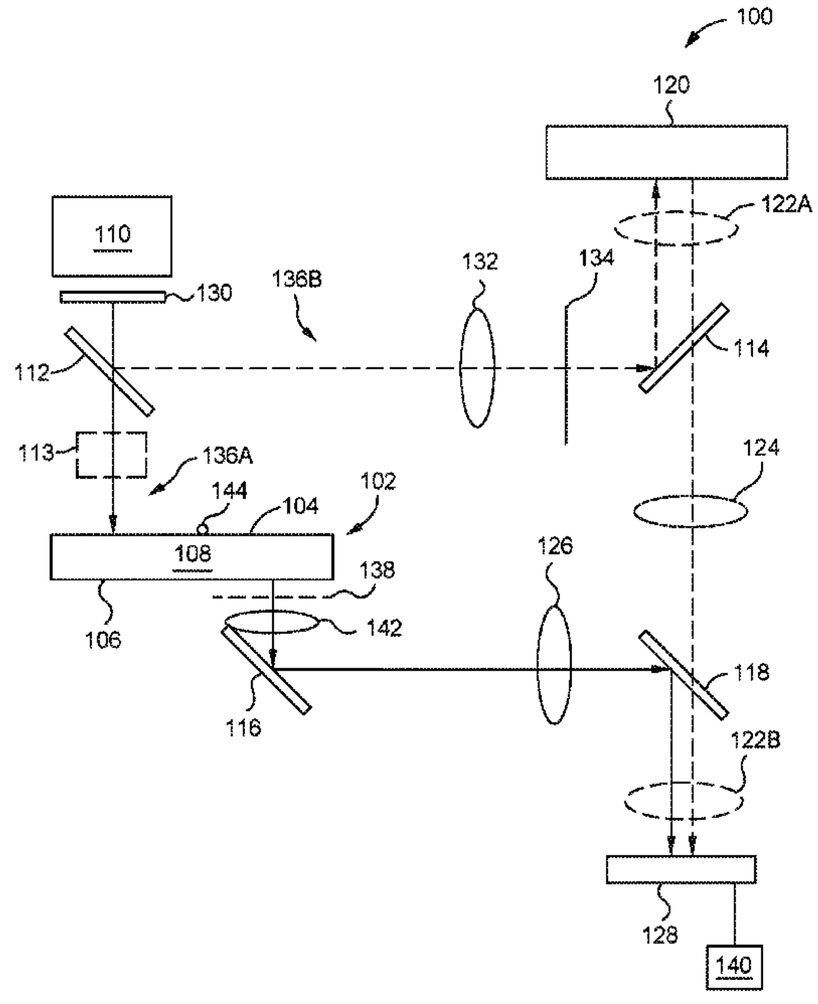
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(57) **ABSTRACT**

Embodiments described herein provide for metrology tools and methods of obtaining a full-field optical field of an optical device to determine multiple metrology metrics of the optical device. A metrology tool is utilized to split a light beam into a first light path and a second light path. The first light path and the second light path are combined into a combined light beam and delivered to the detector. The detector measures the intensity of the combined light beam. A first equation and second equation are utilized in combination with the intensity measurements to determine an amplitude and phase ψ at a reference point directly adjacent to a second surface of the at least one optical device.

20 Claims, 3 Drawing Sheets



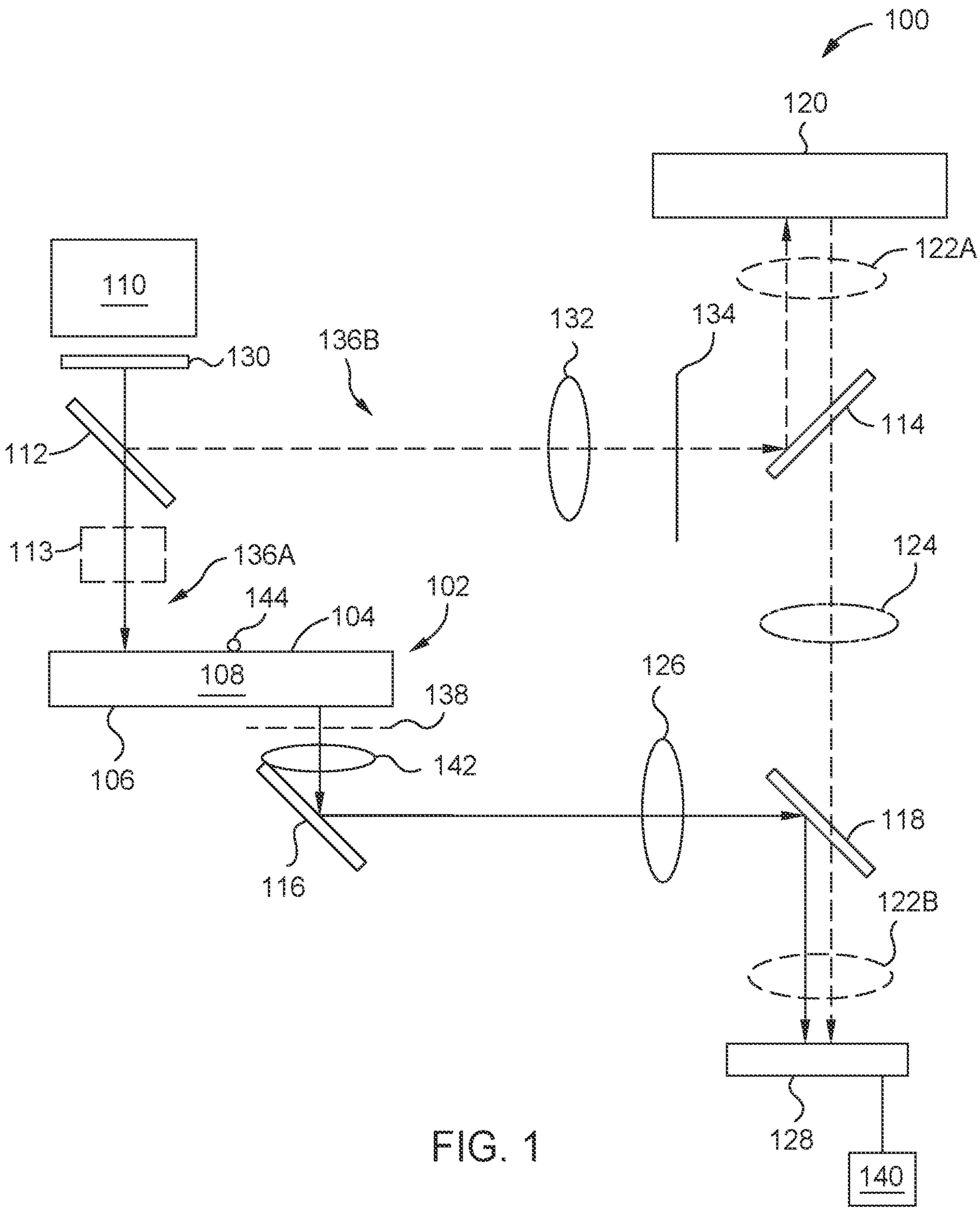

100
120
122A
110
130
136B
132
134
112
114
113
136A
124
102
144
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108
126
138
106
142
116
118
122B
128
140

FIG. 1

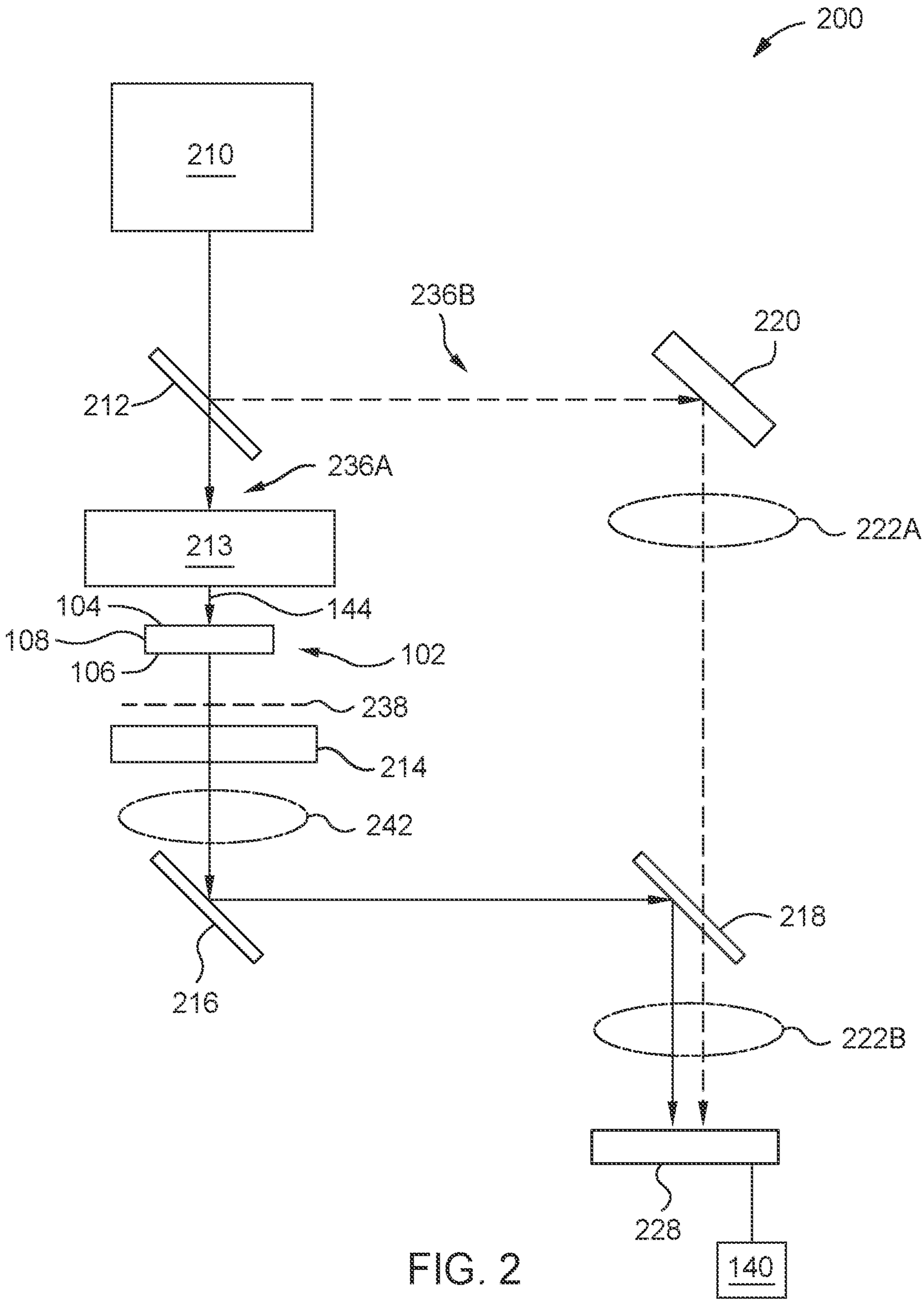

200
210
236B
220
212
236A
222A
213
104
144
108
102
106
238
214
242
216
218
222B
228
140

FIG. 2

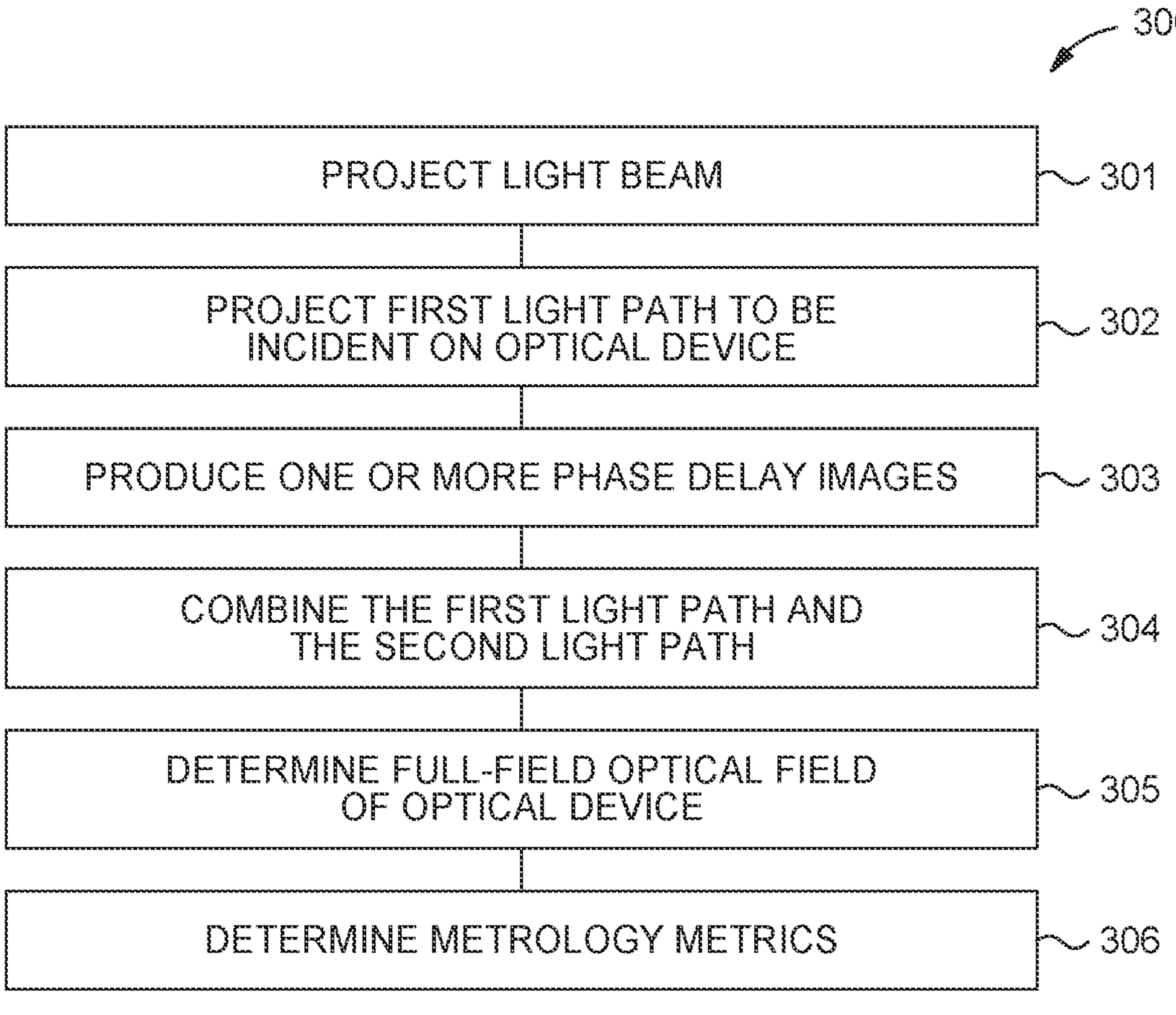

300
PROJECT LIGHT BEAM
301
PROJECT FIRST LIGHT PATH TO BE INCIDENT ON OPTICAL DEVICE
302
PRODUCE ONE OR MORE PHASE DELAY IMAGES
303
COMBINE THE FIRST LIGHT PATH AND THE SECOND LIGHT PATH
304
DETERMINE FULL-FIELD OPTICAL FIELD OF OPTICAL DEVICE
305
DETERMINE METROLOGY METRICS
306

FIG. 3

FULL-FIELD METROLOGY TOOL FOR WAVEGUIDE COMBINERS AND META-SURFACES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application Ser. No. 63/233,126, filed Aug. 13, 2021, which is incorporated by reference herein in its entirety.

BACKGROUND

Field

Embodiments of the present disclosure generally relate to metrology tools. More specifically, embodiments described herein provide for metrology tools and methods of obtaining a full-field optical field of an optical device to determine multiple metrology metrics of the optical device.

Description of the Related Art

Virtual reality is generally considered to be a computer generated simulated environment in which a user has an apparent physical presence. A virtual reality experience can be generated in 3D and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as lenses to display a virtual reality environment that replaces an actual environment.

Augmented reality, however, enables an experience in which a user can still see through the display lenses of the glasses or other HMD device to view the surrounding environment, yet also see images of virtual objects that are generated for display and appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhances or augments the environment that the user experiences. As an emerging technology, there are many challenges and design constraints with augmented reality.

One such challenge is obtaining a full characterization of the optical devices used for virtual reality and augmented reality. To ensure that the optical device design is validated and optical device metrology metrics are monitored, the metrology metrics need to be measured. To obtain the metrology metrics, multiple metrology tools are utilized to determine the different metrics, which may be time consuming, inefficient, and costly. When obtaining the metrology metrics, it is desirable to have a measurement method that is high throughout, low cost, and has a low bandwidth requirement. Thus, a single metrology tool and method that can obtain a full characterization of the optical device is desirable. Accordingly, what is needed in the art are metrology tools and methods of obtaining a full-field optical field of an optical device to determine multiple metrology metrics of the optical device.

SUMMARY

In one embodiment, a metrology tool is provided. The metrology tool includes a light engine operable to project a light beam. The metrology tool further includes a first beam splitter disposed in a path of the light beam. The first beam splitter is operable to split the light beam into a first light path and a second light path and the first light path is operable to be incident on an optical device. The metrology tool further includes a phase modulator disposed in the second light path. The metrology tool further includes a second beam splitter disposed in the first light path and the second light path. The second beam splitter is operable to combine the first light path and the second light path to form a combined light path. The metrology tool further includes a detector disposed in the combined light path. The detector is operable to record an intensity of the combined light path.

In another embodiment, a metrology tool is provided. The metrology tool includes a light engine operable to project a light beam. The metrology tool further includes a first beam splitter disposed in a path of the light beam. The first beam splitter is operable to split the light beam into a first light path and a second light path. The first light path is operable to be incident on an optical device. The metrology tool further incudes a modulation module disposed in the first light path. The modulation module is operable to change a phase, amplitude, or angle of incidence of the first light path. The metrology tool further includes a tilted mirror disposed in the second light path and a second beam splitter disposed in the first light path and the second light path. The second beam splitter is operable to combine the first light path and the second light path to form a combined light path. The metrology tool further includes a detector disposed in the combined light path. The detector is operable to record an intensity of the combined light path.

In yet another embodiment, a method is provided. The method includes projecting a light beam to a first beam splitter. The first beam splitter splits the light beam into a first light path and a second light path. The method further includes projecting the first light path to an optical device. The first light path travels through the optical device. The optical device is a metasurface or a waveguide combiner. The method further includes projecting the second light path to a phase modulator. The phase modulator is operable to generate one or more phase delay images of the second light path. The method further includes combining the first light path and the second light path with a second beam splitter to form a combined light path. The method further includes directing the combined light path to a detector. The detector is operable to record an intensity measurement of the first light path and the second light path. The method further includes determining a full-field optical field of the optical device at a reference point located adjacent to a surface of the optical device where the first light path exits the optical device. The full-field optical field is determined by performing a Fourier transform on the intensity measurement to reconstruct an amplitude and phase of the first light path at the reference point.

BRIEF DESCRIPTION OF THE DRAWINGS

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.

FIG. **1** is a schematic, cross-sectional view of a metrology tool according to embodiments described herein.

FIG. **2** is a schematic, cross-sectional view of a metrology tool according to embodiments described herein.

FIG. **3** is a flow diagram of a method for determining a full-field optical field of at least one optical device according to embodiments described herein.

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

Embodiments of the present disclosure generally relate to metrology tools. More specifically, embodiments described herein provide for metrology tools and methods of obtaining a full-field optical field of an optical device to determine multiple metrology metrics of the optical device. The metrology tool includes a light engine operable to project a light beam. The metrology tool further includes a first beam splitter disposed in a path of the light beam. The first beam splitter is operable to split the light beam into a first light path and a second light path and the first light path is operable to be incident on an optical device. The metrology tool further includes a phase modulator disposed in the second light path. The metrology tool further includes a second beam splitter disposed in the first light path and the second light path. The second beam splitter is operable to combine the first light path and the second light path to form a combined light path. The metrology tool further includes a detector disposed in the combined light path. The detector operable to record an intensity of the combined light path.

FIG. **1** is a schematic, cross-sectional view of a metrology tool **100**. In a first embodiment of a metrology tool **100**, the metrology tool **100** includes a third lens **122**A and a fourth lens **122**B. In a second embodiment of the metrology tool **100**, the metrology tool **100** includes a fifth lens **124**. The metrology tool **100** includes a phase modulator **120**. In a first configuration of the phase modulator **120**, the phase modulator **120** is a spatial light modulator. In a second configuration of the phase modulator **120**, the phase modulator **120** is a piezo driven mirror. In a third configuration of the phase modulator **120**, the phase modulator **120** is a tilted mirror. Any of the first or second embodiments of the metrology tool **100** include the phase modulator **120** of at least one of the first, second, or third configurations.

The metrology tool **100** is operable to retain a substrate **108**. The substrate **108** includes at least one optical device **102** disposed on the substrate **108**. The substrate **108** can be any substrate used in the art, and can be either opaque or transparent to a chosen wavelength depending on the use of the substrate **108**. Additionally, the substrate **108** may be varying shapes, thicknesses, and diameters. The substrate **108** may have a circular, rectangular, or square shape. The substrate **108** is not limited in the number of optical devices **102** that may be disposed on the substrate **108**. Each optical device **102** may include a plurality of optical device structures disposed on the substrate **108**. The optical device structures may be nanostructures having sub-micron dimensions, e.g., nano-sized dimensions.

It is to be understood that the at least one optical device **102** described herein is an exemplary optical device and other optical devices may be used with or modified to accomplish aspects of the present disclosure. In one embodiment, which can be combined with other embodiments described herein, the optical device **102** is a waveguide combiner. The waveguide combiner may be utilized for virtual, augmented, or mixed reality. In embodiments where the optical device **102** is a waveguide combiner, an input coupling region may be disposed on a first surface **104** of the optical device **102**. An output coupling region may be disposed on a second surface **106** of the optical device **102**. The second surface **106** is on an opposing surface of the first surface **104**. In another embodiment, which can be combined with other embodiments described herein, the waveguide combiner includes the input coupling region and the output coupling region on the same surface, for example, one of the first surface **104** or the second surface **106**. In yet another embodiment, which can be combined with other embodiments described herein, the optical device **102** is a flat optical device, such as a metasurface. The metasurface includes but is not limited to, one of a lens, a diffuser, a dot matrix projector, or a sensor.

The metrology tool **100** is operable to measure a full-field optical field of the at least one optical device **102**. The method described herein improves throughput, reduces storage and bandwidth requirements, and reduces costs associated with analysis of the optical devices. The full-field optical field includes the amplitude and the phase of the light beam. The full-field optical field provides direct information of the optical device **102**, by measuring the full-field optical field in parallel. To ensure that the design of the optical device **102** is validated and optical device metrology metrics are monitored, metrology metrics may be obtained from the full-field optical field. Embodiments of the metrology tool **100** described herein provide for the ability to obtain multiple metrology metrics with increased throughput. The metrology metrics include one or more of an angular uniformity metric, a contrast metric, an efficiency metric, a color uniformity metric, a modulation transfer function (MTF) metric, a field of view (FOV) metric, a ghost image metric, or an eye box metric for waveguide combiners. The metrology metrics include one or more of an efficiency metric, a point spread function (PSF) metric, or a phase error metric for metasurfaces.

The metrology tool **100** includes a light engine **110**, a first beam splitter **112**, a second beam splitter **114**, a mirror **116**, a third beam splitter **118**, a phase modulator **120**, a first lens **126**, and a detector **128**. In some embodiments, which can be combined with other embodiments described herein, the metrology tool **100** includes one or more of a linear polarizer **130**, a second lens **132**, a pinhole **134**, and an auxiliary lens **142**. In a first embodiment of the metrology tool **100**, the metrology tool **100** includes a third lens **122**A and a fourth lens **122**B. In a second embodiment of the metrology tool **100**, the metrology tool **100** includes a fifth lens **124**.

The light engine **110** is operable to project a light beam to the first beam splitter **112**. In one embodiment, which can be combined with other embodiments described herein, the light engine **110** is a light-emitting diode (LED) or a laser. In another embodiment, which can be combined with other embodiments described herein, the light engine **110** includes a display module. The display module is operable to project a pattern to the optical device **102**. The display module may include a micro LED module, a liquid crystal on silicon (LCOS) module, digital light processing (DLP) module, or laser projection module. In yet another embodiment, which can be combined with other embodiments described herein, the light beam is incident on the linear polarizer **130** prior to contacting the first beam splitter **112**. The linear polarizer **130** is operable to linearly polarize the incoming light beam. The linear polarizer **130** may be a half wave plate.

The first beam splitter **112** splits the light beam into a first light path **136**A and a second light path **136**B. The optical device **102** is disposed in the first light path **136**A. The

optical device **102** may be any suitable optical device, such as a waveguide combiner or a metasurface. The first light path **136**A is directed to the optical device **102** to be measured. The first light path **136**A is incident on the first surface **104** of the optical device **102**. In some embodiments, a modulation module **113** is positioned adjacent to the first surface **104**. The modulation module **113** is operable to change the phase, amplitude, or angle of incidence of the first light path **136**A.

In embodiments where the optical device **102** is a waveguide combiner, as shown in FIG. **1**, the first light path **136**A is incident on the input coupling region. The first light path **136**A passes through the waveguide combiner. The first light path **136**A exits the output coupling region of the waveguide combiner. Although FIG. **1** depicts the optical device **102** as a waveguide combiner, the optical device **102** may be any suitable optical device, such as a metasurface. In embodiments where the optical device **102** is a metasurface, the first light path **136**A is incident on the first surface **104** of the metasurface. The first light path **136**A is directed to a centerpoint **144** of the metasurface. The first light path **136**A passes through the metasurface and exits the centerpoint **144** of the metasurface.

The first light path **136**A is operable to be incident on the mirror **116**. The mirror **116** is positioned adjacent to the second surface **106** of the optical device **102** along the first light path **136**A. The mirror **116** is operable to direct the first light path **136**A to the first lens **126**. The first lens **126** is operable to direct the first light path **136**A to the third beam splitter **118**. In one embodiment, which can be combined with other embodiments described herein, the first lens **126** may be positioned between the second surface **106** and the mirror **116**. In another embodiment, which can be combined with other embodiments described herein, the first lens **126**, as shown in FIG. **1**, may be positioned between the mirror **116** and the third beam splitter **118**. The first lens **126** is a relay lens. In yet another embodiment, which can be combined with other embodiments described herein, the auxiliary lens **142** is positioned between the optical device **102** and the mirror **116**. The auxiliary lens **142** is a relay lens.

The second light path **136**B is incident on the second beam splitter **114**. In one embodiment, which can be combined with other embodiments described herein, one or both of the second lens **132** and the pinhole **134** are positioned between the first beam splitter **112** and the second beam splitter **114** in the second light path **136**B. The second light path **136**B may pass through one or both of the second lens **132** and the pinhole **134**. The second lens **132** is a relay lens. The pinhole **134** is operable to act as a low-pass filter for the second light path **136**B. The second beam splitter **114** is positioned adjacent to the phase modulator **120**. The second beam splitter **114** is operable to direct the second light path **136**B to the phase modulator **120**.

The phase modulator **120** is operable to change the phase of the second light path **136**B. In a first configuration of the phase modulator **120**, the phase modulator **120** is a spatial light modulator. In a second configuration of the phase modulator **120**, the phase modulator **120** is a piezo driven mirror. In a third configuration of the phase modulator **120**, the phase modulator **120** is a tilted mirror. The phase modulator **120** changes the phase of the second light path **136**B. The second light path **136**B is directed to the third beam splitter **118**. The phase modulator **120** generates one or more phase modulated images of the second light path **136**B. In embodiments with the first configuration or the second configuration, one or more phase delay images may be produced. In embodiments with the third configuration, one or more linear phase delay images may be produced.

In the first embodiment, the third lens **122**A and the fourth lens **122**B are positioned along the second light path **136**B. The third lens **122**A is adjacent to the phase modulator **120**. The fourth lens **122**B is adjacent to the detector **128**. In the second embodiment, the fifth lens **124** is positioned along the second light path **136**B. The first embodiment utilizes the third lens **122**A and the fourth lens **122**B and the second embodiment utilizes the fifth lens **124** to direct the second light path **136**B within the metrology tool **100**. The third lens **122**A, the fourth lens **122**B, and the fifth lens **124** are relay lenses.

The third beam splitter **118** is operable to direct the first light path **136**A and the second light path **136**B toward the detector **128**. The third beam splitter **118** combines the first light path **136**A and the second light path **136**B into a combined light path. The detector **128** is operable to obtain an intensity measurement of the combined light path. The detector **128** is operable to utilize the intensity measurement to reconstruct a full-field optical field at reference point **138**. The reference point **138** is located directly adjacent to the second surface **106**. The reference point **138** is located adjacent to the surface of the optical device **102** where the first light path **136**A exits the optical device. The metrology metrics of the optical device **102** are derived from the full-field optical field during post-processing. The metrology tool **100** is in communication with a controller **140** operable to control operation of the metrology tool **100**.

FIG. **2** is a schematic, cross-sectional view of a metrology tool **200**. The metrology tool **200** is operable to retain a substrate **108**. The substrate **108** includes at least one optical device **102** disposed on the substrate **108**.

It is to be understood that the at least one optical device **102** described herein is an exemplary optical device and other optical devices may be used with or modified to accomplish aspects of the present disclosure. In one embodiment, which can be combined with other embodiments described herein, the optical device **102** is a waveguide combiner. The waveguide combiner may be utilized for virtual, augmented, or mixed reality. In embodiments where the optical device **102** is a waveguide combiner, an input coupling region may be disposed on a first surface **104** of the optical device **102**. An output coupling region may be disposed on a second surface **106** of the optical device **102**. The second surface **106** is on an opposing surface of the first surface **104**. In another embodiment, which can be combined with other embodiments described herein, the waveguide combiner includes the input coupling region and the output coupling region on the same surface, for example, one of the first surface **104** or the second surface **106**. In yet another embodiment, which can be combined with other embodiments described herein, the optical device **102** is a flat optical device, such as a metasurface.

The metrology tool **200** is operable to measure a full-field optical field of the at least one optical device **102**. The full-field optical field of the optical device **102** provides a full characterization of the optical device **102**. The full-field optical field includes the amplitude and the phase of the light beam. The full-field optical field provides direct information of the optical device **102**, by measuring the full-field optical field in parallel. To ensure that the design of the optical device **102** is validated and optical device metrology metrics are monitored, metrology metrics may be obtained from the full-field optical field. Embodiments of the metrology tool **200** described herein provide for the ability to obtain multiple metrology metrics with increased throughput. The

metrology metrics include one or more of an angular uniformity metric, a contrast metric, an efficiency metric, a color uniformity metric, a modulation transfer function (MTF) metric, a field of view (FOV) metric, a ghost image metric, or an eye box metric for a waveguide combiner and an efficiency metric, a point spread function (PSF) metric, a modulation transfer MTF metric, or a phase error metric for metasurfaces.

The metrology tool **200** includes a light engine **210**, a first beam splitter **212**, a second beam splitter **218**, a mirror **216**, a tilted mirror **220**, a first lens **222**A, a second lens **222**B, an auxiliary lens **242**, and a detector **228**. The light engine **210** is operable to project a light beam to the first beam splitter **212**. In one embodiment, which can be combined with other embodiments described herein, the light engine **210** is a light-emitting diode (LED) or a laser. In another embodiment, which can be combined with other embodiments described herein, the light engine **210** includes a display module. The display module is operable to project a pattern to the optical device **102**. The display module may include a micro LED module, a liquid crystal on silicon (LCOS) module, digital light processing (DLP) module, or laser projection module.

The first beam splitter **212** splits the light beam into a first light path **236**A and a second light path **236**B. The optical device **102** is disposed in the first light path **236**A. The optical device **102** may be any suitable optical device, such as a waveguide combiner or a metasurface. The first light path **236**A is directed to the optical device **102** to be measured. The first light path **236**A is incident on the first surface **104** of the optical device **102**. In some embodiments, which can be combined with other embodiments described herein, a first modulation module **213** and a second modulation module **214** are positioned adjacent to the first surface **104** of the optical device **102**. The first modulation module **213** and the second modulation module **214** are positioned on either side of the optical device **102**. The first modulation module **213** and the second modulation module **214** are operable to change the phase, amplitude, or angle of incidence of the first light path **236**A.

In embodiments where the optical device **102** is a metasurface, as shown in FIG. **2**, the first light path **236**A is incident on the first surface **104** of metasurface. The first light path **236**A is directed to a centerpoint **144** of the metasurface. The first light path **236**A passes through the metasurface and exits the centerpoint **144** of the metasurface. Although FIG. **2** depicts the optical device **102** as a metasurface, the optical device **102** may be any suitable optical device, such as a waveguide combiner.

In embodiments where the optical device **102** is a waveguide combiner, as shown in FIG. **1**, the first light path **236**A is incident on the input coupling region. The first light path **236**A passes through the waveguide combiner. The first light path **236**A exits the output coupling region of the waveguide combiner.

The first light path **236**A is operable to be incident on the mirror **216**. The auxiliary lens **242** is positioned between the optical device **102** and the mirror **216**. The auxiliary lens **242** is a relay lens. The mirror **216** is positioned adjacent to the second surface **106** of the optical device **102** along the first light path **236**A. The mirror **216** is operable to direct the first light path **236**A to the second beam splitter **218**.

The second light path **236**B is incident on the tilted mirror **220**. The tilted mirror **220** is operable to change the phase of the second light path **236**B. The tilted mirror **220** changes the phase of the second light path **236**B. The second light path **236**B is directed to the second beam splitter **218**. The tilted mirror **220** generates one or more linear phase delay images of the second light path **236**B. The first lens **222**A and the second lens **222**B are positioned along the second light path **236**B. The first lens **222**A is adjacent to the tilted mirror **220**. The second lens **222**B is adjacent to the detector **228**. The first lens **222**A and the second lens **222***b* are relay lenses.

The second beam splitter **218** is operable to direct the first light path **236**A and the second light path **236**B toward the detector **228**. The second beam splitter **218** combines the first light path **236**A and the second light path **236**B into a combined light path. The detector **228** is operable to obtain an intensity measurement of the combined light path. The detector **228** is operable to utilize the intensity measurement to reconstruct a full-field optical field at reference point **238**. The reference point **238** is located directly adjacent to the second surface **106**. The reference point **238** is located adjacent to the surface of the optical device **102** where the first light path **236**A exits the optical device **102**. The metrology metrics of the optical device **102** are derived from the full-field optical field during post-processing. The metrology tool **200** is in communication with a controller **140** operable to control operation of the metrology tool **200**.

FIG. **3** is a flow diagram of a method **300** for determining a full-field optical field of at least one optical device **102**. The at least one optical device **102** is disposed on a substrate **108** disposed in a metrology tool **100**. To facilitate explanation, the method **300** is described with reference to the metrology tool **100**, as shown in FIG. **1**. A controller **140** of the metrology tool **100** is operable to facilitate the operations of the method **300**. The method **300** is operable to be performed in conjunction with the metrology tool **200**.

At operation **301**, a light beam is projected. The light beam is projected from a light engine **110** to a first beam splitter **112**. The first beam splitter **112** splits the light beam into a first light path **136**A and a second light path **136**B.

At operation **302**, the first light path **136**A is projected to be incident on the optical device **102**. In embodiments where the optical device **102** is a waveguide combiner, the first light path **136**A is incident on the input coupling region, corresponding to a first surface **104**. The first light path **136**A passes through the optical device **102**. The first light path **136**A exits the output coupling region of the optical device **102**. The waveguide combiner is positioned such that the first light path **136**A is operable to be incident on the input coupling region of the waveguide combiner. In embodiments where the optical device **102** is a metasurface, the first light path **136**A is incident on the first surface **104** of the metasurface. The first light path **136**A is directed to a centerpoint **144** of the metasurface. The first light path **136**A passes through the metasurface and exits via the centerpoint **144** of the metasurface through the second surface **106**. The metasurface is positioned such that the first light path **136**A is operable to be incident on the centerpoint **144** of the metasurface. The first light path **136**A is directed to the detector **128**.

At operation **303**, one or more phase modulated images are produced. In one embodiment, which can be combined with other embodiments described herein, the one or more phase modulated images are phase delay images. The second light path **136**B is incident on a phase modulator **120** to produce the one or more phase delay images. In a first configuration and a second configuration of the phase modulator **120**, the phase modulator **120** is a spatial light modulator or a piezo driven mirror. When the phase modulator **120** is in the first configuration or the second configuration, the phase modulator **120** is operable to generate one or more

phase delays of the second light path **136**B. For example, four phase delay images (i.e., 0.5π, π, 1.5π, 2π) of the second light path **136**B are provided to the detector **128** to be recorded. Each phase delay image will alter the intensity of the first light path **136**A and the second light path **136**B on the detector **128**. Additionally, three or more phase delay images reduce the effects of noise on the detector **128**. In a third configuration of the phase modulator **120**, the phase modulator **120** is a tilted mirror.

In another embodiment, which can be combined with other embodiments described herein, the one or more phase modulated images are linear phase delay images. When the phase modulator **120** is in the third configuration, a tilted mirror is utilized. The tilted mirror forms one or more linear phase delay images with a linear phase change. The tilted mirror is angled at a predefined angle such that that the one or more linear phase delay images may be formed without aliasing. The linear phase delay images of the second light path **136**B are provided to the detector **128**.

At operation **304**, the first light path **136**A and the second light path **136**B are combined. The first light path **136**A and the second light path **136**B are combined by the third beam splitter **118**. The first light path **136**A and the second light path **136**B are combined to form a combined light path. The combined light path is incident on the detector **128**. A first lens **126** relays the first light path **136**A to the detector **128**. In some embodiments, a fourth lens **122**B also relays the reference field to the detector **128**. A second lens **132** relays the light field of the one or more phase delay images from the phase modulator **120** to the detector **128**. In some embodiments, a third lens **122**A or a fifth lens **124** also relays the light field of the one or more phase delay images to the detector **128**.

At operation **305**, a full-field optical field of the optical device **102** at a reference point **138** is determined. The reference point **138** is located directly adjacent to the second surface **106**. In one embodiment, which can be combined with other embodiments described herein, the reference point **138** is located at the output coupling region of the optical device **102**. The full-field optical field provides a full characterization of the optical device **102**. The full-field optical field at the reference point **138** includes determining amplitude and phase at the reference point **138**. In one embodiment, which can be combined with other embodiments described herein, a profile of the phase can be directly compared with the design of the optical device **102** and thus, provide feedback to the manufacturing process. The detector **128** records an intensity measurement of the combined light path to determine the amplitude and the phase. When the phase modulator **120** is in the first configuration or the second configuration, a first equation may be utilized to determine the intensity measurement of the combined light beam, I(x,y;Φ):

$$I(x,y;\Phi)=I_1(x,y)+I_2(x,y)\cos(\psi(x,y)+\Phi)$$

where I_1 is the intensity measurement of the first light path **136**A, I_2 is the intensity measurement of the second light path **136**B, Φ is the phase of the one or more phase delay images introduced by the phase modulator **120**, and ψ is the phase of the first light path **136**A at the reference point **138**. I_1 and I_2 contain the amplitude information at the reference point **138**. By changing the phase of the phase delay images Φ with the phase modulator **120**, multiple different images are utilized to solve for the amplitude and phase ψ at the reference point **138**. For example, a Fourier transform of (x,;Φ) will reconstruct the amplitude and phase ψ at the reference point **138**. The amplitude and phase **1**P at the reference point **138** correspond to the full-field optical field.

When the phase modulator **120** is in the third configuration, a second equation may be utilized to determine the intensity measurement of the combined light beam, I(x,Y; $\Phi_{x,y}$):

$$I(x,y;\Phi)=I_1(x,y)+I_2(x,y)\cos(\psi(x,y)+\Phi_{x,y})$$

where I_1 is the intensity measurement of the first light path **136**A, I_2 is the intensity measurement of the second light path **136**B, Φ is the phase of the linear phase delay image introduced by the phase modulator **120**, and ψ is the phase of the first light path **136**A at the reference point **138**. I_1 and I_2 contain the amplitude information at the reference point **138**. The tilted mirror carries the phase delay image Φ onto the high frequency domain. The image is utilized to solve for the amplitude and phase ψ at the reference point **138**. For example, Fourier transform of (x,;Φ) will reconstruct the amplitude and phase ψ at the reference point **138**. The amplitude and phase ψ at the reference point **138** correspond to the full-field optical field.

In one embodiment, which can be combined with other embodiments described herein, when the optical device **102** is a waveguide combiner, the full-field optical field at the reference point **138** may be examined to determine a correlation with the image quality of the waveguide combiner. Additionally, the full-field optical can be utilized to monitor the uniformity of optical device structures across the waveguide combiner. To monitor the uniformity of optical device structures across the waveguide combiner including the optical device structure critical dimensions, depth, trench filling, overcoatings, etc., the variation between each waveguide combiner will be collected and formulated into a library of empirical data.

At operation **306**, metrology metrics are determined. The full-field optical field at the reference point **138** is determined in operation **305**. The metrology metrics of the optical device **102** are derived from the full-field optical field during post-processing. The metrology metrics may be utilized to predict the performance of the optical device in the far-field. The metrology metrics may be utilized to validate optical device design and monitor optical device performance. In embodiments where the optical device **102** is a waveguide combiner, the metrology metrics include but are not limited to, one or more of an angular uniformity metric, a contrast metric, an efficiency metric, a color uniformity metric, a modulation transfer function (MTF) metric, a field of view (FOV) metric, a ghost image metric, or an eye box metric. In embodiments where the optical device **102** is a metasurface, the metrology metrics include but are not limited to, one or more of an efficiency metric, a point spread function (PSF) metric, a MTF metric, or a phase error metric. The ability to derive any desired metrology metric from a single physical measurement improves throughput, reduces storage and bandwidth requirements, and reduces costs associated with analysis of the optical device **102**.

In summation, metrology tools and methods of obtaining a full-field optical field of an optical device to determine multiple metrology metrics of the optical device are provided herein. A metrology tool is utilized to split a light beam into a first light path and a second light path. The first light path travels through at least one optical device, such as a metasurface or a waveguide combiner, and is directed to a detector. The second light path is directed to a phase modulator. One or more phase modulated images of the second light path are captured by the detector. The first light path and the second light path are combined into a combined

light beam and delivered to the detector. The detector measures the intensity of the combined light beam. A first equation and second equation are utilized in combination with the intensity measurements to determine an amplitude and phase ψ at a reference point directly adjacent to a second surface of the at least one optical device. The amplitude and phase ψ correspond to the full-field optical field of the optical device. Metrology metrics may be derived from the full-field optical field. The method described herein improves throughput, reduces storage and bandwidth requirements, and reduces costs associated with analysis of the optical devices.

While the foregoing is directed to embodiments of the present disclosure, other embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A metrology tool, comprising:
- a light engine operable to project a light beam;
- a first beam splitter disposed in a path of the light beam, the first beam splitter operable to split the light beam into a first light path and a second light path, the first light path operable to be incident on an optical device;
- a phase modulator disposed in the second light path;
- a second beam splitter disposed in the first light path and the second light path, the second beam splitter operable to combine the first light path and the second light path to form a combined light path;
- a detector disposed in the combined light path, the detector operable to record an intensity measurement of the combined light path; and
- a controller comprising instructions that, when executed, cause a plurality of operations to be conducted, the plurality of operations, comprising:
  - determining a full-field optical field of the optical device at a reference point located adjacent to a surface of the optical device where the first light path exits the optical device, wherein the full-field optical field is determined by performing a Fourier transform on the intensity measurement to reconstruct an amplitude and phase of the first light path at the reference point.

2. The metrology tool of claim **1**, wherein the optical device is a waveguide combiner, wherein the waveguide combiner is positioned such that the first light path is operable to be incident on an input coupling region of the waveguide combiner.

3. The metrology tool of claim **1**, wherein the optical device is a metasurface, wherein the metasurface is positioned such that the first light path is operable to be incident on a centerpoint of the metasurface.

4. The metrology tool of claim **1**, wherein the phase modulator is one of a spatial light modulator, a piezo driven mirror, or a tilted mirror.

5. The metrology tool of claim **1**, wherein the light engine projects a laser.

6. The metrology tool of claim **1**, wherein the phase modulator is operable to change a phase of the second light path.

7. The metrology tool of claim **1**, further comprising:
- a first lens disposed in the first light path, the first lens operable to relay the first light path;
- a second lens disposed in the second light path, the second lens operable to relay the second light path;
- a third lens disposed in the second light path, the third lens operable to relay the second light path; and
- a fourth lens disposed in the second light path, the fourth lens operable to relay the second light path.

8. The metrology tool of claim **1**, further comprising a linear polarizer operable to polarize the light beam.

9. The metrology tool of claim **1**, further comprising an auxiliary lens disposed in the first light path, the auxiliary lens operable to relay the first light path.

10. A metrology tool, comprising:
- a light engine operable to project a light beam;
- a first beam splitter disposed in a path of the light beam, the first beam splitter operable to split the light beam into a first light path and a second light path, the first light path operable to be incident on an optical device;
- a modulation module disposed in the first light path, the modulation module operable to change a phase, amplitude, or angle of incidence of the first light path;
- a tilted mirror disposed in the second light path;
- a second beam splitter disposed in the first light path and the second light path, the second beam splitter operable to combine the first light path and the second light path to form a combined light path;
- a detector disposed in the combined light path, the detector operable to record an intensity measurement of the combined light path; and
- a controller comprising instructions that, when executed, cause a plurality of operations to be conducted, the plurality of operations, comprising:
  - determining a full-field optical field of the optical device at a reference point located adjacent to a surface of the optical device where the first light path exits the optical device, wherein the full-field optical field is determined by performing a Fourier transform on the intensity measurement to reconstruct an amplitude and phase of the first light path at the reference point.

11. The metrology tool of claim **10**, wherein the optical device is a waveguide combiner, wherein the waveguide combiner is positioned such that the first light path is operable to be incident on an input coupling region of the waveguide combiner.

12. The metrology tool of claim **10**, wherein the optical device is a metasurface, wherein the metasurface is positioned such that the first light path is operable to be incident on a centerpoint of the metasurface.

13. The metrology tool of claim **10**, further comprising:
- a first lens disposed in the second light path, the first lens operable to relay the second light path;
- a second lens disposed in the second light path, the second lens operable to relay the combined light path; and
- an auxiliary lens disposed in the second light path, the second lens operable to relay the second light path.

14. A method, comprising:
- projecting a light beam to a first beam splitter, the first beam splitter splitting the light beam into a first light path and a second light path;
- projecting the first light path to an optical device, the first light path travelling through the optical device, wherein the optical device is a metasurface or a waveguide combiner;
- projecting the second light path to a phase modulator, the phase modulator operable to generate one or more phase delay images of the second light path;
- combining the first light path and the second light path with a second beam splitter to form a combined light path;

directing the combined light path to a detector, the detector operable to record an intensity measurement of the first light path and the second light path; and

determining a full-field optical field of the optical device at a reference point located adjacent to a surface of the optical device where the first light path exits the optical device, wherein the full-field optical field is determined by performing a Fourier transform on the intensity measurement to reconstruct an amplitude and phase of the first light path at the reference point.

15. The method of claim **14**, further comprising determining metrology metrics, the metrology metrics determined from the full-field optical field during post-processing.

16. The method of claim **15**, wherein the metrology metrics include one or more of an angular uniformity metric, a contrast metric, an efficiency metric, a color uniformity metric, a modulation transfer function (MTF) metric, a field of view (FOV) metric, a ghost image metric, or an eye box metric.

17. The method of claim **14**, wherein the full-field optical field is determined at a high frequency domain.

18. The method of claim **14**, wherein each of the one or more phase delay images alter the intensity measurement of the combined light path on the detector.

19. The method of claim **14**, wherein the optical device is the waveguide combiner, further comprising positioning the optical device such that the first light path is operable to be incident on an input coupling region of the optical device.

20. The method of claim **14**, wherein the optical device is the metasurface further comprising positioning the optical device such that the first light path is incident on a center-point of the optical device.

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