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Yu et al.

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(54) **WAVEFRONT DETECTOR**

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(51) **Int. Cl.**

G01B 9/02	(2006.01)
G01J 9/02	(2006.01)
H01L 27/146	(2006.01)

(52) **U.S. Cl.**
CPC ***G01J 9/0215*** (2013.01); ***H01L 27/14643*** (2013.01)

(58) **Field of Classification Search**
CPC .. G01J 9/0215; G01B 9/02098; H01L 27/146; H01L 27/14643; H01L 27/148; H01L 27/14806
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

9,163,984	B2 *	10/2015	Nakamura	G01J 3/0256
2013/0229486	A1	9/2013	Molnar et al.	
2016/0218127	A1 *	7/2016	Kato	H01L 27/14609
2018/0182798	A1 *	6/2018	Tack	G01J 3/26

OTHER PUBLICATIONS

Guoan Zheng "Angle-sensitive pixel design for wavefront sensing." arXiv preprint arXiv:1304.7339 (2013), California, US.

* cited by examiner

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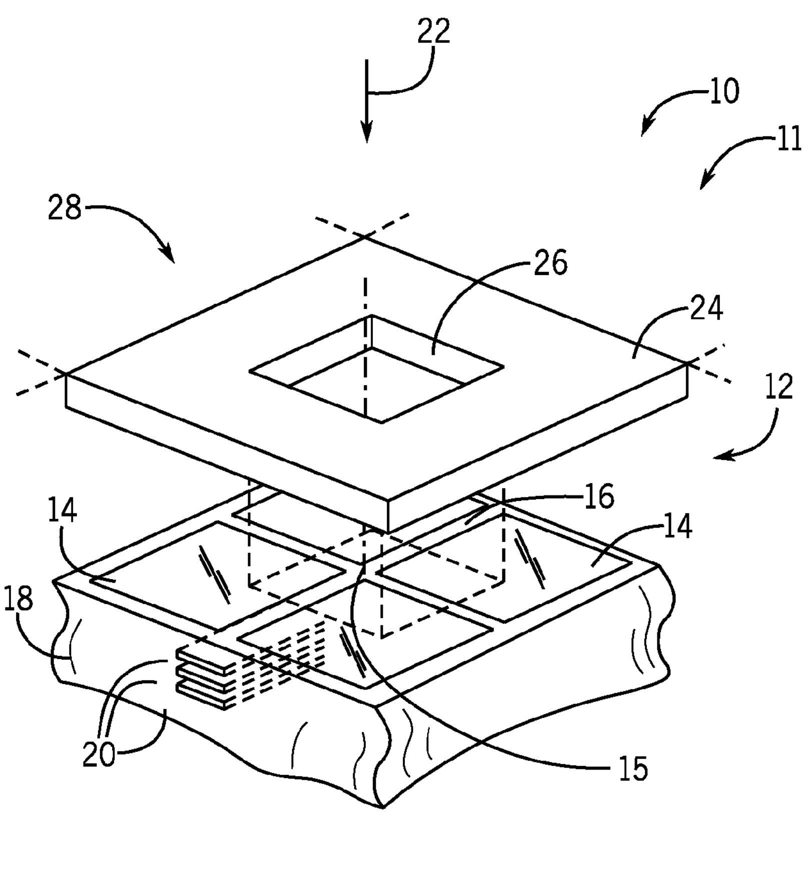
(57) **ABSTRACT**

A wavefront sensor system suitable for integration into an integrated circuit light detector may provide for wave angle sensors having varying functional relationships between the wave angle and signal to provide improved dynamic range. These wave angle sensors may be combined with integrated circuit phase angle sensors for a more complete analysis of the waveform.

8 Claims, 7 Drawing Sheets



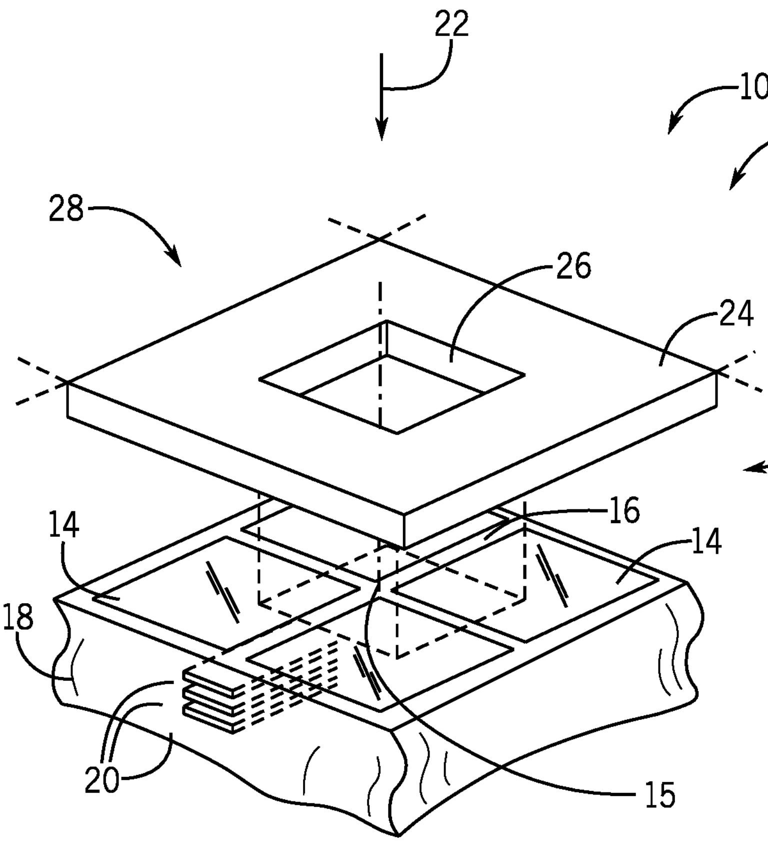

22
10
11
28
26
24
12
16
14
14
18
20
15

FIG. 1

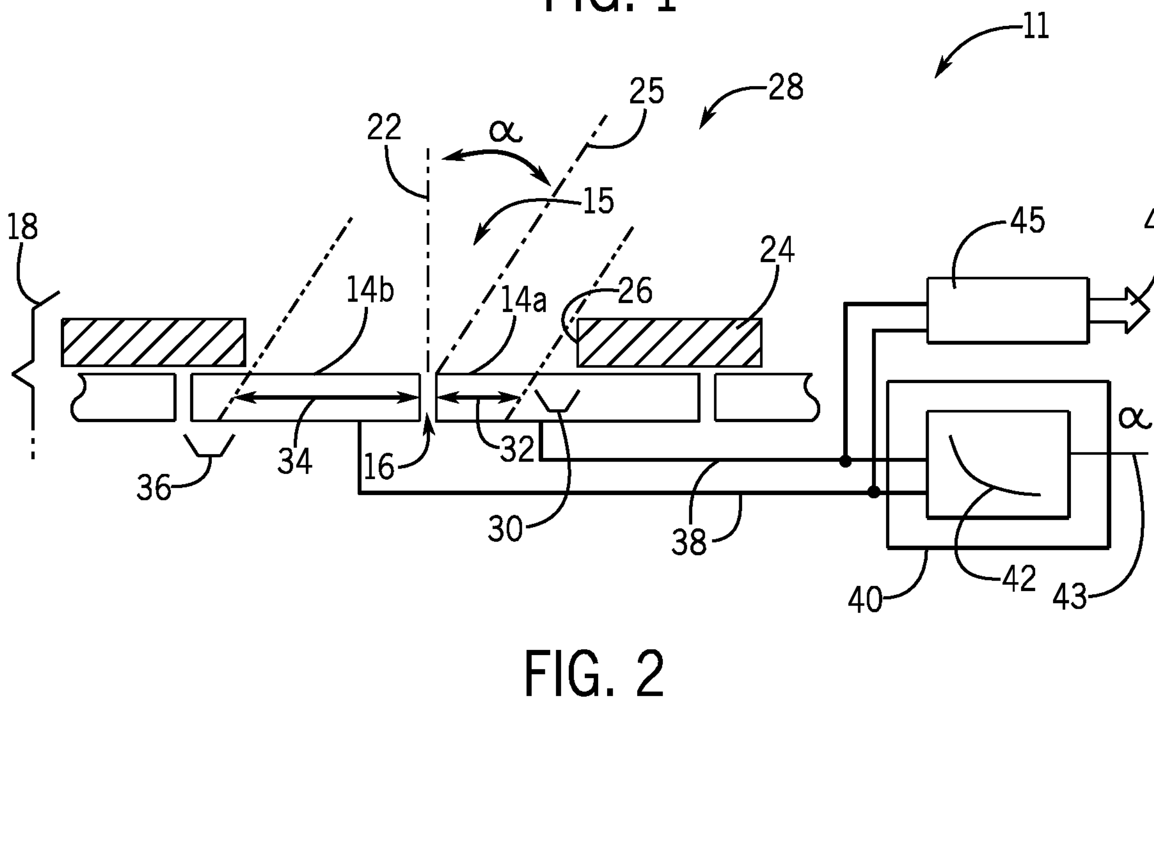

11
28
25
22
α
15
18
45
46
14b
14a
26
24
α
36
34
16
32
30
38
40
42
43

FIG. 2

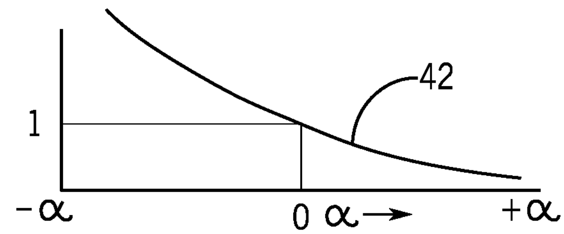


FIG. 3

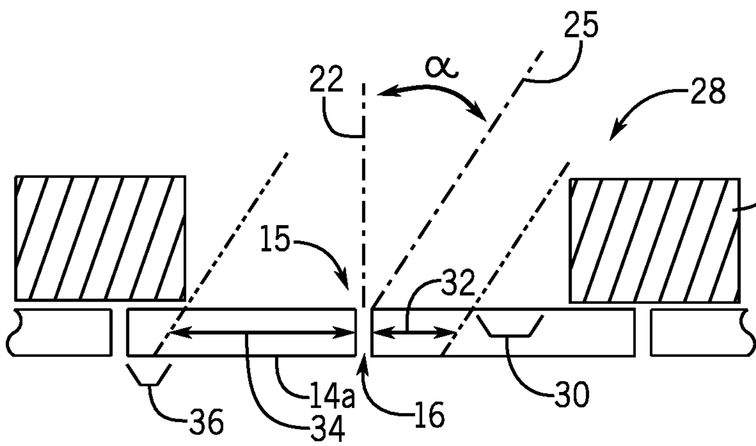


FIG. 4

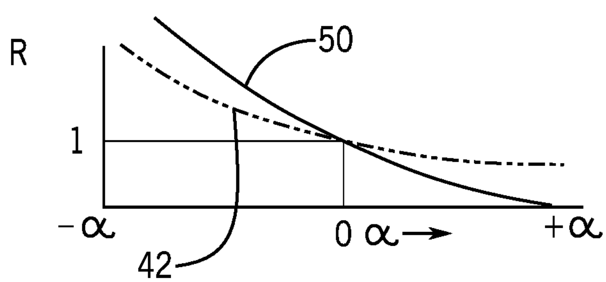


FIG. 5

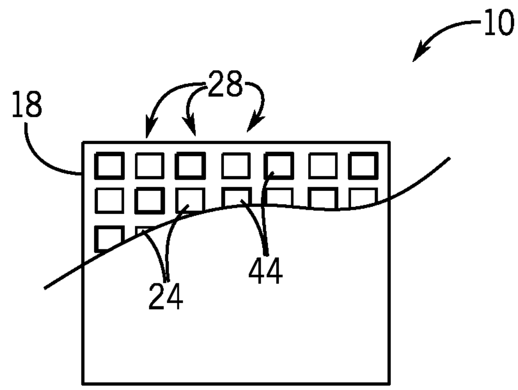


FIG. 6

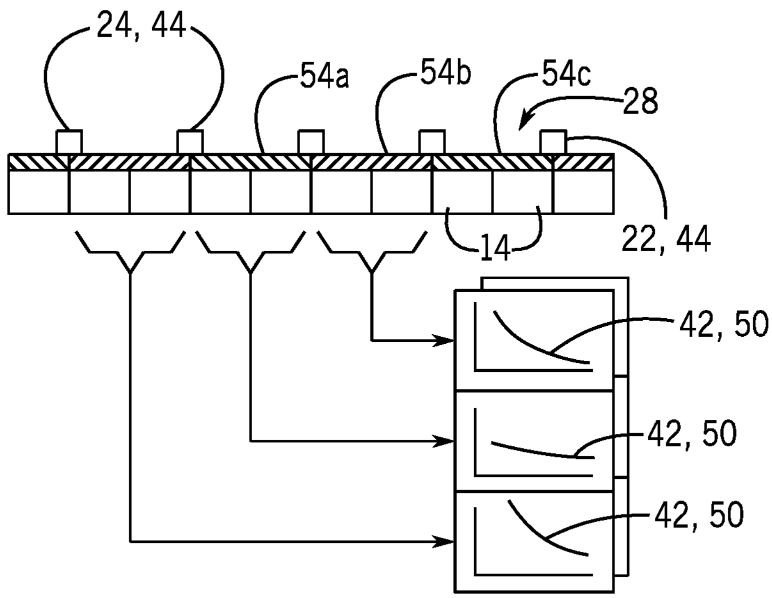


FIG. 7

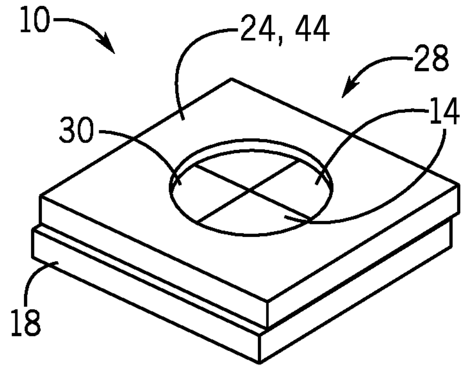


FIG. 8a

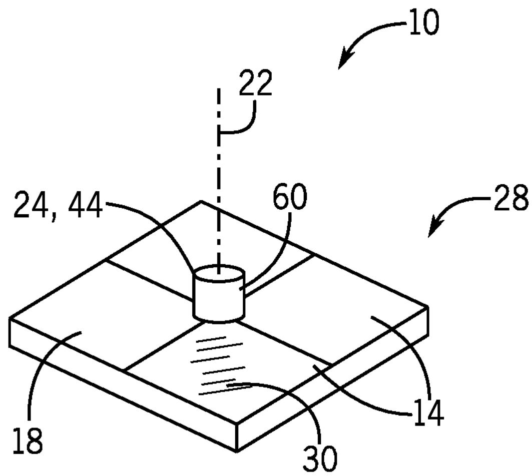


FIG. 8b

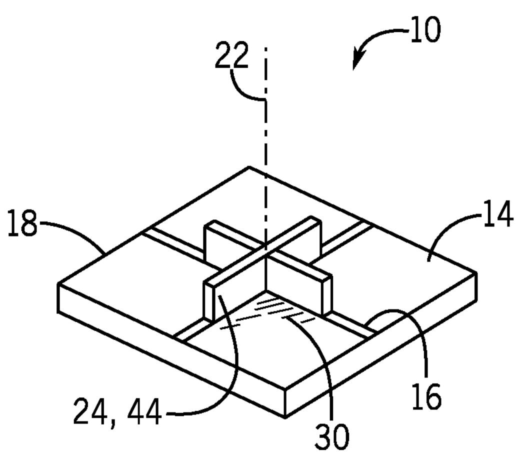
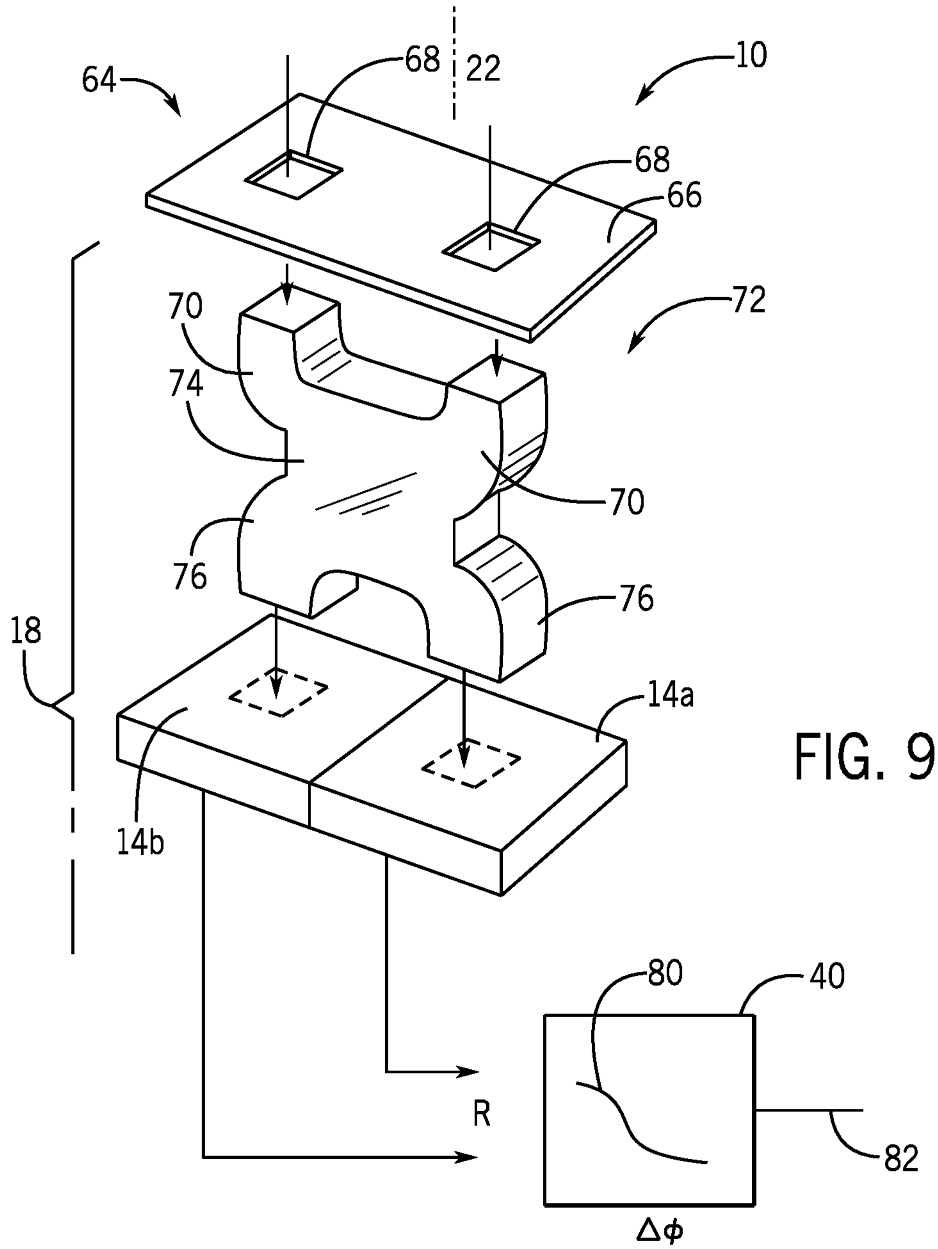
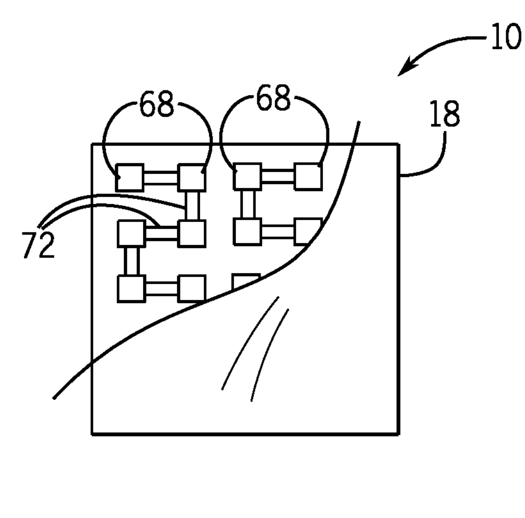


FIG. 8c



64
68
22
10
68
66
70
72
74
70
76
76
18
14a
14b
80
40
R
82
Δφ

FIG. 9



10
68
68
18
72

FIG. 10

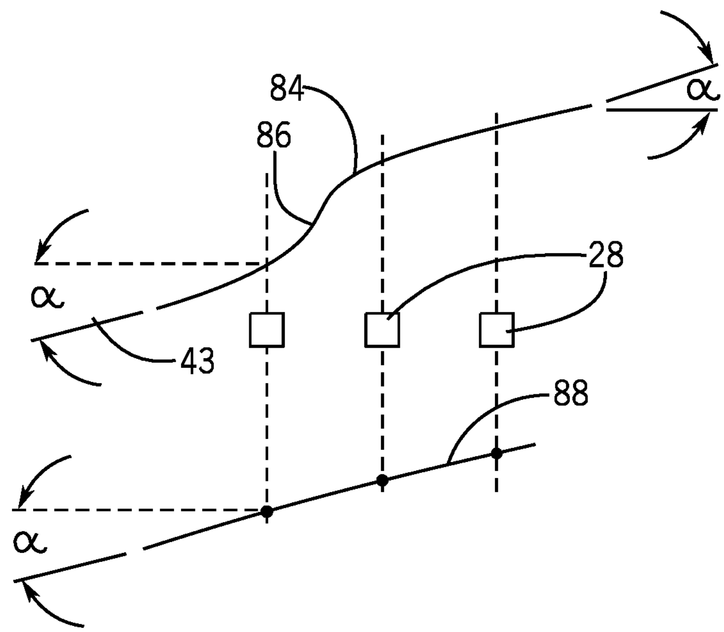


FIG. 11a

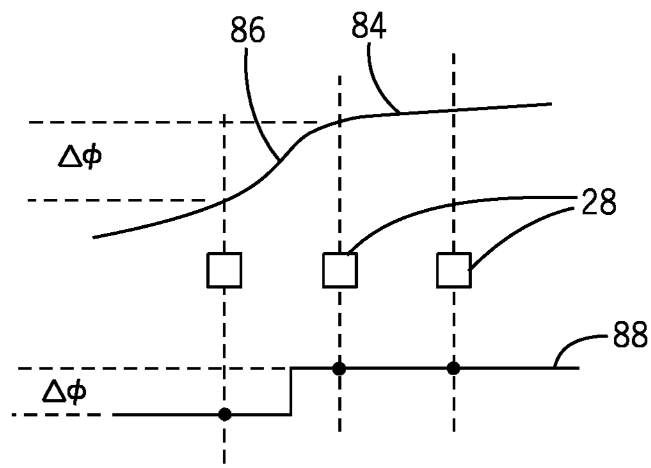


FIG. 11b

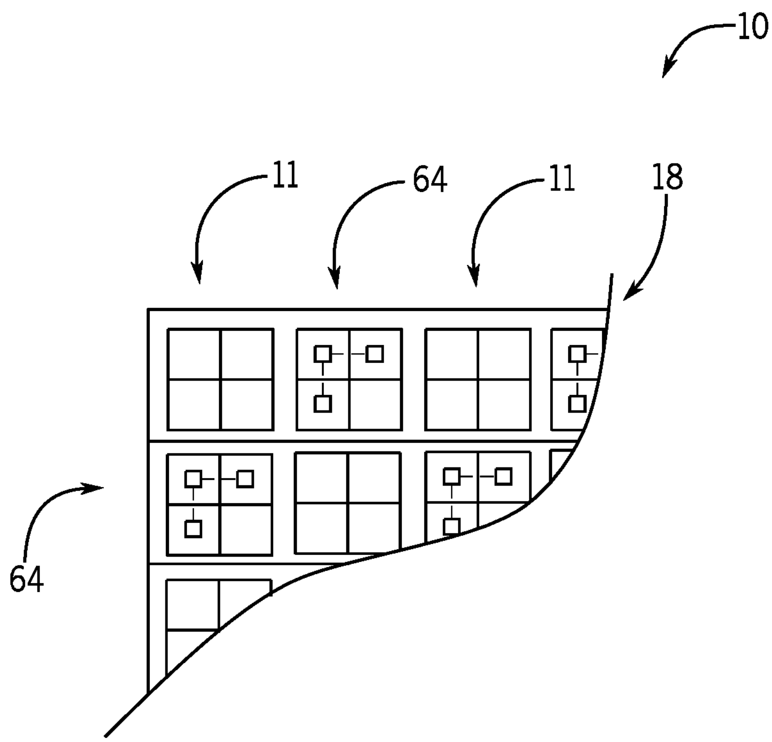


FIG. 12

WAVEFRONT DETECTOR

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under DE-NA0002915 awarded by the U.S. Department of Energy. The government has certain rights in the invention.

CROSS REFERENCE TO RELATED APPLICATION

NA

BACKGROUND OF THE INVENTION

The present invention relates generally to imaging devices and in particular to wavefront angle or wavefront phase sensitive imaging devices.

Conventional digital cameras record light intensity from an illuminated scene, for example, using electronic sensors distributed over a focal plane, to each sense a "pixel" of the image to produce the image. By incorporating colored filters over the electronic sensors, light frequency as well as intensity may be recorded providing colored images.

Conventional digital cameras do not capture important information about the light received from an illuminated scene that may be expressed in the light's wavefront angle or phase. "Light field" or "plenoptic" cameras, however, can capture this wavefront information together with light intensity information providing a more complete representation of the illuminated scene. As a result, such cameras can change the focal distance and depth of field after the image is captured. More generally, the captured wavefront information provides a more complete record of the illuminated scene that may be useful in a variety of applications including postprocessing, image recognition, hologram generation, and the like.

The image sensors using conventional digital cameras, such as charge coupled devices (CCD), do not naturally detect wavefront information but can be modified to produce a Shack-Hartman type wavefront detector. Such modifications place an array of micro lenses in front of a standard image sensor, for example, each micro lens being associated with a two-dimensional zone of multiple pixels of the image sensor. Light received by each micro lens provides a focal spot whose position on the multiple pixels of the zone changes depending on the angle of the wavefront. By detecting which pixels detect the greatest light intensity (indicating the location of the focal spot) the wavefront angle may be deduced. The measured intensity of this focal spot is also used to provide the conventional image intensity information.

SUMMARY OF THE INVENTION

The present invention provides a wavefront detector employing "shadow casters" instead of micro lenses greatly simplifying the construction of a Shack-Hartman type wavefront detector, for example, directly on an integrated circuit substrate. Further, by providing shadow casters of different heights, the sensitivity of the wavefront detectors can be varied to effect an improved trade-off between wavefront angle sensitivity and range of wavefront angle detection.

In some embodiments, the shadow casters may be combined with integrated circuit light mixers generating constructive and destructive interference between light received at adjacent pixels to deduce absolute phase difference. This absolute phase difference can be used alone or combined with wave angle measurements for improved wavefront analysis.

A measurement of wavefront angle (for example, using a Shack-Hartman type wavefront detector) and a measurement of absolute phase difference (for example, using light mixing structures) will collectively be referred to as "wavefront detection" or as using a "wavefront sensor" herein.

Specifically, then, the present invention provides a wavefront sensor having an array of light intensity sensor elements tiling a substrate to receive light, the light having a wavefront angle with respect to a surface normal of the substrate. A set of shadow casters is provided where each shadow caster is associated with a group of at least two sensor elements to selectively shade different sensor elements of that group as a function of the wavefront angle. The different shadow casters have different heights above the substrate with respect to the surface normal to provide different shadow lengths along the substrate as a function of wavefront angle.

It is thus a feature of at least one embodiment of the invention to provide improved sensitivity in wavefront angle measurement while avoiding "clipping" or saturation that can cause the loss of information at high wavefront angles.

The wavefront sensor may include a circuit comparing light intensity measured by different sensor elements in a group to provide an output signal related to wavefront angle, and the circuit may apply a first or second predetermined function to light intensity measurements of the different sensors of the group depending on the height of the shadow caster associated with the group to provide the output signal.

It is thus a feature of at least one embodiment of the invention to accommodate arbitrarily complex changes in the functional relationship between brightness and wavefront angle for different shadow caster heights.

Each group of light sensing elements may be associated with a color filter, and the circuit may apply a different predetermined function to light intensity measurements of the different sensors of the group depending on the filter color.

It is thus a feature of at least one embodiment of the invention to correct for changes in the functional relationship between wavefront angle and sensor reading that occurs with different frequencies as noted by the inventors.

The group of sensor elements may be adjacent and separated over two dimensions along the substrate.

It is thus a feature of at least one embodiment of the invention to permit two dimensions of wavefront angle determination.

The shadow caster may be a perimeter wall surrounding a group of sensing elements.

It is thus a feature of at least one embodiment of the invention to provide a simple structure for fabrication using integrated circuit techniques.

The perimeter wall may partially cover the sensing elements.

It is thus a feature of at least one embodiment of the invention to permit ready adjustment of the sensitivity of the wavefront sensor by controlling the exposed area of the sensor elements where smaller exposed areas provide increased angular sensitivity.

The sensing elements may be displaced beneath a surface of the substrate.

It is thus a feature of at least one embodiment of the invention to provide a system that can work with common image sensing architectures in which the light sensors are positioned beneath a circuitry and connection layer.

The shadow casters of different heights are uniformly distributed over the surface of the substrate.

It is thus a feature of at least one embodiment of the invention to allow both high dynamic range and high sensitivity measurements throughout the image area.

The wavefront sensor may further include a set of mixers each associated with at least two sensor elements to receive light from adjacent separated locations along the plane of the substrate and to mix that light together before providing mixed light independently to each of the at least two sensor elements. The intensity of the light provided to the at least two sensor elements varies in intensity as a function of phase difference of light received by the mixer at the separated locations.

It is thus a feature of at least one embodiment of the invention to provide a wavefront sensor that can reveal absolute phase differences between sensing locations.

Each mixer may provide a first and second inlet light pipe leading from respective adjacent separated locations and communicating with a common cavity and may further provide a first and second outlet light pipe leading from the cavity to two different sensor elements.

It is thus a feature of at least one embodiment of the invention to provide a structure that can be simply integrated into an integrated circuit image sensor.

The mixer may be a transparent semiconductor material of the substrate embedded with in a substrate material a different index of refraction.

It is thus a feature of at least one embodiment of the invention to provide a wavefront sensor using readily available integrated circuit materials.

Different ones of the set of mixers maybe associated with pairs of adjacent separated locations displaced along different dimensions of the plane of the substrate.

It is thus a feature of at least one embodiment of the invention to provide phase difference measurements in two orthogonal directions to provide a better reconstruction of two-dimensional wavefronts.

The circuit may further compare light intensity measured by the at least two sensor elements associated with a mixer to provide an output equal to a phase difference between light received at the adjacent separated locations.

It is thus a feature of at least one embodiment of the invention to provide a decoding of phase information to be added to other information from the image sensor.

The circuit may combine the phase differences from the mixer with the wavefront angle to provide a description of a wavefront received at the substrate.

It is thus a feature of at least one embodiment of the invention to provide a more complete description of the wavefront by combining wavefront angle and absolute phase differences.

Some sensor elements of the substrate are associated with shadow casters and do not have mixers and some sensors of the substrate have mixers and are not associated with shadow casters.

It is thus a feature of at least one embodiment of the invention to provide wavefront angle and wavefront phase measurements in the single sensor system.

These particular objects and advantages may apply to only some embodiments falling within the claims and thus do not define the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a fragmentary, exploded perspective view of a portion of an image sensor showing individual sensor elements in regular rows and columns positioned behind a shadow casting mask for identification of wavefront angle;

FIG. **2** is a cross-section along line **2**-**2** of FIG. **1** showing the effect of the shadow generated by the shadow casting mask in changing exposed areas of the sensor elements as may be measured to deduce wavefront angle;

FIG. **3** is a plot of a ratio of the intensity of the light in the pixel elements of FIG. **2** as a function of angle in a simplified two-dimensional example such as may be used by circuitry to create an angle measurement from this ratio information;

FIG. **4** is a figure similar to FIG. **2** showing a shadow caster having a higher elevation from the sensor substrate such as produces greater sensitivity to wavefront angle;

FIG. **5** is a figure similar to that of FIG. **3** showing a plot of the ratio of the intensity of light in the pixel elements of FIG. **4** as a function of angle as compared to the same plot of FIG. **3** showing the change in sensitivity commensurate with the reduction in measurement range;

FIG. **6** is a fragmentary top plan view of an image sensor incorporating the shadow casters of FIGS. **2** and **4** to provide both high sensitivity and high range type sensors;

FIG. **7** is a cross-sectional view similar to FIGS. **3** and **4** showing interposition of colored filters, for example, used for color imaging, to produce signals applied to different functions converting the intensity ratios into wavefront angles for the different colors;

FIG. **8***a*-*c* are fragmentary perspective views similar to that of FIG. **1** but unexploded showing alternative shadow casters including a circular mask in FIG. **8***a*, a post structure in FIG. **8***b*, and a partial wall structure in FIG. **8***c;*

FIG. **9** is a figure similar to FIG. **1** showing an alternative wavefront sensor design providing absolute phase difference measurements between adjacent pixels using an integrated circuit-mounted light mixing element;

FIG. **10** is a figure similar to FIG. **6** showing interconnection of the mixers at various image points to provide two-dimensional phase difference measurements;

FIGS. **11***a* and **11***b* are example waveforms received by the sensor systems of FIGS. **1** and **9** respectively showing interpretation of that data; and

FIG. **12** is a top plan view of an integrated circuit substrate for light sensing similar to FIGS. **6** and **10** showing a hybrid sensor element incorporating both wavefront angle and wavefront phase sensing.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. **1**, a wavefront detector **10** of the present invention may provide a wavefront angle sensor **11** working in conjunction with a standard integrated circuit image sensor **12** having an array of light sensing elements (pixels **14**) arranged in rows and columns separated by gutters **16** on an integrated circuit substrate **18**. Generally, the light sensing elements may be photodiodes either positioned adjacent to an upper planar surface of the substrate **18** or on a lower layer of the substrate **18** (as depicted) with light passing through upper layers of the substrate **18** to reach the photodiodes. In this latter case, processing circuitry and intercommunicating conductors **20** may be placed between the pixels **14**, for example, in the gutters **16**. In either case, the pixels **14** are sensitive to light passing along (not necessarily parallel to) an axis **22** aligned with a surface normal of the substrate **18** and provide independent electrical signals indicating light received within the area of the pixel **14**.

Referring also to FIG. **2**, a shadow-casting mask **24** may be placed over the pixels **14** to block some but not all incoming light along axis **22**. Generally, the mask **24** includes an opening **26** exposing portions of four adjacent pixels **14** positioned around a shared centerpoint **15** in the center of the mask **24**. The mask **24** exposes a detection zone **28** of the adjacent pixels **14**.

In this embodiment, the mask **24** provides a square frame that covers portions of each of the pixels **14** along an outer periphery of that detection zone **28**. The mask **24**, for example, may be a metallization layer and may have many different openings **26** defining corresponding multiple zones **28** over the entire area of the image sensor **12** having many pixels **14**.

Referring now to FIG. **3**, light passing along a light axis **25** at an angle α with respect to axis **22** and through centerpoint **15** will generate a shadow **30** over at least one pixel **14***a* caused by an inner wall of the opening **26**, the latter extending along axis **22**. The particular pixel **14***a* being shadowed will be pixel **14** whose surface forms an acute angle with respect to the light axis **25**.

The shadow **30** on the pixel **14***a* and the mask **44** decreases a total area of illumination of this pixel **14***a* to a reduced area **32**.

Conversely pixel **14***b* who surface forms an obtuse angle with respect to light axis **25** does not have a shadow **30** and provides a larger exposure area **34** equal to the full area of the exposed portion of the pixel **14***b* through the mask **24** as well as a leakage area **36** of light passing underneath the mask **24** into the pixel **14***b*. In addition, some portion of light entering the surface of pixel **14***a* near axis **22** with incident angle α can travel long enough to reach the pixel **14***b*.

Electrical signals **38** from the pixels **14***a* and **14***b* may be received by comparison circuitry **40** to deduce the wavefront angle **43** (angle α) by applying a ratio formed from the light intensity measured by pixels **14***a* and **14***b* to an empirically described transform curve **42**. While in this simple example only a single dimension of pixels **14***a* and **14***b* is shown, this angle can be readily extended to two perpendicular directions by considering the ratio of the intensity of light in each of the four pixels **14** of the zone **28**. So, for example, a ratio between the two columns of pixels **14** may determine light angle in one direction, and a ratio between the two rows of pixels **14** may determine a light angle in the perpendicular direction.

Referring now to FIG. **3**, this transform curve will generally show a ratio moving between a value of one for angles of α equal 0 and to higher or lower angles as a ratio deviates above and below 1. This transformation between a ratio value and an angle α may be accomplished through discrete circuitry or through a microprocessor executing a simple program accessing a lookup table or performing the calculation based on an established formula. These same electrical signals **38** may be received by conventional image processing circuitry **45** for the generation of an intensity image **46** as is understood in the art.

Referring now to FIG. **4**, some zones **28** may employ a thicker mask **44** having a larger height measured along axis **22** than the height of mask **24** shown in FIG. **2**. This taller mask **44** will provide larger shadows **30** for a given angle α; however, it will generally not change the leakage areas **36**. Nevertheless, the proportionally greater shadow **30** will produce a greater sensitivity to values of a as shown by transform curve **50** compared to transform curve **42**. On the other hand, this greater sensitivity means that the transform curve **50** can operate in a narrower range of angle α since the angle α where the shadow **30** will cover the whole pixel **14***a* is smaller when mask **44** is used instead of mask **24**.

Referring to FIG. **6**, the present invention contemplates that at least two thicknesses of masks **24** and **44** may be used on different zones **28** of wavefront detector **10** to provide a trade-off between high sensitivity and high dynamic range. For example, masks **24** and **44** may be alternated along given rows and columns of the zones **28**. Each of these zones **28** will be associated with circuitry using either transform curve **42** or **50** as is appropriate for the height of the mask **24** or **44** associated with that zone **28**. The invention further contemplates that masks of multiple different thicknesses (not just two) may be used if desired, again, with corresponding transform curves.

Referring now to FIG. **7**, a color camera may be implemented by associating colored filters **54***a*-**54***c* (typically red, green, and blue) with each zone **28** of pixels **14**. The inventors have determined that such filtration can modify curves **42** and **50** and, accordingly, a set of different curves (three associated with masks **24** and three associated with masks **44**, one mask for each color) may be used by the circuitry **40** in deducing angle α. A combined signal from the pixels **14** of each zone **28**, according to their particular filter **54**, may also be sent to the image processor **45** for the development of a standard color image. The circuitry **40** completes the wavefront angle sensor **11**.

Referring now to FIG. **8***a*, it will be appreciated that the mask **24** or **44** may have a circular opening rather than the square opening of opening **26** shown in FIG. **1** to provide improved symmetry but at the cost of reduced exposed pixel area. In some embodiments, the mask **24** and **44** may be placed totally over the gutter area to reduce blockage of the pixels **14**. As shown in FIG. **8***b*, other shadow casting structures may be readily used including a post **60** or other gnomon structure extending upward along axis **22**, for example, centered within the zone **28** of four pixels with a shadow **30** falling on one or more of the pixels **14** depending on the angle of the light axis **25** of the incoming light. As shown in FIG. **8***c*, the post may be compressed to a cruciform lying completely within the gutter **16** of the light sensor. As before, the height of the structures may be adjusted to effect a trade-off between sensitivity and dynamic range as discussed above.

Referring now to FIG. **9**, a phase difference sensor **64** may be constructed indicating an absolute phase difference between the adjacent locations of light reception on the wavefront detector **10**. The phase difference sensor **64** provides phase information rather than waveform angle provided by the wavefront angle sensor **11** discussed above. The difference between these types of sensors will be discussed in more detail below with respect to FIG. **11**.

In this embodiment, a mask structure **66** (for example, a metallization layer) may be positioned over the pixels **14** providing a sample aperture **68**, for example, centered over each pixel **14** and otherwise blocking light transmission to the pixel **14**. Light from the adjacent apertures **68** (which will be displaced laterally from each other) may be received by corresponding light pipes **70** of a mixer **72** formed in the integrated circuit material of the substrate **18** beneath the mask structure **66**. For example, the light pipes **70** may be constructed from transparent silicone dioxide surrounded by a material of higher index of refraction to provide a reflective interface.

The light pipes **70** may join to a light cavity **74** of similar material so that the light from each of the light pipes **70** mixes together to constructively and destructively interfere. After this mixing, the light is then conducted out of exit light pipes **76** (of similar material to the light cavity **74**) carrying this light to respective pixels **14***a* and **14***b*, for example, being adjacent along a given axis of the array and beneath the corresponding aperture **68**.

The cavity **74** may be designed as an interferometer in the manner of the combining portion of a Mach-Zehnder interferometer. More generally, the light exiting from the different light pipes **76** will have different intensities based on different interference paths in the light cavity **74** from the light received by the two entrance light pipes **70**. For example, a rightmost light pipe **76** may sum together some light frequencies received by the light pipe **70** whereas the leftmost light pipe **76** may subtract those frequencies. More generally, the output from the light pipes **76** will be different complex summations of the light from the two entrance light pipes **70** with varying frequency offsets.

The intensity of light measured by the pixels **14***a* and **14***b* may be compared (for example, using a ratio) and this comparison applied to an empirically derived transform curve **80** to produce a phase difference signal **82** indicating the phase difference between the lights arriving at the aperture **68**. This light may be pre-filtered by colored filters as discussed above. More generally a phase difference signal **82** may be generated by a multidimensional function directly receiving intensity signals **38** from the pixels **14**.

Referring momentarily to FIG. **10**, the sample apertures **68** may extend regularly in two dimensions over the surface of the substrate **18** and may be pairwise connected by mixers **72** along two perpendicular directions of the substrate **18**, for example, in a serpentine path as depicted, to provide phase difference measurements into orthogonal directions. In this regard each aperture **68** may feed two different mixers **72**.

Referring now to FIGS. **11***a* and **11***b*, the difference between measurement of a wavefront angle **43** (per the wavefront angle sensor **11** shown in FIG. **2**) and a phase difference measurement (per the phase difference sensor **64** shown in FIG. **9**) can be understood by reviewing an example waveform **84** having a step phase shift **86**. A set of spaced measurement zones **28** that can detect only wavefront angle α, for example, per the sensors shown in FIGS. **1**-**8** and will provide identical measurements of wavefront angle **43** at each zone **28** based on the incident of wavefront angles at the zones **28** resulting in a reconstructed waveform **88** blind to the step phase shift **86**, as shown in FIG. **11***a*.

In contrast, as shown in FIG. **11***b*, a sensor of the type shown in FIG. **9** measuring a change in phase angle will accurately reflect the step phase shift **86** in a reconstructed waveform **88** made from measurements at zones **28**, albeit without capturing the wavefront angle **43**. By combining these two types of data, an improved waveform can be developed approximating waveform **84** by enforcing the necessary angles on the wavefront at the angle measurement points and the necessary phase differences at the phase difference points.

Referring now to FIG. **12**, the benefit of both of these different types of measurements of wavefront angle and absolute phase difference may be provided by alternating or otherwise distributing wavefront angle sensors **11** and phase difference sensors **64** over the surface of the substrate **18** to blend these types of measurements to create a more accurate rendition of the incoming waveform. It will be appreciated that light collected by the wavefront angle sensor **11** and phase difference sensors **64** may also be used in the construction of the standard image, for example, by tapping into the signals as shown in FIG. **2**. In addition, the wavefront angle sensors **11** may include both sensor masks **24** and **44** to provide improved dynamic range.

Certain terminology is used herein for purposes of reference only, and thus is not intended to be limiting. For example, terms such as "upper", "lower", "above", and "below" refer to directions in the drawings to which reference is made. Terms such as "front", "back", "rear", "bottom" and "side", describe the orientation of portions of the component within a consistent but arbitrary frame of reference which is made clear by reference to the text and the associated drawings describing the component under discussion. Such terminology may include the words specifically mentioned above, derivatives thereof, and words of similar import. Similarly, the terms "first", "second" and other such numerical terms referring to structures do not imply a sequence or order unless clearly indicated by the context.

When introducing elements or features of the present disclosure and the exemplary embodiments, the articles "a", "an", "the" and "said" are intended to mean that there are one or more of such elements or features. The terms "comprising", "including" and "having" are intended to be inclusive and mean that there may be additional elements or features other than those specifically noted. It is further to be understood that the method steps, processes, and operations described herein are not to be construed as necessarily requiring their performance in the particular order discussed or illustrated, unless specifically identified as an order of performance. It is also to be understood that additional or alternative steps may be employed.

References to "a microprocessor" and "a processor" or "the microprocessor" and "the processor," can be understood to include one or more microprocessors that can communicate in a stand-alone and/or a distributed environment(s), and can thus be configured to communicate via wired or wireless communications with other processors, where such one or more processor can be configured to operate on one or more processor-controlled devices that can be similar or different devices. Furthermore, references to memory, unless otherwise specified, can include one or more processor-readable and accessible memory elements and/or components that can be internal to the processor-controlled device, external to the processor-controlled device, and can be accessed via a wired or wireless network.

It is specifically intended that the present invention not be limited to the embodiments and illustrations contained herein and the claims should be understood to include modified forms of those embodiments including portions of the embodiments and combinations of elements of different embodiments as come within the scope of the following claims. All of the publications described herein, including patents and non-patent publications, are hereby incorporated herein by reference in their entireties.

What we claim is:

1. A wavefront sensor comprising:

an array of light intensity sensing elements tiling a substrate to receive light having a wavefront angle with respect to a surface normal of the substrate;

a set of shadow casters, each shadow caster associated with a group of at least two sensing elements to selectively shade different sensing elements of that group as a function of the wavefront angle;

wherein different shadow casters have different heights above the substrate with respect to the surface normal to provide different shadow lengths along the substrate as a function of wavefront angle; and

a circuit comparing light intensity measured by different sensing elements in a group to provide an output signal related to wavefront angle.

2. The wavefront sensor of claim 1 wherein the circuit applies at least a first and second predetermined function to light intensity measurements of the different sensors of the group depending on the height of the shadow caster associated with the group to provide the output signal.

3. The wavefront sensor of claim 2 wherein the group of light sensing elements is associated with a color filter and wherein the circuit applies a different predetermined function to light intensity measurements of the different sensors of the group depending on a color of the filter.

4. The wavefront sensor of claim 1 wherein the group of sensing elements are adjacent and are separated over two dimensions along the substrate.

5. The wavefront sensor of claim 1 wherein the shadow caster is a perimeter wall surrounding a group of sensing elements.

6. The wavefront sensor of claim 5 wherein the perimeter wall partially covers the sensing elements.

7. The wavefront sensor of claim 1 wherein the sensing elements are displaced beneath a surface of the substrate.

8. The wavefront sensor of claim 1 wherein shadow casters of different heights are uniformly distributed over the surface of the substrate.

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