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Karri et al.

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(54) **OLED DISPLAY MODULE STRUCTURE FOR MITIGATING DARK SPOT VISIBILITY IN BACK COVER OPEN REGIONS**

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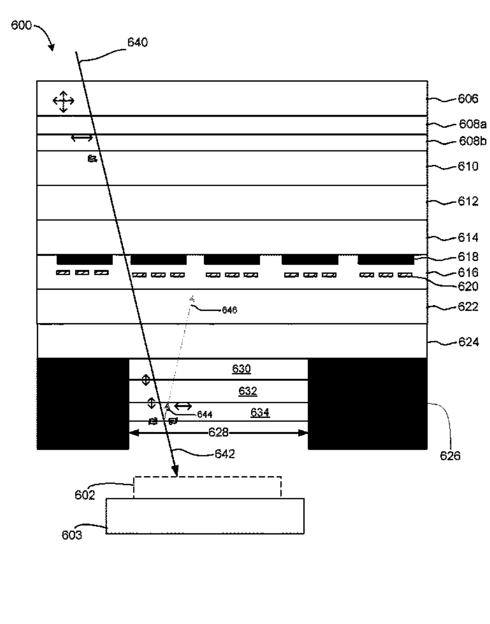
(57) **ABSTRACT**

A mobile computing device includes an emissive display panel configured to emit light from a front surface of the display panel, with the display panel having a plurality of transparent layers and an opaque back cover layer. The mobile computing device also includes a light sensor located behind the opaque back cover layer, and the opaque back cover layer includes an opening through which light from outside the display that is transmitted through the transparent layers of the display can pass to reach the sensor. An air gap separates the light sensor from the transparent layers of the display panel. The plurality of transparent layers includes a reflection attenuating layer on a back side of the display panel configured to attenuate the reflection of light from an interface between a transparent layer of the display panel and the air gap.

21 Claims, 10 Drawing Sheets



(51) **Int. Cl.**
H10K 50/87 (2023.01)
H10K 59/80 (2023.01)
H10K 85/10 (2023.01)

(52) **U.S. Cl.**
CPC ***H10K 59/8791*** (2023.02); ***H10K 85/111*** (2023.02); *H10K 59/8794* (2023.02)

(58) **Field of Classification Search**
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See application file for complete search history.

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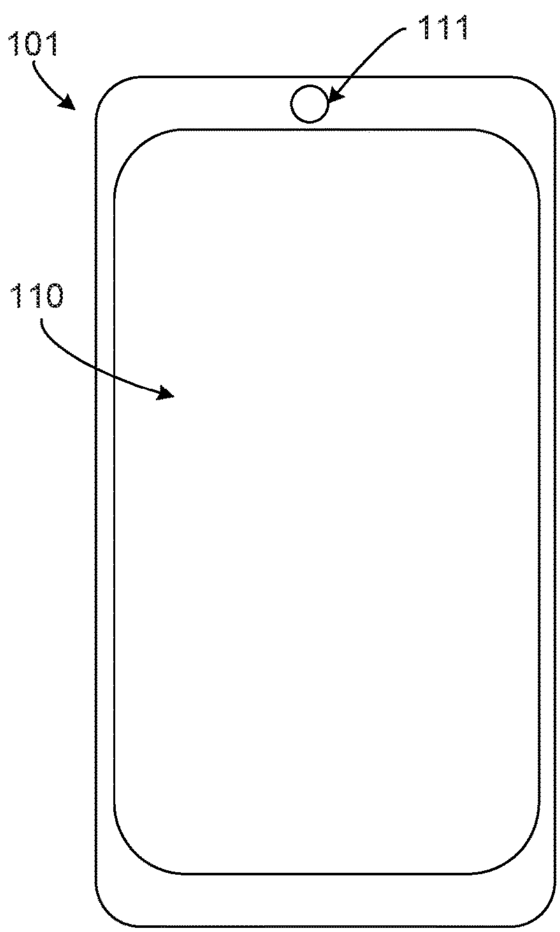


FIG. 1A

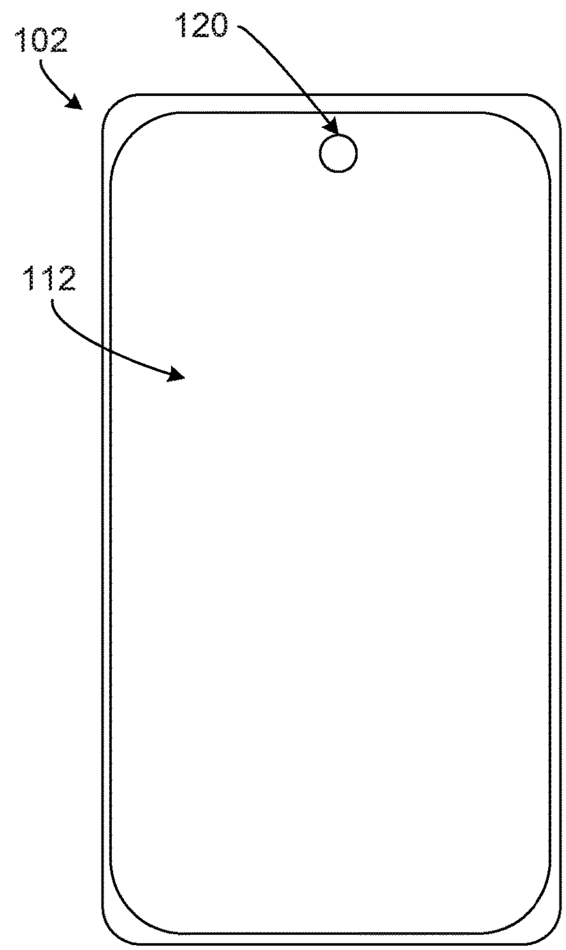


FIG. 1B

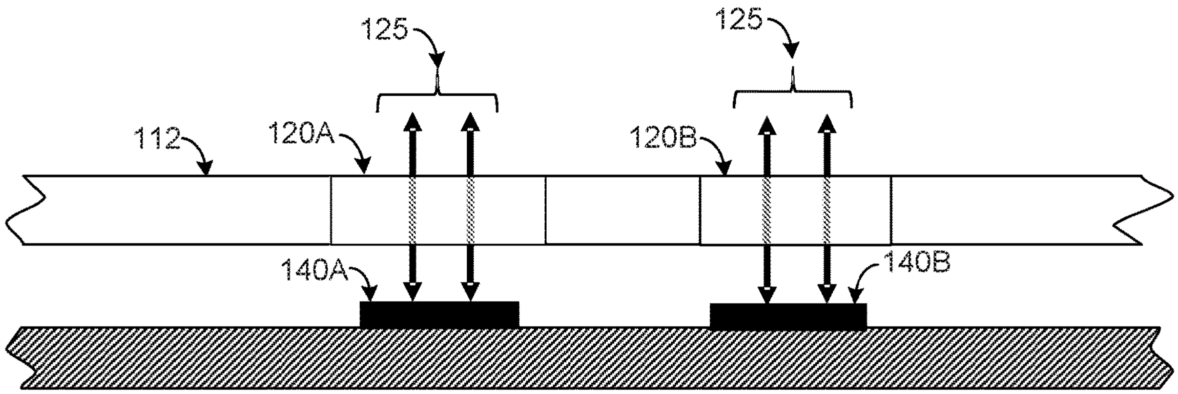


FIG. 2A

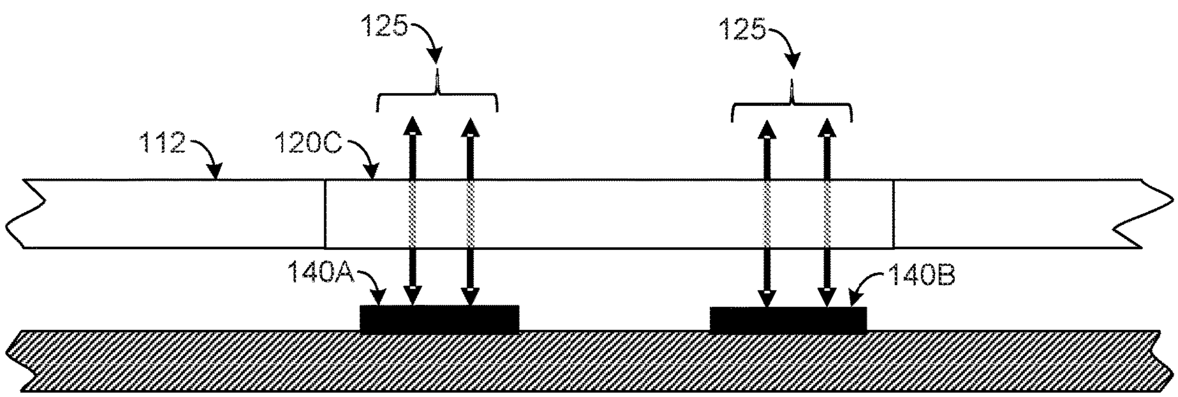
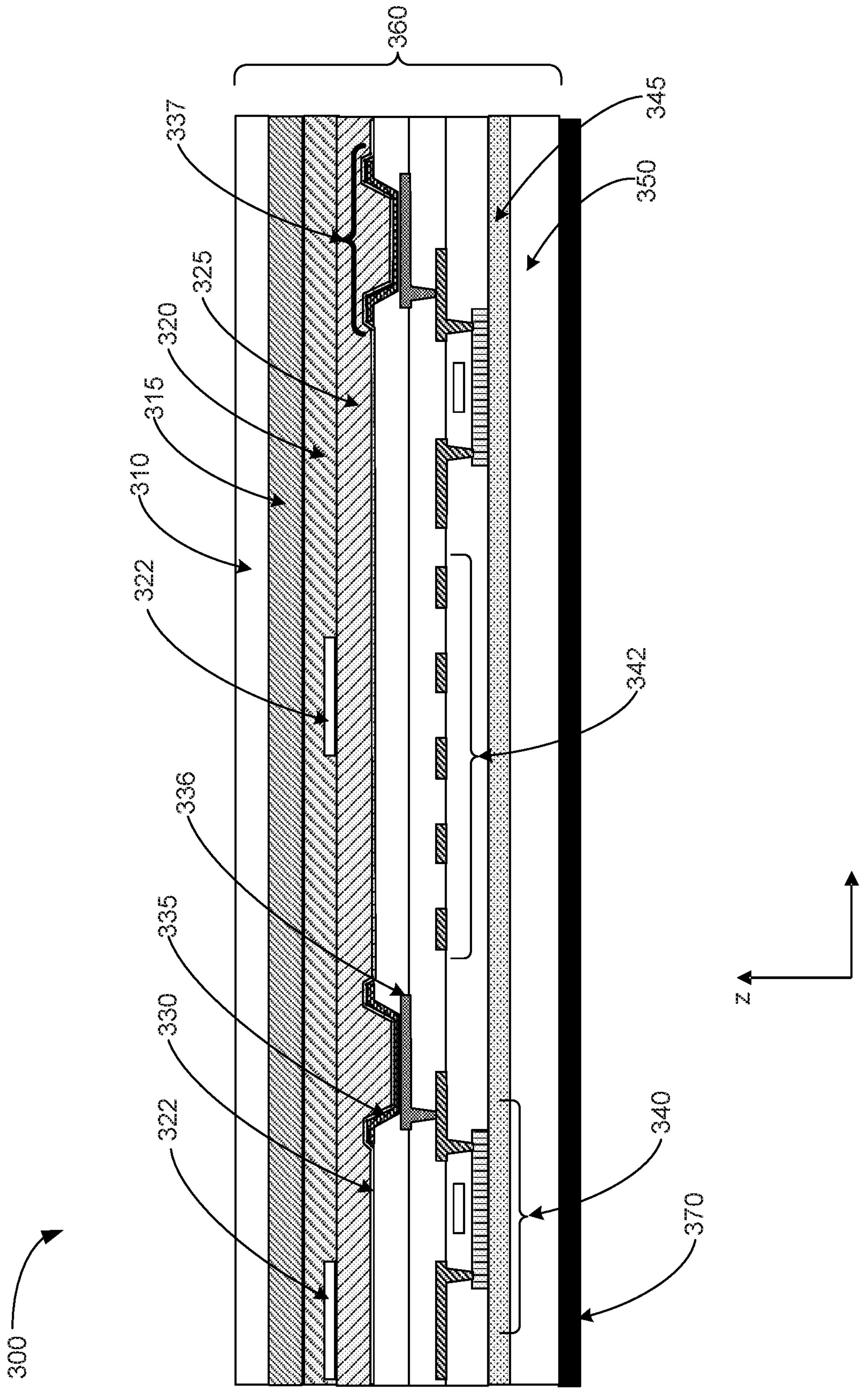


FIG. 2B


360
337
325
320
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310
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342
340
370
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FIG. 3

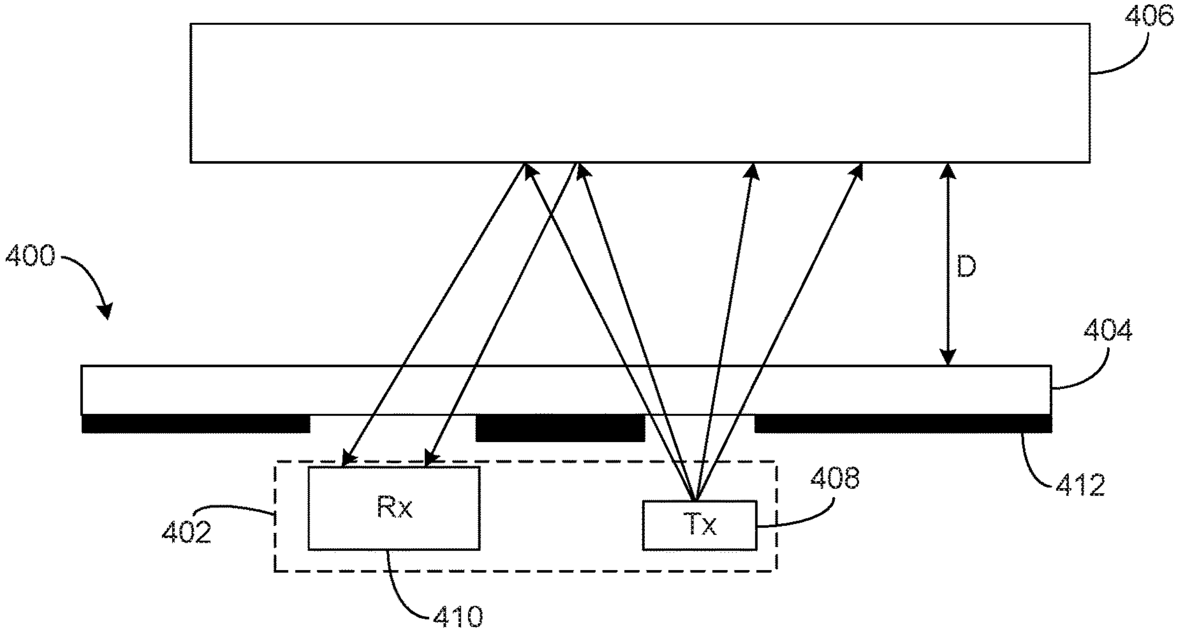
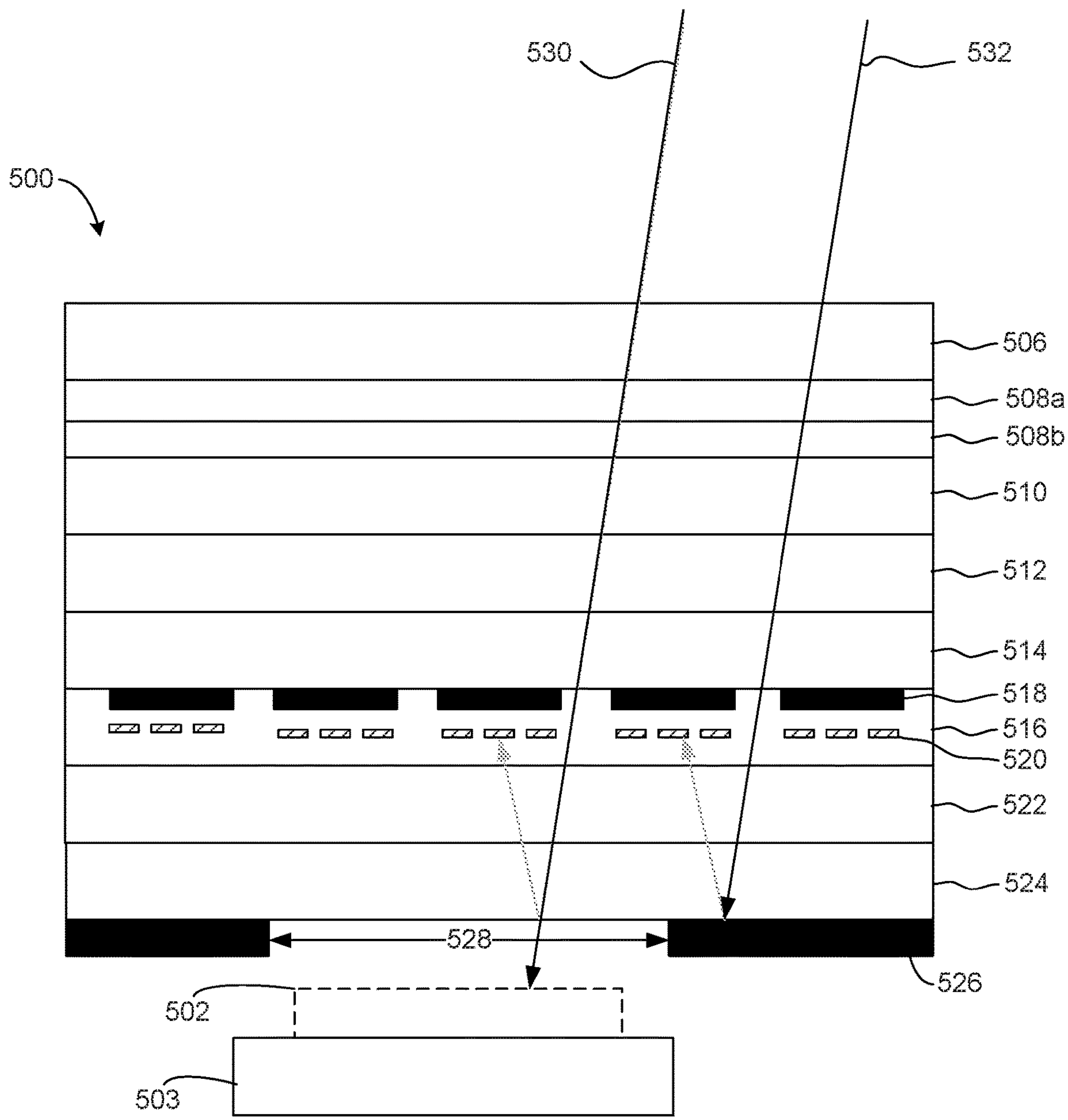


FIG. 4


530
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508a
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528
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503

FIG. 5

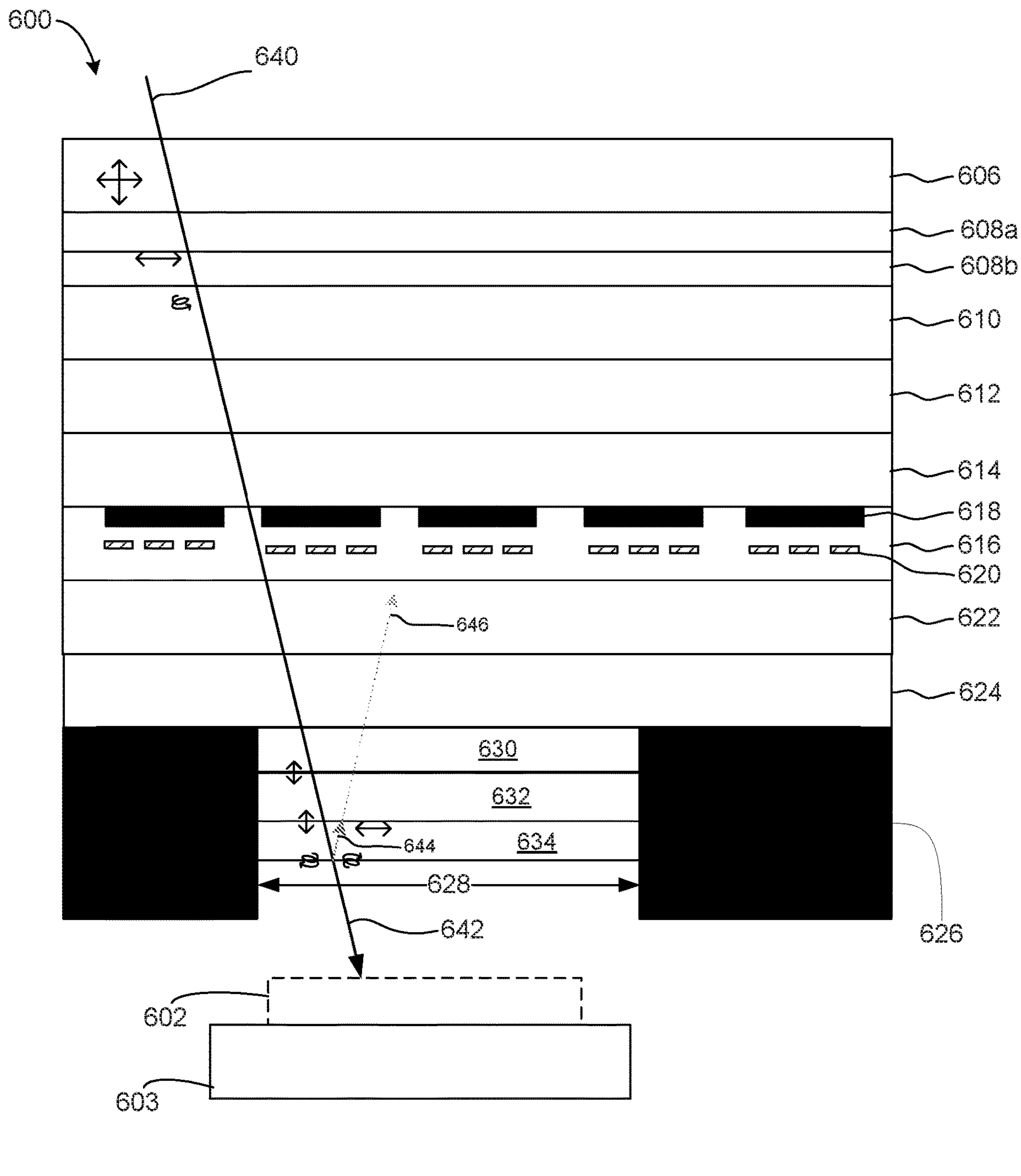
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FIG. 6

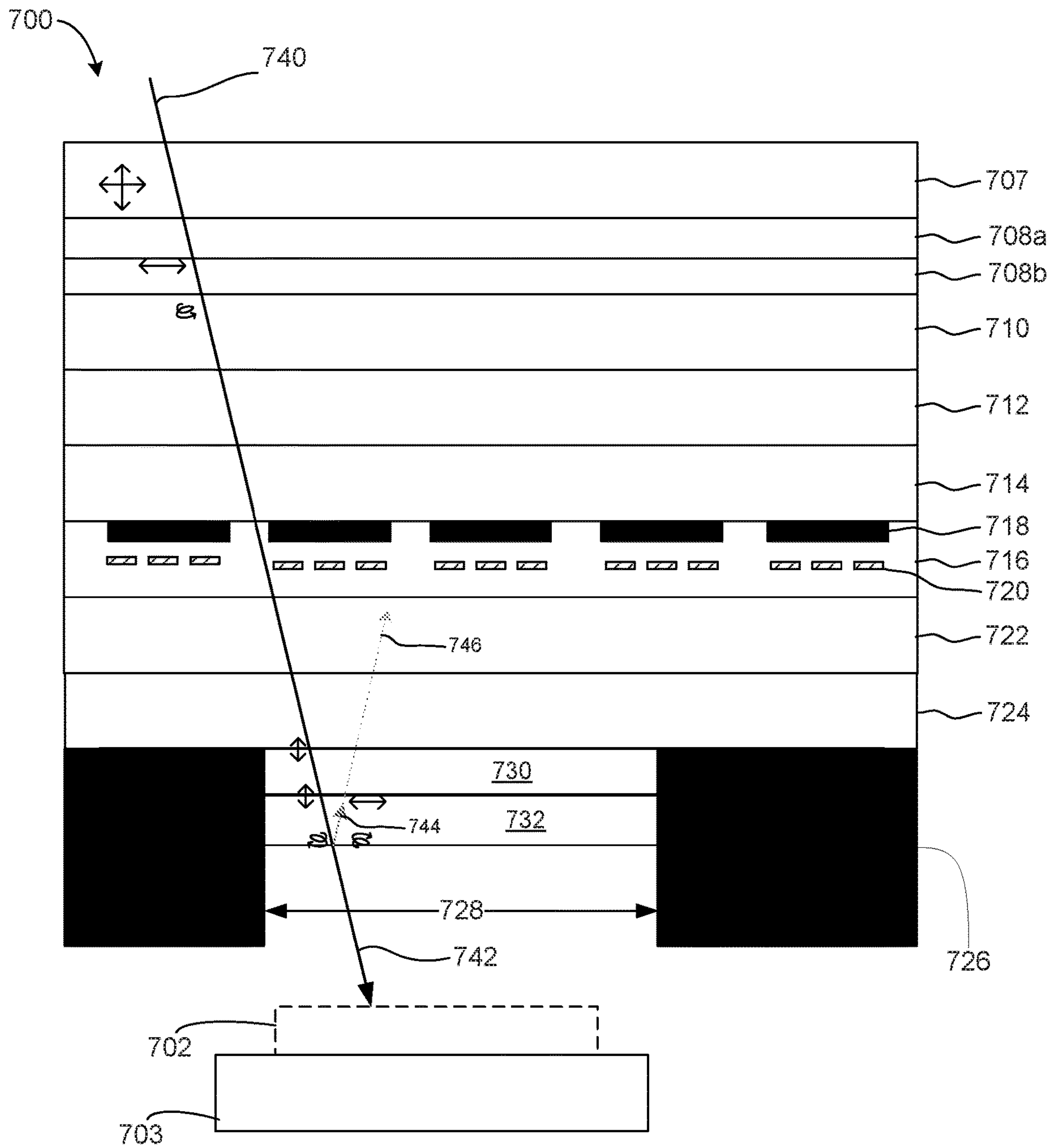

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FIG. 7

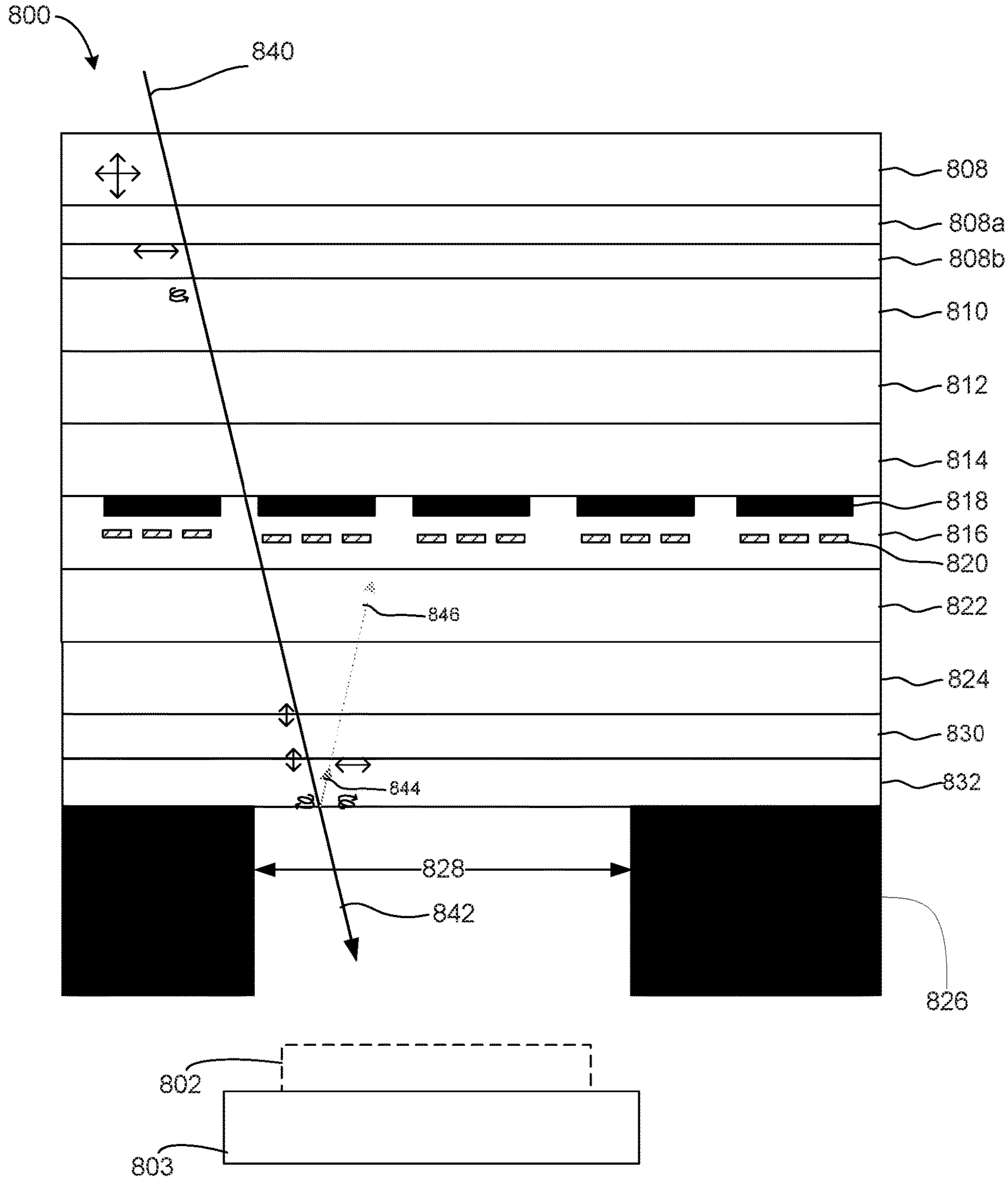
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FIG. 8

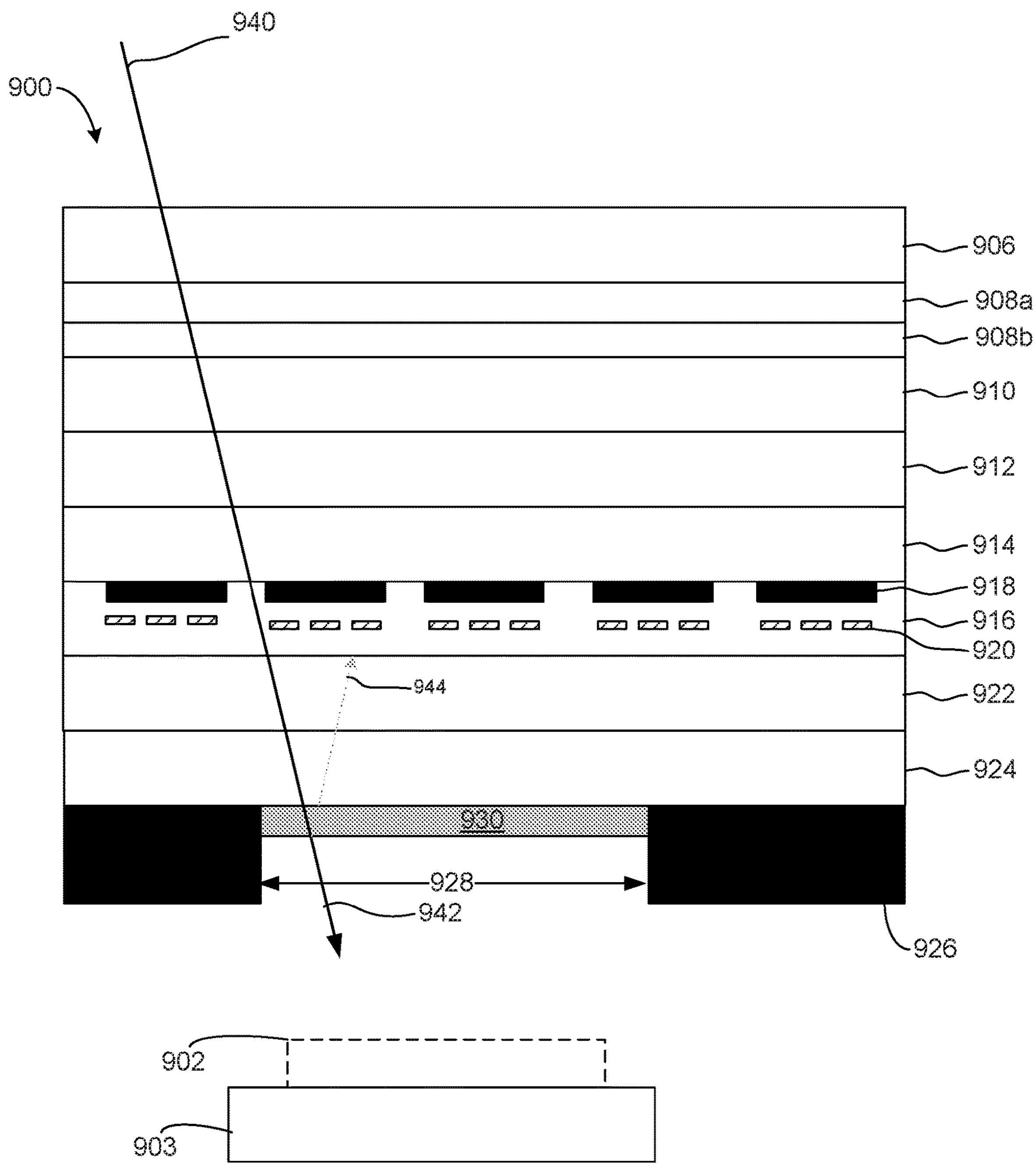
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FIG. 9A

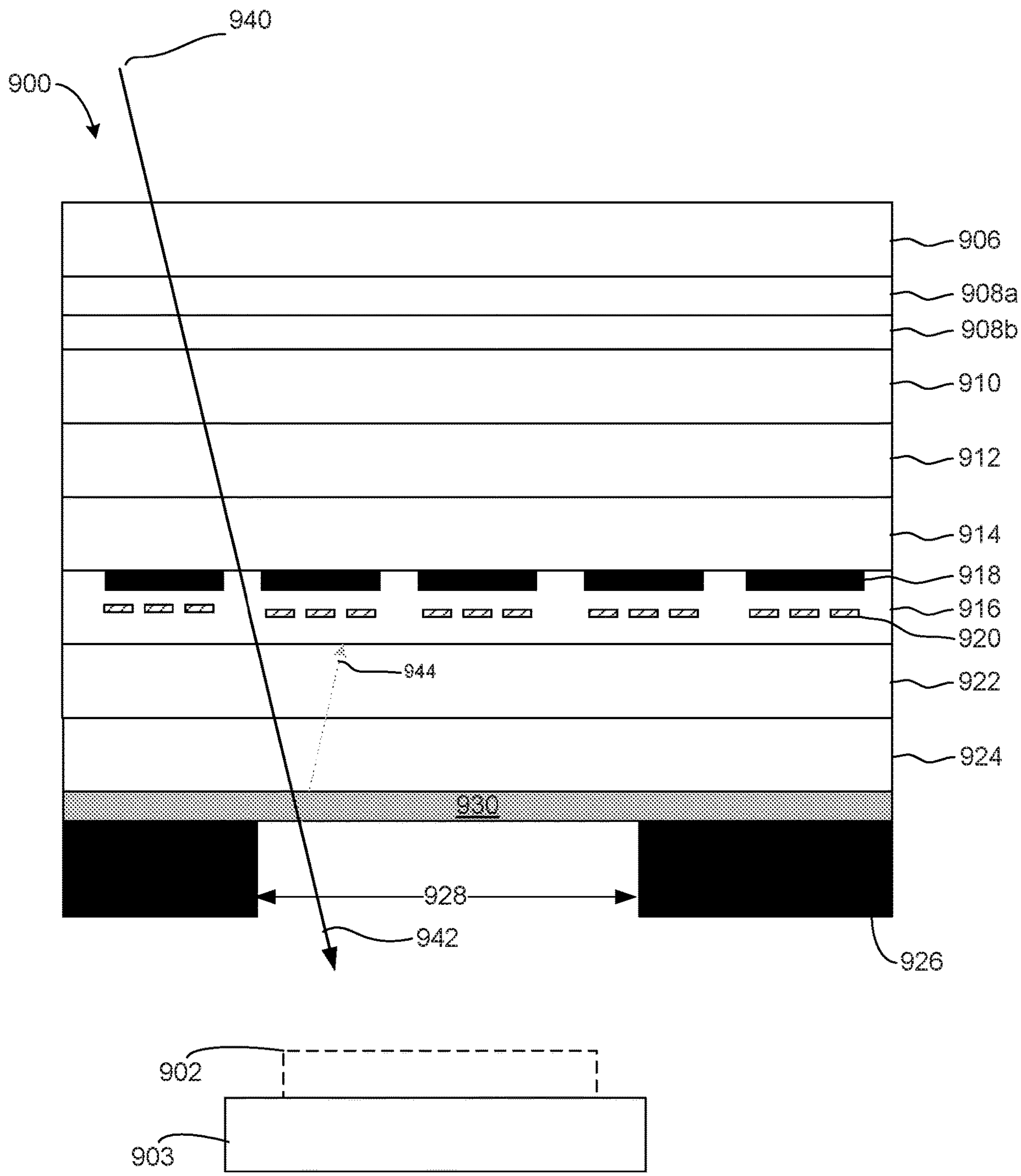

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FIG. 9B

OLED DISPLAY MODULE STRUCTURE FOR MITIGATING DARK SPOT VISIBILITY IN BACK COVER OPEN REGIONS

CROSS REFERENCE TO RELATED APPLICATION

This application is a 35 U.S.C. § 371 National Stage Entry from PCT/US2020/070481, filed Aug. 28, 2020, the disclosure of which is hereby incorporated by reference in its entirety.

FIELD OF THE DISCLOSURE

The present disclosure relates to flat panel displays and more specifically to displays that include a through-the-display optical components (e.g., optical sensors/emitters).

BACKGROUND

Expanding a display to cover more area of a mobile device (e.g., mobile phone, tablet, etc.) may be desirable from, at least, a user experience standpoint. However, electro-optical devices positioned on a side of the mobile device that also includes the display (e.g., a front-facing camera, a light sensor, a proximity sensor, etc.) may compete for real estate on the side of the device that includes the display. Thus, a sensor on display side of the device may be located under the display, such that light passes through the display to reach the sensor. However, the presence of the sensor under the display may cause undesirable distortions to the appearance of the display.

SUMMARY

In a first general aspect, a mobile computing device includes an emissive display panel configured to emit light from a front surface of the display panel, with the display panel having a plurality of transparent layers and an opaque back cover layer. The mobile computing device also includes a light sensor located behind the opaque back cover layer, and the opaque back cover layer includes an opening through which light from outside the display that is transmitted through the transparent layers of the display can pass to reach the sensor. An air gap separates the light sensor from the transparent layers of the display panel. The plurality of transparent layers includes a reflection attenuating layer on a back side of the display panel configured to attenuate the reflection of light from an interface between a transparent layer of the display panel and the air gap.

Implementations can include one or more of the following features, alone, or in any combination with each other.

In an example, the display panel can include an active matrix organic light emitting diode (AMOLED) display.

In another example, the opaque back cover layer can include a metal layer configured to spread heat through the metal layer.

In another example, the reflection attenuating layer can include a first quarter wave plate, a linear polarizer, and a second quarter wave plate, wherein the linear polarizer is located between the first and second quarter wave plates.

In another example, the first quarter wave plate, the linear polarizer, and the second quarter wave plate can be located within the opening of the opaque back cover layer.

In another example, the first quarter wave plate, the linear polarizer, and the second quarter wave plate can be located above the opaque back cover layer, between the back cover layer and the front surface of the display panel.

In another example, the linear polarizer, and the second quarter wave plate can be located within the opening of the opaque back cover layer, and the first quarter wave plate can be located above the opaque back cover layer, between the back cover layer and the front surface of the display panel.

In another example, the first quarter wave plate can include a PET film layer.

In another example, the first quarter wave plate can include a combination of a PET film layer and a birefringent, non-PET, film layer.

In another example, one or more of the first quarter wave plate, the linear polarizer, or the second quarter wave plate can include a partially-transmissive, partially-opaque layer.

In another example, the reflection attenuating layer can include a partially-transmissive, partially-opaque layer that attenuates an intensity of light that passes through the layer.

In another example, the partially-transmissive, partially-opaque layer can be located within the opening of the opaque back cover layer.

In another example, the partially-transmissive, partially-opaque layer can be located above the opaque back cover layer, between the back cover layer and the front surface of the display panel.

In another example, the display panel can include a polarization layer that receives randomly-polarized light from outside the display panel and circularly polarizes the light as a result of the light propagating through the polarization layer.

In another example, the display panel can include OLED emitters and semiconductor circuit elements configured to control a luminance of light emitted from the OLED emitters, where the semiconductor circuit elements are shielded from direct light received from outside the display panel by at least some opaque structures in the display panel.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A depicts a top (front) surface of a mobile computing device including a display and an optical device that occupy different portions of the front surface.

FIG. **1**B depicts a top (front) surface of a mobile computing device including a display with a light sensor positioned behind an area of the display according to a possible implementation of the disclosure.

FIG. **2**A depicts a side, cross-sectional view of a mobile device including a plurality of optical devices, each positioned behind a respective through-transmissive area of an emissive (e.g. OLED, micro-OLED or micro LED) display according to a possible implementation of the disclosure.

FIG. **2**B depicts a side, cross-sectional view of a mobile device including a plurality of optical devices positioned by a single through-transmissive area of an emissive display according to a possible implementation of the disclosure.

FIG. **3** depicts a possible side, cross-sectional view of an emissive display.

FIG. **4** is a schematic diagram of a display panel and a sensor located under the display panel interacting with an object that is a distance away from a front surface of the display panel.

FIG. **5** is a schematic diagram an implementation of a display panel and a sensor located under the display panel illustrating light propagating through the display panel to the sensor.

FIG. **6** is a schematic diagram another implementation of a display panel and a sensor located under the display panel illustrating light propagating through the display panel to the sensor.

FIG. **7** is a schematic diagram another implementation of a display panel and a sensor located under the display panel illustrating light propagating through the display panel to the sensor, including polarization states of the light.

FIG. **8** is a schematic diagram another implementation of a display panel and a sensor located under the display panel illustrating light propagating through the display panel to the sensor, including polarization states of the light.

FIG. **9**A is a schematic diagram another implementation of a display panel and a sensor located under the display panel illustrating light propagating through the display panel to the sensor.

FIG. **9**B is a schematic diagram another implementation of a display panel and a sensor located under the display panel illustrating light propagating through the display panel to the sensor.

The components in the drawings are not necessarily drawn to scale and may not be in scale relative to each other. Like reference numerals designate corresponding parts throughout the several views.

DETAILED DESCRIPTION

The present disclosure describes a flat panel display (i.e., display) that can be used with a computing device (e.g., mobile phone, tablet, etc.). The front surface of a mobile device includes a display typically operating as a graphic user interface (GUI) and one or more optical devices operating as sensors/emitters in areas below the display and facing the front surface. The one or more optical devices can be configured for a variety of functions, including (but not limited to) sensing lighting conditions (e.g. an ambient light sensor), sensing proximity of objects near the display (e.g., electromagnetic sensor), capturing images (e.g., a fingerprint sensor).

A proximity sensor may include a transmitter and a receiver of electromagnetic radiation, which are used to determine proximity of the display to an object that reflects electromagnetic radiation transmitted by the transmitter, which radiation is then reflected by the object and received by the receiver. For example, when a percentage of the transmitted radiation intensity received at the receiver, after being reflected by an object, exceeds a threshold value, a signal from the proximity sensor may determine that the display is closer to the object than a threshold distance.

A fingerprint sensor also may include a transmitter and a receiver of electromagnetic radiation, which are used to image a fingerprint on a finger pressed to the display. For example, radiation can be transmitted from a transmitter of the fingerprint sensor, reflected off the finger, and then detected by the receiver. A fingerprint pattern can be determined based on the reflected light received at the receiver and may be compared to a stored data associated with a fingerprint.

An ambient light sensor may include a receiver of light and may determine an amount of ambient light received by the sensor.

Light sensors are used in many mobile devices. Recent advances in emissive display technology (e.g., active matrix organic light emitting diode (AMOLED)) facilitate extending the emissive (i.e., active) area of the display towards (e.g., to) the edges of the mobile device. By extending the active area of the display towards the edges of the mobile device, a user may experience the benefits of a larger display without the drawbacks of a larger device. However, this may leave insufficient space for light sensors or other optical devices outside the area of the emissive display on the front side of the mobile device.

The emissive display disclosed herein is configured to share the front surface of a mobile device with one or more sensors so that the active area of the display can be extended to the edges, without the need for leaving a gap in the display, or space around the display, for the light sensor(s). Accordingly, one or more portions of the disclosed display covering the light sensors can be configured so that the light sensor(s), positioned behind the display, can transmit and receive electromagnetic radiation through the display. Generally, an air gap separates the back side of the display panel from the light sensor(s).

Ideally, when a light sensor is located under the display panel light would pass unimpeded through the display panel to the sensor. However, in reality, light is scattered, absorbed, and reflected by elements within the display panel. Some the reflected and/or scattered light may interfere with the operation of the pixel circuits in the display panel, causing unintended operation of at least some of the pixel circuits. In particular, light (e.g., ambient light that passes through the display) can reflect off an interface between a back side of the display panel and an air gap between the panel and a light sensor and then strike semiconductor circuits that control the pixel luminance of OLEDs above the air gap. This reflected light can interfere with the intended luminance of the OLEDs, such that the OLEDs may have a different intensity and/or color than they are programmed to produce.

To mitigate this effect, structures are disclosed herein that reduce the amount of light reflected from the interface between a back side of the display panel and an air gap between the panel and a light sensor. For example, an antireflection polarizer or an attenuator can be placed at the interface to reduce reflections.

Traditionally, the display and the optical devices located on a surface of the device that includes the display have occupied separate areas of the front surface. For example, FIG. **1**A depicts a mobile device **101** having a display **110** and a light sensor (e.g., ambient light sensor, proximity sensor, etc.) **111** that occupy different portions of the front surface.

FIG. **1**B illustrates a mobile device **102** with a display **112** that extends towards the edges of the device and that occupies a larger portion of the surface of the device **102** than does the display **110** of device **101**. Unlike mobile devices in which the display is excluded from an area reserved for optical devices, the light-emitting (i.e., active) area of the display **112** extends over substantially the entire front surface. Accordingly, nearly the entire front surface of the mobile device **102** may be used to present color, black-and-white, or gray-scale images, graphics, and/or characters. In some implementations, the display **112** can include one or more areas **120** behind which (i.e., below which) a light sensor or emitter may be disposed.

The size, shape, and/or position of the area **120** may be implemented variously. For example, the area **120** shown in FIG. **1**B has a rounded (e.g., circular) shape and is positioned apart from edges of the display **112**, but this need not be the case. For example, the area **120** can have rectangular in shape and can be positioned along an edge of the display **112**.

FIG. **2**A depicts a side, cross-sectional view of a mobile device having a display **112** with areas **120**A, **120**B through which electromagnetic radiation can be transmitted to an underlying optical device, for example, a fingerprint sensor, an ambient light sensor, or a proximity sensor. The mobile device can include multiple optical devices **140**A, **140**B, each positioned behind a different area **120**A, **120**B. FIG. **2**B depicts a side, cross-sectional view of a mobile device having a display **112** with a single region **120**C for use by the multiple optical devices **140**A, **140**B. The optical devices **140**A, **140**B may transmit and/or receive electromagnetic radiation **125** through the areas **120**A, **120**B, **120**C.

FIG. **3** illustrates a side, cross-sectional view of an emissive display (e.g., an AMOLED display) suitable for use with the mobile device of FIG. **1**. While the principles of the disclosure may be applied to display technologies other than AMOLED displays, the implementation of an AMOLED display will be considered throughout the disclosure.

As shown in FIG. **3**, the AMOLED display **300** includes a plurality of layers that make up a display panel **360**. The layers include a cover glass layer **310** that can form the front surface of the mobile device **102**. In a possible implementation, the display **300** can include a polarizer film layer **315**. The display **300** can also include a touch sensor layer **320** that includes touch sensor electrodes **322**. Pixels **337** for the display are formed from a cathode layer **330**, an OLED emitter stack **335**, and separate elements of an anode layer **336**. Elements of the anode layer **336** may be reflective so that light emitted from the OLED emitter stack **335** is directed in a vertical (z) direction from the anode layer **336**. An element of the anode layer **336** can be coupled to a thin film transistor (TFT) semiconductor structure **340** that includes a source, a gate, and a drain, which can be controlled by electrical signals transmitted over signal lines **342**. The display **300** can further include a transparent barrier layer **345** that includes, for example, SiNx or SiONx and a transparent substrate layer **350** that includes, for example, polyimide (PI) and/or polyethylene terephthalate (PET). An opaque layer/film **370** for mechanical support, heat spreading, and electrical shielding can be located below the display panel **360** to protect the display from localized hot spots due to heat-generating elements in the mobile device, such as, for example, a CPU, a GPU, etc., as well as from electrical signals/electrical noise from electrical components in the device located below the display **300**.

The layers of the display **300** may include transparent and non-transparent circuit elements. For example, the TFT structure **340**, the pixels **337**, the signal lines **342**, and/or touch sensor electrodes **322** may all block light from propagating through the display **300**. Light can be either reflected or absorbed by the non-transparent (i.e., opaque) circuit elements.

FIG. **4** is a schematic diagram of mobile device **400** that includes a light sensor (e.g., a proximity sensor) **402** located under a display panel **404** interacting with an object **406** that is a distance, D, away from a front surface of the display panel **404**. The light sensor **402** can include a transmitter **408** and a receiver **410** of electromagnetic radiation (e.g., infrared light). An opaque layer **412** for heat spreading and/or electrical shielding can be disposed between the display panel **404**, and the proximity sensor **402** and/or an opaque layer **412** can be disposed between a layer that includes OLED emitters of the display and the proximity sensor **402**. The opaque layer **412** can include one or more openings through which electromagnetic radiation can pass when transmitted to the object **406** and when received from the object. In some implementations, the electromagnetic radiation transmitted to the object **406** and received from the object can pass through different openings in the opaque layer **412** that are spatially separated from each other, and in some implementations, the electromagnetic radiation transmitted to the object **406** and received from the object can pass through the same opening, The proximity sensor **402** can operate by determining an amount of electromagnetic radiation (e.g., an intensity) that is emitted from the transmitter **408**, reflected off the object **406**, and then is received by the receiver **410**. The amount of light received by the receiver **410** can be used as a signal for how close the front surface of the display panel **404** is to an object **406** under the assumption that the amount of light received by the intensity of received light increases monotonically with decreasing distance, D, between the display panel **404** and the object **406**. The amount of light received at the receiver can be correlated with a distance between the object and the display panel, where the correlation is based on either an empirical calibration between received intensity and distance, or is based on a theoretical model of the propagation of light from the transmitter **408** to the object **406** and from the object **406** to the receiver **410**, or a combination of the two.

FIG. **5** is a schematic diagram of an implementation of a display panel **500** and a sensor **502** located under the display panel **500** illustrating light propagating through the display panel to the sensor. The sensor **502** can be coupled to a sensor module **503** containing control electronics for operating the sensor.

The display panel can include multiple layers. For example, the display panel **500** can include a cover glass layer **506**, a polarizer layer that can include a linear polarizer **508***a* and a quarter-waveplate **508***b* that can reduce the amount of light reflected off of an OLED layer in the panel that exits the front surface of the display, an encapsulation/touch sensor layer **510** containing touch sensor electrodes, a cathode layer, **512**, an OLED layer **514**, a pixel circuit layer **516** containing anodes **518** for supplying current to the OLEDs and semiconductor circuit elements **520** for controlling the current provided to the anodes, a PI layer **522**, a PET layer **524**, and an opaque back cover layer **526**. An opening in the back cover layer **526** allows light from outside the display panel to pass through the panel and through the opening **528** to reach the sensor.

Two paths **530**, **532** of light passing through the display panel **500** are shown in FIG. **5**, with each path showing a possible reflection of light within the panel. In one path **532**, light can traverse the transparent elements of the display panel and be reflected by a top surface of the back cover **526**, such that the light is then directed back into the panel **500**. However, the amount of light reflected from beam path **532** from the top surface of the back cover **526** can be relatively small due to the low reflectivity of the back cover **526** (e.g. 0.1% of the light in the incoming light). In another path **530**, light can traverse the transparent elements of the display panel and be reflected by an the interface between a transparent layer (e.g., PET layer **524**) and an air gap between the panel and a light sensor located below an opening **528** in the back cover **526** (i.e., as a result of a mismatch in the indices of refraction between air and the transparent layer), which also results in the reflection of light from the interface back into the panel **500**. The reflection from the interface of the light path **530** can be appreciably higher (e.g. 4% of the incoming light) than the reflection of light along path **532** from the top surface of the back cover layer **526**, and the difference results in higher exposure of the reflected light to the bottom surface of the semiconductor layer of the display pixel circuits than the rest of the display areas that are covered by the back cover **526**.

In some cases, reflected light that strikes semiconductor circuit elements **520** can cause reduction in light emission from pixels, in turn resulting in unintended dark spots in the display. For example, although semiconductor circuit elements **520** are shielded from direct light that enters the front surface of the panel through the cover window layer **506** (e.g., by the anodes **518** or the OLEDs themselves), reflected light (e.g., high-intensity, short wavelength light) that strikes semiconductor circuit elements **520** can increase the TFT leakage current of a circuit that controls the emission of light from a pixel. In some cases, the increased leakage current can be due to the photelectric effect caused by the reflected light on the circuit. The increased TFT leakage current for a circuit can cause a pixel controlled by the circuit to appear darker than intended. Because the semiconductor layer and the associated pixel circuits located over the opening **528** in the back cover **526** are struck by higher intensity reflected light, as compared with the rest of the display regions that are covered by the back cover **526**, the display panel **500** may appear to have odd dark spots above the locations of under-the-display light sensors.

FIG. **6** is a schematic diagram another implementation of a display panel **600** and a sensor **602** located under the display panel **600** illustrating light propagating through the display panel to the sensor. The sensor **602** can be coupled to a sensor module **603** containing control electronics for operating the sensor.

The display panel can include multiple layers. For example, the display panel **600** can include a cover glass layer **606**, a polarizer layer that can include a linear polarizer **608***a* and a quarter wave plate **608***b*, an encapsulation/touch sensor layer **610** containing touch sensor electrodes, a cathode layer, **612**, an OLED layer **614**, a pixel circuit layer **616** containing anodes **618** for supplying current to the OLEDs and semiconductor circuit elements **620** for controlling the current provided to the anodes, a PI layer **622**, a PET layer **624**, and an opaque back cover layer **626**. An opening **628** in the back cover layer **626** allows light from outside the display panel to pass through the panel and through the opening **628** to reach the sensor. A reflection attenuating layer on the back side of the display panel including a first film layer **630**, a linear polarizer **632**, and another quarter wave plate layer **634** can be included in the opening **628**.

A path **640** of light passing through the display panel **600** is shown in FIG. **6**. The structure of the additional layers **630**, **632**, **634** in display panel **600** as compared with the panel **500** can be used to reduce the amount of light reflected from the interface between the panel and the air gap between the panel and the light sensor **602**. For example, when light enters the panel **600** through the cover window layer **606** the light can be randomly polarized. Then, after passing through the linear polarizer layer **608***a*, which is polarized in a first direction in a plane of the layer **608***a*, the light can be linearly polarized in the first direction. Then, after passing through the quarter wave plate **610**, the light can be circularly polarized with a first chirality (e.g., right circularly polarized).

In some implementations, the first film layer **630** can include birefringent material, such that the layer **630** functions as a quarter wave plate for light transmitted through the layer. Thus, after passing through the first film layer **630** in the opening **628**, the light can be linearly polarized in a second linear polarization direction, wherein the second linear polarization direction is orthogonal to the first linear polarization direction due to film **608***a*. This second linear polarization direction of the light can be transmitted with close to zero attenuation by the linear polarization layer **632**, whose polarization axis is aligned with the second linear polarization direction of the light. Then, after passing through the second quarter wave plate layer **634** in the opening **628**, the light can be circularly polarized with a second chirality (e.g., left circularly polarized), opposite to the first chirality. When the light interacts with the interface between the interface between the bottom transparent layer **634** of the panel and the air gap between the panel and the light sensor **602**, a first portion **642** of the light is transmitted through the interface and a second portion **644** is reflected from the interface. The reflected portion of the light has the chirality of its polarization reversed, so that it is circularly polarized with the first chirality. Then, after again passing through the quarter wave plate **634** the reflected light is linearly polarized in the first direction. Because the first linear polarization direction is orthogonal to the polarization axis of the linear polarization layer **632**, the reflected light is sharply attenuated by the layer **632**, and very little light **646** is transmitted though the layer **632** in a direction from the back side of the panel toward the front side of the panel. Therefore, very little reflected light reaches the pixel circuit layer **616** containing semiconductor circuit elements **620** for controlling the current provided to the anodes **618** of the OLEDs. Therefore, the TFT leakage current of the pixels circuits does not increase, and the OLEDs emit their designed amounts of light, so that a dark spot in the display over the opening **628** for the sensor **602** can be avoided.

In some implementations, the transparent PET layer **624** of the display panel can introduce some polarization rotation to light passing through the layer **624**. Therefore, the thickness, composition, and other material properties of the first film layer **630** can be selected, such that the combination of the PET layer **630** and the first film layer **630**, which can include birefringent PET or non-PET material acts as a quarter wave plate to light passing through the combination of layers. In some implementations, one or more of layers **630**, **632**, **634** can be applied as coatings to the display panel **600**.

FIG. **7** is a schematic diagram another implementation of a display panel **700** and a sensor **702** located under the display panel **700** illustrating light propagating through the display panel to the sensor. The sensor **702** can be coupled to a sensor module **703** containing control electronics for operating the sensor.

The display panel can include multiple layers. For example, the display panel **700** can include a cover glass layer **706**, a polarizer layer that can include a linear polarizer **708***a* and a quarter wave plate **708***b*, an encapsulation/touch sensor layer **710** containing touch sensor electrodes, a cathode layer, **712**, an OLED layer **714**, a pixel circuit layer **716** containing anodes **718** for supplying current to the OLEDs and semiconductor circuit elements **720** for controlling the current provided to the anodes, a PI layer **722**, a first film layer (e.g., a PET film layer) **724**, and an opaque back cover layer **726**. An opening **728** in the back cover layer **726** allows light from outside the display panel to pass through the panel and through the opening **728** to reach the sensor. A reflection attenuating layer on the back side of the display panel including the first film layer **724**, a linear polarizer **730**, and a quarter wave plate layer **732**, with at least some of the layers of the reflection attenuating layer being included in the opening **728**. In some implementations, one or more of layers **724**, **730**, **732** can be applied as coatings to the display panel **700**.

A path **740** of light passing through the display panel **700** is shown in FIG. **7**. The reflection attenuating layer in display panel **700** can be used to reduce the amount of light reflected from the interface between the panel and the air gap between the panel and the light sensor **702**. For example, when light enters the panel **700** through the cover window layer **706** the light can be randomly polarized. Then, after passing through the linear polarizer layer **708***a*, which is polarized in a first direction in a plane of the layer **708***a*, the light can be linearly polarized in the first direction. Then, after passing through the quarter wave plate **710**, the light can be circularly polarized with a first chirality (e.g., right circularly polarized).

In some implementations, the first film layer **724**, which in some implementations can include PET film, can include birefringent material, such that the layer **724** functions as a quarter wave plate for light transmitted through the layer. Thus, after passing through the first film layer **724**, the light can be linearly polarized in a second linear polarization direction, wherein the second linear polarization direction is perpendicular to the first linear polarization direction. This second linear polarization direction of the light can be transmitted with close to zero attenuation by the linear polarization layer **730**, whose polarization axis is aligned with the second linear polarization direction of the light. Then, after passing through the quarter wave plate layer **732** in the opening **728**, the light can be circularly polarized with a second chirality (e.g., left circularly polarized), opposite to the first chirality. When the light interacts with the interface between the interface between the bottom transparent layer **732** of the panel and the air gap between the panel and the light sensor **702**, a first portion **742** of the light is transmitted through the interface and a second portion **744** is reflected from the interface. The reflected portion of the light has the chirality of its polarization reversed, so that it is circularly polarized with the first chirality. Then, after again passing through the quarter wave plate **732** the reflected light is linearly polarized in the first direction. Because the first linear polarization direction is orthogonal to the polarization axis of the linear polarization layer **730**, the reflected light is sharply attenuated by the layer **730**, and very little light **746** is transmitted though the layer **730** in a direction from the back side of the panel toward the front side of the panel. Therefore, very little reflected light reaches the pixel circuit layer **716** containing semiconductor circuit elements **720** for controlling the current provided to the anodes **718** of the OLEDs. Therefore, the TFT leakage current of the pixels circuits does not increase, and the OLEDs emit their designed amounts of light, so that a dark spot in the display over the opening **728** for the sensor **702** can be avoided.

FIG. **8** is a schematic diagram another implementation of a display panel **800** and a sensor **802** located under the display panel **800** illustrating light propagating through the display panel to the sensor. The sensor **802** can be coupled to a sensor module **803** containing control electronics for operating the sensor. Like the display panels of FIGS. **6** and **7**, the display panel **800** can include a reflection attenuating layer on the back side of the panel, but, unlike the display panels of FIGS. **6** and **7**, the reflection attenuating layer in panel **800** can be located above the opaque back cover layer **826**.

Thus, the display panel can include multiple layers, such as a cover glass layer **806**, a polarizer layer that can include a linear polarizer **808***a* and a quarter wave plate **808***b*, an encapsulation/touch sensor layer **810** containing touch sensor electrodes, a cathode layer, **812**, an OLED layer **814**, a pixel circuit layer **816** containing anodes **818** for supplying current to the OLEDs and semiconductor circuit elements **820** for controlling the current provided to the anodes, a PI layer **822**, a first film layer (e.g., a PET film layer) **824**, a linear polarizer layer **830**, a quarter wave plate layer **832**, and an opaque back cover layer **826**. An opening **828** in the back cover layer **826** allows light from outside the display panel to pass through the panel and through the opening **828** to reach the sensor. A reflection attenuating layer on the back side of the display panel **800** above the opaque back cover layer **826** can include the first film layer **824**, the linear polarizer layer **830**, and the quarter wave plate layer **832**. In some implementations, one or more of layers **824**, **830**, **832** can be applied as coatings to the display panel **800**.

In the implementation shown in FIG. **8**, the first film layer **824**, which in some implementations can include PET film, can include birefringent material, such that the layer **824** functions as a quarter wave plate for light transmitted through the layer. Thus, after passing through the first film layer **824**, the light can be linearly polarized in a second linear polarization direction, wherein the second linear polarization direction is perpendicular to the first linear polarization direction. This second linear polarization direction of the light can be transmitted with close to zero attenuation by the linear polarization layer **830**, whose polarization axis is aligned with the second linear polarization direction of the light. Then, after passing through the quarter wave plate layer **832**, the light can be circularly polarized with a second chirality (e.g., left circularly polarized), opposite to the first chirality. When the light interacts with the interface between the interface between the bottom transparent layer **832** of the panel and the air gap between the panel and the light sensor **802**, a first portion **842** of the light is transmitted through the interface and a second portion **844** is reflected from the interface. The reflected portion of the light has the chirality of its polarization reversed, so that it is circularly polarized with the first chirality. Then, after again passing through the quarter wave plate **832** the reflected light is linearly polarized in the first direction. Because the first linear polarization direction is orthogonal to the polarization axis of the linear polarization layer **830**, the reflected light is sharply attenuated by the layer **830**, and very little light **846** is transmitted though the layer **830** in a direction from the back side of the panel toward the front side of the panel. Therefore, very little reflected light reaches the pixel circuit layer **816** containing semiconductor circuit elements **820** for controlling the current provided to the anodes **818** of the OLEDs. Therefore, the TFT leakage current of the pixels circuits does not increase, and the OLEDs emit their designed amounts of light, so that a dark spot in the display over the opening **828** for the sensor **802** can be avoided.

In some cases, the implementation of FIG. **8**, in which the reflection attenuating layer is located above the opening **828**, rather than at least partially within the opening, can be easier to manufacture than an implementation with part of the reflection attenuating layer be located in the opening **828**, but the cost of the materials (e.g., for polarization layers **824**, **830**, **832** that span the width of the display) may be higher.

FIG. **9**A is a schematic diagram another implementation of a display panel **900** and a sensor **902** located under the display panel **900** illustrating light propagating through the display panel to the sensor. The sensor **902** can be coupled to a sensor module **903** containing control electronics for operating the sensor. The display panel **900** can include a reflection attenuating layer on the back side of the panel, where the reflection attenuating layer includes a partially-transmissive, partially-opaque layer or coating that attenuates the intensity of light that passes through the layer.

The display panel **900** can include multiple layers, such as a cover glass layer **906**, a polarizer layer that can include a linear polarizer **908**a and a quarter wave plate **908**b, an encapsulation/touch sensor layer **910** containing touch sensor electrodes, a cathode layer, **912**, an OLED layer **914**, a pixel circuit layer **916** containing anodes **918** for supplying current to the OLEDs and semiconductor circuit elements **920** for controlling the current provided to the anodes, a PI layer **922**, and a clear PET film layer **924**. An opening **928** in the back cover layer **926** allows light from outside the display panel **900** to pass through the panel and through the opening **928** to reach the sensor **902**. A reflection attenuating layer on the back side of the display panel **900** within the opening **928** in the opaque back cover layer **926** can include partially-transmissive, partially-opaque material layer **930** (e.g., a neutral density filter) that attenuates the light passing through the layer.

In the implementation shown in FIG. **9**A, the transmissivity of the partially-transmissive, partially-opaque material layer **930** can be selected such that enough transmitted light **942** passes through the layer **930** for the sensor **902** to function as designed, but such that when light is transmitted through the layer twice (i.e., once in a direction toward the sensor **902** and once, after reflection from the interface with the air gap, in a direction away from the sensor **902**), that the intensity of light **944** reflected from the air gap is attenuated enough that reflected light **944** does not interfere significantly with the operation of the semiconductor circuit elements **920** for controlling the current provided to the anodes **918** of the OLED emitters.

FIG. **9**B is a schematic diagram another implementation of a display panel and a sensor located under the display panel illustrating light propagating through the display panel to the sensor, wherein the implementation is similar to that of FIG. **9**A, except that the partially-transmissive, partially-opaque material layer **930** is located above the opaque back cover layer **926**. In some implementations, the layer **930** can be applied as a coating to the display panel **900**.

In some implementations, one or more layers of the reflection attenuating layers of display panels **600**, **700**, or **800** can include a partially-transmissive, partially-opaque layer that attenuates the intensity of light that passes through the layer. For example, quarter wave plate layer or a linear polarizer layer of the reflection attenuating layers of display panels **600**, **700**, or **800** can include a partially-transmissive, partially-opaque layer.

The disclosed displays have been presented in the context of a mobile device, such as a tablet or a smart phone. The principles and techniques disclosed, however, may be applied more generally to any display in which it is desirable to position a sensor behind the display. For example, a virtual agent home terminal, a television, or an automatic teller machine (ATM) are a non-limiting set of alternative applications that could utilize a light sensor positioned behind an active area of a display. Further, the motivation for placing a light sensor behind a display is not limited to an expansion of the display to the edges of a device. For example, it may be desirable to place the light sensor behind a display for aesthetic or stealth reasons.

In the specification and/or figures, typical embodiments have been disclosed. The present disclosure is not limited to such exemplary embodiments. The use of the term "and/or" includes any and all combinations of one or more of the associated listed items. Unless otherwise noted, specific terms have been used in a generic and descriptive sense and not for purposes of limitation. As used in this specification, spatial relative terms (e.g., in front of, behind, above, below, and so forth) are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. For example, a "front surface" of a mobile computing device may be a surface facing a user, in which case the phrase "in front of" implies closer to the user. Additionally, a "top surface" of a display may be the surface facing a user, in which case the phrase "below" implies deeper into an interior of the mobile computing device.

While certain features of the described implementations have been illustrated as described herein, many modifications, substitutions, changes, and equivalents will now occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the scope of the implementations. It should be understood that they have been presented by way of example only, not limitation, and various changes in form and details may be made. Any portion of the apparatus and/or methods described herein may be combined in any combination, except mutually exclusive combinations. The implementations described herein can include various combinations and/or sub-combinations of the functions, components, and/or features of the different implementations described.

What is claimed is:

1. A mobile computing device comprising:

an emissive display panel configured to emit light from a front surface of the emissive display panel, the emissive display panel having a plurality of transparent layers and an opaque back cover layer; and

a light sensor located behind the opaque back cover layer, wherein the opaque back cover layer includes an opening through which light from outside the emissive display panel that is transmitted through the transparent layers of the emissive display panel is configured to pass to reach the light sensor, wherein an air gap separates the light sensor from the transparent layers of the emissive display panel, and wherein the light sensor is located behind an active area of the emissive display panel;

wherein the plurality of transparent layers includes a reflection attenuating layer on a back side of the emissive display panel configured to attenuate the reflection of light from an interface between a transparent layer of the emissive display panel and the air gap.

2. The mobile computing device of claim **1**, wherein the emissive display panel includes an active matrix organic light emitting diode (AMOLED) display.

3. The mobile computing device of claim **1**, wherein the opaque back cover layer includes a metal layer configured to spread heat through the metal layer.

4. The mobile computing device of claim **1**, wherein the reflection attenuating layer includes a first quarter wave plate, a linear polarizer, and a second quarter wave plate, wherein the linear polarizer is located between the first and second quarter wave plates.

5. The mobile computing device of claim **4**, wherein the first quarter wave plate, the linear polarizer, and the second quarter wave plate are located within the opening of the opaque back cover layer.

6. The mobile computing device of claim **4**, wherein the first quarter wave plate, the linear polarizer, and the second quarter wave plate are located above the opaque back cover layer, between the back cover layer and the front surface of the emissive display panel.

7. The mobile computing device of claim **4**, wherein the linear polarizer, and the second quarter wave plate are located within the opening of the opaque back cover layer, and wherein the first quarter wave plate is located above the opaque back cover layer, between the back cover layer and the front surface of the emissive display panel.

8. The mobile computing device of claim **4**, wherein the first quarter wave plate includes a PET film layer.

9. The mobile computing device of claim **4**, wherein the first quarter wave plate includes a combination of a PET film layer and a birefringent non-PET film layer.

10. The mobile computing device of claim **4**, wherein one or more of the first quarter wave plate, the linear polarizer, or the second quarter wave plate includes a partially-transmissive, partially-opaque layer.

11. The mobile computing device of claim **1** wherein the reflection attenuating layer includes a partially-transmissive, partially-opaque layer that attenuates an intensity of light that passes through the layer.

12. The mobile computing device of claim **11**, wherein the partially-transmissive, partially-opaque layer is located within the opening of the opaque back cover layer.

13. The mobile computing device of claim **11**, wherein the partially-transmissive, partially-opaque layer is located above the opaque back cover layer, between the back cover layer and the front surface of the emissive display panel.

14. The mobile computing device of claim **1**, wherein:

the active area of the emissive display panel that is located in front of the light sensor includes organic light emitting diode (OLED) emitters and semiconductor circuit elements configured to control a luminance of light emitted from the OLED emitters; and

the emissive display panel includes a polarization layer that receives randomly-polarized light from outside the emissive display panel and circularly polarizes the light as a result of the light propagating through the polarization layer, the polarization layer being located between the front surface of the emissive display panel and the OLED emitters that are located in front of the light sensor.

15. The mobile computing device of claim **1**, wherein:

the active area of the emissive display panel that is located in front of the light sensor includes organic light emitting diode (OLED) emitters and semiconductor circuit elements configured to control a luminance of light emitted from the OLED emitters; and

the semiconductor circuit elements that are located in front of the light sensor are shielded from direct light received from outside the emissive display panel by at least some opaque structures in the emissive display panel.

16. An emissive display panel configured to emit light from a front surface of the emissive display panel, the emissive display panel comprising:

a plurality of transparent layers;

an opaque back cover layer, wherein the opaque back cover layer includes an opening through which light from outside the emissive display panel that is transmitted through the transparent layers of the emissive display panel is configured to pass to reach a light sensor located behind the opaque back cover layer and separated by an air gap from the transparent layers of the emissive display panel, wherein the transparent layers of the emissive display panel through which the light from outside the emissive display panel is configured to pass to reach the light sensor comprise an active area of the emissive display panel; and

a reflection attenuating layer on a back side of the emissive display panel configured to attenuate the reflection of light from an interface between a transparent layer of the emissive display panel and the air gap.

17. The emissive display panel of claim **16**, wherein the opaque back cover layer includes a metal layer configured to spread heat through the metal layer.

18. The emissive display panel of claim **16**, wherein the reflection attenuating layer includes a first quarter wave plate, a linear polarizer, and a second quarter wave plate, wherein the linear polarizer is located between the first and second quarter wave plates.

19. The emissive display panel of claim **18**, wherein the first quarter wave plate, the linear polarizer, and the second quarter wave plate are located within the opening of the opaque back cover layer.

20. The emissive display panel of claim **16**, wherein:

the active area of the emissive display panel that is located in front of the light sensor includes organic light emitting diode (OLED) emitters and semiconductor circuit elements configured to control a luminance of light emitted from the OLED emitters; and

the emissive display panel further comprises a polarization layer that receives randomly-polarized light from outside the emissive display panel and circularly polarizes the light as a result of the light propagating through the polarization layer, the polarization layer being located between the front surface of the emissive display panel and the OLED emitters that are located in front of the light sensor.

21. The emissive display panel of claim **16**, wherein:

the active area of the emissive display panel that is located in front of the light sensor includes organic light emitting diode (OLED) emitters and semiconductor circuit elements configured to control a luminance of light emitted from the OLED emitters; and

the semiconductor circuit elements that are located in front of the light sensor are shielded from direct light received from outside the emissive display panel by at least some opaque structures in the emissive display panel.

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