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(54) **TRANSPARENT ANTENNAS ON A DISPLAY DEVICE**

(71) Applicant: **QUALCOMM MEMS TECHNOLOGIES, INC.**, San Diego, CA (US)

(72) Inventors: **David William Burns**, San Jose, CA (US); **Jonathan Charles Griffiths**, Fremont, CA (US)

(73) Assignee: **QUALCOMM MEMS TECHNOLOGIES, INC.**, San Diego, CA (US)

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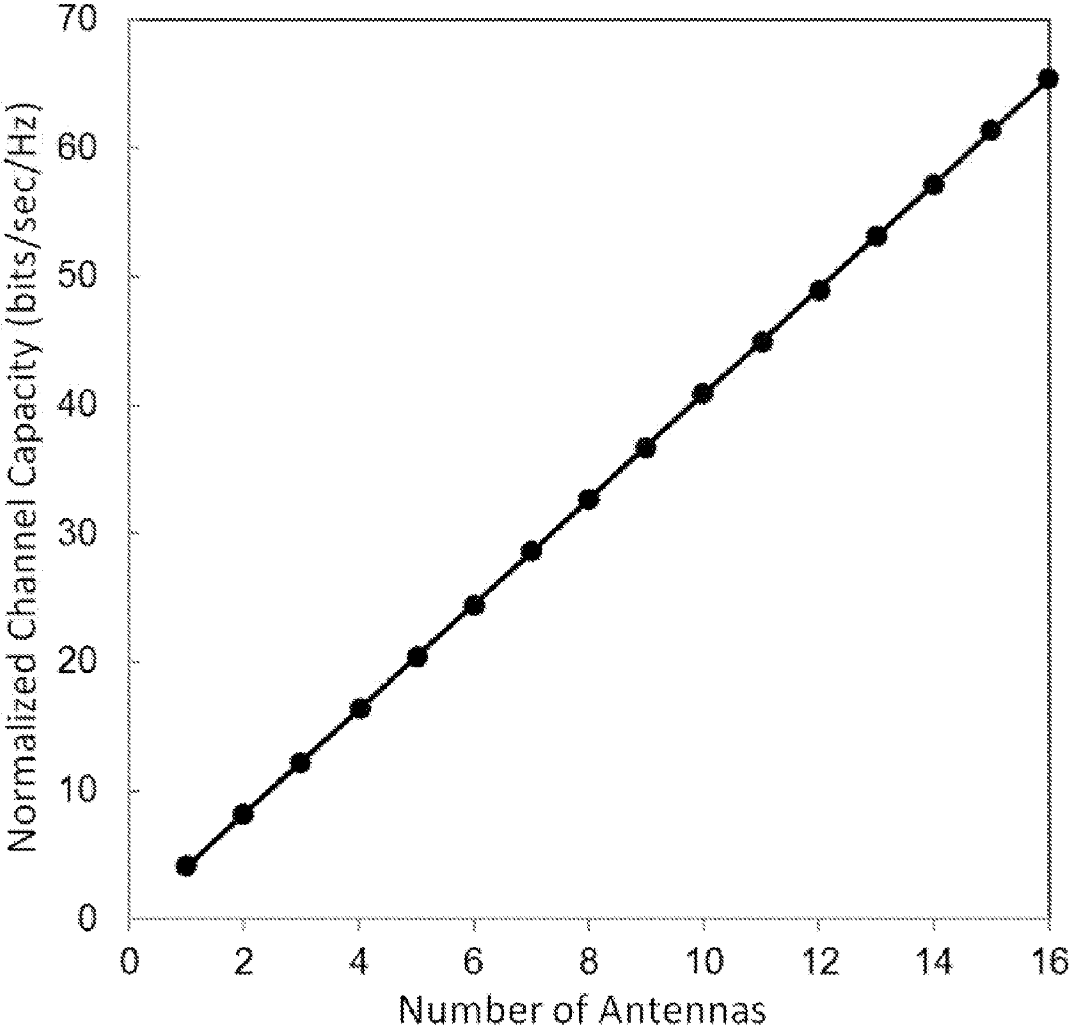
(52) **U.S. Cl.**
USPC **345/156**; 345/501; 343/702; 427/108

(57) **ABSTRACT**

This disclosure provides systems, methods and apparatus for a display device with at least one transparent antenna. In one aspect, the transparent antenna is formed on a surface of a transparent substrate and may be electrically reinforced with one or more electrically conductive traces. The transparent antenna can avoid substantial interference with images produced by the display device.



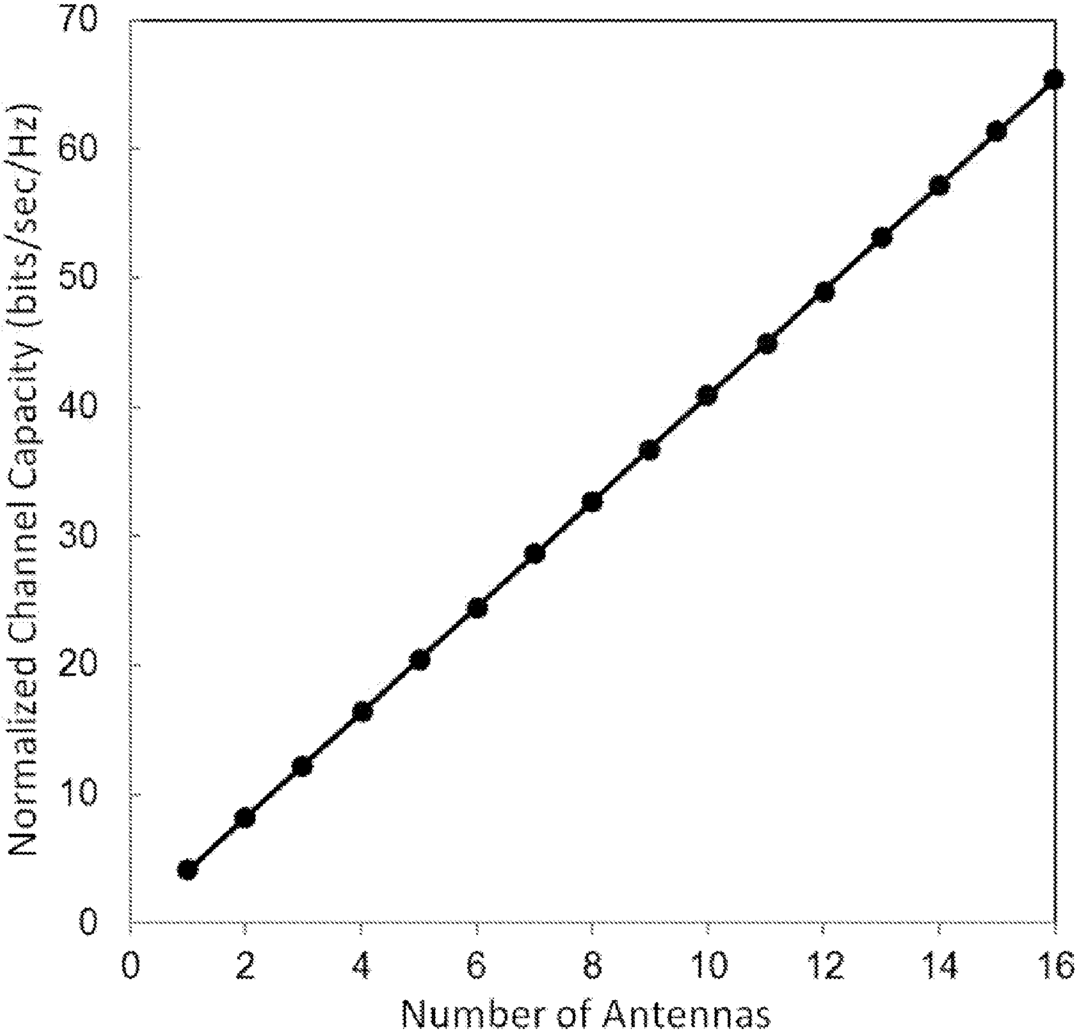

70
60
50
40
30
20
10
0
Normalized Channel Capacity (bits/sec/Hz)
0
2
4
6
8
10
12
14
16
Number of Antennas

FIG. 1

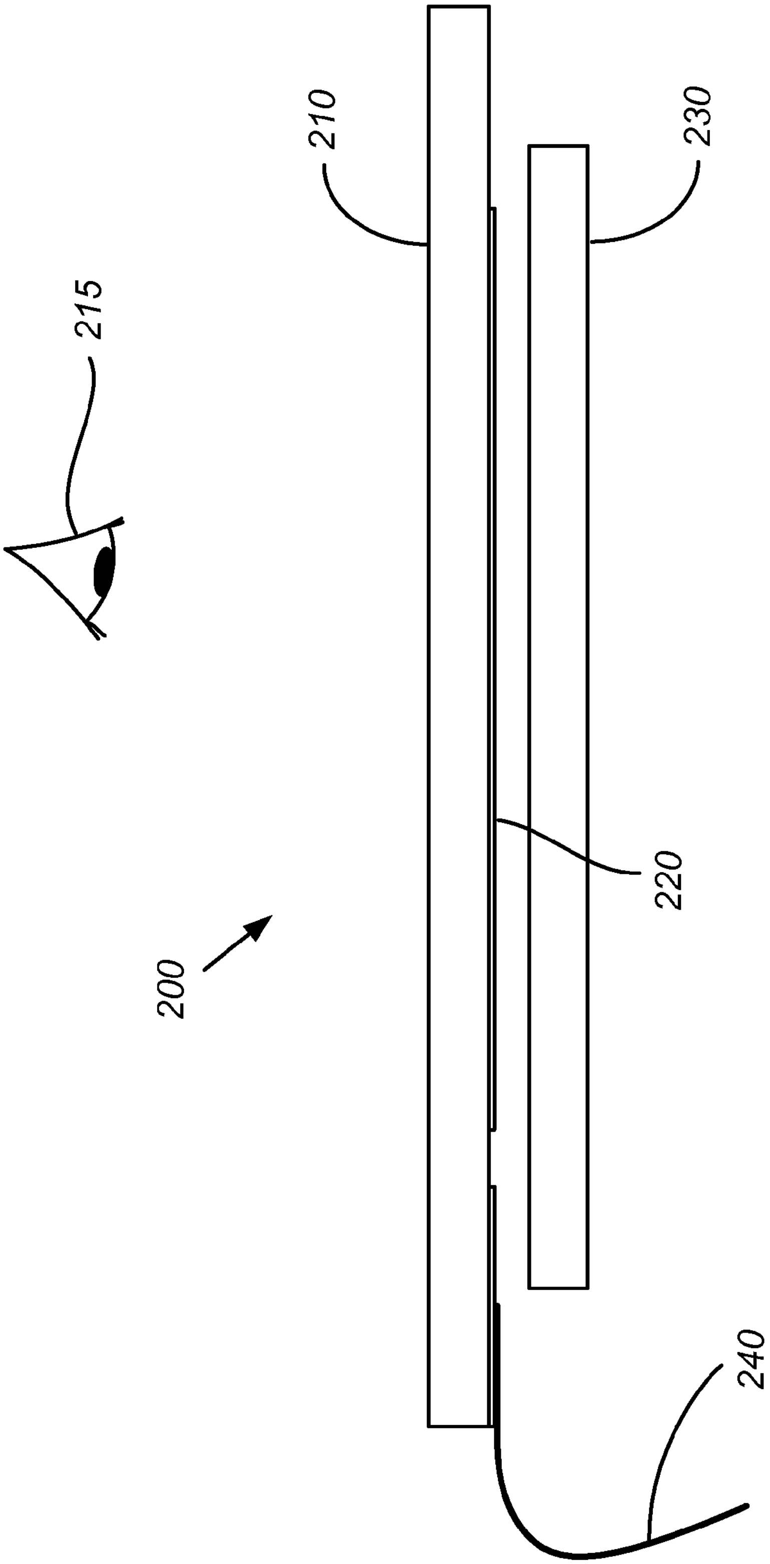


FIG. 2A

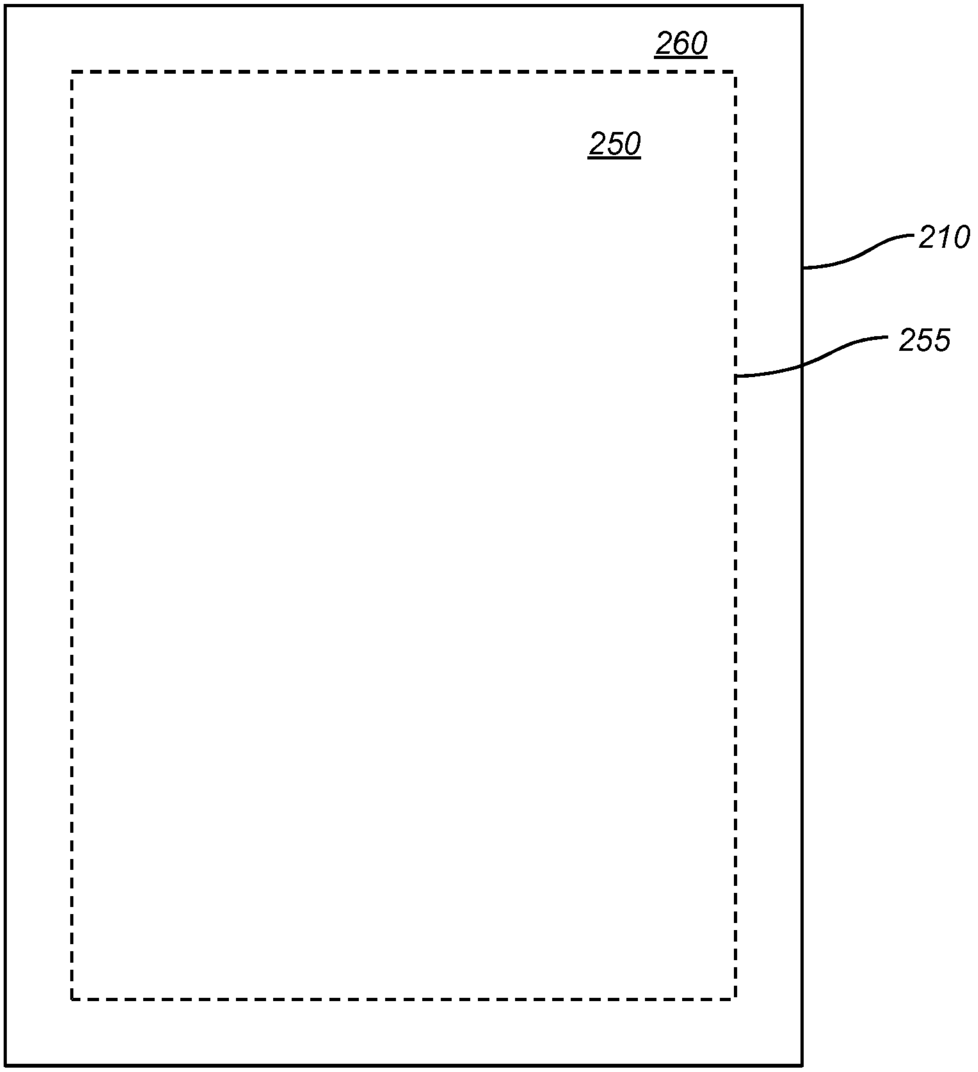


FIG. 2B

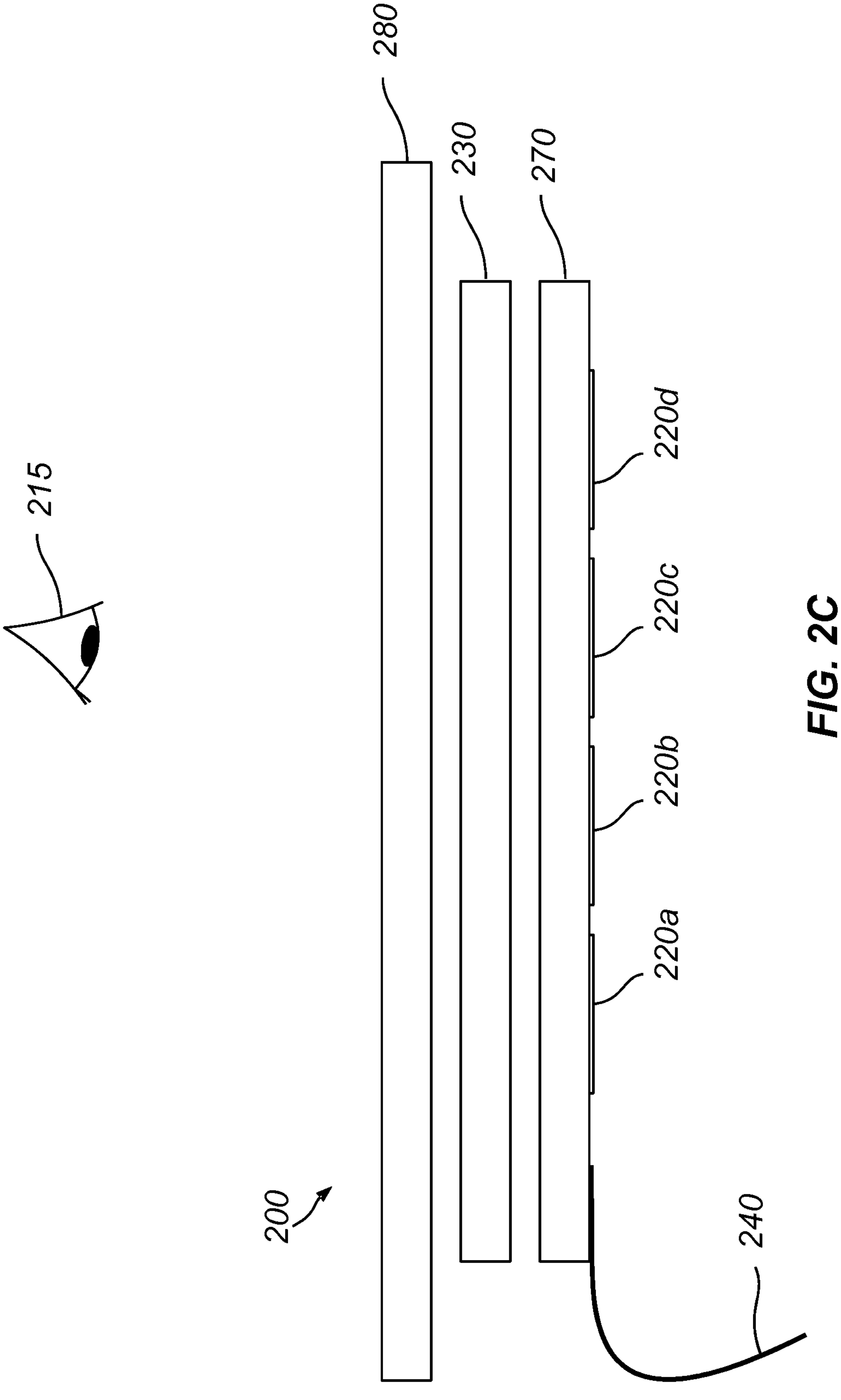


FIG. 2C

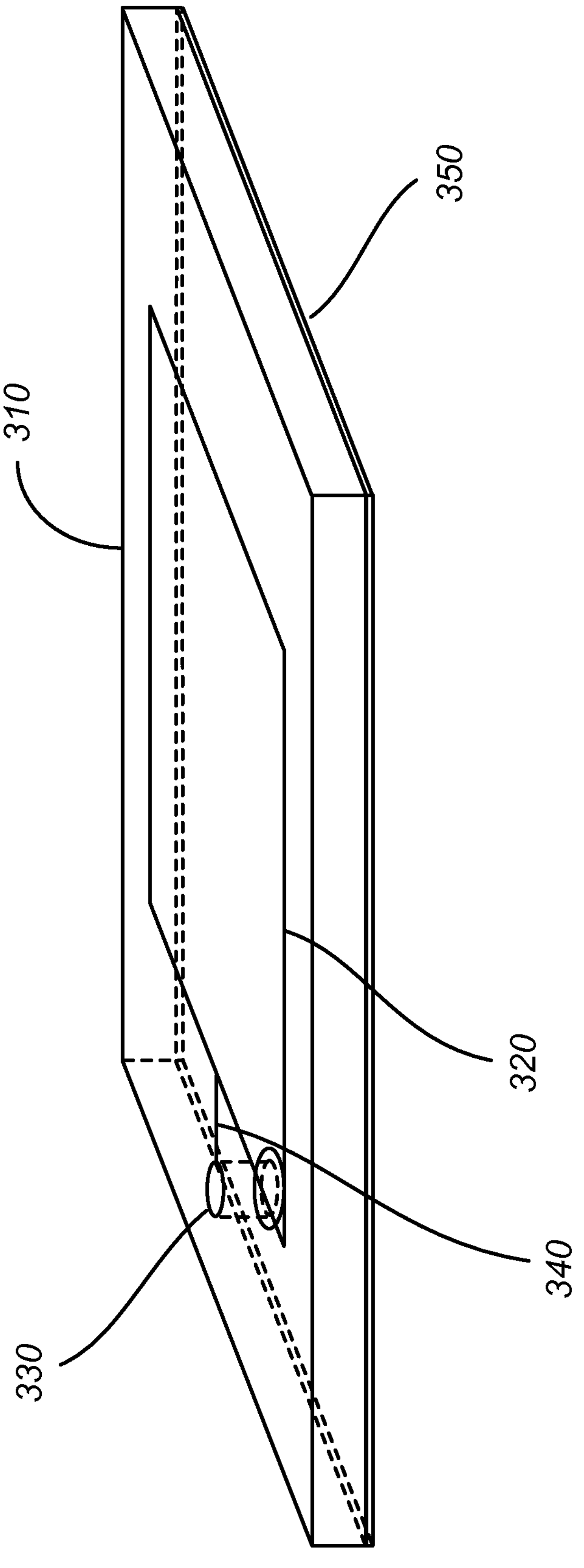


FIG. 3A

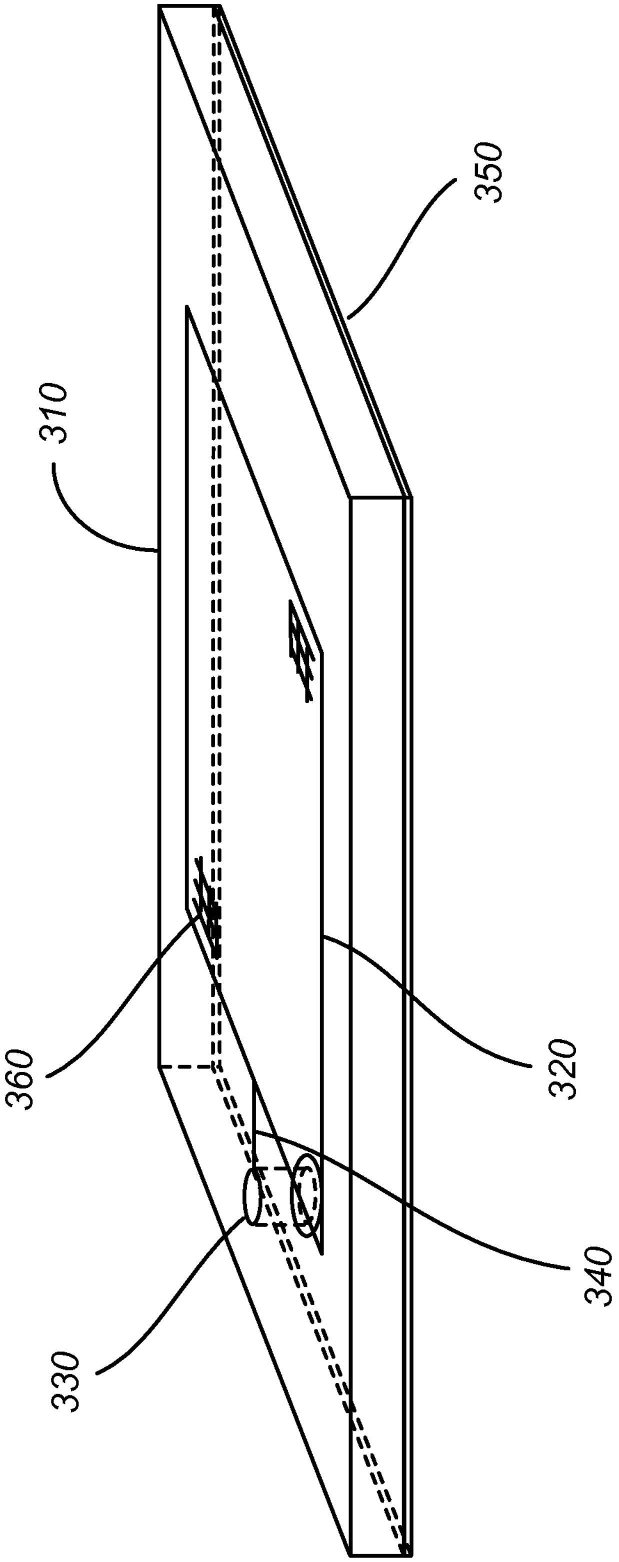


FIG. 3B

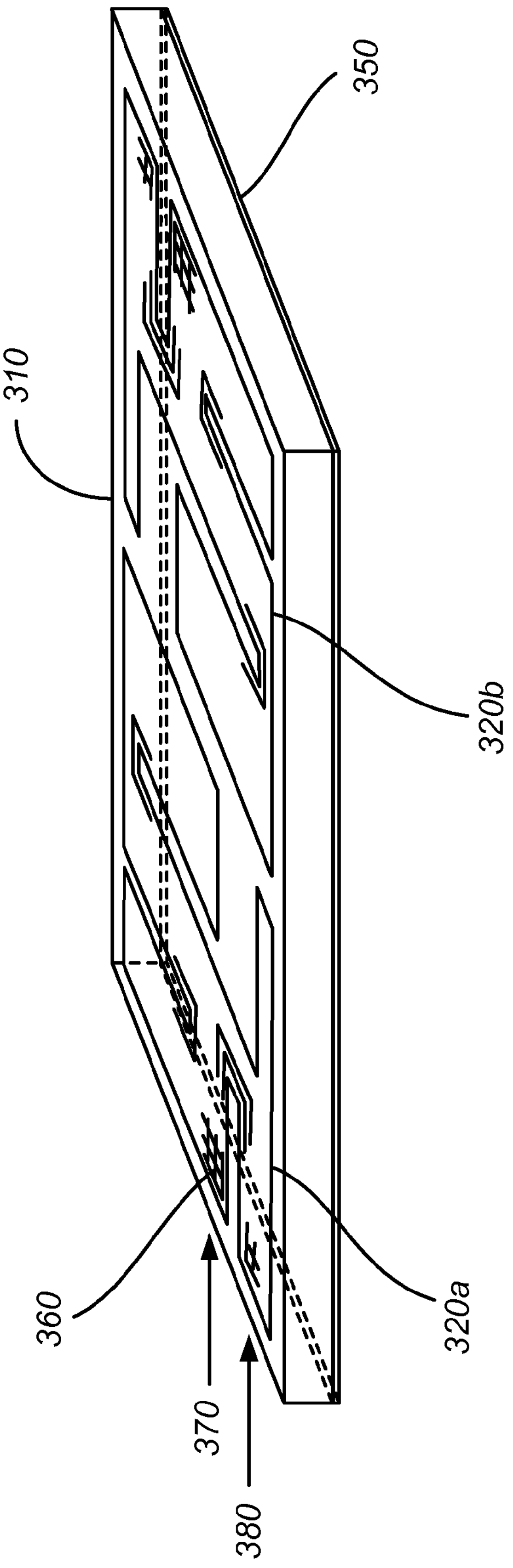


FIG. 3C

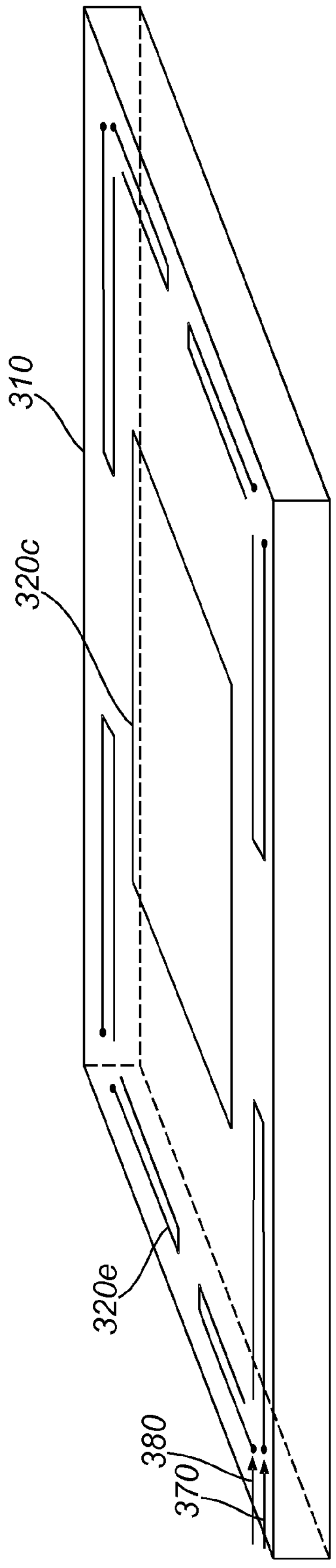


FIG. 3D

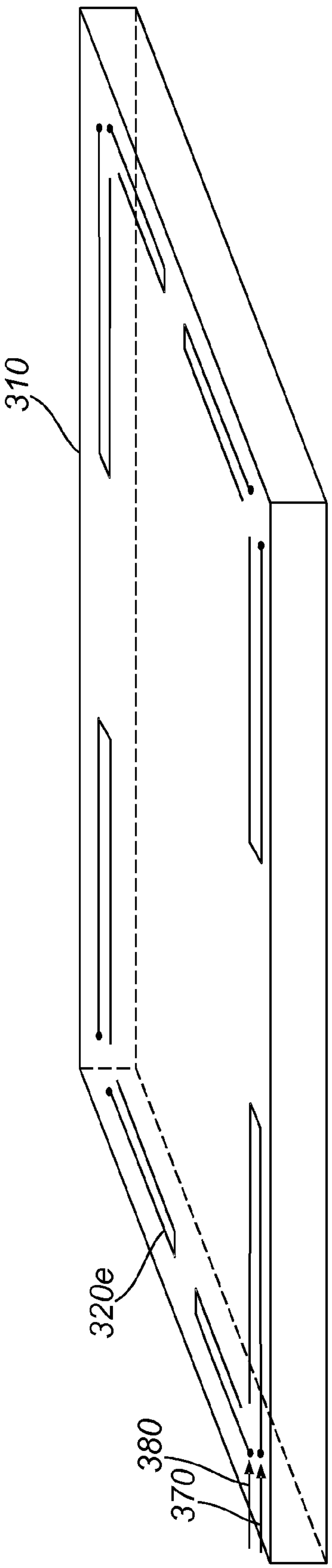


FIG. 3E

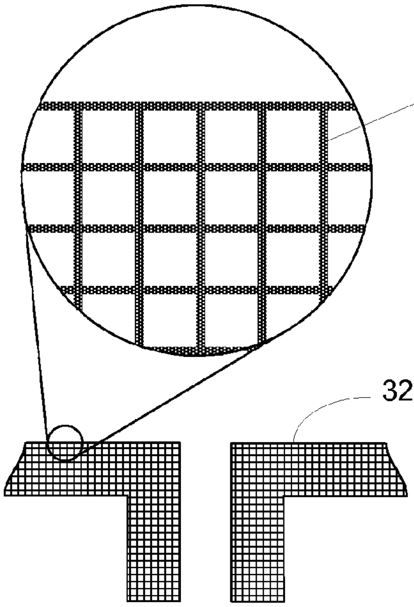


FIG. 3F

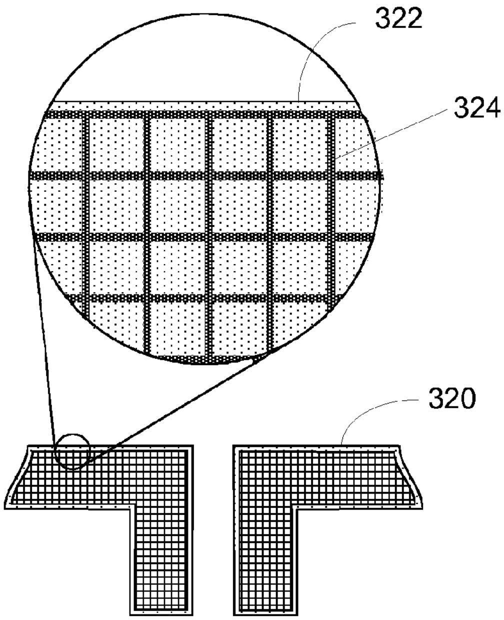


FIG. 3G

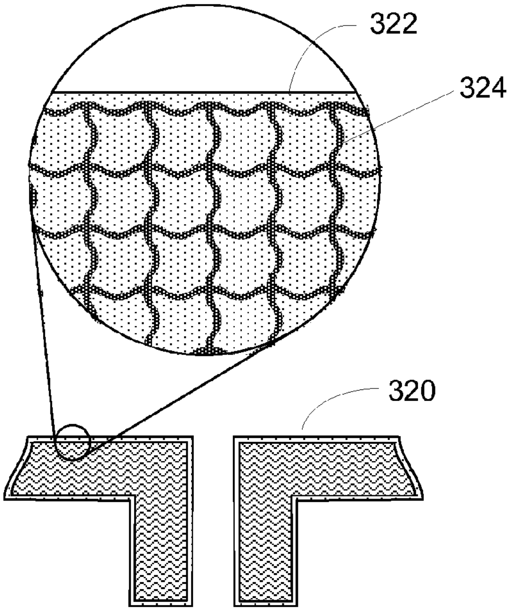


FIG. 3H

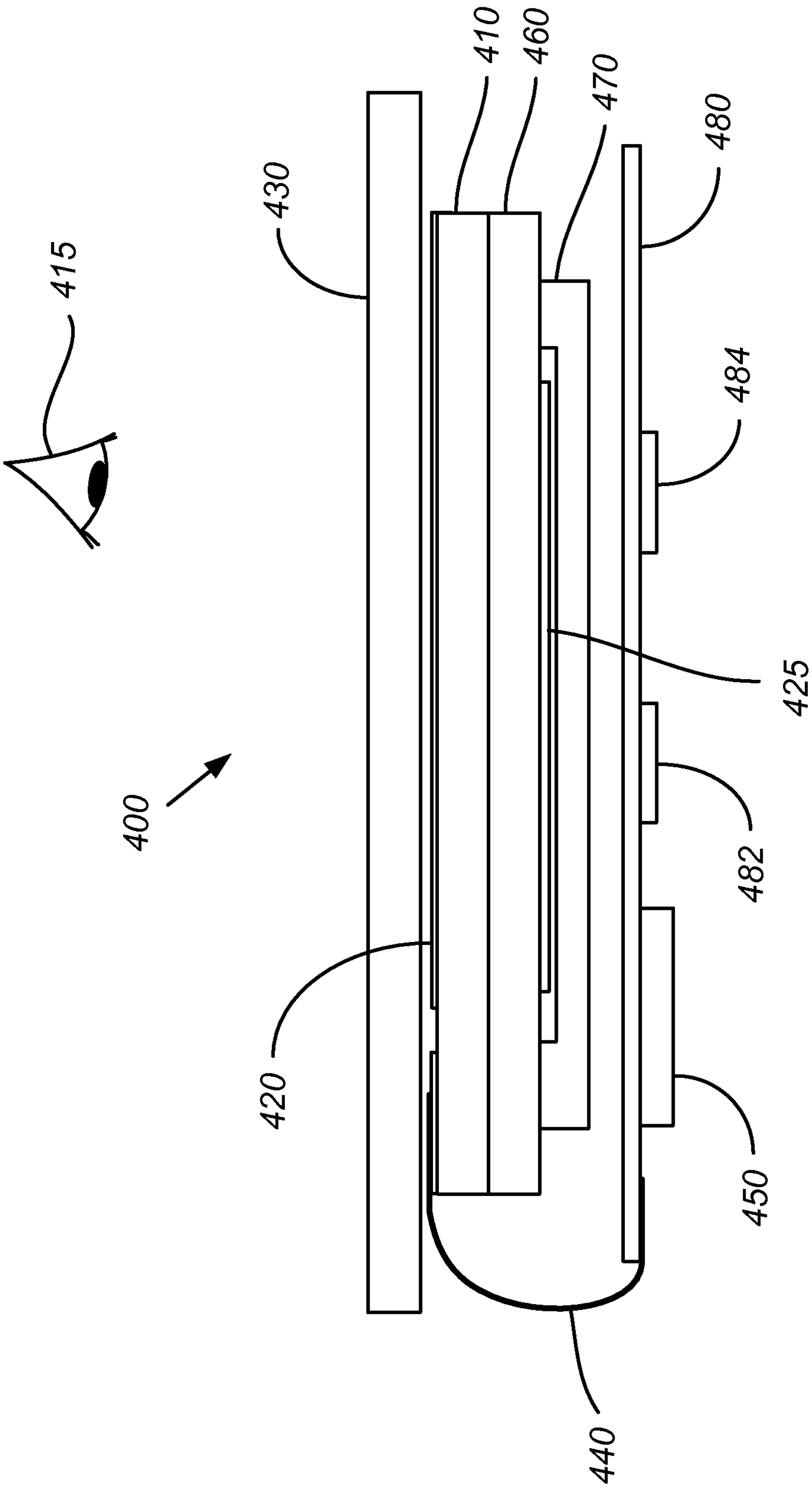


FIG. 4

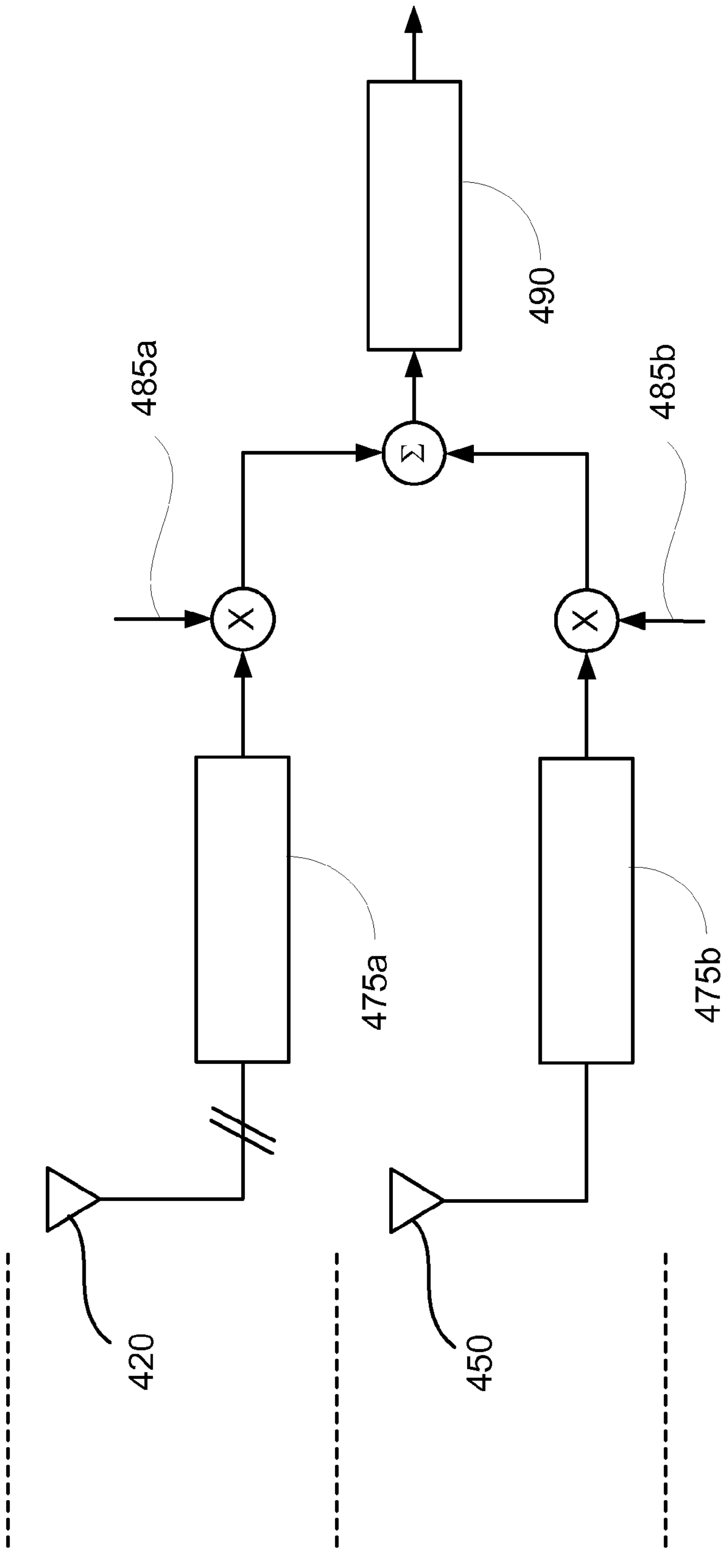
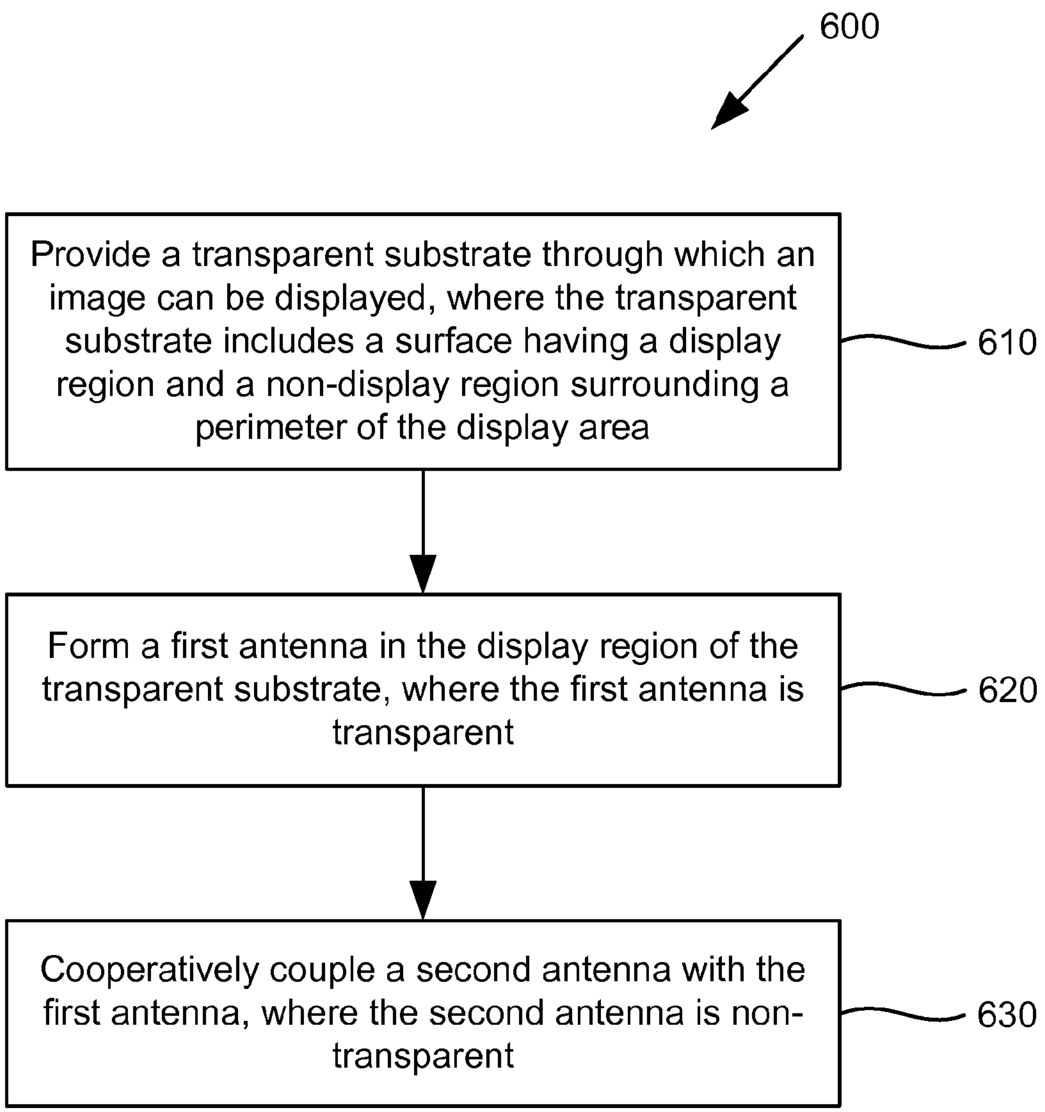


FIG. 5



Provide a transparent substrate through which an image can be displayed, where the transparent substrate includes a surface having a display region and a non-display region surrounding a perimeter of the display area

Form a first antenna in the display region of the transparent substrate, where the first antenna is transparent

Cooperatively couple a second antenna with the first antenna, where the second antenna is non-transparent

FIG. 6

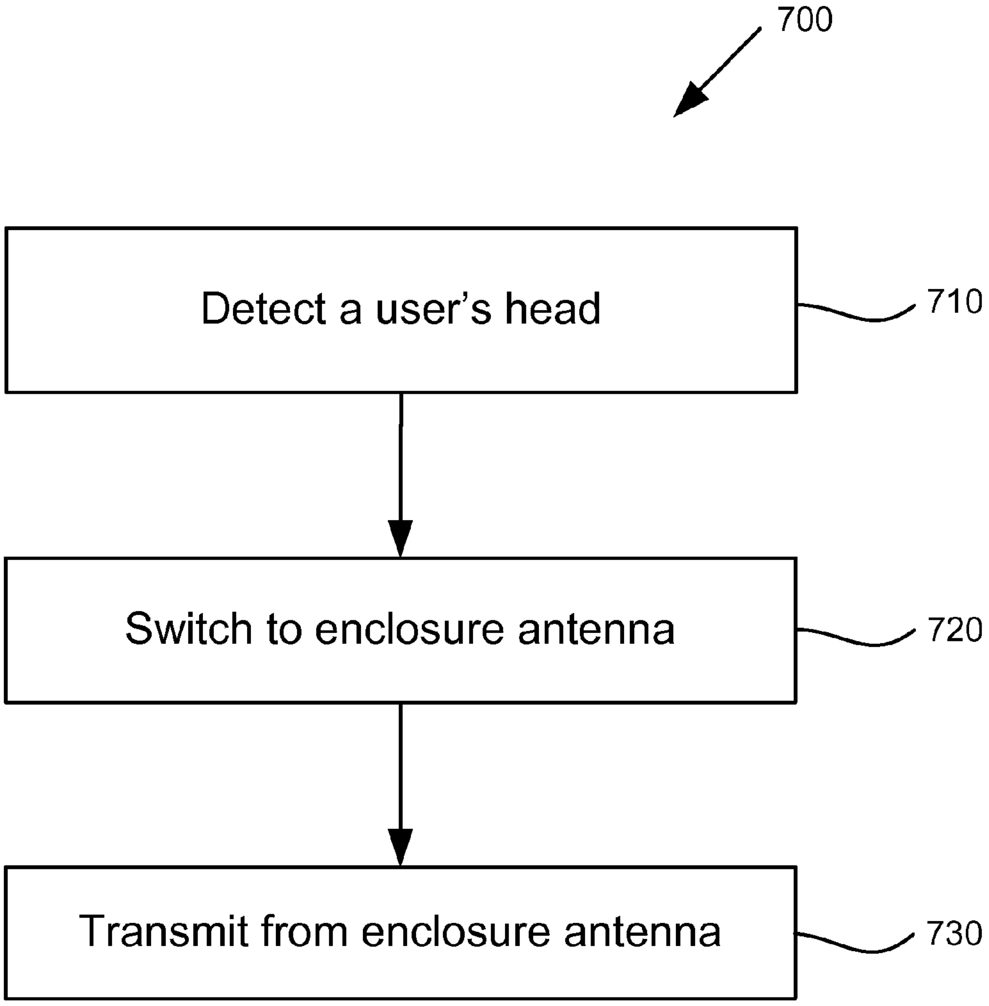

700
Detect a user's head
710
Switch to enclosure antenna
720
Transmit from enclosure antenna
730

FIG. 7

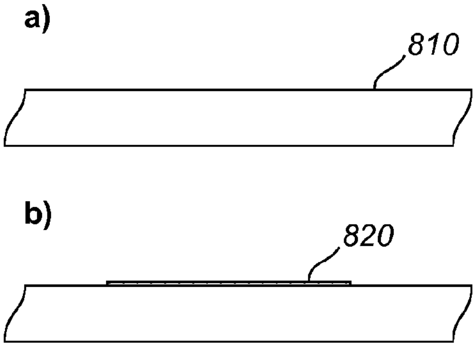


FIG. 8

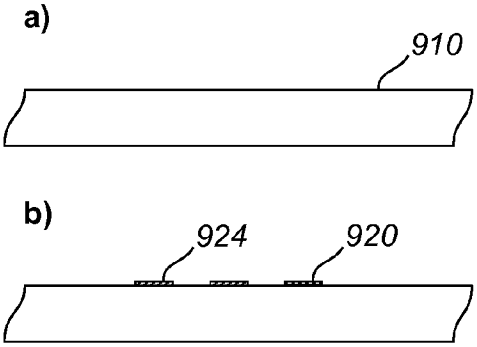


FIG. 9

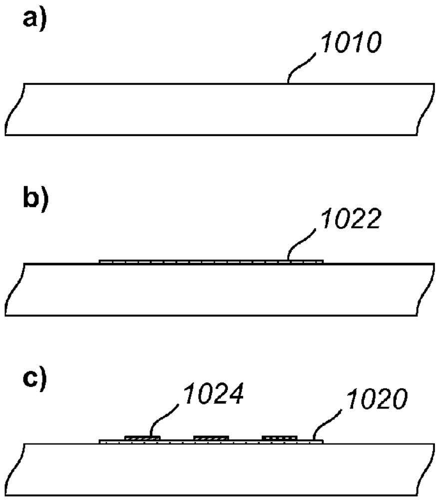


FIG. 10

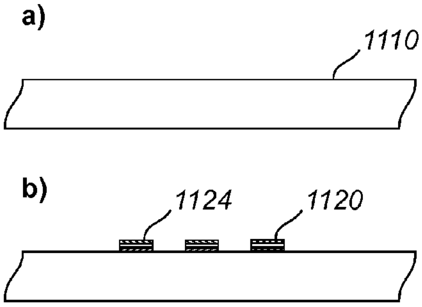


FIG. 11

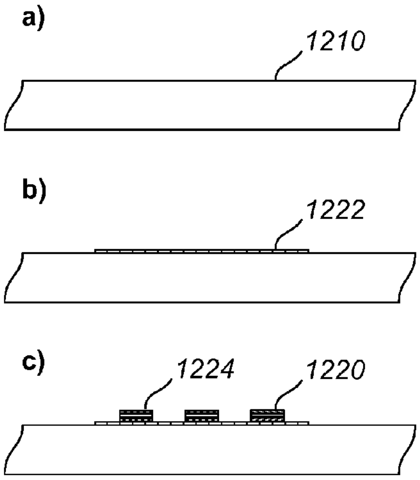


FIG. 12

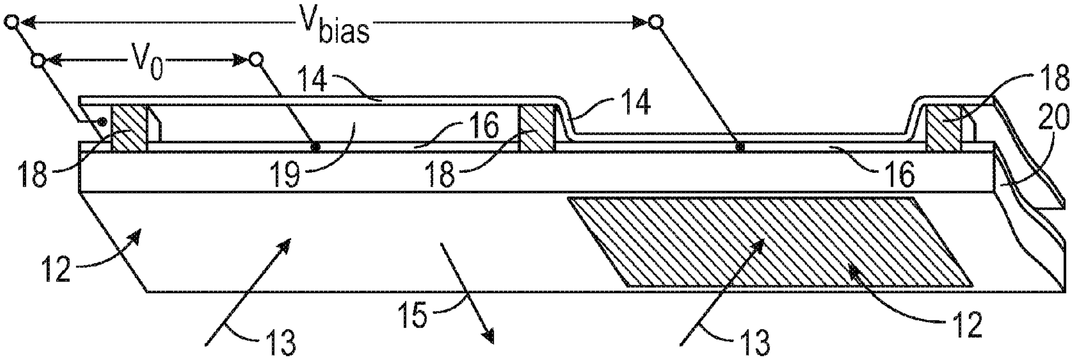

Vbias
V0
14
14
18
16
20
18
19
18
16
12
13
15
13
12

FIG. 13

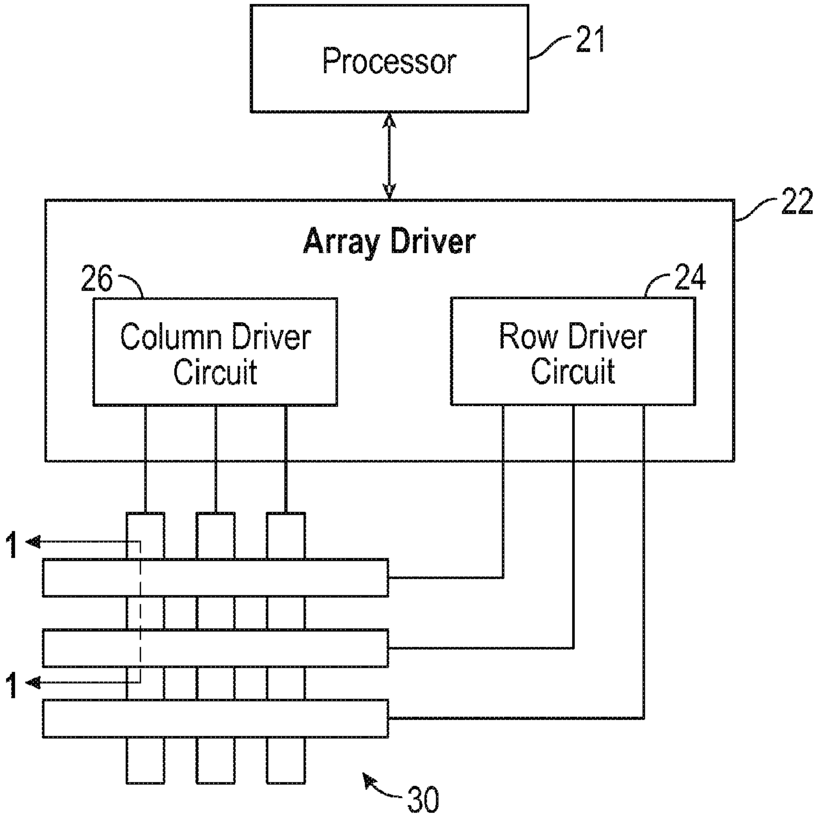

Processor
21
Array Driver
22
26
24
Column Driver Circuit
Row Driver Circuit
1
1
30

FIG. 14

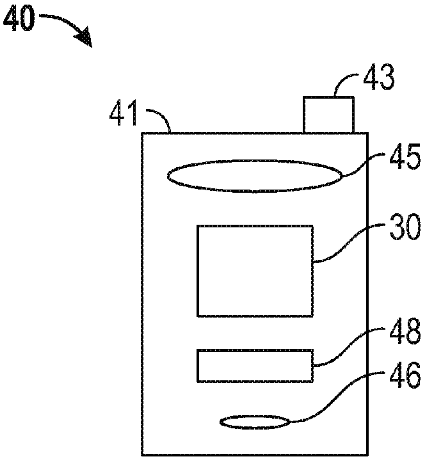


FIG. 15A

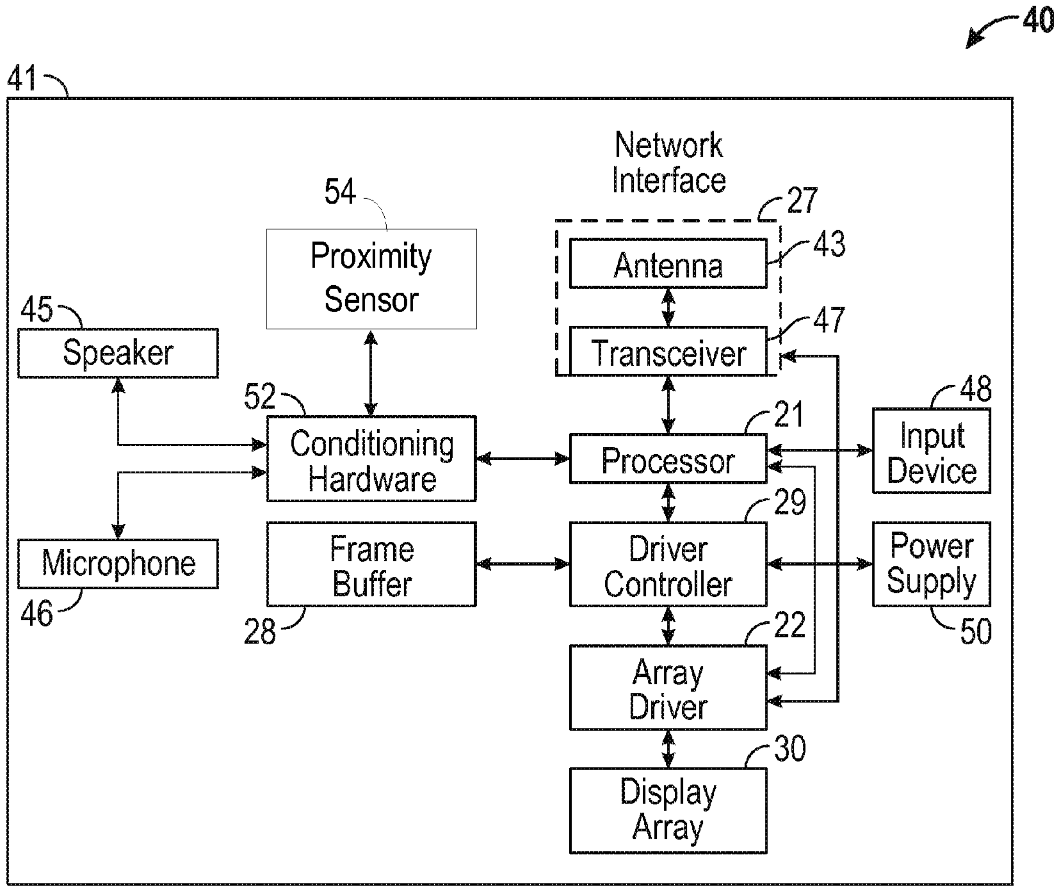


FIG. 15B

TRANSPARENT ANTENNAS ON A DISPLAY DEVICE

TECHNICAL FIELD

[0001] This disclosure relates generally to antennas and more particularly to transparent antennas on a display device, such as an electromechanical systems (EMS) display device.

DESCRIPTION OF THE RELATED TECHNOLOGY

[0002] Electromechanical systems (EMS) include devices having electrical and mechanical elements, actuators, transducers, sensors, optical components such as mirrors and optical films, and electronics. EMS devices or elements can be manufactured at a variety of scales including, but not limited to, microscales and nanoscales. For example, microelectromechanical systems (MEMS) devices can include structures having sizes ranging from about a micron to hundreds of microns or more. Nanoelectromechanical systems (NEMS) devices can include structures having sizes smaller than a micron including, for example, sizes smaller than several hundred nanometers. Electromechanical elements may be created using deposition, etching, lithography, and/or other micromachining processes that etch away parts of substrates and/or deposited material layers, or that add layers to form electrical and electromechanical devices.

[0003] One type of EMS device is called an interferometric modulator (IMOD). The term IMOD or interferometric light modulator refers to a device that selectively absorbs and/or reflects light using the principles of optical interference. In some implementations, an IMOD display element may include a pair of conductive plates, one or both of which may be transparent and/or reflective, wholly or in part, and capable of relative motion upon application of an appropriate electrical signal. For example, one plate may include a stationary layer deposited over, on or supported by a substrate and the other plate may include a reflective membrane separated from the stationary layer by an air gap. The position of one plate in relation to another can change the optical interference of light incident on the IMOD display element. IMOD-based display devices have a wide range of applications, and are anticipated to be used in improving existing products and creating new products, especially those with display capabilities.

[0004] Many mobile display devices such as cellular phones, smart phones, e-readers, and tablet computers have increasingly limited space to place antennas for wireless communications, while demands for higher data rates and operation over multiple bands and protocols have increased. To avoid interfering with images formed on a display device, antennas are conventionally buried inside or attached to a sidewall of an enclosure, or may protrude from a body of the display device. In part because mobile display devices are increasingly required to accommodate features such as GPS, Wi-Fi, and NFC in addition to one or more cellular bands along with higher data transfer rates, alternative antenna configurations and placements are being explored.

SUMMARY

[0005] The systems, methods and devices of this disclosure each have several innovative aspects, no single one of which is solely responsible for the desirable attributes disclosed herein.

[0006] One innovative aspect of the subject matter described in this disclosure can be implemented in a display device. The display device can include a transparent substrate through which an image can be displayed, a first substantially transparent antenna formed on a surface of the transparent substrate, and one or more electrically conductive traces formed on the first substantially transparent antenna and configured to electrically reinforce the transparent antenna.

[0007] In some implementations, the one or more electrically conductive traces include a substantially black interferometric stack structure. In some implementations, the transparent substrate includes a surface having a display region and a non-display region that surrounds at least a portion of a perimeter of the display region, and the one or more electrically conductive traces are in the non-display region of the transparent substrate. In some implementations, the one or more electrically conductive traces have a thickness greater than a thickness of the first substantially transparent antenna. In some implementations, the one or more electrically conductive traces have a resistivity less than a resistivity of the first substantially transparent antenna. In some implementations, the first substantially transparent antenna and the electrically conductive traces are formed of different materials. In some implementations, the display device further includes a second antenna formed on the same surface of the transparent substrate as the first substantially transparent antenna, where the second antenna is spatially diverse from the first substantially transparent antenna. In some implementations, each of the one or more electrically conductive traces has a width between about 10 nm and about 10 μm. In some implementations, the first substantially transparent antenna includes a plurality of slots, where the one or more electrically conductive traces are proximate to at least one of the slots.

[0008] Another innovative aspect of the subject matter described in this disclosure can be implemented in a method of manufacturing an antenna panel. The method can include providing a transparent substrate, where the transparent substrate includes a surface having a display region and a non-display region that surrounds at least a portion of a perimeter of the display region, depositing a layer of substantially transparent electrically conductive material on the transparent substrate, and patterning the layer to form a substantially transparent antenna in the display region of the transparent substrate.

[0009] In some implementations, the method further includes forming a second antenna in the non-display region of the transparent substrate. In some implementations, the method further includes depositing a film of electrically conductive material on the substantially transparent antenna, and patterning the film to form electrically conductive traces on the substantially transparent antenna. In some implementations, the method further includes depositing a substantially black interferometric stack structure on the substantially transparent antenna, and patterning the substantially black interferometric stack structure to form electrically conductive traces on the substantially transparent antenna.

[0010] Details of one or more implementations of the subject matter described in this disclosure are set forth in the accompanying drawings and the description below. Although the examples provided in this disclosure are primarily described in terms of EMS and MEMS-based displays, the concepts provided herein may apply to other types of displays such as liquid crystal displays, organic light-emitting diode

("OLED") displays, and field emission displays. Other features, aspects, and advantages will become apparent from the description, the drawings and the claims. Note that the relative dimensions of the following figures may not be drawn to scale.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1** is an example of a graph illustrating channel capacity as a function of the number of antennas.

[0012] FIG. **2**A is an example of a cross-sectional side view schematic illustration of an antenna in front of a display of a display device.

[0013] FIG. **2**B is an example of a topside view of a transparent substrate having a display region and a non-display region.

[0014] FIG. **2**C is an example of a cross-sectional side view schematic illustration of an antenna panel behind a display of a display device.

[0015] FIG. **3**A is an example of a perspective view of a transparent antenna on a transparent substrate.

[0016] FIG. **3**B is an example of a perspective view of a transparent antenna with electrically conductive traces on a transparent substrate.

[0017] FIG. **3**C is an example of a perspective view of multiple antennas on a transparent substrate.

[0018] FIG. **3**D is an example of a perspective view of a transparent antenna in a display region of a transparent substrate and one or more antennas in a non-display region of the transparent substrate.

[0019] FIG. **3**E is an example of a perspective view of multiple antennas in a non-display region of a transparent substrate.

[0020] FIG. **3**F is an example of a detailed view of a grid that forms a portion of a substantially transparent antenna.

[0021] FIG. **3**G is an example of a detailed view of an electrically reinforcing grid on a substantially transparent antenna.

[0022] FIG. **3**H is an example of a detailed view of a curvilinear reinforcing grid on a substantially transparent antenna.

[0023] FIG. **4** is an example of a cross-sectional side view schematic illustration of a first antenna on a transparent substrate and a second antenna on a printed circuit board.

[0024] FIG. **5** is an example of a diagram illustrating an operating mode of a multi-antenna system.

[0025] FIG. **6** is an example of a flow diagram illustrating a method of manufacturing a display device.

[0026] FIG. **7** is an example of a flow diagram illustrating a method of operating a mobile display device.

[0027] FIG. **8** is an example of a cross-sectional side view illustrating a process sequence for fabricating a transparent antenna.

[0028] FIG. **9** is an example of a cross-sectional side view illustrating a process sequence for fabricating a transparent antenna with a substantially transparent grid.

[0029] FIG. **10** is an example of a cross-sectional side view illustrating a process sequence for fabricating a transparent antenna with electrically reinforcing traces on a substantially transparent antenna.

[0030] FIG. **11** is an example of a cross-sectional side view illustrating a process sequence for fabricating a transparent antenna with a substantially transparent grid of a black interferometric stack structure.

[0031] FIG. **12** is an example of a cross-sectional side view illustrating a process sequence for fabricating a transparent antenna with electrically reinforcing traces of a black interferometric stack structure on a substantially transparent antenna.

[0032] FIG. **13** is an isometric view illustration depicting two adjacent interferometric modulator (IMOD) display elements in a series or array of display elements of an IMOD display device.

[0033] FIG. **14** is a system block diagram illustrating an electronic device incorporating an IMOD-based display including a three-element by three-element array of IMOD display elements.

[0034] FIGS. **15**A and **15**B are system block diagrams illustrating a display device that includes a plurality of IMOD display elements.

[0035] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0036] The following description is directed to certain implementations for the purposes of describing the innovative aspects of this disclosure. However, a person having ordinary skill in the art will readily recognize that the teachings herein can be applied in a multitude of different ways. The described implementations may be implemented in any device, apparatus, or system that can be configured to display an image, whether in motion (such as video) or stationary (such as still images), and whether textual, graphical or pictorial. More particularly, it is contemplated that the described implementations may be included in or associated with a variety of electronic devices such as, but not limited to: mobile telephones, multimedia Internet enabled cellular telephones, mobile television receivers, wireless devices, smartphones, Bluetooth® devices, personal data assistants (PDAs), wireless electronic mail receivers, hand-held or portable computers, netbooks, notebooks, smartbooks, tablets, printers, copiers, scanners, facsimile devices, global positioning system (GPS) receivers/navigators, cameras, digital media players (such as MP3 players), camcorders, game consoles, wrist watches, clocks, calculators, television monitors, flat panel displays, electronic reading devices (e.g., e-readers), computer monitors, auto displays (including odometer and speedometer displays, etc.), cockpit controls and/or displays, camera view displays (such as the display of a rear view camera in a vehicle), electronic photographs, electronic billboards or signs, projectors, architectural structures, microwaves, refrigerators, stereo systems, cassette recorders or players, DVD players, CD players, VCRs, radios, portable memory chips, washers, dryers, washer/dryers, parking meters, packaging (such as in electromechanical systems (EMS) applications including microelectromechanical systems (MEMS) applications, as well as non-EMS applications), aesthetic structures (such as display of images on a piece of jewelry or clothing) and a variety of EMS devices. The teachings herein also can be used in non-display applications such as, but not limited to, electronic switching devices, radio frequency filters, sensors, accelerometers, gyroscopes, motion-sensing devices, magnetometers, inertial components for consumer electronics, parts of consumer electronics products, varactors, liquid crystal devices, electrophoretic devices, drive schemes, manufacturing processes and electronic test equipment. Thus, the teachings are not intended to be limited to the implementations depicted solely in the Figures, but instead have wide applicability as will be readily apparent to one having ordinary skill in the art.

[0037] Some implementations described herein relate to display devices with one or more antennas on a transparent substrate through which a display may be viewed. The one or more antennas on the transparent substrate may be substantially transparent to allow suitable viewing of an underlying display. In some implementations, narrow electrically conductive traces may serve as the antenna or the electrically conductive traces may augment the performance of an antenna formed from a transparent conductive film. The electrically conductive traces may augment the performance of the antenna by electrically reinforcing it. In some implementations, the antenna may be transparent and cooperatively coupled with a second antenna that may or may not be transparent. The antenna may cooperatively couple with the second antenna by having both antennas used together in a single system, under control of a single system, used interchangeably, or used independently or together within a single system. In some implementations, the second antenna may lie in a non-display region of the transparent substrate. In some implementations, the second antenna may be positioned within an enclosure of the display device, such as on a printed circuit board or on a sidewall or interior surface of the enclosure. In some implementations, multiple antennas on the transparent substrate may provide access to one or more cellular or non-cellular wireless bands. In some implementations, multiple antennas may be configured in front of or behind the display to provide enhanced data transfer rates through adaptive antenna arrays, beam forming, or multiple-input multiple-output based (MIMO-based) wireless communications.

[0038] Particular implementations of the subject matter described in this disclosure may be implemented to realize one or more of the following potential advantages. The use of a transparent antenna increases the regions for suitable placement of an antenna in a display device, by allowing placement in regions where an image may be displayed. Multiple antennas may be formed on a display device or positioned in an enclosure of the display device so that the wireless communication system may benefit from antenna diversity, such as, for example, spatial, frequency, temporal, or polarization diversity, etc. Antenna diversity is the use of two or more antennas to improve the quality and reliability of a wireless signal. While a transparent antenna alone may have less than desirable antenna gain resulting from the relatively low electrical conductivity of most transparent conductive materials, in some implementations a transparent antenna augmented or electrically reinforced with narrow, electrically conductive traces may improve the overall antenna efficiency. A transparent antenna cooperatively coupled with one or more antennas on the display or within the enclosure of the display device may provide increased channel capacity for higher data rates and/or improved system performance with increased spatial, frequency, temporal, or polarization diversity. For example, a transparent antenna cooperatively coupled with a second antenna may increase the frequency bands over which the display device operates.

[0039] A transparent antenna cooperatively coupled with a second antenna may provide multiple operating modes by allowing the selective switching between antennas. In some implementations, a display-side antenna and an enclosure antenna may be selectively switched to receive the signal with the highest signal level. In some implementations, a display-side antenna may be used to receive low-level signals and an enclosure antenna may be used to transmit high-level signals. In some implementations, an enclosure antenna may be used for transmission when a user's face or head is detected near a display-side antenna. In some implementations, two, three, four or more antennas may be positioned on the display side of the display device, optionally cooperatively coupled with one or more antennas within the enclosure of the display device and switched accordingly to achieve increased uplink and downlink data rates using MIMO (multiple-input, multiple-out) configurations, beam-forming, or adaptive antenna arrays.

[0040] In some implementations, a transparent antenna electrically reinforced with electrically conductive traces or cooperatively coupled with a transparent or non-transparent antenna may be formed on or over a display device, such as, for example, an EMS or MEMS display device, or other type of display device such as an LCD, OLED, or electrophoretic display. An example of a suitable EMS or MEMS device or apparatus, to which the described implementations may apply, is a reflective display device. Reflective display devices can incorporate interferometric modulator (IMOD) display elements that can be implemented to selectively absorb and/or reflect light incident thereon using principles of optical interference. IMOD display elements can include a partial optical absorber, a reflector that is movable with respect to the absorber, and an optical resonant cavity defined between the absorber and the reflector. In some implementations, the reflector can be moved to two or more different positions, which can change the size of the optical resonant cavity and thereby affect the reflectance of the IMOD. The reflectance spectra of IMOD display elements can create fairly broad spectral bands that can be shifted across the visible wavelengths to generate different colors. The position of the spectral band can be adjusted by changing the thickness of the optical resonant cavity. One way of changing the optical resonant cavity is by changing the position of the reflector with respect to the absorber.

[0041] In recent years, wireless communications have become more widespread in display devices, including EMS and MEMS display devices. Specialized antennas are incorporated in mobile display devices to respond to increasing demands in wireless communications. However, with the performance of display devices becoming higher and the size of some display devices becoming smaller, the space for allocating antennas is becoming increasingly limited.

[0042] Furthermore, an increasingly larger group of communication frequencies has proliferated, including non-cellular wireless standards such as global positioning systems (GPS), Bluetooth protocols, wireless local area networks (WLAN), Wi-Fi networks, worldwide interoperability for microwave access (WiMax) networks, radio frequency identification (RFID), near field communications (NFC), high-definition television (HDTV), frequency modulation (FM) broadcast radio, multiple-input multiple-output (MIMO) systems, and ultra-wide band (UWB) protocols. Some of the frequency bands related to these standards and others are going to higher frequencies, such as 2-5 GHz, 5-10 GHz and higher, such as in the 60 GHz range.

[0043] In addition, demand for higher data rates has grown. With larger amounts of data being transmitted wirelessly, display devices are being adapted for increased channel capacity for reliably transmitting data over one or more communication channels. However, the channel capacity of a display device may be limited by the type, quality, size, placement, and quantity of the associated antennas.

[0044] Transparent antennas positioned on or over a display may provide greater amounts of space to allocate one or more antennas. However, many transparent antennas, such as those made of indium-tin-oxide (ITO), have relatively low electrical conductivity that can result in low antenna efficiency. While transparent antennas based on an electrically conductive oxide alone may not be able to meet the increasing demands for more frequency bands and higher data rates, the transparent antennas may be cooperatively coupled with another transparent or non-transparent antenna or otherwise augmented to improve antenna and overall system performance. Cooperatively coupling an antenna with another antenna as used herein may define using the antennas together in a single system or as part of a single device, using the antennas under the control of a single system, using the antennas interchangeably under a single system, or operating the antennas independently or together in a single system. Augmenting an antenna as used herein may define electrically reinforcing the antenna to improve antenna performance.

[0045] In some implementations, the performance and capability of a mobile display device may be improved by increasing the channel capacity for transferring data wirelessly. Methods to increase the channel capacity include increasing the bandwidth of the communication link, improving the signal-to-noise (S/N) ratio for the system, or adding antennas with adequate diversity to either or both sides of the link (upstream and downstream). FIG. **1** is an example of a graph illustrating channel capacity as a function of the number of antennas, assuming independent and identically distributed sources of noise. The Shannon-Hartley capacity theorem relates channel capacity C as a function of bandwidth B and logarithmically with the signal-to-noise ratio S/N. This may be expressed as

$$C=B*\log_2(1+S/N)$$

with the bandwidth B in Hertz and the channel capacity C in bits per second. Hence, achieving higher data rates may involve increasing the signal bandwidth or increasing the S/N ratio. The use of MIMO systems with multiple antennas may further increase the channel capacity. MIMO antenna systems may use multiple antennas at the transmitter and the receiver end. Multiple independent data streams may be transmitted and received by the antennas at each end of the link. Note that the number of streams may be less than or equal to the lower of the number of antennas at either end. The Shannon-Hartley capacity theorem may be modified in MIMO antenna systems to include the number of streams M.

$$C=M*B*\log_2(1+S/N)$$

In FIG. **1**, the normalized channel capacity (C/B) linearly increases with the number of antennas. The potential number of streams is largely correlated with the number of antennas. In this case, the signal-to-noise ratio is set to 16 dB. Thus, multiple antennas in a display device may increase data rates two-fold, four-fold, ten-fold or more. Note that if the streams are not independent or have correlated noise sources, the channel capacity C may be appreciably less than that shown.

[0046] Multiple antenna schemes are not limited to MIMO antenna configurations. Multiple antenna schemes may also take advantage of antenna diversity to improve overall device performance. The basic concept of antenna diversity is to transmit a signal via several independent paths to get independent signal copies at the receiver via spatial diversity, frequency diversity, temporal diversity, polarization diversity, and/or other diversity types. This may mitigate the undesirable effects of fading and other types of attenuation loss, and allow the receiver to select the signal with the highest signal quality. Signal quality can be evaluated based on various quantities and/or parameters, including, but not limited to, signal-to-noise ratio, signal strength, bit error rate, data transmission rate, and fading condition.

[0047] Spatial diversity may employ multiple antennas that are physically separated from one another, which may be on the order of about one to five wavelengths or more apart. Spatial diversity may improve the robustness of the signal by providing multiple copies of the same signal propagating in space. This may reduce the probability that different signal paths between the transmitter and the receiver undergo the same amount of fading, for example. Spatial diversity may be achieved using multiple transmitter antennas and/or multiple receiving antennas. Spatial diversity may also be a part of a MIMO antenna system.

[0048] To benefit from frequency diversity, signals may be transmitted over multiple channels having different carrier frequencies, or the signal may be spread over a wide spectrum that may have portions affected by frequency-dependent fading or attenuation. Antenna configurations and systems that transmit the signal over different frequencies may reduce the effects of frequency-dependent fading or attenuation, for example.

[0049] Temporal or time diversity involves transmitting the same parts of a signal at different instances in time. Temporal diversity may be used to reduce the effects of error bursts due to time-varying channel conditions, which may be caused by fading in combination with a moving receiver, transmitter, or obstacle, or by intermittent electromagnetic interference or co-channel interference.

[0050] Polarization diversity takes multiple versions of the signal and transmits them with different polarizations. In some implementations, the antennas may be linearly polarized (e.g., horizontal/vertical) or circularly polarized (left-hand or right-hand), although other polarizations (e.g., elliptical) are possible. Pairs of antennas may be configured to have orthogonal polarizations that may result in increased signal strength from one or the other. By pairing complementary polarizations, an antenna array may be further immunized from polarization mismatches and signal fading.

[0051] Many display devices, including cellular phones, smart phones, e-readers, and tablet computers, have limited space to position antennas for wireless communications. Antennas may be limited to incorporation in or on the device enclosure, which generally limit antenna gain, efficiency, and directionality. These limitations on antenna configurations may further restrict opportunities to take advantage of antenna diversity and spatial multiplexing, as discussed earlier herein, as well as opportunities for beam steering and adaptive antenna arrays.

[0052] In some implementations, antennas may be placed on or in front of a display of a display device. FIG. **2**A is an example of a cross-sectional side view schematic illustration of an antenna in front of a display of a display device. The display device **200** may include a transparent substrate **210** over a display **230**. In some implementations, the transparent substrate **210** may be made of glass, plastic, or other substantially transparent material. The transparent substrate **210** may be, for example, an antenna panel, a cover plate, a cover glass, a touch panel, a front light, or a display glass. In some implementations, the antenna(s) may be on a backplane or back plate of the display device, or configured behind or under the display such as on or part of a backlight (not shown). The display **230** may include any suitable display type, such as a transmissive display, a reflective display, or a self-emitting display. For example, the display **230** may include an IMOD display, a liquid crystal display (LCD), an OLED display, a micro-shutter based display, or other type of display.

[0053] As illustrated in the example in FIG. **2**A, an antenna **220** may be formed on a transparent substrate **210**. Some examples of such a transparent substrate **210** have been provided above. An image (not shown) may be formed on the display **230**. In some implementations, the transparent substrate **210** with the antenna **220** may be positioned on a display side of the display device **200** to allow a viewer **215** to see images produced by the display **230** while avoiding substantial interference with the produced images. Positioning the antenna **220** on the display side may provide more direct pathways for incident and transmitted radio-frequency signals than an antenna enclosed inside the display device. Forming an antenna **220** on the transparent substrate **210** or otherwise configuring the antenna on the display side of the display device **200** may provide additional space to allocate antennas on or within the display device **200**. With more space, multiple antennas including antenna **220** may open opportunities in the display device **200** for multiple frequency bands, antenna diversity, and spatial multiplexing, along with beam steering and adaptive antenna arrays. Beam steering can increase the effective RF signal strength by directing RF energy selectively towards a receiving antenna, allowing higher signal-to-noise ratios and/or a reduction in transmitting power. Adaptive antenna arrays allow one or more antennas in an array to selectively transmit and receive signals with increased directionality.

[0054] In some implementations, the antenna **220** may be transparent or substantially transparent. A transparent antenna may include an antenna made of a transparent conductive material, such as a transparent conductive oxide. For example, a transparent conductive oxide may include ITO. In some implementations, a transparent antenna may include an antenna made of very narrow electrically conductive traces, such as a mesh structure of electrically conductive material, irrespective of whether the electrically conductive material is transparent itself. In some implementations, the transparent antenna may include an antenna formed from a transparent conductive material that is augmented or electrically reinforced with narrow traces of conductive material (which may be non-transparent). Transparency as used herein is defined as transmittance of visible light of about 70% or more, such as about 80% or more or about 90% or more. An empirical definition of transparency for the transparent antenna is the fraction of light transmitted through the transparent antenna at which a displayed image may still be effectively viewed by a viewer. With highly emitting OLED displays or with high-intensity backlights for LCD displays, the transparency of the antenna panel may be below about 70% and still be considered transparent or substantially transparent.

[0055] The display device **200** may further include one or more antenna feed lines **240** connected to the antenna **220**. The antenna feed lines **240** allow electrical connections between a radio transmitter or receiver and the antenna **220**. The antenna feed lines **240** may provide radio frequency (RF) current or voltage from the transmitter to the antenna **220**, or transfer RF current or voltage from the antenna **220** to the receiver. In some implementations, the antenna feed lines **240** may include but are not limited to a coaxial cable, a twin-lead cable, a twisted pair, a wire, a cable, a flex tape, a transmission line, an impedance-matched flex tape, a coplanar waveguide, or a through-substrate via. The antenna feed lines **240** may be attached to the transparent substrate **210** with solder, anisotropic conductive film (ACF), a clamp, a socket, or other suitable technique.

[0056] FIG. **2**B is an example of a topside view of a transparent substrate having a display region and a non-display region. The transparent substrate **210** has a display region **250** through which an image may be displayed and viewed, and a non-display region **260** that surrounds at least a portion of a perimeter **255** of the display region **250**. Non-display region **260** may correspond, for example, with regions on an underlying display (not shown) where traces and other connecting features for the display are located. One or more antennas (not shown) may be formed in either the display region **250** or the non-display region **260** or both.

[0057] FIG. **2**C is an example of a cross-sectional side view schematic illustration of an antenna panel behind a display of a display device. The antenna panel **270**, which may be transparent or non-transparent, includes one or more transparent or non-transparent antennas **220***a-d* that may be formed on a transparent or non-transparent substrate. In some implementations, the antenna panel **270** may be attached to or formed as part of a backlight or a back plate of the display **230**, and positioned in an enclosure (not shown) of a mobile display device **200**. An optional cover glass **280** may be positioned in front of the display **230**. The cover glass **280** may also include one or more transparent antennas (not shown).

[0058] FIG. **3**A is an example of a perspective view of a transparent antenna on a transparent substrate. A transparent antenna **320** may be formed on a surface of a transparent substrate **310**. As illustrated in the example of FIG. **3**A, the transparent antenna **320** may be a patch antenna. The transparent antenna **320** may be substantially planar with the transparent substrate **310** and may have any suitable size or shape. For example, the transparent antenna **320** may be square, round, or rectangular in shape. In some implementations, the transparent antenna **320** may cover a substantial portion of a surface of the transparent substrate **310**. Because of the relatively large area that the transparent antenna **320** may encompass on the transparent substrate **310**, larger and more efficient antennas **320** may be formed. In some implementations, the transparent antenna **320** may be one-half or a full wavelength long. In some implementations, the transparent antenna **320** may be formed from a substantially transparent conductive thin film deposited or otherwise attached to the transparent substrate **310**. The thickness of the transparent substrate may be between about 10 μm and about 700 μm. The conductive thin film may have a thickness between about 10 nm and about 10 μm. In some implementations, the transparent antenna **320** may be formed from a gridwork of relatively narrow electrically conductive traces, which may have a thickness between about 10 nm and about 10 um or more. The width of the electrically conductive traces may be between about 1 μm and about 10 μm to limit the potential occlusion of a displayed image. In some implementations, the width of the conductive traces may be between about 3 μm and about 5 μm. In some implementations, the transparent antenna **320** may be formed from a substantially transparent conductive thin film such as ITO that is electrically reinforced locally with narrow traces of a non-transparent electrically conductive metal or a substantially black interferometric stack structure. In some implementations, the substantially black interferometric stack structure may be formed from a multi-layer composite of materials including an absorber, a dielectric, and a reflector, with the dielectric serving as an optical cavity between the absorber and the reflector. The material stack is sometimes referred to as a black matrix, a black mask, or a black stack. To a viewer, this combination may appear dark or substantially black. Dark features may aid in retaining the contrast of an underlying display.

[0059] The transparent antenna **320** may be electrically coupled to a ground plane **350**. In the example illustrated in FIG. **3**A, the ground plane **350** may be formed on a surface of the transparent substrate **310** opposite the transparent antenna **320**. For a patch antenna as illustrated in FIG. **3**A, the transparent antenna **320** is on a different plane than the ground plane **350**. However, the ground plane **350** may be formed on other parts of the transparent substrate **310**, or positioned external yet proximal to the transparent substrate **310**. In some implementations, the ground plane **350** may be transparent or substantially transparent. For example, the ground plane **350** may be made of ITO or other transparent conductive material, a mesh or grid of narrow traces of metal or a black stack, or a composite of transparent conductive material augmented with narrow traces of metal or a black stack.

[0060] A through-substrate via (TSV) **330** or through-glass via (TGV) may extend between two sides of the transparent substrate **310** to provide backside electrical interconnection to the transparent antenna **320** as shown in FIG. **3**A. The TSV **330** may be transparent or non-transparent and may include a via hole that is coated or filled with one or more transparent or non-transparent conductive materials. In some implementations, the TSV **330** may include a transparent conductive oxide such as ITO and/or a transparent conductive polymer, a nanotube-filled resin, a metal nanowire-filled resin, a particle-filled resin, a metal particle-filled resin, or other suitably conductive material. In some implementations, the TSV **330** may be formed from an electroplated or deposited metal. The TSV **330** may be connected to the transparent antenna **320** via a feed line **340**. The feed line **340** and the TSV **330** provide a conductive pathway from the transparent antenna **320** through the substrate **310** to allow electrical connections on the backside of substrate **310** along with electrical connections to the ground plane **350**. In some implementations, electrical interconnections to the transparent antenna **320** and the ground plane **350** may be made on the topside or the bottom side of transparent substrate **310** without a conductive via using a coaxial cable, a flex tape, a waveguide, or other suitable means. In some implementations, a TSV **330** may locally connect a portion of the transparent antenna **320** directly with a portion of the ground plane **350**.

[0061] The transparent antenna **320** may be made of a transparent conductive material such as ITO. Thus, the transparent antenna **320** may be positioned in a display region of the transparent substrate **310**. However, as transparent conductive materials typically have high resistivity, the transparent conductive material may unduly attenuate a radio-frequency signal, resulting in low antenna gain. Therefore, a transparent antenna **320** such as the patch antenna illustrated in FIG. **3**A may provide insufficient antenna performance by itself.

[0062] FIG. **3**B is an example of a perspective view of a transparent antenna with electrically conductive traces on a transparent substrate. In some implementations, the transparent antenna **320** may be a patch antenna. The electrically conductive traces **360** may be formed on the transparent antenna **320** and configured to electrically reinforce the transparent antenna **320**. The transparent antenna **320** and the electrically conductive traces **360** formed thereon may include different materials.

[0063] Since the transparent antenna **320** formed of a transparent conductive oxide such as ITO may conduct electricity relatively poorly, the electrically conductive traces **360** may electrically reinforce the transparent antenna **320**. In some implementations, the electrically conductive traces **360** may be made of lower resistivity material than the transparent antenna **320**. In some implementations, the electrically conductive traces **360** may have a greater thickness than the transparent antenna **320**. In some implementations, the electrically conductive traces **360** may modify the local and overall impedance of the transparent antenna, lowering the resistance to reduce internal losses and improving matching with free space to reduce transmission and receiving losses. Therefore, the electrically conductive traces **360** may electrically reinforce the transparent antenna **320** to reduce antenna losses.

[0064] In some implementations, the electrically conductive traces **360** may be formed in a non-display region of the transparent substrate **310**. The transparent substrate **310** may include a surface having a display region and a non-display region that surrounds at least a portion of the perimeter of the display region. Thus, the electrically conductive traces **360** may avoid occluding an image (not shown) in the display region of the transparent substrate **310** by placing the traces in the non-display region, such as to provide low-resistance feed lines or to selectively reinforce the transparent antenna in regions outside of the display region. In addition, the width of the electrically conductive traces **360** may be between about a few micrometers and several millimeters. Hence, the electrically conductive traces **360** may improve the antenna performance without obstructing a users' view of the display region, regardless of whether the electrically conductive traces **360** are in the display region or non-display region of the transparent substrate **310**.

[0065] In some implementations, the electrically conductive traces **360** may be very narrow and made of relatively low-resistivity metals. For example, the electrically conductive traces **360** may include at least one of aluminum, an aluminum alloy, aluminum-silicon, copper, chromium, molybdenum, molybdenum-chromium, or silver. Though the electrically conductive traces **360** may be made of material that is non-transparent to visible light, the electrically conductive traces **360** may be sufficiently narrow to appear to be substantially transparent to a viewer of the display. For example, the width of the electrically conductive traces **360** may be between about 10 nm and about 10 μm or larger, and typically between about 1 μm and about 5 μm for patterned features. Some configurations may include thin meshes of copper and/or silver nanowires. The electrically conductive traces **360** may be positioned in the display region of the transparent substrate **310** without substantially interfering with images formed in the display region. In some implementations, the electrically conductive traces **360** may be formed from a multi-layer composite of materials including an absorber, a dielectric, and a reflector, with the dielectric serving as an optical cavity between the absorber and the reflector. The material stack is sometimes referred to as a black matrix, a black mask, a substantially black interferometric stack structure, or a black stack. To a viewer, this combination appears dark or substantially black. Dark features may aid in retaining the contrast of an underlying display.

[0066] FIG. **3**C is an example of a perspective view of multiple antennas on a transparent substrate. Each of the antennas **320***a* and **320***b* may be transparent or substantially transparent and may be formed on a surface of the transparent substrate **310**. As illustrated in the example in FIG. **3**C, each of the transparent antennas **320***a* and **320***b* may be a planar inverted-F antenna (PIFA). PIFAs may be resonant at a quarter-wavelength and may occupy less space than a patch antenna. PIFAs may have a low profile on the order of the thickness of the transparent substrate **310** and may have a largely omnidirectional pattern.

[0067] In some implementations, the transparent antennas **320***a* and **320***b* may be spaced apart to provide spatial diversity. By having multiple antennas **320***a* and **320***b* on the transparent substrate **310** with spatial diversity, the robustness and data rates of wireless transmissions may improve. In some implementations, the transparent antenna **320***b* is arranged in a rotated configuration from the transparent antenna **320***a*. Flipped or rotated antenna configurations may allow feed lines for each antenna to be located at the periphery of the transparent substrate **310** for ready connection with external circuitry.

[0068] In some implementations, each of the transparent antennas **320***a* and **320***b* may have one or more slots formed in the transparent antennas **320***a* and **320***b*. Each of the slots may correspond to different operating frequencies to allow multi-band operation and/or frequency diversity in the transparent antennas **320***a* and **320***b*. By having one or more slots, multiple communication bands may be accommodated with the same antenna. In the example illustrated in FIG. **3**C, the transparent antennas **320***a* and **320***b* are triple-band antennas that may receive and transmit signals in at least three different frequency ranges.

[0069] In some implementations, the transparent antennas **320***a* and **320***b* may have different operating frequencies. With higher frequencies, the size of the antenna generally reduces. At frequencies between about 2-3 GHz to about 60 GHz and above, one or more transparent antennas **320***a* and **320***b* may be readily placed on the transparent substrate **310** for use in front of a display of a mobile display device. At higher frequencies where the current density occurs increasingly closer to the surface of a conductor, the skin depth for the RF excitations is reduced, allowing the use of a relatively thin conductive film with minimal loss. The transparent antennas **320***a* and **320***b* may have different operating frequencies. Either or both antennas transparent **320***a* and **320***b* may accommodate one or more standards or protocols including but not limited to GPS, a Bluetooth protocol, WLAN, a Wi-Fi network, a WiMax network, an RFID band, an NFC band, an HDTV band, an FM band, a MIMO system, or a UWB protocol. Although shown with two antennas **320***a* and **320***b*, three or more antennas of the same or different type may be included on the transparent substrate **310**.

[0070] In some implementations, one or more electrically conductive traces **360** may be formed on portions of or throughout the transparent antennas **320***a* and **320***b* to improve the antenna performance. The electrically conductive traces **360** may electrically reinforce the transparent antennas **320***a* and **320***b*, increasing the effective conductivity of the antennas **320***a* and **320***b* in places where the electrically conductive traces **360** are located, such as near bends or interior corners of the antennas **320***a* and **320***b* where the current density is larger. The transparent antennas **320***a* and **320***b* may be formed of different materials from the electrically conductive traces **360**. In some implementations, the electrically conductive traces **360** may be made of lower resistivity material than the transparent antennas **320***a* and **320***b* or have a greater thickness than the transparent antennas **320***a* and **320***b*. For example, ITO may have a resistivity of about 9.3 ohm-cm, whereas copper and aluminum may have resistivities between about 1.7×10^{-6} and 2.8×10^{-6} ohm-cm. Generally, the electrically conductive traces **360** lower the impedance of the transparent antennas **320***a* and **320***b* in regions where the traces are located. Therefore, where the resistivity or resistance of each of the non-reinforced transparent antennas **320***a* and **320***b* is too high, the electrically conductive traces **360** may locally and electrically reinforce parts of the transparent antennas **320***a* and **320***b* to reduce antenna losses and improve antenna matching.

[0071] In some implementations, the electrically conductive traces **360** may be formed in a non-display region of the transparent substrate **310**. The width of electrically conductive traces **360** in a non-display region may be wider than those in a display region, as no portions of a displayed image are blocked. For example, the width of the electrically conductive traces **360** may extend from a few microns to a few millimeters wide or more for many display devices. In some implementations, the electrically conductive traces **360** may form part of a low-resistivity metal grid or mesh in the display region or the non-display region of the transparent substrate **310**. The electrically conductive traces **360**, in some implementations, may have widths between about 1 μm and about 10 μm. In some implementations, the width of the electrically conductive traces **360** may be reduced in the display region compared to the width of the electrically conductive traces **360** in the non-display region, such that the electrically conductive traces **360** in the display region are less visible to a viewer of the display. Other techniques may be applied to reduce the visibility of the electrically conductive traces **360** in either the display region or the non-display region. For example, the electrically conductive traces **360** may be formed from a grid of a black interferometric stack structure, such that the traces appear dark or substantially black to a viewer. In another example, the electrically conductive traces **360** may have curvilinear features such as successively interconnected arcs or randomized segments that make the traces **360** less visible to a viewer.

[0072] In some implementations, the electrically conductive traces **360** may be formed in regions of high current density in the transparent antennas **320***a* and **320***b*. Regions of high current density may occur where the transparent antennas **320***a* and **320***b* have slots and/or bends. Such regions may be electrically reinforced with electrically conductive traces **360**. Thus, the electrically conductive traces **360** may be formed proximate to slots and/or bends in the transparent antennas **320***a* and **320***b*.

[0073] In the example in FIG. **3**C, the transparent substrate **310** may also include a ground plane **350** on a surface of the transparent substrate **310** opposite the transparent antennas **320***a* and **320***b*. In some implementations, the ground plane **350** may be formed on parts of the transparent substrate **310** separate from the transparent antennas **320***a* and **320***b*, or outside of the transparent substrate **310** itself such as on another layer or as part of the display. The ground plane **350** may also be substantially transparent. For example, the ground plane **350** may be made of ITO or other transparent conductive material. The ground plane **350** may be electrically reinforced with electrically conductive traces or grids (not shown). In some implementations, the ground plane **350** may be formed from an array of narrow electrically conductive traces such as a grid or mesh with a small fill factor such that the traces are substantially transparent to a viewer. The narrow traces may be on the order of about one to ten microns wide to avoid substantially occluding a user's view of a displayed image. In some implementations, the grid may be formed from narrow traces of a metal or a black stack. The fill factor may be less than about 10 percent to retain high viewability, and in some implementations the fill factor may be less than about 5 percent.

[0074] A portion of the transparent antennas **320***a* and **320***b* may be in direct electrical communication with a portion of the ground plane **350**. For example, a transparent TGV or TSV (not shown) may extend through the transparent substrate **310** and electrically connect the transparent antennas **320***a* and **320***b* directly with a portion of the ground plane **350**. Radio-frequency signals may be applied to each antenna **320***a* and/or **320***b* via one or more feed lines **370** and **380**. In some implementations, feed line **370** serves as a ground line and feed line **380** serves as a signal line. In some implementations, feed lines **370** and **380** are differentially driven or differentially received. External connections are generally provided between transparent antennas **320***a* and **320***b* and associated RF transmitter and receiver circuitry. For example, feed lines **370** and **380** may be connected to a duplexer. In one example, feed lines **370** and **380** for one or both transparent antennas **320***a* and **320***b* are connected to external RF circuitry via an impedance-matched flex tape. Other examples for connection with the transparent antennas **320***a* and **320***b* include a coaxial cable, a twin-lead cable, a twisted pair, a wire, a cable, a flex tape, a transmission line, a waveguide, or other suitable means.

[0075] FIG. **3**D is an example of a perspective view of a transparent antenna in a display region of a transparent substrate and one or more antennas in a non-display region of the transparent substrate. The transparent substrate **310** may be partitioned so as to provide a display region through which an image may be displayed, and a non-display region through which no image is displayed. The transparent antenna **320***c* may be formed in the display region of the transparent substrate **310**. One or more transparent or non-transparent antennas **320***e* may be cooperatively coupled with the transparent antenna **320***c*. As illustrated in the example in FIG. **3**D, the transparent or non-transparent antennas **320***e* may be formed on the same surface of the transparent substrate **310** as the transparent antenna **320***c*. In some implementations, the transparent or non-transparent antennas **320***e* may be formed in the non-display region of the transparent substrate **310**, where the non-display region surrounds at least a portion of a perimeter of the display region of the transparent substrate **310**. The transparent or non-transparent antennas **320***e* may have a thickness the same or greater than the transparent antenna **320***c*. The transparent or non-transparent antennas **320***e* may be formed of a material that is the same as or different than the transparent antenna **320***c*. In some implementations, the transparent or non-transparent antennas **320***e* may include narrow conductive traces (not shown) throughout or in select portions of either or both antennas **320***c* and **320***e*, and the width of the conductive traces (if used), may be wider or significantly wider in the non-display region. Since the antennas **320***e* in a non-display region do not substantially interfere with the display region of the display, the antennas **320***e* may have a thickness between about 0.1 μm to about 50 μm or more.

[0076] The transparent antenna **320***c* may be a patch antenna as illustrated in the example of FIG. **3**D. However, the transparent antenna **320***c* or **320***e*, like the antennas described with respect to FIG. **2** and FIGS. **3**A-**3**C above and FIG. **3**E below, may be any suitable type of antenna such as a dipole antenna, a planar inverted-F antenna (PIFA), a slot antenna, a planar antenna, a meander-line antenna, a fractal antenna, a multi-band antenna, an ultra-wide band antenna, a circularly polarized antenna, a duplex antenna, a cancellation antenna, a beam-forming antenna, a steerable antenna, an adaptive antenna, or a combination thereof.

[0077] For example, the transparent or non-transparent antennas **320***e* may include one or more folded dipole antennas as illustrated in the example of FIG. **3**D. The folded dipole antennas may be L-shaped to fit into the corners of transparent substrate **310**. Other dipole antennas such as a straight folded dipole or a conventional full or half-wave dipole (non-folded) may be used along one or more sides of transparent substrate **310**. The L-shaped folded dipole antenna may have the tips of the antenna folded inwards until they almost meet at the feed points. Feed lines **370** and **380** may connect to the feed points of the folded dipole antenna. The feed points may be interior to the folded dipole antenna, with electrical connections made through, for example, a TGV or a TSV (not shown). The feed points may be exterior to the folded dipole antenna and closer to the periphery of transparent substrate **310** as shown in FIG. **3**D, with electrical connections made to the feed points through one or more flex tapes, coaxial cables, twisted pairs, wires, coplanar waveguides, and the like. In some implementations, the feed lines **370** and **380** may include traces (not shown) that cross over or under portions of the antennas to allow connections to external RF circuitry. The folded dipole antenna may be resonant at one entire wavelength. This arrangement for a folded dipole antenna allows for greater bandwidth and higher sensitivity compared to one-half wavelength or one-quarter wavelength antennas. In some implementations, the transparent or non-transparent antennas **320***e* may be any suitable antenna type, including antenna types discussed earlier herein.

[0078] The transparent or non-transparent antennas **320***e* may be formed at the corners or along the sides of the transparent substrate **310**. The transparent antenna **320***c* and the transparent or non-transparent antennas **320***e* may be arranged as an array of antennas. Each of the antennas may have at least one of spatial diversity, frequency diversity, temporal diversity, polarization diversity, and other diversity type with the other antennas in the array. In some implementations, each of the transparent or non-transparent antennas **320***e* may be spatially diverse from one another. In some implementations, the transparent or non-transparent antennas **320***e* may form part of a MIMO antenna array for spatial multiplexing. This may increase the data rates for wireless communications by two-fold, four-fold, ten-fold, or more. In some implementations, multiple transparent or non-transparent antennas **320***e* may be used for beam-steering or beamforming to improve RF signal transmissions.

[0079] FIG. **3**E is an example of a perspective view of multiple antennas in a non-display region of a transparent substrate. Transparent substrate **310** may have one or more transparent or non-transparent antennas **320***e* formed or otherwise disposed in a non-display region of the transparent substrate **310**. Each of the antennas **320***e* may have one or more feed lines **370** and **380** to allow electrical connections with external wireless circuitry. Antennas **320***e* in the non-display region of the transparent substrate **310** does not obscure or otherwise substantially occlude the viewing of the display region of the display device while allowing ready access to the transmission and reception of wireless signals from and to the display device.

[0080] FIG. 3F is an example of a detailed view of a grid that forms a portion of a substantially transparent antenna. A portion of a substantially transparent antenna **320** includes a grid or mesh of relatively narrow transparent or non-transparent traces **324**. The width of traces **324** is selected to be largely invisible when directly viewed with a human eye, whereas the openings between the traces **324** provide for viewing through the grid with an acceptable loss of transparency. In some implementations, the width of the traces **324** may be between about 1 μm and about 10 μm

[0081] FIG. 3G is an example of a detailed view of an electrically reinforcing grid on a substantially transparent antenna. A portion of a substantially transparent antenna **320** includes a grid or mesh of relatively narrow transparent or non-transparent traces **324** disposed on a layer of substantially transparent conductive material **322** such as ITO. The traces **324** may electrically reinforce antenna **320**. In some implementations, the traces **324** may provide electrical connection to the feed lines (not shown) of antenna **320**.

[0082] FIG. 3H is an example of a detailed view of a curvilinear reinforcing grid on a substantially transparent antenna. A portion of a substantially transparent antenna **320** includes relatively narrow transparent or non-transparent traces **324** disposed on a layer of substantially transparent conductive material **322**. The traces **324** are shown as curvilinear. Traces **324** with curvilinear segments may have reduced visibility to a user compared to straight segments. As discussed earlier herein, curvilinear features are nonlinear or curved features such as successively interconnected arcs or randomized segments that make the traces **324** less visible to a viewer.

[0083] FIG. **4** is an example of a cross-sectional side view schematic illustration of a first antenna on a transparent substrate and a second antenna on a printed circuit board. The display device **400** may include a transparent substrate **410** through which an image (not shown) may be displayed to a viewer **415**. The transparent substrate **410** may be an antenna panel, a cover plate, a cover glass, a touch panel, a front light, a display glass, or other layer positioned between the display and a viewer. In the example illustrated in FIG. **4**, a first antenna **420** may be disposed on a surface of the transparent substrate **410**. In some implementations, the first antenna **420** is substantially transparent. For example, the first antenna **420** may include a transparent conductive oxide such as ITO, a grid of narrow conductive traces, or a transparent conductive material augmented with narrow conductive traces. In some implementations, the first antenna **420** may be substantially non-transparent, such as when the antenna is positioned in a non-display region near the periphery of transparent substrate **410**.

[0084] The transparent substrate **410** may be formed or otherwise positioned over a display element **425**. In some implementations, the display element **425** may be a reflective display element, a transmissive display element, or self-emitting display element. For example, the display element **425** may be an IMOD, LCD, OLED, or other type of display. The display element **425** may be enclosed between a backplane **470** (e.g., a back glass, back plate or backlight) and a display substrate **460** (e.g., a display glass), which may protect the display element **425** from external conditions.

[0085] The first antenna **420** may be positioned between the transparent substrate **410** and a cover plate **430**. The cover plate **430** may protect the first antenna **420** from ambient conditions and provide scratch protection. While shown on a separate substrate **410**, the first antenna **420** may be formed on other parts of the display device **400** such as the cover plate **430**, display substrate **460**, or backplane **470**.

[0086] In some implementations, the display device **400** may further include a printed circuit board (PCB) **480** under or behind the display element **425**. The PCB **480** may be spaced apart from the display element **425** and the cover plate **430**, and enclosed within the display device **400**. The PCB **480** may be in electrical communication with the first antenna **420**. The PCB **480** may further include an RF module **482** and a processor **484**.

[0087] A second antenna **450** may be mounted on or otherwise connected to the PCB **480**. As illustrated in the example of FIG. **4**, the second antenna **450** may be attached to the PCB **480**. In some implementations, the second antenna **450** may be formed from traces or features on or within the PCB **480**. The second antenna **450** may be non-transparent. In some implementations, the second antenna **450** may be a PCB antenna, a non-transparent metal-film patch antenna, a low-temperature co-fired ceramic (LTCC) antenna, a wire antenna, or other antenna type connected to or formed on or in the PCB **480**. The second antenna **450** may be cooperatively coupled to the first antenna **420**. The first antenna **420** may be electrically connected to the RF module **482** via one or more feed lines **440** illustrated as a flex tape or a wire connection in FIG. **4**. The second antenna **450** may be connected to the RF module **482** via traces on the PCB **480** (not shown) or by some other suitable mechanisms, such as a connector, a cable, or a wire.

[0088] The second antenna **450** may be positioned below or behind the display element **425**, as illustrated in FIG. **4**. In some implementations, the first antenna **420** and the second antenna **450** may be on opposite sides of the display element **425**. In such an arrangement, antennas on both sides of the display element **425** may provide exposure to wireless signals independent of orientation, which may be of particular use when the display element **425** exhibits excessive shielding of RF signals.

[0089] A substantially non-transparent antenna mounted or otherwise connected to the PCB **480**, such as the second antenna **450**, is typically small to reduce weight and area on the PCB **480**. However, this configuration can reduce direct exposure to incident and transmitted wireless signals because the antenna is buried inside an enclosed space that may have a large number of metallic elements nearby. As a result, the second antenna **450** by itself may experience reduced antenna gain when in an enclosure of the display device **400**.

[0090] Cooperatively coupling the first antenna **420** with one or more second antennas **450** may increase overall system performance by providing antenna diversity. The first antenna **420** and the second antenna **450** may have at least one of spatial diversity, temporal diversity, frequency diversity, polarization diversity, and other diversity type. In addition, the first antenna **420** and the second antenna **450** may provide opportunities for beam steering and adaptive antenna arrays.

Beam steering can increase the effective RF signal strength by directing RF energy selectively towards a receiving antenna, allowing higher signal-to-noise ratios and/or a reduction in transmitting power. Adaptive antenna arrays allow one or more antennas in an array to selectively transmit and receive signals with increased directionality.

[0091] Cooperatively coupling the first antenna **420** with the second antenna **450** may increase the channel capacity of the display device **400** via MIMO. In some implementations, the RF module **482** of display device **400** may be configured to selectively switch between the first antenna **420** and the second antenna **450** for receiving (e.g., downloading) and transmitting (e.g., uploading). In some implementations, the first antenna **420** on the transparent substrate **410** may be configured for receiving wireless signals while the second antenna **450** connected to the PCB **480** may be configured for transmitting wireless signals. For example, a display-side antenna or first antenna **420** may be used for improved reception of RF signals while a PCB antenna or second antenna **450** is used for higher-power transmissions from display device **400** to reduce the exposure of RF power to a user. In some implementations, the first antenna **420** or the second antenna **450** may be selected for reception when the signal strength from each antenna has been determined. In some implementations, the transmit frequencies may be different than the receive frequencies, and the antenna **420** or **450** may be selected for transmission or reception based on the frequency. In some implementations with one or more display-side antennas (e.g., first antenna **420**) and optionally an enclosed antenna (e.g., second antenna **450**), MIMO may be used to increase the transfer rate of data.

[0092] Generally, a MIMO system configuration combines multiple transmit antennas and/or multiple receive antennas for the transmission of multiple independent data streams. In some implementations, the first antenna **420** may be part of an array of receive antennas, and the second antenna **450** may be part of an array of transmit antennas, or vice versa. In some implementations, the first antenna **420** and the second antenna **450** may both be a part of an array of receive or transmit antennas.

[0093] FIG. **5** is an example of a diagram illustrating an operating mode of a multi-antenna system. The elements of FIG. **5** may apply to the first antenna and the second antenna of the display device shown in FIG. **4**. The first antenna **420** may be a display-side antenna and the second antenna **450** may be a PCB antenna. Even if the first antenna **420** is lossy compared to the second antenna **450**, arranging the first antenna **420** to be cooperatively coupled to the second antenna **450** may increase channel capacity and/or otherwise improve system performance. When arranged in a MIMO system or a multi-antenna system, the first antenna **420** may be cooperatively coupled with the second antenna **450** to improve data throughput.

[0094] As shown in FIG. **5**, the display device **400** may include a detector **490** and RF modules **475***a* and **475***b* electrically connected between antennas **420** and **450** and the detector **490**. The first antenna **420** may be configured to receive or transmit wireless signals and the second antenna **450** may be configured to receive or transmit wireless signals. For example, when the first antenna **420** receives a wireless signal, the received wireless signal may be transferred to the first RF module **475***a*. When the second antenna **450** receives a wireless signal, the received wireless signal may be transferred to a second RF module **475***b*. A weighting coefficient **485***a* and **485***b* may be calculated by the RF modules **475***a* or **475***b*, the detector **490**, or a wireless communication controller (not shown). The weighting coefficients may effectively serve as an RF switch to selectively switch between antennas **420** and **450**, along with any others in the system. In some implementations, the weighting coefficient may depend on the strength of the received or transmitted wireless signal. For example, if a received wireless signal from the first antenna **420** has a higher signal strength than a received wireless signal from the second antenna **450**, then the weighting coefficients **485***a* and **485***b* may be adjusted to pass the signal from the first antenna **420** into the detector **490**. If a received wireless signal from the second antenna **450** has higher signal strength than the received wireless signal from the first antenna **420**, then the weighting coefficients **485***a* and **485***b* may be adjusted to pass the signal from the second antenna **450** into the detector **490**. In some implementations, the weighting coefficients may be based on signal quality. The weighting coefficients **485***a* and **485***b* may effectively determine whether an antenna is turned on or off. In some implementations, one or more RF switches (not shown) may be configured to selectively switch between the first antenna **420** and the second antenna **450** and any other antennas in the system for either transmission or reception. When operating in a transmitting mode, the system may select antenna **420**, antenna **450**, or other display-side or enclosure antenna for the transmission of wireless signals, and switch an RF transmission signal accordingly.

[0095] In some implementations, the display device **400** may include a proximity sensor (not shown). A proximity sensor such as a camera or an infrared sensor may be configured to provide input to a controller or processor to allow selective switching of the first antenna **420** and the second antenna **450** for RF transmissions. For example, when the proximity sensor detects a user's head or body proximate to a surface of the transparent substrate **410**, RF transmissions from the first antenna **420** may be curtailed and the RF signals sent to the second antenna **450** for transmission.

[0096] FIG. **6** is an example of a flow diagram illustrating a method of manufacturing a display device. It is understood that additional processes not shown in FIG. **6** may be present. For example, deposition of underlying or overlying layers and features may be achieved by various film deposition processes, such as PVD, PECVD, thermal CVD, ALD, spin-on coating, and electroplating. Patterning techniques, such as photolithography, may be used to transfer patterns on a mask to a layer of material. Etching processes may be performed after patterning to remove unwanted materials.

[0097] The process **600** begins at block **610**, where a transparent substrate through which an image may be displayed is provided. The transparent substrate may include a surface having a display region and a non-display region that surrounds at least a portion of a perimeter of the display region. In some implementations, the transparent substrate may be made of glass, plastic, or other substantially transparent material. For example, the transparent substrate may be one of an antenna panel, a cover plate, a cover glass, a touch panel, a front light, a display glass, a backplane, a back plate, or a backlight. In some implementations, the transparent substrate may have a thickness between about 10 μm and about 700 μm. In some implementations, the transparent substrate may have a thickness between about 300 μm and 500 μm.

[0098] The process **600** continues at block **620**, where a first antenna is formed in the display region of the transparent substrate. The first antenna may be transparent or non-transparent. For example, the first antenna may be transparent and positioned in a display region of the transparent substrate. In another example, the first antenna may be transparent or non-transparent and positioned in a non-display region of the transparent substrate. In some implementations, the first antenna may be made of a transparent conductive oxide, such as ITO. In some implementations, the first antenna may include a transparent material and electrically reinforced with narrow, transparent or non-transparent traces. In some implementations, the first antenna may include a grid of narrow, transparent or non-transparent traces. The first antenna may include, for example, a patch antenna, a dipole antenna, a PIFA, a slot antenna, a planar antenna, a meander-line antenna, a fractal antenna, a multi-band antenna, an ultra-wide band antenna, a circularly polarized antenna, a duplex antenna, a cancellation antenna, a beam-forming antenna, a steerable antenna, or an adaptive antenna.

[0099] In some implementations, the first antenna may be part of multiple antennas on the transparent substrate. The first antenna may have at least one of spatial diversity, frequency diversity, temporal diversity, polarization diversity, and other diversity type with the other antennas on the transparent substrate.

[0100] In some implementations, the first antenna may be augmented or electrically reinforced with electrically conductive traces formed on the first antenna. The electrically conductive traces may be made of aluminum, an aluminum alloy, aluminum-silicon, copper, chromium, molybdenum, molybdenum-chromium, silver, or a combination thereof. The electrically conductive traces may be made of non-transparent material while not substantially occluding the image of the display, and/or the electrically conductive traces may be formed in the non-display region of the transparent substrate to avoid interference with the image of the display.

[0101] The process **600** continues at block **630**, where a second antenna is cooperatively coupled with the first antenna, and the second antenna is either transparent or non-transparent. In some implementations, a PCB may be provided with the display device and configured to be in electrical communication with the first antenna, where the second antenna is connected or otherwise disposed on the PCB. In some implementations, a display element may be configured between the PCB and the transparent substrate.

[0102] In some implementations, the second antenna may be a PCB antenna, a non-transparent metal-film patch antenna, a low-temperature co-fired ceramic (LTCC) antenna, a wire antenna, or another antenna type discussed earlier herein. In some implementations, the second antenna may be transparent or non-transparent, and formed in a non-display region of the transparent substrate. In some implementations, the second antenna may be transparent and formed in the display region of the transparent substrate along with the first antenna. The first antenna and the second antenna may be part of a MIMO system to increase channel capacity. The first antenna and the second antenna may exhibit antenna diversity, including but not limited to at least one of spatial diversity, temporal diversity, frequency diversity, and polarization diversity.

[0103] In some implementations, the second antenna may be configured to operate in a different mode from the first antenna. For example, the second antenna may be configured to transmit wireless signals while the first antenna may be configured to receive wireless signals. In some implementations, an RF switch or weighting coefficients that serve as an RF switch may be provided or generated to differentiate and selectively switch between the operating modes.

[0104] FIG. **7** is an example of a flow diagram illustrating a method of operating a display device. The method **700** can be implemented using hardware (such as application specific integrated circuits (ASIC), programmable logic devices, etc.), software (which includes instructions embodied in a tangible storage medium, executable by a processing device), or a combination of both. The method **700** begins at block **710** where a portion of a user's body such as a head or a face is detected. The head may be detected, for example, with a proximity sensor such as a camera or an infrared sensor coupled to the display device. When a head is detected near a display-side antenna, the display device may switch from the display-side antenna to an enclosure antenna as shown in block **720**. The display-side antenna may be disposed on an exterior surface of the display device and the enclosure antenna may be disposed on an interior surface of the display device. The display device may transmit one or more wireless signals from the enclosure antenna as shown in block **730**. The display-side antenna may include one or more transparent antennas in a display region above or over a display (such as those discussed above), and/or optionally one or more transparent or non-transparent antennas in a non-display region at the periphery of the display region (such as those discussed above). The enclosure antenna may include one or more PCB antennas or antennas connected to an underlying PCB. In some implementations, the enclosure antenna may include an antenna mounted on a sidewall or back of an enclosure of the display device. In some implementations, the enclosure antenna may extend from an enclosure of the display device. In some implementations, the enclosure antenna may include one or more transparent or non-transparent antennas on an antenna panel positioned under or behind the display. In some implementations, the display device may switch from the enclosure antenna back to the display-side antenna when the head is not proximate the display-side antenna. The display device may receive one or more wireless signals from the display-side antenna. Alternatively, the display device may turn on both the enclosure antenna and the display-side antenna when no body part (e.g., the head, the face, etc.) is detected to be proximate the display-side antenna, and turn off the display-side antenna, keeping the enclosure antenna on, when a specific body part is detected to be proximate the display-side antenna.

[0105] FIG. **8** is an example of a cross-sectional side view illustrating a process sequence for fabricating a transparent antenna. A method for making an antenna panel with one or more transparent antennas includes providing a transparent substrate **810** as shown in FIG. **8***a* such as a glass or plastic substrate or sheet. A substantially transparent conductive material such as ITO is deposited on the transparent substrate **810** and patterned to form a substantially transparent antenna **820** in a display or non-display region of the transparent substrate **810** as shown in FIG. **8***b*. A second transparent or non-transparent antenna (not shown) may be formed in a display or non-display region of the transparent substrate **810**.

[0106] FIG. **9** is an example of a cross-sectional side view illustrating a process sequence for fabricating a transparent antenna with a substantially transparent grid. A method for making an antenna panel with at least one transparent antenna includes providing a transparent substrate **910** as shown in FIG. **9***a*. A transparent or non-transparent film such as aluminum, chromium, or molybdenum is deposited on the transparent substrate **910** and patterned to form a substantially transparent antenna **920** with relatively narrow traces **924** in a display or non-display region of the transparent substrate **910** as shown in FIG. **9***b*. Other antennas (not shown) may be formed in a display or non-display region of the transparent substrate **910**.

[0107] FIG. **10** is an example of a cross-sectional side view illustrating a process sequence for fabricating a transparent antenna with electrically reinforcing traces on a substantially transparent antenna. A method for making an antenna panel with one or more antenna having electrically reinforced traces includes providing a transparent substrate **1010** as shown in FIG. **10***a*. A layer of substantially transparent conductive material **1022** such as ITO is deposited on the transparent substrate **1010** and patterned to form a substantially transparent antenna **1020** in a display or non-display region of the transparent substrate **1010** as shown in FIG. **10***b*. A transparent or non-transparent film is deposited on the transparent conductive material **1022** and patterned to form relatively narrow traces **1024** as shown in FIG. **10***c*.

[0108] FIG. **11** is an example of a cross-sectional side view illustrating a process sequence for fabricating a transparent antenna with a substantially transparent grid of a black interferometric stack structure. A method for making an antenna panel with at least one transparent antenna includes providing a transparent substrate **1110** as shown in FIG. **11***a*. A stack of films including an absorber, a dielectric, and a reflector, which can be referred to as a black stack may be deposited on the transparent substrate **1110** and patterned to form a substantially transparent antenna **1120** having relatively narrow traces **1124** in a display or non-display region of the transparent substrate **1110** as shown in FIG. **1** lb. In some implementations, the electrically conductive traces **1124** may be formed from a multi-layer composite of a black stack, with a dielectric serving as an optical cavity between the absorber and the reflector. In some embodiments, the stack may be formed of Cr/ITO, Mo/ITO, Ti/ITO, Cr, Mo or Ti as the absorber, SiO_2 as the dielectric, and Al, Cr, Mo, or other metallic material as the reflector. For example, the thickness of the absorber may be on the order of about 6 nm, the thickness of the dielectric may be between about 30 and 80 nm, and the thickness of the reflector may be between about 0.2 μm and about 2.0 μm thick, according to certain implementations. The combination may be selected to appear dark or substantially black to a viewer.

[0109] FIG. **12** is an example of a cross-sectional side view illustrating a process sequence for fabricating a transparent antenna with electrically reinforcing traces of a black interferometric stack structure on a substantially transparent antenna. A method for making an antenna panel with one or more substantially transparent antennas having electrically reinforced traces includes providing a transparent substrate **1210**, as shown in FIG. **12***a*. A layer of substantially transparent conductive material **1222** is deposited on the transparent substrate **1210** and patterned to form a substantially transparent antenna **1220** in a display or non-display region of the transparent substrate **1210**, as shown in FIG. **12***b*. A set of layers such as a black stack is deposited on the transparent conductive material **1222** and patterned to form narrow traces **1224** that electrically reinforce the transparent antenna **1220**, as shown in FIG. **12***c*.

[0110] As described above, one example of a suitable display device to which the described implementations may apply, is a reflective display device such as an IMOD display device. FIG. **13** is an isometric view illustration depicting two adjacent IMOD display elements in a series or array of display elements of an IMOD display device. The IMOD display device includes one or more interferometric EMS, such as MEMS, display elements. In these devices, the interferometric MEMS display elements can be configured in either a bright or dark state. In the bright ("relaxed," "open" or "on," etc.) state, the display element reflects a large portion of incident visible light. Conversely, in the dark ("actuated," "closed" or "off," etc.) state, the display element reflects little incident visible light. MEMS display elements can be configured to reflect predominantly at particular wavelengths of light allowing for a color display in addition to black and white. In some implementations, by using multiple display elements, different intensities of color primaries and shades of gray can be achieved.

[0111] The IMOD display device can include an array of IMOD display elements which may be arranged in rows and columns. Each display element in the array can include at least a pair of reflective and semi-reflective layers, such as a movable reflective layer (i.e., a movable layer, also referred to as a mechanical layer) and a fixed partially reflective layer (i.e., a stationary layer), positioned at a variable and controllable distance from each other to form an air gap (also referred to as an optical gap, cavity or optical resonant cavity). The movable reflective layer may be moved between at least two positions. For example, in a first position, i.e., a relaxed position, the movable reflective layer can be positioned at a distance from the fixed partially reflective layer. In a second position, i.e., an actuated position, the movable reflective layer can be positioned more closely to the partially reflective layer. Incident light that reflects from the two layers can interfere constructively and/or destructively depending on the position of the movable reflective layer and the wavelength(s) of the incident light, producing either an overall reflective or non-reflective state for each display element. In some implementations, the display element may be in a reflective state when unactuated, reflecting light within the visible spectrum, and may be in a dark state when actuated, absorbing and/or destructively interfering light within the visible range. In some other implementations, however, an IMOD display element may be in a dark state when unactuated, and in a reflective state when actuated. In some implementations, the introduction of an applied voltage can drive the display elements to change states. In some other implementations, an applied charge can drive the display elements to change states.

[0112] The depicted portion of the array in FIG. **13** includes two adjacent interferometric MEMS display elements in the form of IMOD display elements **12**. In the display element **12** on the right (as illustrated), the movable reflective layer **14** is illustrated in an actuated position near, adjacent or touching the optical stack **16**. The voltage V_{bias} applied across the display element **12** on the right is sufficient to move and also maintain the movable reflective layer **14** in the actuated position. In the display element **12** on the left (as illustrated), a movable reflective layer **14** is illustrated in a relaxed position at a distance (which may be predetermined based on design parameters) from an optical stack **16**, which includes a partially reflective layer. The voltage V_0 applied across the display element **12** on the left is insufficient to cause actuation of the movable reflective layer **14** to an actuated position such as that of the display element **12** on the right.

[0113] In FIG. **13**, the reflective properties of IMOD display elements **12** are generally illustrated with arrows indicating light **13** incident upon the IMOD display elements **12**, and light **15** reflecting from the display element **12** on the left. Most of the light **13** incident upon the display elements **12** may be transmitted through the transparent substrate **20**, toward the optical stack **16**. A portion of the light incident upon the optical stack **16** may be transmitted through the partially reflective layer of the optical stack **16**, and a portion will be reflected back through the transparent substrate **20**. The portion of light **13** that is transmitted through the optical stack **16** may be reflected from the movable reflective layer **14**, back toward (and through) the transparent substrate **20**. Interference (constructive and/or destructive) between the light reflected from the partially reflective layer of the optical stack **16** and the light reflected from the movable reflective layer **14** will determine in part the intensity of wavelength(s) of light **15** reflected from the display element **12** on the viewing or substrate side of the device. In some implementations, the transparent substrate **20** can be a glass substrate (sometimes referred to as a glass plate or panel). The glass substrate may be or include, for example, a borosilicate glass, a soda lime glass, quartz, Pyrex, or other suitable glass material. In some implementations, the glass substrate may have a thickness of 0.3, 0.5 or 0.7 millimeters, although in some implementations the glass substrate can be thicker (such as tens of millimeters) or thinner (such as less than 0.3 millimeters). In some implementations, a non-glass substrate can be used, such as a polycarbonate, acrylic, polyethylene terephthalate (PET) or polyether ether ketone (PEEK) substrate. In such an implementation, the non-glass substrate will likely have a thickness of less than 0.7 millimeters, although the substrate may be thicker depending on the design considerations. In some implementations, a non-transparent substrate, such as a metal foil or stainless steel-based substrate can be used. For example, a reverse-IMOD-based display, which includes a fixed reflective layer and a movable layer which is partially transmissive and partially reflective, may be configured to be viewed from the opposite side of a substrate as the display elements **12** of FIG. **13** and may be supported by a non-transparent substrate.

[0114] The optical stack **16** can include a single layer or several layers. The layer(s) can include one or more of an electrode layer, a partially reflective and partially transmissive layer, and a transparent dielectric layer. In some implementations, the optical stack **16** is electrically conductive, partially transparent and partially reflective, and may be fabricated, for example, by depositing one or more of the above layers onto a transparent substrate **20**. The electrode layer can be formed from a variety of materials, such as various metals, for example indium tin oxide (ITO). The partially reflective layer can be formed from a variety of materials that are partially reflective, such as various metals (e.g., chromium and/or molybdenum), semiconductors, and dielectrics. The partially reflective layer can be formed of one or more layers of materials, and each of the layers can be formed of a single material or a combination of materials. In some implementations, certain portions of the optical stack **16** can include a single semi-transparent thickness of metal or semiconductor which serves as both a partial optical absorber and electrical conductor, while different, electrically more conductive layers or portions (e.g., of the optical stack **16** or of other structures of the display element) can serve to bus signals between IMOD display elements. The optical stack **16** also can include one or more insulating or dielectric layers covering one or more conductive layers or an electrically conductive/partially absorptive layer.

[0115] In some implementations, at least some of the layer (s) of the optical stack **16** can be patterned into parallel strips, and may form row electrodes in a display device as described further below. As will be understood by one having ordinary skill in the art, the term "patterned" is used herein to refer to masking as well as etching processes. In some implementations, a highly conductive and reflective material, such as aluminum (Al), may be used for the movable reflective layer **14**, and these strips may form column electrodes in a display device. The movable reflective layer **14** may be formed as a series of parallel strips of a deposited metal layer or layers (orthogonal to the row electrodes of the optical stack **16**) to form columns deposited on top of supports, such as the illustrated posts **18**, and an intervening sacrificial material located between the posts **18**. When the sacrificial material is etched away, a defined gap **19**, or optical cavity, can be formed between the movable reflective layer **14** and the optical stack **16**. In some implementations, the spacing between posts **18** may be approximately 1-1000 μm, while the gap **19** may be approximately less than 10,000 Angstroms (Å).

[0116] In some implementations, each IMOD display element, whether in the actuated or relaxed state, can be considered as a capacitor formed by the fixed and moving reflective layers. When no voltage is applied, the movable reflective layer **14** remains in a mechanically relaxed state, as illustrated by the display element **12** on the left in FIG. **13**, with the gap **19** between the movable reflective layer **14** and optical stack **16**. However, when a potential difference, i.e., a voltage, is applied to at least one of a selected row and column, the capacitor formed at the intersection of the row and column electrodes at the corresponding display element becomes charged, and electrostatic forces pull the electrodes together. If the applied voltage exceeds a threshold, the movable reflective layer **14** can deform and move near or against the optical stack **16**. A dielectric layer (not shown) within the optical stack **16** may prevent shorting and control the separation distance between the layers **14** and **16**, as illustrated by the actuated display element **12** on the right in FIG. **13**. The behavior can be the same regardless of the polarity of the applied potential difference. Though a series of display elements in an array may be referred to in some instances as "rows" or "columns," a person having ordinary skill in the art will readily understand that referring to one direction as a "row" and another as a "column" is arbitrary. Restated, in some orientations, the rows can be considered columns, and the columns considered to be rows. In some implementations, the rows may be referred to as "common" lines and the columns may be referred to as "segment" lines, or vice versa. Furthermore, the display elements may be evenly arranged in orthogonal rows and columns (an "array"), or arranged in non-linear configurations, for example, having certain positional offsets with respect to one another (a "mosaic"). The terms "array" and "mosaic" may refer to either configuration. Thus, although the display is referred to as including an "array" or "mosaic," the elements themselves need not be arranged orthogonally to one another, or disposed in an even distribution, in any instance, but may include arrangements having asymmetric shapes and unevenly distributed elements.

[0117] FIG. **14** is a system block diagram illustrating an electronic device incorporating an IMOD-based display including a three-element by three-element array of IMOD display elements. The electronic device includes a processor **21** that may be configured to execute one or more software modules. In addition to executing an operating system, the processor **21** may be configured to execute one or more software applications, including a web browser, a telephone application, an email program, or any other software application.

[0118] The processor **21** can be configured to communicate with an array driver **22**. The array driver **22** can include a row driver circuit **24** and a column driver circuit **26** that provide signals to, for example a display array or panel **30**. The cross section of the IMOD display device illustrated in FIG. **13** is shown by the lines **1-1** in FIG. **14**. Although FIG. **14** illustrates a 3×3 array of IMOD display elements for the sake of clarity, the display array **30** may contain a very large number of IMOD display elements, and may have a different number of IMOD display elements in rows than in columns, and vice versa.

[0119] FIGS. **15**A and **15**B are system block diagrams illustrating a display device **40** that includes a plurality of IMOD display elements. The display device **40** can be, for example, a smart phone, a cellular or mobile telephone. However, the same components of the display device **40** or slight variations thereof are also illustrative of various types of display devices such as televisions, computers, tablets, e-readers, hand-held devices and portable media devices.

[0120] The display device **40** includes a housing **41**, a display **30**, an antenna **43**, a speaker **45**, an input device **48** and a microphone **46**. The housing **41** can be formed from any of a variety of manufacturing processes, including injection molding, and vacuum forming. In addition, the housing **41** may be made from any of a variety of materials, including, but not limited to: plastic, metal, glass, rubber and ceramic, or a combination thereof. The housing **41** can include removable portions (not shown) that may be interchanged with other removable portions of different color, or containing different logos, pictures, or symbols.

[0121] The display **30** may be any of a variety of displays, including a bi-stable or analog display, as described herein. The display **30** also can be configured to include a flat-panel display, such as plasma, EL, OLED, STN LCD, or TFT LCD, or a non-flat-panel display, such as a CRT or other tube device. In addition, the display **30** can include an IMOD-based display, as described herein.

[0122] The components of the display device **40** are schematically illustrated in FIG. **15**A. The display device **40** includes a housing **41** and can include additional components at least partially enclosed therein. For example, the display device **40** includes a network interface **27** that includes an antenna **43** which can be coupled to a transceiver **47**. The network interface **27** may be a source for image data that could be displayed on the display device **40**. Accordingly, the network interface **27** is one example of an image source module, but the processor **21** and the input device **48** also may serve as an image source module. The transceiver **47** is connected to a processor **21**, which is connected to conditioning hardware **52**. The conditioning hardware **52** may be configured to condition a signal (such as filter or otherwise manipulate a signal). The conditioning hardware **52** can be connected to a speaker **45** and a microphone **46**. The conditioning hardware **52** also may be connected to a proximity sensor **54**. The proximity sensor **54** may be configured to provide input to the processor **21** of the display device **40** via the conditioning hardware **52**. The processor **21** also can be connected to an input device **48** and a driver controller **29**. The driver controller **29** can be coupled to a frame buffer **28**, and to an array driver **22**, which in turn can be coupled to a display array **30**. One or more elements in the display device **40**, including elements not specifically depicted in FIG. **15**A, can be configured to function as a memory device and be configured to communicate with the processor **21**. In some implementations, a power supply **50** can provide power to substantially all components in the particular display device **40** design.

[0123] The network interface **27** includes one or more antennas **43** and the transceiver **47** so that the display device **40** can communicate with one or more devices over a network. The network interface **27** also may have some processing capabilities to relieve, for example, data processing requirements of the processor **21**. The antenna **43** can transmit and receive signals. In some implementations, the antenna **43** transmits and receives RF signals according to the IEEE 16.11 standard, including IEEE 16.11(a), (b), or (g), or the IEEE 802.11 standard, including IEEE 802.11a, b, g, n, and further implementations thereof. In some other implementations, the antenna **43** transmits and receives RF signals according to the Bluetooth® standard. In the case of a cellular telephone, the antenna **43** can be designed to receive code division multiple access (CDMA), frequency division multiple access (FDMA), time division multiple access (TDMA), Global System for Mobile communications (GSM), GSM/General Packet Radio Service (GPRS), Enhanced Data GSM Environment (EDGE), Terrestrial Trunked Radio (TETRA), Wideband-CDMA (W-CDMA), Evolution Data Optimized (EV-DO), 1×EV-DO, EV-DO Rev A, EV-DO Rev B, High Speed Packet Access (HSPA), High Speed Downlink Packet Access (HSDPA), High Speed Uplink Packet Access (HSUPA), Evolved High Speed Packet Access (HSPA+), Long Term Evolution (LTE), AMPS, or other known signals that are used to communicate within a wireless network, such as a system utilizing 3G, 4G or 5G technology. The transceiver **47** can pre-process the signals received from the antenna **43** so that they may be received by and further manipulated by the processor **21**. The transceiver **47** also can process signals received from the processor **21** so that they may be transmitted from the display device **40** via the antenna **43**.

[0124] In some implementations, the transceiver **47** can be replaced by a receiver. In addition, in some implementations, the network interface **27** can be replaced by an image source, which can store or generate image data to be sent to the processor **21**. The processor **21** can control the overall operation of the display device **40**. The processor **21** receives data, such as compressed image data from the network interface **27** or an image source, and processes the data into raw image data or into a format that can be readily processed into raw image data. The processor **21** can send the processed data to the driver controller **29** or to the frame buffer **28** for storage. Raw data typically refers to the information that identifies the image characteristics at each location within an image. For example, such image characteristics can include color, saturation and gray-scale level.

[0125] The processor **21** can include a microcontroller, CPU, or logic unit to control operation of the display device **40**. The conditioning hardware **52** may include amplifiers and filters for transmitting signals to the speaker **45**, and for receiving signals from the microphone **46**. The conditioning hardware **52** may be discrete components within the display device **40**, or may be incorporated within the processor **21** or other components.

[0126] The driver controller **29** can take the raw image data generated by the processor **21** either directly from the processor **21** or from the frame buffer **28** and can re-format the raw image data appropriately for high speed transmission to the array driver **22**. In some implementations, the driver controller **29** can re-format the raw image data into a data flow having a raster-like format, such that it has a time order suitable for scanning across the display array **30**. Then the driver controller **29** sends the formatted information to the array driver **22**. Although a driver controller **29**, such as an LCD controller, is often associated with the system processor **21** as a stand-alone integrated circuit (IC), such controllers may be implemented in many ways. For example, controllers may be embedded in the processor **21** as hardware, embedded in the processor **21** as software, or fully integrated in hardware with the array driver **22**.

[0127] The array driver **22** can receive the formatted information from the driver controller **29** and can re-format the video data into a parallel set of waveforms that are applied many times per second to the hundreds, and sometimes thousands (or more), of leads coming from the display's x-y matrix of display elements.

[0128] In some implementations, the driver controller **29**, the array driver **22**, and the display array **30** are appropriate for any of the types of displays described herein. For example, the driver controller **29** can be a conventional display controller or a bi-stable display controller (such as an IMOD display element controller). Additionally, the array driver **22** can be a conventional driver or a bi-stable display driver (such as an IMOD display element driver). Moreover, the display array **30** can be a conventional display array or a bi-stable display array (such as a display including an array of IMOD display elements). In some implementations, the driver controller **29** can be integrated with the array driver **22**. Such an implementation can be useful in highly integrated systems, for example, mobile phones, portable-electronic devices, watches or small-area displays.

[0129] In some implementations, the input device **48** can be configured to allow, for example, a user to control the operation of the display device **40**. The input device **48** can include a keypad, such as a QWERTY keyboard or a telephone keypad, a button, a switch, a rocker, a touch-sensitive screen, a touch-sensitive screen integrated with the display array **30**, or a pressure- or heat-sensitive membrane. The microphone **46** can be configured as an input device for the display device **40**. In some implementations, voice commands through the microphone **46** can be used for controlling operations of the display device **40**.

[0130] The power supply **50** can include a variety of energy storage devices. For example, the power supply **50** can be a rechargeable battery, such as a nickel-cadmium battery or a lithium-ion battery. In implementations using a rechargeable battery, the rechargeable battery may be chargeable using power coming from, for example, a wall socket or a photovoltaic device or array. Alternatively, the rechargeable battery can be wirelessly chargeable. The power supply **50** also can be a renewable energy source, a capacitor, or a solar cell, including a plastic solar cell or solar-cell paint. The power supply **50** also can be configured to receive power from a wall outlet.

[0131] In some implementations, control programmability resides in the driver controller **29** which can be located in several places in the electronic display system. In some other implementations, control programmability resides in the array driver **22**. The above-described optimization may be implemented in any number of hardware and/or software components and in various configurations.

[0132] As used herein, a phrase referring to "at least one of" a list of items refers to any combination of those items, including single members. As an example, "at least one of: a, b, or c" is intended to cover: a, b, c, a-b, a-c, b-c, and a-b-c.

[0133] The various illustrative logics, logical blocks, modules, circuits and algorithm steps described in connection with the implementations disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. The interchangeability of hardware and software has been described generally, in terms of functionality, and illustrated in the various illustrative components, blocks, modules, circuits and steps described above. Whether such functionality is implemented in hardware or software depends upon the particular application and design constraints imposed on the overall system.

[0134] The hardware and data processing apparatus used to implement the various illustrative logics, logical blocks, modules and circuits described in connection with the aspects disclosed herein may be implemented or performed with a general purpose single- or multi-chip processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, or, any conventional processor, controller, microcontroller, or state machine. A processor also may be implemented as a combination of computing devices, such as a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. In some implementations, particular steps and methods may be performed by circuitry that is specific to a given function.

[0135] In one or more aspects, the functions described may be implemented in hardware, digital electronic circuitry, computer software, firmware, including the structures disclosed in this specification and their structural equivalents thereof, or in any combination thereof. Implementations of the subject matter described in this specification also can be implemented as one or more computer programs, i.e., one or more modules of computer program instructions, encoded on a computer storage media for execution by, or to control the operation of, data processing apparatus.

[0136] If implemented in software, the functions may be stored on or transmitted over as one or more instructions or code on a computer-readable medium. The steps of a method or algorithm disclosed herein may be implemented in a processor-executable software module which may reside on a computer-readable medium. Computer-readable media includes both computer storage media and communication media including any medium that can be enabled to transfer a computer program from one place to another. A storage media may be any available media that may be accessed by a computer. By way of example, and not limitation, such computer-readable media may include RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that may be used to store desired program code in the form of instructions or data structures and that may be accessed by a computer. Also, any connection can be properly termed a computer-readable medium. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk, and blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above also may be included within the scope of computer-readable media. Additionally, the operations of a method or algorithm may reside as one or any combination or set of codes and instructions on a machine readable medium and computer-readable medium, which may be incorporated into a computer program product.

[0137] Various modifications to the implementations described in this disclosure may be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other implementations without departing from the spirit or scope of this disclosure. Thus, the claims are not intended to be limited to the implementations shown herein, but are to be accorded the widest scope consistent with this disclosure, the principles and the novel features disclosed herein. Additionally, a person having ordinary skill in the art will readily appreciate, the terms "upper" and "lower" are sometimes used for ease of describing the figures, and indicate relative positions corresponding to the orientation of the figure on a properly oriented page, and may not reflect the proper orientation of, e.g., an IMOD display element as implemented.

[0138] Certain features that are described in this specification in the context of separate implementations also can be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation also can be implemented in multiple implementations separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

[0139] Similarly, while operations are depicted in the drawings in a particular order, a person having ordinary skill in the art will readily recognize that such operations need not be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. Further, the drawings may schematically depict one more example processes in the form of a flow diagram. However, other operations that are not depicted can be incorporated in the example processes that are schematically illustrated. For example, one or more additional operations can be performed before, after, simultaneously, or between any of the illustrated operations. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products. Additionally, other implementations are within the scope of the following claims. In some cases, the actions recited in the claims can be performed in a different order and still achieve desirable results.

What is claimed is:

1. A display device comprising:

a transparent substrate through which an image can be displayed;

a first substantially transparent antenna formed on a surface of the transparent substrate; and

one or more electrically conductive traces formed on the transparent antenna and configured to electrically reinforce the first substantially transparent antenna.

2. The display device of claim **1**, wherein the one or more electrically conductive traces include at least one of aluminum, an aluminum alloy, aluminum-silicon, copper, chromium, molybdenum, molybdenum-chromium, or silver.

3. The display device of claim **1**, wherein the one or more electrically conductive traces include a substantially black interferometric stack structure.

4. The display device of claim **1**, wherein the transparent substrate includes a surface having a display region and a non-display region that surrounds at least a portion of a perimeter of the display region, and wherein the one or more electrically conductive traces are in the non-display region of the transparent substrate.

5. The display device of claim **1**, wherein the first substantially transparent antenna includes a transparent conductive material.

6. The display device of claim **5**, wherein the transparent conductive material includes indium tin oxide.

7. The display device of claim **1**, wherein the one or more electrically conductive traces have a thickness greater than a thickness of the first substantially transparent antenna.

8. The display device of claim **1**, wherein the one or more electrically conductive traces have a resistivity less than a resistivity of the first substantially transparent antenna.

9. The display device of claim **1**, wherein the first substantially transparent antenna and the electrically conductive traces are formed of different materials.

10. The display device of claim **1**, wherein the first substantially transparent antenna is configured to receive and transmit signals in at least one operating frequency band.

11. The display device of claim **1**, further comprising a second antenna formed on the same surface of the transparent substrate as the first substantially transparent antenna, wherein the second antenna is spatially diverse from the first substantially transparent antenna.

12. The display device of claim **11**, wherein the transparent substrate includes a surface having a display region and a non-display region that surrounds at least a portion of a perimeter of the display region, the second antenna formed in the non-display region of the transparent substrate.

13. The display device of claim **1**, wherein each of the one or more electrically conductive traces has a width between about 10 nm and about 1 μm.

14. The display device of claim **1**, further comprising a ground plane in electrical communication with the first substantially transparent antenna.

15. The display device of claim **14**, further comprising one or more electrically conductive grids formed on the ground plane.

16. The display device of claim **14**, wherein the ground plane includes indium tin oxide.

17. The display device of claim **1**, further comprising a through-substrate via extending through the transparent substrate, the via electrically connected to a portion of the first substantially transparent antenna.

18. The display device of claim **1**, wherein the first substantially transparent antenna includes a plurality of slots, the one or more electrically conductive traces being proximate to at least one of the slots.

19. The display device of claim **1**, further comprising:
a display element;
a processor that is configured to communicate with the display element, the processor being configured to process image data; and
a memory device that is configured to communicate with the processor.

20. The display device of claim **19**, further comprising:
a driver circuit configured to send at least one signal to the display element; and
a controller configured to send at least a portion of the image data to the driver circuit.

21. The display device of claim **19**, further comprising:
an image source module configured to send the image data to the processor, wherein the image source module comprises at least one of a receiver, transceiver, and transmitter; and
an input device configured to receive input data and to communicate the input data to the processor.

22. A method of manufacturing an antenna panel, comprising:
providing a transparent substrate, wherein the transparent substrate includes a surface having a display region and a non-display region that surrounds at least a portion of a perimeter of the display region;
depositing a layer of substantially transparent electrically conductive material on the transparent substrate; and
patterning the layer to form a substantially transparent antenna in the display region of the transparent substrate.

23. The method of claim **22**, further comprising forming a second antenna in the non-display region of the transparent substrate.

24. The method of claim **22**, further comprising:
depositing a film of electrically conductive material on the substantially transparent antenna; and
patterning the film to form electrically conductive traces on the substantially transparent antenna.

25. The method of claim **24**, wherein the film includes at least one of aluminum, chromium, or molybdenum.

26. The method of claim **22**, further comprising:
depositing a substantially black interferometric stack structure on the substantially transparent antenna; and
patterning the substantially black interferometric stack structure to form electrically conductive traces on the substantially transparent antenna.

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