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### ANTENNA-ON-PACKAGE SYSTEM

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#### Abstract

One example includes an antenna-on-package system that includes a multi-layer antenna structure. The antenna structure includes a first conductive layer having a patch antenna and a transmission line. The transmission line extends from a feed-side edge of the patch antenna to terminate in a launch structure. The antenna structure also includes a second conductive layer having a ground reflector spaced apart from the first conductive layer by a layer of dielectric material. An integrated circuit (IC) die has a signal terminal on a surface of the IC die, and a conductive signal interconnect extends through the layer of dielectric material and is coupled between the signal terminal and the launch structure.

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## Background/Summary

[0001] This application is a continuation of U.S. patent application Ser. No. 17/854,197, filed Jun. 30, 2022, the contents of which are herein incorporated by reference in its entirety.

### TECHNICAL FIELD

[0002] This description relates generally to communication systems, and more particularly to an antenna-on-package system.

### BACKGROUND

[0003] Antennas provide a means of propagating wireless communications signals from transmitters and to receivers. As communications bandwidth increases, the size of antennas is increasingly being reduced to accommodate smaller wavelengths in a more compact form-factor. One manner of manufacturing antennas is to fabricate an antenna on an integrated circuit (IC), such as to form an antenna-on-package (AoP). Such antennas can be fabricated in a very small form-factor in a simplistic manner.

### SUMMARY

[0004] One example provides an antenna-on-package (AoP) system that includes a multi-layer antenna structure. The antenna structure includes a first conductive layer having a patch antenna and a transmission line. The transmission line extends from a feed-side edge of the patch antenna to terminate in a launch structure. The antenna structure also includes a second conductive layer having a ground reflector spaced apart from the first conductive layer by a layer of dielectric material. An integrated circuit (IC) die has a signal terminal on a surface of the IC die, and a conductive signal interconnect extends through the layer of dielectric material and is coupled between the signal terminal and the launch structure.

[0005] Another example described herein includes a method includes forming a ground reflector patterned of a first conductive layer over a respective surface of an embedded die. The method also includes forming a layer of dielectric material over the first conductive layer. The method also includes forming a patch antenna and a transmission line of a second conductive layer over the layer of dielectric material, and the transmission line extends from a feed-side edge of the patch antenna to terminate in a launch structure. The method also includes forming an interconnect between the launch structure of the transmission line and a terminal of the embedded die so as to form an antenna-on-package (AoP) device.

[0006] Another example described herein includes a communication system includes a printed circuit board and an antenna-on-package (AoP) device. The printed circuit board includes an arrangement of mounting terminals. The AoP device includes a first conductive layer comprising a patch antenna and a transmission line, in which the transmission line extends from a feed-side edge of the patch antenna to terminate in a launch structure. A second conductive layer includes a ground reflector spaced apart from the first conductive layer by a layer of dielectric material. An integrated circuit (IC) die includes a signal terminal on first surface and an arrangement of connecting terminals on a second surface of the IC die opposite the first surface. A conductive signal interconnect extends through the layer of dielectric material and is coupled between the signal terminal and the launch structure. The AoP device is mounted to the printed circuit board so the connecting terminals are coupled to respective mounting terminals.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 is an example of a communication system.

[0008] FIGS. 2A and 2B are an example of an antenna-on-package (AoP) device mounted to a

PCB.

[0009] FIGS. 3A and 3B are cross-sectional view showing part of the AoP device of FIG. 2A, including FIG. 3B showing an enlarged view of a launch structure.

[0010] FIG. 4 is a cross-sectional view showing part of another example AoP device.

[0011] FIG. 5 is another example of an AoP device mounted to a PCB.

[0012] FIG. 6 is a cross-sectional view showing part the AoP device of FIG. 5.

[0013] FIG. 7 is a flow diagram showing an example of a method for fabricating an AoP system.

[0014] FIGS. 8-23 are cross-sectional views of an AOP device during the method of fabrication.

[0015] FIG. 24 is a graph showing insertion loss and return loss for an example AoP device.

[0016] FIG. 25 is a graph showing impedance matching for an AoP device.

[0017] FIG. 26 is a graph showing return loss for the example AoP devices of FIGS. 2 and 5 over a range of frequencies.

[0018] FIGS. 27A-27F are plots showing radiation patterns for the AoP device of FIG. 2 at different frequencies.

[0019] FIGS. 28A-28F are plots showing radiation patterns for the AoP device of FIG. 5 at different frequencies.

#### DETAILED DESCRIPTION

[0020] This description relates generally to an antenna-on-package (AoP) device, which can be formed on an integrated circuit (IC) package having one or more embedded IC dies. The IC package can be mounted on a printed circuit board (PCB) to provide a communication systems.

[0021] As an example, an AoP device includes a first conductive layer patterned to form a patch antenna and a transmission line, in which the transmission line extends from a feed-side edge of the patch antenna to terminate in a launch structure for the patch antenna. A second conductive layer includes a ground reflector that is spaced apart from the first conductive layer by a layer of dielectric material. An embedded IC die has a signal terminal (e.g., a pad or other contact), which is adapted to send and/or receive radio frequency (RF) signals relative to circuitry on the die. A conductive signal interconnect (e.g., conductive via) is formed through the layer of dielectric material and coupled between the signal terminal and the launch structure of the patch antenna. In an example, first conductive layer, which forms the patch antenna and transmission line, and the second conductive layer, which forms the ground reflector, are implemented as respective redistribution layers formed during IC packaging of a wafer-level chip scale package that ultimately forms the AoP device. To increase antenna efficiency, the antenna can be formed on a top surface of the IC package over the IC die to enable direct air radiation. For example, the AoP device is configured (e.g., tuned) to operate over a desired bandwidth, such as WR-5 (e.g., 140 GHz-220 GHz) or other frequency range according to application requirements. In some examples, the patch antenna structure can be formed directly overlying the IC die to reduce the overall package size. The AoP device further can be mounted to a printed circuit board (PCB), such as through soldering or other method according to the type of IC packaging technology.

[0022] FIG. 1 is a schematic block diagram showing an example of a communication system **100** that includes an AoP device **102** mounted to a PCB **104**. The AoP device **102** includes a multi-layer antenna structure **106** formed over an embedded IC die **108**. As described herein, the AoP device **102** can be formed during packaging of the IC die **108**, in which the IC die is embedded within an insulating material, such as such as an Ajinomoto Build-up Film (ABF) insulating material or another insulating materials (e.g., a pre-preg material or an epoxy). The multilayer antenna includes a first conductive layer configured to form a patch antenna and a transmission line. For example, a first redistribution layer (RDL) has a conductive layer patterned to form the patch antenna and transmission line over the IC die. In one example, the RDL is formed from an electrically conductive material such as can be electroplated, sputtered, or evaporated over the layers a dielectric material or other preceding layer(s) as described herein. Example conductive materials include copper (e.g., electroplated) and aluminum (e.g., sputtered or evaporated).

[0023] The first layer structures (e.g., patch antenna and transmission line) can be formed at or near a top surface **110** of the AoP device **102** so the antenna can implement direct air radiation. The transmission line can extend from a feed-side edge of the patch antenna to terminate in a launch structure (e.g., coplanar waveguide launch). In an example, the patch antenna is configured as an E-shaped antenna having a pair of notches in the feed-side edge of the patch antenna on opposite sides of from where the transmission line extends.

[0024] The antenna structure **106** also includes a second conductive layer configured to form a ground reflector. For example, a second RDL has a respective conductive layer patterned to form the ground reflector located beneath the first layer (e.g., closer to the IC die than the first layer). The second conductive layer is spaced apart from the first conductive layer by a layer of dielectric material. A conductive signal interconnect (e.g., conductive via), shown as **112**, extends through the layer of dielectric material to couple a signal terminal of the IC die to the launch structure. In an example, the first conductive layer also includes a guard ring formed around the patch antenna. The guard ring can include an opening through which the transmission line extends. The guard ring can be coupled to the ground plane by an arrangement of conductive signal interconnects (e.g., conductive vias) through the layer of dielectric material.

[0025] The IC die **108** includes circuitry **114**. The circuitry **114** can be configured to perform a variety of circuit functions, including to transmit and/or receive RF signals over a range of frequencies to which the antenna is tuned. For example, the antenna **106** is configured to communicate signals having a frequency in a range from about 140 GHz to about 220 GHz (e.g., WR-5 frequency spectrum). The antenna **106** can be configured to communicate signals in other frequency ranges as may vary according to application requirements. The AoP device **102** can be mounted to the PCB **104**, such as through an interconnect **116** of the IC die **108**. For example, the AoP device **102** can be soldered or fastened to the PCB substrate **204** in any of a variety of ways, such as by solder bumps or another interconnect technology **116**.

[0026] FIGS. 2 and 3 illustrate an example of a communication system **200** that includes an AoP device **202** mounted to a substrate **204**, such as a PCB. The AoP device **202** is an example embodiment of the AoP device **102** of FIG. 1. The AoP device **202** includes a first conductive layer **206** that includes a patch antenna **208** and a transmission line **210**. The transmission line **210** can extend from a feed-side edge **212** of the patch antenna to terminate in a launch structure (e.g., coplanar waveguide launch) **214**. In the example of FIG. 2, the patch antenna **208** is configured as an E-shaped antenna having a pair of notches **216** and **218** in the feed-side edge **212** of the antenna on opposite sides of a location from where the transmission line **210** extends.

[0027] The first conductive layer **206** can also include a guard ring **220** formed configured to surround the patch antenna **208**. The guard ring **220** can include an opening **222** between spaced apart edges of opposing guard ring end portions **224** and **226**. The guard ring end portions **224** and **226** can extend (e.g., as legs) from a feed-side of the guard ring **220** in a direction parallel to the transmission line **210**. The transmission line **210** thus can extend longitudinally at least partially through the opening **222**.

[0028] The AoP device **202** also includes a second conductive layer **234** configured to form a ground reflector **236**. For example, the second conductive layer is a second RDL that is patterned to form a rectangular ground reflector **236** located beneath the first layer (e.g., closer to an IC die **240** than the first layer). The second conductive layer **234** is spaced apart from the first conductive layer **206** by a layer of dielectric material **242**. The area of the ground reflector **236** is at least as large and can be larger than an area of the guard ring **220**. The ground reflector **236** also can have a comparable rectangular configuration to the periphery of the guard ring **220**. For example, the plane of the ground reflector **236** extends outwardly beyond edges of the ground reflector (e.g., in the x-and y-directions) along each edge of the ground reflector except a feed-side edge thereof. As shown in the example of FIGS. 2 and 3, an arrangement of conductive interconnects (e.g., conductive vias) **241** are distributed along a periphery of the guard ring **220** and extend through the

layer of dielectric material **242** to couple the guard ring to the ground reflector **236** around the antenna **208**.

[0029] In an example, the launch structure **214** has a circular shape, and the guard ring end portions **224** and **226** include opposing curved recessed edges **228** and **230** along opposite sides of the circular-shaped launch structure **214** so edges of the guard ring end portions **224** and **226** surround the circular-shaped launch structure. The AoP device **202** thus includes a circular-shaped via feed structure **244** that includes the launch structure **214** of the first conductive layer **206** and a conductive signal interconnect **246**. The signal interconnect **246** can be formed as a conductive via along a Z axis orthogonal to a surface of conductive layer **206**, which extend through the layer of dielectric material **242** and is coupled to a respective terminal **248** patterned in the second conductive layer **234**. The signal interconnect **246** is electrically isolated from the ground reflector **236**. The patterned terminal **248** of the second conductive layer **234** is coupled to a respective signal terminal (e.g., an electrically conductive pad or other contact) **250**, which is coupled to circuitry of the IC die **240** through an opening **252** in the second conductive layer **234** (e.g., RDL) and through a passivation coating or layer **251** on the die **240**. In some examples, a polyimide layer **253** can be formed over the passivation layer **251**.

[0030] In a further example, the feed structure **244** is implemented as a ground-signal-ground (GSG) launch. For example, the feed structure **244** includes a first ground interconnect (e.g., conductive via) **254** that extends from a guard ring end portion **224** through the layer of dielectric material **242** and is coupled to a respective ground terminal **256**, which is patterned in the second conductive layer **234**. The feed structure includes another ground element having a second ground interconnect **258** that extends from the other guard ring end portion **226** through the layer of dielectric material **242** and is coupled to a respective ground terminal **260** patterned in the second conductive layer **234**. The ground terminals **256** and **260** of the second conductive layer **234** can be coupled to a respective ground terminal of the IC die **240**.

[0031] As described above, the AoP device **202** can be mounted to a substrate (e.g., PCB) **204**, such as through a solder bumps or another interconnect technology of the packaged die **240**. The AoP device **202** also includes conductive vias **264** coupled between the antenna structure and one or more other layers **266** and **268** of the integrated package structure. For example, the vias **264** can be configured to carry ground or other signals between the antenna and circuitry of the package, such as through conductive traces implemented on or within the respective layers **266** and **268**.

[0032] FIG. **4** is a cross-sectional view showing another example of part of an AoP device **400**. The AoP device **400** includes an antenna structure formed over a die **404** embedded within a volume of an insulating material **406**, such as an ABF insulating material. The cross-sectional view in the example of FIG. **4** is along a similar view as the enlarged portion of FIG. **3**, such as to show structural features near a signal launch. For example, a signal terminal (e.g., a pad) **408** is formed on the die **404**, such as patterned conductive material (e.g., copper or aluminum), by etching through passivation and polyimide layers **410** and **412**, respectively. A conductive RDL **414** (e.g., the second conductive layer **234**) is formed over the polyimide layer **412**. For example the redistribution layer **414** is patterned to form a ground reflector **416** (e.g., ground reflector **236**) and conductive traces **418** electrically isolated from the ground reflector and coupled to the signal terminal **408**.

[0033] A layer of dielectric material **420** is formed over the patterned redistribution layer **414**, such as described herein. Another conductive RDL **422** is formed over the dielectric material layer **420**. As described herein, the RDL **422** is patterned to form a transmission line **424** (e.g., transmission line **210**) and a patch antenna (e.g., patch antenna **208**). A conductive via **426** is formed through the dielectric layer **420** to couple a launch at the distal end of the transmission line **424** to the conductive trace **418**. A solder mask **428** of an insulating material photoresist is deposited over the RDL **422** and exposed portions of the dielectric material layer **420**. The opening in the solder mask leaves the antenna structure exposed to promote a desired radiation pattern for the antenna at the

top of the AoP device **400**.

[0034] FIGS. **5** and **6** show different views of another example a communication system **500** that includes an AoP device **502** mounted to a PCB **504**. The AoP device **502** is another example embodiment of the AoP device **102** of FIG. **1**. The AoP device **502** is shown having a similar configuration and can be fabricated using the same process flow as the example of FIGS. **2** and **3**. That is, in that the AoP device **502** includes an antenna **506** and an embedded IC die **508**. However, in the example of FIGS. **5** and **6** the antenna **506** is positioned laterally relative to the embedded IC die **508**, whereas in the example of FIGS. **2** and **3**, the antenna **208** is positioned directly over the embedded IC die **240**. For example, as shown in FIGS. **2** and **3** the patch antenna **208** has a periphery positioned directly over and within a virtual projection extending orthogonally from a periphery of the IC die **240**. The offset configuration of the AoP device **502** in FIGS. **5** and **6** provides more space to route signal inputs/outputs and power (e.g., through the packaging material in which the die **508** is mounted), which can also reduce noise due to the reduced signal line density, but at the cost of needing a larger package size. Thus, the AoP device **202** in the example of FIGS. **2** and **3** can provide a more compact package having reduced surface area, though has a higher signal line density.

[0035] The AoP device **502** includes a first conductive layer **510** (e.g., an RDL) that is patterned to form the patch antenna **506** (e.g., an E-shaped patch antenna) and a transmission line **512**. The transmission line **512** can extend from a feed-side edge **514** of the patch antenna to terminate in a launch structure (e.g., coplanar waveguide launch) **516**. In an example, as shown in the cross-sectional view of FIG. **6**, the launch structure **516** extends over a portion of IC die **508**, and an interconnect (e.g., a conductive via extending along a Z axis) **518** couples the transmission line **516** to a respective signal terminal of the IC die **508**. In an example, the launch structure **516** can be implemented as a GSG launch, such as shown in the enlarged view of FIG. **2**.

[0036] The first conductive layer **510** can also include a guard ring **520** formed configured to surround the patch antenna **506**. The guard ring **520** can include an opening between spaced apart edges of opposing guard ring end portions **524** and **526**, such as described herein (see, e.g., the enlarged view of FIG. **2**). The transmission line **512** thus can extend longitudinally at least partially through the opening so the transmission line is electrically isolated from the guard ring **520**.

[0037] The AoP device **502** also includes a second conductive layer **530** configured to form a ground reflector **532**. For example, the second conductive layer **530** is a second RDL that is patterned to form a planar sheet ground reflector **532** and one or more conductive traces (not shown, but see, e.g., FIGS. **2** and **3**) beneath the first conductive layer **510**. The first and second conductive layers **510** and **530** are spaced apart from each other by a layer of dielectric material **534**. The area of the ground reflector **532** can have an area that is at least commensurate (e.g., approximately the same size or larger) with an area of the guard ring **520**, and have a similar shape. An arrangement of conductive interconnects (e.g., conductive vias) **536** are distributed along a periphery of the guard ring **520** and extend through the layer of dielectric material **534** to couple the guard ring to the ground reflector **532**. The signal via **518** also extends through the dielectric material between the respective layers **510** and **530**.

[0038] As described herein, the AoP device **502** can be mounted to the PCB **504**, such as through a solder bumps or another interconnect technology. The AoP device **202** also includes conductive vias **540** coupled between the antenna structure and additional layers **542** and **544** within the package. For example, the vias **540** can be implemented to connect to ground, power or carry other signals between the antenna and other circuitry of the integrated system package **502**.

[0039] FIG. **7** is a flow diagram illustrating an example method **700** of fabricating an AoP device, such as the devices of FIGS. **1-6**. The method **700** can be performed, for example, as part of a larger process of packaging the IC die, and is not to be limited to the order or actions described herein. The method **700** is described in relation to the cross-sectional views of FIGS. **8-21**, which show an example processing progression for forming an AoP device according to the method.

[0040] At **702**, the method **700** includes attaching and embedding one or more dies within a frame. For example, as shown in FIG. **8** a frame (also referred to as a core) **800** can be attached to an adhesive tape **802**, such as by laminating the tape to the frame. The frame **800** can include a plurality of conductive vias, such as etched along a periphery of the frame (e.g., vias **264** or **540**). Cavities **806** can also be cut into the frame (e.g., prior to attaching to the tape) between respective core. As shown in FIG. **9**, a die **900** can be placed into a respective cavity **806**. The die **900** can include an arrangement of conductive terminals (e.g., pads or pillars) **902** along a respective front surface of the die. The configuration of terminals **902** can vary depending on the type of die. In FIG. **10**, an insulating material **1000**, such as ABE, is applied (e.g., using a vacuum laminator) to laminate onto a backside of the die **900** and to fill gaps between the die and frame **800**. The lamination can be cured to fix the dies in the cavity **806** with respect to the frames. As shown in FIG. **11**, a top portion of the lamination can be removed, such as by plasma cleaning (e.g., treating with oxygen plasma) or another cleaning process. In FIG. **12**, the adhesive tape has been removed and the intermediate structure is flipped over so the conductive terminals are at the top. FIG. **12** thus shows an example of an embedded die on which an antenna structure can be formed, as described herein.

[0041] At **704**, conductive seed layers are formed along both surfaces. For example, as shown in FIG. **13**, seed layers **1302** and **1304** are deposited on the respective surfaces, such as by spin coating or another deposition process. At **706**, a dielectric film layer is formed. For example, as shown in FIG. **14**, respective dielectric film layers **1402** and **1404** are formed over the respective seed layers **1302** and **1304**. The dielectric film layers **1402** and **1404** can be applied as a coating using a vacuum lamination or another process. At **708**, the dielectric film is patterned and etched. For example, as shown in FIG. **15**, portions of the dielectric film can be removed on respective sides, such as by selective etching through a patterned hardmask, shown schematically at **1502**.

[0042] At **710**, respective conductive layers are formed over the portions of the seed layer exposed following removal of the dielectric film (at **708**). For example, as shown in FIG. **16**, respective conductive layers **1602** and **1604** are formed on the exposed surfaces over the seed layers where the dielectric film layers **1402** and **1404** had been removed. In one example, the conductive layers **1602** and **1604** are formed as an electrically conductive RDLs, such as including a layer of copper that is electroplated onto the seed layers **1302** and **1304**. In another example, the conductive RDLs **1602** and **1604** can include aluminum that is sputtered or evaporated onto the seed layers **1302** and **1304**. The RDL **1602** can define a ground plane of an antenna structure being formed. The other RDL **1604** can include respective traces coupled to terminals of the IC die and routing traces in the respective vias **804** for carrying signals and/or power. At **712**, the remaining dielectric film is removed, such as by etching (e.g., a wet cleaning or ashing process). Thus, as shown in FIG. **17**, the dielectric film layers **1402** and **1404** have been removed.

[0043] At **714**, the seed layer is etched. For example, in areas where the conductive RDLs **1602** and **1604** do not cover the seed layers **1302** and **1304**, the exposed seed layer can be etched, such as shown schematically at **1802** and **1804** in FIG. **18**. At **716**, a dielectric layer is formed over the RDL at the top surface. For example, as shown in FIG. **19**, the dielectric layer **1902** is formed over the RDL ground plane layer. At **718**, another conductive layer is formed over portions of the dielectric layer (formed at **716**). For example, as shown in FIG. **20**, the conductive layer **2002** is formed as an electrically conductive RDL patterned over the dielectric layers **1902**, such as to form an E-shaped antenna, a transmission line and a guard ring. As described herein, the guard ring can be electrically coupled to the ground plane of RDL **1602** through conductive vias formed through the dielectric layer **1902**, such as described herein. Additionally, the launch structure of the transmission line can be electrically coupled to a feed through a respective conductive via formed through the dielectric layer **1902**. The RDL **2002** can be formed copper or aluminum, such as described with respect to the RDL **1602**.

[0044] At **720**, laminated dielectric layers can be formed over the respective surfaces of the

package, such as shown at **2102** and **2104** in the example of FIG. **21**. At **722**, respective openings are formed through the lamination layers and, at **724** metal layer pads are formed through the openings over the bottom RDL **1604**. For example, as shown at **2204** in FIG. **22**, selective portions of the laminated dielectric layers can be etched away to expose the respective conductive layer (RDLs) **1604**. FIG. **23** shows an example of pad surfaces **2302** being formed over the respective conductive layer **1604**, such as by electroplating (e.g., for copper pads) or by sputtering or evaporating (e.g., for aluminum pads). Metal pads are not formed over the top RDL **1602** to enable a desired radiation pattern for the antenna structure that is formed thereon. The AoP device can be formed in a batch in which respective packages can be removed from the frame through a package separate process. Each AoP device can then be mounted on a respective PCB, such as described herein.

[0045] FIG. **24** is a graph **2400** showing plots **2402**, **2404** and **2406** for insertion loss and return loss for an example AoP device (e.g., device **202** or **502**). The plot **2402** shows insertion loss of the feed structure at less than about  $-0.5$  dB. The plot **2404** shows return loss for an S11 scattering parameter, and the plot **2406** shows return loss for an S22 scattering parameter. The example AoP device thus can achieve better than  $-15$  dB return loss.

[0046] FIG. **25** is a graph **2500** showing impedance matching for a port of an example AoP device (e.g., device **202** or **502**). The graph demonstrates a well-controlled impedance of about **502** for the WR-5 band.

[0047] FIG. **26** is a graph showing plots **2602** and **2604** of return loss for the example AoP devices **202** and **502** of FIGS. **2** and **5** over a range of frequencies. For example, the plots **2602** and **2604** show admittance over a frequency range from about 140 GHz to about 220 GHz, demonstrating that both example AoP devices **202** and **502** can achieve good bandwidth performance of about 20 GHz+ within the WR-5 band. Both antenna designs further can achieve good peak gain (e.g., maximum of about 7 dB) and radiation efficiency (e.g., maximum of about 55%).

[0048] FIGS. **27A-27F** are plots showing radiation patterns from a surface of the antenna **208** from a surface of the AoP device **202** of FIGS. **2-3**. FIG. **27F** shows a three-dimensional radiation pattern **2700**, and FIGS. **27A-27E** show section views through the radiation pattern **2700** at different distances from the antenna surface for different frequencies, as shown. For example, FIG. **27A** shows radiation patterns **2702** and **2704** for 185 GHz. FIG. **27B** shows radiation patterns **2706** and **2708** for 190 GHz. FIG. **27C** shows radiation patterns **2710** and **2712** for 200 GHz. FIG. **27D** shows radiation patterns **2714** and **2716** for 210 GHz, and FIG. **27E** shows radiation patterns **2718** and **2720** for 220 GHz. A review of the plots of FIGS. **27A-27E** demonstrates the AoP device can achieve good radiation pattern across the bandwidth, with better radiation being achieved near 210 GHz.

[0049] FIGS. **28A-28F** are plots showing radiation patterns from a surface of the antenna **208** from a surface of the AoP device **502** of FIGS. **4-5**. FIG. **28F** shows a three-dimensional radiation pattern **2800**, and FIGS. **28A-28E** show section views through the radiation pattern **2800** at different distances from the antenna surface for different frequencies, as shown. For example, FIG. **28A** shows radiation patterns **2802** and **2804** for 185 GHz. FIG. **28B** shows radiation patterns **2806** and **2808** for 190 GHz. FIG. **28C** shows radiation patterns **2810** and **2812** for 200 GHz. FIG. **28D** shows radiation patterns **2814** and **2816** for 210 GHz, and FIG. **28E** shows radiation patterns **2818** and **2820** for 220 GHz. A review of the plots of FIGS. **28A-28E** demonstrates the AoP device can achieve good radiation pattern across the bandwidth, with better radiation being achieved near 220 GHz.

[0050] In this description, numerical designations “first”, “second”, etc. are not necessarily consistent with same designations in the claims herein. Additionally, the term “couple” may cover connections, communications, or signal paths that enable a functional relationship consistent with this description. For example, if device A generates a signal to control device B to perform an action, then: (a) in a first example, device A is directly coupled to device B; or (b) in a second



example, device A is indirectly coupled to device B through intervening component C if intervening component C does not alter the functional relationship between device A and device B, so device B is controlled by device A via the control signal generated by device A.

[0051] Also, in this description, a device that is “configured to” perform a task or function may be configured (e.g., programmed and/or hardwired) at a time of manufacturing by a manufacturer to perform the function and/or may be configurable (or reconfigurable) by a user after manufacturing to perform the function and/or other additional or alternative functions. The configuring may be through firmware and/or software programming of the device, through a construction and/or layout of hardware components and interconnections of the device, or a combination thereof.

Furthermore, a circuit or device described herein as including certain components may instead be configured to couple to those components to form the described circuitry or device. For example, a structure described as including one or more semiconductor elements (such as transistors), one or more passive elements (such as resistors, capacitors, and/or inductors), and/or one or more sources (such as voltage and/or current sources) may instead include only the semiconductor elements within a single physical device (e.g., a semiconductor wafer and/or integrated circuit (IC) package) and may be configured to couple to at least some of the passive elements and/or the sources to form the described structure, either at a time of manufacture or after a time of manufacture, such as by an end user and/or a third party.

[0052] Modifications are possible in the described embodiments, and other embodiments are possible, within the scope of the claims.

## Claims

1. An apparatus, comprising: a multi-layer antenna structure, the multi-layer antenna structure comprising: a first conductive layer comprising an antenna and a transmission line, the transmission line extending from a first edge of the antenna to a first terminal; and a second conductive layer spaced apart from the first conductive layer by a layer of dielectric material; an integrated circuit (IC) die having a signal terminal on a surface of the IC die; a conductive signal interconnect extending through the layer of dielectric material and coupled between the signal terminal and the first terminal; a guard structure formed of the first conductive layer that is coplanar with the antenna, the guard structure being spaced apart from and around the antenna; a first ground interconnect extending through the layer of dielectric material and coupled between a first ground terminal of the IC die and a first guard structure end portion; and a second ground interconnect extending through the layer of dielectric material and coupled between a second ground terminal of the IC die and a second guard structure end portion.
2. The apparatus of claim 1, wherein the second conductive layer comprises a ground reflector.
3. The apparatus of claim 2, further comprising a plurality of conductive vias coupled between the guard structure and the ground reflector.
4. The apparatus of claim 1, wherein the antenna comprises a patch antenna.
5. The apparatus of claim 4, wherein the patch antenna comprises an E-shaped patch antenna having a pair of notches in the first edge.
6. The apparatus of claim 1, wherein the transmission line extends at least partially through an opening between the first guard structure end portion and the second guard structure end portion.
7. The apparatus of claim 6, wherein the first terminal is circular-shaped, and the first and second guard structure end portions include opposing curved recessed edges along opposite sides of the circular-shaped first terminal.
8. The apparatus of claim 1, wherein the multi-layer antenna structure is configured to communicate signals having a frequency in a range from about 140 GHz to about 220 GHz.
9. The apparatus of claim 1, wherein the IC die is embedded within an insulating material, the IC die comprising at least a transmitter and/or a receiver, and the first conductive layer comprises a

redistribution layer on a surface of the multi-layer antenna structure spaced apart from the surface of the IC die.

**10.** The apparatus of claim 1, wherein the IC die comprises interconnects on another surface of the IC die opposite of the surface having the signal terminal, the apparatus further comprising a printed circuit board coupled to the IC die by the interconnects.

**11.** The apparatus of claim 1, wherein the antenna has a periphery positioned directly over and within a virtual projection extending orthogonally of the IC die.

**12.** A method, comprising: forming a first conductive layer over a respective surface of an embedded die; forming a layer of dielectric material over the first conductive layer; forming an antenna and a transmission line in a second conductive layer over the layer of dielectric material, the transmission line extending from a first edge of the antenna to a first terminal; forming an interconnect between the first terminal and a terminal of the embedded die; forming a guard structure in the second conductive layer, the guard structure having an inner periphery spaced outwardly from an outer periphery of the antenna; forming a first ground interconnect extending through the layer of dielectric material to couple a first ground terminal of the embedded die and a first guard structure end portion; and forming a second ground interconnect extending through the layer of dielectric material to couple a second ground terminal of the embedded die and a second guard structure end portion.

**13.** The method of claim 12, wherein the first conductive layer comprises a ground reflector.

**14.** The method of claim 13, further comprising forming a plurality of conductive vias between the guard structure and the ground reflector.

**15.** The method of claim 12, wherein the transmission line extends at least partially through an opening between the first guard structure end portion and the second guard structure end portion.

**16.** The method of claim 15, wherein the first terminal is circular-shaped, and the first and second guard structure end portions include opposing curved recessed edges formed along opposite sides of the circular-shaped first terminal.

**17.** The method of claim 12, wherein the antenna comprises a patch antenna.

**18.** The method of claim 17, wherein the patch antenna comprises an E-shaped patch antenna having a pair of notches in the first edge.

**19.** The method of claim 12, wherein the first and second conductive layers comprise redistribution layers.

**20.** A communication system, comprising: a printed circuit board including an arrangement of mounting terminals; and a device comprising: a first conductive layer comprising an antenna and a transmission line, the transmission line extending from a first edge of the antenna to a first terminal; a second conductive layer spaced apart from the first conductive layer by a layer of dielectric material; an integrated circuit (IC) die including a signal terminal on a first surface and an arrangement of connecting terminals on a second surface opposite the first surface; a conductive signal interconnect extending through the layer of dielectric material and coupled between the signal terminal and the first terminal; a guard structure formed of the first conductive layer around the antenna and at least a portion of the transmission line; a first ground interconnect extending through the layer of dielectric material and coupled between a first ground terminal of the IC die and a first guard structure end portion; and a second ground interconnect extending through the layer of dielectric material and coupled between a second ground terminal of the IC die and a second guard structure end portion.

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