US 20210013582A1

(19) United States
(12) Patent Application Publication
(10) Pub. No.: US 2021/0013582 A1
(43) Pub. Date: Jan. 14, 2021
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(54) RADIO FREQUENCY MODULES WITH MILLIMETER-WAVE AIR-GAP PHASED-ARRAY ANTENNA

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(21) Appl. No.: **16/925,831**

(22) Filed: **Jul. 10, 2020**

Related U.S. Application Data

(60) Provisional application No. 62/872,759, filed on Jul. 11, 2019.

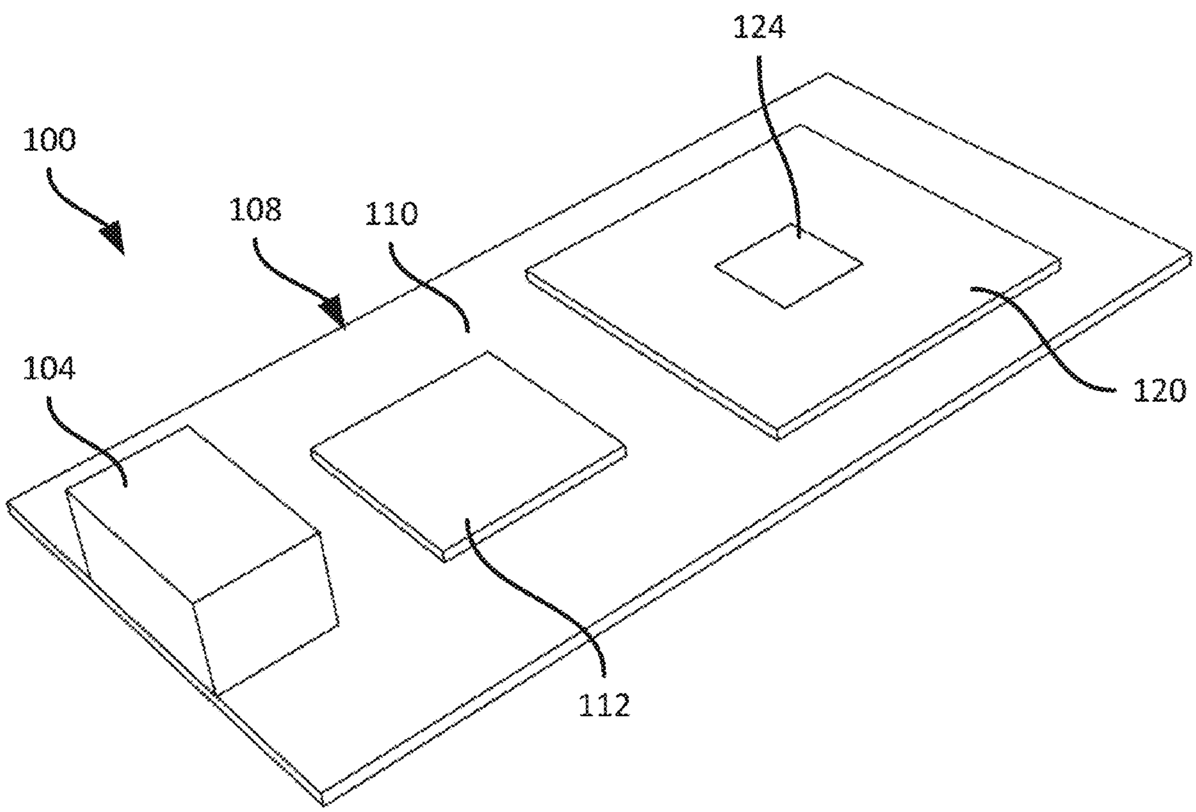
Publication Classification

(51) **Int. Cl.**
H01Q 1/16 (2006.01)
H01Q 23/00 (2006.01)
H01Q 1/22 (2006.01)

(52) **U.S. Cl.**
CPC ***H01Q 1/16*** (2013.01); ***H01Q 1/2283*** (2013.01); ***H01Q 23/00*** (2013.01)

(57) **ABSTRACT**

A radio frequency module includes: a primary board including: an upper surface carrying a radio controller; and a lower surface carrying antenna control elements; a spacer affixed to the lower surface and having a predefined height extending away from the lower surface; and a secondary board affixed to the spacer, separated from the lower surface by an air gap having the predetermined height; the secondary board supporting a phased array of antenna elements.



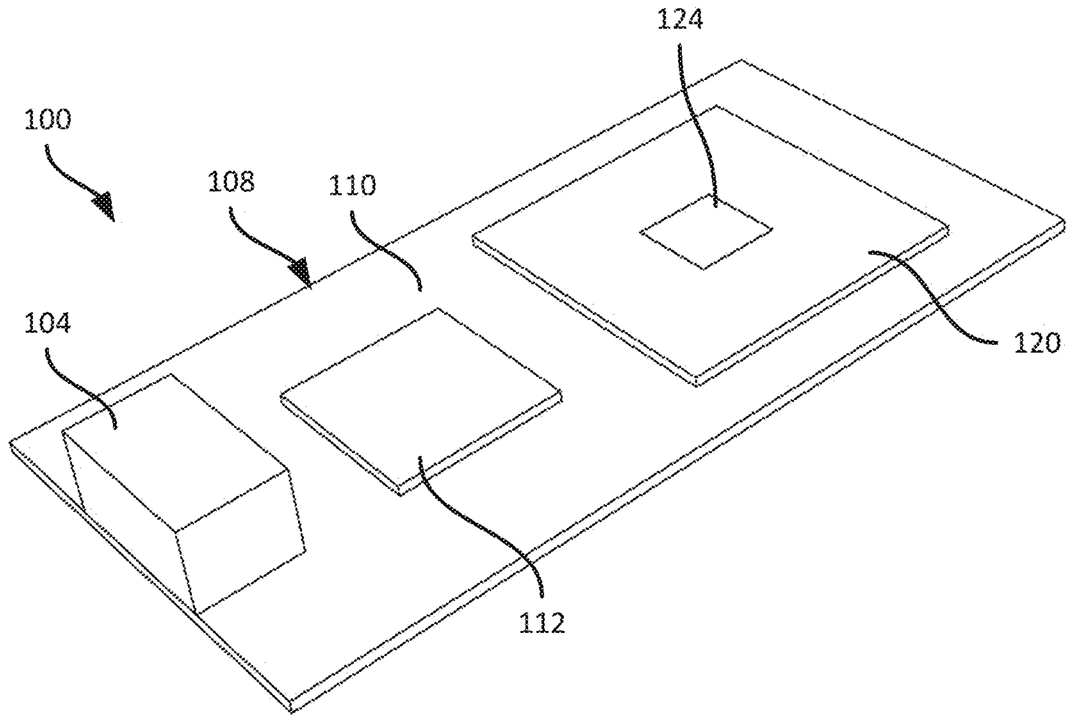


FIG. 1A

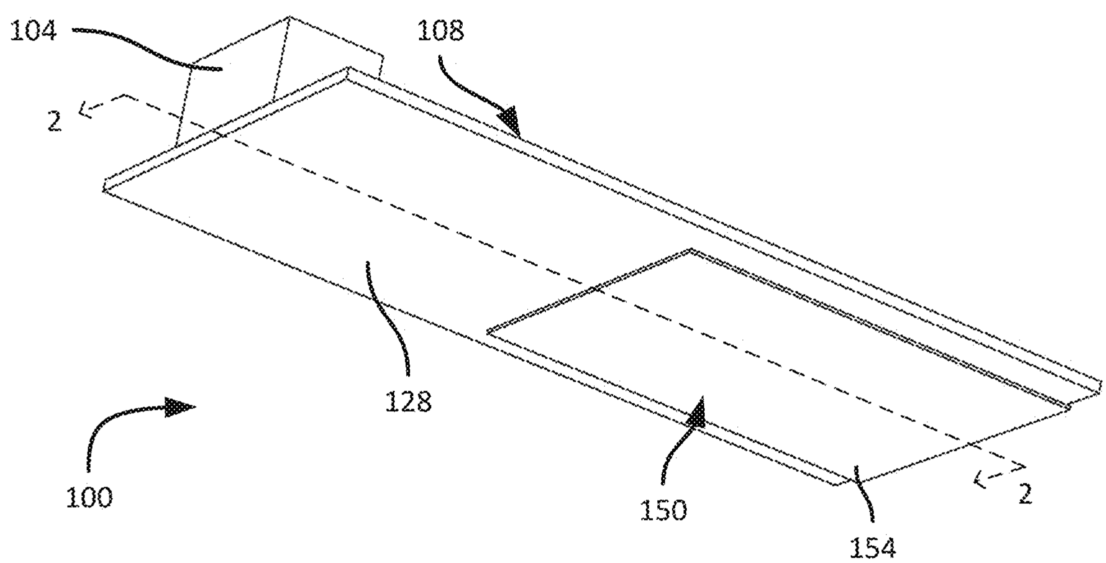


FIG. 1B

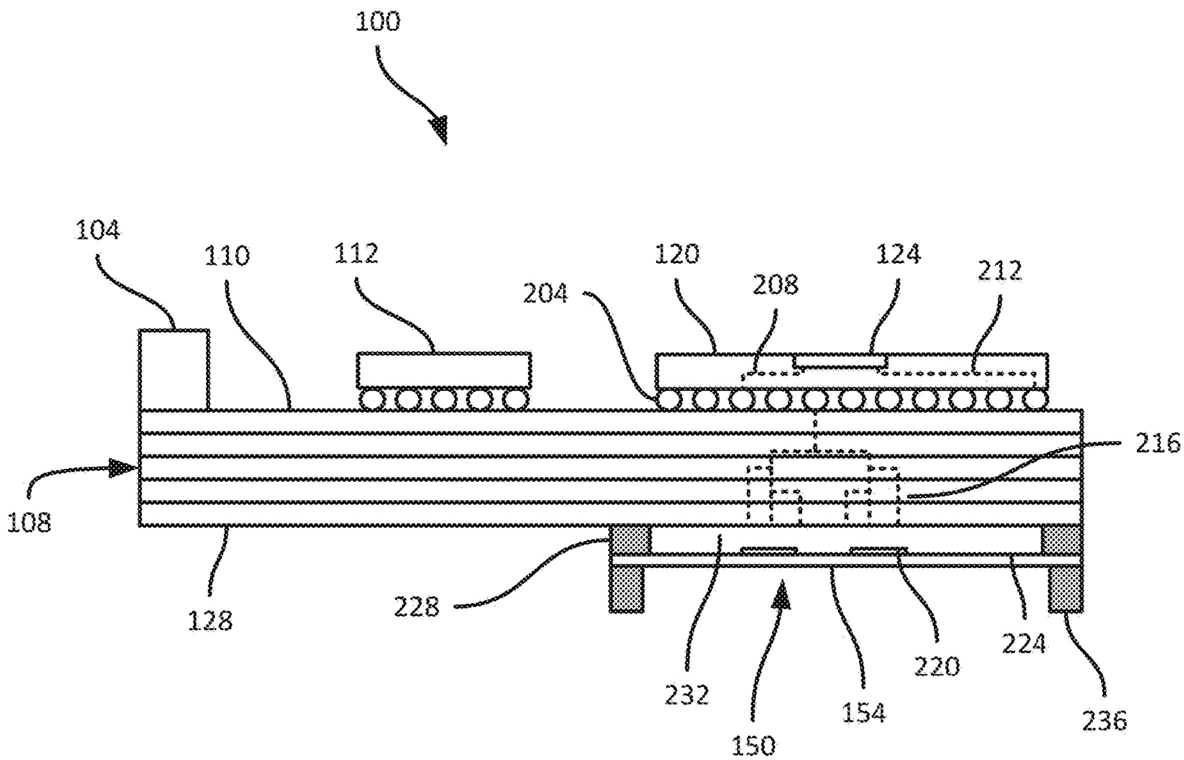

100
104
110
112
120
208
124
212
204
216
108
128
228
232
150
154
220
224
236

FIG. 2

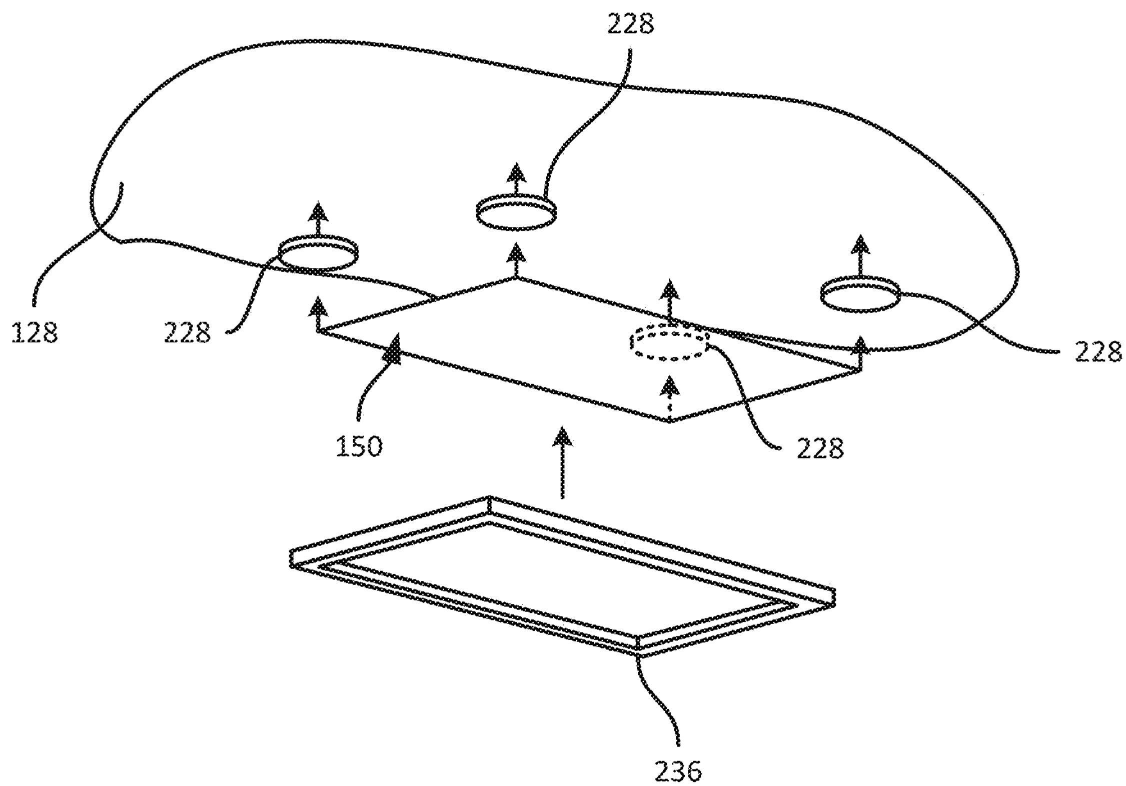


FIG. 3

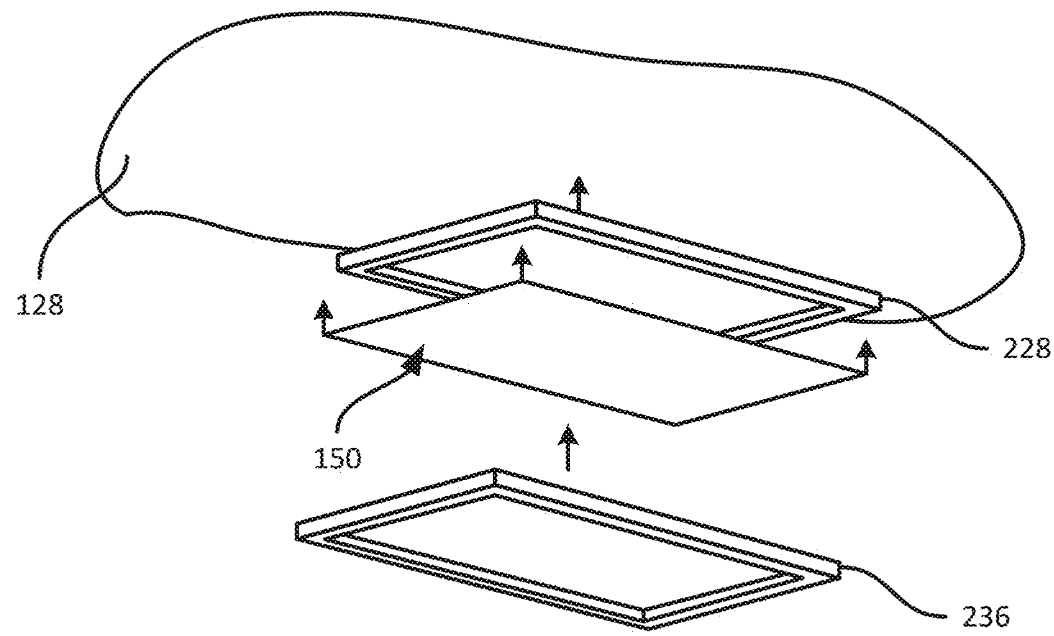


FIG. 4

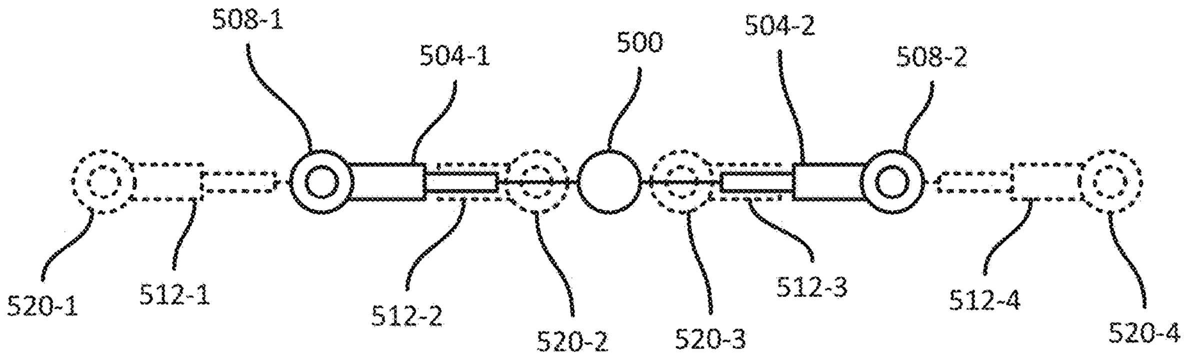

508-1
504-1
500
504-2
508-2
520-1
512-1
512-2
520-2
520-3
512-3
512-4
520-4

FIG. 5A

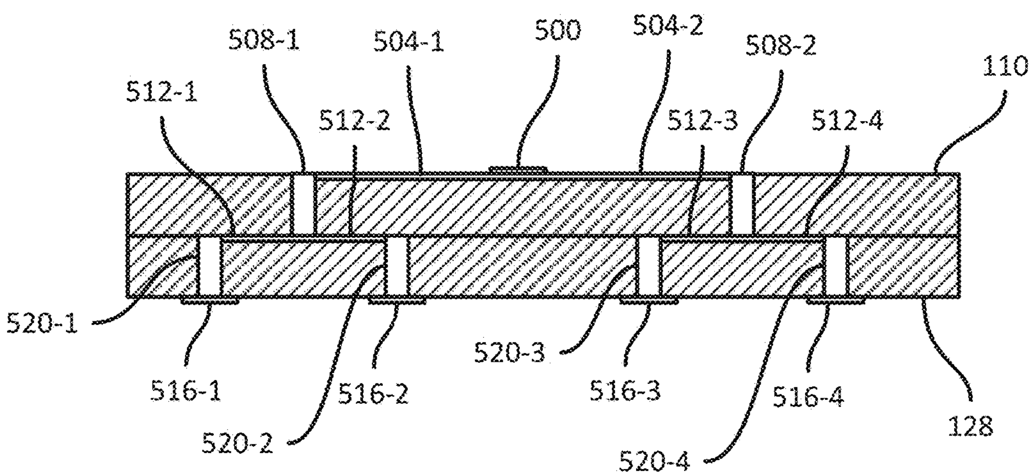

508-1
504-1
500
504-2
508-2
110
512-1
512-2
512-3
512-4
520-1
516-1
516-2
520-2
520-3
516-3
516-4
520-4
128

FIG. 5B

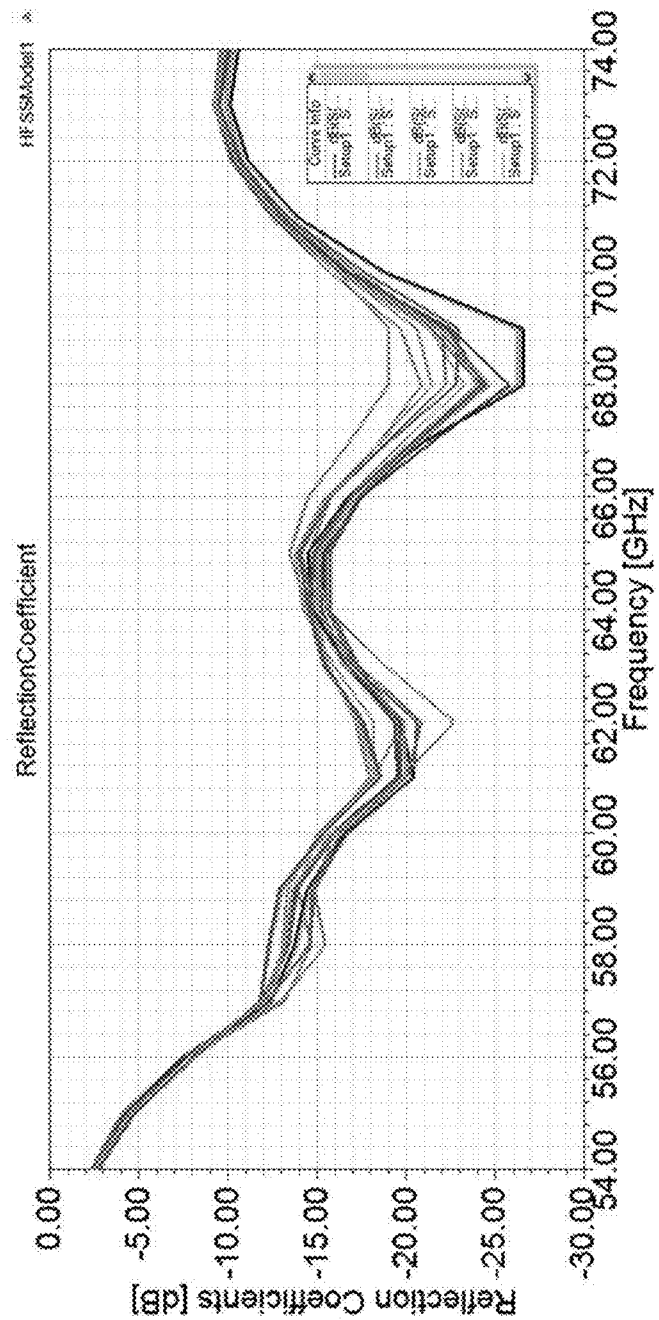

ReflectionCoefficient
HFSSModel1
Reflection Coefficients [dB]
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
Frequency [GHz]
54.00
56.00
58.00
60.00
62.00
64.00
66.00
68.00
70.00
72.00
74.00

FIG. 6

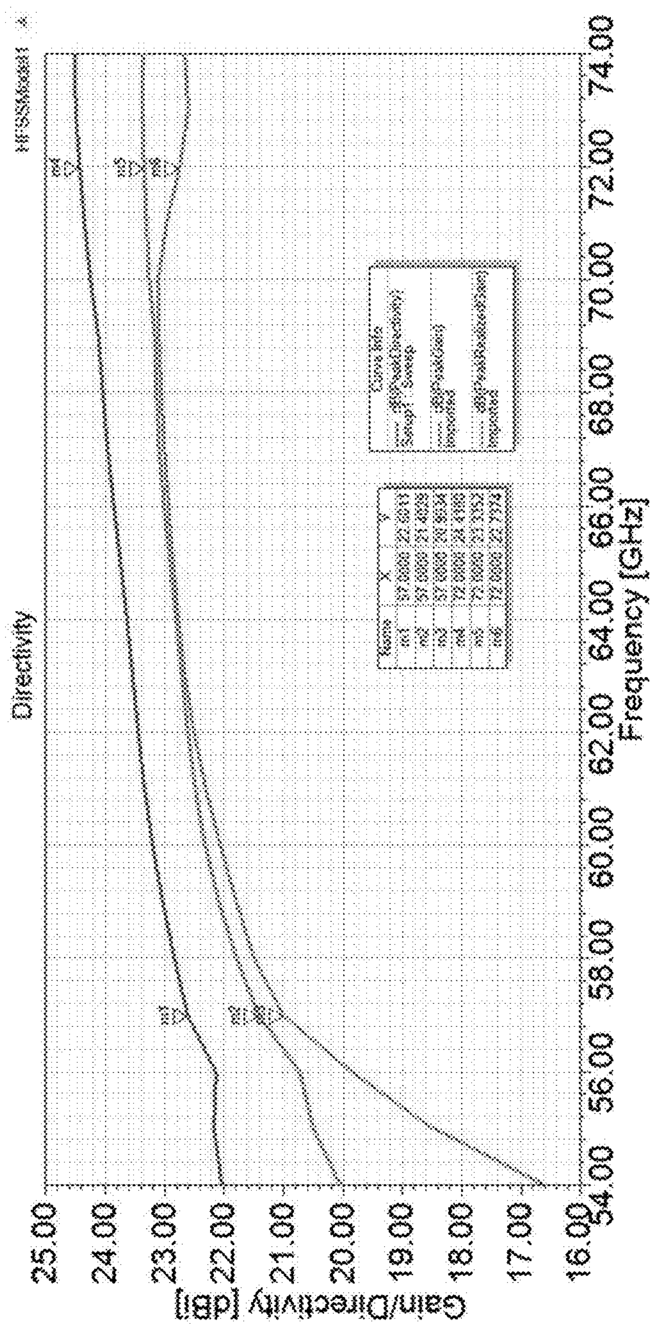

Directivity
Gain/Directivity [dBi]
25.00
24.00
23.00
22.00
21.00
20.00
19.00
18.00
17.00
16.00
54.00
56.00
58.00
60.00
62.00
64.00
66.00
68.00
70.00
72.00
74.00
Frequency [GHz]

FIG. 7

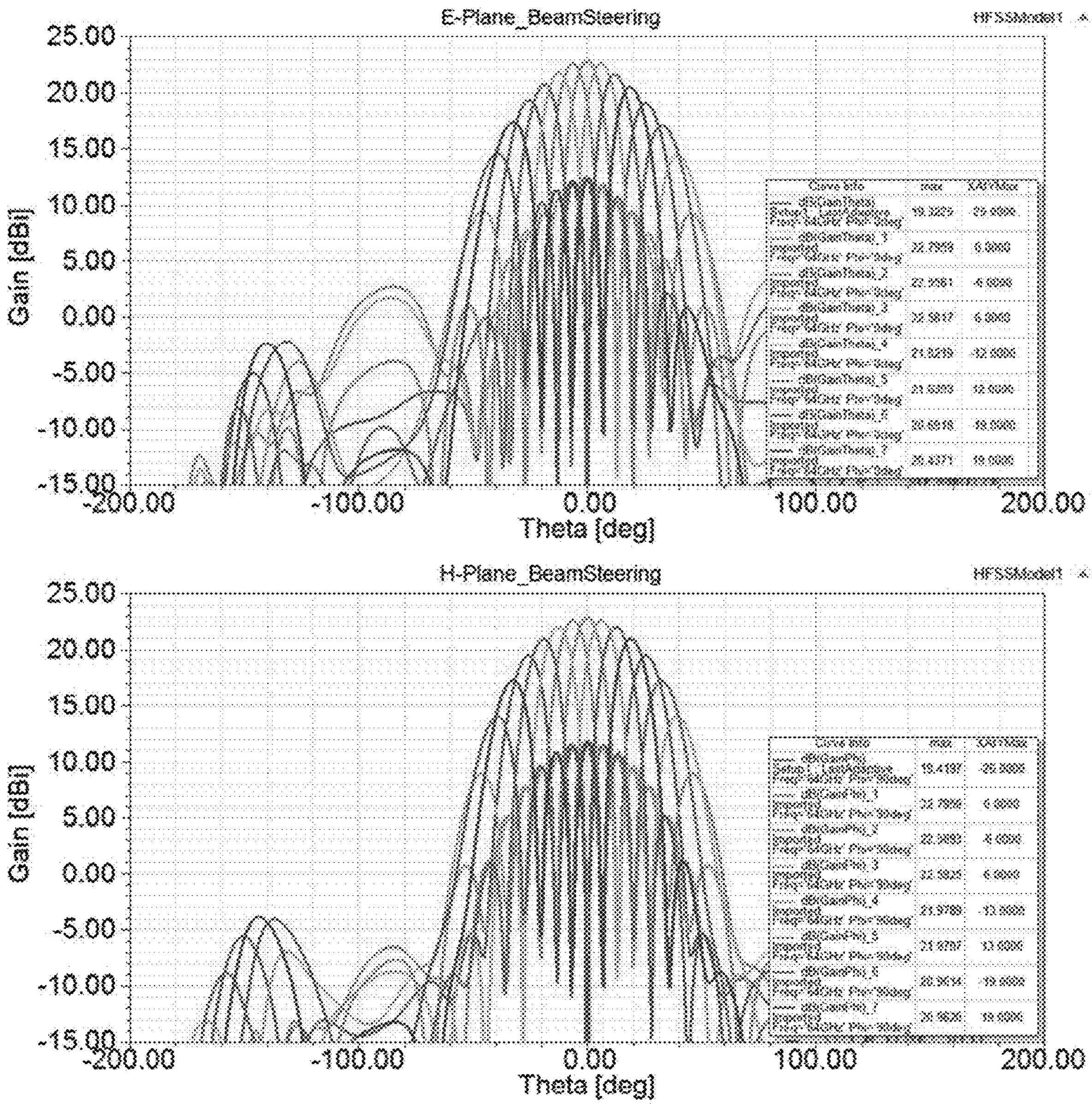

E-Plane_BeamSteering
HFSSModel1
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Gain [dBi]
-200.00
-100.00
0.00
100.00
200.00
Theta [deg]
H-Plane_BeamSteering
HFSSModel1
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Gain [dBi]
-200.00
-100.00
0.00
100.00
200.00
Theta [deg]

FIG. 8

RADIO FREQUENCY MODULES WITH MILLIMETER-WAVE AIR-GAP PHASED-ARRAY ANTENNA

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority from U.S. provisional patent application No. 62/872,759, filed Jul. 11, 2019 and entitled "Air-Gap High-Gain Antenna", the contents of which is incorporated herein by reference.

FIELD

[0002] The specification relates generally to wireless communications, and specifically to a radio frequency module with millimeter-wave air-gap phased array antenna.

BACKGROUND

[0003] The performance of wireless antenna elements is dependent, in part, on the precision of antenna geometry and on the characteristics and geometry of the antenna substrate—the material between the antenna elements and the ground layer, which is typically a dielectric material supporting the antenna elements. Certain substrate materials, as well as assembly configurations, have superior performance characteristics to others, but may also be costlier to fabricate, have larger physical footprints, and the like.

SUMMARY

[0004] An aspect of the specification provides a radio frequency module, comprising: a primary board including: an upper surface carrying a radio controller; and a lower surface carrying antenna control elements; a spacer affixed to the lower surface and having a predefined height extending away from the lower surface; and a secondary board affixed to the spacer, separated from the lower surface by an air gap having the predetermined height; the secondary board supporting a phased array of antenna elements.

BRIEF DESCRIPTIONS OF THE DRAWINGS

[0005] Embodiments are described with reference to the following figures, in which:

[0006] FIGS. **1**A and **1**B depict perspective views of a radio frequency module, from above and below;

[0007] FIG. **2** depicts a cross-section of the module of FIG. **1**;

[0008] FIG. **3** depicts an exploded view of a portion of the module of FIG. **1**, illustrating example spacer and stiffener structures;

[0009] FIG. **4** depicts an exploded view of a portion of the module of FIG. **1**, illustrating further example spacer and stiffener structures;

[0010] FIG. **5**A depicts an overhead view of a feed network of the module of FIG. **1**;

[0011] FIG. **5**B depicts a cross-sectional view of the feed network of FIG. **5**A;

[0012] FIG. **6** depicts reflection coefficients for an example configuration of the module of FIG. **1**, across WiGig frequencies;

[0013] FIG. **7** depicts gain relative to frequency for an example configuration of the module of FIG. **1**; and

[0014] FIG. **8** depicts gain relative to steering angle in E and H planes for an example configuration of the module of FIG. **1**.

DETAILED DESCRIPTION

[0015] FIG. **1**A depicts an example wireless communications assembly **100**, also referred to as a radio frequency (RF) module **100** or simply the module **100**, in accordance with the teachings of this disclosure. The module **100**, in general, is configured to enable wireless data communications between computing devices (not shown). In the present example, the wireless data communications enabled by the module **100** are conducted according to the Institute of Electrical and Electronics Engineers (IEEE) 802.11ay standard, also referred to as WiGig, which employs frequencies of about 57 GHz to about 71 GHz (across six channels, each with a bandwidth of about 2 GHz). As will be apparent, however, the module **100** may also enable wireless communications according to other suitable standards, employing other frequency bands.

[0016] Antenna assemblies configured to communicate via standards such as WiGig may be subject to competing constraints. A first example of such constraints includes strict fabrication tolerances to provide desired performance attributes such as antenna bandwidth (e.g. to cover all six of the above-mentioned channels). A second example constraint is a reduction in production complexity and cost. As will be apparent to those skilled in the art, the above constraints may be in conflict, in that fabricating wireless communications assemblies to satisfy strict tolerances tends to increase cost and complexity of fabrication. As will be discussed below, the wireless communications module **100** includes various features to enable the provision of certain desirable performance attributes (such as full spectrum coverage of the WiGig frequency band) while mitigating the impact on fabrication cost and complexity that would typically be associated with such performance attributes.

[0017] The module **100** can be integrated with a computing device, or in other examples, can be implemented as a discrete device that is removably connected to a computing device. In examples in which the module **100** is configured to be removably connected to a computing device, the module **100** includes a communications interface **104**, such as a Universal Serial Bus (USB) port, configured to connect the remaining components of the module **100** to a host computing device (not shown).

[0018] The module **100** includes a primary board **108**, which may also be referred to as a primary support. In the present example, the primary board **108** is a printed circuit board (PCB), for example fabricated with FR4 material, carrying either directly or via additional boards, the remaining components of the module **100**. In particular, the primary board **108** carries, e.g. on an upper surface **110** thereof, the above-mentioned communications interface **104**. The upper surface **110** is referred to as "upper" to distinguish from the opposing surface, to be discussed below, and does not indicate a required orientation of the module **100** in use.

[0019] The primary board **108** also carries, on the upper surface **110**, a baseband controller **112**. The baseband controller **112** is implemented as a discrete integrated circuit (IC) in the present example, such as a field-programmable gate array (FPGA). In other examples, the baseband controller **112** may be implemented as two or more discrete components. In further examples, the baseband controller

112 can be integrated within the primary board **108** (i.e. be defined within the conductive layers of the primary board **108**) rather than carried on the upper surface **110**.

[0020] In the present example, the baseband controller **112** is connected to the primary board **108** via any suitable surface-mount package, such as a ball-grid array (BGA) package that electrically couples the baseband controller **112** to signal paths (also referred to as leads, traces and the like) formed within the primary board **108** and connected to other components of the module **100**. For example, the primary board **108** defines signal paths (not shown) between the baseband controller **112** and the communications interface **104**. Via such signal paths, the baseband controller **112** transmits data received at the module **100** to the communications interface for delivery to a host computing device, and also receives data from the host computing device for wireless transmission by the module **100** to another computing device. Further, the primary board **108** defines additional signals paths extending between the baseband controller **112** and further components of the module **100**, to be discussed below.

[0021] The module **100** further includes an interposer **120** carrying a radio controller **124**. The interposer **120** is a discrete component mounted on the upper surface **110** via a suitable surface-mount package (e.g. BGA). The interposer **120** itself carries the radio controller **124**, and contains signal paths (also referred to as feed lines) for connecting control ports of the radio controller **124** to the baseband controller **112**, and for connecting further control ports of the radio controller **124** to antenna elements to be discussed in greater detail below. The radio controller **124** may, for example, be placed onto or into the interposer **120** via a pin grid array or other suitable surface-mount package.

[0022] The module **100** may include a heatsink (not shown) placed over the baseband controller **112**, the interposer **120** and the radio controller **124**, and in contact with upper surfaces of those components, e.g. to exhaust heat generated by the components. In other examples, separate heat sinks may be placed over the baseband controller **112**, and the combination of the interposer **120** and radio controller **124**.

[0023] The radio controller **124** includes a transmit and a receive port for connection, via the interposer **120** and traces defined by the primary board **108**, to the baseband controller **112**. The radio controller **124** also includes a plurality of antenna ports for connection, via the interposer **120**, to corresponding contacts on the upper surface **110** of the primary board **108**. Those contacts, in turn, are connected to elements on the opposing lower surface of the primary board **108**, to carry signals between the radio controller **124** and the above-mentioned antenna elements.

[0024] Turning to FIG. **1**B, a lower surface **128** of the primary board **108** is shown opposite the upper surface **110**. The above-mentioned antenna elements, such as a phased array of sixty-four antenna elements (although other arrangements of antenna elements are also contemplated), are supported on a secondary board **150**, also referred to as a secondary support **150**. The secondary board **150** includes an outer surface **154** (i.e. a surface facing away from the primary board **108**) and an opposing inner surface (not visible in FIG. **1**B) facing the primary board **108**, and specifically, facing the lower surface **128** of the primary board **108**. The antenna elements may be supported on the inner surface of the secondary board **150** in the present example. In other examples, however, the antenna elements may be supported on the outer surface **154** of the secondary board **150**.

[0025] The module **100** includes additional components coupling the secondary board **150** to the primary board **108**, which are not illustrated in FIG. **1**B for simplicity, but are shown in subsequent figures and described below in greater detail.

[0026] Turning to FIG. **2**, the cross-section **2-2** indicated in FIG. **1**B is illustrated. As seen in FIG. **2**, the interposer **120** is connected to the upper surface **110** via a surface-mount package **204**, which in the present example is a BGA package. The interposer **120** contains a plurality of internal feed lines, examples **208** and **212** of which are shown in FIG. **2**, connecting control ports of the radio controller **124** to elements of the package **204** for electrical connection with control contacts on the upper surface **110**. At least a portion of the control contacts on the upper surface **110** are connected to conduits extending through the primary board **108** from the upper surface **110** to the lower surface **128**.

[0027] The conduits **216**, also referred to as a feed network, convey signals from the radio controller **124** to a series of excitation patches or other antenna patch control elements on the lower surface **128**, which are electromagnetically coupled to a series of antenna elements **220** disposed on the inner surface **224** of the secondary board **150** (e.g. the above-mentioned 64-element array). In other examples, the antenna elements **220** can be disposed on the outer surface **154** of the secondary board **150**. The conduits **216** therefore also carry signals from the antenna elements **220**, via the excitation patches, to the radio controller **124**. As will be discussed in greater detail herein, the conduits **216** may connect to first subset of contacts at the upper surface **110** with a larger subset of contacts (i.e. having a greater number of contacts than the first subset) at the lower surface **128** (e.g. sixty-four, corresponding to the number of excitation patches deployed to power the sixty-four-element antenna array on the secondary board **150**).

[0028] The secondary board **150** is affixed to the lower surface **128** of the primary board **108** by at least one spacer **228**. The spacer **228** can be fabricated separately from the primary board **108** and the secondary board **150**, e.g. from a material enabling strict dimensional tolerance (e.g. steel, aluminum, or the like). The spacer(s) **228** are affixed to the lower surface **128** and the secondary board **150** is affixed to the spacer(s) **228**, an air gap **232** is formed between the inner surface **224** of the secondary board **150** and the lower surface **128**. The air gap **232** provides sufficient impedance bandwidth for the antenna array carried by the secondary board **150**. In addition, the dimensions (particularly the depth, as in the distance between the surfaces **128** and **224**) of the air gap may be tightly controlled through fabrication of the spacer(s) **228**.

[0029] The module **100** can also include a stiffener, or stiffening member, **236**, affixed to the outer surface **154** of the secondary board **150**. The stiffener **236** can be affixed to the secondary board via screws or other fasteners, which may also traverse the board **150**, the spacer(s) **228** and terminate in the primary board **108**. The stiffener **236** can mitigate warping of the secondary board **150**, which may have a relatively small thickness and therefore be prone to warping in the absence of the stiffener **236**. In other examples, the stiffener **236** may be omitted. The stiffener **236** can be fabricated from a metal (e.g. steel, aluminum), ceramic, or the like.

[0030] Various structures are contemplated for the spacer (s) **228**. Turning to FIG. **3**, a portion of the module **100** is illustrated in exploded form, illustrating part of the lower surface **128** of the primary board **108**, as well as the secondary board **150**, the spacer(s) **228**, and the stiffener **236**. In the illustrated example, the stiffener **236** is a frame configured to extend around the perimeter of the secondary board **150**. The spacers **228** are implemented as a set of discrete spacers **228**, e.g. affixed to the corners of the secondary board **150**.

[0031] In other examples, additional spacers **228** can be provided at other points along the perimeter of the secondary board **150**. In still other examples, spacers **228** may be provided between the lower surface **128** and an interior portion of the secondary board **150** (i.e. in addition to, or instead of, those placed along the perimeter of the secondary board **150**). The stiffener **236**, secondary board **150**, spacers **228** and primary board **108** can be assembled by inserting screws or other fasteners (e.g. four, in the present example) through the stiffener **236**, the secondary board **150**, and the spacers **228** into openings in the lower surface **128**.

[0032] FIG. **4** illustrates a further implementation in which the spacer **228** and the stiffener **236** are both implemented as frames extending around the perimeter of the secondary board. Fasteners may be inserted through the stiffener **236**, the secondary board **150**, and the spacer **228** into the primary board **108**, e.g. at the corners thereof. The spacer **228** and the stiffener **236** can include openings therethrough to receive fasteners such as screws. In other examples, the spacer **228** and the stiffener **228** can include openings between the corners thereof as well as, or instead of, at the corners.

[0033] The dimensions of the spacers **228**, the stiffener **236**, and the secondary board **150** can vary according to the desired transmission/reception characteristics of the module **100**, the materials employed for the above components, and the like. In some examples, the spacer(s) **228** can have a thickness (as measured between the lower surface **128** and the inner surface **224**, defining the depth of the air gap **232**) of about 0.1 mm. The stiffener can have a thickness of about 0.4 mm, and the secondary board **150** can be a single-layer PCB having a thickness of about 0.3 mm. A wide variety of other dimensions may also be employed, however. Further, in other examples the secondary board **150** can be a multi-layer PCB to accommodate more complex antenna arrays, antenna arrays on both sides thereof, and the like.

[0034] As noted earlier, the conduits **216** allow the exchange of signals between the antenna elements **220** (via the excitation patches on the lower surface **128**) and the radio controller **124**, by subdividing a first set of contacts on the upper surface **110** into a larger second set of contacts on the lower surface **128**. Turning to FIGS. **5**A and **5**B, a simplified example set of conduits is shown in an overhead view (FIG. **5**A) and a cross-sectional view (FIG. **5**B).

[0035] The simplified feed networks in FIGS. **5**A and **5**B illustrate a first contact **500**, e.g. on the upper surface **110**, and connected to the radio controller **124** via the interposer **120**. From the contact **500**, feed lines (e.g. which may have wider traces as they depart from the contact **500**) **504-1** and **504-2** travel to vias **508-1** and **508-2** (which may also be referred to as intermediate contacts). The vias **508** carry signals to a second conductive layer (e.g. separated from the conductive layer carrying the contact **500** by a dielectric core layer). On the second layer, additional feed lines **512-1**, **512-2**, **512-3**, and **512-4** carry signals to excitations patches **516-1**, **516-2**, **516-3**, and **516-4** through vias **520-1**, **520-2**, **520-3**, and **520-4**.

[0036] A wide variety of other structures for the conduits **216** can also be deployed. In general, as seen in FIGS. **5**A and **5**B, the stacked arrangement of conduits contemplated herein is more compact than an entirely planar feed network (e.g. contained entirely in one conductive layer), and may therefore reduce the complexity and cost of fabricating a primary board **108** with a set of excitation patches on the lower surface **108** with the spacing and placement to power the antenna elements **220**.

[0037] Certain configurations of the module **100** for use in WiGig communications achieve reflection coefficients below −10 dB for frequencies between 56.5 GHz and 72 GHz (i.e. across substantially the entire WiGig spectrum), as shown in FIG. **6**, which illustrates reflection coefficients across sixteen ports. That is, all six WiGig channels may be employed by such an assembly. Further, the assembly configurations noted above may achieve gain up to 23 dBi, as shown in FIG. **7**. Still further, such an assembly may be steered over angles of 30 degrees to either side of a center orientation with a decrease in signal strength of less than about 4 dB, as shown in FIG. **8**.

[0038] The scope of the claims should not be limited by the embodiments set forth in the above examples, but should be given the broadest interpretation consistent with the description as a whole.

1. A radio frequency module, comprising:
a primary board including:
an upper surface carrying a radio controller; and
a lower surface carrying antenna control elements;
a spacer affixed to the lower surface and having a predefined height extending away from the lower surface; and
a secondary board affixed to the spacer, separated from the lower surface by an air gap having the predetermined height; the secondary board supporting a phased array of antenna elements.

2. The radio frequency module of claim **1**, wherein the spacer comprises a frame extending around a perimeter of the secondary board.

3. The radio frequency module of claim **1**, wherein the spacer comprises a plurality of discrete spacer elements.

4. The radio frequency module of claim **3**, wherein the plurality of discrete spacer elements are disposed at a perimeter of the secondary board.

5. The radio frequency module of claim **1**, further comprising a stiffening member affixed to an outer surface of the secondary board, the outer surface opposite an inner surface of the secondary board affixed to the spacer.

6. The radio frequency module of claim **5**, wherein the stiffening member comprises a stiffening frame extending around a perimeter of the secondary board.

7. The radio frequency module of claim **1**, further comprising a communications interface on the upper surface of the primary board.

8. The radio frequency module of claim **1**, wherein the communications interface comprises a Universal Serial Bus (USB) interface.

9. The radio frequency module of claim **1**, further comprising a baseband controller on the upper surface of the primary board.

10. The radio frequency module of claim **1**, wherein the phased array of antenna elements is controllable to receive and transmit signals at frequencies between about 57 GHz and about 71 GHz.

11. The radio frequency module of claim **1**, further comprising:

a plurality of excitation patches on the lower surface, electromagnetically coupled with the phased array;

a feed network connecting a subset of radio controller contacts with the excitation patches, the feed network including:

a first layer connecting the subset of radio controller contacts to a set of intermediate contacts greater in number than the subset of radio controller contacts; and

a second layer connecting the set of intermediate contacts to the excitation patches.

* * * * *