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(54) Title: MODULAR PHASED ARRAYS USING END-FIRE ANTENNA ELEMENTS

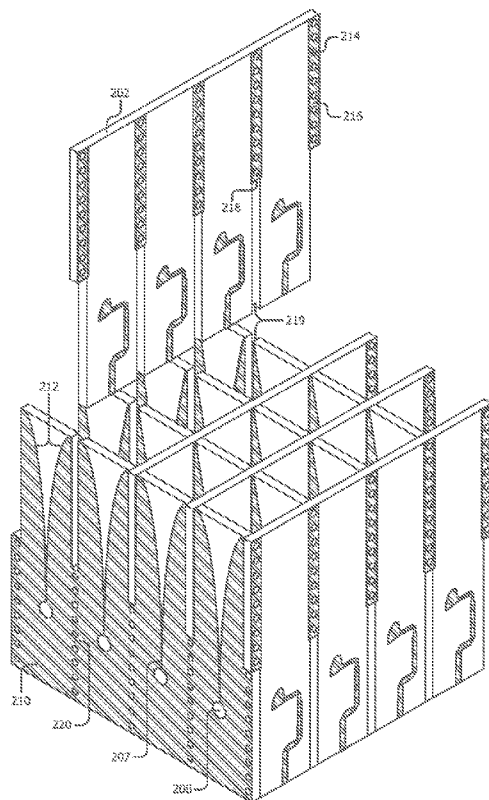


FIG. 2A

(57) Abstract: Apparatus comprising first and second planar tapered slot antenna elements arranged substantially perpendicularly to each other, at least one of the first and second planar antenna elements including a slot serving to interlock the first and second antenna elements in the substantially perpendicular arrangement, and at least one metallic strip on one side of the first planar antenna element located in the region of interlocking. Other features of the antenna elements are also discussed.

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MODULAR PHASED ARRAYS USING END-FIRE ANTENNA ELEMENTS

The present invention relates to improvements of antennas, and in particular, improvements in the type of tapered-slot antennas with dual polarisation for wideband phased array applications.

Research and development work on phased antenna arrays have been progressed through the years. There is an increased level of interest on wideband phased arrays, which is primarily driven by modern requirements of high performance, low manufacturing costs and multi-functionality. Multi-/wideband aperture sharing mechanism (i.e. the combining of the functionality of several antennas into one aperture) is demanded in order to consolidate and reduce the number of antennas on mobile platforms owing to regions of limited space when integrated with other sensor systems. The capability of handling a large amount of signals with unique processing features has been considered, and has become reality due to powerful computation methods. Wideband phased array systems are capable of operating over octaves of bandwidths, can use hybrid scanning for various mission types and can use beam-forming techniques down to element level on antenna apertures.

A wideband phased array requires its antenna element to exhibit good impedance matching over a wide range of frequencies when served in an array environment with various electronic scanning and beam-forming schemes. Such feature constitutes the Wheeler's current sheet model, such that the electromagnetic currents induced from the antenna elements interact with phase matching of electromagnetic currents in order to minimise unexpected energy diffractions and in-structure resonances that degrade the performance of the entire antenna array. A slot-line radiator, introduced by Reuss and known as a tapered-slot antenna, can be considered to implement aperture matching over a wide frequency range.

A conventional tapered slot antenna element comprises a section of slot line that is narrow at one end and opens in a V-shaped flare at the other end. The antenna, which is usually fabricated using printed circuit processing techniques on a copper-clad dielectric substrate is excited by a microstrip feed line printed on one

side of the substrate. The V-shaped flare printed on the other side acts as an impedance transformation network between free space and the microstrip feed line. Radiation from the antenna occurs when the slot line impedance is matched to the impedance of free space. The narrower region supports radiation at high frequencies,
5 whereas the broader region supports radiation at low frequencies.

According to one aspect of the present invention, there is provided apparatus comprising first and second planar tapered slot antenna elements arranged substantially perpendicularly to each other, at least one of the first and second planar antenna elements including a slot serving to interlock the first and second antenna
10 elements in the substantially perpendicular arrangement, and at least one metallic strip on one side of the first planar antenna element located in the region of interlocking.

According to a second aspect of the present invention, there is provided a method comprising forming one or more corresponding slots in first and second
15 planar tapered slot antenna elements and interlocking the the first and second planar antenna elements substantially perpendicularly to each other, the arrangement being such that at least one metallic strip on one side of the first planar antenna element is located in the region of interlocking.

Owing to these aspects of the present invention, a dual polarised tapered slot
20 antenna structure can be constructed for use with wide frequency bands. In this way, detection possibilities are improved in, for example, electronic warfare systems.

Advantageously, a plurality of first and second antenna elements are arranged in an interlocking crate-like structure. Furthermore, each of the first and second antenna elements have corresponding slots machined into them to
25 preferably around half the length of the elements, each slot in the first antenna elements being associated with a metallic strip which is an elongate metallic strip located above the respective slot in the first antenna element and extending substantially co-axially of the slot towards the opposite side of the element to that at which the opening of the slot is present.

30 Modular antenna arrays may comprise planar antenna elements for emitting electromagnetic waves in an end-fire direction. Each antenna module can be

fabricated on one dielectric substrate with slotting formed therein for assembly of orthogonal antenna modules for the application of dual polarisation, and include the elongate metallic strip in the form of a strip-through cavity array that eliminates in-band resonances.

5 The strip-through cavity arrays are fabricated on one conducting layer where the feeding network is deposited with arrays of conductive connections from the elongate metallic strips to the notched ground plane fabricated on the other side of the substrate which are formed by either insertion of metallic posts or, preferably, by through-hole plating in conjunction with the deposition of antenna patterns using
10 photolithographic processes.

 Dimensions of the strip, including its length and width, diameter of the metallic post and distance between adjacent metallic posts are designed so as to facilitate assemblies of orthogonal array modules, remove in-band resonances and improve the operating bandwidth of the entire array.

15 According to a third aspect of the present invention, there is provided apparatus including a tapered slot antenna element on a dielectric substrate and comprising a slot line on one side of the substrate which has a narrow portion at the junction with a closed aperture, a feed line on an opposite side of the substrate to the slot line and terminating in a stub portion, wherein the feed line includes an
20 impedance transformer section.

 Owing to this aspect, the arrangement of a feed line-to-slot line transition is such that the operating bandwidth of the antenna element is greater than 20:1. The impedance transformer is preferably comprised of a plurality of line sections of different widths to yield an optimum matching to the terminating stub of the feed line.
25 In relation to the stub and the closed aperture, they can be of any suitable shape as long as their geometric area is appropriate for the best impedance matching.

 The impedance transformer section as the feed and a design of feed line-to-slot line transition of each antenna element together with an optimum number of sections and a unique combination of characteristic impedances of the sections, the
30 stub portion and the closed aperture of specific geometric areas achieves an operating bandwidth ($SWR \leq 2$) of more than 20:1.

Advantageously, each antenna element consists of two dielectric substrates incorporating three conducting layers; one for each of two notched ground planes and one for a feeding network. One notched ground plane is fabricated on to one side of one substrate whilst leaving the substrate blank on the other side. The other
5 notched ground plane is fabricated on one side of the other substrate while the feeding network is fabricated on the other side of such other substrate. The two substrates are laminated such that the layer of the feeding network is embedded. Sets of conductive connections may be fabricated using a through-hole plating process to remove all nominated in-band resonances.

10 According to a fourth aspect of the present invention, there is provided apparatus including a tapered slot antenna element on a dielectric substrate and comprising a slot line on one side of the substrate which has a narrow portion at the junction with a substantially circular closed aperture, a feed line on an opposite side of the substrate to the slot line and terminating in a stub, wherein the stub includes
15 an arched edge.

Owing to this aspect of the invention, impedance matching of the closed aperture and open stub can be achieved whilst avoiding any unwanted angular or right-angular bends.

According to a fifth aspect of the present invention, there is provided
20 apparatus comprising an antenna element having a free edge thereto, the region of the antenna element at the free edge including a wave termination structure comprising one or more tapered portions narrowing towards the free edge of the antenna element.

Owing to this aspect of the invention, energy return and the occurrence of
25 standing waves can be minimised to improve the performance of the antenna element.

According to a sixth aspect of the present invention, there is provided
30 apparatus comprising a matrix of planar antenna elements, in which matrix a first group of antenna elements are arranged substantially parallelly to each other and a second group of antenna elements are arranged substantially parallelly to each other and substantially perpendicularly to the first group of antenna elements, wherein the

matrix includes antenna elements of different sizes, the size of the antenna elements decreasing inwardly of an outer edge of the matrix.

According to a seventh aspect of the present invention, there is provided a method comprising forming a matrix of planar antenna elements, in which matrix a first group of antenna elements are arranged substantially parallel to each other and a second group of antenna elements are arranged substantially parallel to each other and substantially perpendicularly to the first group of antenna elements, wherein the matrix includes antenna elements of different sizes, the size of the antenna elements decreasing inwardly of an outer edge of the matrix.

Owing to these aspects, a wideband phased array with constant antenna gain or beamwidth over an entire operating bandwidth can be achieved with relatively few antenna elements.

Matrices of arrays comprising tapered-slot antenna elements demonstrate arrangements of a number of sub-array modules operating at overlapped frequency bands with redundancy of elements for requirements of constant antenna beamwidth over the frequency bands and various beam-forming schemes.

In order that the present invention can be clearly and completely disclosed, reference will now be made, by way of example only, to the accompanying drawings, in which:-

Figure 1 is a diagrammatic view illustrating a conventional planar tapered-slot antenna element;

Figure 2A is a diagrammatic view illustrating a dual-polarised tapered-slot antenna array according to the present invention;

Figure 2B is a diagrammatic view illustrating the configuration of a feed of the tapered-slot antenna array according to the present invention;

Figure 3 is a graph showing comparative performance of conventional antenna designs and the present invention in terms of the standing wave ratio as a function of frequency for the array of FIG. 2A;

Figure 4A is a diagrammatic view illustrating one circuit board of a sub-array module comprising antenna elements according to the present invention;

Figure 4B is a diagrammatic view illustrating another circuit board of a sub-

array module comprising antenna elements according to the present invention;

Figure 4C is a diagrammatic view illustrating a plurality of terminations attached to the antenna elements at the edges of each sub-array module;

Figure 5 is a graph showing comparative performance of conventional
5 antenna designs and the present invention in terms of the standing wave ratio as a function of frequency for the apparatus of Figures 4A to 4C;

Figure 6A is a graph showing standing wave ratio in E-plane scan as a function of frequency for the apparatus of Figures 4A to 4C;

Figure 6B is a graph showing standing wave ratio in H-plane scan as a
10 function of frequency for the apparatus of Figures 4A to 4C;

Figure 7A is a diagrammatic view illustrating a sequential arrangement of a matrix using the modular arrays according to the present invention; and

Figure 7B is a diagrammatic view illustrating a concentric arrangement of a matrix using the modular arrays.

15 Referring to Figure 1, a conventional planar tapered-slot antenna element consists of at least one dielectric substrate 101 with a pre-coated metallic cladding on which the patterns of the antenna design are deposited by way of photolithography processes on to metal-coated dielectric substrates. The pattern includes, but is not limited to, a feeding line 102 that is deposited on one side of the
20 dielectric substrate 101, and a notched ground plane 110 deposited on the other side of the dielectric substrate. The profile 108 of the notched flare etched from the ground plane has a certain tapering rate from the shorter edge of the dielectric substrate, as the aperture of the antenna element, to a closed side, connected to a slot section, known as slot line 107. The width of the notch, which has a
25 characteristic impedance, is selected so as to transform the wave impedance of free space to the impedance of the antenna system. Conventional tapered-slot antenna designs adopt a microstrip line 102 as the feed line with a characteristic impedance of 50 ohms which matches to the system by way of a transition network through electromagnetic coupling, which is formed by an open microstrip stub 104,
30 connected by the feed 102, and a closed aperture 106 etched from the ground plane, which connects to the slot line 107. The open microstrip stub 104, which has a

specific geometric area, generates a certain reactance of the input impedance seen from the feed 102, which neutralises the imaginary part of the input impedance seen at the junction between the closed aperture 106 and the slot line 107 in a conjugated manner to match propagating waves on to the opening flare 108 of the antenna. The opening flare then transforms propagating fields into radiating waves in free space. Consequently, a tapered-slot antenna is of an end-fire type where the radiation emanates from the edge of the dielectric substrate 101.

The thickness of the substrate 101 is selected according to the highest operating frequency so as to avoid the excitation of higher order non-TEM mode. The performance of an array comprising antenna elements of Figure 1 is noted as "50- Ω FEED" in Figure 3, which demonstrates an impedance bandwidth ($SWR \leq 2$) of up to 2:1.

A wideband antenna element requires both a radiating element that utilizes the enclosed volume efficiently over a wide frequency range, and a feeding network with wideband matching performance. Tapered-slot antennas may exhibit a wideband response only if they are excited by a wideband feeding network. This can be achieved via modification of the matching conditions on the transition network in conjunction with the respective feed. Optimum input impedance exists when the microstrip feed 102 yields an optimum matching on to the characteristic impedance of the slotline 107 whose width relies on tolerance and resolution of fabrication processes. The open microstrip stub 104 then generates a certain reactance of the input impedance seen from the microstrip feed 102 that neutralises the imaginary part of the input impedance generated by the closed aperture 106 etched from the ground plane at the other side of the substrate 101. Such matching condition should be optimized in conjunction with the length and the profile of the tapering flare 108 for wideband operation.

Tapered-slot antennas can be used either as a broadside element or in an array environment. The configuration of a tapered-slot antenna element lends itself suitable to be used as a linear array, sharing a common ground plane for electromagnetic current flow over the aperture, which implements the Wheeler's current sheet model for wideband arrays. The width of antenna elements in the array

should be selected so as to avoid appearance of grating lobes when scanned off-broadside up to the highest frequency of interest. The tapering length of antenna elements should be selected for the lowest frequency of interests, which compromises trade-offs between boresight gain (i.e. the maximum radiated power of the directional antenna), dielectric losses and profile of the antenna.

5 Tapered-slot antennas are linearly polarised owing to the E-component of the propagating fields along the antenna being oriented in a single direction across the tapered slot. A number of linear arrays can be fabricated and arranged in an orthogonal manner, forming a crating structure, having the capability of emanating radiations with dual polarisation. Such a mechanism is implemented by either insertion of metallic rods with slots on each face of the antenna elements with pre-determined dimensions for slotting of each antenna element together, or by machining slots between antenna elements on sub-array modules for interlocking assembly. Both of these methods offer electronic and electromagnetic conduction between orthogonal sub-array modules to guarantee a continuous electromagnetic current flow over the entire antenna aperture. Metallic rods can be fabricated by high-pressure extrusion from a die as the mould. However, the manufacturing tolerances may not ensure suitable repeatability of the result, especially for operation at higher frequency. Furthermore, it is challenging to ensure that each antenna element is inserted properly into the slots on the rods, resulting in lengthy and costly assembling processes. Slots with a half-depth of the antenna sub-array module for an interlocking cross-assembly seems intuitive for dual polarisation, however, the electromagnetic current induced on the common notched ground plane of the module encounters an effectively open-circuited termination owing to the presence of the machined slots. These machined slots effectively form discontinuities for the current where reflections occur that interact back with the incoming energy, resulting in standing waves. Resonance thus occurs at some frequency when the energy added out-of-phase, which effectively traps the propagating field on the taper, results in total reflection back. Such a phenomenon is noted on the graph of Figure 3 as "DIRECT SLOTTING". Such resonance is referred to as a kind of cavity resonance occurring between neighbouring antenna elements in the array.

A tapered-slot antenna element can be expanded into an array fabricated on to a common dielectric substrate for phased array applications. The width of the open end of each antenna element in the array is selected to be half air-wavelength at the highest frequency of interest such that it offers a scanning environment without the appearance of grating lobes. Antenna elements in the array effectively share a common metallic plane, which lends itself suitable to serve as the medium to facilitate electromagnetic current flow over the array to implement the Wheeler's current sheet model for wideband operation. For the application of antenna arrays with dual polarisation, owing to the fact that the E-component of the propagating fields of the antenna is defined by the orientation of the opening flare of the notch, a number of antenna sub-array modules can be assembled to create a crossed arrangement, being able to generate radiating waves with two orthogonal polarisations. Sub-array modules can be machined, slotted and crated for structural rigidity. However, the slots and any blank portions on the common antenna plane introduce discontinuity that effectively results in degradation of performance of the antenna. The back-scattered fields destructively interact with neighbouring elements, and introduce unexpected resonances when the distance between adjacent slots is close to half wavelength in the dielectric substrate at some frequencies. Propagating fields along the flared notch of the antenna around these frequencies resonate within the elements, and result in high energy return back to the system. Such an issue significantly limits the use of tapered-slot antenna arrays to use with single polarisation in narrowband systems, although they possess other attractive features such as being low in volume and mass, structural simplicity, and a solution to low-cost multi-static radar systems, in which wideband, multi-functional, dual polarised apertures are required for particular purposes.

This resonance can be eliminated by the adoption of the antenna elements shown in the array of Figure 2A in order to guarantee a continuous electromagnetic current flow on the common metallic ground plane between the antenna elements. A dual-polarised tapered-slot antenna array comprises a number of sub-array modules with substantially orthogonal slotting. Each module includes a linear array of the antenna elements fabricated on one dielectric substrate comprising a notched

ground plane 210, a microstrip feeder including an impedance transformer 201, 203, 204, 205, 209 (see Figure 2B), a transition network comprising the open stub 206 and the closed aperture 208, and a strip-through cavity array 216. Substrates of low relative dielectric constant are preferred for better radiation efficiency and whose thickness is selected for the microstrip feeder without the excitation of higher order non-TEM mode. An exponential profile 212 is adopted preferably for the tapered slot of the antenna element, being analysed and considered to be the optimum for the application of wideband phased arrays. The feed comprises a 50-ohm line 201 that connects to the remainder of the impedance transformer comprising multiple line sections 203, 204, 205, 209 (detail being shown in Figure 2B) whose impedances are selected to optimally match the input impedance from the system to that at the slot line 207. The input impedance is selected to accommodate tolerance and resolution of fabrication processes, as well as overall matching of the transition network. The transition network is, as mentioned above, composed of the microstrip stub 206 connected to the impedance transformer, and the closed aperture 208 etched from the shared ground plane. Both can be of any shape, avoiding right-angle corners or sudden geometric changes along its profile, or preferably, as shown, the closed aperture 208 being substantially circular with the microstrip stub 206 having an arched edge furthest from the junction with the impedance transformer or having at least some radial portion. It is not their profiles, but their geometric areas that improves the overall impedance matching of the antenna. The preferred embodiment as shown in Figure 2A yields an impedance bandwidth ($SWR \leq 2$) of more than 20:1, which is sufficient for the wideband application.

The aforementioned resonances occurring between neighbouring sub-array modules owing to orthogonal slotting for dual polarisation are eliminated by the introduction of one or more of the strip-through cavity arrays 216 to facilitate electromagnetic currents from each module to flow over the entire antenna aperture, implementing Wheeler's current sheet model for wideband phased array systems. The embodiment shown in Figure 2A includes arrays of elongate metallic strips 216 and associated arrays of metallic vias 214. The metallic strips 216 are fabricated on the side of the dielectric substrate where the feeder 201, 203, 204, 205, 209 and

stub 206 are present. The arrays of metallic vias 214 are fabricated by plating processes through the substrate for electronic and electromagnetic conductions between the metallic strips 216 and the common notched antenna plane 210 on the opposite side of the substrate. The dimensions of the metallic strips 216, including their width 218, and associated slots 219 for assembling of orthogonal sub-array modules should be selected such that they align with the overall length of sub-array modules and thickness of the substrate, which shall include at least the substrate thickness, its metallic cladding and if applicable, bonding materials for lamination processes. The diameter of the vias 214 should be selected to avoid self-resonance, and to comply with the resolution of fabrication processes. The width 218 of the elongate metallic strips 216 is substantially the same as the width of the corresponding slots 219. The distance 220 between adjacent vias 214 in the array is selected such that it supports the current flow without resonances occurring between the metallic strip arrays 216 and the common notched antenna plane 210. The resultant antenna design according to embodiments of the present invention yield an impedance bandwidth ($SWR \leq 2$) of 4.3:1, noted as "PREFERRED EMBODIMENT" shown in Figure 3.

Referring specifically to Figure 3, the performance of an antenna is defined by how much power is reflected back to the system, measured as the standing wave ratio (SWR) of the antenna. For wideband antennas, the ratio bandwidth of $SWR \leq 2$ is normally used to define the impedance match of such antennas. In Figure 3, the antenna of "PREFERRED EMBODIMENT" operates from 1.72GHz to 7.4GHz, exhibiting a ratio bandwidth of 4.3:1. Referring to the result of the "50OHM-FEED" in Figure 3, the SWR is larger than 2 from about 3.2GHz to the highest frequency of interest. Referring to the result of the "DIRECT SLOTTING" in Figure 3, owing to the presence of slots, the result is an unwanted resonance that occurs at about 4.5GHz. Such resonance results in nearly total reflected power back to the system. As a result, the antenna of "DIRECT SLOTTING" works as a multi-band antenna, but not a wideband one, one band ($SWR \leq 2$) being from about 2.3GHz to 4.5GHz whilst another being from about 4.7GHz to 7.2GHz. This is not ideal as another antenna is needed to cover the frequency band where cavity resonances occur. It should be

noted that the nominated frequencies are the result of a specific design and would vary with different configurations, geometries and dimensions of the antenna.

Phased arrays using conventional tapered-slot antenna elements exhibit an impedance bandwidth ($SWR \leq 2$) of up to 2:1, as already mentioned. It is realised that the bandwidth can be significantly improved by utilising a wideband feeding network, which includes both the feed line 201, 203, 204, 205, 209 and associated transition network 206, 208. A section of the 50-ohm feed can be replaced by a multi-section impedance transformer 201, 203, 204, 205, 209 (see Figure 2B) designed at substantially the centre of the frequencies of interest. The input impedance seen at the junction between the impedance transformer and the open stub should be selected in conjunction with the characteristic impedance of the slot line 207, which is associated to its width and limited by the resolution of the fabrication process. Furthermore, it is found that the geometric areas of the open stub 206 and the closed aperture 208 of the transition network are associated to the impedance matching performance of the antenna. It is their geometric areas that generate effective reactance to the impedance matching of the transition network.

Figures 4A and 4B are diagrammatic views illustrating parts for lamination in order to produce advantageous antenna modules suitable for the application of dual polarisation. Each sub-array module is made of two dielectric substrates, upon which associated designs and structures are manufactured. One part of the module, as illustrated in Figure 4A, comprises a first dielectric substrate 402, on which slots 420 which have pre-determined dimensions and the shape of a lower profile 422 are machined. One conducting layer 406 is provided for depositions of notches 404 of the antenna elements, the slot line 412, the closed aperture 414, and sets of arrays 408, 410, 416, 418 of blank portions for through-hole plating process. The other part of the module, as illustrated in Figure 4B, comprises a second dielectric substrate 403 with machined slots 420 with pre-determined dimensions to align with the ones on the first substrate 402, one conducting layer 407 on one side of the second substrate 403, for depositions of notches 405 of the antenna elements, the slot line 412, the closed aperture 414, and sets of arrays 408, 410, 416, 418 of blank portions for through-hole plating process, and one conducting layer for depositions of an

array of the feeder on the other side of the second substrate 403, comprising a microstrip line 421, an impedance transformer 415, and an open stub 413. The impedance transformer 415 and the open stub 413 are implemented using a stripline structure embedded between the two notched antenna planes 406 and 407. The two
5 dielectric substrates are laminated with through-hole plating on the blank portions to produce electronic and electromagnetic conductions between the two notched antenna planes 406 and 407, serving as metallic via arrays for eliminations of various in-band resonances. Orthogonal sub-array modules are fabricated with identical features aforementioned except locations for fabrications of the slots 420
10 and the metallic via array 408 are exchanged for cross assembling to produce a dual polarised phased array module.

In operation, propagating fields are loaded from certain connection medium to the microstrip feed 421, transformed by way of a microstrip-to-stripline transition, and matched to the notch of the antenna elements from a transition network 413, 414 by
15 way of the stripline impedance transformer 415. The thickness of the first and second substrates 402 and 403, preferably being substantially identical, is selected for both the microstrip and the stripline feeds to guarantee the condition that fields propagate in (quasi)-TEM mode only over the frequency band of interest, and to produce symmetrical field distributions between the notches to maintain polarisation
20 linearity. The impedance transformer 415 and the transition network comprising the open stripline stub 413 and the closed aperture 414 follow the design criteria for the ones 201, 203, 204, 205, 206, 208, 209 shown in Figure 2A and 2B, to match the fields on to the slotline 412 and the tapered notch 404 for radiations.

Tapered slot antenna arrays of this kind with the aforementioned configuration,
25 comprising two dielectric substrates and excited by stripline feeds yield an impedance bandwidth ($SWR \leq 2$) of typically up to 4:1, which is better than conventional tapered slot antenna arrays that consist of a single dielectric substrate, and which are excited by microstrip feeds. This is because of the fact that this type of tapered slot antenna with two substrates couples radiating fields more efficiently to
30 free space within the volume that encloses the aperture in comparison with the type with one substrate. Such phenomenon is noted more apparently at lower frequencies.

Nevertheless, a number of frequency anomalies are noted within the frequency band of interest, which is due to the presence of two notched antenna planes and slots machined on each sub-array module for the application of dual polarisation, which significantly limits their use in wideband phased array systems.

5 The stripline feed is thus embedded between the two ground planes. Consequently, a certain transition is required to transform the feed into a certain type of transmission line that is suitable for external connections. A bounded stripline-to-microstrip transition as shown comprises a tapered microstrip line 421 and a tapered opening gap profile 422 for wideband matching. The thickness of the dielectric
10 substrates 402, 403 is selected to guarantee that fields propagate in stripline mode in the structure without excitation of parallel-plate mode, which is TEM propagation, and may co-exist and couple to the stripline mode with an increase of substrate thickness. Such interaction degrades matching of the structure, noted especially at higher frequencies. The width of the tapered ground section, namely the width of the
15 tapered slot at the open end is selected to accommodate the width of each antenna element in the sub-array module for grating-lobe free scanning up to the highest frequency of interest. The length of the tapered ground section is selected to maintain acceptable impedance matching over the entire bandwidth. Profiles of the opening gap 422 and the tapered microstrip line 421 are selected, preferably, with
20 positive exponential tapering rates, for optimum matching. Incorporation of aforementioned features of the embodiment yields an impedance bandwidth ($SWR \leq 2$) of more than 20:1.

 Synthesis of metallic via arrays in the antenna module illustrated in Figures 4A and 4B ensures that no resonance occurs within the frequency bands of interest.
25 Figure 5 shows a comparative performance of conventional antenna designs and the present invention in terms of the standing wave ratio as a function of frequency for the apparatus of Figures 4A to 4C. Four potentially unwanted resonances may occur in conventional tapered slot arrays using two dielectric substrates when served in a scanning environment with dual polarisation. Such resonances result in complete
30 energy return back to the system, seriously degrading the radiation efficiency of the antenna. Firstly, resonance may occur under the condition when the dimensions of

an equivalent cavity formed by neighbouring antenna elements are close to half of air wavelength at some frequency within the operating band. Noted as an anomaly at about 4.2GHz shown in Figure 5 for one sample design, this type of resonance can be minimised by the introduction of metallic via array 408 in conjunction with the slots for orthogonal assemblies to null the voltage potential within the antenna structure. Secondly, resonance may occur within the open notches between adjacent antenna elements, which effectively form a parallel-plate structure. Induced fields introduce resonance when the volume enclosed by the effective parallel plate structure is close to its self-resonant frequency, known as cavity resonance. Noted as an anomaly at about 7GHz in Figure 5 for one sample design, this type of resonance can be eliminated by the introduction of metallic via array 410 along the opening notch 404, 405 of the antenna module. Thirdly, dimensions of the closed apertures 414 etched from the two notched antenna planes 406, 407 are varied to optimise the impedance matching of the antenna. The result may introduce frequency anomalies when the effective volume between the apertures is close to its self-resonant frequency that occurs at the frequency within the bands of interest. Noted as an anomaly at about 15.3GHz in Figure 5 for one sample design, this type of resonance can be suppressed by the introduction of metallic via array 416 fabricated about the circumference of the closed apertures 414. Lastly, the impedance transformer 415 as a stripline structure is effectively embedded between the two ground planes of infinite size. Resonance may occur between the two ground planes forming an effective cavity structure when the volume enclosed in the cavity is close to its self-resonant frequency, known as cavity resonance. Noted as an anomaly at about 12.8GHz in Figure 5 for one sample design, this type of resonance can be removed by the introduction of metallic via array 418 fabricated along the stripline feed to reduce the effective volume enclosed within the cavity so as to shift its self-resonance out of the operating band. Parameters of the various via arrays, including their diameter and mutual distance, are selected to accommodate standard fabrication processes, and to assure no potential resonances exist within the operating band for the particular application. It should be noted that the nominated frequencies are the result of a certain design, and they would vary with

different configurations, geometries and dimensions of the antenna of this type.

A wideband phased array requires that its electromagnetic currents flow smoothly along the entire antenna aperture. Any discontinuity introduces energy return and standing waves that potentially result in unwanted resonances to degrade the performance of the antenna. Reflections and diffractions occur on conventional tapered slot antenna arrays when electromagnetic currents encounter discontinuity on the side edges of the dielectric substrate, degrading the impedance matching of, particularly, edge antenna elements. Conventionally, ferrite tile and carbon loaded wave absorbing materials are considered, which may require assemblies in advance and thus increased manufacturing costs. Referring to Figure 4C, a wave termination structure to dampen electromagnetic currents at the edges of the substrate can be fabricated with the antenna modules with no additional processing time and costs. The wave termination structure consists of an array of tapered patches 424 electronically connected to one notched antenna plane 406. The patches 424 are backed by a common ground plane 423 connected to the other notched antenna plane 407. The number of patches can be selected such that it accommodates the width 432 of the patch aligning the length of the antenna element while leaving adequate room for, if any, external connections 425 to matched loads or suitable terminations 427. The length of each tapered patch 424 should be selected in accordance with a tapering angle 428 for optimal termination efficiency. A tapering profile 426 of each patch can be of any type, but preferably rectilinear for the optimum result.

Incorporation of the aforementioned features, including a microstrip-to-bounded stripline transition, a multi-section impedance transformer, a bounded stripline-to-slotline transition, synthesis of metallic via arrays and a wave termination structure, on the modular antenna sub-arrays yields results shown in Figures 6A and 6B, demonstrating the scanning performance up to 45 degrees off-broadside along the E- and H-plane cuts as a function of frequency, respectively, for an antenna comprising the sub-array elements of Figures 4A to 4C. Although a small number of peaks at the higher angles of scanning went a little higher than $SWR = 2$, there is relatively good matching over nearly the entire frequency band of interest, even

when scanned off-broadside (up to 45 degrees).

A plurality of matrix arrangements for implementation of wideband phased arrays with constant antenna gain or beam width over the entire operating band, are shown in Figures 7A and 7B. This concept produces a wideband antenna aperture
5 that includes sub-array modules of different electrical dimensions of antenna elements to operate at the bands of interest in an overlapped manner such that fewer elements are needed in an array of identical size to produce the required antenna gain at lower operating frequencies. The overall size of the aperture is selected according to the lowest operating frequency such that sub-arrays of larger
10 antenna elements are used whilst sub-arrays of smaller antenna elements of an identical matrix with a pre-determined scaling factor can be used to achieve identical performance up to the highest operating frequency.

Referring to Figure 7A, a sequential arrangement of an array matrix comprising dual polarised modular arrays with scaled dimensions of the elements is
15 shown with a first group of antenna elements arranged substantially parallelly to each other and a second group of antenna elements arranged substantially parallelly to each other and substantially perpendicularly to the first group, wherein the first and second groups of the matrix includes antenna elements of different sizes, the size of the antenna elements decreasing inwardly of an outer edge of the matrix. Assuming
20 " f " to be the lowest operating frequency and a scaling factor of 2 (not limited to this number, but can be others where appropriate or suitable for fabrications and assemblies), as implemented in the configuration, sub-array modules of larger elements 702, 704 of the first and second groups of the matrix can be arranged to operate from f to $2f$, namely a 2:1 bandwidth. Sub-array modules of intermediate
25 elements 706, 708 of the first and second groups of the matrix can be arranged to operate from f to $4f$, namely a 4:1 bandwidth. Sub-array modules of smaller elements 710, 712 of the first and second groups can be arranged to operate from f to $8f$, namely an 8:1 bandwidth. Conventionally, the entire antenna aperture is formed by the smaller elements, and in operation, all elements are excited to produce the
30 required antenna gain at the lowest operating frequency. In comparison, the same can be achieved by the use of up to only one quarter of the elements, thus

significantly reducing processing time, structural complexity, assembling reliability and repeatability, and manufacturing costs.

Referring to Figure 7B, an array matrix with a concentric arrangement comprising dual polarised modular arrays with scaled dimensions of the elements is shown. The operation resembles the configuration illustrated in Figure 7A, except that the sub-array modules of the smaller elements 710, 712 are located in phase centre of the antenna aperture. This arrangement serves an identical purpose to that of the arrangement illustrated in Figure 7A, with the addition that it also offers the capability for more versatile beam-forming schemes by optimising the characteristics of signals on more antenna elements for finer control and better accuracy. The aforementioned features rely significantly on the continuity of electromagnetic current flow over the antenna aperture for the entire operating band, which is implemented by the use of the preferred sub-array elements illustrated in Figures 4A and 4B for orthogonal assemblies 716, 718, and the wave termination structure illustrated in Figure 4C on edge antenna elements 714.

It will be understood that the modular antenna arrays and associated embodiments in accordance with the present invention may be fabricated via photolithographic processes and subsequent machining and assembling, as conventional tapered slot antennas are. The type of construction will depend upon the type of the feed of the antenna array, which consequently depends upon the particular class of antenna implemented.

The present invention addresses the problem of dual polarisation found with conventional tapered-slot antenna arrays owing to the need of slots being machined on the substrates for assemblies, resulting in unwanted resonances occurring within the antenna arrays. Integration of the preferred structures into the antenna effectively suppresses these resonances and guarantees continuous electromagnetic current flow on the common metallic plane between the antenna elements in the array.

CLAIMS

1. Apparatus comprising first and second planar tapered slot antenna elements arranged substantially perpendicularly to each other, at least one of the first and second planar antenna elements including a slot serving to interlock the first and second antenna elements in the substantially perpendicular arrangement, and at least one metallic strip on one side of the first planar antenna element located in the region of interlocking.
2. Apparatus according to claim 1, and further comprising a plurality of first and second antenna elements arranged in an interlocking crate-like structure.
3. Apparatus according to claim 1 or 2, wherein each of the first and second antenna elements have the corresponding slots around half the length of the elements machined into them, each slot in the or each first antenna elements being associated with the metallic strip.
4. Apparatus according to claim 3, wherein the metallic strip is elongate and located above the respective slot in the or each first antenna element and extending substantially co-axially of the slot towards the opposite side of the element to that at which the opening of the slot is present.
5. Apparatus according to claim 4, wherein the elongate metallic strip is in the form of a strip-through cavity array.
6. Apparatus according to claim 5, wherein the strip-through cavity array is fabricated on one conducting layer where a feeding network is deposited with arrays of conductive connections from the elongate metallic strips to a notched ground plane fabricated on the other side of the substrate and which are formed by through-hole plating in conjunction with the deposition of antenna patterns.
7. Apparatus according to claim 2 or any one of claims 3 to 6 as appended to claim 2, and further comprising arrays of elongate metallic strips and associated arrays of metallic vias.
8. Apparatus according to claim 7, wherein the antenna yields an

impedance bandwidth ($SWR \leq 2$) of 4.3:1.

- 5 9. Apparatus according to any preceding claim, wherein the tapered slot antenna elements on a dielectric substrate comprise a slot line on one side of the substrate which has a narrow portion at the junction with a closed aperture, a feed line on an opposite side of the substrate to the slot line and terminating in a stub portion, wherein the feed line includes an impedance transformer section
- 10 10. Apparatus according to claim 9, wherein the stub portion includes an arched edge.
- 10 11. Apparatus according to any preceding claim, wherein the or each antenna element has a free edge thereto, the region of the or each antenna element at the free edge including a wave termination structure comprising one or more tapered portions narrowing towards the free edge of the or each antenna element.
- 15 12. Apparatus according to claim 2 or any one of claims 3 to 11 as appended to claim 2, and further comprising a matrix of planar antenna elements, in which matrix a first group of antenna elements are arranged substantially parallelly to each other and a second group of antenna elements are arranged substantially parallelly to each other and substantially perpendicularly to the first group of antenna elements, wherein the matrix includes antenna elements of different sizes, the size of the antenna elements decreasing inwardly of an outer edge of the matrix.
- 20 13. A method comprising forming one or more corresponding slots in first and second planar tapered slot antenna elements and interlocking the first and second planar antenna elements substantially perpendicularly to each other, the arrangement being such that at least one metallic strip on one side of the first planar antenna element is located in the region of interlocking.
- 25 14. A method according to claim 13, wherein said interlocking comprises arranging in an interlocking crate-like structure.
- 30 15. A method according to claim 12 or 13, wherein the metallic strip is in the form of a strip-through cavity array, the method further comprising

fabricating the strip-through cavity array on one conducting layer where a feeding network is deposited with arrays of conductive connections from the elongate metallic strips to a notched ground plane fabricated on the other side of the substrate.

5 16. A method according to claim 14 or claim 15 as appended to claim 14, comprising forming a matrix of planar antenna elements, in which matrix a first group of antenna elements are arranged substantially parallel to each other and a second group of antenna elements are arranged substantially parallel to each other and substantially perpendicularly to the first group of antenna
10 elements, wherein the matrix includes antenna elements of different sizes, the size of the antenna elements decreasing inwardly of an outer edge of the matrix.

17. Apparatus including a tapered slot antenna element on a dielectric substrate and comprising a slot line on one side of the substrate which has a
15 narrow portion at the junction with a closed aperture, a feed line on an opposite side of the substrate to the slot line and terminating in a stub portion, wherein the feed line includes an impedance transformer section.

18. Apparatus according to claim 17, wherein the impedance transformer section is comprised of a plurality of line sections of different widths to yield an
20 optimum matching to the stub portion of the feed line.

19. Apparatus according to claim 17 or 18, and further comprising a second antenna element, wherein each antenna element consists of two dielectric substrates incorporating three conducting layers; one for each of two notched ground planes and one for a feeding network.

25 20. Apparatus according to claim 19, wherein one notched ground plane is fabricated on to one side of one substrate whilst leaving the substrate blank on the other side, the other notched ground plane is fabricated on one side of the other substrate while the feeding network is fabricated on the other side of such other substrate, the two substrates being laminated such that the layer
30 of the feeding network is embedded.

21. Apparatus according to claim 19, and further comprising one or more

arrays of metallic vias in the notched ground planes.

22. Apparatus according to anyone of claims 17 to 21, wherein the closed aperture is substantially circular, and the stub includes an arched edge.

5 23. Apparatus according to any one of claims 17 to 22, wherein the antenna element has a free edge thereto, the region of the antenna element at the free edge including a wave termination structure comprising one or more tapered portions narrowing towards the free edge of the antenna element.

10 24. Apparatus according to any one of claims 17 to 23, and comprising a matrix of antenna elements, in which matrix a first group of antenna elements are arranged substantially parallelly to each other and a second group of antenna elements are arranged substantially parallelly to each other and substantially perpendicularly to the first group of antenna elements, wherein the matrix includes antenna elements of different sizes, the size of the
15 antenna elements decreasing inwardly of an outer edge of the matrix.

20 25. Apparatus including a tapered slot antenna element on a dielectric substrate and comprising a slot line on one side of the substrate which has a narrow portion at the junction with a substantially circular closed aperture, a feed line on an opposite side of the substrate to the slot line and terminating in a stub, wherein the stub includes an arched edge.

26. Apparatus according to claim 25, wherein said arched edge is located furthest from the junction with the feed line.

27. Apparatus according to claim 25 or 26, wherein the antenna element yields an impedance bandwidth ($SWR \leq 2$) of more than 20:1.

25 28. Apparatus comprising an antenna element having a free edge thereto, the region of the antenna element at the free edge including a wave termination structure comprising one or more tapered portions narrowing towards the free edge of the antenna element.

30 29. Apparatus according to claim 28, wherein the wave termination structure is electronically connected to one notched antenna plane.

30. Apparatus according to claim 29, wherein the tapered portions are

backed by a common ground plane connected to another notched antenna plane.

5 31. Apparatus according to any one of claims 28 to 30, wherein the length of each tapered portion should be selected in accordance with a tapering angle.

32. Apparatus according to any one of claims 28 to 31, wherein a tapering profile of each tapered portion is rectilinear.

10 33. Apparatus comprising a matrix of planar antenna elements, in which matrix a first group of antenna elements are arranged substantially parallelly to each other and a second group of antenna elements are arranged substantially parallelly to each other and substantially perpendicularly to the first group of antenna elements, wherein the matrix includes antenna elements of different sizes, the size of the antenna elements decreasing inwardly of an outer edge of the matrix.

15 34. Apparatus according to claim 33, wherein the antenna elements have a concentric arrangement.

20 35. A method comprising forming a matrix of planar antenna elements, in which matrix a first group of antenna elements are arranged substantially parallel to each other and a second group of antenna elements are arranged substantially parallel to each other and substantially perpendicularly to the first group of antenna elements, wherein the matrix includes antenna elements of different sizes, the size of the antenna elements decreasing inwardly of an outer edge of the matrix.

25

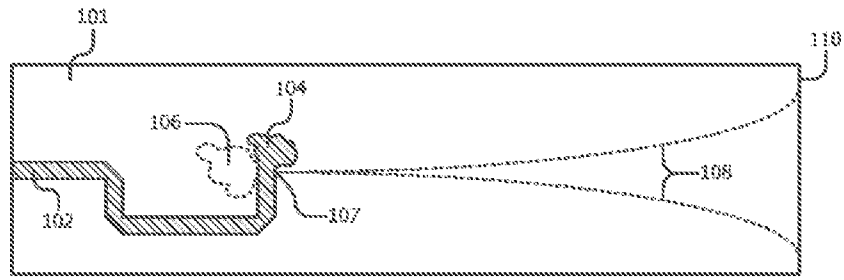


FIG. 1

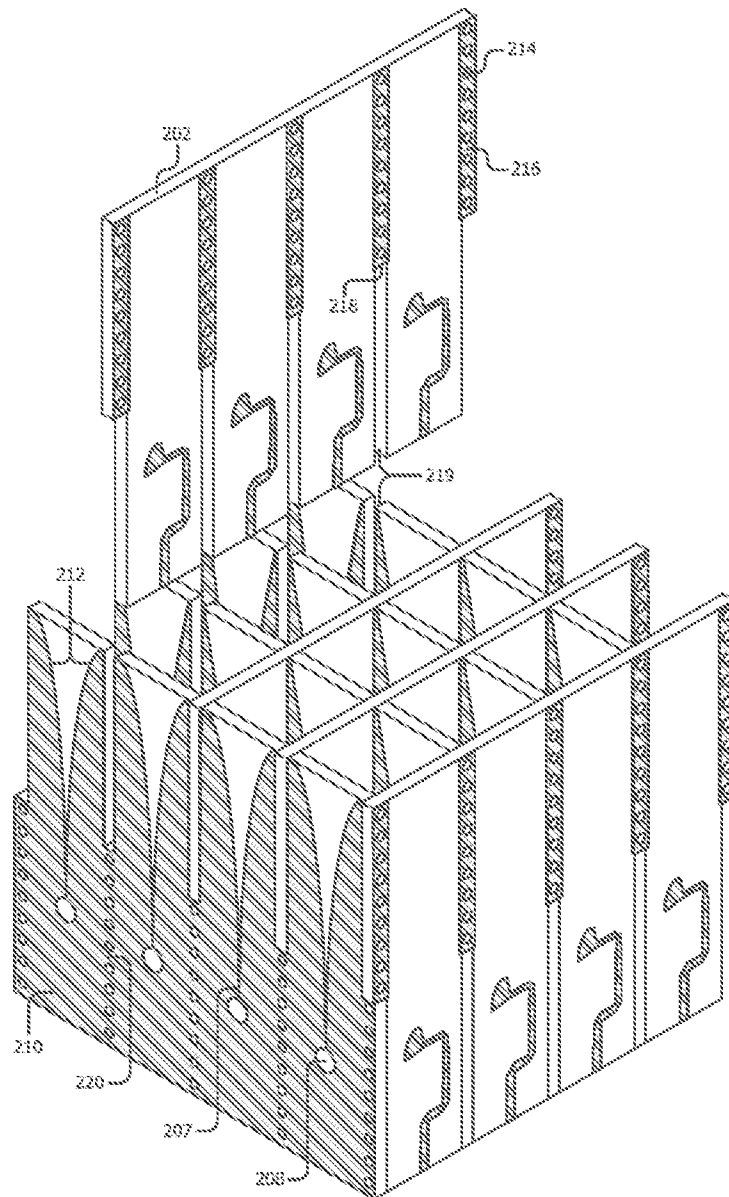


FIG. 2A

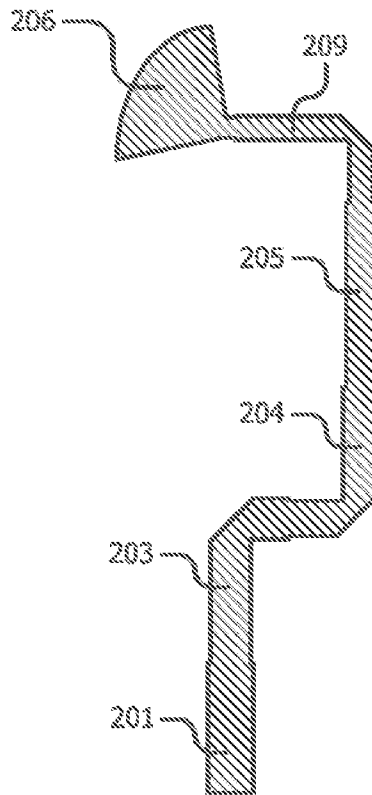


FIG. 2B

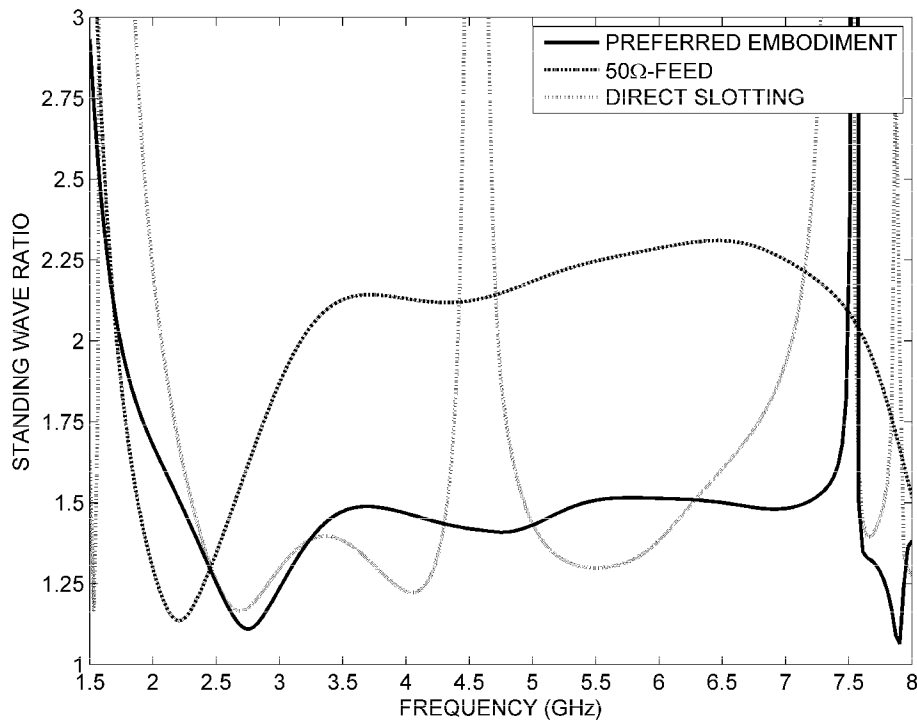


FIG. 3

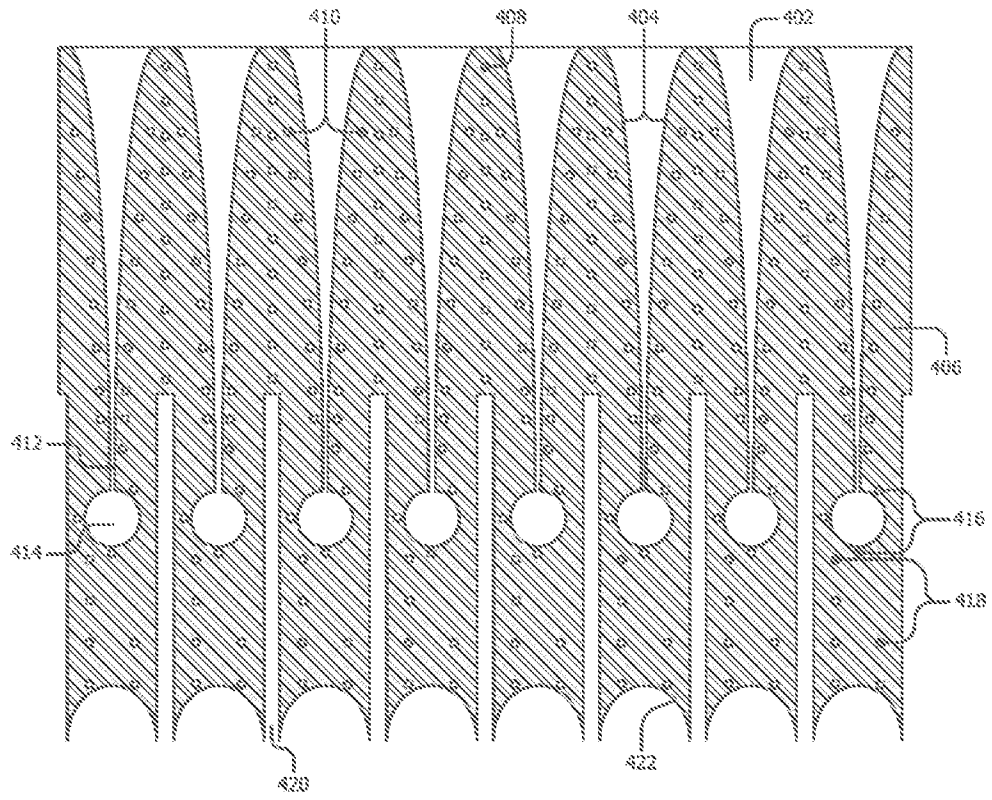


FIG. 4A

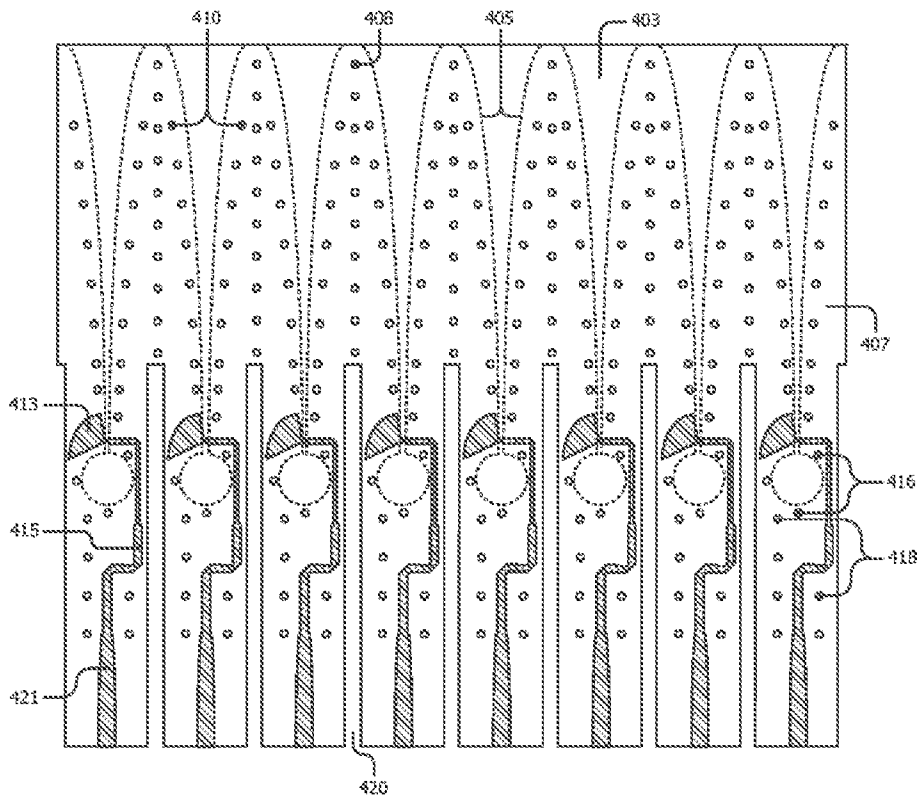


FIG. 4B

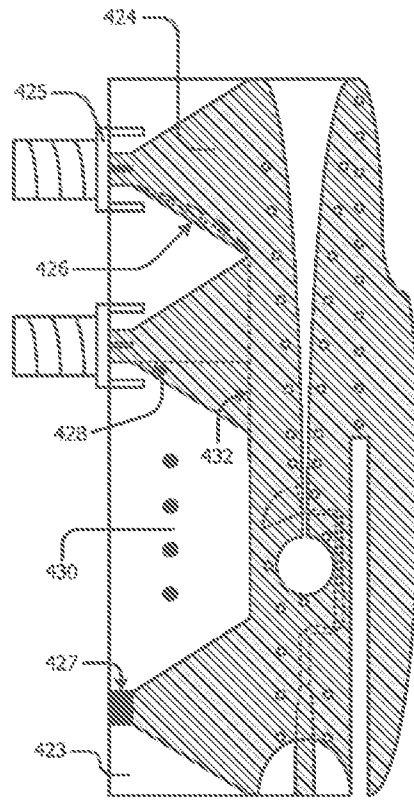


FIG. 4C

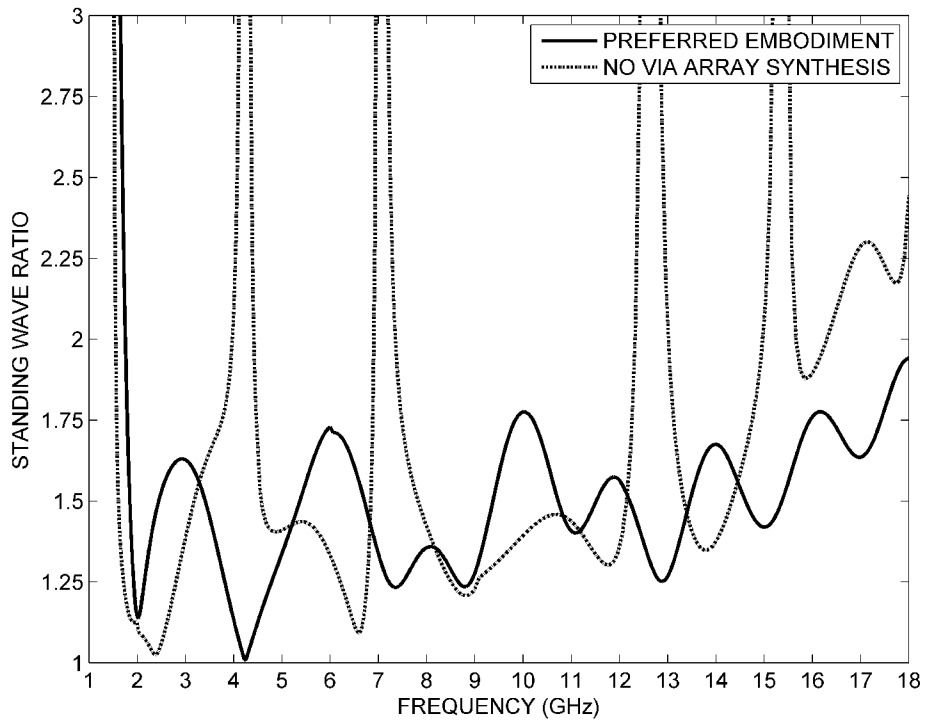


FIG. 5

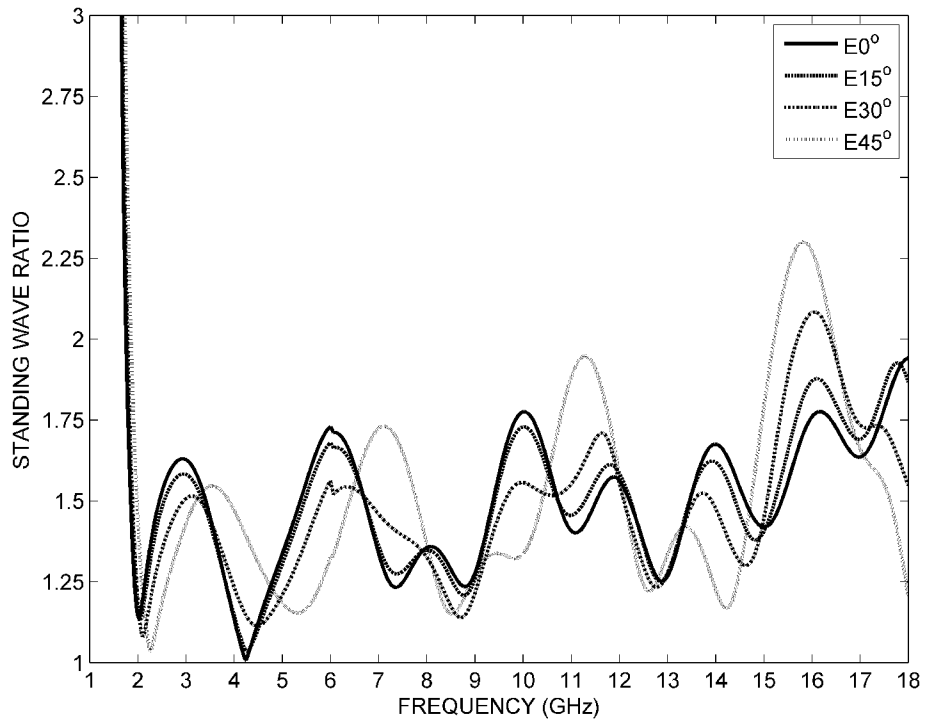


FIG. 6A

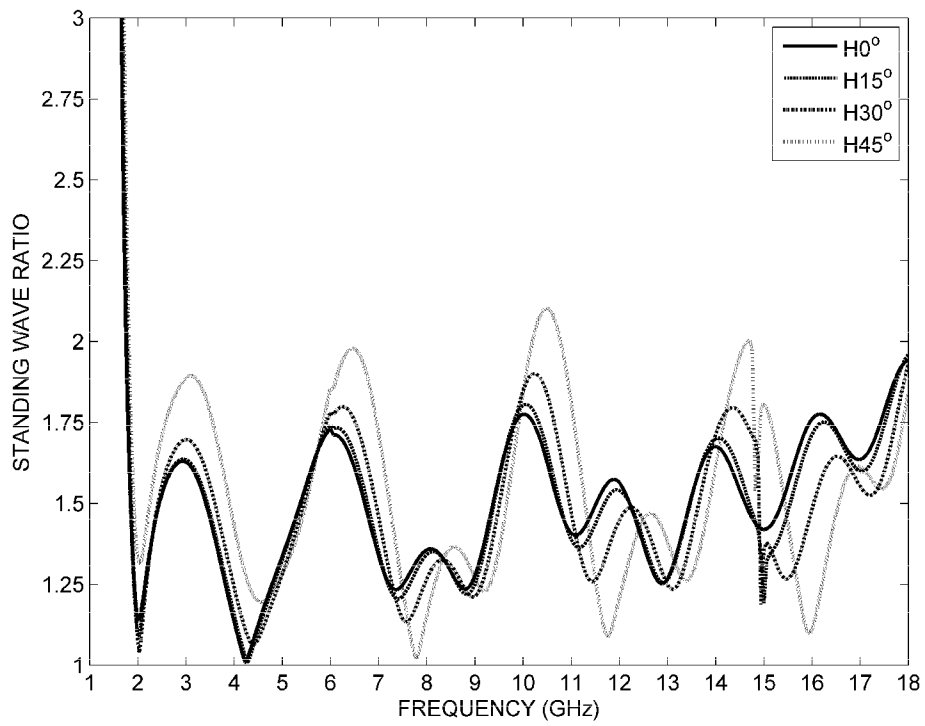


FIG. 6B

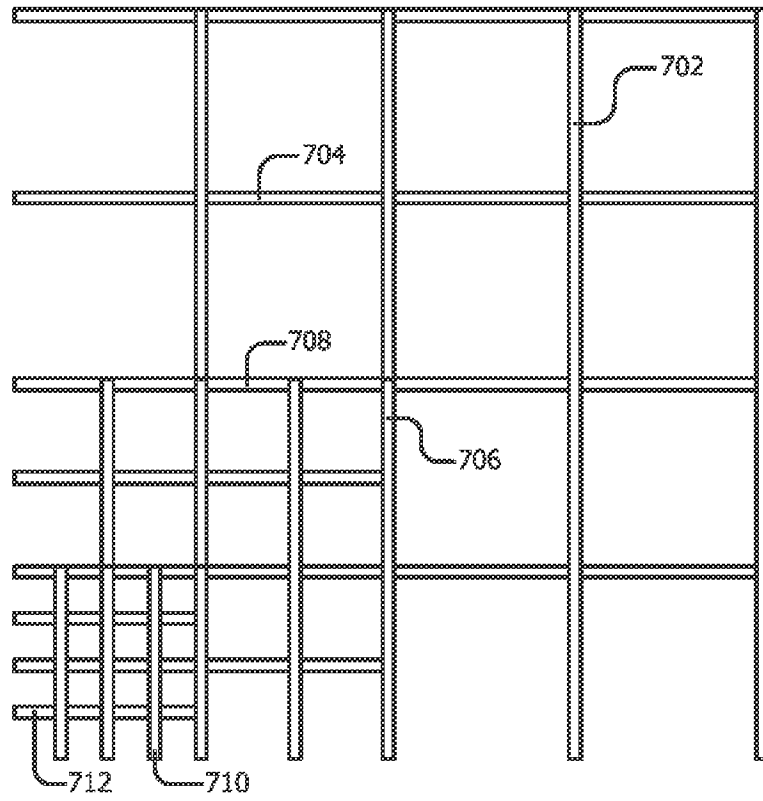


FIG. 7A

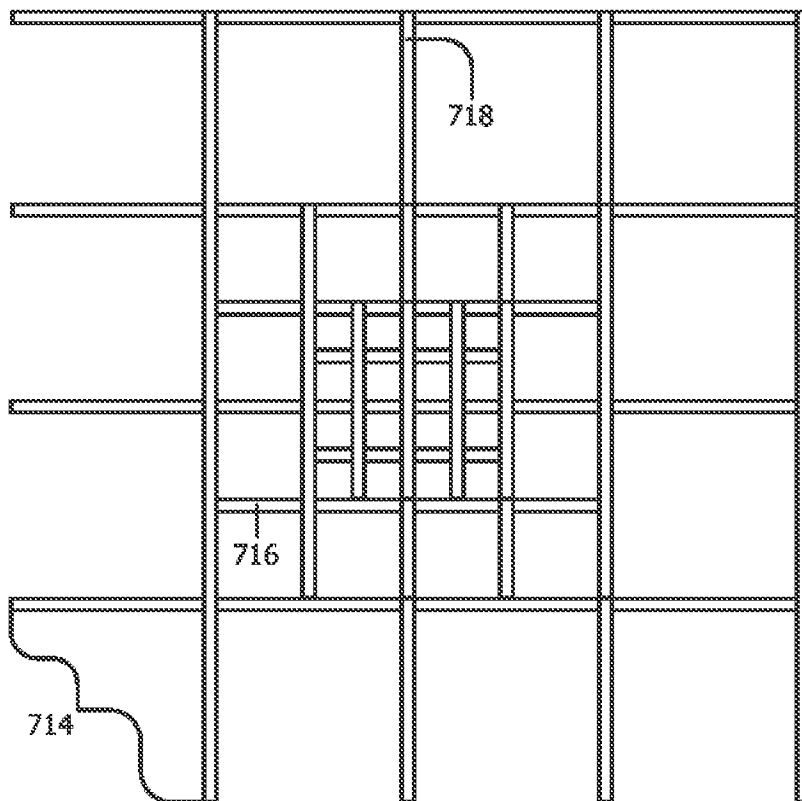


FIG. 7B