(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
**28 February 2013 (28.02.2013)**

WIPO | PCT

(10) **International Publication Number**
**WO 2013/027029 A1**

(51) **International Patent Classification**:
***H01Q 1/52*** (2006.01) ***H01Q 15/00*** (2006.01)

(21) **International Application Number**:
PCT/GB2012/052010

(22) **International Filing Date**:
16 August 2012 (16.08.2012)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:
1114625.5 24 August 2011 (24.08.2011) GB

(71) **Applicant** *(for all designated States except US)*: **ANTENOVA LIMITED** [GB/GB]; Far Field House, Albert Road, Stow-Cum-Quy, Cambridge CB5 9AR (GB).

(72) **Inventor; and**
(75) **Inventor/Applicant** *(for US only)*: **HARPER, Marc** [GB/GB]; Far Field House, Albert Road, Stow-Cum-Quy, Cambridge CB5 9AR (GB).

(74) **Agent**: **HARRISON GODDARD FOOTE**; Belgrave Hall, Belgrave Street, Leeds LS2 8DD (GB).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

**Declarations under Rule 4.17**:
— *of inventorship (Rule 4.17(iv))*

**Published**:
— *with international search report (Art. 21(3))*

(54) **Title**: ANTENNA ISOLATION USING METAMATERIAL

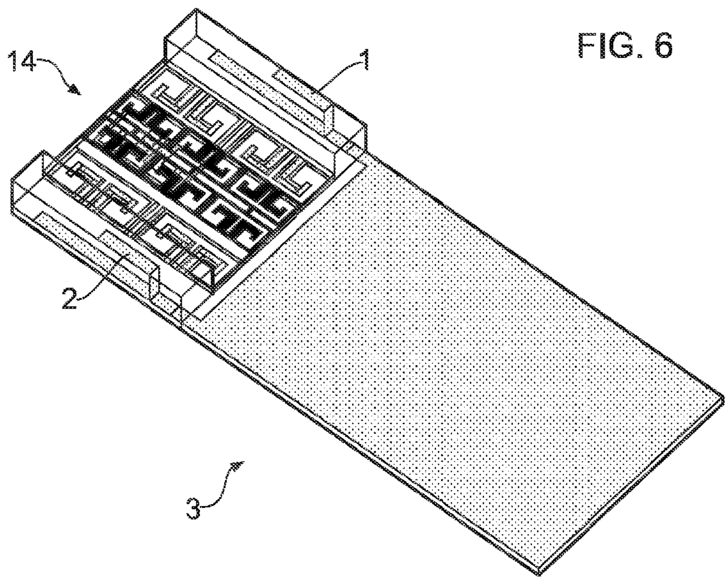



FIG. 6

(57) **Abstract**: There is disclosed a metamaterial comprising an array of unit cells each formed by at least one conductive track. At least one conductive track of at least one of the unit cells has a different length or width or thickness to the at least one conductive track of the other unit cells. The metamaterial can be placed between two or more antennas to improve isolation between the antennas.

WO 2013/027029 A1

# ANTENNA ISOLATION USING METAMATERIAL

**[0001]** This invention relates to techniques for improving isolation between antennas by using metamaterials, to the metamaterials themselves, and to antenna devices comprising such metamaterials.

## BACKGROUND

**[0002]** A metamaterial is an artificial material engineered to have properties that are not found in nature. Naturally occurring materials exhibit electromagnetic behaviour determined by their atomic and molecular structures. With metamaterials, the electromagnetic behaviour is modified by introducing structural features into the material that are smaller than the wavelength electromagnetic wave propagating through the material. Typically these features will have a size $\lambda/10$ to $\lambda/20$. In their simplest form, these structural features are distributed capacitive and inductive elements fabricated on a dielectric substrate such as FR4 (commonly used in printed circuit boards (PCBs)). More complex structures are possible and the use of discrete components, such as commercial capacitors, has also been explored.

**[0003]** From the antenna designer's perspective, one of the potentially most useful properties of metamaterials is the engineering of a structure having a negative refractive index. Negative refractive index materials are not naturally occurring because all natural materials have positive values for both permittivity ε and permeability μ. There are many interesting properties of negative refractive index materials including changes to the normal geometric rules of diffraction, reversal of the Doppler shift, etc. However, the property usually of most interest to the radio and antenna engineer is that a material having either negative ε or negative μ (but not both) is opaque to electromagnetic radiation. The electromagnetic properties of a transparent material are fully specified by the parameters ε and μ, but it is common practice to refer to the refractive index $n$ determined from $n = \pm\sqrt{(\varepsilon\mu)}$. When $n$ becomes negative, a common dielectric substrate material such as FR4 (which is naturally translucent at microwave radio frequencies) can be made opaque to radio waves. This can have applications for shielding an antenna from nearby conducting surfaces and for improving the isolation between antennas.

**[0004]** Negative refractive index metamaterials can be constructed at microwave frequencies using arrays of electrically conductive elements engineered to have a suitable capacitance **C** and inductance **L**. One of the earliest and most commonly used elements is the Split Ring Resonator (SRR) [Pendry, J B.; AJ Holden, DJ Robbins, and WJ Stewart.

"Magnetism from Conductors and Enhanced Nonlinear Phenomena" *IEEE Trans. Microwave Theory Tech* 47 (11): 2075–2084, 1999]. Each SRR element comprises two or more concentric rings, each having a split. The capacitance of each element arises from the close spacing between the concentric rings and the inductance from the thin printed traces used to create the rings.

**[0005]** It is known to provide a left-handed metamaterial with double L-shaped resonator inclusions [J. H. Lv, X. W. Hu, M.H. Liu, B. R. Yan and L. H. Kong.: "Negative refraction of a double L-shaped metamaterial", J. Opt. A: Pure Appl. Opt. 11 085101, 2009]. Here, the L-shaped resonators are formed of copper wire on an FR4 substrate, with each unit cell comprising a pair of L-shaped resonators arranged with one rotated by 180° to the other.

**[0006]** It is also known from Hsu, C-C et al. ["Design of MIMO Antennas with Strong Isolation for Portable Applications"; IEEE Antennas and Propagation Society International Symposium, 2009, pp 1-4] to provide a metamaterial with back-to-back L-shaped conductive members surrounded by a perimetral track. The metamaterial may be placed between a MIMO antenna pair to improve isolation.

**[0007]** Other metamaterials include those with split-ring resonator unit cells, as described, for example, in Moser, H O et al. ["Electromagnetic metamaterials over the whole THz range – achievements and perspectives"; ELECTROMAGNETIC MATERIALS Proceedings of the Symposium R, ICMAT 2005 (World Scientific Publishing Co.): 18].

**[0008]** A commonly used microwave radio frequency is 2.4 GHz, which is employed for Bluetooth™ links, wireless local area networks (WLAN), etc. The wavelength at 2.4 GHz is around 120 mm and so each **LC** element in the array might be expected to have a size typically in the order of 6-12 mm.

## BRIEF SUMMARY OF THE DISCLOSURE

**[0009]** Modern radio communication systems often make use of antenna diversity or MIMO (Multiple Input, Multiple Output) antenna technology. Both diversity and MIMO systems require more than one antenna operating at the same time and on the same frequency and so good isolation between the antennas becomes important. Poor isolation leads to a loss of antenna efficiency because power from one antenna ends up in other antennas instead of being radiated. Poor isolation also leads to a loss of diversity and MIMO performance because the coupling between the antennas means they are not receiving sufficiently independent samples of the radio multipath environment.

**[0010]** Viewed from a first aspect, there is provided a metamaterial comprising an array of unit cells each formed by at least one conductive track, wherein the at least one conductive track of at least one of the unit cells has a different length or width or thickness to the at least one conductive track of the other unit cells.

**[0011]** The metamaterial may comprise a 2D array of unit cells formed on or in a dielectric substrate.

**[0012]** In some embodiments, the metamaterial may comprise a stack of 2D arrays of unit cells, each 2D array of unit cells formed on or in a respective dielectric substrate. At least one of the dielectric substrates in the stack may be made of a material having a different dielectric constant to at least one other of the dielectric substrates in the stack. This can help to improve the bandwidth over which the metamaterial provides isolation between two or more antennas.

**[0013]** The metamaterial may comprise a first 2D array of unit cells on a first surface of a dielectric substrate, and a second 2D array of unit cells on an opposed, second surface of the dielectric substrate. At least one further 2D array of unit cells may be formed as in interstitial layer within the dielectric substrate between the first and second 2D arrays.

**[0014]** The unit cells of at least one 2D array may each be formed by at least one conductive track having a different length or width or thickness to the at least one conductive track of the unit cells in at least one other 2D array. This can help to improve the bandwidth over which the metamaterial provides isolation between two or more antennas.

**[0015]** At least one and generally each unit cell may comprise at least one conductive track configured as a split-ring resonator. The split-ring resonator may be symmetrical about a mirror plane, or may be asymmetrical. In the present context, asymmetrical denotes a split-ring resonator that does not have a mirror symmetry plane perpendicular to the plane of the conductive track. Asymmetrical arrangements may provide isolation over a wider bandwidth than symmetrical arrangements.

**[0016]** At least one unit cell may comprises first and second L-shaped conductive members disposed back-to-back in a plane with a gap between the members, and connected together by a perimetral conductive track that runs from an arm of the first L-shaped conductive member to an arm of the second L-shaped conductive member so as substantially to surround both L-shaped conductive members in the plane.

**[0017]** Preferably, the L-shaped conductive members, the split-ring resonators and/or the perimetral conductive track are formed on a dielectric substrate, for example a printed circuit board (PCB) substrate such as Duroid® or FR4, or on a flexible plastics substrate such as that used for flexi-circuits. In some embodiments, the L-shaped conductive members, the split-ring resonators and/or the perimetral conductive track may be printed or formed on a dielectric substrate in the form of an adhesive tape, which can then be applied to a PCB substrate as required.

**[0018]** In some embodiments, the perimetral conductive track may be generally rectangular in outline. Alternatively, generally circular, elliptical, oval or other polygonal outlines may be employed.

**[0019]** A gap may be defined in the perimetral conductive track corresponding to the gap between the back-to-back L-shaped conductive members. In other words, the perimetral conductive track may be split between the two L-shaped members.

**[0020]** Alternatively, the perimetral conductive track is not split between the two L-shaped members, but forms a continuous perimeter.

**[0021]** The array of elements may be configured as an n x m array having a generally 2-D configuration. Alternatively, the array of elements may be configured as an l x n x m array having a generally 3-D configuration. In yet further embodiments, several layers of metamaterial may be stacked on top of each other, with each layer having the same or different 2-D arrays of elements formed thereon.

**[0022]** The elements within any given array may be generally of the same shape and size. Alternatively, one or more elements within any given array may have slightly different sizes or shapes so that the elements are resonant at slightly different frequencies. Alternatively or in addition, one of the L-shaped conductive members in at least one of the elements may be differently sized and/or shaped than the other L-shaped conductive member. These arrangements may help to improve bandwidth.

**[0023]** It is not necessary for each array of elements to be a filled array. Indeed, one or more elements may be omitted from an array, and this has been found to improve the degree of isolation across a wider bandwidth. Moreover, it is possible to provide a degree of tuning by altering a position of one or more elements where space is made available through not filling the array. For example, an incompletely filled array may comprise a left hand column of two elements, a right hand column of two elements, and a middle column with only one element. By moving the element in the middle column up or down the column, the bandwidth of the metamaterial can be fine-tuned as required.

**[0024]** The metamaterial may be used to improve isolation between two or more antennas. This is of particular advantage in antenna systems using antenna diversity or MIMO technology, since these employ several antennas operating simultaneously within a small space.

**[0025]** Viewed from a second aspect, the present invention provides an antenna system comprising at least two antennas disposed on a substrate and a portion of metamaterial of the first aspect disposed between the at least two antennas.

**[0026]** It is also possible to use a metamaterial comprising a dielectric substrate with first and second opposed surfaces, with a first pattern of elements formed on the first surface and a second pattern of elements formed on the second surface. The first and second patterns of elements may be tuned to different frequencies or frequency bands, and the dual surface metamaterial, when disposed between a pair of dual-band antennas, can improve antenna isolation on both bands.

**[0027]** A similar result may be achieved by forming a first metamaterial comprising a dielectric substrate with a first pattern of elements, forming a second metamaterial comprising a dielectric substrate with a second pattern of elements, and then positioning the second metamaterial on top of the first metamaterial between a pair of antennas.

**[0028]** This principle may be extended to multiple metamaterial layers or surfaces so as to improve isolation between two antennas in several bands.

**[0029]** The metamaterial can also be used to improve isolation between several (more than two) antennas, including several antennas disposed in a co-planar fashion and in geometries other than co-planar.

**[0030]** In some embodiments, the conductive structures of the metamaterial are printed or otherwise formed on one or both surfaces of a dielectric substrate material, for example FR4. In other embodiments, the conductive structures are printed or otherwise formed on an interstitial layer of dielectric substrate material, such as FR4. It will be appreciated that other common PCB substrate materials, including Duroid®, may also be used. Multiple layers of dielectric substrate with the same or different dielectric constant may be used.

**[0031]** Other low or high dielectric constant materials (typically in the range of 1 to 90) may be used as substrates for the metamaterial.

**[0032]** The novel metamaterial structure of certain embodiments can be used to increase the isolation between a pair of closely spaced antennas. The metamaterial structure of some embodiments may be low cost as it can be printed on a layer of FR4, a low cost substrate material often use in the radio industry. Some embodiments have a further advantage that, for dual band antennas and antenna arrangement, the metamaterial can be engineered to improve the isolation between both bands. This can be achieved by introducing an additional layer of dielectric substrate, printed with a different array of **LC** elements, above or below the first layer. Indeed, isolation between more bands is possible by introducing more layers.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0033]** Embodiments of the invention are further described hereinafter with reference to the accompanying drawings, in which:

Figure 1 shows a prior art arrangement comprising a pair of closely spaced dual-band WLAN antennas on a PCB;

Figure 2 is a plot showing the isolation between the two WLAN antennas of the Figure 1 arrangement;

Figure 3 shows a first embodiment comprising a metamaterial on a PCB;

Figure 4 shows a second embodiment comprising a metamaterial on a PCB;

Figure 5 shows a third embodiment comprising a dual-band composite metamaterial comprising a first layer of the Figure 3 embodiment and a second layer of the Figure 4 embodiment;

Figure 6 shows the metamaterial of Figure 5 disposed between a pair of WLAN antennas similar to those shown in Figure 1;

Figure 7 is a plot showing the isolation between the two WLAN antennas of the Figure 6 arrangement;

Figure 8 shows how the metamaterial of the Figure 5 embodiment can be tuned by moving a middle element on one layer of metamaterial;

Figure 9 is a plot showing the isolation between the two WLAN antennas of the Figure 6 arrangement when a middle element on one layer of metamaterial is moved;

Figure 10 shows a metamaterial comprising a 2D array of split-ring resonators on a dielectric substrate with one or more of the split-ring resonators having a different size to the others;

Figure 11 shows a metamaterial comprising a 2D array of split-ring resonators on a dielectric substrate with one or more of the split-ring resonators having a different shape to the others;

Figure 12 shows a metamaterial comprising a 2D array of split-ring resonators having a first configuration on one surface of a dielectric substrate, and a 2D array of split-ring resonators having a second, different configuration on the other surface of the dielectric substrate; and

Figure 13 shows a metamaterial comprising a 2D array of split-ring resonators having a first configuration on one surface of a dielectric substrate, a 2D array of split-ring resonators having a second, different configuration on the other surface of the dielectric substrate, and an interstitial 2D array of split-ring resonators having a third, different configuration between the surfaces of the dielectric substrate.

## DETAILED DESCRIPTION

**[0034]** Figure 1 shows two coplanar 2.4/5 GHz dual-band quarter-wave monopole antennas 1, 2 are closely spaced in a generally parallel arrangement on a PCB 3 comprising a dielectric substrate 4 with a conductive groundplane 5 over part of the substrate 4, and an area 6 free of groundplane 5 where the antennas 1, 2 are located. It will be appreciated that this is just an exemplary arrangement, and that other types of antenna and other frequency bands may be used with embodiments of the present application given suitable adjustments of the metamaterial design. In Figure 1, the width of the PCB 3 is 20 mm and the antenna area 6 clear of groundplane 5 is 15 mm long. The long lower portion 7 of the antenna is generally responsible for the radiation of 2.4 GHz and the elevated portions 1, 2 for the 5 GHz radiation. The height of the antenna at its tallest part is 3.2 mm.

**[0035]** In the 2.40 - 2.48 GHz WLAN band, the monopole antennas 1, 2 are spaced only about $\lambda/6$ apart and so the isolation between them is poor at around –6 dB, see Figure 2. In the 4.9 - 5.9 GHz WLAN band, the monopole antennas 1, 2 are electrically further apart, but even so, the worst-case the isolation remains poor at around –8 dB.

**[0036]** A metamaterial structure of an embodiment of the present application is shown in Figure 3. A plurality of conductive **LC** (inductive capacitive) elements 8 are printed on a single surface of FR4 substrate 9 and require no vias to ground (used in some metamaterial structures). In the illustrated embodiment, the elements 8 are not conductively connected to each other. The inductance of each element 8 arises from the narrow conductive tracks 10 and the capacitance primarily from the closely spaced back-to-back L-shaped elements 11. The use of double L-shaped metamaterials has been described in the literature [J. H. Lv, X. W. Hu, M.H. Liu, B. R. Yan and L. H. Kong.: “Negative refraction of a double L-shaped metamaterial”, J. Opt. A: Pure Appl. Opt. 11 085101, 2009], but here one L-shape is inverted with respect to the other and not back-to-back as described in the present application. It has been found advantageous to use an unfilled array of elements 8, as shown in Figure 3, where an element 8 is absent at location 12. Removing an element has been found to improve bandwidth and moving the remaining centre element 13 (in this example) up and down may be used to tune the bandwidth to a particular application. The metamaterial structure of Figure 3 provides good electromagnetic isolation at around 2.4 GHz.

**[0037]** An alternative metamaterial design is shown in Figure 4, and is tuned to the 5 GHz band. As with the Figure 3 embodiment, a plurality of conductive **LC** elements 8' are printed on a single surface of FR4 substrate 9, but in the Figure 4 embodiment, the elements 8' are conductively linked to each other and arranged as a pair of closely spaced columns. Other arrangments are possible.

**[0038]** In order to achieve a practical dual-band device, two different metamaterial surfaces can be combined. For example, a 5 GHz surface of the Figure 4 embodiment can be mounted on top of and appropriately registered or aligned with a 2.4 GHz surface of the Figure 3 embodiment, as shown in Figure 5, to provide a dual-band metamaterial 14.

**[0039]** Figure 6 shows a complete structure of a pair of monopole antennas 1, 2 on a PCB 3, with a dual-band combined metamaterial 14 of Figure 5 disposed between the monopole antennas 1, 2.

**[0040]** With the dual-band metamaterial 14 in place, the isolation between the antennas 1, 2 is improved in both bands, as shown in Figure 7. In the lower 2.4 GHz band the isolation has a very deep null and even at the band edges it is around –12 dB. This could be improved by careful tuning of the metamaterial 14 to put the null exactly in the centre of the band. In the high frequency band the isolation around 5 GHz is –20 dB. This notch may be moved to any part of the 4.9 – 5.9 GHz band by retuning the metamaterial 14.

**[0041]** The lower layer of the dual-band metamaterial 14 is an unfilled array and has one element missing in the centre column (see Figure 3). Moving the position of the element within the column, see Figure 8, can be used to change the bandwidth of isolation in the 5GHz band without much affecting the isolation frequency of the 2.4 GHz. This effect is shown in Figure 9.

**[0042]** In this exemplary arrangement the 2.4 GHz metamaterial has been shown as a 3x2 element array, whereas the 5 GHz metamaterial has been shown as a 2x3 array. It will be appreciated that other array configurations are possible with greater or smaller number of elements. It will also be appreciated that more than one array element may be removed to tune the bandwidth of the isolation effect.

**[0043]** In the exemplary arrangement described above, FR4 has been used as the substrate material. Many other types of substrate materials may be used including low and high dielectric materials. Generally the beneficial characteristics of a metamaterial improve with increasing numbers of elements in the array. For a given platform size, the use of a high dielectric substrate may be used to shrink the element size and allow more elements to be used in the array.

**[0044]** The exemplary arrangement above describes a dual-band metamaterial comprising two layers. In general, n-band metamaterials can be created using n-layer substrates.

**[0045]** Although isolation between two antennas has been described in the exemplary arrangement above, isolation between greater numbers is possible by suitably disposing metamaterial elements between all the pairs.

**[0046]** The exemplary arrangement above describes two coplanar antennas, but the metamaterial described may also be used to improve isolation between antennas disposed using other geometries.

**[0047]** Figure 10 shows a metamaterial comprising a 2D array of split-ring resonators 8 on a dielectric substrate 9 with one or more of the split-ring resonators 8 having a different size to the others. This may help to provide isolation over a wider bandwidth.

**[0048]** Figure 11 shows a metamaterial comprising a 2D array of split-ring resonators 8 on a dielectric substrate 9 with one or more of the split-ring resonators 8 having a different shape to the others. This may help to provide isolation over a wider bandwidth.

**[0049]** Figure 12 shows a metamaterial comprising a 2D array of split-ring resonators 8 having a first configuration on one surface of a dielectric substrate 9, and a 2D array of split-ring resonators 8’ having a second, different configuration on the other surface of the dielectric substrate 9. This may help to provide isolation over a wider bandwidth.

**[0050]** Figure 13 shows a metamaterial comprising a 2D array of split-ring resonators 8 having a first configuration on one surface of a dielectric substrate 9, a 2D array of split-ring resonators 8’ having a second, different configuration on the other surface of the dielectric substrate 9, and an interstitial 2D array of split-ring resonators 8’’ having a third, different configuration between the surfaces of the dielectric substrate 9. This may help to provide isolation over a wider bandwidth.

**[0051]** Throughout the description and claims of this specification, the words “comprise” and “contain” and variations of them mean “including but not limited to”, and they are not intended to (and do not) exclude other moieties, additives, components, integers or steps. Throughout the description and claims of this specification, the singular encompasses the plural unless the context otherwise requires. In particular, where the indefinite article is used, the specification is to be understood as contemplating plurality as well as singularity, unless the context requires otherwise.

**[0052]** Features, integers, characteristics, compounds, chemical moieties or groups described in conjunction with a particular aspect, embodiment or example of the invention are to be understood to be applicable to any other aspect, embodiment or example described herein unless incompatible therewith. All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive. The invention is not restricted to the details of any foregoing embodiments. The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

**[0053]** The reader's attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference.

**CLAIMS:**

1. A metamaterial comprising an array of unit cells each formed by at least one conductive track, wherein the at least one conductive track of at least one of the unit cells has a different length or width or thickness to the at least one conductive track of the other unit cells.

2. A metamaterial as claimed in claim 1, comprising a 2D array of unit cells formed on or in a dielectric substrate.

3. A metamaterial as claimed in claim 1, comprising a stack of 2D arrays of unit cells, each 2D array of unit cells formed on or in a respective dielectric substrate.

4. A metamaterial as claimed in claim 3, wherein at least one of the dielectric substrates in the stack is made of a material having a different dielectric constant to at least one other of the dielectric substrates in the stack.

5. A metamaterial as claimed in claim 1, comprising a first 2D array of unit cells on a first surface of a dielectric substrate, and a second 2D array of unit cells on an opposed, second surface of the dielectric substrate.

6. A metamaterial as claimed in claim 5, further comprising at least one further 2D array of unit cells formed as in interstitial layer within the dielectric substrate between the first and second 2D arrays.

7. A metamaterial as claimed in any one of claims 3 to 6, wherein the unit cells of at least one 2D array are each formed by at least one conductive track having a different length or width or thickness to the at least one conductive track of the unit cells in at least one other 2D array.

8. A metamaterial as claimed in any preceding claim, wherein at least one unit cell comprises at least one conductive track configured as a split-ring resonator.

9. A metamaterial as claimed in any preceding claim, wherein each unit cell comprises at least one conductive track configured as a split-ring resonator.

10. A metamaterial as claimed in any preceding claim, wherein at least one unit cell comprises first and second L-shaped conductive members disposed back-to-back in a plane with a gap between the members, and connected together by a perimetral conductive track that runs from an arm of the first L-shaped conductive member to an arm of the second L-shaped conductive member so as substantially to surround both L-shaped conductive members in the plane.

11. A metamaterial as claimed in claim 10, wherein the perimetral conductive track of at least one unit cell is generally rectangular in outline.

12. A metamaterial as claimed in claim 10, wherein the perimetral conductive track of at least one unit cell is generally circular, elliptical, oval or polygonal in outline.

13. A metamaterial as claimed in any one of claims 10 to 12, wherein for at least one unit cell, a gap is defined in the perimetral conductive track corresponding to the gap between the back-to-back L-shaped conductive members.

14. A metamaterial as claimed in any one of claims 10 to 13, wherein for at least one element, the perimetral conductive track is not split between the two L-shaped members, but forms a continuous perimeter.

15. A metamaterial as claimed in any one of claims 10 to 14, wherein the first and second L-shaped conductive members in at least one of the unit cells are differently sized and/or shaped to each other.

16. A metamaterial as claimed in claim 8 or 9, wherein at least one split-ring resonator is configured asymmetrically.

17. A metamaterial of any one of claims 1 to 16, wherein one or more unit cells have different sizes or shapes so that the unit cells are resonant at different frequencies.

18. A metamaterial as claimed in any preceding claim, wherein the array of unit cells is not a filled array, one or more elements having been omitted therefrom.

19. An antenna system comprising at least two antennas disposed on a substrate and a portion of metamaterial as claimed in any one of claims 1 to 18 disposed between the at least two antennas.

20. A metamaterial substantially as hereinbefore described with reference to or as shown in Figures 3 to 13 of the accompanying drawings.

21. An antenna system substantially as hereinbefore described with reference to or as shown in Figures 3 to 13 of the accompanying drawings.

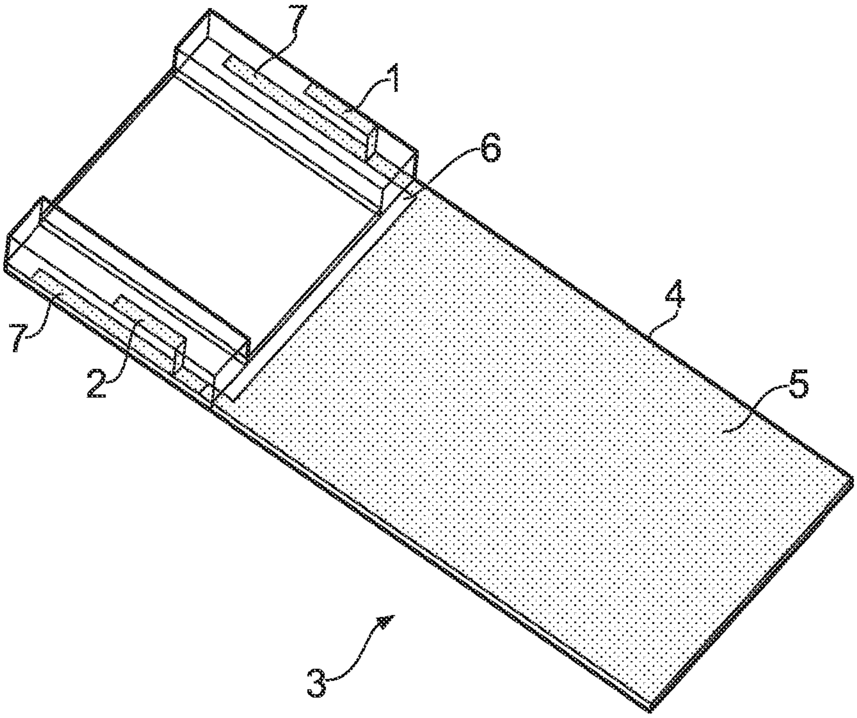
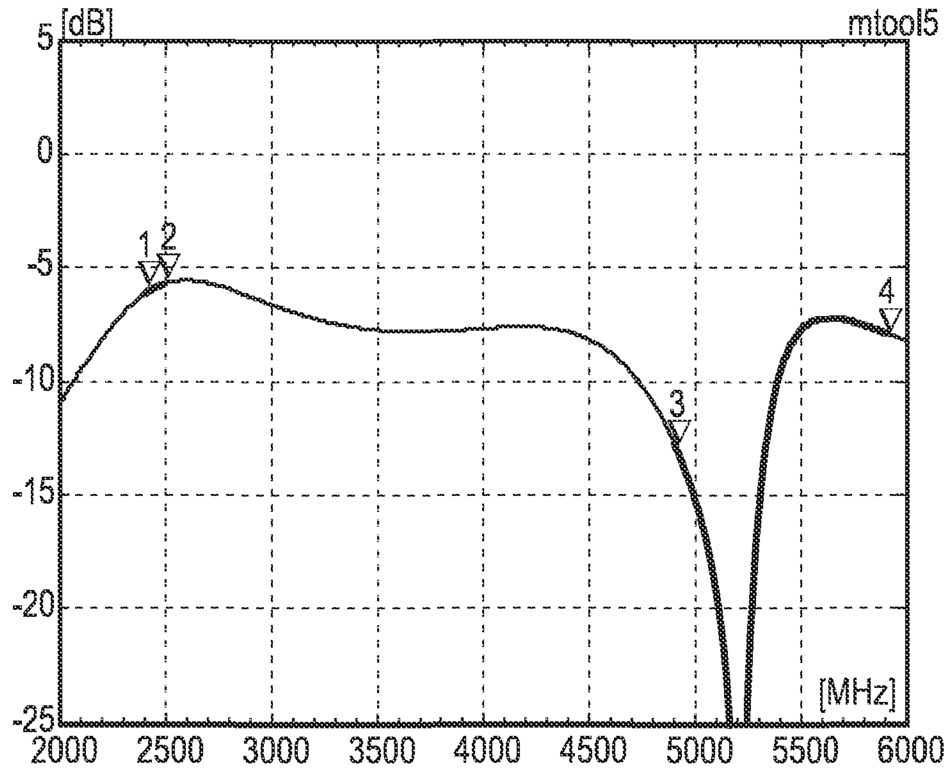



FIG. 1




| MARKERS: | MHz | dB | MHz | dB |
|---|---|---|---|---|
| 10000_mxh_MSdualbandnoisolation HFSSDesign1.s2p | | | | |
| | 1: 2400 | -6.17 | 3: 4900 | -12.72 |
| | 2: 2497 | -5.72 | 4: 5900 | -7.89 |

FIG. 2

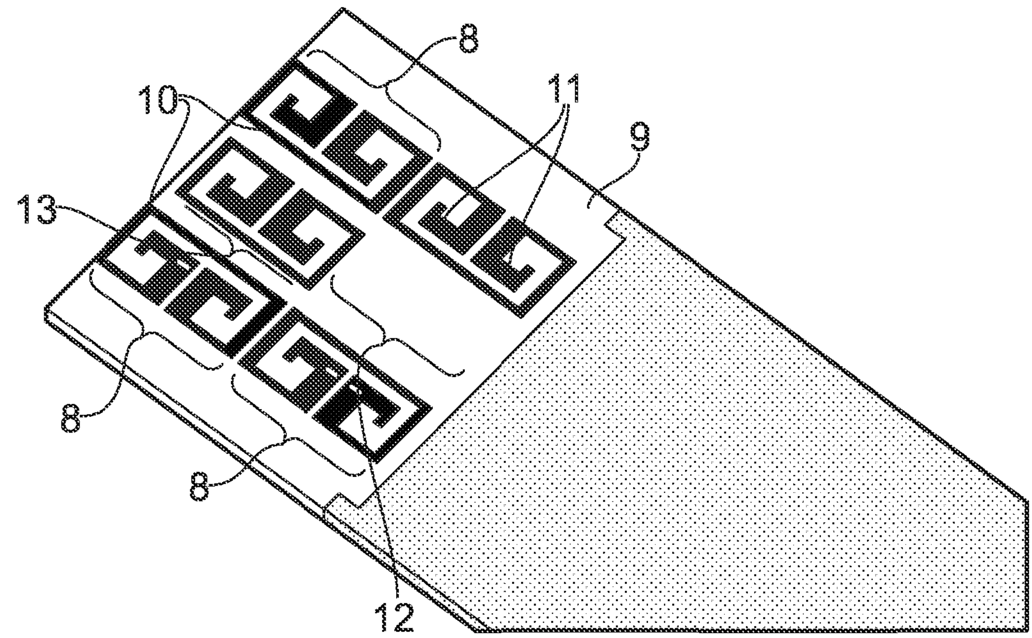



FIG. 3

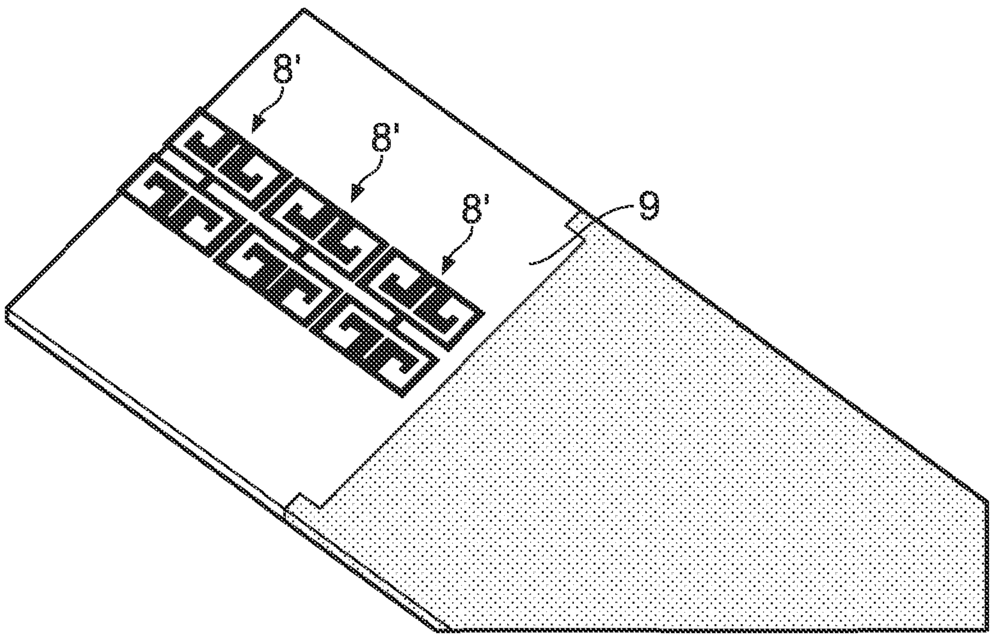



FIG. 4

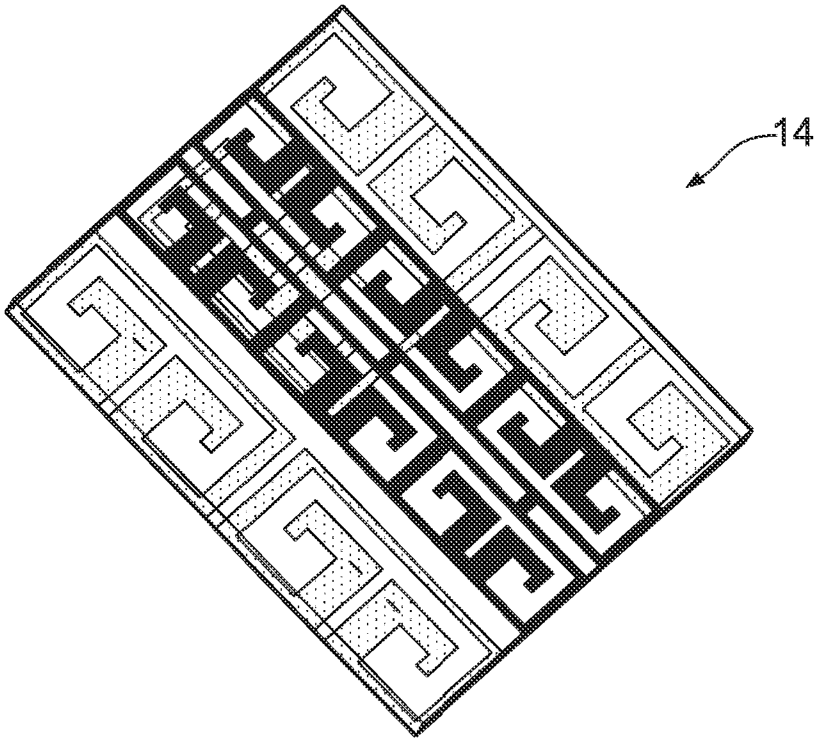



FIG. 5

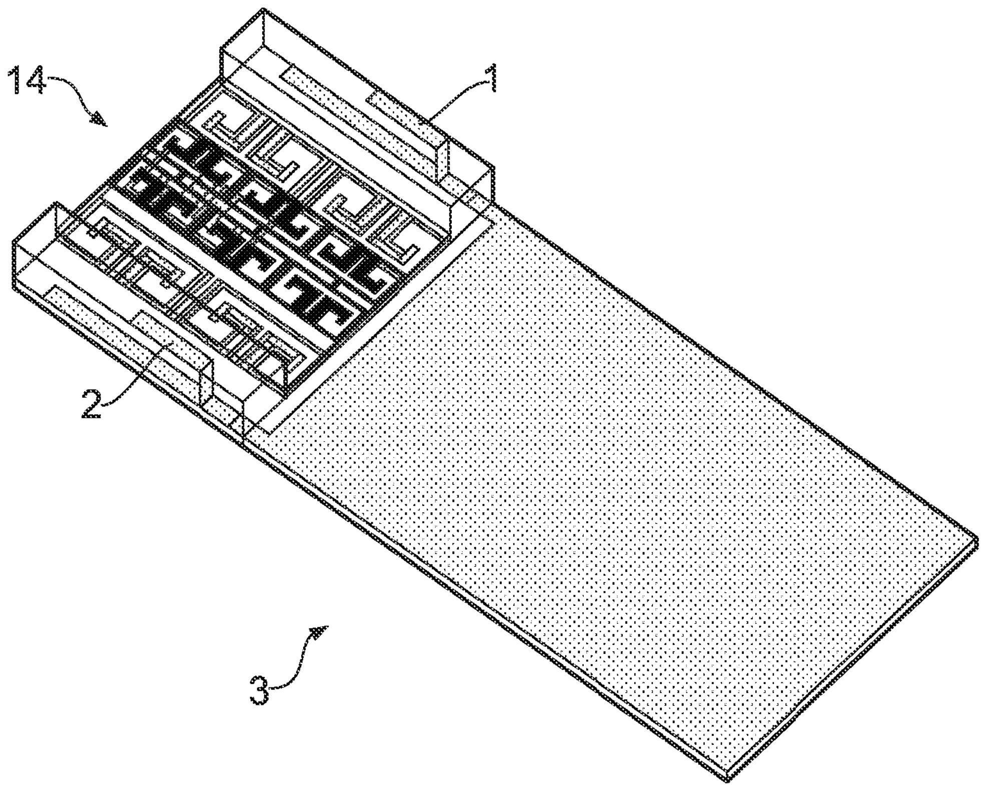



FIG. 6

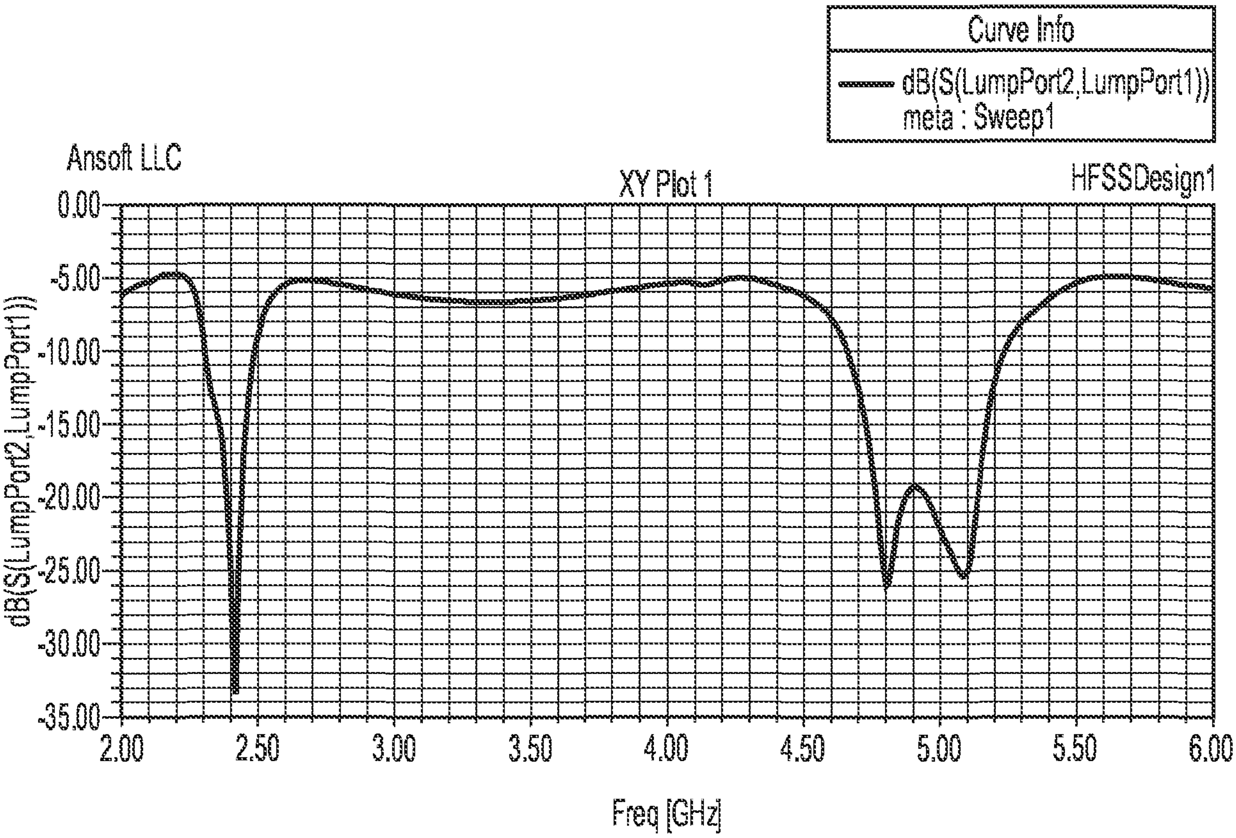

Curve Info
dB(S(LumpPort2,LumpPort1))
meta : Sweep1
Ansoft LLC
XY Plot 1
HFSSDesign1
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
-35.00
dB(S(LumpPort2,LumpPort1))
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
6.00
Freq [GHz]

FIG. 7

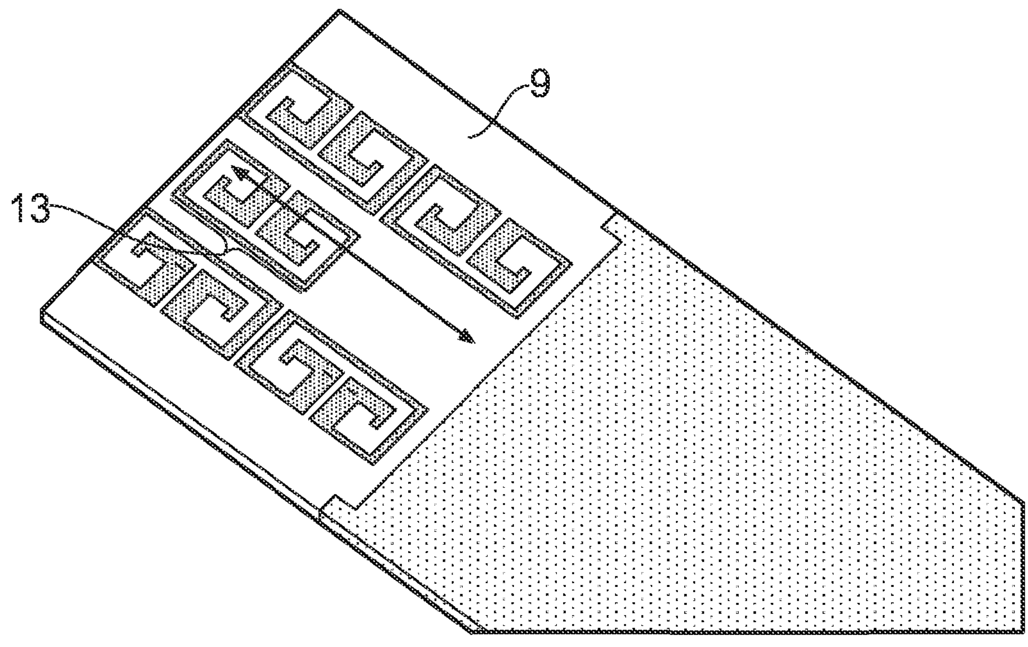

9
13

FIG. 8

5/7

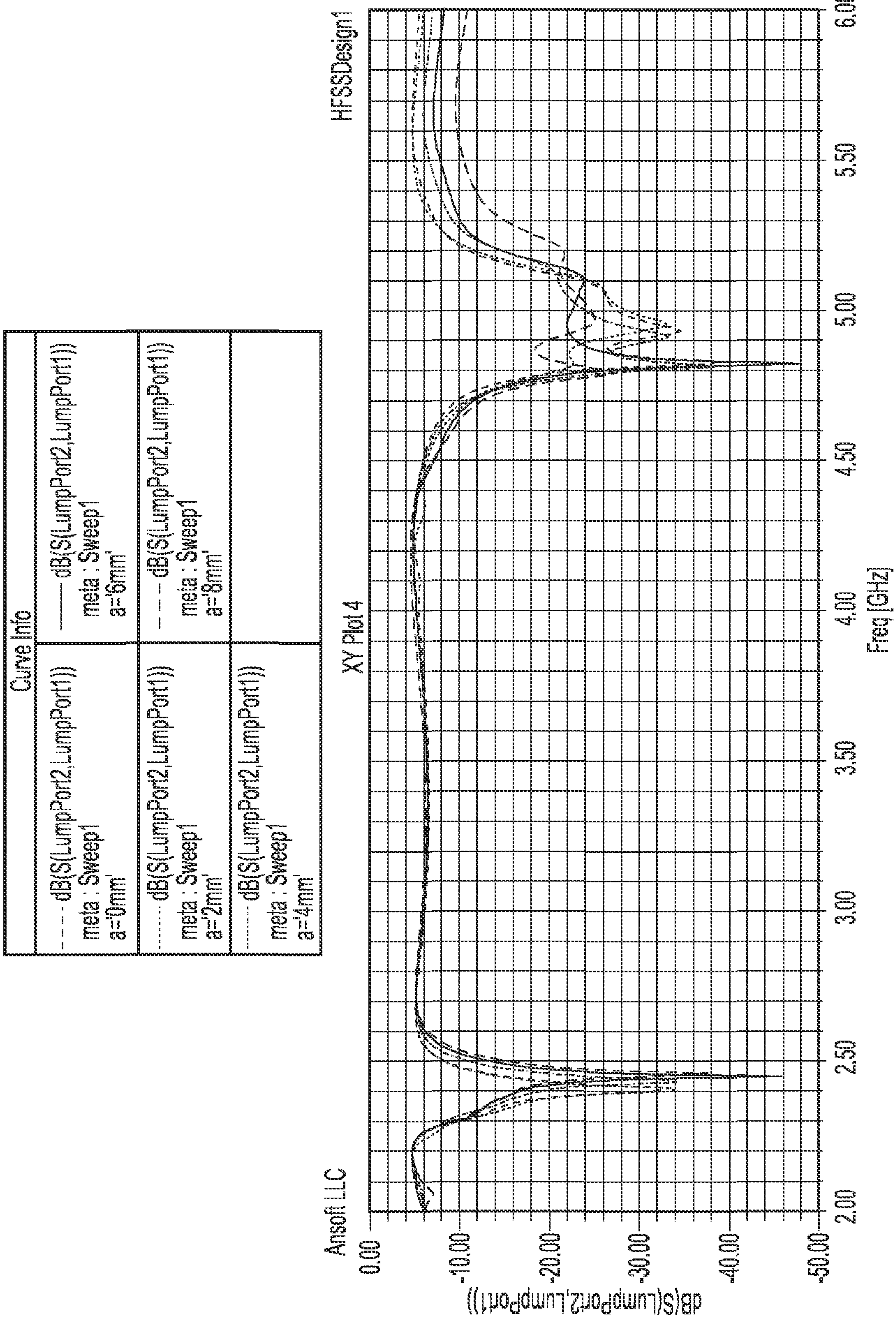

Curve Info
dB(S(LumpPort2,LumpPort1))
meta : Sweep1
a='0mm'
dB(S(LumpPort2,LumpPort1))
meta : Sweep1
a='2mm'
dB(S(LumpPort2,LumpPort1))
meta : Sweep1
a='4mm'
dB(S(LumpPort2,LumpPort1))
meta : Sweep1
a='6mm'
dB(S(LumpPort2,LumpPort1))
meta : Sweep1
a='8mm'
Ansoft LLC
XY Plot 4
HFSSDesign1
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
dB(S(LumpPort2,LumpPort1))
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
6.00
Freq [GHz]

FIG. 9

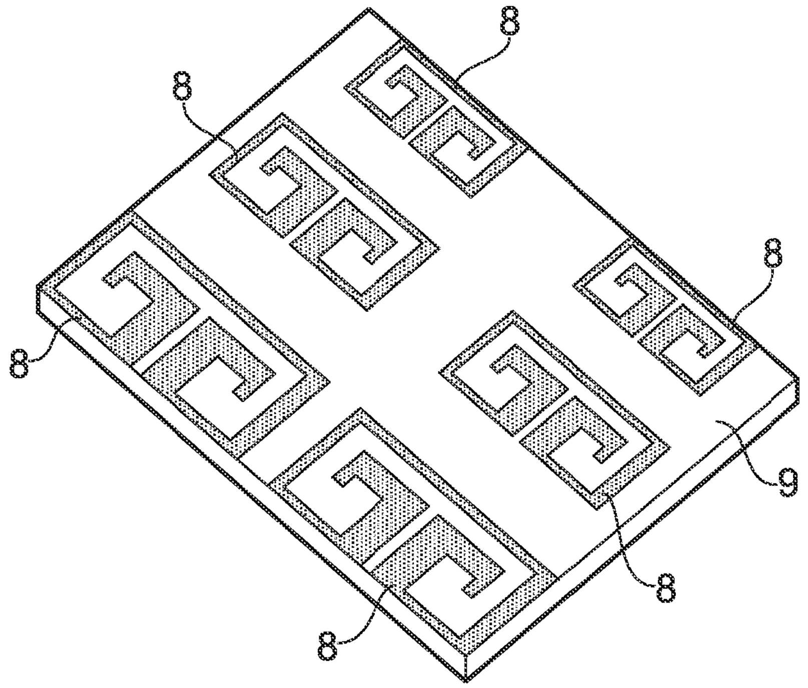



FIG. 10

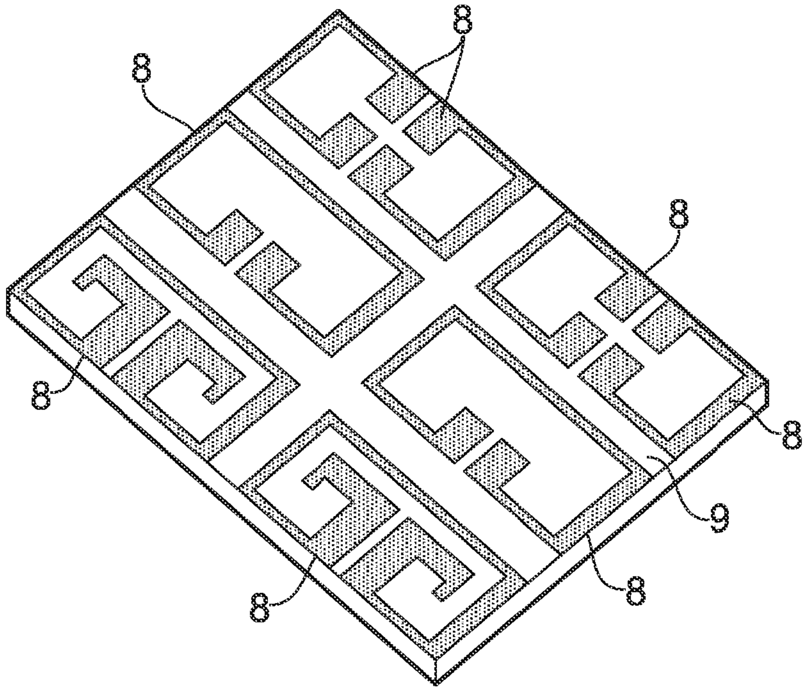



FIG. 11

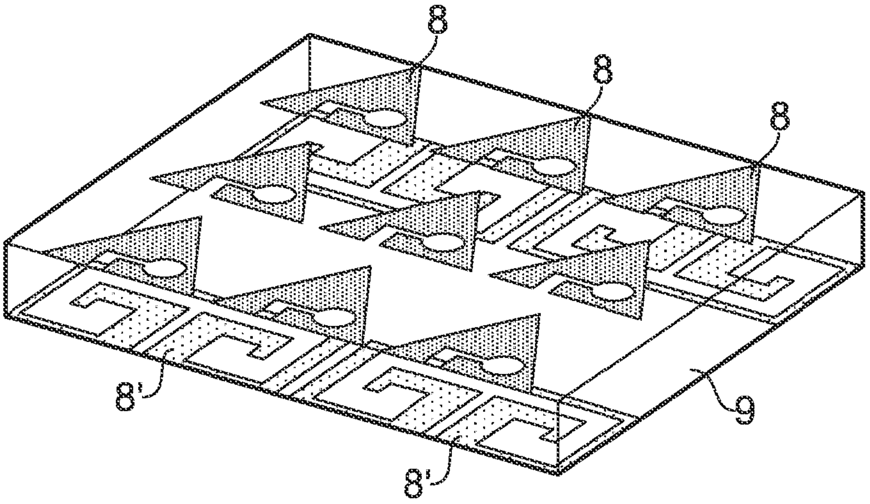



FIG. 12

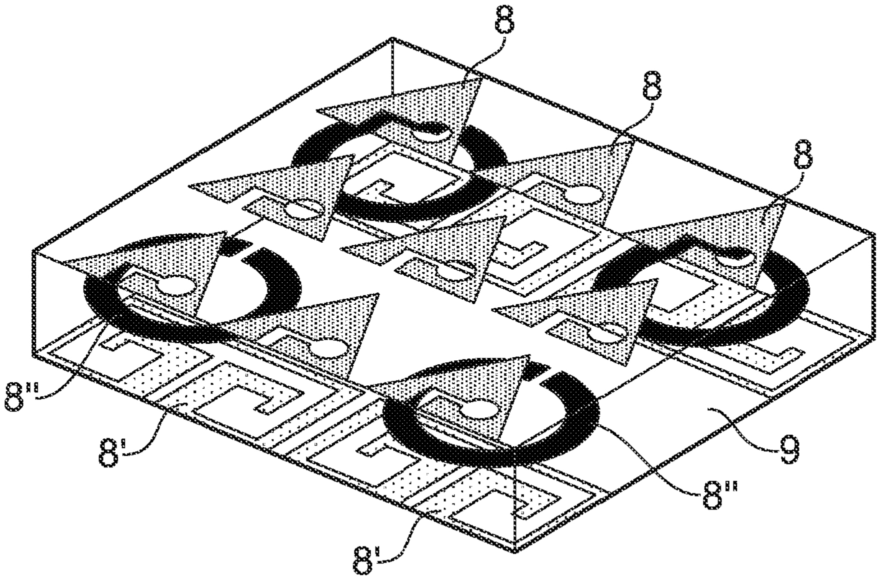



FIG. 13

# INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2012/052010

**A. CLASSIFICATION OF SUBJECT MATTER**
INV. H01Q1/52 H01Q15/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X<br><br>Y | SU H-L ET AL: "Dual-band insulator design by stacking capacitively loaded loops for MIMO antennas", THE INSTITUTION OF ENGINEERING AND TECHNOLOGY. JOURNAL,, vol. 46, no. 20, 30 September 2010 (2010-09-30), pages 1364-1365, XP006036973, ISSN: 1350-911X, DOI: 10.1049/EL:20101756<br>the whole document<br>----- | 1,2,5, 7-14, 17-21<br><br>3,4,6, 15,16 |

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 31 October 2012 | 07/11/2012 |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040,<br>Fax: (+31-70) 340-3016 | Kruck, Peter |

1

# INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2012/052010

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | GU S ET AL: "A broadband low-reflection metamaterial absorber", JOURNAL OF APPLIED PHYSICS, AMERICAN INSTITUTE OF PHYSICS. NEW YORK, US, vol. 108, no. 6, 30 September 2010 (2010-09-30), pages 64913-64913, XP012143037, ISSN: 0021-8979, DOI: 10.1063/1.3485808 | 3,4,6 |
| A | the whole document | 1 |
| | ----- | |
| A | LI HUI ET AL: "Ultrathin multiband gigahertz metamaterial absorbers", JOURNAL OF APPLIED PHYSICS, AMERICAN INSTITUTE OF PHYSICS. NEW YORK, US, vol. 110, no. 1, 12 July 2011 (2011-07-12) , pages 14909-14909, XP012149269, ISSN: 0021-8979, DOI: 10.1063/1.3608246 the whole document | 1,2,17 |
| | ----- | |
| A | EP 2 256 866 A2 (IND TECH RES INST [TW]; UNIV NAT SUN YAT SEN [TW]) 1 December 2010 (2010-12-01) paragraphs [0031] - [0070] figures 1,2,6-13,15 | 1,2,8-21 |
| | ----- | |
| A | BAIT SUWAILAM M M ET AL: "Mutual coupling reduction in MIMO antennas using artificial magnetic materials", ANTENNA TECHNOLOGY AND APPLIED ELECTROMAGNETICS AND THE CANADIAN RADIO SCIENCE MEETING, 2009. ANTEM/URSI 2009. 13TH INTERNATIONAL SYMPOSIUM ON, IEEE, PISCATAWAY, NJ, USA, 15 February 2009 (2009-02-15), pages 1-4, XP031444129, ISBN: 978-1-4244-2979-0 the whole document | 1,19 |
| | ----- | |
| Y | CHENG ZHU ET AL: "Multiresonant Metamaterial Based on Asymmetric Triangular Electromagnetic Resonators", IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, IEEE, PISCATAWAY, NJ, US, vol. 9, 1 January 2010 (2010-01-01), pages 99-102, XP011331224, ISSN: 1536-1225, DOI: 10.1109/LAWP.2010.2042922 | 15,16 |
| A | the whole document | 1 |
| | ----- | |

1

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2012/052010

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
|---|---|---|---|
| EP 2256866 A2 | 01-12-2010 | EP 2256866 A2 | 01-12-2010 |
| | | TW 201042820 A | 01-12-2010 |
| | | US 2010295739 A1 | 25-11-2010 |