

(43) International Publication Date
6 April 2017 (06.04.2017)

(51) International Patent Classification:

H01Q 15/00 (2006.01) *H01Q 15/23* (2006.01)
H01Q 15/08 (2006.01)

(21) International Application Number:

PCT/GB2016/052822

(22) International Filing Date:

13 September 2016 (13.09.2016)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

1516322.3 15 September 2015 (15.09.2015) GB

(71) Applicant: UNIVERSITY COLLEGE CARDIFF CONSULTANTS LTD [GB/GB]; c/o Dr Rhodri Turner, 7th Floor, RIS, 30-36 Newport Road, Cardiff University, Crrdiff, South Wales CF24 0DE (GB).

(72) Inventor; and

(71) Applicant (for US only): PISANO, Giampaolo [IT/GB]; 35 John Bachelor Way, Penarth, South Glamorgan CF64 1SD (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, IR, IS, JP, KE, KG, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, 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, ST, 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, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: AN ARTIFICIAL MAGNETIC CONDUCTOR

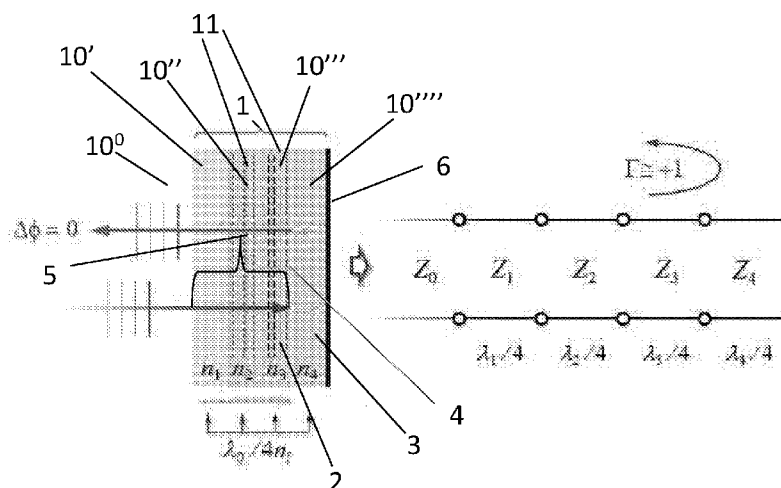


Fig 6a

Fig 6b

(57) Abstract: An Artificial Magnetic Conductor (1) for mm and sub mm electromagnetic applications comprising a first medium (2) having a first refractive index associated therewith, a second medium (3) having a second refractive index associated therewith and differing from the first refractive index, the first and second medium (2, 3) defining a refractive index interface (4) therebetween. Associated methods.

An Artificial Magnetic Conductor

This invention relates to an Artificial Magnetic Conductor, in particular a meta-material based Artificial Magnetic Conductor for manipulating an electromagnetic wave at millimetre and sub-millimetre wavelengths.

5 It is well known to use metamaterials, which are materials with engineered properties, to influence electromagnetic radiation in a manner not observed in materials found in nature.

The potential applications of metamaterials are diverse ranging from military to aerospace applications.

10 An Artificial Magnetic Conductor surface (AMC), also known as a High impedance surface (HIS), is an artificial device designed to provide electric field in-phase reflection within a pre-determined frequency band. Within the specified bandwidth the AMC behaves sufficiently closely to a Perfect Magnetic Conductor (PMC). In a PMC the magnetic field vector is reversed while the electric
15 component remains unchanged. In transmission line theory, a PMC is equivalent to an open transmission line circuit ending into an infinite impedance load, $Z_L = \infty$.

In the past AMC surfaces have been realised using Frequency Selective Surfaces (FSSs). These are designed to achieve high surface impedances over bandwidths in the range of $BW_{\pm 90} \sim 10-70\%$. Some also operate over multiple
20 bands.

AMCs are applicable in many applications ranging from ground planes on low profile antennas and thin absorbers (Salisbury screens) in the microwave region to molecular spectroscopy and analogous of 'superconductors' at optical frequencies. In these applications, in addition to the large bandwidth requirement,

another important performance parameter is the angular stability associated with the device. It is also desirable for the AMC device to exhibit the same reflection behaviour over a wide range of incidence angles.

It is known that the simplest AMC can be realised with a quarter-wavelength air-gap followed by a metallic planar surface. This provides the required phase shift of the magnetic component of the electromagnetic wave at the principle frequency and its higher harmonic frequencies.

The requirement to have thin structures in microwave applications has led to the design of AMCs based on PEC-backed metal-dielectric FSS, as shown in Figure 1a. This AMC 1 provides in-phase reflection at a resonance frequency and then departs from it more or less rapidly dependent upon the specific design of the AMC. The substrate thickness can be reduced down, however thinner substrates imply narrower bandwidths of operation. For example, by reducing the substrate thickness to $\sim \lambda_0/25$ the bandwidth is expected to be at a 10% level.

The AMC can be modelled using transmission line theory as shown in Figure 1b.

Whilst there are many different sophisticated designs for FSS-based AMCs, there are theoretical limits on the maximum achievable bandwidth and known AMCs have approached but not exceeded this intrinsic limit. In general these devices systematically show steep in-band phase shift gradients rapidly departing from the ideal zero phase change. Moreover, these types of AMCs work around resonances providing losses that need to be taken into account.

Therefore, embodiments of the present invention are intended to address at least some of the above described problems and desires. In particular the Artificial Magnetic Conductor of the invention (AMC) is based on a different

working principle and provides large operational bandwidths, showing strong angular stability and provides almost identical performance up to large off-axis incidence angles. In addition the AMC device is also beneficially almost polarisation independent.

5 According to a first aspect of the invention there is provided an Artificial Magnetic Conductor for mm and sub mm electromagnetic applications comprising: a first medium having a first refractive index associated therewith; and a second medium having a second refractive index associated therewith, the second refractive index differing to the first refractive index and the first medium
10 and second medium being configured to define a refractive index interface therebetween, the first medium being configured to, in use, receive electromagnetic radiation prior to the second medium such that passage of the electromagnetic radiation between the first medium and the second medium provides reflection of the electromagnetic radiation at a position within the Artificial Magnetic Conductor,
15 wherein the electromagnetic radiation to be received is provided in free space and the electromagnetic radiation in free space is impedance matched with the electromagnetic radiation in the first medium.

 The first refractive index associated with the first medium may have a value that is greater than the value of the second refractive index associated with the
20 second medium such that a high-to-low refractive index interface is provided between the first medium and the second medium.

 At the refractive index interface there may be provided a change in refractive index from a high value refractive index to a low value refractive index.

The high refractive index value may be two times greater than the low refractive index value. "Low" means a refractive index value (associated with the second medium) that is less than the refractive index value associated with the first medium. In fact a low refractive index value associated with the second medium is considerably lower in value than the higher refractive index medium (i.e. the first medium) in order to provide the total internal reflection effect required. Therefore low and high refer to the relative refractive index values of the first and second region.

The first refractive index value and the second refractive index value may be predetermined and may be configured to provide, in use, substantially unitary in phase reflection of electromagnetic radiation within the Artificial Magnetic Conductor and at the refractive index interface.

The Artificial Magnetic Conductor may further comprise a back short for defining the central frequency of operation of the Artificial Magnetic Conductor.

The back short may be arranged at a distance from the refractive index interface, the distance equating to a quarter wavelength of the incident electromagnetic wave in the second medium, thereby providing the central frequency within the operational bandwidth.

The second medium may comprise a layer of low refractive index material sandwiched between the first medium and the back short, the thickness of the layer equating to a quarter of a wavelength of the electromagnetic radiation in that material.

Alternatively, the second medium may be a free space layer, the thickness of the free space layer equating to a quarter of a wavelength of the electromagnetic radiation in free space.

5 The back short may be a metal back plate. Alternatively the back plate may be constructed by an alternative conductor, for example graphene, however bad conductors may also be implemented, but they will provide a lossy device.

The impedance matching may occur across the entire operational bandwidth of the Artificial Magnetic Material.

The impedance matching may be provided in discrete intervals.

10 The discrete intervals may be provided by applying at least one discrete layer of material having a refractive index value intermediate to that of free space and that of the first medium.

Multiple layers of material may be provided, each having incrementally increasing refractive index values associated therewith.

15 The number of layers of material may be proportional to the bandwidth of operation of the Artificial Magnetic Conductor.

The Artificial Magnetic Conductor may comprise three layers.

20 The layer width may be defined by a finite number of quarter wavelengths corresponding to the central frequency of the electromagnetic radiation in that material. The finite number may be an odd number.

At least one layer of material may comprise a meta-material so as to provide a refractive index value not obtainable in a material found in nature.

The meta-material may comprise an artificial dielectric.

At least part of at least one region of the meta-material may comprise at least one mesh structure for customising the refractive index associated therewith.

At least part of the at least one region may comprise a substrate in which may be provided the mesh structure.

5 The mesh structure may comprise metal.

 The substrate may comprise a polymer.

 The polymer may comprise polypropylene.

 At least one layer of the Artificial Magnetic Conductor may comprise a naturally occurring porous dielectric.

10 The at least one layer of the Artificial Magnetic Conductor may comprise porous teflon and/or porous polypropylene.

 The impedance matching may alternatively be provided in a material possessing a continuous gradient index.

 In a further aspect of the invention there is provided a method of passing
15 an electromagnetic wave through the above-mentioned Artificial Magnetic Conductor, comprising:

 passing an electromagnetic signal through a region of a first medium having a first refractive index and subsequently passing the electromagnetic signal through a region of a second medium having a second refractive index
20 differing to the first refractive index; and

 causing reflection of at least part of the electromagnetic wave within the Artificial Magnetic Conductor at the boundary of the first medium and second medium, the method further comprising impedance matching the incident

electromagnetic signal in free space with the electromagnetic signal in the first medium.

The value of the first refractive index may be greater than the value of the second refractive index.

5 The impedance matching may comprise applying a discrete layer of material having a refractive index value greater than that of free space, but less than that of the first material so as to provide improved impedance matching.

10 The impedance matching may be provided in discrete intervals by applying a discrete multiple number of layers of material each having incrementally increasing refractive index values associated therewith.

The refractive index values may lie between the free space value and the refractive index value at the first medium.

At least one layer of material may comprise a meta-material for providing a refractive index value not available in nature.

15 Alternatively, the impedance matching may be provided by continuous matching whereby a single medium is utilised having a continuous gradient index of refraction.

In a further aspect of the invention there is provided a method of manufacturing an Artificial Magnetic Conductor comprising:

20 providing a first medium having a first refractive index associated therewith;

providing a second medium having a second refractive index associated therewith, the second refractive index differing to the first refractive index;

configuring the first medium and second medium to define a discrete refractive index interface there-between;

5 configuring the first medium to, in use, receive electromagnetic radiation prior to passage of the electromagnetic radiation through the second medium so as to, in use, cause reflection of the electromagnetic wave within the metamaterial and at the refractive index interface, and configuring at least one layer of material in front of the first medium so as to optimise impedance matching between the
10 incident electromagnetic signal in free space and the electromagnetic signal in the first medium.

Therefore, the losses associated with radiation passing from free space into the first medium are minimised.

 The first medium may have a refractive index that is greater than that of
15 the second medium.

 The refractive index of the first medium may be two times greater than the refractive index of the second medium.

 The impedance matching may occur across the entire operational bandwidth of the Artificial Magnetic Material.

20 The electromagnetic radiation propagates substantially orthogonal to the at least one layer or layers. The electromagnetic radiation that is incident on the device is initially in free space and then passes through the impedance matching section of the device provided by one or more pre layers of incremental refractive

index. The electromagnetic radiation then passes through the first material and then subsequently through the second material until it reaches a back short.

Whilst the invention has been described above it extends to any inventive combination of the features set out above, or in the following description, drawings
5 or claims. For example, any features described in relation to any one aspect of the invention is understood to be disclosed also in relation to any other aspect of the invention.

The invention will now be described, by way of example only, with reference to the accompanying drawings, in which:-

- 10 Figure 1a is a PEC-backed metal-dielectric FSS of the prior art;
 Figure 1b is a transmission line representation of the FSS of Figure 1a;
 Figure 2a is a schematic of the gradient index material of a continuous AMC and internal reflection;
 Fig 2b is a transmission line representation of the continuous AMC of
15 Figure 2a;
 Figure 3a is a schematic of a discretised gradient index material of an AMC;
 Figure 3b is a transmission line representation of the discretised gradient index material of Figure 3a;
 Figure 4a is an AMC with an embedded PMC;
20 Figure 4b is an AMC with an embedded PMC and PEC;
 Figure 4c is an AMC with a free space PMC;
 Figure 5 is an image of an AMC prototype;
 Figure 6 is a schematic of an AMC comprising metamaterials, wherein the second and third layers are formed of a polymer and mesh assembly;

Figure 7 is a sketch of the FEA model used to design the metamaterials of the AMC;

Figure 8 is a graph of the optimised reflection coefficients vs frequency for the two artificial dielectric slabs of Figure 6;

5 Figure 9 is a schematic of an AMC prototype where half acts as an embedded AMC and the other half acts as an embedded PEC with finite element models for the unit cells of each part of the AMC are shown at each corresponding side;

Figure 10 is a simulation of the embedded AMC on-axis phase-shift;

10 Figure 11 is the simulated results for the embedded AMC/PEC absorption coefficients;

Figure 12 is a simulation of the free space AMC on-axis phase-shift;

Figure 13 is a simulation of the embedded AMC reflection coefficients vs incidence angle for the S and P polarisations of the EM wave;

15 Figure 14 is a schematic of the VNA set up used for the experimental tests;

Figure 15 is a graph of embedded AMC Phase-Shift vs frequency for the S and P polarisations, obtained via the VNA set up and superimposed on the modelled results, whereby the model considers differing incidence angles;

20 Figure 16 is a schematic of the FTS set up for the experimental tests across the entire bandwidth of operation;

Figure 17 is a graphical representation of the AMC phase shift vs frequency for the S and P polarisations, obtained via the VNA and FTS set up which are superimposed on the modelled results; and

Figure 18 is an interferogram of the PEC and the AMC.

Referring firstly to Figure 2a, there is shown a meta-material-based Artificial Magnetic Conductor (AMC) 1 for mm and sub mm electromagnetic applications which comprises a first medium 2 having a first refractive index associated therewith and a second medium 3 having a second refractive index associated therewith. The second refractive index differs to the first refractive index and the first and second medium are configured to define a discrete refractive index interface 4 there-between. The first medium 2 is configured to, in use, receive an incident electromagnetic wave prior to the second medium 3 such that passage of the electromagnetic wave between the first medium 2 and the second medium 3 provides reflection thereof at a position within the AMC 1. The schematic of Figure 2a can be modelled using transmission line theory as depicted in Figure 2b.

In order to get the wave from the high index refractive medium 2 to the low index refractive medium 3 the wave must firstly be provided in the high index medium 2. This is achieved by gradually matching the free space impedance with the high index one using a gradient index medium 5. After that there is provided a sudden jump in refractive index between the high index medium 2 to a much lower index medium 3.

The first medium 2 forms a first layer 2a of the AMC 1 and the second medium 3 forms the second layer 3b of the AMC 1 such that in use an incident electromagnetic wave passes through the first layer 2a prior to becoming incident on the second layer 3a. The first layer 2a and second layer 3a are slabs of differing material arranged face to face. The first layer 2a and the second layer 3a are arranged in contact with each-other and the layer widths e.g 2b are defined by a

finite number of quarter wavelengths of the electromagnetic wave in that particular material.

The gradient index medium 5 is positioned in front of the first layer 2a so as to form the preliminary layer 5a of the AMC 1. In Figure 2a this preliminary layer is a continuous layer providing a gradual increase in the refractive index as shown in Figure 2a. However in Figure 3a the gradient index medium 5 is formed by an array of layers 5', 5'', each of the refractive indices being of a different value so as to form a gradient index layer 5 ending with a high refractive index value. The value of the refractive index at the end of the gradient index layer 5''' differs to and is higher than that of the previous layer 5''. The gradient index layer 5 is terminated by the first medium layer 2 which has the highest refractive index value in the device 1. The first medium 2 is positioned in front of and in contact with the second medium 3 having a lower refractive index such that a high-to-low refractive index interface is provided. Such a high-to-low refractive index interface provides a substantially unitary in-phase reflection of an incident electromagnetic wave within the AMC 1.

Therefore, as shown in Figure 3a the AMC 1 is provided with at least three layers 5', 5'', 5''' providing a gradient index medium 5 ranging from n_0 to $n_{\max}$ having discrete layers offering a number of interfaces 4', 4'', 4''' there-between.

An artificial magnetic conductor (AMC) 1 is arranged such that the AMC requires the in-phase reflection to occur within the device 1, not at its front surface as per standard AMCs 1. Therefore, the in-phase reflection occurs within the layered AMC 1 structure which is significantly different to, for example, the FSS arrangement.

The AMC 1 comprises a back short 6 positioned at the end of the device 1 and adjacent to the low refractive index layer 3a. The second medium 3 is a slab of low refractive index material that is applied to represent freespace and is of a thickness equating to a quarter wavelength of the incident electromagnetic wave in that material 3. Therefore, by applying the back short 6 in contact with the second medium 3 (i.e. final layer) the central frequency of operation of the AMC 1 is defined. The back-short 6 may, for example, be formed of metal plate, for example copper, aluminium or gold.

Due to the configuration of the AMC 1 the in-phase reflection occurs specifically at the end of the gradient index, i.e. at the high-to-low index interface 4.

Three types of applications of the AMC may be identified:

a) Applications where the in-phase Perfect Magnetic Conductor (PMC) reflection is required to happen at a specific plane within a medium, see Figure 4a for this embedded PMC structure. Such a PMC may be applied to a Salisbury screen absorber (not shown). This can be simply implemented loading the high-to-low index interface 4 within the AMC 1 with a resistive layer.

b) Applications where an in-phase Perfect Magnetic Conductor (PMC) reflection is used in combination with an out-of-phase Perfect Electric Conductor (PEC) reflection and both happen within the same medium and at the same reference plane, see Figure 4b for this embedded PMC and PEC arrangement 8. In this case metal patterns at the high-to-low index interface

are applied to obtain the PEC reflection where required. Phase switching modulation ($0-180^\circ$) is one use of the AMC.

c) Applications where an in-phase Perfect Magnetic Conductor (PMC) reflection is required to happen at a specific reference plane in free space, see Figure 4c for free space PMC 9. Although there is knowledge of where the exact position of the PMC reflection occurs within the AMC 1, it is necessary to identify the 'equivalent' reference plane where the same reflection would happen if the AMC was an ideal PMC surface in free-space. In practice the real optical path within the gradient index medium must be taken into account. This technique could be used in interferometric applications where the radiation is split into two beams, subsequently sent onto a PEC or a PMC, and then recombined after travelling symmetric paths (not shown).

An AMC 1 of type b) has been modelled and a prototype has been constructed as shown in Figure 5. The device includes both embedded PMC 8a and PEC 8b structures with the same reflection plane. This facilitates the differential phase measurement that requires the probing of just two areas of the surface. The same device, although not optimised for it, can also be used for a type c) application provided the equivalent reference plane is used as a reference.

There are potential trade-offs between performance parameters and the various types of applications for this device 1. Depending on the application,

the requirements can be in terms of relative bandwidth, phase flatness, losses, dimensions, etc. As an example, in HIS-based antennas operating across 10-20% bandwidths, the AMC thickness can be as low as $\sim\lambda_0/25$. Although adopting the AMC described herein would not represent a gain in terms of thickness ($\sim\lambda_0/2$) it would dramatically increase the operational bandwidth up to $\sim 150\%$, a range never achieved before in application types b) and c) and greater than the theoretical limit of the usual Frequency Selective Surface (FSS) based AMCs.

The AMC 1 has been modelled using four dielectric layers $10'$, $10''$, $10'''$, $10''''$ as shown in Figure 6a and it has been found that this configuration achieves bandwidths of the order of 150%. Each layer is a quarter-wavelength thick in its own medium. The first three layers $10'$, $10''$, $10'''$ build up the gradient index 5 and the last layer $10''''$ replaces the ideal low-index air-gap. In reality providing an air gap would require accurate alignment and the requirement for holding structures, for example using a frame arrangement. Such holding structures are easily avoided by using a material with sufficiently low refractive index for the desired bandwidth of use, for example polypropylene.

It is noted that the electromagnetic radiation propagates orthogonal to the layers and that the reflection happens within the internal layers and not just at the surface of the device.

The structure 1 was modelled with a finite element code that simulated a transmission line that assumed ideal dielectric layers. The central frequency was selected to be $\nu_0=240$ GHz. An optimisation procedure was used to obtain a flat differential phase response around the central frequency. The differential phase was calculated as the difference between the reflected phase of the AMC 1 and the reflected phase obtained using the same structure with a metal mirror positioned at the high-to-low index interface, as sketched in Figure 4b. The layers of the final optimised design have the following refractive indices: $n_1 \cong 1.2$, $n_2 \cong 1.8$, $n_3 \cong 3.0$ and $n_4 \cong 1.5$.

Given the materials availability and associated losses in the millimetre and sub-millimetre region only the first 10' and the last 10''' layers can be realised using existing materials found in nature. The first layer 10' (n_1) is made with porous teflon, a material normally used for anti-reflection coatings, whereas the last layer 10''' (n_4) is made with polypropylene. The two middle layers 10'', 10''' (n_2, n_3) are artificially built by loading polypropylene (PP) with mesh grids 11. The desired refractive index is obtained by applying grids of variable number, geometries and spacings.

This configuration dramatically simplifies the manufacture process of the AMC 1 because three out of the four layers are made by using the same material. The polypropylene has been selected as the basic substrate because it is the material commonly used in known mesh-filter technology.

The two artificial dielectric layers 10'', 10''', which are the second and third layers as shown in Figure 6a, are therefore formed of meta-materials 11 which use a mesh structure 12 embedded in a polymer substrate 13'', 13'''. Figure 6b shows the equivalent transmission line circuit representing the device of Figure 6a.

Artificial dielectrics have been successfully realised in the past using the mesh-filter technology typically used for filters, polarisers, retarders and lenses. For this purpose, the electromagnetic wave was modelled using a finite element tool. The target was to design two quarter-wavelength thick slabs with refractive indices $n_2=1.8$ and $n_3=3.0$ starting from the lower index material that was used as a substrate 13', for example polypropylene ($n_{PP}\cong 1.5$). The model consisted of a unit cell periodic structure with pitch much smaller than the minimum operational wavelength ($100\mu\text{m}$). The mesh-loaded polypropylene slab 14 was sandwiched between two semi-infinite slabs 15, 16 with the generic refractive index that was to be mimicked, as shown in Figure 7. During the optimisation procedure the number of grids, their geometry and their spacing were optimised in order to minimise the reflection coefficient, across the whole band of interest. The final modelled results for the two quarter-wavelength slabs are shown in Figure 8. The reflection coefficients are very low ($\leq -28\text{dB}$) across a very wide frequency range, 10 - 490 GHz, corresponding to a bandwidth $BW\sim 190\%$. This means that the two synthesised slabs are almost indistinguishable from homogeneous slabs with the targeted refractive indices.

The AMC device, of the type shown in 4b, is divided into two parts behaving differently. Half of the surface is an embedded AMC 8b, whereas the other half is an embedded PEC 8a.

The above-mentioned transmission line modelling was used to quantify
5 the refractive indices and the number of dielectric layers required to achieve the target broadband performance. However, the real device includes the metamaterial based artificial dielectrics 11 and, in order to accurately model the final AMC 1, finite element analysis was used. It was only required to simulate two unit cells, corresponding to the two different configurations as
10 shown in Figure 9, namely half is an embedded AMC 8b and the other half is an embedded PEC 8a. On each side the respective finite-element models were used to simulate the RF performance.

In both models, homogeneous materials were used for the first and fourth layers 10', 10''''', whereas the two optimised artificial dielectric layers 10'', 10'''
15 were inserted with their grid/mesh 12 detail. The frequency dependence of the polypropylene refractive index and loss tangent were taken into account. These values came from previous experimental characterisations of the same material, carried out using Fourier Transform Spectroscopy.

Master and slave periodic boundary conditions were used in the model
20 to simulate infinitely extended slabs, allowing also off-axis incidence studies.

The electromagnetic sources were plane-waves with arbitrary angles of incidence. The only difference between the AMC and the PEC models was a

finite conductivity (copper at room temperature) assigned to the high-to-low index interface in the latter case. This is equivalent to a mirror that completely reflects the radiation at the end of the gradient index.

To verify the correct functioning of the device the phase-shift introduced by the AMC 1 at the reflection surface had to be computed. Given the similarity between the two paths this was achieved by calculating the overall differential phase-shift of the reflected waves of the two models at a certain distance from the device surface and then, knowing that the PEC surface introduces a phase-shift of π , this latter value was subtracted.

The results of the on-axis finite-element simulations are shown in Figure 10, together with the transmission line predictions. The transition line model is a very good approximation of the more detailed Finite Element Analysis model that includes the metamaterial structures 11. The embedded AMC phase-shift is kept within $\pm 90^\circ$ across an extremely large bandwidth, of the order of $BW_{\pm 90} \sim 147\%$. In the usual FSS based AMCs (as shown in Figure 10) the phase crosses zero at the central frequency and moves away from it almost linearly. In contrast, the phase relating to the AMC 1 described herein oscillates around zero across a large frequency range to then reach $\pm 90^\circ$. This can be quantified by computing the bandwidth within which the phase-shift is kept within $\pm 45^\circ$. This results in a bandwidth of the order of $BW_{\pm 45} \sim 137\%$, which is a value not too different from the previous one. The FSS AMCs limit is also shown on Figure 10.

Using the abovementioned models the absorption coefficients of the embedded AMC 8b and PEC 8a surfaces were calculated as shown in Figure 11. Within the $BW_{\pm 90}$ frequency range the average absorption coefficient results were quite small: $\alpha_{AMC}=0.007$ and $\alpha_{PEC}=0.010$. The AMC 8b absorption was slightly lower than the PEC 8b one because the radiation is mostly reflected at the high-to-low dielectric interface and almost does not interact with the finite conductivity back short mirror. Although the transmission Line models are qualitatively similar to the FEA ones, they systematically predict lower losses because they do not take into account the finite conductivity of the grids used for the artificial dielectric layers. Beneficially, there is a complete absence of lossy resonances around the central frequency, typical of FSS based AMCs, due to the completely different working principle of the AMC herein-described.

In a second embodiment of the invention and as indicated previously, the AMC designed for type b) (as displayed in Figure 4b) can also be used in a free space application (i.e. type c) displayed in Figure 4c). In this case, it is required to locate the equivalent reference plane where the PMC reflection would happen in free-space. The optical path from the first surface of the AMC to the high-to-low index interface is equal to three quarter-wavelengths ($\lambda_0/4n_1+\lambda_0/4n_2+\lambda_0/4n_3$). This means that the equivalent free-space reflection plane will be located at a distance $3\lambda_0/4$ from the first surface of the AMC (for example it is $\sim 190\text{mm}$ behind the metal back short).

The phase-shift introduced by the AMC in this configuration is calculated in a way similar to that of the embedded case. Here, the second model is just a free-space volume where the PEC surface is positioned at the equivalent reference plane. Again, subtracting the π value from the differential phase-shift of the two models provides the equivalent AMC phase-shift. The results of the on-axis Finite Element Analysis and transmission line simulations are reported in Figure 12. Also in this case the device shows very broadband performance with $BW_{\pm 90} \sim 138\%$ and $BW_{\pm 45} \sim 119\%$. However, if the device was originally designed to work in a free-space application, much better performance (similar to the embedded case shown in Figure 10) could have been achieved by optimising the metamaterial refractive indices accordingly.

Devices are made by means of standard photolithographic techniques consisting of embedding the metal grids 12 within polypropylene. This is achieved by stacking the grids and the polypropylene layers and hot pressing the stack as a whole so as to obtain a final uniform block of polypropylene containing the metallic structures with a defined geometric distribution.

A first medium 2 is provided having a first refractive index associated therewith. A second medium 3 is provided having a second refractive index associated therewith, the second refractive index differing to the first refractive index. The first medium 2 and second medium 3 are configured to define a discrete refractive index interface there-between; and such that the first medium 2, in use, receives electromagnetic radiation (or an electromagnetic signal) prior to passage of the electromagnetic radiation through the second medium 3. By

applying this configuration, in use, reflection of the electromagnetic wave is caused within the AMC 1 and at the refractive index interface 4. The first medium 2 is provided with a refractive index that is greater than that of the second medium 3, for example two times greater than the refractive index of the second medium.

5 Configuring at least one layer of material 5a in front of the first medium 2 optimises the impedance matching between the Electromagnetic wave in free space (from which, in use, the electromagnetic wave is provided) and the electromagnetic wave in the first medium. This, of course is only the case if the refractive index of the at least one layer of material 5a has a refractive index of a value between that
10 of free space and that of the first medium 2.

Figure 5 shows that the embedded AMC is formed of two halves, one with and one without a metal plane 17 at the level of the PMC surface. The device is ~10 cm in diameter with a thickness of 745 μm and the white material, i.e. the material with the lowest possible refractive index, is the lowest index material used
15 in the device.

The AMC 1 was characterised using a Vector Network Analyser (VNA). The VNA allowed for direct measurements of the reflected phase to be obtained between a first frequency range of 75-110 GHz and a second frequency range of 170-260 GHz.

20 Tests were carried out using a Rhode-Schwarz ZVA67 VNA equipped with heads working at the above-mentioned frequencies. The AMC was tested off-axis at $\theta=40^\circ$ incidence angle as shown in Figure 14, whereby T_x is the source and R_x is the detected signal.

The AMC was rotated giving the possibility of using either the PEC 8b or PMC 8a surfaces. This allowed for the taking of differential measurements by rotating the device by 180° about its axis. The AMC phase shift was calculated by subtracting a value of π from the differential phase-shift between the PEC and 5 PMC surfaces. The results are shown in Figure 15 and are superimposed on the modelled expectations. In both frequency ranges considered, the differential phase shift is not far from the expected modelled results and within $\pm 90^\circ$. As such, the benefits that were modelled over existing AMC technology have been realised.

The performance of the AMC 1 across the full frequency range of 100-400 10 GHz has been measured and was found to provide good matching with the modelled results across this entire frequency range. This was achieved using a Fourier Transform Spectrometer 20 which can work over very wide range of frequencies. The detected signal 21 is an intensity interferogram, i.e. the signal resulting from the interference of two beams propagating across the two arms 15 22a, 22b of the interferometer 20, one of which has its optical path length varied during the data acquisition. In the usual setup the device 1 under test is positioned after the recombination of the two signals. This set up is shown in Figure 16. Interferograms are acquired with and without the device 1 and are then Fourier transformed to get the relative spectra. The final spectrum is obtained by 20 normalising the device spectrum by the background one. This configuration can provide either the transmission or the reflection amplitudes vs frequency.

In order to get the phase information it is required to position the device 1 in place of one of the mirrors 23 in one of the two optical paths of the Mach-Zehnder interferometer 20, as shown in Figure 16. When the rotating device 24 shows the

PEC side, that provides the usual π phase-shift, the FTS will work in the usual way and an interferogram will be acquired as reference. By rotating the device by 180 degrees the AMC 1 surface will now provide a null phase-shift to all the frequency components within its operational bandwidth. In the ideal case the overall effect would be to reverse the interferogram upside-down. This happens because each Fourier component interferes now destructively at the zero-path-length position. However, the AMC 1 does not provide exactly null phase-shifts and the interferogram will not necessarily be the exact mirror image of the previous one. In order to extract the phase information it is required to compute the complex Fourier transform of the two interferograms, calculate their complex arguments and then subtract them. The differential phase-shift between the PEC and AMC 1 surface is determined whereby the AMC phase-shift is obtained by again subtracting a value of π . The AMC 1 phase-shift measured with the modified FTS setup is shown in Figure 17. The data, acquired by using a cryogenically cooled bolometer (not shown) working at 1.6K, covers the whole AMC operational bandwidth. The PEC and AMC interferograms are shown in Figure 18.

In use, electromagnetic radiation is applied to the AMC device 1 comprising the meta-material layer 11 such that the electromagnetic radiation is transferred between free space 10⁰ and is then passed through an impedance matching arrangement 5a prior to reaching the first medium 2 of the AMC 1 having a first refractive index and subsequently passed through a second medium 3 of the AMC having a second refractive index differing to the first refractive index; thereby resulting in reflection of at least part of the electromagnetic wave within the AMC 1. The reflection occurs at the refractive index interface 4 located at the boundary

between the first medium 2 and second medium 3. To provide the substantially unitary in-phase reflection the value of the first refractive index of the first medium 2 is greater than the value of the second refractive index of the second medium 3. Therefore the first medium has a refractive index that has a value which is higher than the refractive index value of the second medium. The first medium 2 forms a first layer 2a of the device and the second medium 3 forms a second layer 3a of the device.

The impedance matching is achieved by using a further array of discrete layers 18 with incrementally increasing refractive indices. The values of the refractive indices that provide the target bandwidth of operation are obtained through a finite element model of transmission line and it was found that some of the refractive index values are not achievable in materials found in nature. For this reason a meta-material 11 is applied to provide the desired value of the refractive index in such cases so as to optimise the bandwidth of the device 1. The initial layer of the impedance matching arrangement 5a is a low index material 10' and the refractive index of subsequent materials 10'', 10''' (and therefore subsequent layers) is incrementally increased.

Various modifications to the principles described above would suggest themselves to the skilled person. For example, another type of polymer may be applied rather than polypropylene, for example polyethylene.

Alternatively to using the final layer 10'''' of polypropylene (as the second medium) an air gap may be provided, but the difficulties with providing a real structure, as described above, must be considered.

The initial low index material of porous Teflon 10' may be substituted with an alternative material, for example porous polypropylene.

5 The back short 6 may be made from, for example, gold or copper. However, the back short 6 and the mesh 12 need not be made from metal, but can alternatively be made from an alternative material that is a good conductor, for example graphene. It is feasible that a material that is a poor conductor may also be implemented for the back short, but it is noted that the final device will be lossy as a result and would not provide an optimised device.

10 The grid 12 used in the meta-material 11 is made from a high refractive index material, whereby an alternative to metal may be magnetic ferrites, or another material having high permittivity.

15 Instead of the second medium 3, 10'''' being a dielectric, a free space layer may be implemented between the high to low interface and the back-short. The distance of the back short 6 from the high to low interface 4 would need to be adjusted accordingly if the same central frequency of operation is desired. Alternative low loss dielectrics to be used in the device may be, for example LDPE, Teflon or Duroid.

20 Instead of a polymer for the substrate 13', an alternative low loss material may be implemented, for example a crystal. Any form of low refractive index material may be used for the initial impedance matching 10' and for the second medium 3, 10''''.

The device 1 need not be circular and may instead, for example, be square shaped or of another form.

The width of a layer can be interpreted as the thickness of the region.

The metamaterial 11 to provide the desired refractive index (for optimising the impedance matching between free space and the high refractive index material) need not incorporate a mesh structure 12, but may instead, for example comprise a spherical structure that may be deposited in the substrate. As such, alternative ways of tuning the refractive index of the layer 10'', 10''' may be implemented which applies different shaped structures compared to that of the grid. Therefore, it is required to provide the high-to-low interface 4 and to optimise the bandwidth of operation of the device 1 it has been shown that tuning the refractive index of materials in a model provides the need to use metamaterials 11 having refractive indices not found in nature in the actual device.

Whilst two layers 10', 10'' have been implemented in the device prior to the first medium 2, 10''' as shown in Figure 3, the number of layers is dependent on the desired bandwidth of the device. Therefore, more layers may be applied if desired.

The terms device 1 and Artificial Magnetic Conductor 1 are used interchangeably throughout this document.

Alternatively to the first medium 2 being considered as terminating the gradient index medium 5, the first medium 2 could be considered as being provided subsequently to the gradient index medium 5. In such a case the gradient index medium 5 (a preliminary layer formed of an array of layers) is brought into contact with the first medium 2. Therefore, it is possible for either the first medium 2, 10''' or a layer in the preliminary layer 10''' to be formed of a metamaterial depending on the central frequency of operation and the desired operational bandwidth of the device 1.

Instead of discrete layers 18 to form the refractive index gradient a continuous gradient 19 may be provided as shown in Figure 2a.

CLAIMS

1. An Artificial Magnetic Conductor for mm and sub mm electromagnetic applications comprising:

a first medium having a first refractive index associated therewith; and
a second medium having a second refractive index associated therewith, the second refractive index differing to the first refractive index and the first medium and second medium being configured to define a refractive index interface there-between,

the first medium being configured to, in use, receive electromagnetic radiation prior to the second medium such that passage of the electromagnetic radiation between the first medium and the second medium provides reflection of the electromagnetic radiation at a position within the Artificial Magnetic Conductor, wherein the electromagnetic radiation to be received is provided in free space and the electromagnetic radiation in free space is impedance matched with the electromagnetic radiation in the first medium.

2. An Artificial Magnetic Conductor according to claim 1, wherein the first refractive index associated with the first medium has a value that is greater than the value of the second refractive index associated with the second medium such that a high-to-low refractive index interface is provided between the first medium and the second medium.

3. An Artificial Magnetic Conductor according to claim 1 or claim 2, wherein at the refractive index interface there is provided a change in refractive index from a high value refractive index to a low value refractive index.
- 5 4. An Artificial Magnetic Conductor according to claim 3, wherein the high refractive index value is two times greater than the low refractive index value.
5. An Artificial Magnetic Conductor according to any preceding claim, wherein the first refractive index value and the second refractive index
10 value are predetermined and configured to provide, in use, substantially unitary in phase reflection of electromagnetic radiation within the Artificial Magnetic Conductor and at the refractive index interface.
6. An Artificial Magnetic Conductor according to any preceding claim,
15 further comprising a back short for defining the central frequency of operation of the Artificial Magnetic Conductor.
7. An Artificial Magnetic Conductor according to claim 6, wherein the back short is arranged at a distance from the refractive index interface, the distance equating to a quarter wavelength of the electromagnetic
20 wave in the second medium.
8. An Artificial Magnetic Conductor according to claim 7, wherein the second medium comprises a layer of low refractive index material sandwiched between the first medium and the back short, the

thickness of the layer equating to a quarter of a wavelength of the electromagnetic radiation in that material.

9. An Artificial Magnetic Conductor according to claim 7, wherein the second medium is a free space layer, the thickness of the free space layer equating to a quarter of a wavelength of the electromagnetic radiation in free space.

10. An Artificial Magnetic Conductor according to any of claims 6 to 9, wherein the back short is a metal back plate.

11. An Artificial Magnetic Conductor according to any preceding claim, wherein the impedance matching occurs across the entire operational bandwidth of the Artificial Magnetic Conductor.

12. An Artificial Magnetic Conductor according to claim 11, wherein the impedance matching is provided in discrete intervals prior to the electromagnetic wave reaching the first medium.

13. An Artificial Magnetic Conductor according to claim 12, wherein the discrete intervals are provided by applying at least one discrete layer of material having a refractive index value intermediate to that of free space and that of the first medium.

14. An Artificial Magnetic Conductor according to claim 13, wherein there are provided multiple layers of material each having incrementally increasing refractive index values associated therewith.

15. An Artificial Magnetic Conductor according to claim 14, wherein the number of layers of material is proportional to the bandwidth of operation of the Artificial Magnetic Conductor.
- 5 16. An Artificial Magnetic Conductor according to any of claims 13 to 15, comprising three layers.
17. An Artificial Magnetic Conductor according to claim 16, wherein one of the layers forms the first medium.
18. An Artificial Magnetic Conductor according to any of claims 13 to 17, wherein the layer width is defined by a finite number of quarter
10 wavelengths corresponding to the central frequency of the electromagnetic radiation in that material.
19. An Artificial Magnetic Conductor according to any of claims 13 to 18, wherein at least one layer of material comprises a meta-material so as to provide a refractive index value not obtainable in a material found
15 in nature.
20. An Artificial Magnetic Conductor according to claim 19, wherein the meta-material comprises an artificial dielectric.
21. An Artificial Magnetic Conductor according to claim 19 or 20, wherein at least part of at least one region of the meta-material comprises at
20 least one mesh or grid structure for customising the refractive index associated therewith.
22. An Artificial Magnetic Conductor according to claim 21, wherein at least part of the at least one region comprises a substrate in which is provided the mesh or grid structure.

23. An Artificial Magnetic Conductor according to claim 22, wherein the substrate comprises a polymer.
24. An Artificial Magnetic Conductor according to claim 23, wherein the polymer comprises polypropylene.
- 5 25. An Artificial Magnetic Conductor according to any of claims 21 to 24, wherein the mesh or grid structure comprises metal.
26. An Artificial Magnetic Conductor according to any of claims 13 to 25, wherein at least one layer of the Artificial Magnetic Conductor comprises a naturally occurring porous dielectric.
- 10 27. An Artificial Magnetic Conductor according to claim 26 wherein the at least one layer of the Artificial Magnetic Conductor comprises porous teflon and/or porous polypropylene.
28. An Artificial Magnetic Conductor according to any of claims 13 to 27, wherein the electromagnetic radiation propagates substantially
- 15 orthogonal to the at least one layer or layers.
29. An Artificial Magnetic Conductor according to any of claims 1 to 11, wherein the impedance matching is provided in a material possessing a continuous gradient index.
30. A method of passing an electromagnetic wave through the Artificial
- 20 Magnetic Conductor of claim 1, comprising:
passing an electromagnetic signal through a region of a first medium having a first refractive index and subsequently passing the electromagnetic signal through a region of a second medium having a second refractive index differing to the first refractive index; and

causing reflection of at least part of the electromagnetic wave within the Artificial Magnetic Conductor at the boundary of the first medium and second medium, the method further comprising impedance matching the incident electromagnetic signal in free space with the electromagnetic signal in the first medium.

31. A method according to claim 30, wherein the value of the first refractive index is greater than the value of the second refractive index.

32. A method according to claim 31, comprising applying a discrete layer of material having a refractive index value greater than that of free space, but less than that of the first material so as to provide improved impedance matching.

33. A method according to claim 31, comprising applying a discrete number of multiple layers of material each having incrementally increasing refractive index values associated therewith so as to provide impedance matching at discrete intervals.

34. A method according to claim 33, wherein the refractive index values lie between the free space value and the refractive index value at the first medium.

35. A method according to claim 34, wherein at least one layer of material comprises a meta-material for providing a material with a refractive index value not available in nature.

36. A method according to claim 31, wherein the impedance matching is provided by continuous matching whereby a single medium is utilised having a continuous gradient index of refraction.

37. A method of manufacturing an Artificial Magnetic Conductor comprising:

providing a first medium having a first refractive index associated therewith;

providing a second medium having a second refractive index associated therewith, the second refractive index differing to the first refractive index;

configuring the first medium and second medium to define a discrete refractive index interface there-between;

configuring the first medium to, in use, receive electromagnetic radiation prior to passage of the electromagnetic radiation through the second medium so as to, in use, cause reflection of the electromagnetic wave within the metamaterial and at the refractive index interface; and

configuring at least one layer of material in front of the first medium so as to optimise impedance matching between the incident electromagnetic radiation in free space and the electromagnetic radiation in the first medium.

38. A method of manufacturing an Artificial Magnetic Conductor according to claim 37, wherein the first medium has a refractive index that is greater than that of the second medium.

5 39. A method of manufacturing an Artificial Magnetic Conductor according to claim 37 or 38, wherein the refractive index of the first medium is two times greater than the refractive index of the second medium.

40. An Artificial Magnetic Conductor as hereinbefore described in reference to the accompanying drawings.

10 41. A method of passing electromagnetic radiation through an Artificial Magnetic Conductor as hereinbefore described in reference to the accompanying drawings.

1/18

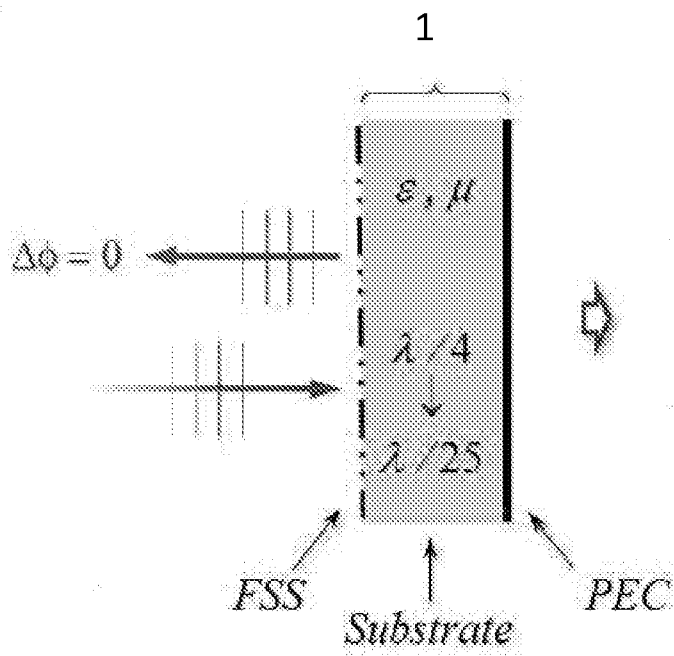


Fig 1a

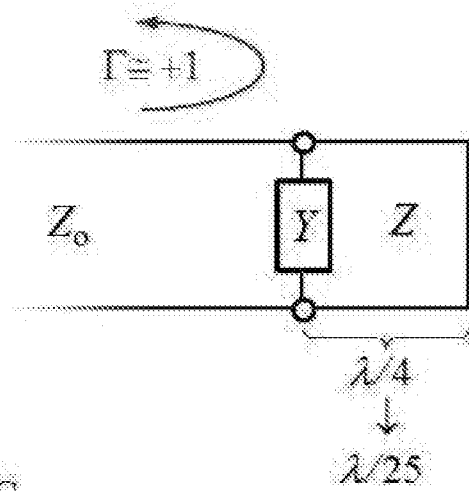


Fig 1b

2/18

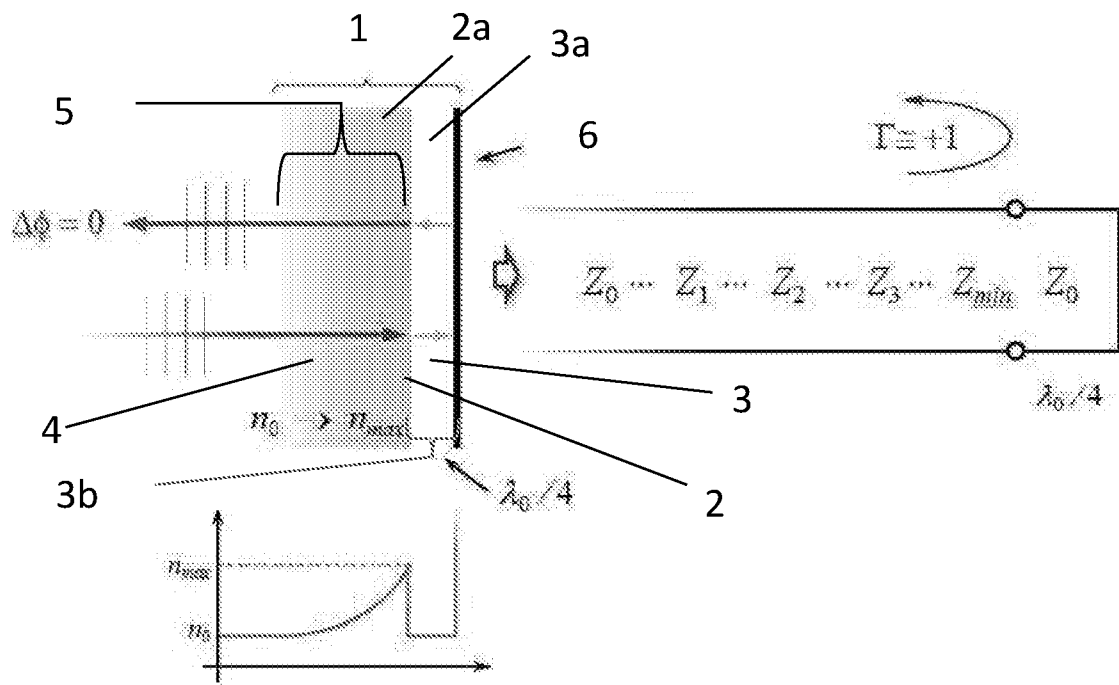


Fig 2a

Fig 2b

3/18

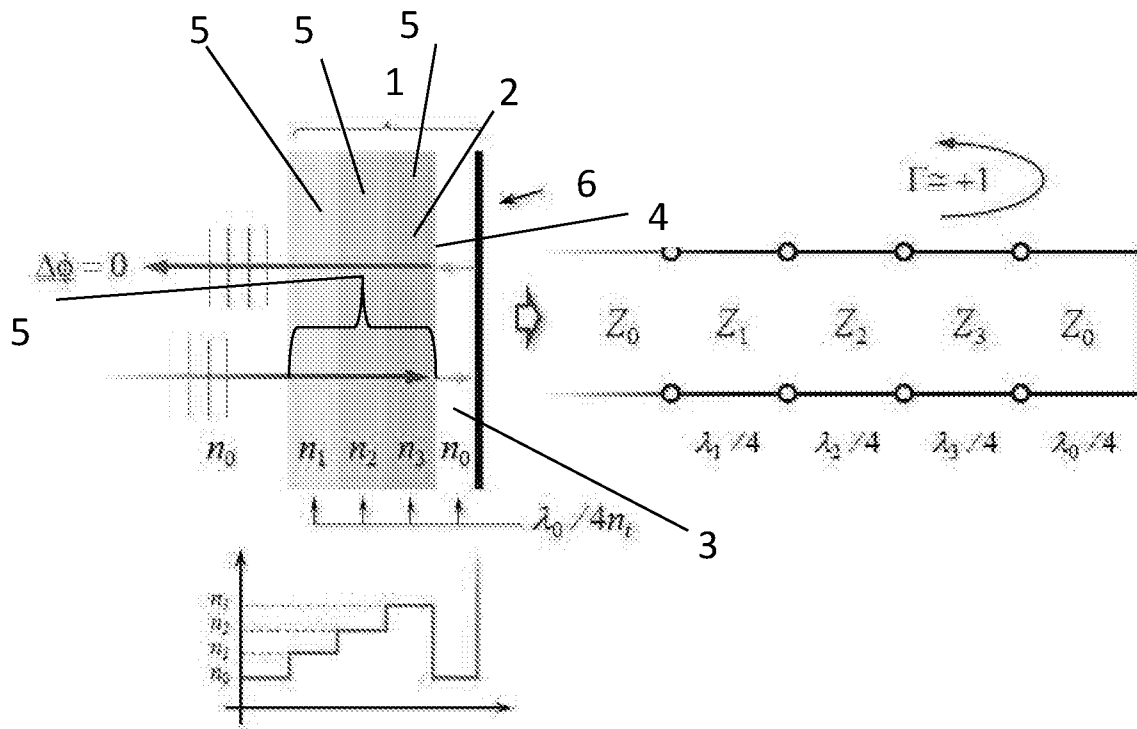


Fig 3a

Fig 3b

4/18

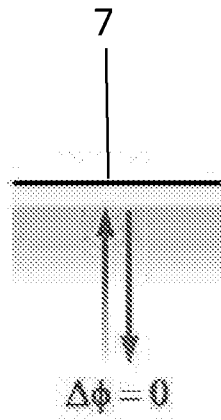


Fig 4a

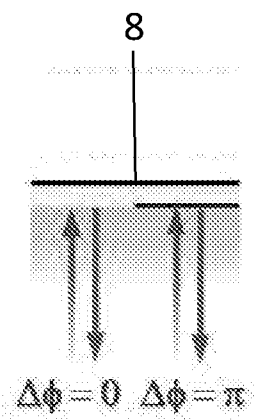


Fig 4b

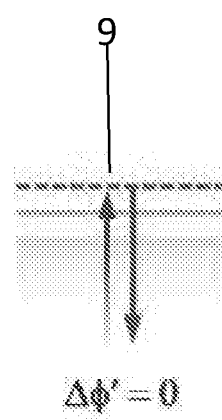


Fig 4c

5/18

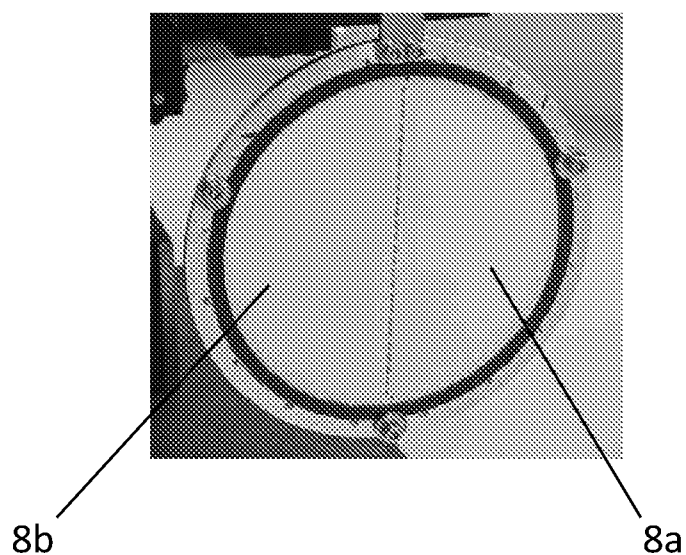


Figure 5

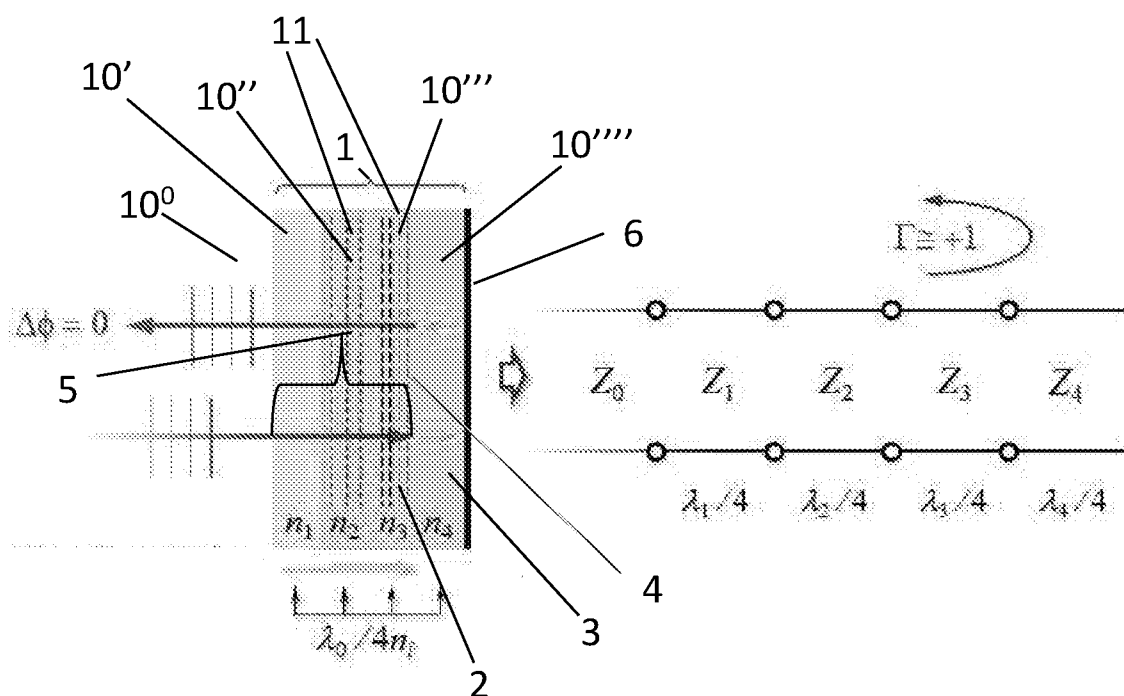


Fig 6a

Fig 6b

7/18

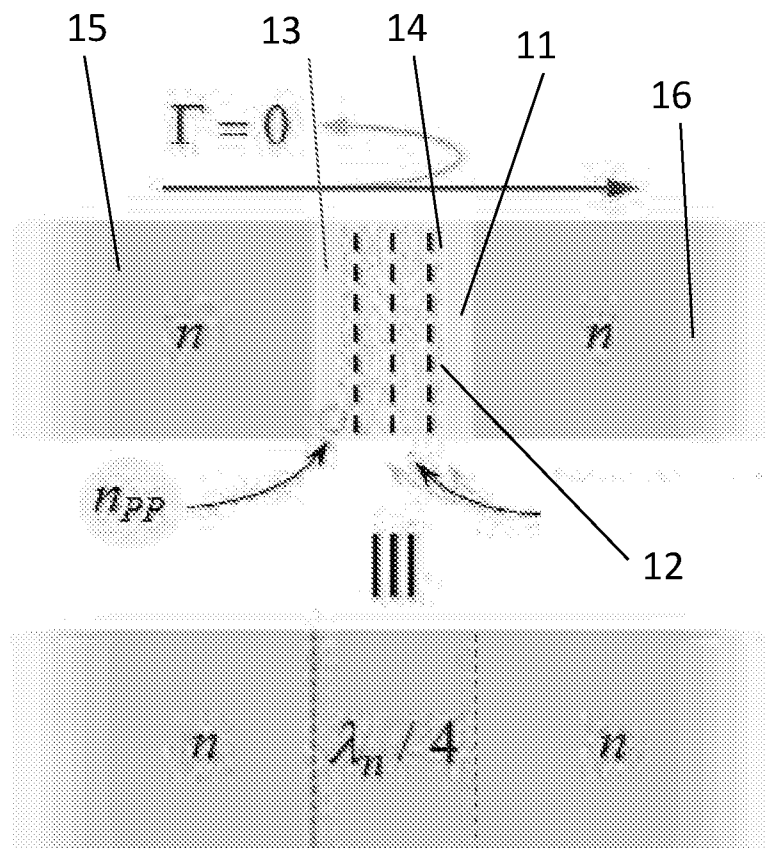


Fig 7

8/18

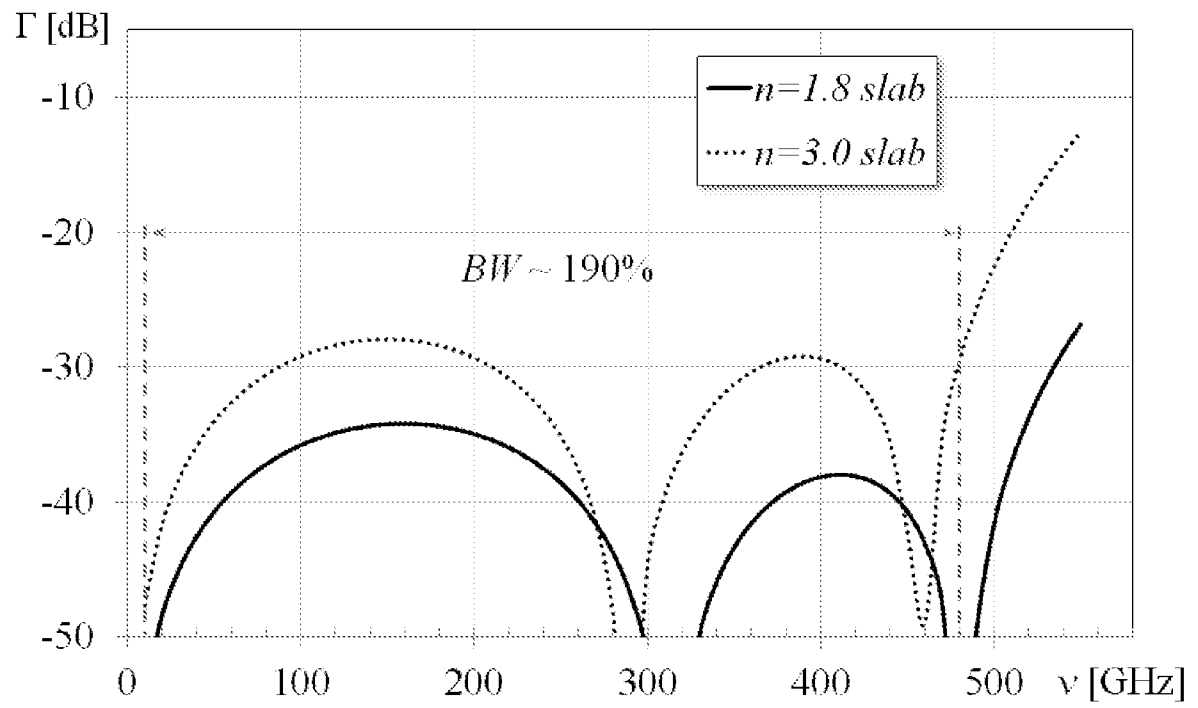


Fig 8

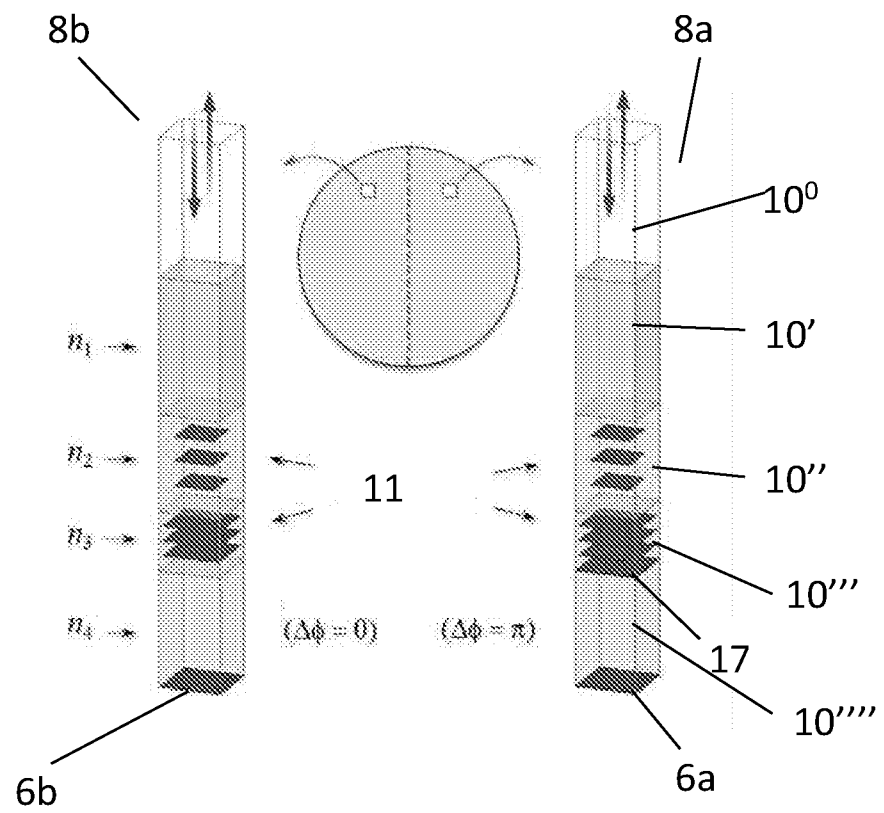


Fig 9

10/18

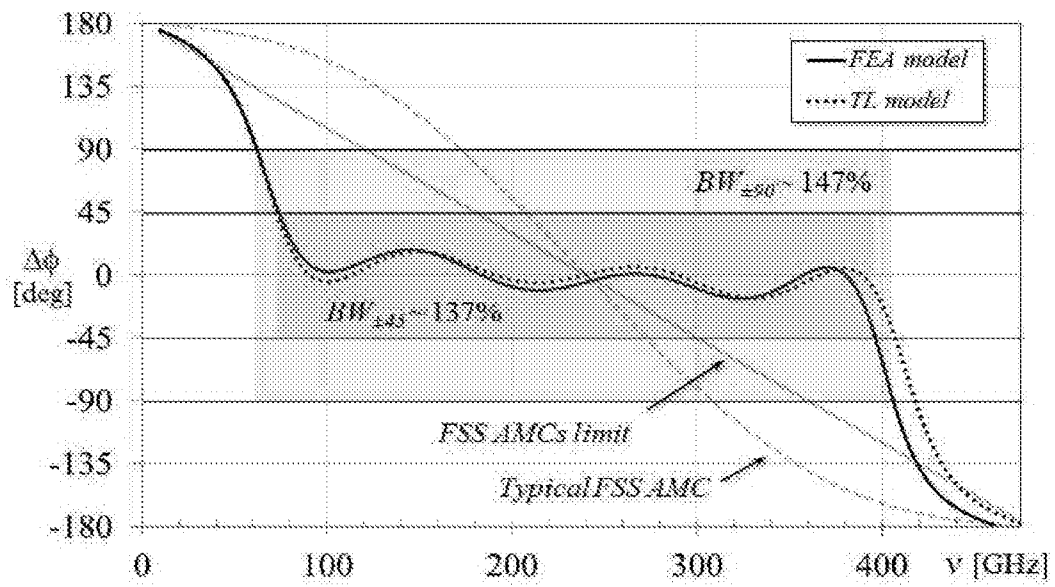


Fig 10

11/18

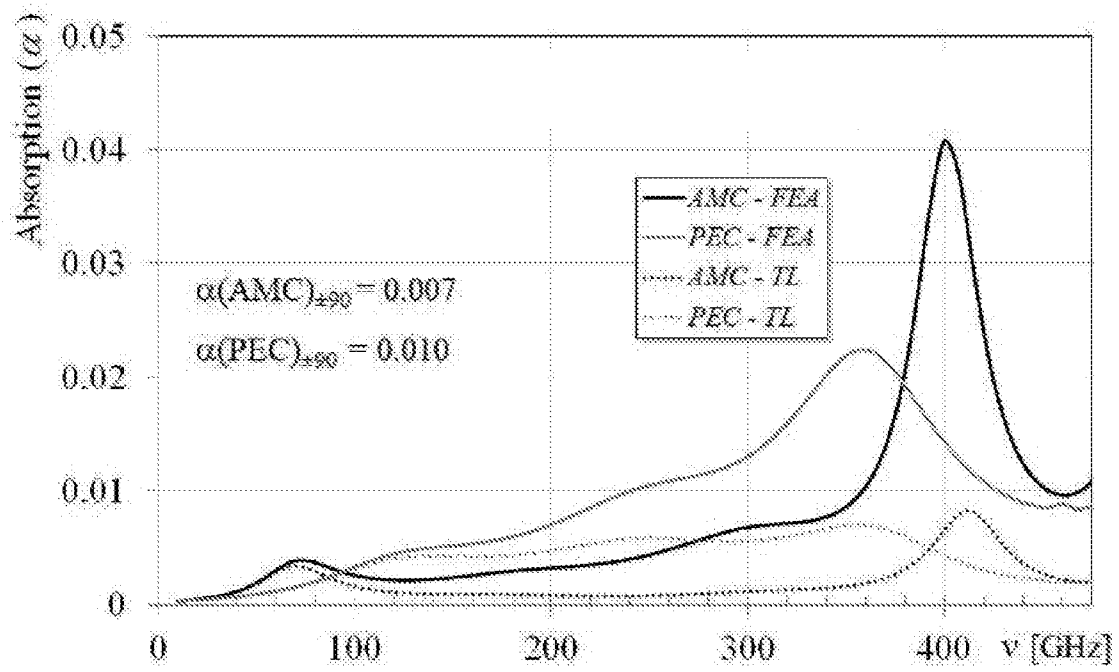


Fig 11

12/18

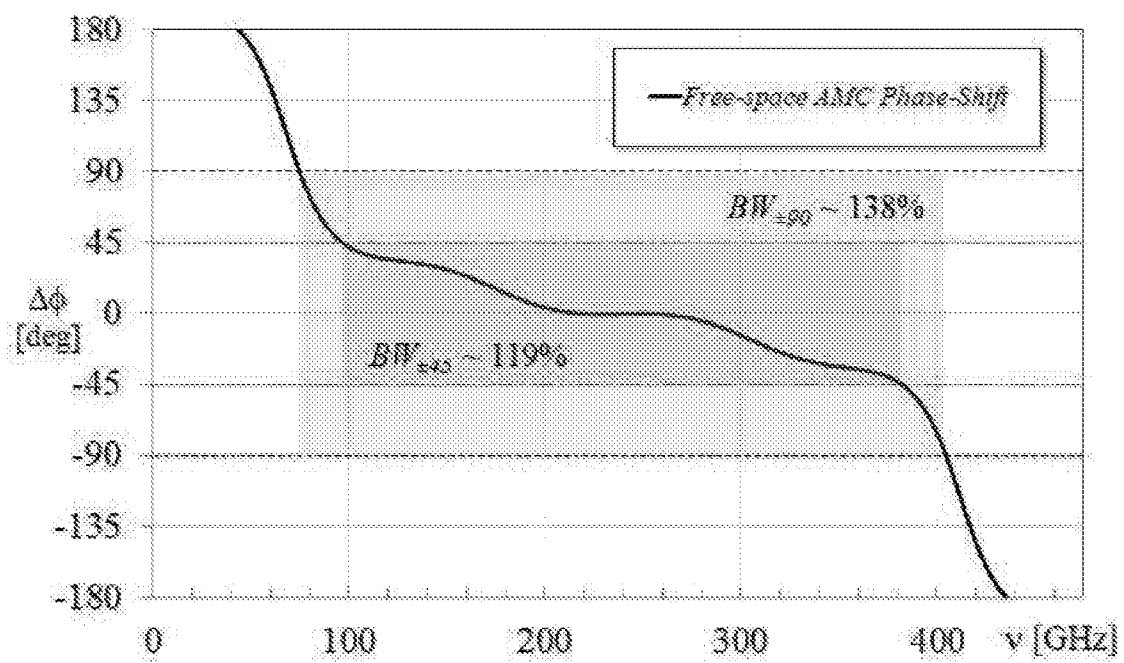


Fig 12

13/18

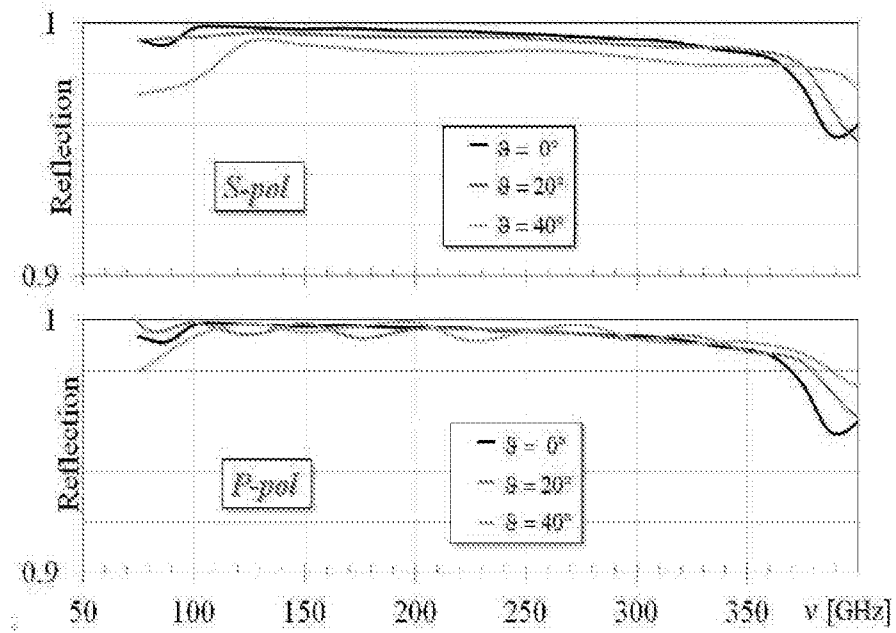


Fig 13

14/18

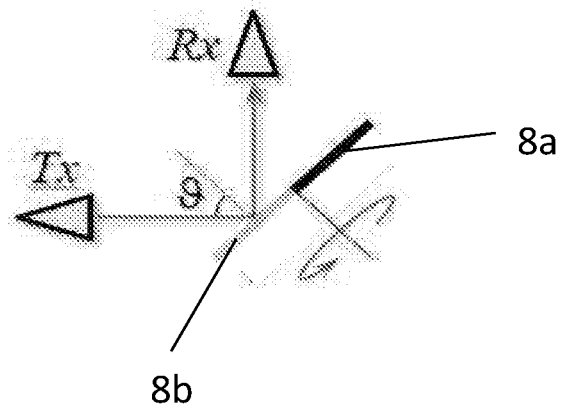


Fig 14

15/18

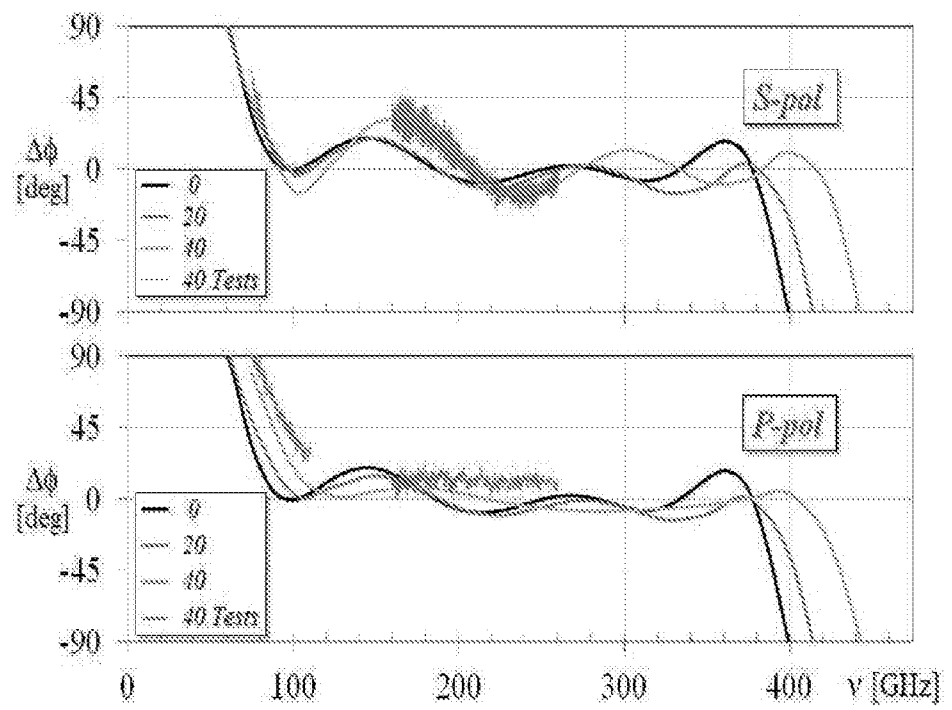


Fig 15

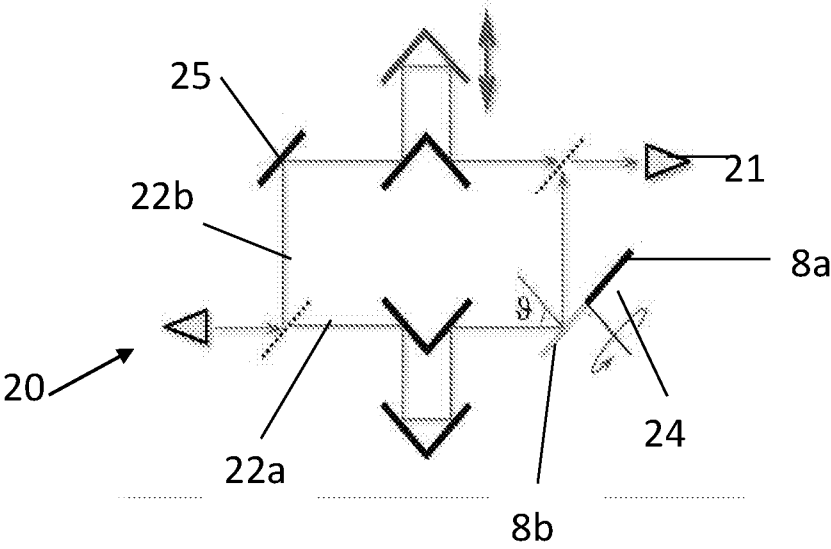


Fig 16

17/18

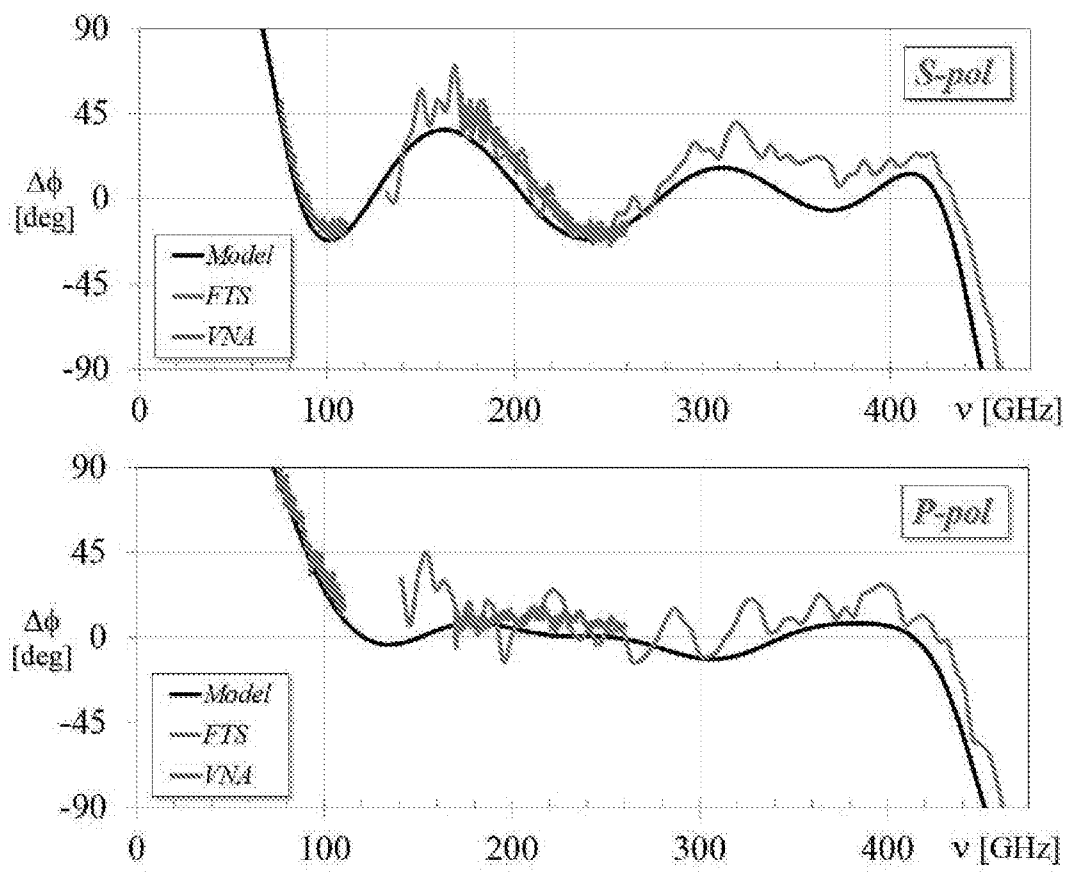


Fig 17

18/18

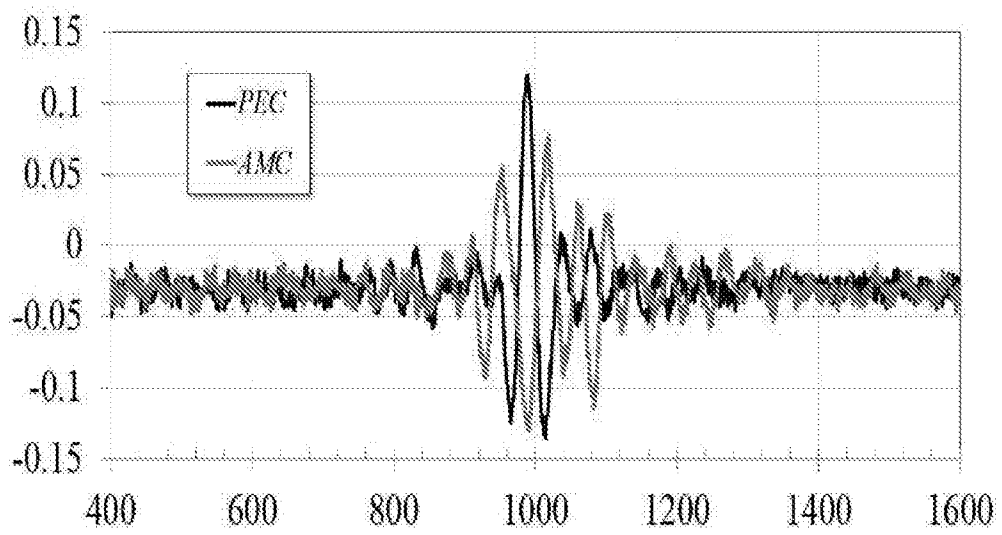


Fig 18

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2016/052822

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01Q15/00 H01Q15/08 H01Q15/23
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, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	RAYNO JENNIFER ET AL: "Synthesis of broadband 3D AMC ground planes using genetic programming", 2013 IEEE ANTENNAS AND PROPAGATION SOCIETY INTERNATIONAL SYMPOSIUM (APSURSI), IEEE, 6 July 2014 (2014-07-06), pages 35-36, XP032645200, ISSN: 1522-3965, DOI: 10.1109/APS.2014.6904349 ISBN: 978-1-4799-3538-3 [retrieved on 2014-09-18]	1-6,10, 11, 19-28, 30,31, 35,37-41
Y	the whole document	12-18, 29, 32-34,36 7-9
A	----- -/-	



Further documents are listed in the continuation of Box C.



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

9 December 2016

Date of mailing of the international search report

16/12/2016

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Ribbe, Jonas

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2016/052822

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 420 137 A2 (HUGHES AIRCRAFT CO [US]) 3 April 1991 (1991-04-03) columns 3-4; figure 1 -----	12-18, 29, 32-34,36
X	RAYNO JENNIFER ET AL: "Synthesis of Broadband True-3D Metamaterial Artificial Magnetic Conductor Ground Planes Using Genetic Programming", IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 62, no. 11, 1 November 2014 (2014-11-01), pages 5732-5744, XP011563037, ISSN: 0018-926X, DOI: 10.1109/TAP.2014.2357416 [retrieved on 2014-10-28] the whole document -----	1-6,10, 11, 19-28, 30,31, 35,37-41

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2016/052822

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0420137	A2	03-04-1991	
		AU 625586 B2	16-07-1992
		AU 6221090 A	16-05-1991
		CA 2024118 A1	27-03-1991
		DE 69013839 D1	08-12-1994
		DE 69013839 T2	23-03-1995
		EP 0420137 A2	03-04-1991
		ES 2062243 T3	16-12-1994
		IL 95519 A	24-06-1994
		JP H03119807 A	22-05-1991
		US 5017939 A	21-05-1991
