(19) DANMARK

(10) **DK/EP 3231038 T3**

Patent- og Varemærkestyrelsen

(12) Oversættelse af europæisk patentskrift

(51) Int.Cl.: ***H 01 Q 15/00 (2006.01)***

(45) Oversættelsen bekendtgjort den: **2020-04-14**

(80) Dato for Den Europæiske Patentmyndigheds bekendtgørelse om meddelelse af patentet: **2020-01-08**

(86) Europæisk ansøgning nr.: **15817487.0**

(86) Europæisk indleveringsdag: **2015-12-07**

(87) Den europæiske ansøgnings publiceringsdag: **2017-10-18**

(86) International ansøgning nr.: **FR2015053361**

(87) Internationalt publikationsnr.: **WO2016092191**

(30) Prioritet: **2014-12-08 FR 1462076**

(84) Designerede stater: **AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR**

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(54) Benævnelse: **FREMGANGSMÅDE TIL FREMSTILLING AF ET DIELEKTRISK ELEMENT MED NET, DER DANNER ET TREDIMENSIONELT SOLIDT GITTERNETVÆRK, OG SÅLEDES FREMSTILLET DIELEKTRISK ELEMENT**

(56) Fremdragne publikationer:
EP-A1- 2 712 027
GARCIA C R ET AL: "3D printing of anisotropic metamaterials", PROGRESS IN ELECTROMAGNETICS RESEARCH LETTERS EMW PUBLISHING USA, vol. 34, 2012, pages 75-82, XP002744969, ISSN: 1937-6480 cité dans la demande

A METHOD FOR MANUFACTURING A DIELECTRIC PART WITH MESHES FORMING A THREE-DIMENSIONAL SOLID NETWORK AND A DIELECTRIC PART MANUFACTURED THEREBY

The invention concerns a method for manufacturing a solid dielectric part having at least one determined tensor [ε_r], [μ_r] of at least one relative electromagnetic constant ε_r, μ_r, by nesting of several dielectric materials at least one of which is in the solid state. It also covers a solid dielectric part manufactured thereby.

In some applications such as miniature antennas formed by metamaterials for transmissions in the microwave range (frequencies higher than 100 MHz), one seeks to use dielectric substrates having determined electromagnetic characteristics so that the dielectric substrate itself has a certain electric and/or magnetic response to an electric and/or magnetic field.

It is known that it is possible to control the effective value of at least one relative electromagnetic constant (relative dielectric permittivity and/or relative magnetic permeability) of a dielectric part by nesting of several dielectric materials having different values for this relative electromagnetic constant. Such a nesting may be carried out according to different known processes, in particular chemically: by sol-gel coating; by etching, drilling (micromachining); or by molding (for example US 2014/0057072)…

The chemical or sol-gel coating processes do not allow accurately controlling the nesting structure of the materials, and therefore the effective value of an electromagnetic constant and its gradient and/or its anisotropy within the dielectric part. In particular, they do not allow obtaining values of an electromagnetic constant that are distributed according to a determined tensor. Furthermore, most often, the obtained results have a wide dispersion, the accuracy on the effective value of the electromagnetic constant can be guaranteed only with an accuracy that is at best in the range of 10%. This low reliability prevents their use in fields in which the manufacturing methods and/or the dielectric parts should enable certification thereof, for example in the space or aeronautical industry.

Some mechanical processes (etching, drilling, molding…) allow controlling the nesting structure. Nevertheless, this control is barely accurate, and requires time-consuming, complex and costly steps, in particular when it is desired to obtain a considerable gradient and/or a strong anisotropy within the part.

Furthermore, the inventor has determined that it might be advantageous, at least in some applications, to incorporate and/or circulate at least one dielectric material in the fluidic state (that is to say liquid and/or gaseous) in such a dielectric part. For example, in space applications, when one of the dielectric materials is atmospheric air incorporated into cells of a solid dielectric material during the manufacture on Earth of the dielectric part, one should ensure either a complete absence of degassing, or a perfect degassing of the entirety of the dielectric part, including at its core, when the latter is placed in the outer space vacuum. Furthermore, the incorporation and/or the circulation of a heat-transfer fluid within the part may enable an effective and accurate thermal control. Nevertheless, such an incorporation requires the ability to simultaneously have a large degree of freedom in the geometry and the dimensions of the nesting structure, and a very high accuracy in its practical making.

The publication « 3D printing of anisotropic metamaterials » C. R. Garcia *et al.*, progress in electromagnetics research letters EMW Publishing, USA, vol. 34, 2012, pages 75-82 describes a method for manufacturing a dielectric part according to a one-axis network in three dimensions having an anisotropy of the effective dielectric permittivity by three-dimensional printing of polycarbonate. Such a one-axis network provides room for only limited variations of the dielectric permittivity of the part. In particular, such a one-axis network does not produce a gradient of the dielectric permittivity simultaneously with an anisotropy, and does not allow controlling the incorporation and/or the circulation of a fluid within such a dielectric part. Furthermore, it does not allow optimizing, in proper conditions, the other characteristics of the dielectric part, in particular the mechanical and/or thermal and/or optical characteristics.

Hence, the invention aims at overcoming these drawbacks.

In particular, it aims at providing a method for manufacturing a dielectric part allowing for an accurate control of the value of at least one relative electromagnetic constant at every point of the dielectric part, and in particular with gradients and/or anisotropies of this value, that is to say a tensor distribution of the values of this electromagnetic constant throughout the volume of the dielectric part.

Thus, it aims at providing a method for manufacturing a dielectric part having at least one determined tensor $[\varepsilon_r]$, $[\mu_r]$ of at least one relative electromagnetic constant ε_r, μ_r (that is to say having an effective relative dielectric permittivity tensor $[\varepsilon_r]$ and/or an effective relative magnetic permeability tensor $[\mu_r]$) whose values can be accurately determined. In this respect, it aims at enabling a certification of the manufacturing method and/or of the characteristics of the dielectric part in compliance with the regulatory requirements, in particular in the space or aeronautical industries.

More particularly, it aims at providing a method for manufacturing a dielectric part intended to be used in the microwave range, that is to say for frequencies higher than 100 MHz and/or for wavelengths comprised between 3 mm and 3 m.

It also aims at providing a method for manufacturing a dielectric part allowing obtaining an incorporation – in particular a uniform incorporation – and/or a circulation in said part of at least one dielectric material in the fluidic state which may be selected amongst numerous liquid and/or gaseous compositions (including the outer space vacuum).

It also aims at providing such a manufacturing method also allowing controlling other characteristics of the dielectric part, in particular characteristics selected from the group of mechanical characteristics, thermal characteristics, optical characteristics, and fluidic characteristics (incorporation and/or circulation of at least one fluid within the part).

Throughout the entire text, the following terminology is adopted:

– electromagnetic constant: the dielectric permittivity or the magnetic permeability,

– fluid: liquid and/or gas (including the outer space vacuum),

– mesh: any polyhedral geometric pattern (that is to say having planar faces or at least one portion of the faces thereof may be clumsy) and/or polygonal (that is to say having sides or edges which consist of line segments or at least one portion of the sides or edges thereof may be curved) of a finite portion of a solid network,

– elementary mesh: any mesh allowing generating at least one area of a solid network by a homothetic translation with a ratio equal to 1, or not,

– peripheral meshes: meshes located at the periphery of a dielectric part,

– non-peripheral meshes: meshes other than the peripheral meshes,

– curved polyhedral mesh: a mesh having the shape of a curved polyhedron that is to say having at least one clumsy face and/or at least one curved edge,

– solid wall of a three-dimensional solid network: any solid portion of the network; it may consist of a solid or perforated face, or of a more or less thick edge.

Hence, the invention concerns a method for manufacturing a dielectric part wherein a nesting of several dielectric materials including at least one in the solid state is carried out, said dielectric materials having at least one relative electromagnetic constant ε_r, μ_r with different values,

characterized in that:

– said nesting is carried out by selecting:

o a nesting structure of said dielectric materials formed by a three-dimensional solid network constituted by a repetition in all directions of space – in particular in three orthogonal directions of space - of meshes of the at least one of said dielectric materials in the solid state,

- and dielectric materials adapted to enable a manufacture of the three-dimensional solid network by three-dimensional printing of each solid dielectric material, wherein each homogeneous area of any of said dielectric materials has in any direction of space a maximum dimension smaller than a value $a_{max}=\alpha.\lambda_0$, where α is a real number lower than 10, - in particular lower than 1, in particular lower than 0.1 –, and λ_0 is a wavelength of an electromagnetic radiation to which the dielectric part should be adapted,

– the dielectric part is manufactured by three-dimensional printing of the three-dimensional solid network,

so that the dielectric part has at least one determined tensor $[\varepsilon_r]$, $[\mu_r]$ of at least one relative electromagnetic constant ε_r, μ_r.

The invention also covers a dielectric part obtained by a method according to the invention. A dielectric part according to the invention is intended to be used in a radiation with a wavelength λ_0.

Hence, the invention concerns a dielectric part comprising a nesting of several dielectric materials including at least one in the solid state, and having at least one relative electromagnetic constant ε_r, μ_r with different values,

characterized in that said nesting is carried out according to a nesting structure of said dielectric materials formed by a three-dimensional solid network:

– constituted by a repetition in all directions of space – in particular in three orthogonal directions of space – of meshes of the at least one of said dielectric materials in the solid state,

– wherein each homogeneous area of any of said dielectric materials has in any direction of space a maximum dimension smaller than a value $a_{max}=\alpha.\lambda_0$, where α is a real number lower than 10, - in particular lower than 1, in particular lower than 0.1 –, and λ_0 is a wavelength of an electromagnetic radiation to which the dielectric part is adapted,

– printed by three-dimensional printing, so that it has at least one determined tensor $[\varepsilon_r]$, $[\mu_r]$ of at least one relative electromagnetic constant ε_r, μ_r.

Thus, in a method and a part according to the invention, the nesting structure is a meshed three-dimensional solid network, that is to say a three-dimensional paving of space by said meshes, and has, like a crystalline solid network, in any direction of space, that is to say in each one of three orthogonal directions x, y, z of any orthogonal reference frame fixed with respect to said part, a repetition of several adjacent meshes. In other words, in any direction of space, the part according to the invention has a number of adjacent meshes larger than 1.

The result is that it is possible to obtain a dielectric part having at least one determined tensor $[\varepsilon_r]$, $[\mu_r]$ of at least one relative electromagnetic constant ε_r, μ_r, whose value at every point of the part, in particular at every mesh of the three-dimensional solid network, can be accurately selected and controlled, featuring at least one gradient and/or one anisotropy. What is more, it has turned out that it were possible to confer other characteristics to this dielectric part, in particular characteristics selected from the group of mechanical characteristics, thermal characteristics, optical characteristics, and fluidic characteristics (incorporation and/or circulation of at least one fluid within the part). Indeed, the inventor has determined that with such a three-dimensional solid network, there are many different nesting structures all having the same electromagnetic properties, that is to say at least one same tensor $[\varepsilon_r]$, $[\mu_r]$, and even identical dielectric permittivity $[\varepsilon_r]$ and magnetic permeability $[\mu_r]$ tensors, and that it were possible to select and dimension a nesting structure according to said other desired characteristics of the part according to the invention.

In particular, advantageously, a method according to the invention has the following successive steps:

– a step in which at least one tensor $[\varepsilon_r]$, $[\mu_r]$ of at least one relative electromagnetic constant ε_r, μ_r is selected,

– a step in which there are selected at least one dielectric material in the solid state and at least one dielectric material in the fluidic state constitutive of the dielectric part to be manufactured, each dielectric material having a known value ε_{ri}, μ_{ri} of at least one relative electromagnetic constant, the known values ε_{ri}, μ_{ri} being different for the different dielectric materials and selected so as to be able to obtain each value of each tensor $[\varepsilon_r]$, $[\mu_r]$ of said at least one relative electromagnetic constant ε_r, μ_r by nesting of the different dielectric materials,

– a step in which there are selected said value a_{max}, and at least one three-dimensional solid network having proportions of the different dielectric materials constitutive of the dielectric part adapted so as to impart each value of each tensor $[\varepsilon_r]$, $[\mu_r]$ of said at least one relative electromagnetic constant ε_r, μ_r,

– a step in which there are selected other characteristics of the dielectric part – in particular characteristics selected from the group of mechanical characteristics, thermal characteristics, optical characteristics, and fluidic characteristics (incorporation and/or circulation of at least one fluid within the part),

– a step in which the geometry and the topology of said three-dimensional solid network allowing obtaining said other characteristics are selected.

Afterwards, the dielectric part is manufactured by three-dimensional printing of this three-dimensional solid network. Afterwards, it is possible to incorporate a fluid into said three-dimensional solid network.

Moreover, advantageously and according to the invention, at least one of the dielectric materials is selected in the fluidic state. The three-dimensional solid network incorporates each dielectric material in the fluidic state in its meshes. The three-dimensional solid network and the dielectric materials are selected so as to enable the incorporation of each fluidic dielectric material into the meshes of the three-dimensional solid network. This incorporation may be carried out during the three-dimensional printing and/or in a subsequent incorporation step.

Advantageously and according to the invention, there is selected at least one of the dielectric materials in the fluidic state, and a three-dimensional solid network having at least one mesh open in at least two different directions forming therebetween a non-zero angle different from 180°. In this manner, a non-linear circuit of fluid(s) may be created within the dielectric part. It has been noticed that providing openings of the meshes of a three-dimensional solid network according to at least two non-collinear distinct directions of space allows organizing a fluid circulation within at least one portion of this three-dimensional solid network. Such a circulation allows incorporating one or several fluid(s) within at least one portion of the three-dimensional solid network, in a uniform manner, for the manufacture of the dielectric part. Furthermore, it allows providing for a circulation of fluid(s) through and/or within at least one portion of the three-dimensional solid network during the use of the part. For example, these may consist (a non-exhaustive list) of heat-transfer fluids, conductive liquids, electrolytes, liquid crystals, ionized gases (plasmas)… In particular, it should be noted that the invention also allows varying the properties of at least one such a fluid, and therefore of the dielectric part, over time.

In some embodiments, advantageously and according to the invention, there is selected at least one of the dielectric materials in the fluidic state, and a three-dimensional solid network all non-peripheral meshes thereof are open in at least two different directions of space forming therebetween a non-zero angle different from 180°.

In other embodiments, advantageously and according to the invention, only one portion of the non-peripheral meshes of said three-dimensional solid network is open in at least two non-collinear different directions of space (forming therebetween a non-zero angle different from 180°). Thus, it is for example possible to define at least one inner circuit, whether looped or not, for fluid circulation in a part according to the invention. An open face is polygonal within the meaning defined hereinabove.

In some embodiments, advantageously and according to the invention, there is selected a three-dimensional solid network all non-peripheral meshes thereof have the same geometric pattern, and are even identical (the same geometric pattern and the same dimensions), corresponding to an elementary mesh of the three-dimensional solid network. In turn, this elementary mesh is three-dimensional, that is to say repeated by a homothetic translation with a ratio equal to 1, or not, in each of the three dimensions of space, that is to say in any direction of space, and therefore in each of the three directions of any orthogonal reference frame fixed with respect to the part. Hence, the three-dimensional solid network (and the part according to the invention) results from a three-dimensional paving of space from an elementary mesh, which is therefore selected from the group of elementary meshes adapted to generate a three-dimensional paving of space.

In other embodiments, advantageously and according to the invention, the non-peripheral meshes of said three-dimensional solid network are not all identical, or have not all the same geometric pattern. For example, the network may be formed by a plurality of contiguous subnetworks each formed by non-peripheral meshes with the same geometric pattern.

In some embodiments, advantageously and according to the invention, there is selected a three-dimensional solid network from the group formed by networks having meshes having solid walls arranged included within faces of right polyhedral meshes and networks having solid walls arranged included within faces of curved polyhedral meshes.

In particular, in some embodiments, advantageously and according to the invention, said three-dimensional solid network is selected from the group formed by networks with regular hexahedral – in particular parallelepiped, in particular cubic – meshes with open faces, networks with regular hexahedral – in particular parallelepiped, in particular cubic – meshes having some closed faces, networks with irregular hexahedral – in particular parallelepiped, in particular cubic – meshes with open faces, networks with irregular hexahedral – in particular parallelepiped, in particular cubic – meshes having some closed faces, networks with regular tetrahedral meshes with open faces, networks with regular tetrahedral meshes having some closed faces, networks with irregular tetrahedral meshes with open faces, networks with irregular tetrahedral meshes having some closed faces, networks with regular octahedral meshes with open faces, networks with regular octahedral meshes having some closed faces, networks with irregular octahedral meshes with open faces, networks with irregular octahedral meshes having some closed faces, networks with regular hexahedral meshes with open faces, networks with regular hexahedral meshes having some closed faces, networks with irregular hexahedral meshes with open faces, networks with irregular hexahedral meshes having some closed faces, networks with regular dodecahedral meshes with open faces, networks with regular dodecahedral meshes having some closed faces, networks with irregular dodecahedral meshes with open faces, networks with irregular dodecahedral meshes having some closed faces, networks with regular icosahedral meshes with open faces, networks with regular icosahedral meshes having some closed faces, networks with irregular icosahedral meshes with open faces, networks with irregular icosahedral meshes having some closed faces, their curved variants and the combinations thereof. Other three-dimensional solid networks may be used.

Moreover, in some embodiments, advantageously and according to the invention, the three-dimensional solid network comprises at least one mesh open in at least three non-collinear different directions – in particular three directions orthogonal to one another –. In particular, in some embodiments, advantageously and according to the invention, each open mesh of said three-dimensional solid network is open in at least three non-collinear different directions – in particular three directions orthogonal to one another –. In this manner, at least one fluid can circulate in these three directions through and/or within the part.

In some embodiments, advantageously and according to the invention, there is selected a three-dimensional solid network from the group formed by the networks having meshes having openings in each one of the faces of polyhedral meshes.

Moreover, in some embodiments, advantageously and according to the invention, each opening of each face of a polyhedral mesh of the three-dimensional solid network has a surface area larger than the overall surface area of the face incorporated thereby. Thus, the fluid circulation through these openings is promoted. The solid walls are dimensioned so as to meet the minimum mechanical characteristics that are desired for the part.

Moreover, in some embodiments, advantageously and according to the invention, air and a solid dielectric material prone to be printed by three-dimensional printing according to said three-dimensional solid network are selected as dielectric materials. Thus, the nesting structure comprises a three-dimensional solid network of a solid dielectric material prone to be printed by three-dimensional printing whose meshes incorporate air cells and are open in at least two distinct directions – in particular in three orthogonal directions and/or on each one of the faces of these meshes –. Indeed, there is nothing to prevent from providing other dielectric materials, alternatively or in combination.

Moreover, in some embodiments, advantageously and according to the invention, the at least one of said dielectric materials in the solid state is selected from the group formed by metal oxides, carbides, borides, nitrides, fluorides, silicides, titanates, sulphides, synthetic polymers and mixtures thereof. Indeed, there is nothing to prevent from providing other dielectric materials, alternatively or in combination.

Moreover, in some embodiments, advantageously and according to the invention, we use a three-dimensional printing selected from the group formed by additive manufacturing (AM), additive layer manufacturing (ALM), selective laser melting (SLM), selective laser sintering (SLS), selective heat sintering (SHS), fused deposition modeling (FDM or DIW), multi-jet modeling (MJM), stereo-lithography (SLA), laminated object manufacturing (LOM) and film transfer imaging (FTI).

Moreover, in some embodiments, advantageously and according to the invention, said nesting structure is arranged so that each homogeneous area of any of said dielectric materials has in any direction of space a maximum dimension smaller than a value $a_{max}=\alpha.\lambda_0$, where α is a real number lower than 10 – in particular lower than 1, in particular lower than 0.1 –, and λ_0 is the wavelength of an electromagnetic radiation to which a dielectric part according to the invention is adapted. Furthermore, the dielectric part has a dimension in any direction of space which is larger than this value a_{max}.

In other words, for a frequency with a predetermined average value f_0,

$$a_{max} = \alpha.C/(n.f_0)$$

where n is the index of a medium in which the dielectric part is intended to be used, and C is the speed of light in vacuum.

In particular, in some embodiments, advantageously and according to the invention, λ_0 being comprised between 3 mm and 3 m, a_{max} is comprised between 50 µm and 50 cm.

Thus, in some embodiments of a method according to the invention, there is selected a nesting structure of the dielectric materials according to a three-dimensional solid network:

– adapted to enable a manufacture of the dielectric part by three-dimensional printing,

– forming a spatial distribution of the dielectric materials adapted to obtain an effective relative dielectric permittivity tensor $[\varepsilon_r]$ and/or an effective relative magnetic permeability tensor $[\mu_r]$,

– wherein each homogeneous area of one of said dielectric materials has, for a predetermined wavelength λ_0, in any direction of space a maximum dimension smaller than $a_{max}=\alpha.\lambda_0$, where α is a real number lower than 10 – in particular lower than 1, in particular lower than 0.1 –.

Thus, the invention allows obtaining a dielectric part having an effective relative dielectric permittivity tensor $[\varepsilon_r]$ and/or an effective relative magnetic permeability tensor $[\mu_r]$ which can be determined and including other characteristics, in particular characteristics selected from the group of mechanical characteristics, thermal characteristics, optical characteristics, and fluidic characteristics (incorporation and/or circulation of at least one fluid within the part) can also be accurately controlled and selected. In particular, the invention allows obtaining a dielectric part incorporating at least one dielectric fluid in an accurately controlled manner, which can be uniform over at least one portion of the part, forming a circulation and/or enclosing circuit of each dielectric fluid.

Moreover, a dielectric part according to the invention may have peripheral walls that are completely closed and hermetic to each fluidic dielectric material contained therein; or on the contrary have peripheral walls that are partially open enabling the circulation of at least one fluidic dielectric material through the dielectric part; and even have completely open peripheral walls. Each dielectric material in the fluidic state may be incorporated within the three-dimensional solid network in particular by suction, injection (in particular vacuum injection), pumping…

In particular, the invention also allows accurately controlling the mechanical characteristics and/or the thermal characteristics and/or the optical characteristics and/or the dielectric characteristics and/or the magnetic characteristics of a dielectric part.

The mechanical characteristics are determined by those of the three-dimensional solid network and the selection of each solid dielectric material.

The thermal characteristics are determined by that of each of the dielectric materials constituting the dielectric part according to the invention, and in particular by an appropriate selection of at least one dielectric material in the fluidic state.

The optical characteristics are determined by the selection of the optical properties of each one of the dielectric materials constitutive of the part according to the invention.

The effective dielectric characteristics are determined by the selection of the dielectric characteristics of each of the dielectric materials constitutive of the part according to the invention, and by the selection of the nesting structure of these dielectric materials.

In this respect, it should be noted in particular that providing openings with a considerable surface area in the nesting structure may imply that Maxwell Garnett heterogeneous effective medium theory does not provide a reliable assessment of the effective relative dielectric permittivity tensor, if the conditions of application of this theory are not met. In this case, other assessment techniques may be used, such as for example that described in “Electromagnetic parameter retrieval from inhomogeneous metamaterials”, D. R. Smith *et al.*, Phys. Rev. E 71, 036617, 2005.

The effective magnetic characteristics are determined by the selection of the magnetic permeability of each one of the dielectric materials constitutive of the part according to the invention, by the selection of the nesting structure of these dielectric materials.

A dielectric part according to the invention may serve as an emitter and/or receiver of an electromagnetic and/or electric and/or magnetic field. In particular, it may advantageously be used in the microwave range (frequencies higher than 100 MHz, in particular comprised between 1 GHz and 10 GHz), for example (a non-exhaustive list) as:

– antenna substrate (this term also encompassing overlay substrates called “superstrats”),
– dielectric lens,
– radome,
– substrate or insulator for a microwave electrical circuit,
– dielectric resonator in a dielectric resonator filter.

The invention also concerns a manufacturing method and a dielectric part and the applications thereof characterized, in combination, by all or part of the features mentioned hereinabove or hereinafter.

Other objects, features and advantages of the invention will appear on reading the following description provided as a non-limiting example and which refers to the appended figures in which:

– Figure 1 is a block diagram illustrating the main steps of a method according to the invention,
– Figures 2 to 10 are perspective diagrams illustrating different examples of elementary mesh of a three-dimensional solid network of a dielectric part according to the invention,
– Figures 11 to 15 are perspective diagrams illustrating different embodiments of three-dimensional solid networks of a dielectric part according to the invention,
– Figures 16 and 17 respectively are front and profile diagrams of an example of a dielectric part according to the invention having a disk-like general shape.

In a method according to the invention as represented in Figure 1, in a first step 11, at least one desired value of at least one relative electromagnetic constant for a dielectric part to be manufactured, and at least one frequency f_0 and/or at least one wavelength λ_0 of an electromagnetic radiation to which the dielectric part should be adapted, are selected.

It is possible to select an effective desired value of at least one relative electromagnetic constant, this effective desired value being the same at every point of said dielectric part according to the invention.

At each point M(x,y,z) of the volume of the dielectric part, at least one desired value of the relative dielectric permittivity $\varepsilon_r(x,y,z)$ and/or of the relative magnetic permeability $\mu_r(x,y,z)$ may be selected specific to this point. Thus, a gradient of the relative dielectric permittivity $\varepsilon_r(x,y,z)$ and/or of the relative magnetic permeability $\mu_r(x,y,z)$ may be defined.

Furthermore, the dielectric part features an anisotropy for at least one relative electromagnetic constant. Thus, at each point M, at least one desired value of at least one relative electromagnetic constant may also depend on a direction of propagation and/or of incidence of an electromagnetic radiation, so that at least one vector $\vec{\varepsilon}_r(x,y,z)$, $\vec{\mu}_r(x,y,z)$ may be defined for at least one relative electromagnetic constant at this point M. The values of the components of this vector may be constant for all points throughout the volume of the dielectric part, or on the contrary vary in the volume of the dielectric part by forming a gradient for the corresponding relative electromagnetic constant.

Thus, it is possible to select a spatial distribution tensor of at least one relative electromagnetic constant (an effective relative dielectric permittivity tensor $[\varepsilon_r]$ and/or an effective relative magnetic permeability tensor $[\mu_r]$) within the volume of the dielectric part.

In general, the electromagnetic and/or electric and/or magnetic radiation or field to which the dielectric part should be adapted is in the microwave range, that is to say it has a frequency higher than 100 MHz.

During a second step 12, there are selected at least one dielectric material in the solid state and at least one dielectric material in the fluidic (gaseous and/or liquid) state constitutive of the dielectric part to be manufactured. Each dielectric material has a known value ε_{ri}, μ_{ri} of the relative electromagnetic constant(s), the known values ε_{ri}, μ_{ri} being different for the different dielectric materials and selected so as to be able to obtain each desired value – in particular each spatial distribution tensor of said at least one relative electromagnetic constant – by nesting of the different dielectric materials.

In particular, for each relative electromagnetic constant the effective value of which is desirably to be controlled at every point of the dielectric part, there are selected at least one first dielectric material having a known value of this relative electromagnetic constant lower than each desired value for this relative electromagnetic constant, and at least one second dielectric material having a known value of this relative electromagnetic constant higher than each desired value for this relative electromagnetic constant. In some advantageous embodiments, there are selected a dielectric material in the fluidic state as a first dielectric material (that is to say with a known value lower than each desired value), and a dielectric material in the solid state as a second dielectric material (that is to say with a known value higher than each desired value).

In most situations, it is possible to select only one single dielectric material in the solid state, and only one dielectric material in the fluidic state, in particular in the gaseous state, in particular air. However, there is nothing to prevent from selecting a plurality of dielectric materials in the solid state and/or a plurality of dielectric materials in the fluidic state, having similar or different natures, for example a dielectric material in the gaseous state and a dielectric material in the liquid state.

Moreover, each dielectric material in the solid state is selected so as to be able to be printed by three-dimensional printing according to a three-dimensional solid network constituted by meshes of said dielectric material in the solid state. Such a network formed by polyhedral and/or polygonal meshes (within the meaning indicated hereinabove) printed by three-dimensional printing allow controlling, very accurately and very finely, the effective value of at least one – in particular of each – relative electromagnetic constant at every point of the dielectric part and in any direction.

Furthermore, each dielectric material in the solid state is advantageously selected so as to be able to be printed by three-dimensional printing according to a three-dimensional solid network having meshes that are open in at least two non-collinear different directions, that is to say forming therebetween a non-zero angle different from 180°. In this manner, a circulation of a fluid (in an open or closed circuit) may be obtained within the dielectric part.

In some advantageous embodiments, at least one of said dielectric materials in the solid state is selected from the group formed by inorganic ceramics (group of metal oxides, carbides, borides, nitrides, fluorides, silicides, titanates, sulphides and mixtures thereof), and by synthetic polymers (selected in particular from the group of thermoplastics (for example from the group of polyfluorocarbons, such as PTFE, polyamides, FEP (fluorinated ethylene propylene), PFA (perfluoroalkoxy), polyolefins such as polyethylenes, PPO®(poly(p-phenylene oxide)), hydrocarbon resins, photopolymers), and mixtures thereof. Moreover, advantageously and according to the invention, at least one of said dielectric materials in the fluidic state is atmospheric air.

In some embodiments, a dielectric part according to the invention may be manufactured so as to have a completely hermetic peripheral outer envelope enclosing each dielectric material in the fluidic state which remains incorporated within the dielectric part without being able to escape therefrom. Thus, it is possible to trap at least one gaseous and/or liquid composition inside a dielectric part according to the invention, within the three-dimensional solid network formed by each dielectric material in the solid state. For example, such a gaseous and/or liquid composition is selected from the group of heat-transfer fluids, conductive liquids, electrolytes, liquid crystals, atmospheric gases, ionized gases.

In some embodiments, a dielectric part according to the invention may be manufactured so as to have peripheral passage openings for at least one gaseous and/or liquid composition which can circulate at least partially inside the dielectric part through the three-dimensional solid network formed by each dielectric material in the solid state. In particular, the three-dimensional solid network may be of the type forming meshes that are open at the periphery of the dielectric part, this three-dimensional solid network being placed in a gaseous and/or liquid composition volume filling the inside of this three-dimensional solid network. For example, said gaseous and/or liquid composition volume is the atmospheric environment prevailing around the dielectric part, for example the Earth's atmosphere or the outer space vacuum.

In some embodiments, at least one dielectric material in the fluidic state is a composition in the liquid state, selected in particular from the group formed by aqueous compositions, hydroalcoholic compositions, oils, solvents, and liquid crystals. In some embodiments, at least one dielectric material in the fluidic state is a composition in the gaseous state, selected in particular from the group formed by atmospheric gases and ionized gases (plasmas).

In a third step 13, the characteristics of the nesting structure of the different dielectric materials are determined so as to be able to obtain each desired value of at least one relative electromagnetic constant, that is to say in particular the proportions of the different dielectric materials constitutive of the dielectric part to be used to obtain each desired value of at least one relative electromagnetic constant. For this purpose, it is in particular possible to use a renowned theory such as the heterogeneous effective medium theory, for example Maxwell Garnett theory (cf. for example http://en.wikipedia.org/wiki/Effective_medium_approximations), or any other theory that can possibly be applied in this instance.

During this third step 13, a maximum dimension a_{max} of each homogeneous area of each dielectric material in any direction of space is determined, according to the value of the wavelength λ_0 and/or of the frequency with a predetermined average value f_0,

$$a_{max} = \alpha.\lambda_0 = \alpha.C/(n.f_0)$$

where α is a real number lower than 10 – in particular lower than 1, in particular lower than 0.1 –, n is the index of a medium in which the dielectric part is intended to be used, and C is the speed of light in vacuum. Indeed, this maximum dimension a_{max} enables in particular a sufficient application of the heterogeneous effective medium theory, so that the dielectric part actually features effective values of at least one electromagnetic constant corresponding to the nesting of the different dielectric materials. In other words, the dielectric part is equivalent to a homogeneous material in its effects with respect to an electromagnetic radiation.

In particular, in some embodiments, advantageously and according to the invention, λ_0 being comprised between 3 mm and 3 m, a_{max} is comprised between 50 µm and 50 cm.

During the fourth step 14, additional mechanical characteristics and/or thermal characteristics and/or optical characteristics desired for the dielectric part to be manufactured are selected, taking into account nevertheless the mechanical and/or thermal and/or optical properties of the previously selected dielectric materials.

During the fifth step 15, a nesting structure is selected which, on the one hand, corresponds to the previously determined proportions and maximum dimension a_{max} and, on the other hand, allows obtaining the previously selected mechanical and/or thermal and/or optical characteristics. In particular, the geometry and the topology of said three-dimensional solid network are selected. This selection may be performed using computer-aided design software allowing simulating said mechanical and/or thermal and/or optical characteristics.

For example, said three-dimensional solid network is selected from the group formed by networks with regular hexahedral – in particular parallelepiped, in particular cubic – meshes with open faces, networks with regular hexahedral – in particular parallelepiped, in particular cubic – meshes having some closed faces, networks with irregular hexahedral – in particular parallelepiped, in particular cubic – meshes with open faces, networks with irregular hexahedral – in particular parallelepiped, in particular cubic – meshes having some closed faces, networks with regular tetrahedral meshes with open faces, networks with regular tetrahedral meshes having some closed faces, networks with irregular tetrahedral meshes with open faces, networks with irregular tetrahedral meshes having some closed faces, networks with regular octahedral meshes with open faces, networks with regular octahedral meshes having some closed faces, networks with irregular octahedral meshes with open faces, networks with irregular octahedral meshes having some closed faces, networks with regular hexahedral meshes with open faces, networks with regular hexahedral meshes having some closed faces, networks with irregular hexahedral meshes with open faces, networks with irregular hexahedral meshes having some closed faces, networks with regular dodecahedral meshes with open faces, networks with regular dodecahedral meshes having some closed faces, networks with irregular dodecahedral meshes with open faces, networks with irregular dodecahedral meshes having some closed faces, networks with regular icosahedral meshes with open faces, networks with regular icosahedral meshes having some closed faces, networks with irregular icosahedral meshes with open faces, networks with irregular icosahedral meshes having some closed faces, their curved variants and the combinations thereof. Other three-dimensional solid networks may be used.

Moreover, in some embodiments, the three-dimensional solid network comprises at least one mesh open in at least three different directions – in particular three directions orthogonal to one another –. In particular, in some embodiments, advantageously and according to the invention, each open mesh of said three-dimensional solid network is open in at least three different directions – in particular three directions orthogonal to one another –. In this manner, at least one fluid can circulate in these three directions through and/or within the part.

During the sixth step 16, the dielectric part thus determined is manufactured by three-dimensional printing. For this purpose, any three-dimensional printing technology may be considered, depending on the nature of the selected dielectric materials and the three-dimensional solid network 10. For example, it is possible to use a three-dimensional printing selected from the group (a non-exhaustive list) formed by additive manufacturing (AM), additive layer manufacturing (ALM), selective laser melting (SLM), selective laser sintering (SLS), selective heat sintering (SHS), fused deposition modeling (FDM or DIW), multi-jet modeling (MJM), stereo-lithography (SLA), laminated object manufacturing (LOM) and film transfer imaging (FTI).

During an optional seventh step 17, it is possible to incorporate at least one dielectric material in the fluidic state within the three-dimensional solid network, for example by suction or pressurized injection. Depending on the applications, it is also possible to hermetically close all or part of the periphery of the dielectric part by a hermetic envelope, for example by a coating of a hermetic curable composition applied at the periphery of the three-dimensional solid network, in particular by dip-coating or surface deposition, undergoing afterwards a curing step.

Figure 2 is an example of a hexahedral elementary mesh 20 which can be used to form a uniform three-dimensional solid network by repetition of this elementary mesh 20 formed of a solid dielectric material. In the example, the elementary mesh 20 is a parallelepiped whose six faces have rectangular openings, the opposing faces having openings with identical dimensions and the adjacent faces having openings whose dimensions along the common edges are also identical. This parallelepiped elementary mesh 20 has a height a1, a length a2 and a width a3. The opening of the longitudinal vertical faces 21 has a height b1 and a length b2. The opening of the lateral vertical faces 22 has a width b3 and a height b4. The opening of the longitudinal horizontal faces 23 has a width b5 and a length b6. In the represented example, b4=b1, b5=b3, and b6=b2. However, there is nothing to prevent from providing openings with different dimensions between the adjacent faces, that is to say b4≠b1 and/or b5≠b3 and/or b6≠b2.

Figure 11 is an example of a three-dimensional solid network which can be obtained from this parallelepiped elementary mesh which, in the example, is cubic, a1=a2=a3=a and b1=b2=b3=b4=b5=b6=b. Figure 12 is another example of a three-dimensional solid network, which differs from the previous one in that the elementary mesh is shifted by a/2 between two adjacent planes XY of meshes of the network. Figures 13 to 15 are other examples of a three-dimensional solid network corresponding to the elementary mesh 20 of Figure 2 with different values of a1, a2, a3 and of b4=b1, b5=b3, and b6=b2.

Figure 3 represents another example of a hexahedral (cubic) elementary mesh 30 with truncated angles 34. Figure 4 represents another example of an elementary mesh 40 similar to Figure 3 inscribed within a cube but where the faces of the cube have middle edges 45 crossed at the middle thereof. Figure 5 represents another example of an elementary mesh 50 inscribed within a cube whose faces have middle edges 55 crossed at the middle thereof and truncated angles 54 up to the middles of the main edges of the faces of the cube circumscribed by the mesh 50, these truncated angles 54 being formed by solid walls. Figure 6 represents another example of an elementary mesh 60 inscribed within a cube whose faces have two concentric circular edges 66, 67 connected by four middle edges 65 forming radii.

Figure 7 represents a tetrahedral elementary mesh 70. Figure 8 represents an octahedral elementary mesh 80. Figure 9 represents a dodecahedral elementary mesh 90. Figure 10 represent an icosahedral elementary mesh 100. These different elementary meshes may be used to generate three-dimensional solid networks, with some of their faces possibly solid, with openings having dimensions which may be variable or identical, with angles that may be truncated or not…

These different geometric and topological variants allow varying the mechanical and/or thermal and/or optical and/or dielectric and/or magnetic characteristics of the dielectric part thus obtained. The nesting structures thus formed may be manufactured by three-dimensional printing.

The obtained dielectric parts are formed by a three-dimensional solid network whose elementary meshes have open faces according to at least two non-collinear distinct directions, which in particular enables a circulation of the fluid inside the dielectric part.

Figures 16 and 17 represent an example of a dielectric part according to the invention having a disk-like general shape formed by a network of the type like that represented in Figure 13, the direction X of Figure 13 being orthogonal to the main face 110 of the disk, the disk comprising three layers 111 of identical meshes with open rectangular faces, and therefore four stages 112 of rectangular faces oriented in the directions Y, Z of Figure 13. The part comprises at the level of each stage 112 of faces oriented in the directions Y, Z, a peripheral circular edge 113 to which the edges of the peripheral meshes are connected.

In a variant that is not represented, it is possible to form within such a dielectric part one or several circuit(s) enclosing one or several dielectric fluid(s), by sealing some of the faces of the meshes of the network. In particular, it is possible to form an open circuit opening into the periphery of the dielectric part and/or onto one of its main faces so as to form one or several inlet port(s) and/or one or several outlet port(s). In particular, it is also possible to form several independent circuits insulated from one another.

EXAMPLES:

The effective electromagnetic constants of networks of meshes of dielectric parts according to the invention are assessed by the method described in the publication "Electromagnetic parameter retrieval from inhomogeneous metamaterials", D. R. Smith *et al.*, Phys. Rev. E 71, 036617, 2005.

The working frequency f_0 is equal to 4 GHz.

The following Table 1 reports the results obtained for the networks of Figures 11 and 13 having a parallelepiped mesh structure with an open face, with a ceramic (alumina) having a relative permittivity ε_r=10.6 and a relative permeability μ_r=1 as a solid dielectric material, and air ε_r=1, μ_r=1, as a fluidic dielectric material.

Network	Dimensions of the mesh	Effective permittivity	Effective permeability
Figure 11	a1=1mm b1=b4=0.738mm a2=2mm b2=b6=1.5mm a3=0.5mm b3=b5=0.4mm	$\varepsilon_r^x = 1.75$ $\varepsilon_r^y = 1.75$ $\varepsilon_r^z = 1.75$	$\mu_r = 1$
Figure 13	a1=0.5mm b1=b4=0.48mm a2=1mm b2=b6=0.738mm a3=2mm b3=b5=1mm	$\varepsilon_r^x = 1.43$ $\varepsilon_r^y = 1.44$ $\varepsilon_r^z = 1.65$	$\mu_r = 1$

Table 1

As we can see, in the example of Figure 11, we obtain values of the effective electromagnetic constant that are the same in all directions, while the structure of the selected network is not isotropic and allows in particular varying the mechanical and/or thermal characteristics of the dielectric part according to the invention in the different directions of space.

In the example of Figure 13, we see that it is possible to obtain different values of the dielectric permittivity in the different directions of space by selecting an appropriate structure of the network.

A manufacturing method according to the invention may be the object of quite numerous variants. In particular, it is possible to use several dielectric materials in the solid state printed simultaneously, a first dielectric material forming a three-dimensional solid network whose meshes are at least partially filled with another dielectric material in the solid state. It is also possible to only use dielectric materials in the solid state nested by three-dimensional printing, at least one dielectric material in the solid state forming said three-dimensional solid network having meshes filled with at least one other dielectric material in the solid state.

A dielectric part according to the invention may serve as an emitter and/or receiver of an electromagnetic and/or electric and/or magnetic field and may also be the object of quite numerous variants and various applications. In particular, it may advantageously be used in the microwave range (frequencies higher than 100 MHz, in particular comprised between 1 GHz and 10 GHz), for example (a non-exhaustive list) as:

– antenna substrate (this term also encompassing overlay substrates called “superstrats”),
– dielectric lens,
– radome,
– substrate or insulator for a microwave electrical circuit,
– dielectric resonator in a dielectric resonator filter.

Patentkrav

1. Fremgangsmåde til fremstilling af et dielektrisk element, hvor der udføres en sammenfletning af flere dielektriske materialer, hvoraf mindst ét er i fast tilstand, hvilke dielektriske materialer har mindst én relativ elektromagnetisk konstant ε_r, μ_r med forskellige værdier,
kendetegnet ved, at:

- nævnte sammenfletning foretages ved at vælge:

  ◦ (15) en sammenfletningsstruktur af nævnte dielektriske materialer dannet af et tredimensionelt solidt gitternetværk bestående af en gentagelse i alle retninger af rummet af net (20, 30, 40, 50, 60, 70, 80, 90, 100) af det mindst ene af de dielektriske materialer i fast tilstand, og hvor hver homogene zone af det ene af nævnte dielektriske materialer i hver retning af rummet har en maksimal dimension, der er mindre end en værdi $a_{max} = \alpha. \lambda_0$, hvor α er et reelt tal mindre end 10, og λ_0 er en bølgelængde af en elektromagnetisk stråling, til hvilken det dielektriske element skal tilpasses,

  ◦ og (12) dielektriske materialer tilpasset til at muliggøre en fremstilling af det tredimensionelle solide gitternetværk ved tredimensionelt print af hvert solide dielektriske materiale,

- det dielektriske element fremstilles (16) ved tredimensionelt print af det tredimensionelle solide gitternetværk,

således at det dielektriske element har mindst én tensor $[\varepsilon_r]$, $[\mu_r]$ bestemt af mindst én relativ elektromagnetisk konstant ε_r, μ_r.

2. Fremgangsmåde ifølge krav 1, **kendetegnet ved, at** der vælges det mindst ene af de dielektriske materialer i flydende tilstand og et tredimensionelt solidt gitternetværk, der har mindst ét net (20, 30, 40, 50, 60, 70, 80, 90, 100), som er åbent i mindst to forskellige retninger, der mellem sig danner en ikke-nulvinkel, som er forskellig fra 180°.

3. Fremgangsmåde ifølge et hvilket som helst af kravene 1 eller 2, **kendetegnet ved, at** der vælges det mindst ene af de dielektriske materialer i flydende tilstand og et tredimensionelt solidt gitternetværk, i hvilket alle ikke-perifere net (20, 30, 40, 50, 60, 70, 80, 90, 100) er åbne i mindst to forskellige retninger af rummet, der mellem sig danner en ikke-nulvinkel, som er forskellig fra 180°.

4. Fremgangsmåde ifølge et hvilket som helst af kravene 1 til 3, **kendetegnet ved, at** der vælges et tredimensionelt solidt gitternetværk, i hvilket alle ikke-perifere net (20, 30, 40, 50, 60, 70, 80, 90, 100) har et samme geometrisk mønster.

5. Fremgangsmåde ifølge et hvilket som helst af kravene 1 til 4, **kendetegnet ved, at** der vælges et tredimensionelt solidt gitternetværk fra gruppen bestående af gitternetværk med net (20, 30, 40, 50, 60, 70, 80, 90, 100), der har solide vægge indrettet inkluderet i lige flader af polyedernet, og gitternetværk med solide vægge indrettet inkluderet i krumme flader af polyedernet.

6. Fremgangsmåde ifølge krav 5, **kendetegnet ved, at** der vælges et tredimensionelt solidt gitternetværk fra gruppen bestående af gitternetværk med net (20, 30, 40, 50, 60, 70, 80, 90, 100), der har åbninger i hver af fladerne af polyedernet.

7. Fremgangsmåde ifølge et hvilket som helst af kravene 1 til 6, **kendetegnet ved, at** der vælges et tredimensionelt solidt gitternetværk fra gruppen bestående af gitternetværk med net (20, 30, 40, 50, 60, 70, 80, 90, 100), der har solide vægge indrettet inkluderet i flader af polyedernet og mindst én åbning i mindst to separate flader af de ikke-perifere polyedernet, og **ved, at** hver åbning i hver flade af et polyedernet af det tredimensionelle solide gitternetværk har et overfladeareal, der er større end det samlede overfladeareal af den flade, som indeholder den.

8. Fremgangsmåde ifølge et hvilket som helst af kravene 1 til 7, **kendetegnet ved, at** der som dielektriske materialer vælges luft og et solidt dielektrisk materiale, der kan printes ved hjælp af tredimensionelt print i overensstemmelse med nævnte tredimensionelle solide gitternetværk.

9. Fremgangsmåde ifølge et hvilket som helst af kravene 1 til 8, **kendetegnet ved, at** det mindst ene af nævnte dielektriske materialer i fast tilstand vælges fra gruppen bestående af metaloxider, carbider, borider, nitrider, fluorider, silicider, titanater, sulfider, syntetiske polymerer og blandinger deraf.

10. Dielektrisk element, der omfatter en sammenfletning af flere dielektriske materialer, hvoraf mindst ét er i fast tilstand, og som har mindst én relativ elektromagnetisk konstant ε_r, μ_r med forskellige værdier,
kendetegnet ved, at nævnte sammenfletning udføres ifølge en sammenfletningsstruktur af nævnte dielektriske materialer dannet af et tredimensionelt solidt gitternetværk:

- bestående af en gentagelse i alle retninger i rummet af net (20, 30, 40, 50, 60, 70, 80, 90, 100) af det mindst ene af nævnte dielektriske materialer i fast tilstand,

- hvor hver homogene zone af det ene af nævnte dielektriske materialer i hver retning af rummet har en maksimal dimension, der er mindre end en værdi $a_{max} = \alpha . \lambda_0$, hvor α er et reelt tal mindre end 10, og λ_0 er en bølgelængde af en elektromagnetisk stråling, til hvilken det dielektriske element er tilpasset,

- printet ved hjælp af tredimensionelt print,

således at det har mindst én tensor $[\varepsilon_r]$, $[\mu_r]$ bestemt af mindst én relativ elektromagnetisk konstant ε_r, μ_r.

11. Element ifølge krav 10, **kendetegnet ved, at** mindst ét af de dielektriske materialer er i flydende tilstand, og mindst ét net (20, 30, 40, 50, 60, 70, 80, 90, 100) af nævnte tredimensionelle solide gitternetværk er åbent i mindst to forskellige retninger, der mellem sig danner en ikke-nulvinkel, som er forskellig fra 180°.

12. Element ifølge et hvilket som helst af kravene 10 eller 11, **kendetegnet ved, at** mindst ét af de dielektriske materialer er i flydende tilstand, og alle de ikke-perifere net (20, 30, 40, 50, 60, 70, 80, 90, 100) af nævnte tredimensionelle solide gitternetværk er åbne i mindst to forskellige retninger af rummet, der mellem sig danner en ikke-nulvinkel, som er forskellig fra 180°.

13. Element ifølge et hvilket som helst af kravene 10 til 12, **kendetegnet ved, at** alle de ikke-perifere net (20, 30, 40, 50, 60, 70, 80, 90, 100) af nævnte tredimensionelle solide gitternetværk har et samme geometrisk mønster.

14. Element ifølge et hvilket som helst af kravene 10 til 13, **kendetegnet ved, at** nævnte tredimensionelle solide gitternetværk vælges fra gruppen bestående af gitternetværk med net (20, 30, 40, 50, 60, 70, 80, 90, 100), der har solide vægge indrettet inkluderet i lige flader af polyedernet, og gitternetværk med net, der har solide vægge indrettet inkluderet i krumme flader af polyedernet.

15. Element ifølge krav 14, **kendetegnet ved, at** det nævnte tredimensionelle solide gitternetværk vælges fra gruppen bestående af gitternetværk med polyedernet (20, 30, 40, 50, 60, 70, 80, 90, 100), der har åbninger i hver af fladerne af deres flader.

16. Element ifølge et hvilket som helst af kravene 10 til 15, **kendetegnet ved, at** det nævnte tredimensionelle solide gitternetværk vælges fra gruppen bestående af gitternetværk med net (20, 30, 40, 50, 60, 70, 80, 90, 100), der har solide vægge indrettet inkluderet i flader af polyedernet og mindst én åbning i mindst to separate flader af de ikke-perifere polyedernet, og **ved, at** hver åbning i hver flade af et polyedernet af det tredimensionelle solide gitternetværk har et overfladeareal, der er større end det samlede overfladeareal af den flade, som indeholder den.

17. Element ifølge et hvilket som helst af kravene 10 til 16, **kendetegnet ved, at** det som dielektriske materialer omfatter luft og et solidt dielektrisk materiale, der kan printes ved hjælp af tredimensionelt print i overensstemmelse med nævnte tredimensionelle solide gitternetværk.

18. Element ifølge et hvilket som helst af kravene 10 til 17, **kendetegnet ved, at** det mindst ene af nævnte dielektriske materialer i fast tilstand vælges fra gruppen bestående af metaloxider, carbider, borider, nitrider, fluorider, silicider, titanater, sulfider, syntetiske polymerer og blandinger deraf.

Fig 1

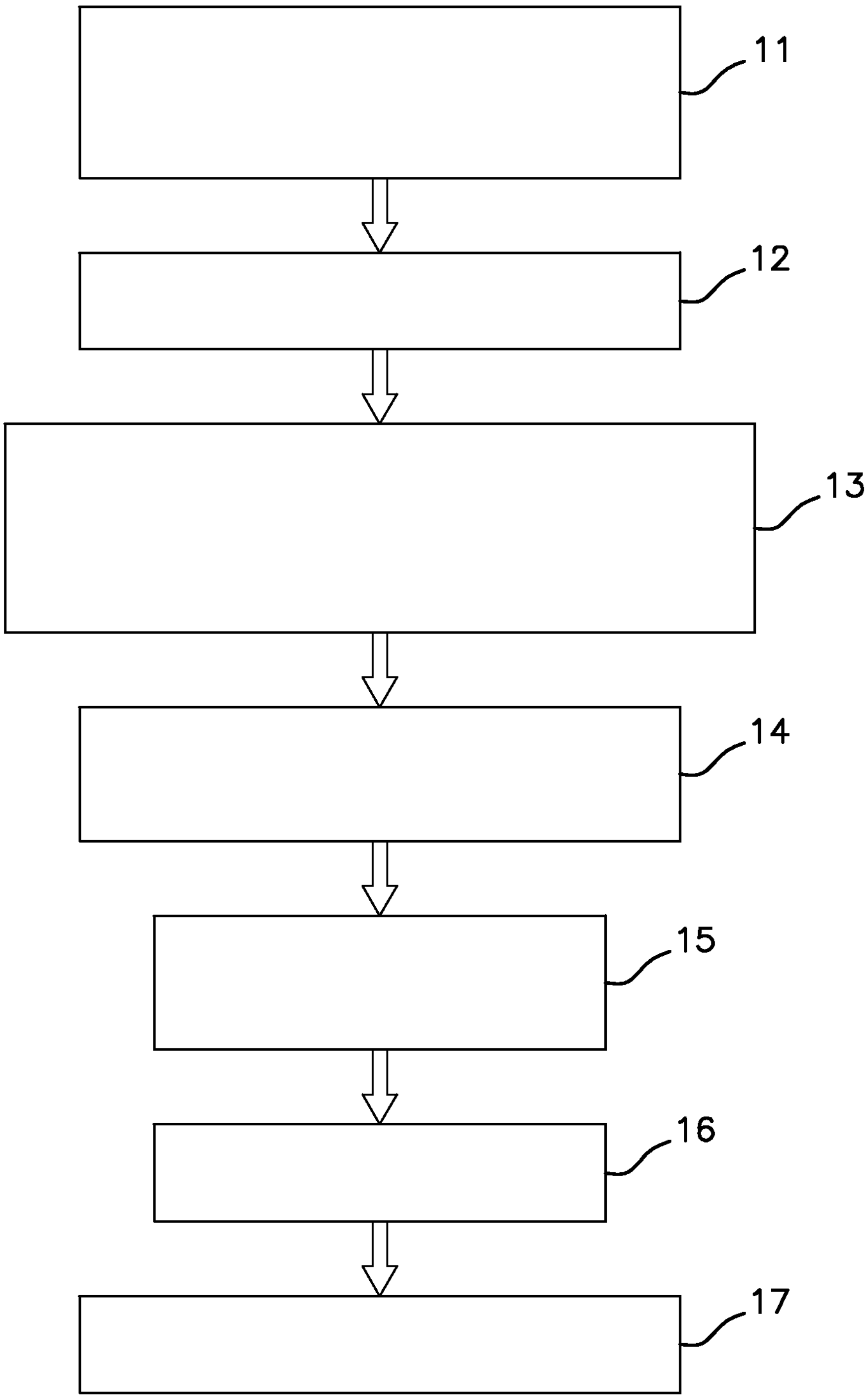

Fig 2

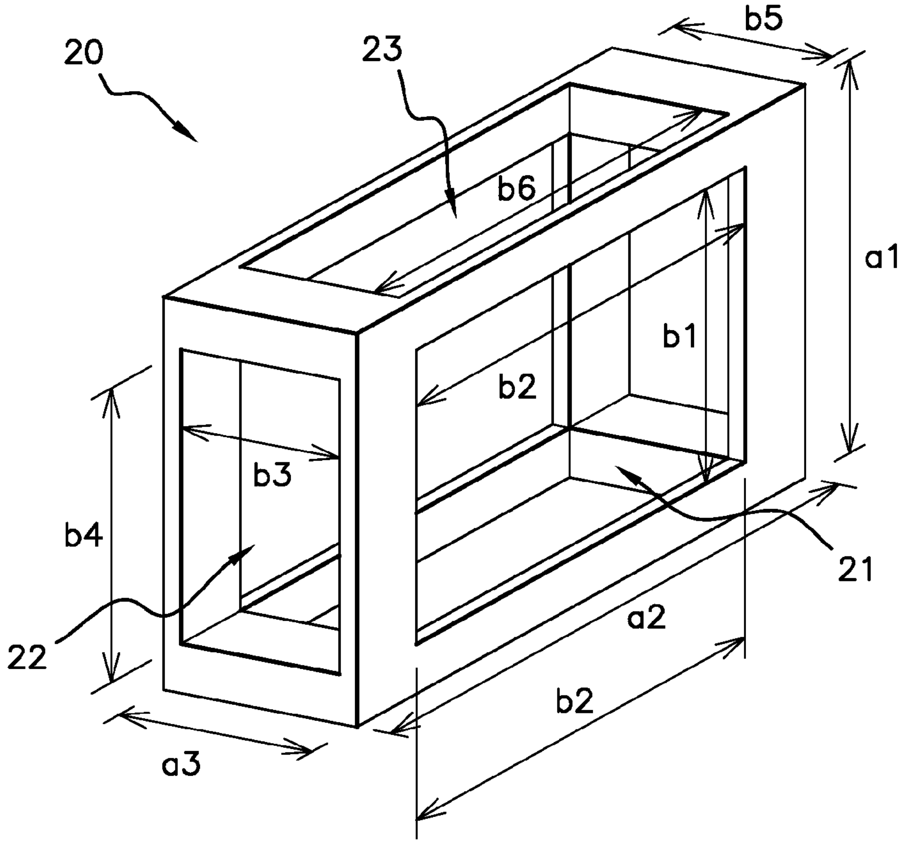

Fig 3

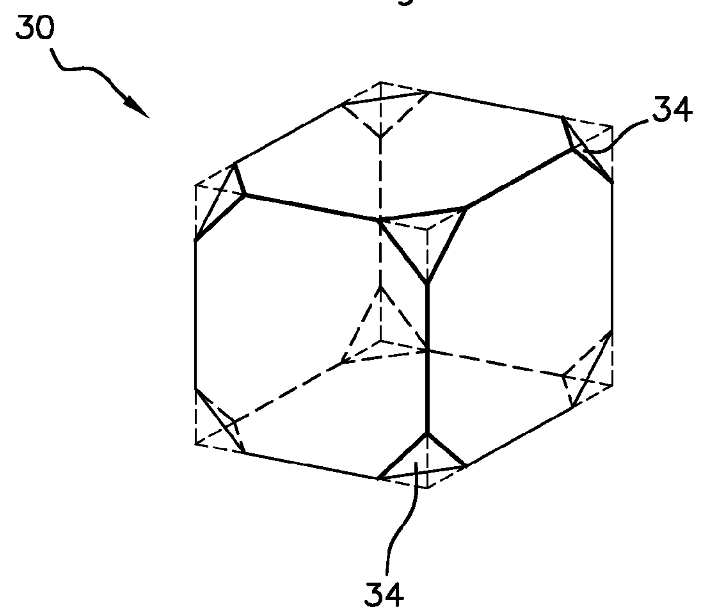

Fig 4

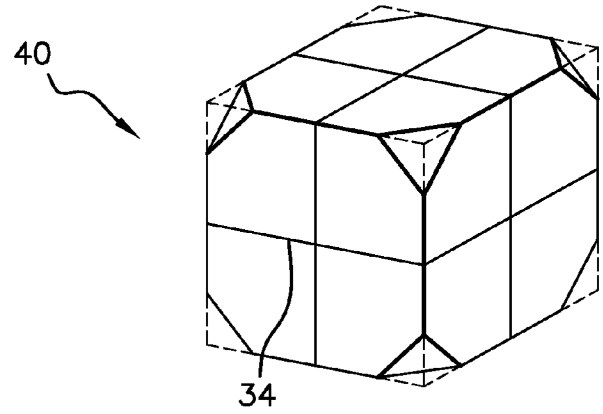

Fig 5

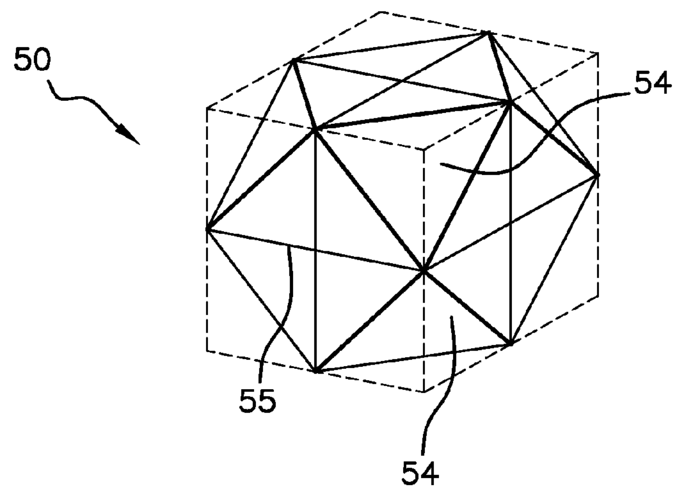

Fig 6

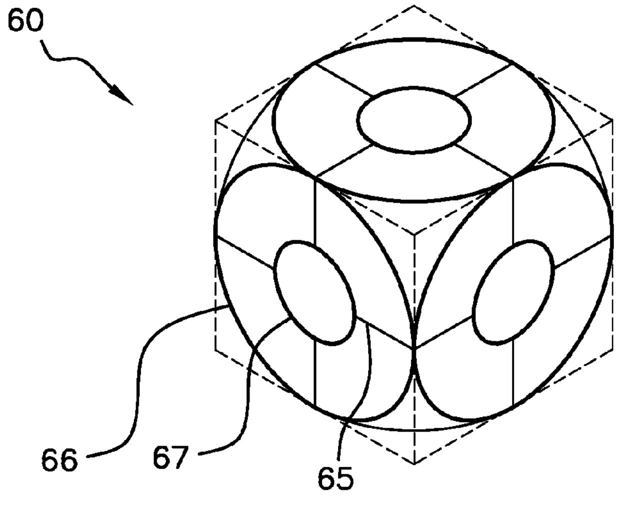

Fig 7

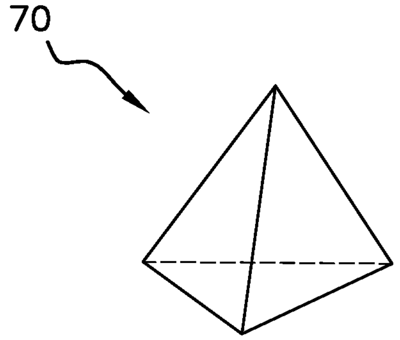

Fig 8

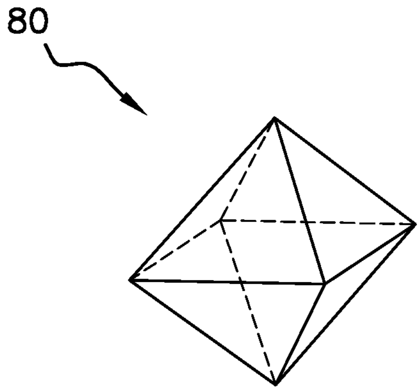

Fig 9

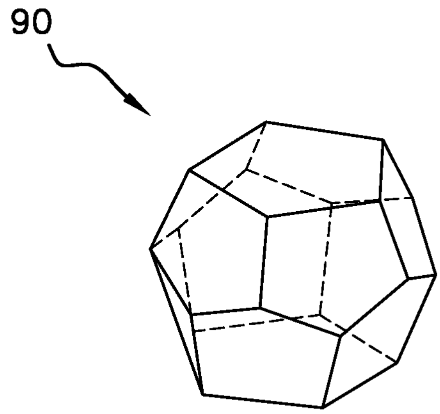

Fig 10

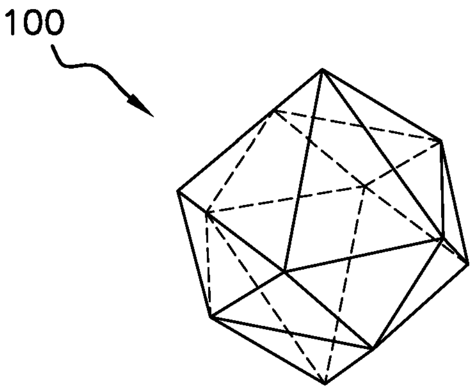

Fig 11

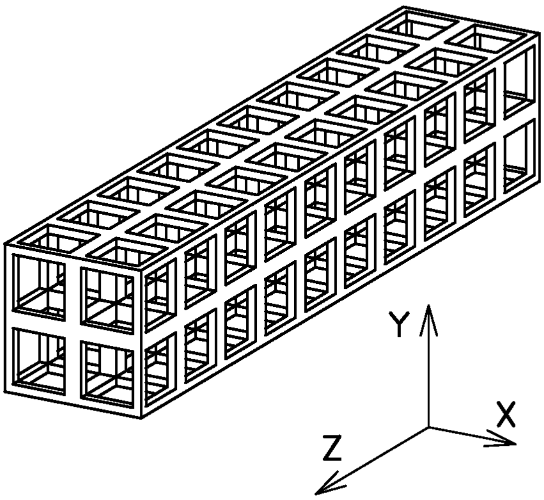

Fig 12

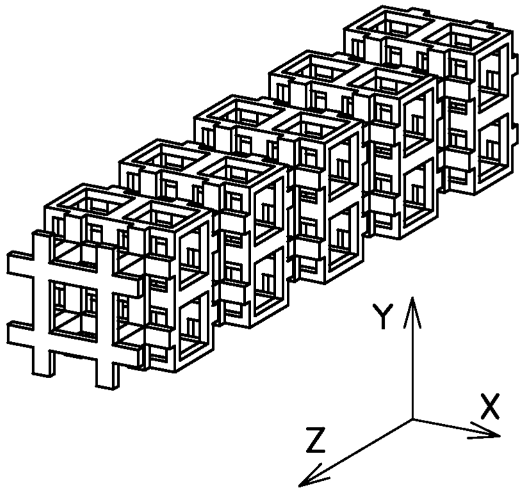

Fig 13

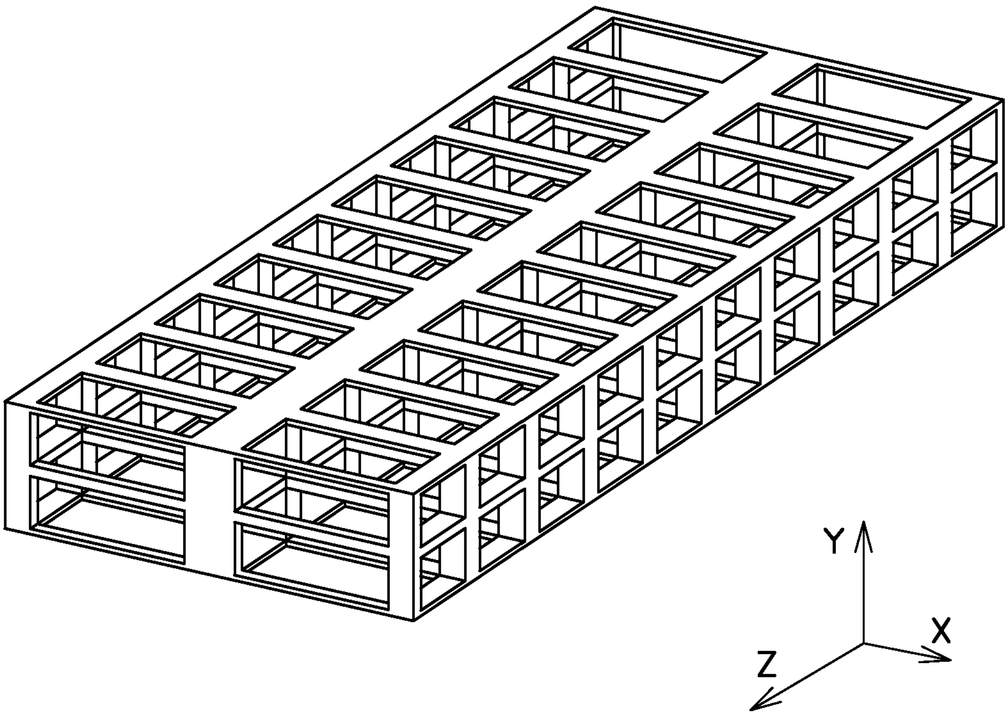

Fig 14

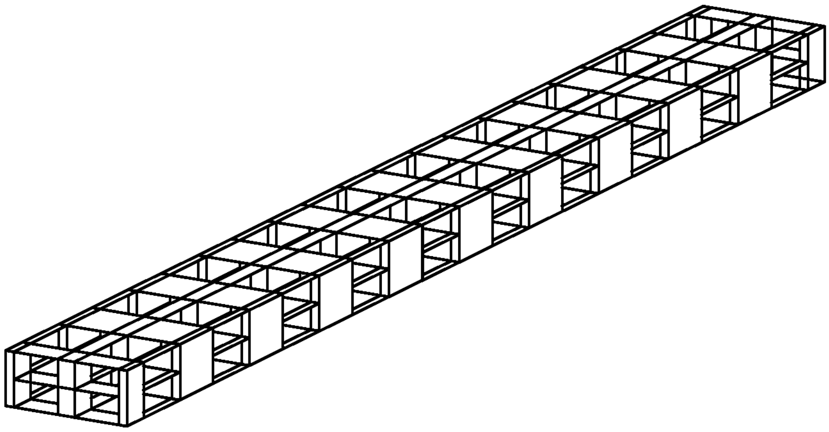

Fig 15

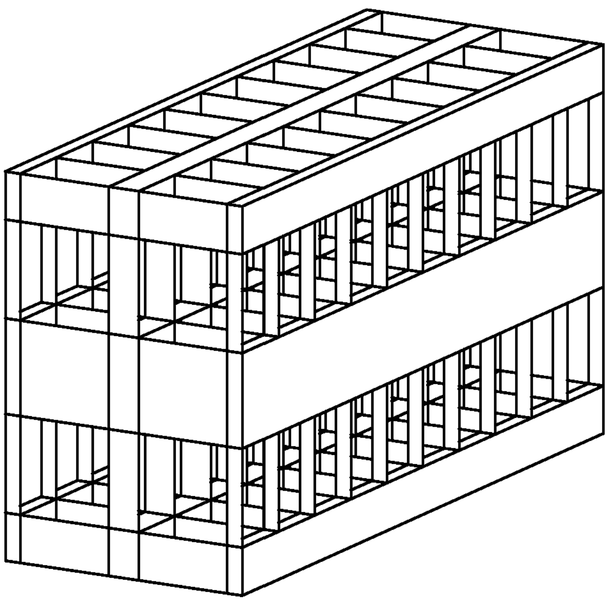

Fig 16

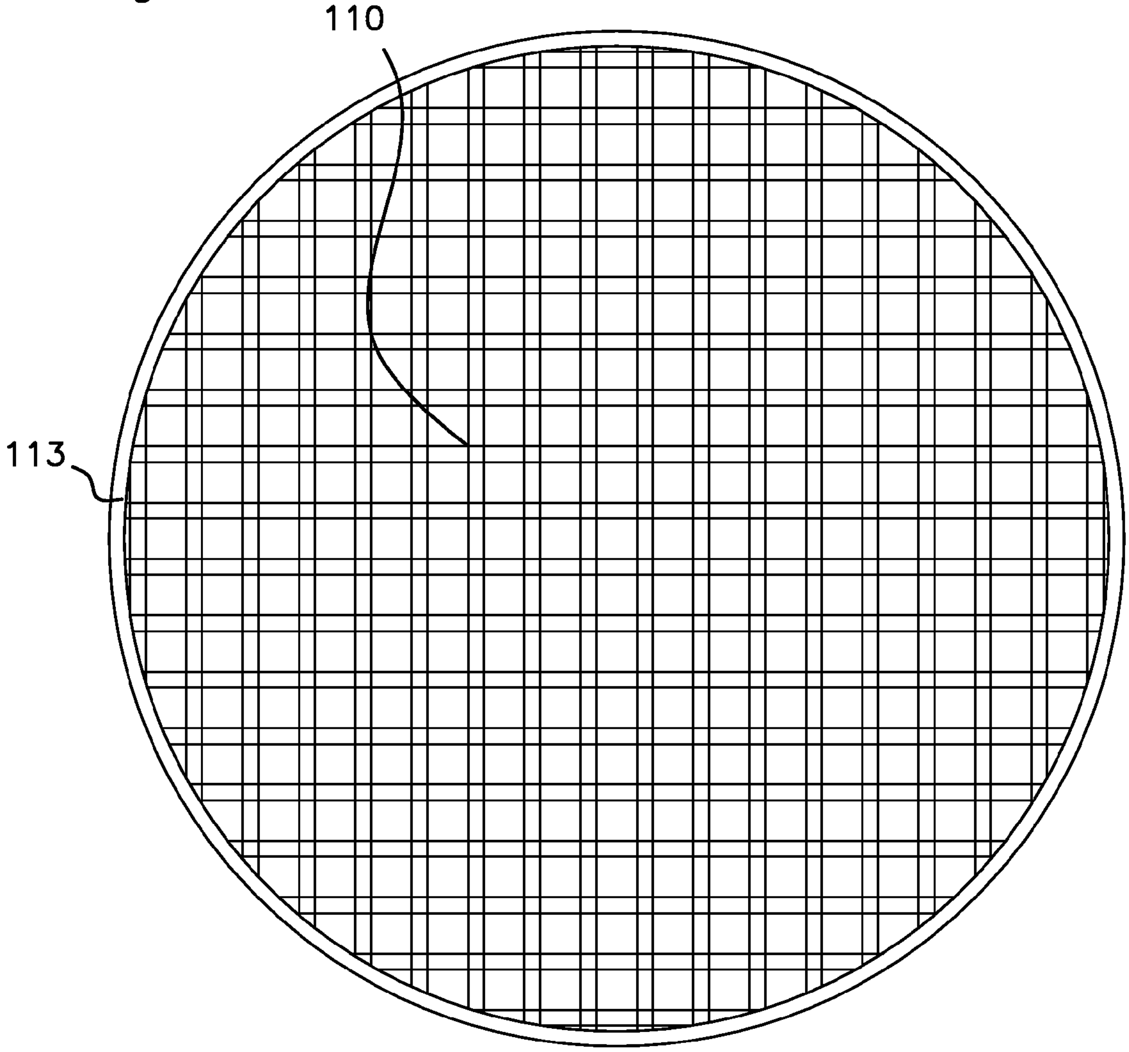

Fig 17