Metamaterials in electromagnetics

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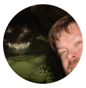

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Invited Review

Metamaterials in electromagnetics

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Abstract

This article takes a look at metamaterials in electromagnetics from a general point of view. The terminology of complex electromagnetic materials is discussed critically. A unique definition for metamaterials does not exist, but certain salient points can be distinguished in the ongoing discussion within the research community and in various formal suggestions for this definition in the literature. Also several different classes of special materials are identified as candidates for metamaterials and their particular characteristics are discussed. Finally it is pointed out that the boundary between "ordinary" materials and metamaterials is difficult to draw because also many everyday natural materials are dielectric mixtures which may display very surprising and non-linear macroscopic response functions.

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Keywords: Metamaterials; Electromagnetics; Bianisotropy; Artificial media; Composites

Contents

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1. Introduction

The problem of understanding materials has troubled scientists for centuries. It is not easy to get a full picture about what there is behind the surface of matter. Handbooks have been written which list various properties of diverse materials under many different ambient parameters. But still, the internal structure of a material sample contains so many degrees of freedom that cataloguing everything would be impossible. The macroscopic characterization always leaves out large amount of information, sometimes essential.

Indeed, in many cases the macroscopic properties of mixtures may be surprisingly differing from those of the ingredients. Ice cream might be a good example of such a behavior: the taste is very different from the sum of tastes of ice and cream. It is common knowledge that cooking is a very nonlinear process but similar effects (i.e., essential changes caused by slight variations in details of how components are mixed together) are known in many fields of science and engineering.

A name for artificial materials that pays respect to this characteristic of unconventional macroscopic properties is “metamaterials.” Especially in connections with electromagnetics, metamaterials are presently in a focus of intense study. In recent years, grand research programs have been launched and institutional networks have been founded with the purpose to study, develop, and design metamaterials and their applications.

Metamaterials are hard to define and classify. An inclusive definition for metamaterials that might satisfy most researchers in the field of electromagnetic materials would probably narrow down the set to those materials that simply are something else than ordinary materials. And even about this one cannot always be sure.

Electromagnetics of complex materials is a field where researchers may have their backgrounds in other, perhaps distant disciplines. This fact is reflected in the language. What do all the concepts mean that are being used in discussions on material electromagnetics? Bianisotropy, chirality, non-reciprocity, gyrotropy, negative-index, indefinity, etc.? And what are all those abbreviations? DNG, ENG, MNG, ND, EBG, PC,. . .?

This article discusses various ways how one can talk about metamaterials, and also, in what settings they are analyzed and treated in the electromagnetics research of today.

2. Search for definition of metamaterials

Ever since the word “metamaterial” emerged into the discussion and printed literature of electromagnetics in the early years of the present century, suggestions were also being proposed to define the concept in a more accurate manner. In 2003, in Ref. [1] I have presented the most important definitions of the time with some analysis and critic. Now, 4 years later, we can observe that a widespread use of this word has affected its meaning. Its connotations are different and perhaps there has been a slight shift in the exact focus on what is meant by metamaterials. In science, words are thought to mean roughly the same thing to different people. However, in the case of discussion concerning metamaterials, concepts seem to be sometimes more subjective. See also the article [2] for a discussion on the metamaterials research directions, including terminology.

Let us analyze some of the most visible metamaterials definitions of the present time.

The electronic web-based dictionary Wikipedia contains the following definition [3] (at present, December 2006)

> In electromagnetism (covering areas like optics and photonics), a meta material (or metamaterial) is an object that gains its (electromagnetic) material properties from its structure rather than inheriting them directly from the materials it is composed of. This term is particularly used when the resulting material has properties not found in naturally formed substances. Metamaterials are promising for a diversity of optical/microwave applications, such as new types of beam steerers, modulators, band-pass filters, superlenses, microwave couplers, and antenna radomes.

The research consortia and networks that are concentrating on metamaterials have formalized their research topic, e.g. the *Metamorphose* Network of Excellence by the European Union [4]:

> Metamaterials are artificial electromagnetic (multi-) functional materials engineered to satisfy the prescribed requirements. The prefix meta means after, beyond and also of a higher kind. Superior properties as compared to what can be found in nature are often underlying in the spelling of metamaterial. These new properties emerge due to specific interactions with electromagnetic fields or due to external electrical control.

and in the USA, the DARPA Technology Thrust program on metamaterials [5]:

> MetaMaterials are a new class of ordered nanocomposites that exhibit exceptional properties not readily observed in nature. These properties arise from qualitatively new response functions that are: (1) not

observed in the constituent materials and (2) result from the inclusion of artificially fabricated, extrinsic, low dimensional inhomogeneities.

Also characterizations exist for metamaterials that use fewer words and attempt to pinpoint the most essential property of these materials, like the one in Ref. [6]:

> Materials made out of carefully fashioned microscopic structures can have electromagnetic properties unlike any naturally occurring substance.

and website [7]:

> Artificially structured metamaterials can extend the electromagnetic properties of conventional materials.

The great activity of present research on metamaterials in electromagnetics is producing a very large amount of publications, and the rate is probably only increasing. It is therefore obvious that the number of definitions that appear in these articles for this concept will overwhelm any attempt to give a complete picture about the manner how researchers in the field do understand this term. Can we say anything that would be universally accepted to be a fundamental property of metamaterials?

It is obvious that in many of the above-cited definitions, the various applications in fields like microwave engineering and optics are mentioned. However, the core of the quality in metamaterials is contained in something more fundamental.

From the listed definitions, two essential properties can be distinguished: metamaterials should exhibit properties

- not observed in the constituent materials,
- not observed in nature.

These two points indeed touch the kernel of the various ways metamaterials are understood. Let us take a closer look at what they say.

The first of these points puts the focus on comparing the character of the constituents with those of the whole. The assumption is obviously a two-level frame. It looks a piece of metamaterial to be composed of "lower-level" components. In other words, it is in some sense a "mixture" of other materials. This aspect does not emphasize the importance of the particular microstructure of the composite. Only the co-existence of homogeneous materials with well-defined response properties causes new properties to appear on the next, higher level. But with those assumptions, the claim in this first item is rather clear. Metamaterial is a vessel for emergence [1].

The second point is more problematic. Metamaterials possess properties that are not observed in nature. What does it mean to be "naturally formed"? Obviously the definition [3] that uses this term refers with metamaterials to man-made materials, materials that are purposely designed and tailored to do a certain function, and one has had to resort to special engineering because nature does not offer materials and media for free which would fulfill these requirements.

This position is vulnerable to at least two objections. Or the criticism can be directed from several angles of looking at the definition. For the first, it hints that metamaterials would be somehow unnatural. But the very ethos of engineering is to obey laws of nature. A deep appreciation of these laws and their thorough understanding are the strongest tools to build new apparatuses, new systems, and new materials.

The other way of questioning the non-naturality of metamaterials is to point out that one is putting the equality sign between what we see around us in everyday life and what is there in nature. One can hear in metamaterialist circles that "radio receivers do not grow in trees" which is a punchy way of pointing out the difference between man-made and natural objects. But then, again every engineered object is non-natural, including the "ordinary" plastic, teflon and steel. And if such materials fit into the class of metamaterials, this probably would be a too loose and inclusive definition, in the opinion of most researchers in the field.

One might also explicate the concept of material property or response functions, which appear in several of the cited definitions. These mean that the essence of the materials are given by certain material parameters, in other words numbers. Of course these numbers can vary depending on (be functions of) several external variables, like temperature, pressure, operating frequency, etc. But anyway the (meta)materials get their meaning through these properties. The complexity of the structure in the microscopic detail is condensed into the effective response functions, and an enormous number of degrees of freedom are bypassed. In the scope of the present paper the response functions are electromagnetic parameters. These are defined through constitutive relations, familiar from any textbook on electromagnetic field theory [8].

In the definitions cited above, also other important aspects than the novelty of properties play a role. Two of these are the scale (physical dimensions) and periodicity (the order of the structure). And here, with respect to both aspects, differing notions are in use for metamaterials. Since often metamaterials are composed of discrete "molecules," man-made scatterers, that are very strongly reacting and therefore dominantly responsible for the macroscopic behavior, the global response is a sensitive function of the size of these scatterers and their neighboring distances.

The concept of material gives an idea of homogeneity. That means that the size of the molecule needs to be small with the sensing capacity of the field that reacts with it. The wavelength has to be sufficiently large. But the wavelength also needs to be large compared with the average distance between the molecule. The requirements often stand for the medium to be "homogeneous," which from certain viewpoints is tantamount to the prerequisites for the material to be called as "material." Indeed, this condition (wavelength overtakes the scatterer neighboring distance) is sometimes taken as *sine qua non* requirement for metamaterials [9]:

> Metamaterials are artificial periodic structures with lattice constants that are much smaller than the wavelength of the incident radiation.

From other viewpoints, this definition looks quite loose: for example, nothing is demanded in terms of emergent properties.

The other parameter, ordering, is another aspect that appears in some definitions and is absent in others. Has a metamaterial to be a lattice in terms of its microstructure? Some characterizations do indeed require this, for example [10]:

> ... periodic metallic structures have the ability to simulate homogeneous materials whose specific properties eventually do not exist for natural materials.

Certainly engineers like structures and designs that follow some type of order. Therefore the emphasis on periodicity in the definitions is perhaps a "side effect." But is it essential? It may well be that also a random placement of complex scatterer would be enough to produce emergent properties in the global response and therefore give us a sample of metamaterial.

3. Other advanced materials in the metamaterials paradigm

In the history of electrical engineering, and engineering in general, there have been periods when researchers and research groups have been coherently aiming at some common goals. In materials studies, some examples of such projects have been the searches for structural materials, smart materials, or functional materials. All these type of materials resemble in some sense metamaterials and the terms are probably being mixed, especially when researchers swear into the metamaterials paradigm after work in other fields or interdisciplinary studies. However, some observations about the use of the terms can be made.

The term *structural materials* is common in the field of construction materials and there the emphasis is naturally on strength and mechanical properties. By clever combination of existing materials it is possible to achieve great improvements in various mechanical properties. And indeed the term *composite* has been borrowed into other fields of engineering, like for example microwave technology where composite materials can be tailored to display desired permittivity and anisotropy values.

Structural materials often are "static" in the sense that even if they may display superior properties compared with homogeneous materials, these properties cannot be controlled. In contrast, *smart materials* are such for which one or more properties can be significantly altered in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH-value, electric or magnetic fields. The mechanism of the control can be any cross-effect, like for example piezoelectricity or magneto-rheostatic viscosity change. The term "smart materials" has been in solid use much earlier than "metamaterials," for example the first volume of *Journal of Smart Materials and Structures* came out in 1992. It is interesting to note that the metamaterials definition by *Metamorphose* network [4] embraces smart materials ("*... new properties emerge [...] due to external electrical control*).

With the term *functional materials* the emphasis is shifted from the internal description of the material to the application. Materials are designed through technological processes in order to fulfill a certain function. This term is common in connection with semiconductors, polymers, pigments, solvents, ceramics, and other materials that are dealt with in nanotechnology.

4. Classes of special materials

The variety of heterogeneous materials, both natural and man-made, is enormous. This section mentions some classes of heterogeneous materials which could be considered metamaterials.

4.1. Artificial dielectrics

In 1940s Winston E. Kock suggested to make a dielectric lens lighter by replacing the refractive material by a mixture of metal spheres in a matrix [11,12]. Kock built lenses by spraying conducting paint on polystyrene foam and cellophane sheets. He was probably the one to coin the term *artificial dielectric* which has been later established into the microwave literatures [13,14]. Other contributors in this early wave of tailored dielectrics were Seymour Cohn, John Brown, and Walter Rotman.

Calling such artificial dielectrics metamaterials makes sense because the conducting properties of metals are being changed to a dielectric-type behavior in the macroscopic picture. Similarly also the rodded medium by Rotman [15] is mimicking free-electron plasma and therefore drastically transforming the behavior of the component materials. Such rodded medium anticipated the wire medium which is presently of interest [16].

4.2. Artificial magnetics

Perhaps even more adequate is to classify artificial magnetics within the group of metamaterials. There a truly new property emerges in the composite: magnetic response, even if the component materials are nonmagnetic. Since the circulating current has a magnetic moment, magnetic response can be generated by arranging conducting loops within a host matrix. And this may also take place even without conductors. Dielectric inhomogeneities, if they generate looping paths for the displacement current to flow, can create a (weak) diamagnetic effect.

Artificial magnetics have also a long history (see, for example the article [17]) but only recent years have seen really strong artificial magnetic effects. Such effects have been possible owing to strongly reacting element designs, like Swiss rolls and split-ring resonators.

4.3. Chiral materials

Chiral media provide another clear example of metamaterial with emergent properties. Chiral media consist of handed elements or handed microstructure [18]. In chiral media, the special geometrical character of the internal structure (antisymmetry or nonsymmetry with respect to mirror reflection) creates macroscopic effects that are observed as the rotation of the polarization of the propagating field plane ("optical rotatory power"). This "emergent" rotatory power is due to the magnetoelectric coupling caused by the chiral elements. On the level of constitutive relations that characterize such chiral medium, it is necessary to include crosscoupling terms between the electric and magnetic field excitations and polarization responses.

A man-made chiral sample could be a collection of metal helices, randomly oriented in a neutral polymer matrix. But it is important that all the helices have the same handedness. Only then is there macroscopic rotatory power. If fact, if such kind of material were constructed otherwise the same but half of the helices were mirrored (so that there were equal amounts of both handedness; this is the so-called *racemic mixture*), the situation would be different. All other properties of the macroscopic continuum would be exactly the same but the rotatory power would disappear!

4.4. Anisotropy and bianisotropy

Artificial anisotropy can also be seen as a "metamaterialistic," emergent concept. Mixing two fully isotropic dielectric components with each other the effective medium can be anisotropic if one of the components is shaped as nonsymmetric elements, like needles, and all these needles are aligned. Then obviously the macroscopic response is different for cases of exciting field direction being along the needles and perpendicular to them.

A further generalization is bianisotropy which is a quite useful concept to analyze electromagnetic response of complex materials. If a medium is bianisotropic, it can display both anisotropy and magnetoelectric behavior. (Chirality with its crosscoupling is one example of the latter [8,19]. For randomly mixed helices the macroscopic medium is bi-isotropic but if the helices are aligned, obviously the response is dependent on the vector direction of the exciting field and the continuum is bianisotropic.)

The constitutive relations in bianisotropic media require a matrix to relate the electric (**E**) and magnetic (**H**) fields and electric (**D**) and magnetic (**B**) flux densities:

$$\begin{pmatrix} \mathbf{D} \\ \mathbf{B} \end{pmatrix} = \begin{pmatrix} \bar{\bar{\epsilon}} & \bar{\bar{\xi}} \\ \bar{\bar{\zeta}} & \bar{\bar{\mu}} \end{pmatrix} \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} \quad (1)$$

where also the permittivity, permeability and the magnetoelectric coefficients are dyadics $\bar{\bar{\epsilon}}$, $\bar{\bar{\mu}}$, $\bar{\bar{\xi}}$, $\bar{\bar{\zeta}}$, and contain nine-component parameters each. Table 1 shows the dimensions of the parameter space in the different classes. A more detailed classification of the bianisotropic materials in terms of reciprocity and some other properties can be found in articles [20,21].

4.5. Veselago media

Veselago medium is probably the most famous class of metamaterials in the present wave in complex media electromagnetics. In his study of 1960's [22], Viktor G. Veselago discussed the peculiar behavior of electromagnetic waves in connection with materials that have simultaneously negative permittivity and

Table 1
Magnetoelectric materials and the number of free material parameters in their full characterisation

	Direction independence	Direction dependence
No magnetoelectric coupling	2 (ϵ, μ) (isotropic)	18 ($\bar{\bar{\epsilon}}$, $\bar{\bar{\mu}}$) (anisotropic)
Magnetoelectric coupling	4 (ϵ, μ, ξ, ζ) (bi-isotropic)	36 ($\bar{\bar{\epsilon}}$, $\bar{\bar{\mu}}$, $\bar{\bar{\xi}}$, $\bar{\bar{\zeta}}$) (bianisotropic)

negative permeability. These phenomena (anomalous refraction, reversed Doppler shift, inverse Cherenkov radiation, etc.) were unexpected. Now, after 40 years, ways have been invented to create resonating structures which, when embedded in a support matrix, make the macroscopic response negative in both the electric and magnetic material parameter, although only within a narrow band.

Veselago medium has been called by many names: negative-index media, negative-refraction media, backward wave media, double-negative media, media with simultaneously negative permittivity and permeability, negative phase-velocity media, and even left-handed media (LHM). This last label, left-handed medium, is very unfortunate because there is nothing left-handed (or handed in general) is Veselago medium. Chiral media can be left handed (if it contains an excess amount of left-handed helices), and the irony in the use of the label LHM for Veselago media is that helices can also be used as resonating structures to cause negative electric and magnetic polarizability. But then both left-handed and right-handed helices do the job, and even a racemic combination of them!

An illustrative classification of isotropic materials is the four-field that comes from the combinations of positive and negative values for the permittivity and permeability of the material [23]. Veselago medium is doubly negative (DNG), “ordinary materials” are doubly positive (DPS), and the two remaining “plasmonic media” cannot support propagation of electromagnetic waves. The four-field is shown in Fig. 1.

4.6. Extreme-parameter media

Another interesting classification of media that display special electromagnetic properties is to look whether the material parameters μ and ϵ are very large or very small.

A plane wave propagating in homogeneous dielectric–magnetic medium can be analyzed also with the wave impedance $\eta = \sqrt{\mu/\epsilon}$ and the refractive index $n = \sqrt{\mu\epsilon}$ (assuming the permittivity and permeability relative to the free-space values). Let us only now consider isotropic and positive-valued (DPS) media.

The useful idealized concept in electromagnetics, the perfect electric conductor (PEC) corresponds to $\epsilon \to \infty$, $\mu \to 0$, and the perfect magnetic conductor (PMC) to $\epsilon \to 0$, $\mu \to \infty$. Therefore PEC has an extremely small impedance (“zero-impedance medium”) and PMC extremely large impedance (“infinite-impedance medium”). On the other hand, nothing can be said about the magnitude of the refractive index.

But other combinations of either very large or very small values for the four parameters ϵ, μ, η, n are also possible, which gives the reason to draw the classification of Fig. 2. Materials with such extreme parameter amplitude have been recently suggested to have potential for interesting applications, like increasing the directivity of planar antennas, cloaking objects, and squeezing electromagnetic and optical energy [10,24]. Often also other abbreviations are used for materials with very large or very small permittivities [25,26]: EVL (epsilon-very-large) for IEM, and ENZ (epsilon-near-zero) for ZEM.

4.7. PEMC medium

Another recently introduced material that has extremely strange macroscopic response functions is the perfect electromagnetic conductor (PEMC) material [27]. PEMC is a generalization of PEC and PMC

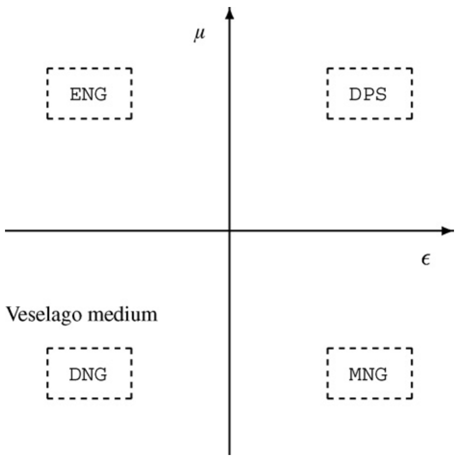

Fig. 1. The classification of the materials in the $\epsilon\mu$-plane in terms of the sign of the permittivity and permeability [23].

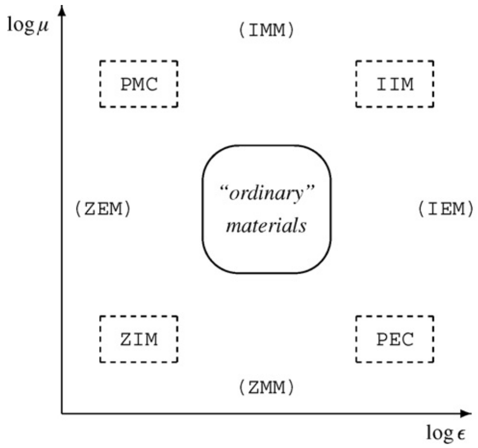

Fig. 2. The classification of the extreme-magnitude materials in the $\epsilon\mu$-plane. The abbreviations are PEC: perfect electric conductor; PMC: perfect magnetic conductor; ZIM: zero-index material; IIM: infinite-index material; ZEM: zero-electric material; IEM: infinite-electric material; ZMM: zero-magnetic material; IMM: infinite-magnetic material.

materials, obeying the following unfamiliar constitutive relations between the electric and magnetic fields and flux densities:

$$\mathbf{D} = M\mathbf{B}, \qquad \mathbf{H} = -M\mathbf{E} \tag{2}$$

Here M is a real scalar admittance-type quantity. The special cases of PEC and PMC come with the choices $1/M = 0$ and $M = 0$, respectively.

The constitutive relation (2) can be written in a form where flux densities are given as functions of fields. However, then the relations read

$$\begin{pmatrix} \mathbf{D} \\ \mathbf{B} \end{pmatrix} = q \begin{pmatrix} M & 1 \\ 1 & \frac{1}{M} \end{pmatrix} \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} \quad \text{with } q \to \infty \tag{3}$$

and the response functions look quite strange, like one might expect in connection with metamaterials. Firstly, the response is bi-isotropic, in other words there is magnetoelectric coupling. It is also non-reciprocal. And finally, all four parameters grow to infinity! One has to note that the limiting behavior of the parameters is very well defined, as their ratios keep all the time the same.

Despite the inconvenient appearance of relations (3), PEMC medium is very fundamental and simple medium. It is the only fully isotropic medium regardless the movement of the observer (it is known that a moving isotropic medium becomes anisotropic in the rest frame of Ref. [8, p. 914]). PEMC medium has been shown to cause many interesting effect on waves [28] which may find applications in antenna engineering.

Of course, again the response functions of PEMC are such that those have to be effectively created by artificial structures. One possible realization of PEMC using resonating layer of ferrite rods has been given in Ref. [29].

4.8. Waveguiding medium

Some materials react to external fields mostly by their surface. PEC, PMC, and PEMC are examples of such materials. But there are other such media, too, and these can be characterized by their surface impedance. An advantage in the surface impedance is that solving electromagnetic field problems becomes much easier since the solution domain can be bounded by this surface and there is no need to find the fields on the "other side."

It turns out that one can make use of the surface impedance concept also within a class of media that are penetrable (in other words fields exist in these media). These are the so-called waveguiding media [30]. The condition for the material to be "waveguiding" is that it should be anisotropic in such a way that both its permittivity and permeability in the direction perpendicular to the surface are very large (in principle infinite, in which case it serves as an ideal waveguiding medium).

4.9. Electromagnetic crystals

In electromagnetic materials research electromagnetic crystals take a special place. These are also known by many other names: photonic crystals, electromagnetic band gap structures (EBG), photonic bandgap structures (PBG). Many researchers are of the opinion that the great umbrella of metamaterials also covers electromagnetic crystals.

Electromagnetic crystals are periodical structures, composed of dielectric or metallic regular lattices with a given unit cell. Their function is to affect the propagation of electromagnetic waves. The design mimics, on a much larger scale, semiconductor crystals for which allowed and forbidden electronic energy bands are determined by the periodic potential function.

Electromagnetic crystals are certainly displaying properties that are qualitatively different from those of their building blocks. They can be transparent or reflecting depending on the wavelength of the radiation. In that sense the "emergent" requirement (in other words the fact that the structure has qualitatively different properties than the simple components of which it is built) is met. The appearance or color of the object like electromagnetic crystal is "structural." Admittedly such coloration is very natural and well known in the world of ordinary crystals but nevertheless it is created by geometry. Hence also "natural" materials may display metamaterial-type properties.

A more problematic point concerning the potential characterization of electromagnetic crystals as metamaterials is that something called "metamaterial" should also be *material*-like. Due to the fact that an electromagnetic crystal has element spacing which is of the order of a wavelength or larger, its response depends on many more wave parameters than that of "ordinary metamaterial" for which the lattice constant is much smaller than wavelength.

Electromagnetic crystals are spatially dispersive: their response depends on the direction and magnitude of the wave vector and they scatter waves in a more complicated manner than a planar surface of homogeneous material. This makes a fundamental difference compared to materials that have inhomogeneity scales much less than the wavelength, for which the effective-medium description is much easier. It is true, however, that media also exist which are spatially dispersive also in the low-frequency limit, e.g., certain wire-structured materials [31].

5. Ordinary materials

After listing and discussing many classes of media that may qualify for metamaterials one might ask what type of media are then "ordinary materials." When a sample of material is looked more closely its microstructure becomes visible. In the structure we find constituent materials. If a metamaterial should have properties that are qualitatively different from those of the constituents, perhaps into the other extreme of material classification we could put "dull materials" for which the macroscopic material parameters are plain averages of the corresponding parameters of the components. But do such dull materials exist?

In engineering the focus is much on such material designs for which the microstructure is regular and lattice-like, as the arrangement of molecules according to solid-state physics. However, materials may be also amorphous and isotropic, and natural materials on the macroscopic level indeed are quite often more of such random-structure type. The microgeometry plays a strong role in determining the macroscopic response. Mixing rules are tools for analyzing such heterogeneities [32].

The message from the study of ordinary mixtures is quite remarkable. Even if such random mixtures have not been designed in any metamaterialistic fashion to optimize strong response parameters, still very interesting phenomena take place. Take, for example the effective permittivity of a mixture that is, even according to the simplest mixing rule, the so-called Maxwell Garnett mixing formula [33], a nonlinear function of the component permittivities. This effective permittivity can behave in ways that can well be said to be emergent from the mixing process.

For example, the geometrical microstructure of the mixture is very critical when it comes to the frequency dispersion of the permittivity. Even simple materials are (temporally) dispersive, in other words, the strength of their polarization response varies with the frequency of the exciting field. But if components of a certain dispersive behavior are mixed (or even if a dispersive material is put in particulate form into dispersionless vacuum) the mixture as a whole displays a different dispersive character. For example, rain or fog (simple spherical droplets of water in air) may have a strong imaginary part of the permittivity at millimeter waves even if the interesting region of the Debye dispersion of bulk water takes place at microwave frequencies.

The phenomenon of percolation is another example of the fact that even in disordered media, the mixture can display very dramatic macrosopic behavior. At percolation threshold, it may happen that new paths are opened for fluxes in the material and the field patterns change drastically both locally and globally. The consequence of percolation is a sensitive and strong change in a macroscopic parameter (for example, electric permittivity) for a small change in a structural parameter like fractional volume of a constituent.

It would be tempting to say that dull materials do not exist. Perhaps even true. The macroscopic material parameters are determined not only by the lower-level media composing the mixture but to a large extent the geometrical patterns of the microstructure. Very often geometry has more weight in this balance of the effective-medium description. It is very true what Johannes Kepler said: "Ubi materia, ibi geometria" [34].

6. More is different?

"Taxonomy (the science of classification) is often undervalued as a glorified form of filing—with each species in its folder, like a stamp in its prescribed place in an album; but taxonomy is a fundamental and dynamic science, dedicated to exploring the causes of relationships and similarities among organisms. Classifications are theories about the basis of natural order, not dull catalogues compiled only to avoid chaos," declares the paleontologist Stephen Jay Gould in *Wonderful Life* [35, p. 98]. Well, cultivating this science of taxonomy is not easy, at least in our case of trying to classify materials. A taxonomy of all metamaterials would have been a challenge to Gould, and even to Carolus Linnaeus.

The definitions for metamaterials are sometimes too restrictive and problematic as was shown in Section 2. But then, in cases when a definition is more inclusive, it is contradictory or at least inconsistent with other metamaterials characterizations. On the other hand, our search for materials from the other extreme, dull materials, was no success story either. Why is it so difficult to find non-ambiguous language?

One of the difficulties arises from the dualistic approach of distinguishing qualitatively the materials properties of the ingredients from those of the whole mixture. The emerging qualities in the metamaterial are supposed to be different from those of the building blocks. There is no "direct inheritance" (cf. metamaterial definition [3]) like in a family between parents and children. But one analogy holds. Parents are also children to someone. So also those constituent materials that are used in the metamaterials designs are built up of lower-level components. Then we should say that they have emergent properties themselves. And below that another layer is found of different quality. A logical conclusion is a hierarchy of material classes: all materials belong to a certain class and the classes are mutually exclusive.

A definition for metamaterials that emphasizes such emergence is faced with the problem of incompatibility of material objects. If all material samples belong to a certain level in the hierarchy of metamaterials with always higher and higher-level qualities, then making mixtures and adding up materials is not as easy as one could think. We must first check that combining objects is possible. In other words, the requirement is that the materials come from the same class of media in this hierarchy!

Common sense requires that all materials should live in the same world, at least to such an extent that they can be compared against each other. The view of hierarchical levels of materials with classes above each other is problematic due to the different and inconsistent qualities of the objects from different levels. And in the extreme, such emergist hierarchy leads to absurdities. But on the other hand, the idea of new qualities in composites due to interaction and geometrical subtleties is appealing and certainly has a kernel of truth in it.

The reductionistic approach in physics says that higher level phenomena are totally explainable by "deeper" disciplines. For example, chemistry reduces to physics, and all chemical phenomena can be predicted from principles of quantum physics. Chemistry is in a way a subset of physics. We lose much when going to a higher level. More is *less*. The metamaterialist idea seems opposite. The whole is *more* than sum of the parts.

But at least both viewpoint agree that *more* is *different*.

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