Contemporary notes on metamaterials

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Abstract: The essence of the metamaterial concept from the structural point of view. Particular attention is paid to the macroscopic description of metamaterials and to the corresponding requirements and precautions for using that concept. General advantages of metamaterials are also pointed out. Next, the main research directions related to metamaterials are briefly overviewed and the key references are provided. Finally, the most probable sources of disagreement and misunderstanding within the field are summarised.

1 Introduction

One of the remarkable aspects of the human civilisational development is the intention to create or construct something that is not available in natural surroundings. Initially, people attempted to merely rearrange the objects around them. Then, they started to modify their shape or structure, to split them into parts, to combine different ones and so on – in other words, to exploit natural materials. A number of sophisticated procedures were developed in order to extract useful substances from natural sources. Yet the demands of progress were insatiable. Then synthesis emerged, and techniques of ever-growing complexity appear continuously, up to manipulations at the molecular level and even the arranging of separate atoms.

From the hierarchical point of view, the main stream of technological activity has so far led towards affecting matter on the deep structural level. The more we manipulate it, the greater we can change properties, gaining a great variety of new and unusual materials, and we must admit that the tremendous success that has accompanied this track. However, there is an obvious dead-end to be recognised: there is no way to step further than playing with atoms. Whatever we can do with atoms as such, they are all known and all the same, listed in the Periodic Table (if we do not account for a slow flow of synthesised heavy elements, which are unstable and technologically useless, and do not offer any qualitatively new properties to the field of our consideration). Therefore we have to find a way beyond the basic branch of the general structural hierarchy. And this is what is implied in the concept of metamaterials, which opens the next era in search for novel material properties.

2 Definitions and prerequisites

Metamaterial is an arrangement of artificial structural elements designed to achieve advantageous and unusual properties. Even such a flexible definition is incomplete but too strict. Indeed, it is not obvious how to define material precisely as well. It is much easier to draw an analogy. Metamaterial is composed of its elements in the same sense as matter consists of atoms. But, these structural elements are made of conventional materials, that is of normal atoms. Accordingly, metamaterial represents the next level of structural organisation and thus has its name. We should note that, originally, the term metamaterial implied ‘artificial material showing properties that are not available in nature’. Such a purely phenomenological definition, however, is more ambiguous and less functional than the organisational one. A detailed consideration of the terminology was presented by Sihvola [1] (discussed in Section 4).

The metamaterial concept is illustrated in Fig. 1. It shows schematically several examples of artificial ‘atoms’, and a material, which can be formed on a larger scale using such elements.

In most cases, metamaterial implies an important particular case: periodic lattice of identical elements (or sets of elements), and this is an analogue for crystal. Random or irregular arrangements, being rarely under consideration, correspond to amorphous substances. Certainly, mentioned analogy is not absolutely complete, but distinctions are not relevant here and can be clarified upon a more detailed insight into metamaterial properties.

Almost the whole range of phenomena, where we speak of material, is encompassed by electromagnetic interaction. Accordingly, technology deals mostly with the electromagnetic properties of materials. It is well known in the solid state physics that these are determined by the nature of constituting atoms as well as by their arrangement, so that the whole material represents something completely different compared to a single atom. Moreover, a good deal of features are only defined for the whole system, but not for the components.

For metamaterials, it is normally implied that we are interested in their response to electromagnetic fields. In contrary to the conventional materials, here, a response of the individual elements is also directly observable, and this simplicity hides a trap, which we will discuss in more detail subsequently. It is important to recognise how different, logically and phenomenologically, these responses are.

Basically, electromagnetic response implies merely how does the material affect the electric and magnetic fields to which it is subjected. Although the whole pattern of this influence is generally rather complicated, with the two responses being mutually dependent, delayed in time, spatially inhomogeneous, nonlinear with respect to field strength, the main effect of most of the materials can be

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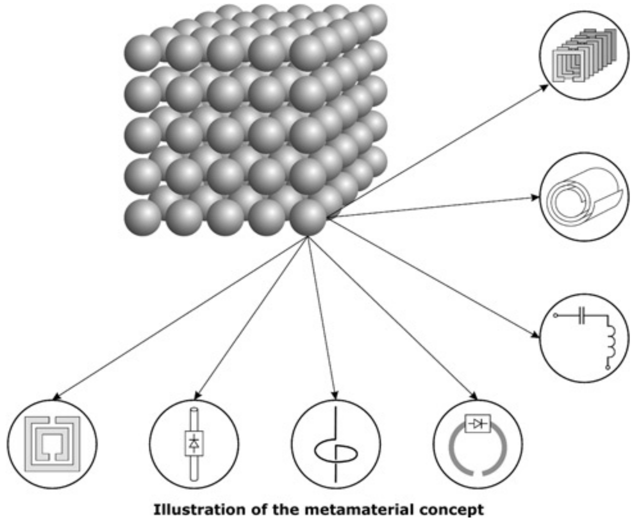

Fig. 1 *Illustration of the metamaterial concept*

reduced to linear modulation of the incident fields and can be described with corresponding material parameters: (electric) permittivity and (magnetic) permeability. It is noteworthy that metamaterials offer even more sophisticated relationships between the mentioned parameters, as well as more pronounced nonlinear features.

Obviously, material parameters depend on the scale they are considered on. When studying characteristics of matter with respect to electromagnetic fields, the scaling is related to the wavelength of the electromagnetic radiation. If the wavelength is much larger than the atomic dimensions and interatomic distances, then the atomic behaviour has collective nature and material parameters can be introduced, substituting a huge number of separate element contributions with an effective medium response. Strictly saying, this is the only case where we are entitled to speak of 'material'. For the corresponding set of problems, metamaterials are quite analogous to the normal ones and the same methods of analysis, well known from the solid state theory, are fully applicable.

When the wavelength is comparable with the scale of structure details, complex diffraction and scattering phenomena take place, which have to be analysed locally, on the level of individual elements. There is no reason, and no unambiguous way, to establish material parameters. Accordingly, in this range, metamaterials can be hardly treated as media, and for most problems no direct analogy to atomic lattices can be drawn.

Finally, for waves with the length much shorter than the element size, the only characteristic of material that retains sense is the nature and density of the nuclei, with which electromagnetic quanta interact in a completely independent way. In the corresponding range, the very concept of metamaterial loses its meaning, and no analogy remains. Indeed, scaling deeper into normal materials, we encounter the fundamental level of matter structure, which cannot be further detailed, whereas with metamaterials we just fall into the structure of the normal materials of which they are assembled. For such waves – the waves, too short for a given metamaterial – the details of structure or material parameters of the separate components become relevant, whereas meta-arrangement on a bigger scale does not play any role.

Now that we agreed on the proper scale for considering metamaterials, let us mention another prerequisite for using this notion. When we speak of a 'material', we imply that there are a number of atoms involved. It becomes even more clear, when we think of compounds made of different atoms – obviously, certain pattern of their arrangement (referred to as a 'unit cell') has to be repeated many times in order to constitute a definite material. To say more precisely, how many, we shall recall the following: with respect to electromagnetic response, 'material' means that, instead of digging into various microscopic atomic events, we take their averaged response, relying on macroscopic material parameters, as discussed earlier. For such a macroscopic averaging to be consistent, at least several structural units have to be involved in each dimension, resulting in hundreds of unit cells to be taken into account. This is well known in solid state physics and has been also explicitly shown for metamaterials.

3 Advantages of metamaterials

So far, we have seen much analogy between metamaterials and normal materials, being valid provided that the discussed requirements are kept. Stepping outside this analogy, however, provides more advantages than restrictions.

The most straightforward one is that the structural units are artificial and can be designed for specific purposes. Accordingly, instead of the fixed set of the elements from the Periodic Table, one can use any 'atom', which imagination and technology allow for. Thus the properties of metamaterial can be directly set up starting from the basic level. These artificial 'atoms' may have a complicated internal structure, including, for instance, electronic circuits with independent power sources or even programmable microcomputers that calculate the desired response to the incident field. This general concept is illustrated in Fig. 2. In this example, effective electric response is provided by a multitude of short dipole antennas with electrically small and shielded loads. Similarly, effective magnetic response is built up by a series of small loaded loop antennas. Then, the material response can be synthesised by designing appropriate circuits in the loads. To appreciate the power of this approach, it is important to note that the auxiliary processes inside the loads are shielded from the electromagnetic fields in the artificial material – the small antenna terminals act like gates into a 'higher-dimensional' space.

Next, arranging structural elements is incomparably easier in metamaterials. Surely, there are ingenious techniques for manipulations with molecules, influencing

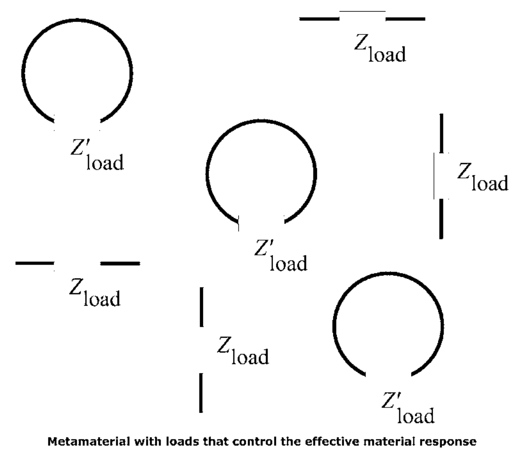

Fig. 2 *Metamaterial with loads that control the effective material response*

crystal composition and symmetry, assembling atomic layers and so on, but all this is quite expensive and complicated. In contrast, metamaterials can be constructed according to one's taste from the very beginning, so that one can marshal the chosen units in a desired way.

Through these features, it is not only possible to build up initially a metamaterial with required properties, but also to adjust and control them during the operation using convenient mechanisms, intrinsic to the structure.

Another side of these advantages is that the analysis of metamaterial behaviour is much easier and more precise, than that of normal materials. Indeed, one can start from the exact characteristics of a single structural unit and continue, using the known mutual distribution, to the macroscopic averaging, calculating the effective response of the whole structure completely within the classical electrodynamics. In contrast, for conventional materials, it is normally extremely complicated to perform such a calculation directly, and quantum physics has to be involved.

Let us see, however, what kinds of practical benefits can be built up relying on the structural features mentioned earlier. It is clear that metamaterials opened a way for producing various artificial electric and magnetic materials possessing unusual properties, designed specially for certain applications. Moreover, they offer a straightforward possibility to combine such unusual properties, arriving at phenomena which were never found in nature. The most striking example is negative refraction, observed in materials with the permittivity and permeability being negative in the same frequency range. Another interesting direction is related to bi-anisotropic materials, having mutually dependent electric and magnetic responses, so that magnetic field causes electric polarisation and vice versa. Also, nonlinear effects can be made rather strong in metamaterials, as compared, for example with nonlinearity in optics. An additional option here is that electric and magnetic sources of nonlinearity can be employed simultaneously.

There is no doubt that numerous attractive possibilities still await consideration and will offer plenty of valuable effects and applications.

4 Terminological discussion

As we have already mentioned, it is quite popular to define metamaterial as an artificial material having properties beyond those of natural materials. Although such an approach highlights nicely the most intriguing side of metamaterials, it lacks functionality and is less definitive. In reality, many authors interpret this in the sense of an object with unusual properties, and this leads to dramatic misunderstanding. It is evident, however, that not every object can be treated as a material. The latter term is much more demanding and can be used only when all the prerequisites discussed earlier are fulfilled. Accepting the structural definition, as we described in the previous sections, we apparently include more artificial materials than it would be commonly implied, for example artificial dielectrics, bi-isotropic and bi-anisotropic media and so on, but this is perfectly justified not only by obvious structural similarities, but also by the historical background of metamaterials.

To see further arguments, let us consider two structures, composed in a similar way out of slightly different elements, so that one of them shows negative refraction (in a certain frequency range), whereas the other does not. It would be hardly appropriate to refer the first one as metamaterial. On the other hand, many unusual properties are also found in photonic crystals, fullerenes and so forth; yet, these are to be analysed in a different way and normally are not called 'metamaterials'. Such an ambiguity, arising from the phenomenological definition, discourages its use, especially that a clear organisational description, based on the structural principle, is present.

The whole range of unusual properties can be perfectly indicated as the most straightforward purpose of metamaterials, the main direction where they are used, but the key principles of material organisation and essence should not be forgotten on this way.

Nonetheless, we admit that there are some good reasons behind many other approaches. An extensive discussion of the essence of metamaterials and an overview of the corresponding terminology is found in the work of Sihvola [1].

5 Historical background

In order to acquaint better with the contemporary research directions, it is worth casting a glance at the historical background of the concept of metamaterials.

The term emerged in 2000 in the works of Smith *et al.* [2] and Pendry [3], in immediate connection with the idea of negative refraction. Conceptually, at this instance, a long but not demanding search for materials with negative-refraction-index merged with the diverse activity in the field of artificial materials. By that time, both research directions had some history, giving only a few general highlights and representative examples rather than aiming for a thorough analysis, practically impossible within the whole width of the related topics.

Although negative refraction and negative group velocity were discussed already in 1945 by Mandelstam [4], an extensive theoretical analysis of media possessing negative permittivity and permeability was given by Veselago [5] in 1967, and at that time he pointed out that there are no known natural materials with the permittivity and permeability being both negative in the same frequency range. Although he suggested certain exotic solutions like gyrotropic plasmas, they still were not quite suitable due to many complications, and no clear experimental evidence was obtained in this direction. Furthermore, it is very likely that there is no way to obtain negative permeability at optical or higher frequencies [6], although there is no common agreement at this issue. In contrary, it is well known that negative permittivity is readily exhibited by many metals in optical and ultra-violet range, whereas at lower frequencies energy dissipation normally dominates. On the other hand, antiferromagnetic resonances, providing anisotropic negative permeability, occur up to terahertz range, but corresponding materials do not possess electric properties that would be suitable for Veselago medium [7]. After all, the quest for negative refraction was not of remarkable relevance for more than 30 years and, definitely was not recognised as a promising and encouraging one.

At the same time, and, in fact, since more than a century [8], there had been considerable interest in various artificial materials which affect wave propagation and show unusual electromagnetic properties. Starting from the works of Lindman [9], research on chiral substances spread into important areas of bi-isotropic and bi-anisotropic materials (see the books of Lindell *et al.* [10] and Serdyukov *et al.* [11] for reviews). A number of methods and approaches, developed in these areas, are readily transferred now into metamaterial research.

Without going into details of wide variety of suggested structures, we can mention some examples of the structural elements, related to those used in metamaterials. Most of the attention was always received by electric effects in the artificial structures, with even nonlinear effects taken into consideration [12]. Magnetic properties of materials based on non-magnetic elements are also studied for more than half a century [13]. In order to develop more efficient artificial magnetic materials, various ring elements (reviewed in the work of Kostin and Shevchenko [14]) and spiral structures were investigated, up to an experimental demonstration of artificial negative permeability at microwave frequencies [15]. Finally, the idea of ring currents was revisited [16], having led to several types of resonant structural elements now being employed by metamaterials. By that time, there was already a way known to achieve negative permittivity at lower frequencies [17, 18] (also in the work of Pendry *et al.* [19]), and then, with a combination of the two structures, negative refraction of microwaves was reported [20].

6 Research directions

Obviously, such a diverse and wide background ensured that a great number of research groups turned their attention to a novel promising direction. Naturally, most of them view the new field from the positions of their previous experience and through the methodology developed earlier. This results in numerous approaches and many different areas of particular interest. With no aim to review thoroughly the stream of research activity, we shall try here to give a brief (and, certainly, incomplete) classification for the most general part of it. We can provide here only a limited number of illustrative references, while there exist hundreds of papers within each of the directions mentioned subsequently; where possible, we refer to appropriate reviews.

6.1 Basic theory

Basic theory is of utmost importance for any scientific issue, especially for a new one. General theoretical consideration of metamaterials splits into two main branches: (i) abstract medium consideration, when certain general properties are analysed regardless of particular implementation [21–24], or for example in a point dipole approximation [25]; and (ii) metamacroscopic theory, which deals with deriving effective parameters from the analysis of the medium on the level of structural details. In that latter issue, separate subsystems of elements, typical for metamaterial design, were investigated.

In particular, wire media were described, starting from the quasi-static approximation [26] up to rigorous analysis accounting for spatial dispersion for one-dimensional (1D) [27] and two-dimensional (2D) [28] arrangements. The differences arising in wire media with periodic loads were discussed [29]. For resonant conductive elements, important for magnetic metamaterials, macroscopic averaging was rigorously applied in the quasi-static limit [30].

Among more exotic structures, we can mention metasolenoids [31] and spiral media [32]. Recently, various kinds of metamaterials based on spherical metallic particles were also studied [33, 34].

When different substructures, responsible for specific electric and magnetic responses, are combined into one medium, the resulting effective parameters, in general, cannot be calculated as a superposition of the properties of the subsystems. This problem was discussed by several authors [27,35–37]. A method to calculate energy density in lossy and dispersive metamaterials was suggested [38].

An important issue relates to the fact, that any practical implementation of metamaterials would cause unavoidable inhomogeneity of the internal structure, influencing macroscopic properties. For 1D structures, effect of disorder was modelled earlier [39], and for 3D magnetic metamaterials this question was recently considered [40] (after earlier experimental studies [41, 42]).

6.2 Properties of the Individual Elements

Properties of the individual elements are then at next importance, constituting a kind of metamicroscopic characteristics of metamaterial. Much work has been done referring to split-ring resonators, including general theoretical investigation and circuit modelling [43–45]. Apart from this, in analytical modelling most researchers rely on simple LC-circuit schemes. Numerical simulations and experimental evaluation of the element properties were also performed, typically in connection with design of metamaterials [45–49].

Here, we can also mention diverse activity related to the discussion of alternative structural elements and their implementation [50–56].

6.3 Nonlinear Phenomena

Nonlinear phenomena in metamaterials represent the next step in the analogy with crystals in optics, whose nonlinear properties are well known and give rise to a number of valuable applications. Research in this direction was initiated in 2003, when a possibility to provide nonlinearity to metamaterial response on the level of structural elements was analysed [57]. Another approach [58] developed the idea of local nonlinear phenomena enhancement in metamaterials [16]. This direction attracted the attention of many other research groups [59–64]. It was shown [65] that exceptionally high nonlinearity (as compared to what is typical for optics) can be readily achieved in bulk metamaterials, and many particular effects were discussed, including band-gap tuning [66], three-wave coupling [65], surface waves and solitons [67], second harmonic generation [68, 69], microwave phase conjugation [70] and focusing [71]. Certain nonlinear effects were also modelled using transmission-line (TL) approach [72, 73].

6.4 Scaling Down

Scaling down of the operational range of metamaterials is one of the most attractive directions from the practical point of view, since the unusual metamaterial properties would be exceptionally useful in optics. It is known that natural materials do not exhibit remarkable magnetic response at optical and higher frequencies, as we have mentioned earlier, and that there is certain argumentation that it is not possible in principle. Although the question of the high-frequency limits of the metamaterials remains open, continuous efforts are made to reduce the scale of metastructures [74,75] and to look for other concepts of metamaterial organisation [76–80]. Experiments in the terahertz range are reported [81–83] and attempts to break into infrared optics are being made [76, 84–87]. Many authors admit that the limits for moving the scale down are nearly reached [88, 89].

6.5 Transmission-line (TL) Realisation

TL realisation of metamaterial concept is a popular direction and is widely employed in practice. With TL-structures, it is possible to model specific features of metamaterials on the phenomenological level. This approach was put forward in 2002 by three research groups [90–92], and further developed by these [93–97] and many others [98–101]. This direction is reviewed by Eleftheriades, Itoh and Caloz [102–104]. For a few years, only 1D and 2D arrangements have been considered, including also anisotropic systems [105–107]. Recently, different varieties of 3D design were reported [108–110] and experimentally supported [111].

6.6 'Perfect Lens'

'Perfect lens' and near-field imaging become the most attractive ideas concerning metamaterial applications. Initial idea by Pendry [3] received huge amount of criticism and corrections [112–117], but subwavelength focusing, although not that 'perfect', remains to be a fruitful concept. In practice, it is suggested to exploit 2D TL meshes [118–120] (see the work of Alù and Engheta [121] for a review concerning TL-modelling), interfaces of resonant particles in planar [122, 123] and cylindrical [124] configurations, layered films [125], planar surface structures [126, 127], or specifically loaded waveguides [128, 129]. Some practical limitations of the TL-focusing were highlighted [130]. Numerical [131] and experimental [132–134] attempts are also made to achieve focusing with 3D metamaterials. Other ways to imaging, employing channelling in wire or layered media, were also suggested [135–138]. Still other alternatives are to employ phase conjugating screens [139] or to use resonator modes in silver sphere chains [140].

Information related to this area is also found in a recent book on negative-refraction metamaterials [141].

6.7 Magnetoinductive Waves

Magnetoinductive waves represent another phenomenon, specific to metamaterials and interesting from the practical point of view. Theoretical study was started in 2002 [39, 42] and supported by experiments in different groups later on [143–145]. Waveguide components and potential applications are described in more detail in the work of Shamonina and Solymar [146]. Imaging possibility based on magnetoinductive principle was considered, with experiments using hexagonal 'swiss-roll' arrays [147] or split-ring interfaces [148, 149] being reported. Imaging with a single layer of elements in a hexagonal arrangement and boundary resonances were also studied [150]. Magnetoinductive waves in bi-periodic structures, with respect to two different sets of elements [151] or various arrangements of the same ones [152], were analysed recently. At present, implementation of magnetoinductive phenomena is mainly concerned with various arrays of metamaterial elements in 1D or 2D. See the work of Shamonina and solymar [153] for a review and that of Syms *et al.* [154] for an overview of magnetoinductive devices.

6.8 Chiral Metamaterials

Chiral metamaterials have been known, in fact, for a long time as artificial media with a mirror-asymmetric structure [10, 11]. Recently, it has been shown that these media can offer more design flexibility in realising backward-wave regime and negative refraction [155–158]. Chirality in metamaterials leads to certain exotic wave phenomena [155] and offers an enhancement of the negative-refraction frequency range [159].

6.9 Abstract Consideration

Abstract consideration started from the very beginning, while a good deal of questions concerning the realisation of metamaterials were still open, and some of them have not even arisen. It deals with properties and application of metamaterials in an abstract way, notwithstanding any particular details of their internal structure. This approach treats metamaterials as a ready substance with certain predefined properties, and focuses then on particular problems or various devices based on such a substance. These include for example considering particular problems [160] or geometries [161, 162], analysing the effect of metamaterial coverings [163] issues related to geometrical 'optics' of metamaterials [164, 165], and even radiation phenomena on the atomic level [166, 167]. Some prospects for applications are reviewed in the work of Engheta and Ziolkowski [168]. We must note that along with specific analysis relevant for future applications, sometimes a kind of 'idealistic' design is reported, which, while being rather encouraging and innovative, may walk out of the range, acceptable for metamaterial concept, and will not be realisable in practice.

6.10 Related Areas

Related areas received remarkable impact as metamaterials became fashionable, but this happened at most in the terminological form, so that photonic crystals and various nanostructures are mixed up with metamaterials [169, 170]. Indeed, the area of photonics has much in common with the present metamaterial research; yet, the scale and the methods of consideration have to be clearly distinguished.

On the other hand, a kind of interdisciplinary interaction occurs, which brings valuable outcome. For example, perfect electromagnetic conductors (PEMC) in connection with metamaterials were discussed [171, 172]. Certain theoretical issues, forgotten for ages, can be now revived with the help of metamaterial properties (e.g. Dyakonov surface waves were recently revisited [173]). Attempts to produce superconducting metamaterials were reported [174, 175]. Analogy with electromagnetic metamaterials went as far as to acoustics [176].

It is clear that metamaterials will have great and growing influence on science and technology, provided careful attention is paid to correctness and consistency of studies.

7 Tracks to disagreement

Not surprisingly, in metamaterial research, like in any new field of study, various confusions and misinterpretations cannot be avoided. In this section, we briefly overview the most general traps that we have observed in the recent literature. Discussing these issues in detail would probably require volumes of critique, so we would rather give merely a classification of the issues.

The most obvious confusions occur in terminology: misuse of the very word 'metamaterial' becomes, unfortunately, more and more common. In particular:

- It is often limited to media showing negative refraction. Despite this potential property being a valuable one and indeed sought by most of researchers, it should be clearly distinguished from the definition and essence of metamaterials.
- It is referred to just a few structural elements. Although several elements may be easily observed and tackled with, unlike atoms of normal media, this does not change the

concept of media at all. It is worth reminding that the number of units in a 3D medium should be of the order of 1000 (or, about 100 for a 2D analogue, or some 10 of them for a 1D realisation).

- A single layer of identical elements is often regarded as a surface of a medium, or even is itself called a 'metamaterial'. This can be, under certain precautions, acceptable for a purely 2D consideration, but not for 3D problems with such interfaces. These kinds of structures, perhaps, can be called 'metasurfaces'.
- TL meshes serve as an excellent representation of macroscopic metamaterials with respect to observable properties, and facilitate experiments considerably, but they should not be confused completely with media and certain care has to be exercised when drawing general conclusions on the basis of analogy.

Another area that hosts a number of discrepancies, relates to effective medium approach. We have discussed the corresponding requirements earlier, but it makes sense to give here a brief summary:

- When metamaterial response is evaluated relying on the properties of individual elements, mutual interaction of the elements is often neglected. This normally leads to significant errors in determining metamaterial parameters.
- In particular, a common approach is to regard the subarrays of two different types of structural units (e.g. split-ring resonators and straight wires) as if they would behave independently from each other, and moreover, would be solely responsible for either electric or magnetic response each. This is an approximation which is not always justified.
- Next, inappropriate frequency is sometimes used for simulations or measurements. Let us remind that for the macroscopic approach to be consistent, wavelength of the considered electromagnetic waves should be much larger than the scale of the structural details. Clearly, properties of metamaterials at higher frequencies can be interesting for a study, but this does not fit into metamaterial concept, and requires other methods of analysis.
- It is also quite common that insufficient number of structural elements is used in experiments and simulations, as it was mentioned earlier. Extraction of material parameters from such data is not justified, as the very idea of material fails there. The most severe cases may bring authors to physically meaningless conclusions.
- It should be evident that the fundamental laws of physics must not be violated, and whenever they contradict the conclusions, it is the conclusion that should be under question first, not the laws. Although electrodynamics of metamaterials indeed offer many unusual phenomena, it is all within, and understandable with, established electrodynamics.

This list is by far not complete, as there are too many particular issues and tiny details, but we hope that this general overview would help to surf successfully through the increasing flow of publications emerging around the name 'metamaterials'.

8 Acknowledgment

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