Invited paper

Metamaterials: A Personal View

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Abstract. *This article discusses fundamental properties of metamaterials. Firstly, it is argued that the defining property of metamaterials is emergence and not that they should display properties not observable in nature. In addition, the regime where matter can be assigned effective properties will be quantified using concepts of metamaterialization period and number of generations.*

Keywords

Metamaterials, complex materials, artificial media, emergence, nanotechnology, metamaterialization period.

1. Introduction

Metamaterials have entered into the mainstream of electromagnetics, high-frequency engineering, and materials science research within a relatively short period. Even if the rapid progress in this field owes (as has been shown in, for example [1], [2]) very much to earlier studies, it has managed to find a distinct profile and visibility within the first decade of the 21st century. Seminars, workshops, sessions, and even congresses dedicated to metamaterials are being organized, and the journal *Metamaterials*, published by Elsevier, runs already its third yearly volume. Several books on the topic have appeared during the latest years [3–9]. The potential for applications of metamaterials in the nanoscale, by manipulation of optical waves, has given rise to the field of *metactronics* [10]. The prominence of metamaterials research wave is affecting the way electromagnetics problems and questions are approached even to the extent that one may talk about a metamaterials paradigm in research.

The essential property in metamaterials is their unusual and desired qualities that appear due to their particular design and structure. These advantageous properties are not straightforward linear functions of the constituents from which the metamaterial is built up. A sample of metamaterial is more than a sum of its parts, analogously to the taste of ice-cream, which is not a direct sum of the flavors of ice and cream.

Taking a more general perspective, we may observe that in the field of electromagnetic materials, there are several examples of media that fully deserve to be labeled metamaterials. Chiral (spatial-parity-breaking structures) materials, artificial magnetism, magnetoelectric materials, percolation processes, extremely anisotropic media, and other special media are complex enough to fall in the category of metamaterials.

This paper discusses fundamental issues associated with metamaterials: possibilities to find a unique definition for them, as well the spatial scales in which one can talk about metamaterials. The extent of the domain spanned by these scales is also quantified using new concepts of metamaterialization period and number of generations.

2. Difficulties in Definition of Metamaterials

Attempts to find an adequate definition for metamaterials have not converged into satisfactory results. In human communications, even if scientific, terminology is inclined to change and meaning of words is by no means stationary. This is obvious but perhaps a more serious obstacle on the road to a universal definition for the term “metamaterial” is the fact that researchers working with these objects do not necessarily agree on their most essential characteristics.

The dynamics of the terminology of the verbal communications of today’s world is reflected in the fact that the encyclopaediae and dictionaries—where people search for the meaning and definition of words—are to ever-larger extent located in electronically accessible web servers. Entries are being constantly updated and “definitions” change accordingly. At present, Wikipedia defines metamaterials as follows [11]:

*A **metamaterial** (or **meta material**) is a material which gains its properties from its structure rather than directly from its composition. To distinguish metamaterials from other composite materials, the metamaterial label is usually used for a material which has unusual properties.*

For example, two years ago the corresponding entry in Wikipedia categorized metamaterials with a more narrow designation [12]; it was also emphasized that metamaterials display properties that are not found in natural materials. This aspect of being “above” nature (the word *meta* coming from Greek means “after” or “beyond”) was even more prominent in the early definitions and attempts to pinpoint what metamaterials are (see [13] for a deconstruction of the usage of this term in the early years of the metamaterials wave of research).

The essential property in metamaterials (as engineered, carefully designed, in-the-small-scale heterogeneous, mixture of available component materials) is indeed that "new" and unusual properties appear on the macroscopic level. The character of the medium is qualitatively different from the properties of the components that it is made from. These new properties emerge as a consequence of to the particular structural combination and arrangement of lower-level materials. It is a coherent interplay of material properties and geometrical shape effects that create the emergent and effective features of a metamaterial at the macroscopic level.

Another way of expressing the meaning of this emergence is to emphasize the purpose of metamaterials, which is "to achieve material performance beyond the limitations of conventional composites" [14]. This attitude, however, may appear somewhat belittling from the point of view of composite materials scientists. The very idea of engineering is to strive for better results (products, systems, materials). The classical composites, ceramics, polymers, semiconductors, and other advanced and functional materials cannot be split into a category separate from the new metamaterials.

One further important characteristic in metamaterials is their large-scale homogeneity. This issue is connected with the fact that the electromagnetic properties of media in general are assigned with reference to a particular frequency of electromagnetic radiation. Then the wavelength corresponding to this frequency defines a basic measuring stick against which lattice constants and spatial inhomogeneities are compared. Within the regime of metamaterials, the molecules (small-scale elements) of which the medium is composed are much smaller in physical size than the wavelength. How much smaller they need to be is not a well-defined question; however, at least we can say that it is always easier to speak about unique effective material parameters, the smaller-scale the microstructure is.

A more problematic issue in the search for definition is the tendency to attach a "non-natural" character to metamaterials. Early definitions emphasized that metamaterials carry properties that cannot be observed in nature [13]. The model example of metamaterials—the Veselago medium [14] with simultaneously negative values for both the permittivity and permeability—may have been a factor for this tendency: negatively refracting materials have not been found to occur naturally.

One of the messages of the present article is that this point of view narrows the domain of metamaterials unnecessarily strictly.

In [12] and [13], some of the problematic aspects of the non-naturality definition were raised, like the difficulty in separating classical composites from the new class of metamaterials. Another, perhaps more fundamental argument against the "over-the-nature" property is that it unnecessarily excludes impressive examples of natural media that could be called metamaterials par excellence.

One such example is formed by structural colors. Such can be observed in the wings of certain butterflies in which bright colors are not caused by chemical pigments but rather they are due to the geometric arrangement of tissues [16]. Because of a regular lattice structure with a periodicity that has a special relation to the wavelength, light with a particular color will be reflected strongly from the structure. Thus the hue of the wing is an emergent property. And even more, it is emergent in the very meaning of the metamaterial definition ("…*which gains its properties from its structure...*")

And finally, one might be tempted to problematize the stress in the metamaterial definition [11] on the *structure* of the composite. Also in unstructured and even amorphous mixtures, emergent properties may appear on the macrolevel. Examples of such behaviour are percolative phenomena [17] that take place in random materials and the change of the dispersion laws (the functional frequency dependence of the permittivity) when particles of certain dispersive materials are mixed with arbitrary orientation and position distribution into a matrix made of material that follows another dispersion law [13].

3. How Much Room Is There at the Bottom?

Metamaterials are homogeneous: the granularity of their microstructure cannot be observed on the macroscale. The elements ("molecules") whose special response and interaction are causing the effective properties on higher level are small in comparison with the wavelength. But even if the individual elements are "hidden", their effects are not. It is worth observing that the relative distance between these two scales (the molecule size on one hand, and the sensing wavelength on the other) can be astonishingly large: it can be several orders of magnitude.

One example of such an effect which carries over multiple scales is the artificial magnetism by so-called Swiss rolls. These are spirally wound metal foils over a cylindrical mandrel [18]. An array structure of such rolls displays magnetic effects. In addition, its effective permeability can be negative, and the frequency range of this artificial magnetism can be as low as 20 MHz, even if the size of the rolls is of the order of centimeters. The span between the microscale to the level where the emergent property takes place is around one thousand, which corresponds to the distance between the scales in solid-state matter (the atom lattice constant is one thousand time smaller than a typical wavelength at which the optical effects due to the band structure have macroscopically observable effects).

Such a jump over several orders of magnitude may seem a waste of limited spectral resource. In other words, if emergence can appear on a much smaller difference in scales, variety and richness in electromagnetic response can be created in much more abundantly by a more efficient “metamaterialization.” Let us define this term as the effect when the new (“new” in the sense of the emergent metamaterial definition) properties can be observed as the spatial sensing scale is increased. If new properties appear when the focus of sight is changed to a two times coarser resolution, the metamaterialization process is certainly much more efficient than in the case of plain Swiss rolls.

This concept, scale, seems to be a very crucial notion. When looking at materials and observing phenomena, the obvious characteristic length in electromagnetics is the wavelength of the radiation.

The relativity of scales may sometimes confuse discussion on the internal structure of materials. The scale where the emergent properties are witnessed is obviously a *macroscale*, and the heterogeneities appear at *microscale*. Often the intermediate region is termed *mesoscale*. However, *microscale* may also mean something more absolute, especially when used in connection with *nanoscale*, since then quite often reference is made to lengths of the order of 10^{-6} m and 10^{-9} m, respectively.

What, then, about the absolute scales? How deep can we travel into the small scales of materials?

The obvious limit, when looking downwards, is the discreteness of the building blocks of all matter, atoms. Their sizes are well known, and really small. But when looking from the continuum material point of view, we are not yet manipulating individual atoms and do not take into account the granularity of matter on the final quantum level. Present-day nanotechnology is entering into always smaller scale environments, and engineers are routinely manipulating objects that are measured in tens of nanometers. This is still considerably larger than the atomic dimensions which are of the order of angstroms (one meter divided by ten billions, 10^{-10} m).

And there is quite much space between the macro- and nanoscales. This is everyday experience: the human spatial scale of 10^0 meters, compared to the atomic dimensions, is an argument sufficient enough to motivate the 50-year old classic expression by Richard P. Feynman, *there's plenty of room at the bottom* [19] (the transcript of Richard P. Feynman's talk at the annual meeting of the American Physical Society on December 29, 1959, is a classic reference in nanoscience).

But how valid is Feynman in the era of nanotechnology?

In fifty years, the technology has given us ever-and-ever high-detailed material structures, which perhaps even Feynman could not have imagined of. However, the small-scale limit of atomic lattice distances has not changed along with the advancement of science and technology. A logical conclusion would be that the regime reserved to unexplored material order is shrinking. An obvious analogue is the vanishing rainforest in Amazonas. How can we keep alive Feynman’s conjecture? Do nanotechnological advancements destroy this dream of unexplored regions in the Wild West?

4. Metaphor of New Generations and Inheritance

What is the scale of metamaterialization? In other words, how much coarser has the focus of sight to be so that qualitatively new phenomena start to appear that would be essential in describing matter?

One picture that may be fruitful in trying to understand this reproduction of novel properties in matter is to replace the zooming in the physical scale with the temporal development of biological processes.

In some of the attempts to define metamaterials appears the idea of inheritance. It is emphasized that “higher-level” medium (the effective metamaterial itself) does not *inherit* the microscale character directly. In a materialistic–deterministic view of electromagnetic media, the idea of inheritance is implicit. It is obvious that the properties of the continuum are directly derivable from those of the building blocks, without any quantum leaps involved. But this is against the ethos of metamaterials: in their world children are fundamentally different from their mother and from their father.

However, as pointed out in [13], there are reasons to respect the metaphor of inheritance. Despite the emerging qualities on the next level, these properties are functions of the earlier generation, even if starkly non-linear. Hence there exists a continuum of generations and a continuum of material properties, because a parent is always a child of someone representing the previous generation.

This brings about an interesting question. On one hand, a sequence of generations exists as described above. On the other, the absolute scale range in which matter can be moulded, although rather wide, is nevertheless limited. One of the consequences is the fact that the number of generations to reach macrolevel is not infinite. Once the characteristic sensitivity in which the effective description of matter is determined, the “scale distance” to granularity at the bottom of the nanoscale is fixed. Why, then, was Feynman so carefree in his exclamation of the vast spaces down there somewhere in the bottom of space and matter?

Suppose that we are able to manipulate quantum clusters that are of the order of some nanometers. Furthermore, let us assume that these structures are metamaterialistically meaningful. Then, at the next (higher) level, one should be able to distinguish one generation in the sequence of materials succession. Obviously this process can continue towards further levels, in other words to larger physical scale lengths.

The crucial question is how “quickly” a new generation can be formed. What is the (spatial) scale factor at which the material is again homogeneous and can be assigned new properties? Does one need to multiply by a factor of ten? Certainly effects carry over much larger distances, as the example of Swiss rolls [18] showed. But in order to maximize the variety in the world of novel materials, this “generation gap” should be as short as possible. Fig. 1 illustrates the spatial dependencies of this question of emergence in scales of increasing amplitude. There the limits of lower nanoscale (granularity and individual molecules) and upper bounds of natural human dimensions span a range where there is room for emerging qualities of matter, but not in arbitrary multiplicative numbers.

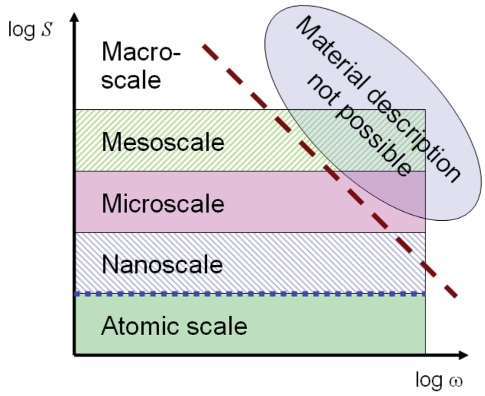

Fig. 1. An abstract description of the domain that Richard P. Feynman described to be vast: *there is plenty of room at the bottom.* With classical physics and mainstream engineering one is able to operate at all regimes down to the nanoscale (the vertical scale *S*). Note that in order to describe materials with effective properties, the wavelength needs to be large enough (the frequency ω sufficiently small). The domain of metamaterials is hence below the dashed line.

The fact that the distance is only finite between macro- and nanolevels may be a reason to be disturbed. Why didn't the grand Feynman worry about this limitation? One reason can have been that during his time one could not talk about nanotechnology in today's meaning. Quantum level—those days—was really far away within the microworld.

To make a quantitative estimate of the global metamaterialization process, let us define and denote the *metamaterialization period* (the analogy to diachronic human history gives motivation to this temporal concept) by *m*. This dimensionless number is the ratio between the scale where the emergent (metamaterialistic) effect can be distinguished and the size of the average molecule dimension in the microscale.

Then the up-to-down distance in "generations" can be calculated. If the macroscopic scale where the metamaterialistic levels are to be observed is *S*, and the microscopic scale is *s*, the room which Feynman claims to be filled with "plenty" space is of the relative size *S/s*. Let us assume that the macroscale is of the order of 10^0 meters, and the nanoscale of the Angstrom scale, 10^{-10} meters. Then the number of generations to span through all this range is

$$n = {}^{m}\log\frac{S}{s} = {}^{m}\log 10^{10} = \frac{10}{\lg m} \qquad (1)$$

where lg denotes the logarithm with base to 10. For example, if the metamaterialization period is $m = 2$, the number of generations is around 33.

In engineering applications, however, the scale of the interesting phenomena is not necessarily the natural human scale of 10^0 meters but it can be smaller. Then also the number of generations counted from the nanoscale decreases. Fig. 2 shows the number *n* as function of the metamaterialization period *m* and the operation scale *S*.

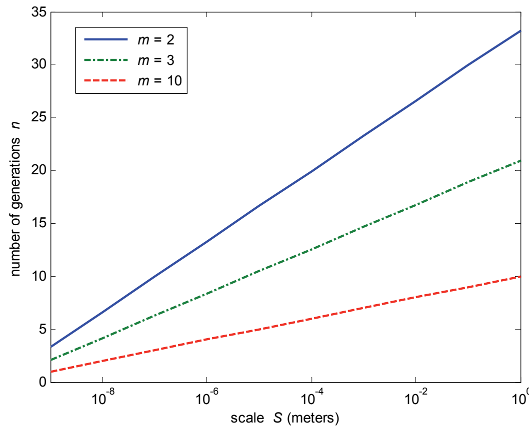

Fig. 2. The number of generations *n* between the nanoscale and scale of phenomena *S*, for varying metamaterialization periods *m*.

The figure illustrates that quite a large number of generations can be hidden below the scale of observed phenomena, and obviously the number is strongly dependent on the parameter *m*. However, one may also infer from the curves that even at the micrometer scale—which is invisible to unaided human eye—there is room for several successive metamaterialization processes inside matter.

5. Concluding Thoughts

No unique definition for metamaterials can be written down. One of the messages of the present article has been that there is a solid core in the attempts to identify and name those; however sometimes the most essential properties are not captured. The argument above has emphasized emergence as the most fundamental and defining character in metamaterials. Accordingly, the "not-in-nature" quality—which is sometimes propagated—does not catch the true meaning of metamaterials.

Although the present article has been rather strongly taking positions concerning of definitions, it is important to keep in mind that terminologies change. Too rigorous control of the exact meaning of words is counterproductive. This is especially true with the use of abstract prefixes like *meta*. A healthy reminder is the following citation from the *New York Times* column in December 2005 [20]; here, however, the author does not discuss materials science but rather literary critique:

" `Meta *is part of the unearned irony of the improperly educated postmodern crowd,´ opines Roger Kimball, an editor of The New Criterion. `It's verbal shorthand that expresses not a depth but an absence of thought. You'll find it in the slums of contemporary literary and art criticism.´* "

Aside from terminology, another important topic which is discussed in this article is the vastness of the material space "on the bottom" (to borrow the words of Richard P. Feynman [19]). How many orders of magnitude of scales are there below the macroworld before the atomic granularity takes over? It seems that with today's nanotechnological advances this regime is disappearing with a fast pace.

The quantitative analysis of the dimensions of this domain was performed using the concepts of metamaterialization period and number of generations. Measured in the number of generations, it was seen that the domains of metamaterials spanned over a very wide range, tens of generations. Hence, a fair judgment of today's post-Feynman era is to observe that "there's still a few layers space below the floor level."

Evolution can provide wonderful effects over an astonishingly small number of generations. Children take their own paths which are not necessarily consonant with those of the parents. Then also qualitative changes take place. Such is the situation also with the effective description of matter: emergence manifests itself after one metamaterialization period. However, the direction is not necessarily uniform and clearly goal-oriented. The emergence of new effects on the children's level may be a protest and revolution against parents. The spatial "history" that can be observed when climbing upwards the scale S from the nanolevel may look very incoherent. Just like with the relations between human generations where children may feel that they are not part of a chain of a great story, the direction of new phenomena in matter can also have a very convoluted evolutionary path.

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