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Electromagnetic Characterization of NAnostructured Materials

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STATE-OF-THE-ART AND MOST PROMISING ANALYTICAL AND NUMERICAL CHARACTERIZATION TECHNIQUES FOR BULK METAMATERIAL LATTICES

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1 Direct and indirect characterization of metamaterial layers. State-of-the-art

1.1 Preliminary remarks

Surveys on so-called *metamaterials* can be found in books [1, 2, 3] (also see review paper [4]). The history of metamaterials (MTM) starts from paper [5] where the goal to create the so-called *perfect lens* was claimed by J. B. Pendry. The development of MTM showed that composite media with extraordinary material properties are suitable not only for subwavelength focusing and resolution and they found a lot of other applications. Simultaneously the concept of MTM was generalized. Now, transmission line networks with periodical loads and resonant artificial surfaces (metasurfaces) also refer to MTM [1, 2, 3]. MTM definitely deserved the special attention paid to them in the modern literature. However, in many papers devoted to them the reader can find mess or wrongly interpreted results. Especially, it concerns the electromagnetic characterization (EMC) of MTM and, especially, the wrong interpretation of results obtained for so-called effective material parameters (EMP). The correct EMC of MTM is very important for their design and optimization.

In the modern literature MTM are often presented by lattices of resonant scatterers whose characteristic size δ and period a at the resonance is small compared to the wavelength in the host medium λ though comparable with it (practically $(a,\delta)/\lambda = 0.05...0.2$). Notice that the resonance of lattice particles at these comparatively low frequencies is the feature that shares MTM lattices out of photonic crystals, but the resonant wavelength (moreover taking in account its shortening in the lattice compared to free space) shares MTM out of previously known artificial magneto-dielectrics and grants unusual properties. MTM can be also a combination of two (or more) periodic building blocks. One of them can be formed by small magnetic scatterers often called as split-ring resonators (see e.g. [6, 7]), another can be an array of long wires. This combination was first experimentally studied in [8] and later developed in numerous works. Some interesting phenomena in MTM arise namely due to the spatial dispersion in the structure of long metal cylinders. The spatial dispersion corresponds to cases when the wave propagates obliquely to wires or along them.

Formally, all periodic structures, e.g. MTM lattices can be characterized through EMP. However, this characterization not always makes sense. It is often thought that once EMP are introduced *the homogenization model* is built. This terminology related with the word "homogenization" turned out to be very unsuccessful with respect to spatially dispersive [25] lattices. It led to a misunderstanding which can be observed over the abundant literature devoted to MTM.

For unbounded system, which may be considered as translation invariant, at least in the statistical sense, we can pass to Fourier transforms of the fields. The EMP obtained for spatially dispersive medium are presented as a function of the wave vector $\mathbf{q}$ and constitutive equations become nonlocal. In media with uniform concentration of particles the propagation of an eigenwave can be described through the refraction index n and wave impedance Z. Instead of these two parameters one can characterize the same wave with a pair of EMP ε and μ. Physically there is no difference between the descriptions of the eigenwave in terms of its $n-Z$ parameters or in terms of ε and μ. We do not consider chiral, bianisotropic, non-reciprocal and energetically active MTM. This way we avoid the discussion about more than two EMP. The magnetism in such lattices is artificial. It arises as the effect of the inclusion complex shape and disappears in the static limit. However, it is erroneous to think that the description of any such lattice in terms of of ε and μ is possible.

Though the MTM lattice can be always described through the scalar (for linearly polarized waves) or tensor (for the general polarization case) refraction index n the introduction of a scalar (seldom) or tensor (in almost all known cases of MTM lattices) impedance Z is sometimes an ill-posed problem even for unbounded lattices. In fact, it is possible for inclusions possessing certain symmetry and is impossible for strongly non-symmetric ones. Then the introduction of ε and μ is not physically sound. If the inclusions are strongly asymmetric any interface violates the translation invariance. As a consequence the boundary conditions are nonlocal even for the Fourier transforms of fields. Thus, the introduction of the boundary conditions stands out in a separate difficult problem. Reducing it to usual Maxwell boundary conditions may lead to incorrect results. The alternative way is the significant complication of boundary conditions by introduction of additional parameters (additional boundary conditions). Even introducing boundary conditions we should allow in this case the dependence of EMP tensors on the incidence angle and sometimes on the polarization type of the wave. Such EMP as well as in the case of the lattice with strong spatial dispersion (nonlocal constitutive equations) refer to the given plane wave and cannot be used in quantitative calculations with another $\mathbf{q}$.

1.2 What is homogenization

Since the process of excitation of any scatterers is governed by Maxwell's equations (the exception to the rule are quantum inclusions) it is naturally to assume that there is a unique approach to treat the MTM in terms of the Maxwell equations. To establish the proper characterization one must go through the tree steps.

At the first step it is recommended (employing computer simulation with commercial or special software or some analytical approaches if accurate enough) to find out the fields inside and outside of the finite-thickness MTM sample. The second step consists in the measurements of real scattered fields. Opposite to the first step there are some restrictions on the obtained information: as a rule, one can measure some integral characteristics missing many details in the field distribution. The third step consists in the choice of a minimal set of EMP constituent in the material Maxwell equations and boundary conditions. This builds a bridge between the firs and second step. In the other words one should elaborate an electromagnetic model of the MTM, in which the equations and parameters are not mesoscopic. This means the independence on the shape of the MTM sample (or at least independence on the thickness of the MTM layer because, in practice, MTM are printed or grown on substrates and form slabs). It is implied that the model is consistent with the fields obtained at the first and second steps. The first step should then be repeated and finished by the homogenization procedure which gives us the homogenized equations with proper parameters.

The problem of a plane wave incidence to an MTM slab (multilayer or a monolayer grating of artificial particles) is due to the periodicity in the tangential plane a standard cell problem for which commercial packages (e.g. the HFSS package) are efficient and reliable. As to the experimental retrieval of EMP, one restricts himself to the measurement of the $R-T$ coefficients.

If there is no spatial dispersion (at least in the unbounded lattice) the usually defined EMP describing the electric and magnetic responses of the unit cell to the macroscopic field are local [25], i.e. independent on $\mathbf{q}$. Below we call such EMP as *Lorentzian EMP*. However, this does not forbid to introduce other set of EMP for the same lattice and same frequency range which will be not local. There are multiple methods how to introduce EMP beyond the static limit. And only one of these methods lead to the Lorentzian EMP. It is important to stress that one can introduce different sets of EMP extracted from same R and T. The explicit set of EMP depends on boundary conditions we impose at the layer interfaces. It is difficult to detect the presence or absence of the spatial dispersion inspecting the non-Lorentzian EMP.

The locality of Lorentzian EMP is equivalent (see, e.g., in [25]) to the system of following conditions:

- Passivity (for the temporal dependence $e^{-i\omega t}$ it implies $\mathrm{Im}(\varepsilon) > 0$ and $\mathrm{Im}(\mu) > 0$ simultaneously at all frequencies, for $e^{j\omega t}$ the sign of both $\mathrm{Im}(\varepsilon)$ and $\mathrm{Im}(\mu)$ should be negative). The violation of passivity in the energetically inactive media (no generators of the electromagnetic oscillations at frequency ω) means the violation of the 2d law of thermodynamics;

- Causality (for media with negligible losses it corresponds to conditions $\partial\left(\omega\varepsilon\right)/\partial\omega > 1$ and $\partial\left(\omega\mu\right))/\partial\omega > 1$. This also means that in the frequency regions where losses are small material parameters obviously grow versus frequency: $\partial\left(\mathrm{Re}(\varepsilon)\right)/\partial\omega > 0$ and $\partial\left(\mathrm{Re}(\mu)\right)/\partial\omega > 0$);

- Absence of radiation losses in arrays with uniform concentration of particles. This means that in lossless arrays the EMP should be real values.

All these properties follow from the independence of the material parameters on the wave vector $\mathbf{q}$ (for given frequency this means the independence of EMP on the propagation direction) [25].

1.3 Literature survey

In the modern literature we have found five main procedures of the characterization of MTM lattices:

- Procedure 1. EMP obtained by a direct extraction of ε and μ from plane-wave reflection and transmission $(R-T)$ coefficients of a composite slab, assuming the slab to be continuous and uniform medium.

- Procedure 2. EMP obtained by an indirect extraction of ε and μ from plane-wave reflection and transmission $(R-T)$ coefficients of a composite slab, assuming the slab to be a 3-layer structure, where all 3 layers are continuous and uniform media. The central layer is characterized by Lorentzian ε_L and μ_L of the bulk medium, and two other layers (called Drude transition layers) are characterized by other EMP. EMP of both central layer and Drude layers can be retrieved.

- Procedure 3. EMP for thin MTM layers (1-3 scatterers across the layer) describing the electromagnetic response of the layer per unit area of the surface (i.e. the response over the whole layer thickness).

- Procedure 4. EMP are obtained from exact simulations of the electromagnetic wave propagation in the lattice using a special procedure of the averaging of microscopic Maxwell equations.

- Procedure 5. EMP introduced through sophisticated line and surface averaging procedures. Line averaging is applied for vectors $\mathbf{E}$ and $\mathbf{H}$. Surface averaging is used for vectors $\mathbf{D}$ and $\mathbf{B}$.

1.3.1 Rarely used characterization models

We start from Procedure 5 introduced by J.B. Pendry in [6, 9, 10]. Material parameters related to such a unusual averaging procedure were obtained as a mathematically intermediate result in the modelling of the transfer matrix of the lattice unit cell. Though one can find many references to this method in the modern literature, there is no one example of the successful retrieval of these EMP from measurements or numerical simulations. One can find only direct calculations of these EMP. Physical meaning of these EMP remains unclear even after a detailed discussion of it in [10]. No one available source explains how to link these EMP to $R-T$ coefficients of MTM layers. We think that there is no way to associate these EMP with any real boundary problem (beyond the static limit, where all 5 aforementioned procedures give the same result).

Procedure 4 developed in works [11, 12, 13] is very accurate and allows one to take into account fine effects. These EMP are extracted as the tensors describing the electromagnetic response of the unit cell to the electric and magnetic fields averaged in the special way. One can show (though it is not explained in papers [11, 12, 13]) that this averaging is sharing out the fundamental Bloch harmonics of microscopic fields and polarizations. These EMP depend obviously on $\mathbf{q}$ at all nonzero frequencies. In the static limit nonlocal EMP [11, 12, 13] transit to static material parameters of the lattice. At low frequencies where the strong spatial dispersion in the infinite lattice is absent this $\mathbf{q}$-dependence describes the attenuating (evanescent) eigenwaves of the lattice that usually are lost in homogenization procedures. Near the interface of the lattice these attenuating waves can exist and are called *polaritons*. It spite of their exponential decay inside the lattice polaritons are not surface waves as their tangential wave number q_t is less than k and can be zero. Polaritons are high-order Floquet modes of the lattice crystal planes.

To apply such non-local EMP to boundary problems with MTM layers beyond the static limit one has to deduce the additional boundary conditions (ABC) and refer them to a properly chosen interface which is not obviously the physical surface of the MTM slab. The successful choice of the interface is crucial for the whole method.

This method is fine in the direct homogenization problem. However, it can be hardly applied for the experimental characterization of the MTM lattices. Really, we do not know a priori which ABC we should apply and where the interface plane should be located. Moreover, these EMP are assumed by definition to be non-local i.e. depending on the wave vector at all frequencies, which makes their experimental extraction almost impossible.

Procedure 3 was introduced in [32] as an evident alternative to Procedure 2 for very thin layers ($N = 1-3$ unit cells across the layer) where the Lorentzian EMP lose physical meaning. The EMP defined by Procedure 3 were called as mesoscopic EMP since they evidently depend on N. Since these EMP really describe the layer unit cell electromagnetic response, they satisfy to locality requirements as well as Lorentzian EMP.

However, except the case of very simple inclusions (unloaded wires or patches) mesoscopic EMP defined through the electric and magnetic response per unit area of the slab do not fit the $R-T$ coefficients and are useless. Therefore, the definitions of mesoscopic EMP from [32] have to be revised.

1.3.2 The most known characterization procedure

Procedure 1 was first applied for MTM layers in papers [14] and [15], and later in hundreds papers (it is also described in all above cited books devoted to MTM). It is the most expanded method which is considered as most successful. In fact, this is nothing but the standard procedure previously known as Nicolson-Ross-Weir (NWR) method of the extraction of material parameters of continuous magneto-dielectric media from measured $S-$parameters. It was first suggested for retrieval of transmission line characteristic impedance and refraction index in [33] and then developed for the characterization of layers of natural media in [34], [35] (dielectrics or magnetics) and in [36] (magneto-dielectrics). The NRW algorithm is based on the material Maxwell equations (implying the local permittivity and permeability) and Maxwell's boundary conditions. Passing to MTM we encounter the problem of the non-locality of the slab electromagnetic response. This non-locality is not the same as the strong spatial dispersion in the infinite lattice. It results from the combination of the discreteness and finiteness of the structure. During the homogenization procedure we loose the details of the real field distribution that influences to the scattering matrix and exhibits itself as the non-locality. Mathematically, it expresses in the difference between the so-called Bloch impedance that describes the reflection from the original lattice and the wave impedance of the homogenized medium that would describe this reflection in the absence of the non-locality. These two impedances are equal to one another only in the static limit [29].

In [16]–[24] and many other works one claims that a composite slabs comprising small number N of monolayers[1] and even the single monolayer $N = 1$ has the same EMP as infinite or semi-infinite MTM lattices $N = \infty$. It is considered in the literature (a detailed survey is given in the next section) as a proof that this indirect homogenization is correct. In other words, the indirect homogenization through extraction of material parameters through simulated or measured R and T is considered in the dominating literature on MTM as a correct procedure of homogenization **because** it gives the same result for $N = 1$ and for $N = \infty$. However, an easy speculation shows that namely this fact means that it is an **incorrect** procedure.

It is clear that in the layer with $N > 1$ grids of point dipoles when the distance a between the grids is not optically negligible the obliquely incident wave refracts. On the contrary, in the case when $N = 1$ the grid of electric and magnetic dipoles (optical thickness is negligible) does not refract the wave (it is commonly known that the interaction of the wave with any planar grid leads to the non-refractive reflection and transmission of waves).

If the host medium in the monolayer does not differ from the media in front of and behind it (i.e. if the monolayer is the grid in free space interval of thickness a) the obliquely incident wave does not refract in it. But it definitely refracts inside the layer of $N \gg 1$ such grids separated by distance a. This is so, in spite of same material parameters attributed to these two different layers.

So, the set of EMP which are unique for layers with $N = 1, 2...\infty$ have nothing to do with the refraction of waves. It is clear from this speculation that the physical meaning of these EMP is special and very different from that of Lorentzian EMP[2]. Therefore these EMP cannot be claimed as "correct" ones.

1.3.3 Bloch material parameters and Bloch lattices

Let us discuss how this unique set of EMP can be extracted for different N and what is the meaning of this set. Which physics is behind these EMP was explained in papers [28, 29, 30].

[1]Monolayer is a single grid of particles placed in the host medium slab of thickness a which is equal to the period of the MTM lattice obtained by the periodic repetition of the monolayer in the normal direction to its interface.

[2]Which evidently have no physical meaning for a single monolayer.

These EMP were named in these works as *Bloch's EMP*. The class of MTM lattices for which these EMP can be introduced was named in these works as Bloch lattices. MTM lattices studied in works [16]–[24] and many others refer to this class. The MTM lattice can be referred to the class of Bloch lattices if after applying Procedure 1 we see that:

- the resonance of the extracted EMP related to the resonance of inclusions holds well below the frequency where the Bragg phenomena in the lattice can appear;
- the response of the slab is reciprocal and there is no optical activity and dichroism;
- the extracted material parameters are independent on N.

The Bloch EMP specified for this class of MTM definitely allow one to interpret a finite-thickness lattice as a uniform continuous medium. They are unique for different N since determine the so-called ABCD[3] matrix of the monolayer (for Bloch lattices this matrix is not affected by presence or absence of adjacent monolayers). However, these scalar parameters are not unique for different incidence angles and not unique for TE and TM polarizations of the refracted wave. Usually one considers these ε_B and μ_B for the normal incidence, only.

The Bloch permittivity ε_B does not describe separately the electric response of the unit cell of the medium and the permeability μ_B does not describe the magnetic response. They describe the wave transmission through the medium unit cell. In fact, the description of the wave transmission through the unit cell is possible in many ways:

- in terms of the ABCD matrix (where only 2 components of 4 are independent in the case of reciprocal non-bianisotropic inclusions),
- in terms of the effective refraction index n and the effective Bloch impedance Z_B,
- in terms of effective (Bloch's) ε_B and μ_B,
- in terms of Lorentzian EMP,
- in other ways.

The Bloch's ε_B and μ_B calculated or extracted from the scattering matrix for a lattice of resonant inclusions are not Lorentzian EMP and therefore

- violate the locality requirements. This violation is often interpreted as the signature of the strong spatial dispersion inside the lattice, and one wrongly concludes that the lattice cannot be homogenized;
- mistakenly indicate the wrong resonance of the one of material parameters.

For Bloch lattices the refraction index extracted from $R-T$ coefficients using the Procedure 1 is the true refraction index of the infinite lattice that can be also obtained through Lorentzian EMP [28, 29, 30][4]. The refraction index n has the physical meaning of the wave phase shift of

[3]The ABCD matrix refers to the transmission-line interpretation of the electromagnetic lattice as a periodically loaded line.

[4]Above it was already mentioned that the wave impedance of the medium which is equal to $\sqrt{\mu_L/\varepsilon_L}$ cannot be extracted for lattices by the Procedure 1. One can extract only the refraction index and the Bloch impedance $\sqrt{\mu_B/\varepsilon_B}$ and only for Bloch lattices.

the wave across one unit cell of the lattice normalized to the phase shift of the wave over the same distance in free space. The Bloch impedance Z_B has the physical meaning of the ratio between tangential components of the electric and magnetic fields averaged over the input or the output cross section of the lattice unit cell. For Bloch lattices the effective wave impedance defined as the ratio of transversally averaged E- and H-fields keeps uniform for any cross section of the cell, e.g. the input plane, the output plane and the central plane. For Bloch lattices both Z_B and n are the same for an infinite lattice and for a finite one, that explains their uniformity over N.

The concept of Bloch lattices fulfills if

- the inclusions are optically small enough to be properly described in terms of p- and m-dipoles [29];
- the electric and magnetic resonances of inclusions either do not overlap or have different magnitudes of the resonance [30];
- the inclusions are symmetric with respect to a crystal axis.

For Bloch lattices the resonance of effective ε_B holds approximately at the frequency of the electric resonance of inclusions and the resonance of effective μ_B holds at the frequency of the magnetic resonance. This is the only correspondence between the Bloch material parameters and the electromagnetic response of the unit cell. In some cases this correspondence can be useful, since the dispersion of the first Bloch parameter correctly shows the resonant frequency and qualitatively indicates the amplitude of the resonance of the true (Lorentzian) material parameter. Then the characterization of MTM lattices in terms of Bloch's material parameters is useful. It gives not only the correct information on the resonance frequency, but even on the nature of the true resonance (electric if the permeability experiences the so-called *antiresonance* or magnetic if the permittivity experiences the "antiresonance"). What is the antiresonance?

At the electric resonance of inclusions not only Bloch's permittivity ε_B resonates, but also Bloch's μ_B, and vice versa. At the magnetic resonance of inclusions not only Bloch's μ_B resonates, but also Bloch's ε_B. In other words, the "second" (or "wrong") Bloch material parameter also experiences the "resonance" which is totaly wrong. This simultaneous resonance in a Bloch lattice [16]–[24] was called antiresonance in [38]. This term also produces the terminological mess. The term "antiresonance" is commonly used in the electrical and radio engineering and means simply the parallel circuit resonance. It has nothing to do with the resonance of the second Bloch parameter which is totally deprived of any physical content.

Let us discuss the reason of the "antiresonant" behavior of the second Bloch parameter. Since the refraction index of a Bloch lattice is correctly extracted using the Procedure 1 the product $\varepsilon_B\mu_B = n^2$ is correct for a Bloch lattice of p-dipoles. In other words, it equals to the product of Lorentzian EMP $n^2 = \varepsilon_L\mu_L = \varepsilon_L$. Since ε_L and ε_B are different it obviously implies the difference in the amplitudes of their resonances. But the amplitude of the resonance of the products $\varepsilon_L\mu_L$ and $\varepsilon_B\mu_B$ is the same, i.e. $\mu_B = \varepsilon_L/\varepsilon_B$. One can show that the ratio of two functions describing the Lorentz dispersion often results in the "antiresonance".

In fact, the description of the Bloch lattice in terms of the effective Bloch's ε_B and μ_B is the alternative to the description of the lattice in terms of the ABCD matrix or in terms of the Bloch impedance Z_B and the refraction index n. And this alternative gives no new insight compared to Z_B and n. When these parameters extracted using the NRW method are applied in problems with obliquely incident waves, resonator modes or evanescent waves this leads to serious errors.

It was explicitly shown in [28] that the Bloch material parameters can be in this meaning *non-local* within same frequency ranges where the Lorentzian EMP are local. In the static limit the numerical difference between Lorentzian EMP and Bloch EMP vanishes.

1.3.4 Characterization of MTM through Lorentzian EMP

Procedure 2 was developed in works [28, 29] and [31]. It allows to find Lorentzian EMP of MTM, which were shown in these works to be accurate generalizations of well-known static EMP to frequency dependent fields. The procedure was developed only for lattices of reciprocal (without elements of natural magnetic media) not magnetoelectric inclusions, the restrictions of applicability (frequency bounds) are the same as for Bloch material parameters.

Local EMP keep the physical meaning of the medium unit volume response to the electric and magnetic fields even in the resonance band of inclusions [28, 29, 30], except special frequencies where the effects of strong spatial dispersion are essential.

The introduction of Lorentz EMP for lattices of resonant inclusions implies a more complicated 3-layer representation of any finite-thickness MTM lattice: inner layer with Lorentzian EMP of the infinite lattice and two thin Drude layers at the interfaces. This approach is related with the serious difficulty: the EMP of Drude layers remain unknown: the transition layer effect is not yet studied enough. Only the special case of the simple cubic lattices of spheres was studied in the classical literature (see also in [31]). However, this study can be reformulated if we combine the microscopic model for the infinite lattice with the extraction algorithm for the 3-layer structure and consider the EMP of transition layers as fitting parameters. This study would be not very difficult and probably will be done in the next future.

1.4 Conclusion

To conclude this overview: there are five most known methods of the characterization of bulk MTM lattices with finite thickness through effective material parameters, from which three procedures are clearly related to the boundary problem. One of them (Procedure 1 or direct extraction of EMP) is most popular, however its improper application and wrong interpretation led to the mess and incorrect results in the literature on MTM. Two other procedures (numbered as 2d and 4th ones) are not popular and therefore weakly developed. It is impossible to judge whether it is related to their inherent shortcomings or simply with their weak promotion. In this situation it is impossible to definitely make the choice of the best method for the characterization of bulk MTM layers. However, it is obvious to promote the existing insight on the physical meaning of extracted material parameters, since wrongly interpreted results in the literature on MTM are, as a rule, related to the lack of theoretical knowledge. From this point, the Procedure 2 should be recognized **for the instance** as the most promising for the promotion in the metamaterial scientific community.

2 Statistical analysis of papers on MTM material parameters in the leading physical journal

The purpose of this section is to confirm the observations made in the previous section with the literature survey. In this section we review the papers concerning MTM which appeared in one of the leading physical journals "Physical Review Letters" (PRL) in the period 2000-2008

Year 2008	19
Year 2007	19
Year 2006	7
Year 2005	22
Year 2004	9
Year 2003	5
Year 2002	10
Year 2001	2
Year 2000	3

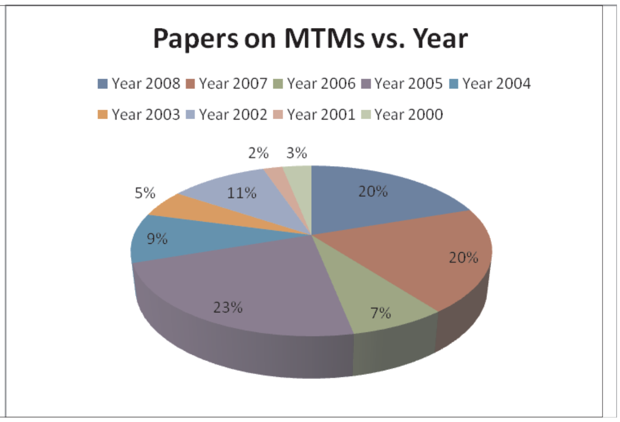

Figure 1: Number of papers appeared on PRL in the years about metamaterials.

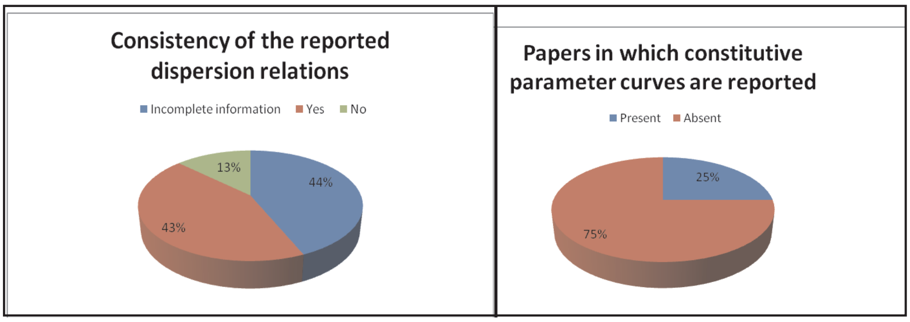

Figure 2: Left – Percentage of the papers reporting constitutive parameter dispersion curves. Right – Percentage of complete or incomplete consistency of the constitutive parameter dispersion curves with the locality requirements.

The review is organized as follows. First, all papers on MTM appeared in PRL are listed and furnished by short comments. The number of the papers per year is reported in Fig.$\tilde{1}$, while the complete list is in Annex I to this document.

The Annex I has been devoted to analyze the papers on metamaterials and in particular those ones presenting effective material parameters dispersion curves. The percentage of the papers where effective parameter curves are presented is reported in Fig. 2. If one condition of the locality concept (e.g. only the passivity or only the causality) is violated in the retrieved or calculated EMP the paper is marked in Annex I as "Incomplete" (convenience with the locality). If both passivity and causality are violated the paper is marked as "No" (completely non-consistent with locality). It is clear that only the papers where the locality is fully respected (papers marked with "Yes") can be recognized as correct ones in view of the content of the previous section. These papers make less than one half of all the papers containing frequency plots of EMP. The percentage of papers where the basic physics is apparently violated is 53%.

Second, all these papers are briefly discussed. Annex II has been devoted to an analysis of the papers in which the EMP have been calculated and their frequency dependencies presented. In particular, consistency of the shown parameter dispersions has been checked. The summary of this activity is reported.

MTM are gaining growing relevance as a topic in PRL during the last years. The average number of the papers on MTM per year is approaching 20. One fourth of these papers presented the dispersion curves of EMP. Only in 43% of papers the curves presented allowed us to understand that these EMP were physically meaningful.

3 Conclusion

The study of the literature on MTM allowed us to conclude that

- The topic of EMP is very important due to an unacceptable amount of inconsistent publications;
- The procedure of the local homogenization of MTM layers involving Drude surface layers needs to be specially promoted in the MTM scientific community.

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