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Electromagnetic Characterization of NAnostructued Materials

DELIVERABLE D2.1

OVERVIEW OF THE STATE-OF-THE-ART AND MOST PROMISING MEASUREMENT TECHNIQUES

(UPDATE 1)

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Dissemination Level		
PU	Public	**PU**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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Summary

The review of state-of-the-art and most promising measurement techniques has been presented in the first report of 30/09/2008. Although no major developments in this area have been reported during the past 3 months, new experimental studies of the nanostructures 3-D metamaterials have recently been published. The presented results have demonstrated deflection of light beam by the metamaterials prism, which was attributed to negative refractive index of the prism. An update of the respective section 2.3.5 of the preceding report is presented. A panel session “Theoretical Issues and Practical Aspects of Metamaterial Characterisation” has been held at the 2nd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics “Metamaterials 2008 Congress”, Pamplona, Spain, September 21-26, 2008. The panel session outline is presented and the minutes are provided in Appendix.

Update to Linear optical characterization of metamaterials

2.3.5. For wedge-type metamaterial samples (rather than the slabs discussed so far), the direction of the transmitted light wave generally changes due to refraction. Measuring the corresponding angles according to Snell's law allows for inferring the refractive index in Snell's law – which, however, is generally distinct from the refractive index n that one refers to when stating that the material phase velocity of light, c, is slower by factor n than the vacuum speed of light, c_0, i.e., $c=c_0/n$. A brief discussion of this aspect can, e.g., be found in Ref. [20]. The experiments addressing the change in the direction of the Poynting vector (energy flow) have been published [9]. The samples investigated there were fabricated via evaporation of a stack of 21 alternating layers of silver and dielectric (corresponding to 10 lattice constants). Next, holes were drilled using focused-ion-beam (FIB) lithography to obtain a cascaded fishnet type structure. Finally, a wedge which forms a prism has been produced, again using FIB lithography. The measured wavelength-dependent changes in beam direction have been compared with the time-domain simulations in CST Microwave Studio. The calculations agree regarding the real part of the refractive index, and the authors have concluded that ten functional layers (lattice constants) suffice for the retrieved effective refractive index to be representative of the value for "bulk" material. However, the same calculations *disagree* with the experiment by a factor larger than five regarding the imaginary part of the refractive index, i.e., the maximum measured figure of merit of about 3 is much smaller than the maximum calculated one of about 20.

It is interesting to note that the statement of the refractive index convergence in [9] is consistent with the findings of another theoretical paper [21] based on a closely similar double-fishnet type negative-index photonic metamaterial design. Ref. [21] reports convergence for four functional layers. However, one should be aware that these numbers are not fundamental at all. Increasing the spacing between adjacent functional layers of the double-fishnet structure will decrease their coupling (see discussion in Section 2.3.1 of the 1st report). As a result, convergence can even be achieved for a single functional layer already [22].

Inferring other optical parameters (e.g., permittivity or permeability) from such refraction experiments [9] again requires making reference to some sort of theoretical modelling.

Panel Session: Theoretical Issues and Practical Aspects of Metamaterial Characterisation

The session has been organised at the 2nd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics "Metamaterials 2008 Congress", Pamplona, Spain, September 21-26, 2008. The session has attracted considerable attention of the participants and has been attended by nearly 100 Congress delegates.

The Panel was composed of the reputable theoreticians and experimentalist working in the field of metamaterials:
Sergei Tretyakov, Helsinki University of Technology, Finland
Allan Boardman, University of Salford, UK
Ricardo Marques, University of Seville, Spain
Stefan Linden, Karlsruhe University, Germany
Yang Hao, Queen Mary University of London, UK
Raj Mittra, Pennsylvania State University, USA
Alex Schuchinsky, Queen's University Belfast, UK

The three main themes have been addressed during the Panel Session:
1. Effective Parameter Definitions & Physical Meaning
2. Parameter Measurements, Extraction & Interpretation
3. Applications to Antennas, Scattering, Imaging and Cloaking Devices

To make the session focused and help the panellist focus on the issues of specific interest for audience, attendees were invited to submit their questions in advance. The dedicated webpage has been created at the Congress website where the visitors could post their questions, comments and suggestions for the discussion during the panel session. Thus all website visitors and the session attendees have identified the most important issues to be addressed during the panel session.

Discussing the experimental characterisation of nano-structured metamaterials, Dr. Stefan Linden emphasised that in terahertz frequency range it is necessary to take into account damping effects of the interfaces in metals. Also in the range of wavelengths commensurable with the lattice constants applicability of the effective medium is questionable. Also all our structures are very anisotropic and are described by tensors which are difficult to obtain for isotropic effective media.

Currently we are mostly dealing with layers rather then with bulk materials, and we do not know how many layers are necessary to mimic bulk properties. So it is better to distinct two cases in characterization: (i) building blocks and (ii) the whole structure as is. We can distinct influence of the separate building blocks and their collective behaviour component. However array measurements are more difficult because the phase information is missing in reflectance and transmission spectra and we loose the dispersion information.

Intereferometric experiments with metamaterials are more precise. They can give group velocity and phase information but their interpretation is still difficult. A zero order transmission measurements are fairly predictive but sometimes we have more complicated wave propagation paths and additional field excitation that does not coincide with the basic ray theory. Extraction of effective parameters from the physical experiment only is insufficient and needs usually comparisons with the numerical modelling results. Also the bi-anisotropy and cross-coupling of the elements should be taken into account. Therefore interpretation of the measurements is much more challenging and requires the close correlation with the theoretical models.

Further details of the panel session discussion are provided in Appendix.

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Appendix

MINUTES OF PANEL SESSION

"Theoretical Issues and Practical Aspects of Metamaterial Characterisation"
organized at the 2nd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics "Metamaterials 2008 Congress", Pamplona, Spain , September 21-26, 2008.
by
METAMORPHOSE Virtual Institute ASBL (http://www.metamorphose-vi.org) and
EU FP7 Coordination action project ECONAM (http://econam.metamorphose-vi.org).

Place: room LUNETA
Date: Wednesday 24.09.2008
Duration: 18:45 - 21:00
Recorder of Minutes: Dr. Vladimir Podlozny, VI Secretary General, TKK, Finland
Number of Appendices: I- VII
People present: Panelists and Metamaterials 2008 Congress attendees

I. Panellists:
Sergei Tretyakov, Helsinki University of Technology, Finland
Allan Boardman, University of Salford, UK
Ricardo Marques, University of Seville, Spain
Stefan Linden, Karlsruhe University, Germany
Yang Hao, Queen Mary University of London, UK
Raj Mittra, Pennsylvania State University, USA
Alex Schuchinsky, Queen's University Belfast, UK

II. Pre-meeting exchanges on the Metamaterials 2008 Congress website.

Announcement published on the Congress website were as follows.

"The session will address the three main themes:
1. Effective Parameter Definitions & Physical Meaning
2. Parameter Measurements, Extraction & Interpretation
3. Applications to Antennas, Scattering, Imaging and Cloaking Devices

To make the session focused and help the panellist address the issues of specific interest for audience, we invite you to submit **by clicking "Write comment" on the "Comments" page (login required)** burning questions pertaining to Metamaterials, in general, and the listed themes,

in particular, that you would like to be discussed in the panel session. You are also encouraged to provide any comments that would help shed light on the issues raised by other participants and share your experiences with us. Thus all visitors to the website can benefit from your input, and we can identify certain important issues to be discussed during the panel session. Please make your comments succinct and specific, so that the webpage remains informative and manageable. Please refrain from making any personal or politically-oriented remarks, but keep them focused on the technical issues alone.
The success of this new paradigm for organizing panel sessions that we are following will depend entirely on your active participation--regardless of whether you are a researcher, a scientist, or a practitioner--a theoretician or an experimentalist--or just curious about the topic of discussion. We are counting on you to keep the website humming with your contributions, and are also hoping that you will actively participate in the panel session in Pamplona."

We have got the following comments (the original nicknames are preserved).

1. Effective Parameter Definitions & Physical Meaning

mittra |Author |2008-06-02 02:22:37
Typically the reflection and transmission properties of a medium, illuminated by a plane wave at normal incidence, is used to characterize its effective medium properties. Suppose we have a slab of wire medium embedded in a dielectric--which could even be air--and, for E-field parallel to the wires, we find that the medium is ENG. This implies the stored electrical energy (reactive) is negative for this medium and we can use it to compensate for the positive reactance of a small antenna. But, if we compute the fields inside the physical slab containing the wires, we will find that (epsilon*E-magnitude square) is positive, in contradiction with the effective medium prediction. Does anyone have an explanation that reconciles this contradiction?

rmarques - **meaning of effective parameters** |Author |2008-06-20 13:37:19
I think we can agree in that any effective parameter that we can extract from any experiment should be more predictive than the simple statement of the result of the experiment. Otherwise it has no physical meaning. Starting from this general consideration, I am everyday amazed by the increasing number of scientific papers which extracts some effective parameters (usually inspired on continuous media theory, such as epsilon or mu) from the measurement of the trasnmission and reflection coefficient of a plane TEM wave impinging on a two-dimensional metalo-dielectric structure. What are the new predictions (aparte from the experimental results itself) that we can infere from these effective parameters, if any?

Lexander - **Effective dielectric constant: constructive discus** |Author |2008-07-07 13:26:56
The question of effective parameters of metamaterials is interesting for me too. I propose to start from a bit simpler structures. Let us consider usual 2D photonic crystal consits of high-index dielectic and air. The particular questions are:
1. Are there any confirmed calculated (or measured) curves dielectric constant(DC) vs. frequency for the most popular materials (silicon, alumina...)?
2. In the long-wavelength limit the meaning of effective DC is more or less clear. What about the range where the wavelength is of the same order or higher than the period of a PhC? Can we really use the "effective DC"? If yes what is the definition?
3. If we increase the filling fraction of high-index material OR somehow increase the DC of one of the materials the band gaps as well as the band structure (and transmission spectrum) will be shifted to the lower frequencies. I would say this happens just because of increasing "effective DC" but I'm not sure how to define this "effective DC"

alexeivinogradov |Author |2008-08-20 11:30:24
Concerning energy. Negative permittivity does not mean negative energy because of frequency dispersion inevitably existing at negative permittivity. Thus, the energy will be positive. Wire medium. It seems very doubtful that wire medium can be described by effective permittivity-permeability even at normal incidence (at oblique incidence the effects of spatial dispersion are

strong enough see Belov-Simovsky-Tretyakov at al). The reason is that (I have no rigorous proof) there is no static solution to the problem of diffraction on a single wire. We always have a scale that is much greater than wavelength that is the infinite length of the wire. Computer simulation shows that is senseless to take into account terms of the order of kD, where D is the maximal size of the inhomogeneity (period of PC, distance between inclusions and so on). Other way we obtain unphysical solution and strong dependence on system size. This concerns S-parameter procedure: exact values may be unphysical, because effective parameters are approximation and they can
describe experiment with accuracy kD only.
PC. There is no effective parameters of 1D PC even the period is much smaller than wavelength. Our computer simulation shows strong dependence on system thickness even D/lamda=10(-6) but system thickness L=lambda. Moreover PCV at BG may frequencies support both TE and TM surface waves. Thus it may be considered simultaneously as SEN amd SMN medium.
Homogenization. There is no mathematically strong background for homogenization of operators which are not positively determined. Thus homogenization of metamaterials is a phenomenological activity.

2. Parameter Measurements, Extraction & Interpretation

ahma - **generalization of old-time extraction methods** |Author |2008-05-27 09:05:20
About parameter extraction: the classical method of finding out the permittivity and permeability of a slab of "ordinary" material is to measure the S-parameters and the inversion is rather unique (except for the phase retrieval which may be multiple wavelengths; for that ambiguity solutions however exist).
Very important is the question whether this extraction method is automatically applicable and can be relied on when the slab is made of some type of "metamaterial." Can the extracted permittivity and permeability be trusted without any additional constraints?
Ari Sihvola

andra |Author |2008-07-07 14:26:56
There are publications on extraction permittivity and permeability of the thin slab. For parameters extraction we should know slab thickness well, what is not a problem for in fact homogenous material. But how do we define the slab thickness for 3D metamaterials? What should we regard as the first and last interfaces of the slab, when we process measurements or simulatuion data?
Andrei Andryieuski

sergei |Publisher |2008-07-24 18:33:28
Dear Andrei, we have recently considered this problem of extremely thin "layers", going to the limit of one layer of particles, here is the reference: E. Saenz, P.M.T. Ikonen, R. Gonzalo, and S.A. Tretyakov, On the definition of effective permittivity and permeability for thin composite layers, J. of Applied Physics, vol. 101, p. 114910, 2007.
Basically, our conclusion is that two "traditional" material parameters can model the layer properties only in a limited sense.
Sergei Tretyakov

andra |Author |2008-08-04 11:22:22
Dear Sergei
Thanks a lot for the link - it is really useful.
Am I right that the described method is applicable only for the simple structures which allows analytical solutions? How can we extend this method for measurements and numerical simulation data processing?
What concerns effective slab thickness, it is written in the article you recommended, that for the case of metal structures "... an effective thickness of Deff=1.5D is chosen but we should bear in mind that that this is only rough estimation, and an accurate determination of this effective slab

thickness is very difficult". So the problem is still open and I would be very glad to learn more about that.
Andrei Andryieuski

3. Applications to Antennas, Scattering, Imaging and Cloaking Devices

admin |**SAdministrator** |2008-06-12 12:38:15
Prof. Raj Mittra:
A. Achieving superlensing by using DNG media that magnify evanescent waves.
Perhaps no topic has drawn more attention of metamaterial researchers as that of fabricating a superlens by using a DNG slab.
The figure that has appeared more than any other in the metamaterial literature is the picture of refracting rays that originate from a point source, undergoing negative refraction through the DNG slab, and then focusing on the other side to form the image in a manner predicted by Vesalago, back in 1968.
The important question we raise is: Does the effective medium approach to characterizing a DNG-type slab, which is physically realized by employing periodic inclusions such as split rings and dipoles in a background medium, accurately describe the refraction of wave in the medium. Or is the real-life behavior of the propagating fields substantially different from that predicted by using the eps_eff and mu_eff parameters to describe the DNG medium?
We have carried out extensive numerical simulation of this type of DNG lens configuration and have found that the behavior of the fields inside the slab (or even outside in the image region) is very different from the refraction of rays predicted by the effective medium description of the DNG slab, which is supposed to exhibit negative refraction.
Has anyone else studied the field propagation inside a DNG slab, comprising of SRRs and dipoles and, if so, would care to share their findings with us? In particular, have they found any evidence of magnification of evanescent waves in actual
physical (not effective) medium?

mittra - **b. Negative Refraction in a DNG slab made of SRRs** |Author |2008-06-16 11:14:55
Let us assume that we have constructed a DNG slab by using SRRs and dipoles and have evaluated its effective medium
properties from its reflection and transmission characteristics at normal incidence. Next let us follow the usual practice of
replacing the slab by its effective ε and μ and let us consider a half-space of this negative index medium with free-space above it. If we now come in from the top with a ray (or a Gaussian beam) from the left of the normal to the interface, we would expect the ray to bend toward the left of the normal in order to satisfy Snell's law at the interface and to match the projections of the k-vectors of the two media along the interface. We have carried out a rigorous numerical simulation of the physical structure of this geometry using a Gaussian beam, and have found that the field behavior inside the slab is very different from that predicted by its effective medium model.
We point out an interesting fact which may be helpful for explaining the discrepancy alluded to above. When we come in with a plane wave at normal incidence, its H-field is normal to the planes of the SRRs and, hence, the wave interactions with the medium to yield negative mu and epsilon. However, we note that the phase matching condition is imposed on the tangential components of the k-vectors, and that the propagation characteristic of a wave traveling along the interface is very different for this medium than it is along the normal direction, since the SRRs do not react with the H-fields of the wave in the former case.
But once we replace the physical structure with its effective medium characteristics, as is the common practice, we implicitly assume that the medium is homogeneous and the propagation characteristics of waves traveling through the homogenized medium are independent of the direction of propagation. This is obviously not true for the SRR+dipole structure we are considering here.

mittra - **c. Performance enhancement of microstrip patch ant** |Author |2008-06-16 11:23:14

A large number of recent publications have proposed performance enhancement of conformal antennas, e.g., microstrip patch antennas (MPAs), by covering them with a DNG superstrate (planar), whose function is to act as a Veselago-type lens, and focus the energy emanating from the MPA at infinity to realize increased directivity. It has been convincingly demonstrated that directivity enhancement can indeed be achieved by using DNG superstrates, comprising of SRRs+dipoles, as well as other DNG materials that are periodic structures. If we think only in terms of their effective medium descriptions, we would restrict ourselves solely to DNG media and rule out the use of DPS or ENG type of superstrates. This is because planar DPS slabs won't exhibit lensing properties, and ENG slabs won't let the radiation from the MPA through (because it's refractive index would be pure imaginary). However, we have found that both DPS and ENG superstrates can not only achieve substantially higher directivities than realized via the use of DNG slabs, but have much lower losses as well. We would like to hear from others who have similar experiences. Comments, questions and explanations, all are welcome.111

mittra - **d. Cloaking** |Author |2008-06-16 11:23:48
Another topic which is currently drawing considerable attention of the metamaterial community is "cloaking". The objective is to coat a target with metamaterials such that it becomes invisible to the interrogating wave. The issue here is the realizability of the desired profile for the effective and that would provide the designed shielding characteristics. This is especially true when we wish the cloak to be effective for arbitrary polarizations and angle of incidence, and to be effective over a wide bandwidth as well. We have seen pictures of missiles and aircrafts in several presentations with the authors claiming that they would make such structures invisible by using cloaking.
Let us first recognize up front that the radar world wants a coating which would work over a wide band, preferably 2-18 GHz, or at least a substantial fraction thereof. In addition, they would like to have the shield working for all incidence angles and both polarizations. Despite all the buzz in the literature and media announcements that we have seen about cloaking, no one but no-one comes close even to realizing these goals. Not only are the cloaks designed to-date very narrowband, their RCS may even be higher than the case without the cloak, when the frequency, the incident angle, the polarization, or combinations thereof are changed.

sergei - **Cloaking - reply to R. Mittra** |Publisher |2008-07-29 06:23:37
Yes, the military would like to hide targets at all frequencies, all incident angles, and all polarizations. However, the
conventional stealth techniques reduce only RCS but not the TOTAL scattering cross section. Shaping of an object only
redistributes scattered power over angles. Even if we cover a target with an IDEAL absorber (zero reflection at all incident
angles and polarizations), the total cross section is reduced only by 50 percent (the shadow is not affected).
Cloaking is a very different technique that reduces the TOTAL scattering cross section, and this can have many different (from stealth) applications. Yes, the first realization based on resonant particles is very narrow band. But there are alternative approaches which show wideband effects. Transmission-line cloaks are very broadband. A known example shows at least 75 percent reduction of the total scattering cross section from very low frequencies up to 2 GHz (although this is still 2D and single-polarization device). Once again, shaping and absorbers cannot reach so high reduction levels due to fundamental restrictions!

rmarques - **Cloaking - reply to Sergei** |Author |2008-08-14 10:25:09
Dear Sergei
There is a very fundamental argument against wideband cloaking of electrically big objects (like aircrafts): Since the
electromagnetic signal must go around the object, the phase velocity near the object surface must be higher than the velocity of light in free space c. However, group velocity can not be higher than c. This means that the medium around the object must be highly dispersive. And this necessarily implies narrow band.

sergei - **Cloaking of electrically large objects** |Publisher |2008-09-11 08:54:56
Dear Ricardo,
Yes, I fully agree with your comment. To overcome this fundamental difference we suggested to let the signal go THROUGH the object. Of course, this implies making holes in it, so this method will apparently be useless for hiding aircrafts. But one can make invisible, for instance, a huge metal mast (if the mast is made not of a solid piece of metal, but of inter-connected metal rails).

4. Other Issues of Metamaterial Characterisation

mittra |Author |2008-06-05 21:06:25
More often than not the inclusions we employ to synthesize a metamaterial medium with interesting properties, e.g., DNG characteristics, are such that the material is anisotropic

III. Panel session transcript (partial interpretation has been done in some places!, please see the full video version on the Congress website).

Prof. Alex Schuchinsky:

I would like to ask the panellist to give their brief overview of the problem. Two questions will be allowed to them. After that we will have an interactive discussion.

Prof. Ricardo Marques:
Any effective physical parameter that we want to introduce to characterize should provide more information than data from one experiment. Another requirement is that such description should be as simple as possible and as complete as possible. (See the examples on the slides.)
Example 1 and the conclusion: negative refraction not always means negative refractive index.
Example 2, 3 and the conclusions: negative refraction index does not provide a complete description of some mediums.

Comment:
Thank you for pointing to the problems. An oblique incidence is always more interesting. More insight in this case is needed.

Prof. Sergei Tretyakov:
I will discuss the definition on the effective parameters. Effective parameters are needed to help us to solve very complicated problems that can not be solved otherwise. The parameters should help us to design new devices within the validity of the used effective parameters. Let us consider some examples of the improper use of effective parameters. (See the examples on the slides.)
So when we are trying to introduce EFP (effective parameters) we should define the limits of their validity. E.g. in the plane wave case. When we publish our results on EFP we must say under which conditions they are valid for not to mislead engineers.

Question:
Do you want to say that epsilon and mu and the effects are not physical in your examples?
Answer – Yes, absolutely. The EFP are valid in this case to calculate T and R only for normal incidence.

Prof. Yang Hao.
Two topics to mention. (See the examples on the slides.)
For effective medium model search, measurements and numerical modelling: there is a need for inclusion into consideration of spatial dispersion phenomena and corrections for better modelling results.
For cloaking configurations: effective medium model gives better results than the numerical simulation experiment (?!).

Other examples: metamaterials application in antennas and cloaking structure. The metamaterials are good for practical applications and not always the materials should have very extreme parameters and that could make the production slightly easier.

Question:
It is known that the shown cloaking structures (Smith's structures) were experimentally tested. Please comment your examples: on which picture the results better correspond to the experimentally verified results: obtained through effective material parameters that you criticize or obtained with your FDTD simulations you treat as "exact".

Answer:
Not to any of them.

Prof. Alex Schuchinsky: let us clarify that later during the discussion.

Prof. Raj Mittra:
My slides are named "challenging the popular notions". (See the slides.)
E.g . there is a problem of matching of wave vector on the boundary between the free space and negative index medium if we are deriving this vector from the reflection and transmission coefficients obtained under normal incidence of wave.
Let us consider also double negative medium and a point source. It is periodic in nature (as nobody knows other type of media of these properties). Here we have a contradiction of the ray theory and backward way description: the propagation inside the structure is not obvious and very much simplified.
In other case an ENG slab for antenna directivity enhancement will perform better than a DNG slab. This fact cannot be derived from the EFP approach easily.
In other case a design of small antenna in a shell can not be easily derived from medium EFP.
In other case you can not predict easily the performance of a microstrip antenna using EFP.

Comment:
Your examples demonstrate two components:
We all make mistakes and if we use effective medium in improper case we will fail, but if we will use that in proper case then we can succeed. And generally when you speak about metals you are still using effective medium approach (no separate electrons).

Dr. Stefan Linden:
In our terahertz frequency range we should take into account damping effects of the interfaces in metals. Also in our range of wave-period ratio we are not very sure about effective medium applicability. Also all our structures are very anisotropic and are described by tensors. This is in contrast to isotropic effective media.

Currently we are dealing with layers rather than with bulk materials. We do not know how many layer we need to mimic bulk properties. So it is better to distinct two cases in characterization: characterization via building blocks and a whole structure as is. It is possible to use building blocks description. We can distinct influence of the separate building blocks and their collective behaviour component.

Array measurements are more difficult because the phase information will be missing in reflectance and transmission spectra. You loose the dispersion information.

Interferometric experiments are more precise and can give group velocity and phase information. But interpretation is still difficult. A zero order transmission is OK but sometimes we have more complicated wave propagation paths and additional field excitation that does not coincide with the beam theory. Be careful in you interpretations.

Extraction of EFP from physical experiment only is insufficient and needs usually comparisons with numerical modelling results.

Also the bianisotropy should be taken into account if the structure under consideration is non-symmetric regarding the propagation direction.

Cross coupling of the elements in the structures should be taken into account also.

Question:
How do you account for the substrate in your characterizations?

Answer:
Yes this substrate should be taken into account. In some cases it does not influence, but this depends on the particular characterization experiment.

Prof. Alan Boardman:
We should not relay mostly on reflectance and transmission measurements. May be there are other measurements available like waveguide measurements, ray optics, subwavelength measurements, transmission-line measurements, super and hyperlense measurements. People start to measure more anisotropic epsilon and mu rather than isotropic parameter.

There are questions of non-linearity and tunability. Almost no one is paying attention to non-linearity.

We need to examine our concepts. Is the refractive index the top-priority?
We need to be careful about optical magnetism as well.
We should decide on the anisotropy - in which cases that is important.
We have to broaden our concepts: where we have materials and where we have structures.

Also there is no use of materials if we can not control their properties. Electro-optics can be one of the ways forward along side with mangneto-optics.

We should look forward and think about the integrating systems based on metamaterials. There will be computational difficulties to describe metamaterials in bigger systems. We need to hear a lot more about genetics algorithms here. That is a one of the good ways forward.
FDTD looks very promising as well finite element methods. But there will be problems of matrix inversion, boundary problems, fine mesh problems. We have tried to reproduce some results for some cloak and it seems that was not possible… John Pendry says the FDTD step should be zero to really see the cloak properties… May be we will need to change our computational strategies?

At the end, 3D problems are challenging.

Question:
Why do we need an isotropic refractive index while we can solve problems with anisotropic parameters.

Answer:
Yes, do not need the isotropic refractive index because it is not in the Maxwell equations.

Prof. Alex Schuchinsky (summary):
What kind of parameters do we need?
What dictates the choice of parameters?
What kind of parameters can be measured directly?
What parameters are fundamental for metamaterials and our measurements?
How are we going to use these parameters?

Usually people measure

- reflectance and transmittance
- Q-factor and resonance frequency
- field mapping and time-domain spectroscopy

We should decide on specific conditions and purposes how we are going to use these parameters.
The applicability of interpretation techniques is an issue too.
How to find applicability and how to prove validity of EFP?
How to take into account interaction between materials and the measurement instruments?

I would like to hear your opinions!

Roberto:

I would like to raise the issue: some researchers in their papers violate the second law of thermodynamics or the first law! But EFP are very well established and their validity is clear sometimes like in optics. The lattice-wavelength ratio is important! For the ratio 1:1000 that works! The theory should be applied properly.

Prof. Raj Mittra:
We apply theory in the frequency range where particles become resonant and we need to think differently. You usually should decide what you want to use: effective medium approach or structure description approach.

Roberto:
The same in optics - resonances exists there too and the EFP work well there!

Prof. Raj Mittra:
In microwaves that is different. Question to the Prof. Sergei Tretyakov: in your examples you just match the EFP to the situation. How can you say that is correct in general? May be that is correct for that particular situation? The problems come when people start to use the claim of the particular EFP values without considering the situation of their extraction.

Prof. Sergei Tretyakov:
Confusion comes when somebody starts to interpret the measured data by the particular characteristics like permittivity.
Indeed, we have problems in optics when the particles and the lattice become resonant in this frequency range. And you start to mix these two resonance responses.

Roberto:
We should not use effective medium approach at those ratios!

Richard Taylor:
It is good to find a common language. You should not compete with each other but work together and develop a common view on that. You should translate you ideas rapidly to industry and telecommunications.

Prof. Alan Boardman: nano-structured materials are here. Our life will be run by these materials. But do we really understand concepts? But we are ready to add value already like for the solar panels e.g. with the existing materials.

Prof. Mark Stockman:

Fundamental physics is needed here. We do not know yet what can come out of that. But there are already many practical applications.

Prof. Ricardo Marques:
It seems there are no universal parameter extractions methods for different measurement cases. You need some insight to the materials at first place (symmetry, etc.). Isotropy is not the key issue. But it is completely useless to describe anisotropic materials with isotropic parameters. That is big mistake.

Prof. Alan Boardman:
We need to broaden our concepts. Photonic metamaterials are going to the markets. But we have to be careful with the concepts.

Comment:
1. We would like to see more discussions on characterization out of electromagnetic but in acoustics etc.
2. Industry needs to see all aspects of characterizations problems.

Prof. Yang Hao:
1. Photonic band gap structures are very good for commercialisation.
2. FDTD is quite good for metamaterials modelling, I think.
3. Effective medium model is very good for metamaterials to verify new ideas.

Prof. Nigel Johnson:
We are actually trying to make transitions from layers to bulk materials description for metamaterials. But photonic band gaps materials are good with two-tree-four-etc. layers already! Analogy with these materials and analysis of the validity there could help us for effective medium approach.

Prof. Filiberto Bilotti:
A bottom-up approach can be useful here. Why not to find the needed parameters of the materials first and then try to build such materials? We could find for particular problem a particular solution based on isotropic concept but under certain conditions like chosen polarisation. Doing similar things we can find way directly to applications.

Prof. Raj Mittra:
Have you seen anybody who solves Maxwell equations with all anisotropic parameters?

Prof. Alex Shuchinsky:
Yes. E.g. ferrites and anisotropic dielectric substrates are described precisely in that way.

Prof. Igor Nefedov:
The group velocity concept should be studied carefully here.

Ricardo Marques: Blind use of concept should be avoided. We should see particular conditions to select proper parameter to extract.

Prof. Raj Mittra:
We should stop now.
Thank you!

P.S. A link to the session video and audio recording will be available at the Metamaterials 2008 Congress website.