METAMATERIAL ANTENNAS*

*OR ARE THEY?

Introductory Remarks
by

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2. Definition of Metamaterials

There are a number of definitions of Metamaterials (MTMs), the most popular among them being "materials that don't exist in nature." This definition, which was introduced when everyone was looking for doubly-negative (DNG) materials to realize a perfect lens, has created much confusion, and has also given a bad name to MTMs that are often labeled as being narrowband, dispersive and lossy. (See slide#5). While that description indeed does fit materials that are artificially synthesized to realize either DNG characteristics, or those with $\varepsilon < 1$, or $\mu < 1$, it should not really concern us, however, since none of them have ever found their place in any practical device anyway. On the other hand, what has worked for us--when we have attempted to enhance the performance of various antennas--resembles an FSS (Frequency Selective Surface) , an EBG (Electronic Band Gap) structure, or a filter comprising of lumped or distributed L's and C's. These structures have been found to be useful for enhancing the performance of an antenna by realizing a higher gain or increased scan capability, or by reducing the mutual coupling between two adjacent antenna elements. The question before the house is: "Is it correct to refer to these structures as MTMs, which seems to be the trend and the vogue at present?"

While "freedom of speech" is a good thing to cherish, it should not be used to create confusion, which seems to be the case in many publications and presentations on MTMs that we come across routinely every day. So, what are we going to do to address this problem? To respond to this burning question, we propose a definition of MTM which, if adopted, would mitigate this problem for good, we hope.

3. PROPOSED DEFINITION OF MTMs

If we design an antenna, or a similar device using an artificially synthesized material, which is a "volume" as opposed to "surface-type" of structure (e.g., a screen), ***and*** we utilize its equivalent ε and μ to carry out the design, it would be legit to called it an MTM-based design. However, if we use a thin FSS screen, or an EBG surface such as an AMC (artificial magnetic conductor), and only make use of their reflection and transmission characteristics, then we should not refer to them as MTMs. We can call them "Metasurfaces" instead, implying that they are artificially synthesized surfaces to produce the desired transmission, reflection or propagation characteristics. (See slide#6)

However, if we either do not, or cannot, define their ε and μ values—how do you define the equivalent ε and μ of an infinitely thin FSS anyway, and why should you even want to, I wonder—then we should refrain from calling them MTMs, and either refer to them by their old familiar names, e.g., soft and hard surfaces, FSSs, EBGs, AMCs, etc., or we can name them Metasurfaces, just to please our sponsors, if we are into playing that kind of a game. Likewise, if we take an antenna and simply load it with lumped or distributed L and C elements, we should strongly resist the temptation to call such antennas "MTM antennas", since we have to stretch our imagination more than just a little to see anything in such a design that resembles any "material" *per se*. The moral of the story is that we should heed the advice of Shakespeare, who warned us to "call a spade a spade" and not give it a fancy name such as an "instrument of animal husbandry," to make it sound more exotic. Likewise, we should not close our eyes and refer to everything in sight as MTMs, that are nothing but old familiar versions of FSSs, AMCs and EBGs, etc., just to get some funding from our sponsors.

4. ADDITIONAL REMARKS

An intriguing way out of this conundrum we face, in regard to the issue of naming the MTMs, is to refer to antennas that have been modified ***not*** by using MTMs, but by using a single element of a periodic structure--which would be an MTM if it were periodic--is to call it an "MTM-inspired" antenna, a name that has been coined by Rick Ziolkowski (see his presentation, which follows next).

I believe that such a definition correctly describes a class of antennas whose geometries have been modified by passively coupling them with the MTM-inspired elements, and it is good to see that the trend in the literature to embrace the use of this terminology to describe antennas of this type, many of which have been successfully developed by a number of workers.

There is one word of caution that I would like to throw in here, however. I think that whoever proposes an MTM-inspired antenna should have an obligation to show us that this approach to enhancing the performance of an antenna, say a small dipole, or whatever his starting antenna configuration is, in terms of gain, bandwidth, etc., yields a design that is superior to one that I might come up with if I were to start from scratch and fill the available volume with an antenna geometry which does a better job of satisfying the Chu-Harrington, or the Gustafson condition, than does the MTM-inspired version.

As Steve Best has shown us by developing several examples of small antenna designs, he can do one better than some of the proposed MTM-inspired designs, without even thinking of getting MTMs in the picture, but just relying upon his expertise and past experience, and using strategies that are a far cry from MTM-based designs, whether inspired or not. He simply **co-designs the active and passive parts of the structure**, so at the end of the day it does not at all look like a dipole, or whatever it was that the MTM-inspired designers started with, and to which they have coupled an MTM-inspired element. So, the moral of this story (inspired by Shakespeare once again) is: We should ask ourselves "What's in a name?" and then go ahead and use whatever strategy gives us the best performance, without worrying about whether or not it is MTM-based and/or inspired. And if our MTM-inspired antenna is bested by a "Best-type" design, then we should go convince our sponsor, who might have dictated us to follow the MTM-route in the first place, that this is the "best" way (pun is intended), because he would need to justify his funding decision for our Metamaterial project to his boss, who holds the purse strings, and assure the Program Manager that his money has been well spent.

5. FYI--Quote From: Research Group/ Duke University

"Any of these concepts for perfect lenses would all need to address the fundamental problem of perfect lenses, which is that losses place a severe limitation on the sub-wavelength focus. I don't think I've seen an example yet where the perfect lens concept can compete with traditional engineering approaches, given the limitation of losses. Adding gain, which is something that Steve Cummer's group at Duke also looked at, seems to be marginal in improving the situation for many reasons. The most encouraging work I've seen has made use of a nonlinear process (four wave mixing) at a metamaterial surface to generate effectively negative refracting waves. Since you can pump in as much power as desired, there might be some hope of achieving significant sub-wavelength focus. Otherwise, the inherent losses of metals are just too much, at nearly any wavelength"

6. Reflectarray Design

Using a Metasurfaces (Metasurface?) (not MTM)

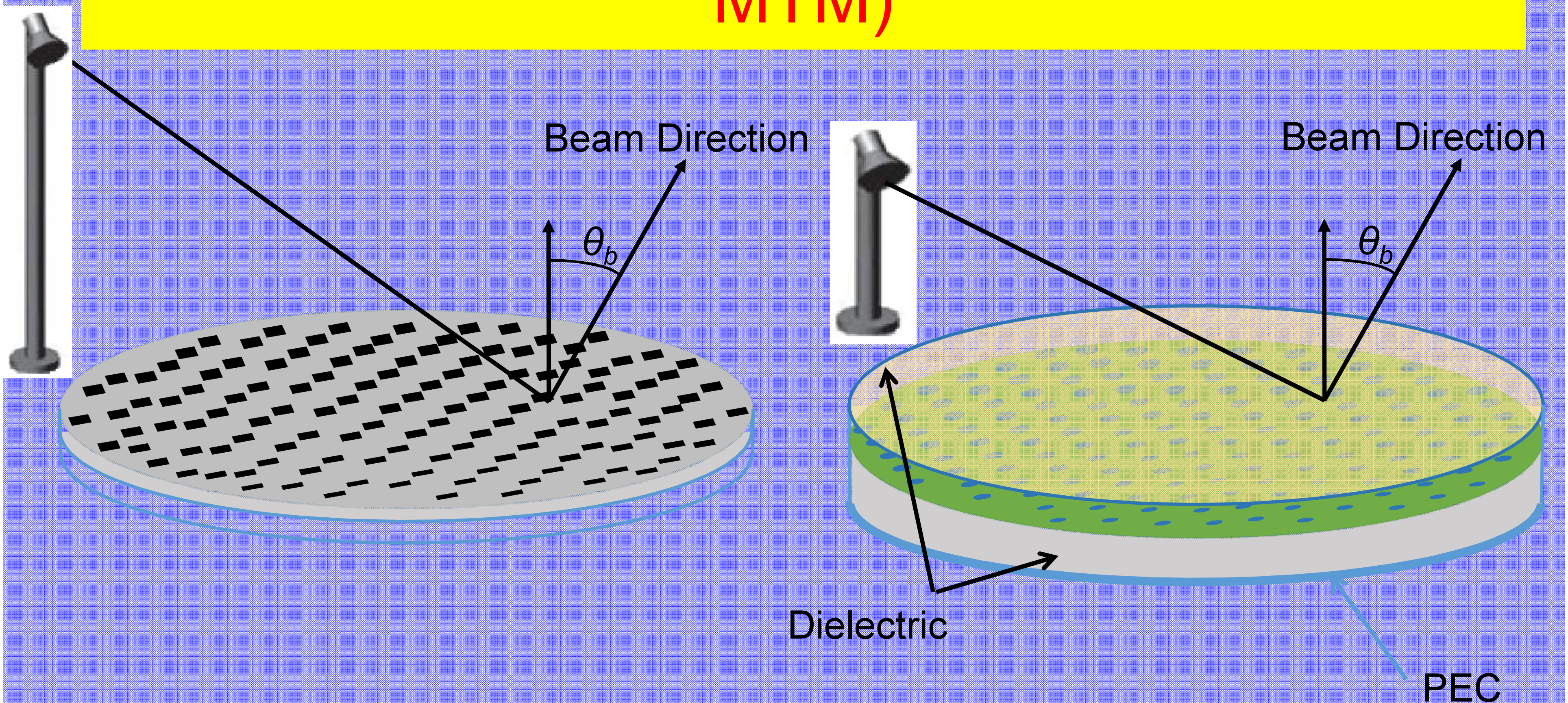


Fig. 1a. Conventional reflectarray based on meta-surface design

Fig.1b. 3D printable dial-a-dielectric design for low loss broadband performance

7. A CHALLENGE

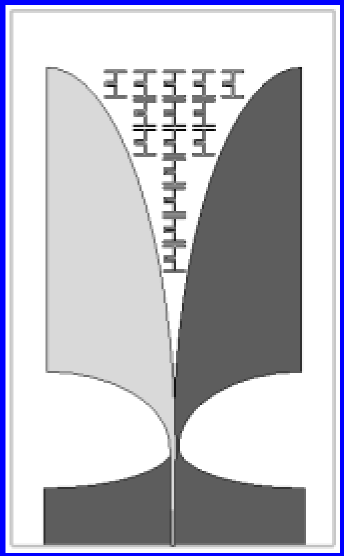
Here is a challenge I throw out to the antenna community in general.

Find an example of:

1. An antenna design which has successfully used either a DNG, an ENG or an MNG material, typically referred to as MTMs, to enhance the performance of a real-world antenna in terms of gain, bandwidth, efficiency, etc., better that what can be done with double-positive materials.
   Note: I have yet to find one, and Zhining (see his presentation below in this section) appears to claim that he didn't find one either in his experience.
2. A Metasurface (artificially-engineered surface with dielectric or metallic inclusions in a background medium), which *cannot* be identified with a single or multilayer FSS, an EBG, or a soft/hard surface.
3. An antenna with a Metasurface where it is advantageous to use effective ε and μ type of representation rather than the reflection and transmission coefficients.
   Note-1: In a Fabry-Perot type of design, we use PRS (partially reflecting surfaces) for the superstrate, which can be called Metasurfaces, rather than Metamterials described by effective ε and μ.
   Note-2: I maintain that in most practical examples of antennas designed with metasurfaces (see example of an antenna designed by Zhining which appears in his presentation (see also next slide), it is better to analyze and simulate the physical structure in an EM simulator, rather than using its highly anisotropic ZIM (zero index medium) type of effective medium representation; otherwise, we suspect that the results would not be accurate, and/or reliable. Furthermore, with only a few scattered elements (inclusions) placed in the mouth of the tapered slot antenna, a material type of description is hardly valid, and treating it as a bulk anistotropic medium is not very meaningful or useful. In addition, it is very difficult to extract the equivalent medium properties of a fully anisotropic medium, especially when these medium properties are strongly angle-dependent, as they often are.

8. POP QUIZ

Is the antenna shown below: (i) A Metamaterial Antenna? (ii)A Metamaterial-inspired antenna? (iii) Or, is it an antenna that uses an artificially-engineered dielectric substrate, *aka* a Metasurface, to control the propagation characteristics of the substrate of the antenna to realize the desired characteristics?



Antipodal TSA (tapered slot antenna)

from Zhining