Editor's Introductory Comments on FORUM on Metamaterial Antennas, Wideband Matching and Active Metamaterials

Reviewing a bit of history of Metamaterials (MTMs), one finds that about a decade ago we were introduced to the unique concept of Metamaterials, *aka*artificially engineered materials, as opposed to the type of materials you could order off-the-shelf from a vendor. The concept of MTMs soon evolved into, and branched off to, a number of different directions such as cloaking, sub-wavelength imaging using superlenses comprised of double-negative (DNG) materials, and enhancing the performance of antennas by using MTMs. The article by Alu *et al.* (Alu-ART-2014-01-007 Cloaking and invisibility: A review) presents a comprehensive coverage of the subject of cloaking, and the write-up by Chen *et al.* (Chen-FOR-2014-01-002 Metamaterials-based Antennas Translation from Physical Concepts to Engineering Technology) reviews the topic of MTM antennas and apprises us about the state-of-the-art of these antennas.

Although combining DNGs with certain types of planar antennas, e.g., a microstrip antenna, did enhance its gain--albeit to a moderate extent--the same could not be said about its bandwidth enhancement, and metamaterial-based antennas were proposed as answers to the small antenna problem to address the bandwidth issue. It is well known that a dipole or monopole antenna whose dimensions are small compared to the wavelength is an inherently narrowband device, and that it presents a formidable challenge when one attempts to impedance-match it by using an inductor to neutralize its highly capacitive input reactance. What exacerbates the problem, even further, is that the radiation resistance of a small dipole antenna is also small; hence its Q is high, which implies that its bandwidth is narrow. One might be tempted to conjecture that if we can find a material whose ε is negative, the stored electrical energy in this material would compensate for the positive electrical energy associated the Capacitance of the antenna and would, therefore, render the small antenna loaded with the ε-negative material a broadband device. Unfortunately, such a conjecture turns out to be false, and attempts to broadband a small antenna by using this strategy have not been successful to-date.

Next, there came a switch from Metamaterial-based to Metamaterial-inspired antennas. The underlying concept upon which the MTM-inspired antennas are based is as follows. Load the small antenna with metallic structures whose geometrical shapes are *inspired* by geometries of the unit-cell elements typically used to realize Metamaterials (MTMs), or artificially synthesized materials, that are inherently periodic in nature. There has been a flurry of activities in recent years in the area of MTM-inspired antennas and the antenna literature is replete with novel designs of such antennas that attempt to provide an efficient and broadband solution to the small antenna problem. The jury is still out on whether or not these antennas perform better than other antennas of similar dimensions, but designed by using space-filling and other strategies from the very beginning, instead of looking at the design problem as that of appropriately "loading" a given antenna, e.g., a dipole, with MTM-inspired geometrical structures to achieve the desired goal. It is all but certain that research into as well as debate of this issue is going to continue for some time to come.

In the meantime, we are witnessing a recent shift in attention from the MTM-inspired designs to the so-called non-Foster designs, which utilize active circuits such as NICs (negative impedance converters) to synthesize negative capacitances that compensate the positive C of the small dipole antenna, for instance, to achieve an impedance match over a much broader bandwidth than could be achieved by using a matching inductance instead. This is because the slope of the reactance of a negative C with frequency is identical to that of a positive C, though its sign is opposite, of course, which is what we want in order to affect the cancellation of the reactance to render the antenna broadband.

It would be interesting, at this point, to inject some "official" views on the topic of Metamaterials. The first one, is a quote from an announcement that came out of Wright Patterson Air Force Base). It reads;

"Metamaterials have been in the news lately--and not only in technical journals. That is because the attributes of metamaterials are seemingly magical. When arranged just so, these extremely small manmade elements can alter the character of electromagnetic radiation in ways that no other material--either natural or manmade--can.

One such metamaterial characteristic which the popular press invariably plays up is the comparison to the stealth capability demonstrated by Harry Potter's invisibility cloak. And yes, it has been shown that metamaterials can re-route light around objects, but the practical application of that attribute is many years hence, if it will ever come to pass. But much more significant, is the imminent transition of several metamaterial capabilities to the commercial world that will have meaningful and practical effects, to include less expensive satellite communications, thinner smartphones, ultrafast optical data processing, and much faster (and cheaper) internet connectivity on-board planes and from mobile phones.

The Air Force Office of Scientific Research, while looking forward to the day when metamaterials may be employed to make objects less visible, can take solace in the results of AFOSR support for early metamaterial researchers that made much of the current success possible.

It was in 2000 that AFOSR program manager Dr. Harold Weinstock was contacted by Dr. Shelly Schultz, an AFOSR-funded research professor at the University of California, San Diego (UCSD), regarding significant advances in metamaterials based on theoretical work done in the 1990s by John Pendry of Imperial College, London. Pendry and his team theorized that an array of tiny copper wires and rings had a negative refractive index for microwaves--designed so that microwave radiation flowing towards the array was deflected in a direction opposite to what was normally observed. This triggered intense interest in metamaterials, admittedly in part, because the ability to bend radiation in such a way had the potential for creating invisibility cloaks. But there is much more to metamaterials than the hoped-for cloaking device.

Schultz and his team, which included senior post-doc David R. Smith, were responsible for the first laboratory demonstration of a metamaterial in 2000. Dr. Weinstock, impressed with the results of the UCSD effort, ultimately provided AFOSR funding to continue this research. Smith, as well as other AFOSR-supported metamaterials researchers, went on to explore new characteristics and applications of this remarkable laboratory material.

Smith, who is now at Duke University in Durham, North Carolina, has turned his attention to metamaterial commercialization efforts. A new company hopes to market a compact antenna that would be one of the first consumer-oriented products based on metamaterials. The relatively inexpensive device would carry broadband satellite communications to and from planes, trains, ships, cars and any other platform required to function in remote locations far from mobile networks. The key to its operation is a flat circuit board with thousands of electronic metamaterial elements which allows the antenna in the device to track a satellite without having to maintain a specific orientation towards it, the way a standard dish antenna does. The antenna's position can remain constant, and the software will instantly adjust the electrical properties of each individual metamaterial element to optimize connectivity with the satellite--in both send and receive modes. Smith notes that this compact design offers "significant savings in terms of cost, weight and power draw."

Another metamaterials innovation by Smith's research group concerns a camera that can create compressed microwave images without a lens--or for that matter, any moving parts. This camera is of particular interest when applied to airport security, as it could significantly reduce the cost and complexity of the airport security scanning process, as it requires very little data storage to produce a detailed image of the scanned object, wherein the metamaterials elements can be fine-tuned to block, or permit, the reflected radiation for the subject being scanned. Although in its elementary stage of development, the ultimate goal would be to replace the current generation of big, slow and expensive airport scanners with thin, inexpensive metamaterials-based cameras whose images are quickly processed via computer. What makes this concept even more attractive is that security scanning would be quicker, less expensive, much less obtrusive, and capable of being placed throughout an airport or wherever security scanning is warranted.

Other aspects of metamaterials are being explored in different ways by three other AFOSR-funded researchers at different universities: Federico Capasso at Harvard University, Xiang Zhang, at the University of California, Berkeley, and Jennifer Dionne at Stanford University. Capasso, Zhang and Dionne, as well as David Smith, were all funded through an AFOSR Multidiciplinary Research Initiative (MURI) beginning in 2004, and managed by AFOSR Program Officer, Dr. Gernot Pomrenke. This MURI effort was a key aspect in kick-starting many of the new avenues of discovery that are now starting the long path from the laboratory to commercialization.

Federico Capasso, who has been supported by AFOSR in several areas, including quantum cascade lasers, wavefront engineering, and designer plasmonics, unveiled a flat metamaterials lens in August 2012 that can focus infrared light to a point in much the same way as a glass lens. While stating that this was not a novel accomplishment, he says that his was "the first group to so clearly put flat optics on the agenda for commercial applications."

Capasso notes that the commercial applications of these flat lenses are still a decade away. One direct application would be in smartphone cameras, as lenses are currently one of the limiting factors in determining a smartphone's thickness. Capasso speculates that a smartphone with a flat camera lens could potentially be made "as thin as a credit card."

There is still another problem to overcome: flat lenses have a diffraction limit just as for conventional glass lenses. This means that no conventional lens can resolve details much smaller than the wavelength of the light that illuminates its target. But metamaterials offer a solution to this conundrum; metamaterial superlenses, and hyperlenses could resolve details beyond the diffraction limit, and capture sub-wavelength details of target objects. This is accomplished by the metamaterials lens capturing what are termed "evanescent" waves of reflected light, that normally vanish soon after being reflected from the object they strike and therefore, cannot be captured by any conventional lens. But a metamaterial super/hyperlens can magnify and capture these light waves.

Just such a lens was demonstrated in 2005 by Dr. Xiang Zhang's AFOSR-funded group at the University of California, Berkeley, and they have been working to refine the concept since that time. Their effort has concentrated on not only the capture of evanescent waves, but transferring them to a conventional optical system. As such, this process would allow hitherto unavailable evanescent light wave details to be transferred and viewed through the eyepiece of a standard microscope. Unfortunately, there are hurdles to overcome with regard to the complex structure of superlenses and hyperlenses, which makes them difficult to manufacture and use in this way.

Zhang is also looking at utilizing these lenses to construct nano-sized objects, as the lenses cannot only capture and direct sub-wavelength beams of light, but can also reverse the process and focus that light for the fabrication of nano-sized structures--such as smaller computer chips--using photolithography. But both Smith and Zhang note that there are drawbacks with this process compared to other advanced lithographic approaches, but the potential exists for ground-breaking applications.

AFOSR, which manages the basic research investment for the United States Air Force, continues to search out and support cutting edge science that promises revolutionary capabilities. Over the years, this funding has been judiciously applied to successfully advance the amazing attributes of metamaterials--making the theoretical, and seemingly magical, into innovative applications for the Air Force and society at large."

As you can see, the writer paints a very optimistic picture of the future of Metamaterials, and also argues that the field has seen a considerable progress already. However, more recently, at the Metamaterial conference in Bordeaux, France, we heard a very different message from a high-level Project monitor who has supported a number of Metamaterial-related projects on behalf of another government agency in Washington. He basically said that his agency has been very disappointed with the lack of progress in the field, since '*much has been promised but little has been delivered,"* he said. In fact he went on to add that his agency will no longer support any further research on Metamaterials except in the areas of infrared and acoustics.

Obviously, these conflicting messages coming from these two agencies are disconcerting and it would be very desirable to see through all the hype about Metamaterials and get to the meat of what has been accomplished to-date and where do we go from here.

To encourage a debate on some of the issues mentioned above, we present the following three items in this section: A short review and a position paper by Zhining Chen (Chen-FOR-2014-01-002 Metamaterials-based Antennas Translation from Physical Concepts to Engineering Technology), and two sets of PPT files by Wenxian Li et al. (Li-FOR-2014-01-003 Wideband Matching of an Electrically Small Antenna Using a Negative Impedance Converter Technique), Khalid Rajab et al. (Rajab-FOR-2014-01-004 Stability & Noise in Active Metamaterials) covering the topics of active matching and active metamaterials, respectively. The PPT files are from symposium presentations by the above authors. We mention that additional information on Li's work may be found in *Wenxing Li, Ning Zhai, Ruilong Chen, and Wenhua Yu, "Non-Foster Impedance Wideband Matching Technique for Electrically Small Active Antenna," International Journal of Antennas and Propagation, Hindawi Publishing Corporation, Volume 2013, Article ID 531419.*

In keeping with the objectives of the Forum section in FERMAT, we pose some key questions for readers to deliberate on and then express their views on these questions pertaining to small antenna designs.

The list of questions we pose is shown below. The readers can feel free to add to this list, and are strongly encouraged to do so.

1. (a) What does the future hold for metamaterial and/or metamaterial-inspired antennas?

   (b) Should we just restrict ourselves solely to the first quadrant of Zhining's Fig.1?

   (c) What are some of the other examples of metamaterial success stories?

   (d) Is there a systematic way to realize artificially synthesized materials wit prescribed material properties, or is it just 'hit and miss'?

2. (a) Is active matching the preferred choice for solving the small antenna matching problem to realize wideband performance?

   (b) What are the fundamental issues that have limited the use of such matching in practical antenna applications, even though the basic concept of NICs has been around, and such active matching concepts have been touted for more than 50 years?

   (c) What does the future look like for non-Foster matching? Where do we expect to be with this approach 5 years from now?

3. What are some of the fundamental difficulties we encounter when we use active metamaterials to overcome some of the shortcomings of conventional metamaterials, e.g., losses and narrow bandwidths, among others? Or, should we simply embrace the strategy proposed by Zhining Chen and simply restrict ourselves to passive materials that belong only to the first quadrant of his Fig.1?

We welcome your comments and additional questions on these issues and encourage the authors to join in as well. Please share with us your success stories, as well as frustrating experiences that you may have had, restricting initially to the Microwave regime (as opposed to Optics or Acoustics), since there are many applications in the Microwave area as has been mentioned above, as well as challenges.