Guest Editorial: Special Cluster on Metamaterials

In 1968, Russian physicist Victor Veselago considered the electromagnetic properties of a hypothetical material whose electric permittivity and magnetic permeability were both negative [1]. Such a material, Veselago noted, did not seem to exist in nature, although there were no apparent fundamental reasons that this should be the case. Veselago went on to study the electrodynamics of his hypothetical material and uncovered a wealth of new phenomena potentially waiting to be explored. In addition to reversing Doppler shifts, the direction of Cerenkov radiation generated by charged particles, and the sign of radiation pressure, materials with negative permittivity and negative permeability had a very basic property: negative index of refraction. The curious electromagnetic behavior associated with negative refraction had been noted in passing by other researchers [2]–[4], but Veselago anticipated that materials with negative index would carry enormous implications for wave-matter interactions at all wavelengths, impacting geometric and wave optics at the most primitive level.

However, negative index materials did not exist. Thus, Veselago’s analysis appeared to be an interesting but mostly futile exercise in electromagnetic theory.

Electromagnetic waves are one of the most important means of sending and receiving information and signals and are an essential tool for imaging, spectroscopy, and myriad technologies. Since electromagnetic waves do not interact with each other, though, materials must be used as a means of controlling and manipulating waves, leveraging the coupling between fields and charges. Insulators and conductors, for example, are used to confine and guide electromagnetic waves, while dielectric materials shaped into lenses can focus or collimate light. Modulating the opacity of a surface produces a diffractive or holographic optic capable of forming complex beam patterns. In all situations, the ability to manage electromagnetic waves is improved by the quality and the range of materials available. Where material properties are more limited, such as in certain terahertz or infrared bands, controlling light becomes commensurately more challenging.

Therefore, any advance that enhances our ability to achieve desired material conditions translates to enhancing our ability to control electromagnetic waves. Additionally, the realization of new material properties potentially translates to new electromagnetic devices and components—which is why Veselago’s hypothetical material was so compelling: An entirely unrealized set of material properties would have clear implications for a vast array of technologies. Yet, the fact of the matter is that many material properties—even those that may already exist in nature—are often not easily achieved, especially at all wavelengths. Magnetic response, for example, is associated with inherently magnetic materials (i.e., those that derive their properties from unpaired electron spins) and is all but absent at frequencies above a few terahertz. For this reason, most optics texts ignore the magnetic permeability entirely, leaving behind the concept of wave impedance and many other aspects of wave propagation common at other wavelengths. In short, while negative index is a new and enticing material property, it is just one of the many types of material properties that are useful, but have limited appearance in naturally occurring materials.

If one looks a little more closely at the situation, though, one finds that the apparent lack of options in material properties has a more subtle origin: the definition of what constitutes a material in the first place. In actuality, a “material”—at least from an electromagnetic wave perspective—is just a collection of objects whose electromagnetic response can be readily distilled into a few key parameters. Those collections can be conceptually formed into imaginary continuous “materials” with homogeneous properties, but they are truly inhomogeneous at the microscopic level. Thus, while the conventional view of a “material” might be of a structure that derives its properties directly from atoms or molecules, there is no requirement that this be the case at the conceptual level. A “material” could be a collection of macroscopic objects, which is fine as long as the wavelength of the wave is larger than the dimensions and rough spacing of the objects forming the collective. In this way, the “material” derives its properties from the structure of the objects inasmuch as it does from the actual chemical composition.

It has been well understood for more than a century that an effective medium can be formed by using objects other than atoms or molecules as conceptual building blocks. As early as 1903, Maxwell Garnett explained the striking colors of stained glass in terms of the effective media created by the mixture of metallic nanoparticles with glass [5]. In the 1940s and 1950s, engineers such as Rotman and Kock fashioned metal structures into artificial media that functioned as lenses, horns, and other elements relevant to antenna technology [6], [7].

However, the concepts and techniques of artificial media really did not catch on in a major way until relatively recently. One can point to a number of reasons as to why, only now, the community has so rapidly adopted the paradigm shift of a metamaterial—the modern term for artificial media. The computational power for ascribing accurate constitutive parameters to an arbitrary collection of scattering objects became commonplace over the past decade. Likewise, micro- and nano-fabrication capabilities have become ubiquitous, enabling the rapid turnaround of metamaterial prototypes and samples. However, perhaps the reason is more basic: In 2000, Veselago’s negative index material was finally demonstrated, and demonstrated through the use of artificial media [8]. The idea that metamaterials could make into reality what had previously been only hypothetical provided more than enough motivation to now explore all that can be offered when we enlarge our definition of a “material.” In fact, in electromagnetics, the past decade has seen an explosion

Digital Object Identifier 10.1109/LAWP.2012.2183989
in researchers probing the possibilities of materials that would have previously been considered irrelevant, such as Veselago’s original conjecture.

The creativity unleashed by the metamaterial concept has allowed the effective medium approach to spread to contexts that might at first seem unlikely. For example, the propagation of a guided wave along a transmission line is often described using the language of circuit models—propagation lines peppered with electrical components, such as capacitors, inductors, and resistors. Still, real transmission lines are ultimately based on materials, from the conductors that serve as leads; to the dielectric materials filling, for example, a coaxially waveguide; to the substrate materials separating a ground plane from a microstrip. Those skilled in the design and implementation of transmission lines and RF circuits realized immediately that the concepts emerging from metamaterials could be transitioned to guided wave technology, resulting in an explosion of new antenna and microwave component paradigms [9], [10]. Even Veselago’s negative index medium has found useful applications in the form of backward-wave transmission-line structures, such as those appearing in this special cluster.

In fact, the diversity of explorations in this special cluster represents how profound the metamaterials concept is and how the possibility of increasing material response can impact many different application areas in electromagnetics. In this section, we see fundamental effective medium concepts continuing to be explored in both the language of materials (Vardaxoglou) and that of transmission lines (Pollock, Selvanayagam). Metamaterials based on patterned surfaces are particularly compelling since losses become much less of an issue and are considered from both fundamental (Maci, Kaipa, Holloway, Gregoire) and applied (Sievenpiper) perspectives. Metamaterial antennas and metamaterial elements that enhance antenna performance still remain a strong topic of interest and a fruitful area of research (Cao, Cheng, Guclu, Jiang, Ibrahim, Nakano).

As application areas are considered, the required properties of metamaterials become increasingly specific and must be constructed to meet often challenging targets. A number of techniques that aid in this sort of specific design and optimization of metamaterial structures are presented in this cluster (Ohira, Bayraktar, Basilio). Ultimately, the ability to reconfigure a material or artificial material at will may prove to be the greatest advantage of metamaterials, which are particularly suited for integration with dynamic tuning or active components. Metamaterials that incorporate such active elements are also considered in this cluster and also represent an important thrust of metamaterials research (Katko, Michishita, Zhu, Gregoire).

Over the years, metamaterials have become not only appreciated for their potential practical impact on electromagnetic devices, but also for their impact on our imaginations. Because of metamaterials, entirely new material-based optical design methodologies have emerged, such as transformation optics [8], that bring exotic—almost science-fiction-like—devices a step closer to reality. Transformation optics is a tremendously elegant, conceptual tool for electromagnetic design, in which wave propagation is managed by pushing and pulling space around using coordinate transformations. The technique produces complex, challenging material designs that perhaps can only be achieved applying the inherent flexibility metamaterials. In this special cluster, the transformation optics approach is illustrated for improving lenses (Demetriadou), while, applying an alternative design approach, Alitalo et al. leverage invisibility cloaks for antenna applications.

The letters contained in this special cluster of the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS collectively represent a snapshot of many of the research directions currently underway in the metamaterials community and are illustrative of the potential that can be unlocked by simply taking a broader view of what constitutes a “material.” While the demonstration of Veselago’s negative index medium initially propelled the metamaterials community, it has now become commonplace to build and demonstrate materials that might have been dismissed as impossible or impractical just a few years before. This special cluster demonstrates that metamaterials concepts are maturing, but that the future holds many more surprises.

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REFERENCES


David Schurig (M’12) received the B.S. degree in engineering physics from the University of California, Berkeley, in 1998, and the Ph.D. degree in physics from the University of California, San Diego, in 2002.

After receiving the B.S. degree, he worked at the Lawrence Berkeley National Laboratory, Berkeley, CA, on laser ablation and photoacoustic spectroscopy. After enrolling in graduate school and performing many unpublished experiments, he submitted a theoretical thesis on negative index media, the perfect lens, and related structures to his committee. He also worked for the California Space Institute, La Jolla, performing space mission feasibility studies, and for Tristan Technologies, San Diego, CA, designing and building cryogenically cooled, SQUID-based instruments. He left California to work for David Smith at Duke University, Durham, NC, where he was supported by the Intelligence Community (IC) Postdoctoral Fellowship Program. He then worked as an Assistant Professor with the Department of Electrical and Computer Engineering, North Carolina State University, Raleigh. He joined the Electrical and Computer Engineering Department, University of Utah, Salt Lake City, in January 2011.

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Prof. Eleftheriades was elected a Fellow of the Royal Society of Canada in 2009. He has served as an IEEE Antennas and Propagation Society (AP-S) Distinguished Lecturer (2004–2009) and as a member of the IEEE AP-S Administrative Committee (AdCom, 2008–2010). He is an Associate Editor of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION and a member of Technical Coordination Committee MTT-15 (Microwave Field Theory). He has been the General Chair of the 2010 IEEE International Symposium on Antennas and Propagation and CNC/USNC/URSI Radio Science Meeting held in Toronto. He was a Co-Guest Editor for the October 2011 issue of the PROCEEDINGS OF THE IEEE on metamaterials. He was the recipient of the 2008 IEEE Kiyo Tomiyasu Technical Field Award “for pioneering contributions to the science and technological applications of negative-refraction electromagnetic materials.” He was the recipient of the 2001 Ontario Premiers’ Research Excellence Award and the 2001 Gordon Slemmon Award presented by the University of Toronto. He was also the recipient of the 2004 E. W. R. Steacie Fellowship presented by the Natural Sciences and Engineering Research Council of Canada. He is the co-recipient (with Loic Markley) of the inaugural 2009 IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS Best Paper Award. One of his papers (with Ashwin Iyer) received the RWP King Best Paper Award in 2008.
David R. Smith (M’10) received the Ph.D. degree in physics from the University of California, San Diego (UCSD), in 1994.

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His research interests include the theory, simulation, and characterization of unique electromagnetic structures, including photonic crystals, metamaterials, and plasmonic nanostructures.

Dr. Smith was elected a member of The Electromagnetics Academy in 2002. In 2005, he was part of a five-member team that received the Descartes Research Prize, awarded by the European Union, for their contributions to metamaterials and other novel electromagnetic materials. In 2006, he was selected as one of the “Scientific American 50,” a group recognized by the editors of Scientific American for achievements in science, technology, and policy. In 2009, he was named a “Citation Laureate” by the Thomson-Reuters ISI Web of Knowledge.

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Prof. Tretyakov served as Chairman of the St. Petersburg IEEE ED/MTT/AP Chapter from 1995 to 1998.