Metamaterial Special Issue Introduction

IN THE PAST few years, there has been a renewed interest in using fabricated structures to develop composite materials that mimic known material responses or that qualitatively have new, physically realizable response functions that do not occur, or may not be readily available, in nature. The history of artificial materials seems to trace back to the late part of the nineteenth century when in 1898 Jagadis Chunder Bose published his work on the rotation of the plane of polarization by man-made twisted structures, which by today's definition, were artificial chiral structures. Karl Ferdinand Lindman in 1914 studied artificial chiral media formed by a collection of randomly-oriented small wire helices. Afterwards, there were several other investigators in the first half of the twentieth century who studied various man-made materials. In the 1950s and 1960s, artificial dielectrics were explored for light-weight microwave antenna lenses. The interest in artificial chiral materials was resurrected in the 1980s and 1990s and they were investigated for microwave radar absorber and other applications.

Recent examples of *engineered* material activities include double negative (DNG) materials, i.e., artificial materials with simultaneous, effective negative real permittivity and permeability properties; negative index of refraction (NIR) materials; electromagnetic band gap (EBG) structured materials; and complex surfaces such as high-impedance ground planes. The qualitatively new response functions of these *metamaterials* are often generated by artificially fabricated inhomogeneities embedded in host media or connected to or embedded on host surfaces. The DNG materials involve elements and distances between them that are much smaller than a wavelength and can be described by the effective media concepts. On the other hand the EBG materials involve distances that are on the order of half a wavelength or more and are described by the periodic media concepts.

This special issue is intended to present recent research advances in the metamaterials area. It includes theoretical, numerical, and experimental contributions to the understanding of the behavior of several classes of metamaterials and to their potential applications in components, devices, and antennas. The papers included are informative and, we sincerely hope, will stimulate discussion and new avenues of research in this area.

This special issue begins with papers that discuss various aspects of DNG metamaterials (MTMs). These MTMs now have several names including left-handed materials, backward-wave materials, NIR materials, etc. We have not asked the authors to conform to any standard nomenclature, because there is none as yet. The Guest Editors favor the DNG name because, in their opinions, it emphasizes the fundamental characteristics of the material rather than its derived effects. We believe that the descriptor "left-handed" may be somewhat confusing because its common usage in the electromagnetics literature is in association with chiral effects in which the distinction between left- and right-handedness is necessary. The connection between DNG materials and backward wave effects has been established but the latter is a derived property from the former. The NIR name has become clouded by the fact that periodic arrangements of double positive (DPS) materials, i.e., materials with simultaneous positive permittivity and permeability, can also produce the NIR effects, which were previously thought obtainable only from DNG materials. The community will eventually have to make a preferred choice; the contents of the papers included here may aid in that task.

Several ground rules were put in place for the organization and coordination of this special issue. We purposely chose not to have specifically invited papers. We also asked not to have more than one manuscript submitted from any one research group in order to provide the opportunity for inclusion of various topics and to incorporate a variety of the different approaches being taken in this gestating area of research. However, because we had no invited papers, not all research groups are necessarily represented. Moreover, other societies have recognized the importance of metamaterials and their applications, have successfully competed for papers, and have fielded their own special issues. We note in particular the April 7, 2003 issue of the on-line journal *Optics Express* of the Optical Society of America (OSA).

This special issue begins with the papers emphasizing the DNG MTMs. We decided not to seek a review paper solely emphasizing the properties of DNG MTMs. Because the topic is so new, each paper in this section includes reviews of the relevant issues already reported in the literature. We do wish to emphasize here the pioneering work of Veselago in 1967; the recognition of its importance by the UC San Diego group led by Smith and Schultz and their announcement of the first purposeful realization of a DNG medium in 2000; and the "perfect" lens proposal by Pendry in the same year. These pioneering efforts stimulated much interest, and the MTM area can now claim well over 100 papers in the physics and engineering literature.

Each paper in this first section contains references to discussions of the exotic properties of DNG MTMs, including, for instance, a negative index of refraction, negative angles of refraction, negative phase yet positive Poynting vector directions. The papers in the first section contain new descriptions or new confirmations of these properties; new realizations; or, because of them, new potential applications. We note that while there has been much debate and controversy associated with whether these properties and their applications are real and realizable, it would appear that here and in the general physics and engineering literature we are beginning to see some consensus in favor of the validity and realizability of many of the early claims. The paper by Ishimaru *et al.* describes some of the fundamental material characterization of the DNG MTMs and one of its current realizations. The paper by Alu and En-

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gheta reveals the electromagnetic properties of a pair of layered negative-permittivity-only and negative-permeability-only materials, their tunneling, interface resonances, and transparency properties, their connection to DNG MTMs, and potential applications. The next three papers by Marques *et al.*, Simovski *et al.*, and Ozbay *et al.*, all consider theoretical and/or experimental characterizations of DNG MTMs formed by the wire electric elements and versions of the split ring resonator class of magnetic elements. The paper by Holloway *et al.* considers the use of a composite medium based on nonconducting spheres to achieve the NIR properties. The next three papers describe planar realizations of DNG MTMs and their applications. The paper by Grbic and Eleftheriades describes the planar circuit realizations and the properties of waves along them. The paper by Balmain *et al.* emphasizes another planar realization from a different physical point of view and demonstrates the negative refraction properties. The paper by Siddiqui *et al.* explores an exotic application of the planar DNG MTMs to achieve a negative group velocity medium. The next paper of this section is by Ziolkowski and Kipple; it details the potential use of DNG MTMs to enhance the radiation characteristics of electrically small antennas. In attempting to deal with a proper calculation of the radiation Q of an antenna in the presence of a DNG MTM, it wrestles with several controversial issues. The next two papers describe other types of MTMs. The paper by Kuester *et al.* discusses the properties of a metafilm. The paper by Tretyakov *et al.* considers quite general MTMs formed by loaded dipole elements.

The next series of papers deals with electromagnetic bandgap (EBG) structures and their antenna applications. The EBG structures are characterized by their periodic nature, which causes a band stop or band pass effect in wave number or frequency in one, two, or three dimensions. While the EBG studies are more mature by several years in the physics community than the DNG ones are, their engineering applications to antennas has surged recently. This section begins with a paper by Enoch *et al.* that reviews many properties of the EBG structures. Because it demonstrates the connections between EBG structures and the NIR effects, it provides a nice transition from the effective-medium scale to the Bragg-scattering scale. The following paper by de Maagt *et al.* is a summary of several recent efforts and illustrates the many applications of EBG structures to antennas. The next five papers describe different approaches to realizing high impedance (Hi-Z) surfaces that lead to artificial magnetic conductor properties for a variety of antenna applications. The paper by Clavijo *et al.* provides a detailed analysis of the properties of mushroom Hi-Z surfaces. The papers by Yang and Rahmat-Samii and by Zhang *et al.* apply the Hi-Z surfaces to wire and patch antennas, respectively. The paper by Sievenpiper *et al.* describes an advanced antenna application of a tunable Hi-Z surface. The paper by Skobelev and Kildal uses a corrugated (hard) surface to achieve the Hi-Z effects for a horn antenna application. The next paper by Kiziltas *et al.* considers the customized design of periodic distributions of materials to achieve particular material characteristics for antenna applications. The paper by Chappell and Gong considers the development of composite EBG substrates for microwave engineering applications.

Finally, this special issue could not have occurred without the generous contributions of time and efforts of over 80 reviewers. We had 38 formal submissions and the reviewers were able to complete all of the reviews in six months. We sincerely thank them. We would dearly like to thank all of the authors for their patience with us and with the review process. Both those authors whose papers made it through the review process successfully and those whose papers did not, spent considerable efforts on their manuscripts and should be congratulated. The fact that the special issue will appear within one year of the submission deadline is a direct result of all of these dedicated efforts.

To conclude this introduction, we would particularly like to thank the Editor-in-Chief, Prof. Allen Glisson, and his very capable editorial assistant, Ms. Sharon Martinez, for all of their tremendous help. When problems arose, they provided excellent support to resolve them. They helped make our efforts easier.

We hope that you will find this special issue interesting. Have fun reading!

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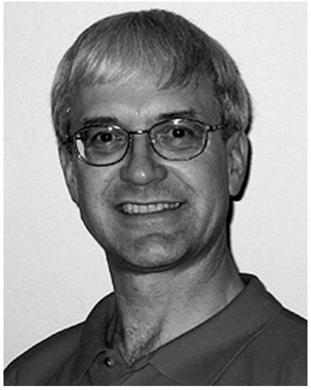

Richard W. Ziolkowski (M'97–SM'91–F'94) received the Sc.B. degree in physics (*magna cum laude*) with honors from Brown University, Providence, RI, in 1974 and the M.S. and Ph.D. degrees in physics from the University of Illinois at Urbana-Champaign, in 1975 and 1980, respectively.

He was a member of the Engineering Research Division, Lawrence Livermore National Laboratory, CA, from 1981 to 1990, and served as the leader of the Computational Electronics and Electromagnetics Thrust Area for the Engineering Directorate, from 1984 to 1990. He joined the Department of Electrical and Computer Engineering, University of Arizona, Tuscon, as an Associate Professor in 1990, and was promoted to Full Professor in 1996. His research interests include the application of new mathematical and numerical methods to linear and nonlinear problems dealing with the interaction of acoustic and electromagnetic waves with realistic materials and structures.

Prof. Ziolkowski is a Member of Tau Beta Pi, Sigma Xi, Phi Kappa Phi, the American Physical Society, the Optical Society of America, the Acoustical Society of America, and Commissions B (Fields and Waves) and D (Electronics and Photonics) of URSI (International Union of Radio Science). He was an Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION from 1993 to 1998. He served as the Vice Chairman of the 1989 IEEE/AP-S and URSI Symposium in San Jose, and as the Technical Program Chairperson for the 1998 IEEE Conference on Electromagnetic Field Computation in Tucson. He served as a member of the IEEE AP-S Administrative Committee (ADCOM) from 2000 to 2002. He is currently serving as Co-Guest Editor with Prof. Nader Engheta for this IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION Special Issue on Metamaterials. For the US URSI Society, he served as Secretary for Commission B (Fields and Waves) from 1993 to 1996 and as Chairperson of the Technical Activities Committee from 1997 to 1999, and as Secretary for Commission D (Electronics and Photonics) from 2001 to 2002. He is currently serving as a Member-at-Large of the U.S. National Committee (USNC) of URSI and as a member of the International Commission B Technical Activities Committee. He was a Co-Guest Editor with Prof. Kurt Oughstun of the 1998 Special Issue of the *Journal of the Optical Society of America A* featuring Mathematics and Modeling in Modern Optics. He was a Co-Organizer with Dr. Brent Little of the Photonics Nanostructures Special Symposia at the 1998, 1999, and 2000 OSA Integrated Photonics Research (IPR) Topical Meetings. He served as the Chair of the IPR subcommittee IV, Nanostructure Photonics, in 2001. He was awarded the Tau Beta Pi Professor of the Year Award in 1993 and the IEEE and Eta Kappa Nu Outstanding Teaching Award in 1993 and 1998. He also holds the title of Sensei with a Nidan rank in Matsunoryu Goshin Jujitsu and a Shodan rank in Kajukenbo.

Nader Engheta (S'81–M'82–SM'89–F'96) received the B.S. degree from the University of Tehran, Iran, in 1978 and the M.S. and Ph.D. degrees (with a minor in physics) from the California Institute of Technology, in 1979 and 1982, respectively, all in electrical engineering.

From June 1982 to June 1983, he was a Postdoctoral Research Fellow at the California Institute of Technology, Pasadena, and from June 1983 to June 1987, he was a Senior Research Scientist at Kaman Sciences Corporation, Dikewood Division, Santa Monica, CA. In July 1987, he joined the faculty of the University of Pennsylvania, where he is currently a Professor in the Department of Electrical and Systems Engineering. He was the graduate group chair of electrical engineering from July 1993 to June 1997. He is also a Member of the David Mahoney Institute of Neurological Sciences, and the Bioengineering Graduate Group, both at the University of Pennsylvania. His research interests and activities are in the areas of fields and waves phenomena, metamaterials and complex media, bio-inspired/biomimetic polarization imaging and polarization vision, wave interaction with unconventional complex structures and complex surfaces, small antennas for wireless applications, bio-inspired hyperspectral sensing, biologically-based visualization and physics of sensing and display of polarization imagery, through-wall microwave imaging, electromagnetics/electrophysics of brain cortical potentials (e.g., EEG), millimeter-wave lensing systems, optics, fractional operators and fractional paradigm in electrodynamics. He has guest edited/coedited several special issues, namely, the special issue of *Journal of Electromagnetic Waves and Applications* on the topic of "Wave Interaction with Chiral and Complex Media" in 1992, part special issue of the *Journal of the Franklin Institute* on the topic of "Antennas and Microwaves (from the 13th Annual Benjamin Franklin Symposium) in 1995, special issue of the *Wave Motion* on the topic of "Electrodynamics in Complex Environments" (with L. B. Felsen) in 2001, and special issue of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION on the topic of "Metamaterials" (with R. W. Ziolkowski).

He is a Guggenheim Fellow, a recipient of the IEEE Third Millennium Medal, and Fellow of the Optical Society of America (OSA). In addition, he has received various awards and distinctions for his scholarly research contributions and teaching activities including the UPS Foundation Distinguished Educator term Chair for July 1999–June 2000, the Fulbright Naples Chair award for Naples, Italy for 1998, a 1989 NSF Presidential Young Investigator (PYI) award, two times (1993, 2002) recipient of the S. Reid Warren, Jr. Award for distinguished teaching from the University of Pennsylvania's School of Engineering and Applied Science, the 1994 Christian F. and Mary R. Lindback Foundation Award, and the W. M. Keck Foundation's 1995 Engineering Teaching Excellence Award. He is an Associate Editor of The IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS (2002–present), and was an Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION (1996–2001), and *Radio Science* (1991–1996). He was on the Editorial Board of the *Journal of Electromagnetic Waves and Applications*. He served as an IEEE Antennas and Propagation Society Distinguished Lecturer for the period 1997–1999. He is a member of the American Physical Society (APS), the American Association for the Advancement of Science (AAAS), Sigma Xi, Commissions B and D of the U.S. National Committee (USNC) of the International Union of Radio Science (URSI), and a member of the Electromagnetics Academy. He was the Chair (1989–1991) and Vice-Chair (1988–1989) of the joint chapter of the IEEE Antennas and Propagation/Microwave Theory and Techniques in the Philadelphia Section. He is an elected member of the Administrative Committee (AdCom) of the IEEE Society of Antennas and Propagation since January 2003.