Metamaterials: Fundamentals and Applications in the Microwave and Optical Regimes

By GEORGE V. ELEFTHERIADES, *Fellow IEEE*
Guest Editor

NADER ENGHETA, *Fellow IEEE*
Guest Editor

Metamaterials are artificially structured media with unusual electromagnetic properties ranging from radio frequency and microwaves all the way up to optical frequencies. In its modern form, the field of "metamaterials," which has its roots in the history of artificial dielectrics, is just over ten years old but has already attracted strong interest from many researchers around the globe. Suddenly, classical electromagnetism took on a fresh and exciting perspective revealing that there are fascinating phenomena still awaiting to be discovered and corresponding applications to be invented. In particular, all this richness is associated with the notion of the macroscopic constitutive parameters such as the permittivity and permeability. What would be possible if we were able to synthesize materials with user-defined constitutive parameters? The richness of these possibilities becomes more evident when we recall the fact that material parameters can in general be anisotropic tensors which can also be spatially inhomogeneous (varying from point to point). Moreover, they can attain values previously not considered, and they can even mix together the electric and magnetic response of a material. This Special Issue contains 16 papers written by some of the internationally renowned leaders in the field who discuss how to prescribe material parameters to obtain exotic new functions, how to physically implement such metamaterials, and how to apply them in the microwaves and optical domains.

This Special Issue on Metamaterials: Artificially Engineered Materials with Electromagnetic Properties covers topics on prescribing material parameters to obtain exotic new functions, physically implementing metamaterials, and applying them in the microwave and optical domains.

Typically, metamaterials are periodic structures consisting of subwavelength metalo-dielectric scatterers having a periodicity that is much smaller than the impinging and guided wavelengths (although nonperiodic metamaterials are also entirely possible). These constituent scatterers or "inclusions" behave like "artificial molecules" that scatter an incident electromagnetic wave giving rise to macroscopic effective material parameters such as a permittivity, a permeability, and a refractive index. Although the term "metamaterial" is relatively new, a precursor concept dates back to the late part of the nineteenth century in the work of Jadagis Chunder Bose on the rotation of the plane of polarization by his man-made twisted structures, resembling chiral structures [1]. In 1914, Karl Ferdinand Lindman investigated artificially engineered chiral media, which he constructed by a collection of wire helices [2]. This was followed by a few other researchers in the first half of the twentieth century studying some other man-made materials. In the late 1940s, 1950s, and 1960s, "artificial dielectrics" became a subject of interest, when Winston E. Kock of the Bell telephone laboratories developed this concept in order to

---

Digital Object Identifier: 10.1109/JPROC.2011.2161808

realize lightweight lenses at microwave frequencies (in the 3–5-GHz range), where the wavelength is long (several centimeters) and thus the corresponding natural dielectric lenses are bulky and heavy [3]. The corresponding "artificial molecules" were electrically small metallic disks periodically arranged in a lens shape. The interest in artificial complex materials, particularly chiral materials, was resurrected in the 1980s and 1990s, mostly with the view towards applications in microwave radar absorbing materials and other microwave devices and components [4]. A comprehensive review of artificial dielectrics, including a rigorous mathematical treatment, from that era can be found in [5].

In the present context, metamaterials can be defined as artificially engineered materials with electromagnetic properties that are inaccessible in nature or are difficult to obtain in natural materials, but are physically realizable. One of the early examples of metamaterials is the so-called "negative-index," "left-handed" or "double negative" metamaterial which is characterized by simultaneously negative permittivity and permeability, thus implying a negative index of refraction. These media were theoretically suggested and studied by Victor Veselago in the 1960s [6]. Inspired by the work of Pendry [7], [8], Shelby, Smith, and Schultz experimentally demonstrated the first left-handed metamaterial in 2001 using arrays of wires (giving rise to negative permittivity) and split-ring resonators (giving rise to negative permeability) at microwave frequencies [9]. In the electrical engineering community, a different realization approach has also been considered at microwaves using 2-D loaded networks of transmission lines [10], [11], which were subsequently extended to the optical regime [12]. Typically this transmission-line approach leads to reduced transmission losses and wide bandwidths due to the tight coupling of the constituent unit cells [13]. The pioneering work on the concept of negative-index metamaterials by Veselago in 1967 [6], the intriguing and groundbreaking notion of the "perfect lens" proposed by Pendry in 2000 [14], and the experimental verification of the negative-index metamaterials in the microwave regime by Shelby, Smith, and Schultz in 2001 [9] stimulated interest in these materials and led to the expansion and growth in this field in the 2000s. The field of metamaterials has now reached a variety of disciplines such as physics, electrical engineering, material science, mathematics, mechanics, acoustics, fluidics, and chemistry just to name a few.

The first paper in this Special Issue is by Kundtz, Smith, and Pendry who introduce and review the notion of "transformation optics" (TO) as a powerful technique for designing electromagnetic metamaterials based on the invariance of Maxwell's equations. Specifically, at the heart of TO lies the use of coordinate transformations which can be translated to material parameters. In this way, several novel electromagnetic device examples are introduced and discussed including cloaks, beam shifters, and beam splitters.

The following paper by Zedler and Eleftheriades introduces a method for synthesizing TO metamaterials at microwaves (hence more appropriately "transformation electromagnetics") using loaded transmission lines. These metamaterials are in general inhomogeneous and anisotropic with nonzero off-diagonal material parameters. A few examples of microwave devices are described including broadband cloaks and flattened retroreflectors. The next paper by Alitalo and Tretyakov describes an alternative approach for cloaking based on transmission-line metamaterials, and also gives a brief overview of some other cloaking techniques.

The next four papers deal with specific ideas for realizations of metamaterials with user-defined parameters. The paper by Marqués, Jelinek, Freire, Baena, and Lapine discusses the realization of 3-D magnetic metamaterials at microwave frequencies using split-ring resonators. The paper makes use of a rigorous homogenization treatment of these metamaterials. Moreover, an exciting application of such magnetic metamaterials is described for enhancing the resolution of surface coils in magnetic resonance imaging (MRI). The paper by Alù and Engheta describes the possible idea for realization of metamaterials in the optical regime based on lumped optical nanocircuit element concepts. The paper establishes a way to realize nanocapacitors and nanoinductors using dielectric and plasmonic nanoparticles. It also presents a method of combining these elements to synthesize complex optical nanocircuits by treating the displacement current using well-known low-frequency circuit theory techniques. Finally, the paper establishes a method for designing 0-D, 1-D, 2-D, and 3-D optical metamaterial structures based on transmission-line concepts thus helping to decrease losses and improve bandwidth. The following paper by Valentine, Zhang, Zentgraf, and Zhang presents the so-called cascaded "fishnet" structures for building broadband low-loss negative-refraction metamaterials. It deals with design, fabrication, and characterization of such materials. The paper shows how coupling of unit cells leads to lower loss and a high figure of merit. Kildishev, Borneman, Shalaev, and Drachev in their paper give an overview of some principles in the development of bianisotropic homogenization techniques for metamaterials, and provide examples in passive and active optical metamaterials.

The next group of six papers describes specific applications of metamaterials at microwave and optical frequencies. The paper by Durán-Sindreu, Vélez, Sisó, Vélez, Selga, Bonache, and Martin reviews recent advances in metamaterial transmission lines based on loading with split-ring resonators. The paper highlights the advantages of transmission-line metamaterials and describes a number of enabled microwave applications. Such applications include compact wideband filters and power splitters. Caloz in his paper reviews the theory and advantages of transmission-line metamaterials with particular emphasis on their frequency dispersion properties. Based on dispersion analysis, the author describes a number of interesting "dispersion engineering" microwave applications including a pulse-position modulator and a real-time spectrum analyzer using leaky-wave antennas. The paper concludes by introducing some interesting microwave nonreciprocal magnetic devices using ferromagnetic nanowires. The papers by Ziolkowski, Jin, and Lin, and by Volakis and Sertel review several interesting and useful applications of metamatamaterials in electrically small antennas. The paper by Ziolkowski, Jin, and Lin focuses on the realization of electrically small but efficient antennas using metamaterial loading. Multiband and multifrequency antennas are also discussed. The paper by Volakis and Sertel describes electrical small antennas based on unique anisotropic metamaterial structures. The paper concludes by describing remarkable wideband arrays based on metamaterial ideas and the concept of the "current sheet." The paper by Hashemi and Itoh reviews the application of transmission-line metamaterials in the realization of leaky-wave antennas. Such leaky-wave antennas exhibit unique beam scanning properties that can continuously scan from backward end fire to forward end fire and even scan through broadside. The paper presents electronically scannable, conformal, and dual polarization leaky-wave antennas. Another application of metamaterials to antennas is discussed by Lam, Vier, Nielsen, Parazzoli, and Tanielian. This application, however, concerns phased arrays as applied, for example, to the case of satellite communications. The paper introduces an interesting metamaterial lens structure that is designed using transformation optics. This lens extends the scanning capability of phased arrays to directions close to the horizon which is a "classical" challenge in conventional phased-array antennas.

The next three papers deal with some special problems and applications of structures that strictly speaking are not metamaterials but are closely related to them. The paper by Notomi describes methods for strong light confinement in dielectric photonic crystals. Ultrahigh-Q cavities with the quality factor on the order of 10^6 and higher are described which are capable of confining light in a wavelength-cubed volume. It is shown that such structures can have applications in low-power, integrated photonic circuits and photonic network-on-chips, in developing extremely slow light systems, and in adiabatic tuning of light. The following paper by Jackson, Burghignoli, Lovat, Capolino, Chen, Wilton, and Oliner tackles the important problem of directive beaming through periodic structures at microwave and optical frequencies. The underlying mechanism is identified as the involvement of weakly attenuated leaky waves. The paper discusses the role of these leaky waves in the near field of the aperture and the far field of the structures. Finally, the last paper by Grbic and Merlin describes some interesting and useful pattern surfaces (near-field plates) that can focus microwaves down to subwavelength spots. Both 1-D and 2-D plates are described as well as their applications to imaging, sensing, and wireless power transfer.

The field of metamaterials has expanded so vastly that it is impossible to represent all its subfields and topics of research in one special issue. As a result, the present collection of papers in this issue is by no means exhaustive. Multivolume handbooks would be necessary to include all the various areas of this field. We refer the interested readers to numerous other special issues of various technical journals, books, and monographs on metamaterials in the fields of engineering, physics, material science, chemistry, and mathematics among others. The metamaterial research is vibrant, progressing steadily and strongly into various exciting forefronts which include quantum metamaterials, superconducting metamaterials, tunable and reconfigurable metamaterials, photonic metamaterials, infra-red metamaterials, and terahetz metamaterials, just to name a few. So the future of this field is quite bright.

We wish to thank the authors for their outstanding contributions and the reviewers whose careful reviews led to the improvement of the quality of the papers. We would also like to express our appreciation to J. Calder, Managing Editor, and J. Sun, Publications Editor, of the Proceedings of the IEEE, for their help and support throughout the preparation of this Special Issue. ■

REFERENCES

[1] J. C. Bose, "On the rotation of plane of polarisation of electric waves by a twisted structure." *Proc. Roy. Soc.*, vol. 63, pp. 146–152, 1898.

[2] I. V. Lindell, A. H. Sihvola, and J. Kurkijarvi, "Karl F. Lindman: The last Hertzian, and a Harbinger of electromagnetic chirality," *IEEE Antennas Propag. Mag.*, vol. 34, no. 3, pp. 24–30, Jun. 1992.

[3] W. Kock, "Metallic delay lenses," *Bell Syst. Tech. J.*, vol. 27, pp. 58–82, 1948.

[4] N. Engheta, Ed."Special Issue on 'Wave interaction with chiral and complex media'," *J. Electromagn. Waves Appl.*, vol. 6, no. 5/6, May/Jun. 1992.

[5] R. E. Collin, *Field Theory of Guided Waves*. Piscataway, NJ: IEEE Press, 1990, ch. 12.

[6] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," *Sov. Phys. Usp.*, vol. 10, pp. 509–514, Jan.–Feb. 1968.

[7] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 11, pp. 2075–2081, Nov. 1999.

[8] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Low-frequency plasmons in thin wire structures," *J. Phys., Condensed Matter.*, vol. 10, pp. 4785–4809, 1998.

[9] R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *Science*, vol. 292, pp. 77–79, Apr. 6, 2001.

[10] G. V. Eleftheriades, A. K. Iyer, and P. C. Kremer, "Planar negative refractive index media using periodically L-C loaded transmission lines," *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 12, pp. 2702–2712, Dec. 2002.

[11] A. Sanada, C. Caloz, and T. Itoh, "Planar distributed structures with negative refractive index," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 4, pp. 1252–1263, Apr. 2004.

[12] A. Alu and N. Engheta, "Three-dimensional nanotransmission lines at optical frequencies: A recipe for broadband negative-refraction optical metamaterials," *Phys. Rev. B.*, vol. 75, Jan. 2007, 024304.

[13] G. V. Eleftheriades, "Analysis of bandwidth and loss in negative-refractive-index transmission-line (NRI-TL) media using coupled resonators," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 6, pp. 412–414, Jun. 2007.

[14] J. B. Pendry, "Negative refraction makes a perfect lens," *Phys. Rev. Lett.*, vol. 85, pp. 3966–3969, Oct. 2000.

ABOUT THE GUEST EDITORS

George V. Eleftheriades (Fellow, IEEE) received the diploma in electrical engineering from the National Technical University of Athens, Athens, Greece, in 1988 and the M.S.E.E. and Ph.D. degrees in electrical engineering from the University of Michigan, Ann Arbor, in 1989 and 1993, respectively.

From 1994 to 1997, he was with the Swiss Federal Institute of Technology, Lausanne, Switzerland. Currently, he is a Professor in the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada, where he holds the Canada Research Chair/Velma M. Rogers Graham Chair in Engineering. He is one of the originators of the field of transmission-line metamaterials which he introduced in 2002. Along with his graduate students he produced the first experimental evidence of imaging beyond the diffraction limit with a negative-index lens and invented a number of novel metamaterial-based microwave devices and antennas. Some of this work has been compiled in the book *Negative-Refraction Metamaterials: Fundamental Principles and Applications* (New York: Wiley/IEEE Press, June 2005, G. V. Eleftheriades and K. G. Balmain, Eds.). His research interests include transmission-line and other electromagnetic metamaterials, small antennas and components for wireless communications, passive and active microwave components, near-field imaging techniques, plasmonic and nanoscale optical structures, fundamental electromagnetic theory, and electromagnetic design of high-speed interconnects.

Prof. Eleftheriades has served as an IEEE Antennas and Propagation Society (APS) Distinguished Lecturer (2004–2009) and as a member of the IEEE APS 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 Microwave Field Theory (MTT-15). 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, ON, Canada. 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 Slemon 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 corecipient (with L. Markley) of the inaugural 2009 IEEE Microwave and Wireless Components Letters Best Paper Award. One of his papers (with A. Iyer) received the RWP King Best Paper Award in 2008. In 2009, he has been elected a Fellow of the Royal Society of Canada.

Nader Engheta (Fellow, IEEE) received the B.S. degree in electrical engineering from the University of Tehran, Tehran, Iran, in 1978 and the M.S. and Ph.D. degrees in electrical engineering from the California Institute of Technology (Caltech), Pasadena, in 1979 and 1982, respectively.

He is the H. Nedwill Ramsey Professor of Electrical and Systems Engineering, and Professor of Bioengineering at the University of Pennsylvania, Philadelphia. After spending one year as a postdoctoral research fellow at Caltech and four years as a Senior Research Scientist as Kaman Sciences Corporation's Dikewood Division in Santa Monica, CA, he joined the faculty of the University of Pennsylvania, where he is currently the Ramsey Professor. He is also a member of the Mahoney Institute of Neurological Sciences. He was the graduate group chair of electrical engineering from July 1993 to June 1997. His current research interests and activities span over a broad range of areas including metamaterials and plasmonics, nano-optics and nanophotonics, nanocircuits and nanostructures modeling, bio-inspired/biomimetic polarization imaging and reverse engineering of polarization vision, miniaturized antennas and nanoantennas, hyperspectral sensing, biologically based visualization and physics of sensing and display of polarization imagery, through-wall microwave imaging, fields and waves phenomena, fractional operators, and fractional paradigm in electrodynamics. He has published numerous journal papers, book chapters, and conference articles in his fields of research. He coedited (with R. W. Ziolkowski) the book *Metamaterials: Physics and Engineering Explorations* (New York: Wiley/IEEE Press, 2006).

Dr. Engheta was selected as one of the *Scientific American Magazine 50 Leaders in Science and Technology* in 2006 for developing the concept of optical lumped nanocircuits. He is a Guggenheim Fellow, an IEEE Third Millennium Medalist, a Fellow of the American Physical Society (APS), the Optical Society of America (OSA), the American Association for the Advancement of Science (AAAS), and the SPIE—The International Society for Optical Engineering. He is the recipient of the 2008 George H. Heilmeier Award for Excellence in Research from UPenn, the Fulbright Naples Chair Award, NSF Presidential Young Investigator award, the UPS Foundation Distinguished Educator term Chair, and several teaching awards including the Christian F. and Mary R. Lindback Foundation Award, the W. M. Keck Foundation's 1995 Engineering Teaching Excellence Award, and two times recipient of S. Reid Warren, Jr. Award. He has been selected to receive the 2012 IEEE Electromagnetics Award for his contributions to the fields of metamaterials and nanoscale optics. He was an Associate Editor of the IEEE Antennas and Wireless Propagation Letters (2002–2007), the IEEE Transactions on Antenna and Propagation (1996–2001), and *Radio Science* (1991–1996). He was on the Editorial Board of the *Journal of Electromagnetic Waves and Applications*. He is currently on the Editorial Board of *Metamaterials*, on the board of *Waves in Random and Complex Media*, and on the Editorial Board of the *Istituto Superiore Mario Boella Book Series in Radio Science*. He served as an IEEE Antennas and Propagation Society Distinguished Lecturer for 1997–1999. He is a member of Sigma Xi, Commissions B, D, and K of the U.S. National Committee (USNC) of the International Union of Radio Science (URSI), and a member of the Electromagnetics Academy. He is the Chair of the Commission B of USNC-URSI for 2009–2011. He is the Chair of the Gordon Research Conference on Plasmonics in 2012. He has organized and chaired various special sessions in international symposia and conferences, and has guest edited/coedited several special issues, namely, the special issue of the *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, special issue of the IEEE Transactions on Antennas and Propagation on the topic of "Metamaterials" (with R. W. Ziolkowski) in 2003, special issue of *Solid State Communications* on the topic of "Negative refraction and metamaterials for optical science and engineering" (with G. Shvets) in 2008, and the special issue of the IEEE Journal of Selected Topics in Quantum Electronics on the topic of "Metamaterials" (with V. Shalaev, N. Litchinitser, R. McPhedran, E. Shamonina, and T. Klar) in 2010.