Guest Editorial

I. INTRODUCTION

METAMATERIALS, the topic of this TRANSACTIONS' Special Issue, is a vague term. Broadly, it means something beyond natural materials, and implies something artificial, not ordinarily found in nature.

Originally, the word metamaterials included a wider range of artificial materials, but in this TRANSACTIONS' Special Issue, the word applies to those materials or structures in which the phase velocity and the group (power transmission) velocity point in opposite directions. This property leads to a series of fascinating performance features, such as a backward electromagnetic wave in the material, a negative index of refraction, a reversed Doppler effect, etc. These performance features in themselves are stimulating to contemplate, but we are learning that novel and practical microwave components can also be devised.

Among these are forward or backward directional couplers with improved features like arbitrary coupling ratios, shorter coupling lengths, broader bandwidths, etc. Other coupling components with improved features include branch-line couplers and hybrid rings. A different type of novel component that followed directly from the backward-wave property is a leaky-wave antenna that can be frequency scanned or electronically scanned from backward endfire through broadside to forward endfire. Previously, such scanning could be obtained by employing the first higher space harmonic, but here, the radiation is supplied by the dominant space harmonic. Yet another novel device is a perfect lens, consisting of a planar slab of metamaterial, which has the startling property that the sharpness of the image is not limited by the wavelength of light. This truly unusual feature follows from its negative-refractive-index property and the fact that evanescent waves are amplified when traversing the metamaterial slab.

All of these structures have been built, and their performances have been verified by measurements at microwave frequencies.

This topic is rather new, about a half-dozen years old, but it has expanded very rapidly, particularly in the physics community. In the microwave community, the contributions began only about three years ago, but progress has also been rapid, although the goals and stress have usually been somewhat different from those in the physics community. The nature of these contributions and their potential for novel applications, however, are not yet widely understood or appreciated by most microwave engineers. It is hoped that this TRANSACTIONS' Special Issue will help to clarify the state-of-the-art for our community and illustrate some of the opportunities for future novel applications in the microwave field.

Since we believe that many people in the microwave field are not very familiar with this topic, we are devoting much of this Guest Editorial to some background information for those who may fit into this category.

II. TERMINOLOGY

The class of materials or structures that are referred to as metamaterials are characterized by various terms such as: 1) left-handed (LH); 2) BW; 3) negative-index (NI) or negative-refractive index (NRI); or 4) double-negative (DNG), and perhaps others. The term "left-handed" was used in the original paper by Veselago, and many people use it for that reason. It signifies a contrast with the well-known "right-hand rule" for the direction of the Poynting vector relative to the directions of the electric and magnetic fields. An objection to its use is that "LH" is used in classifying chiral media and types of circularly polarized radiation. The term BW is not as widely used because backward waves can be produced in several other ways. The NRI property was originally thought to be obtainable only from a metamaterial medium, but it is now known that it is possible to obtain this property from a special periodic arrangement of ordinary materials. Nevertheless, the NRI term is a very appropriate description when dealing with two- or three-dimensional structures.

The terms above represent in each case a property that results from a wave that propagates within the metamaterial structure. The remaining term, double negative, follows from the fundamental properties of the metamaterial itself. Double-negative signifies that the permittivity ε and permeability μ of the material (or the effective values of ε and μ of the structure comprising the metamaterial) are both negative. For ordinary materials, these values are both positive. The letters DNG have been found to be easily generalizable to double-positive (DPS) or to single-negative materials, as only-epsilon-negative (ENG) and only-mu-negative (MNG).

Unfortunately, there is no commonly agreed-upon term, so we have permitted in this TRANSACTIONS' Special Issue each paper to employ its own preference.

III. BRIEF HISTORICAL BACKGROUND

In 1968, Veselago [1] authored a paper that asked what electrodynamic behavior could be found if the ε and μ of a material are simultaneously negative rather than positive. He found that the results would be very interesting and unusual, and he pointed out that, among these new effects, one would find backward waves, a negative refractive index, a reversed Doppler effect, a reversed Čerenkov effect, a planar slab lens, etc. He then asked if any materials in nature could be found with simultaneously negative ε and μ values, and he concluded that there are none.

As a result of this conclusion, no further progress along these lines was made until the recent turn of the century. It had been known for some time that a medium consisting of an array of conducting rods can serve as a medium with a negative value of ε, but what was missing was how to achieve a negative value of μ. The breakthrough was provided in 1999 by Pendry *et al.* in [2], which presented several examples of how one can obtain *negative values of μ from conductors*. The most interesting of

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them was a split-ring resonator, an array of which provided a negative value of μ over a portion of its resonance frequency range. The combination of the rods and split-ring resonators yielded an artificial medium possessing both a negative ε and μ over a narrow frequency range.

Encouraged by the implications of these results, a team at the University of California at San Diego, La Jolla, built a composite medium along these lines at microwave frequencies, and made *measurements* that clearly demonstrated that this medium exhibited a negative index of refraction. These measurements [3] proved that the physical effect is real, and they triggered a flood of papers, especially in the physics community.

The microwave community was also excited by the potential for novel effects and novel components, but it realized that the guiding structure and constituent elements that were available at that time were not suitable for application to microwave integrated circuits. Since the structure on which the measurements were made included a split-ring resonator for the effective negative μ, a widespread perception developed that the array of elements must contain a resonant constituent, which is obviously undesirable because the resonant element is narrow-band and also lossy in precisely the metamaterial range of operation. Another key problem is that the physics community preferred their structures to be three-dimensional (3-D), or at least two-dimensional (2-D), whereas for microwave integrated circuits, the guiding structure must be one-dimensional (1-D).

During June 2002, at the IEEE Microwave Theory and Techniques (MTT) and Antennas and Propagation (AP)/International Scientific Radio Union (URSI) Symposia, solutions were presented by three different groups that successfully addressed the above-mentioned problems. All three used existing transmission lines as the supporting guiding structure; Oliner [4] chose strip line, while Iyer and Eleftheriades [5] and Caloz *et al.* [6] selected microstrip line. All three also chose basically similar discontinuity elements (shunt inductances and series capacitances) to provide the required negative ε and μ values. The big difference between [4] and both [5] and [6] is that [4] employed analytical expressions for the discontinuities valid over a wide frequency range, whereas [5] and [6] used L and C terms and stressed the low-frequency features and the design simplicity associated with the L, C transmission-line approach. These papers provided the *foundation* for both the approach and methodology regarding how to proceed when designing for 1-D transmission lines. This is especially true for the approaches that use L and C. The authors of [5] and [6], together with various additional later contributors, then proceeded to develop a series of novel microwave components for use with microstrip line.

IV. ADDITIONAL OBSERVATIONS

Veselago's original paper [1] is a classic "what-if" paper. It asks, "What if a medium were to have negative values of ε and μ instead of positive values? In what ways would the electrodynamic behaviors be different?" If the behaviors are not much different, or the results otherwise uninteresting, the study would serve to tell us that the structure is not worth investigating further. Or, if the results are interesting, but there is no way in which measurements can be made, the structure must be set aside in the meantime. That was the situation for Veselago's paper until recently. Now that we know how to create an artificial medium with such properties, all of the interesting performance predictions are being verified experimentally. "What-if" papers can, therefore, be very valuable under the right circumstances.

In this TRANSACTIONS' Special Issue, Engheta and Ziolkowski have submitted an excellent invited review paper with the intriguing title "A Positive Future for Double Negative Metamaterials." Many portions of their paper inquire into structures that may lead to potential applications. In that sense, these inquiries are "what-if" papers that may be tested experimentally in the near future. One example that is discussed in their paper was initially a purely "what-if" paper (in 2002), but it has now been experimentally verified in one of the papers in this TRANSACTIONS' Special Issue. The physical structure is a bilayer in which one layer is DNG and the other layer is DPS (an ordinary medium), forming a two-layer resonant cavity that can have a sub-wavelength arbitrarily small thickness. This experimental paper by Li *et al.* is entitled "Experimental Realization of a One-Dimensional LHM–RHM Resonator."

We were hoping for numerous papers with novel applications, but the microwave community is not yet ready for many such papers. Instead, the hardware-oriented creativity is directed more toward novel ways to obtain negative values of ε and μ. One such paper in this TRANSACTIONS' Special Issue is entitled "Simulation of Negative Permittivity and Negative Permeability by Means of Evanescent Waveguide Modes—Theory and Experiment," by Esteban *et al.* The key concept involves the recognition that an empty metallic *waveguide below cutoff* supports a decaying wave comparable to a wave in a stop band or to "propagation" through an over-dense plasma. The authors extend the earlier paper by Marqués *et al.*, which relates a medium with a negative ε to evanescent TE modes, to a new equivalence, between evanescent TM modes and a negative μ.

A second novel structure involves split-ring resonators. The first steps are to miniaturize the size of the split rings and place them in an array along the guide direction. As is well known from earlier studies, such arrays will produce a negative value of permeability. A newer contribution is a dual of such split-ring resonators, called a *complementary split-ring resonator*, which is fabricated by etching the negative image of the split ring in the ground plane of a microstrip line underneath the conductor strip. The complementary resonator produces a negative value of ε, rather than μ. The properties of the original split-ring structure and its complementary version are discussed, and their equivalent circuits are developed, together with how they give rise to bandpass and bandstop filters. The narrow-band and lossy nature of these resonators are still concerns.

It is not our intention to cover all the novel features in this TRANSACTIONS' Table of Contents, but we have listed these few examples as illustrative of their flavor. The field has been moving ahead nicely, and we hope that this TRANSACTIONS' Special Issue will serve to stimulate further creativity, particularly in the direction of novel microwave components.

In these introductory remarks, we have presented much in the way of background information in an attempt to be of help to those who are less well informed on this topic and are in need of some guidance.

We wish to express our sincere thanks to our many reviewers who conscientiously contributed their time and effort in order to help us produce a quality Special Issue. We received almost 40 submitted manuscripts and, in many cases, we needed to call on the same reviewer to evaluate more than one manuscript. We also wish to express our appreciation to those authors who patiently cooperated with the rigors of the review process, and diligently made the modifications requested by the reviewers. We are particularly indebted to this TRANSACTIONS’ Editor-in-Chief, Prof. Michael B. Steer, for providing the necessary guidance in both matters of principle and in the many procedural details. We also greatly appreciate the many ways in which he graciously offered help and kept us on track.

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Department of Electrical Engineering
Los Angeles, CA 90095-1594 USA

ARTHUR A. OLINER, *Guest Editor*
Polytechnic University
Department of Electrical Engineering
Lexington, MA 02421 USA

REFERENCES

[1] 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.

[2] 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. 2075–2084, Nov. 1999.

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

[4] A. A. Oliner, “A periodic-structure negative-refractive-index medium without resonant elements,” in *IEEE AP-S/URSI Int. Symp. Dig.*, San Antonio, TX, Jun. 16–21, 2002, p. 41.

[5] A. K. Iyer and G. V. Eleftheriades, “Negative refractive index metamaterials supporting 2D waves,” in *IEEE MTT-S Int. Microwave Symp. Dig.*, Seattle, WA, Jun. 2–7, 2002, pp. 1067–1070.

[6] C. Caloz, H. Okabe, T. Iwai, and T. Itoh, “Transmission line approach of left-handed materials,” in *IEEE AP-S/URSI Int. Symp. Dig.*, San Antonio, TX, Jun. 16–21, 2002, p. 39.

Tatsuo Itoh (S'69–M'69–SM'74–F'82) received the Ph.D. degree in electrical engineering from the University of Illinois at Urbana-Champaign, in 1969.

From September 1966 to April 1976, he was with the Electrical Engineering Department, University of Illinois at Urbana-Champaign. From April 1976 to August 1977, he was a Senior Research Engineer with the Radio Physics Laboratory, SRI International, Menlo Park, CA. From August 1977 to June 1978, he was an Associate Professor with the University of Kentucky, Lexington. In July 1978, he joined the faculty at The University of Texas at Austin, where he became a Professor of Electrical Engineering in 1981 and Director of the Electrical Engineering Research Laboratory in 1984. During the summer of 1979, he was a Guest Researcher with AEG-Telefunken, Ulm, Germany. In September 1983, he was selected to hold the Hayden Head Centennial Professorship of Engineering at The University of Texas at Austin. In September 1984, he was appointed Associate Chairman for Research and Planning of the Electrical and Computer Engineering Department, The University of Texas at Austin. In January 1991, he joined the University of California at Los Angeles (UCLA) as Professor of Electrical Engineering and Holder of the TRW Endowed Chair in Microwave and Millimeter Wave Electronics. He was an Honorary Visiting Professor with the Nanjing Institute of Technology, Nanjing, China, and at the Japan Defense Academy. In April 1994, he was appointed an Adjunct Research Officer with the Communications Research Laboratory, Ministry of Post and Telecommunication, Japan. He currently holds a Visiting Professorship with The University of Leeds, Leeds, U.K. He has authored or coauthored 350 journal publications, 650 refereed conference presentations, and has written 30 books/book chapters in the area of microwaves, millimeter waves, antennas, and numerical electromagnetics. He has generated 64 Ph.D. students.

Dr. Itoh is a member of the Institute of Electronics and Communication Engineers of Japan, and Commissions B and D of USNC/URSI. He served as the editor of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (1983–1985). He serves on the Administrative Committee of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S). He was vice president of the IEEE MTT-S in 1989 and president in 1990. He was the editor-in-chief of IEEE MICROWAVE AND GUIDED WAVE LETTERS (1991–1994). He was elected an Honorary Life Member of the IEEE MTT-S in 1994. He was elected a member of the National Academy of Engineering in 2003. He was the chairman of the USNC/URSI Commission D (1988–1990) and chairman of Commission D of the International URSI (1993–1996). He is chair of the Long Range Planning Committee of the URSI. He serves on advisory boards and committees for numerous organizations. He has been the recipient of numerous awards including the 1998 Shida Award presented by the Japanese Ministry of Post and Telecommunications, the 1998 Japan Microwave Prize, the 2000 IEEE Third Millennium Medal, and the 2000 IEEE MTT-S Distinguished Educator Award.

Arthur A. Oliner (M'47–SM'52–F'61–LF'87) was born on March 5, 1921, in Shanghai, China. He received the B.A. degree from Brooklyn College, Brooklyn, NY, in 1941, and the Ph.D. degree from Cornell University, Ithaca, NY, in 1946, both in physics.

He joined the Polytechnic Institute of Brooklyn (now Polytechnic University) in 1946, and became Professor in 1957. He then served as Department Head from 1966 to 1974, and was Director of its Microwave Research Institute from 1967 to 1982. He was a Walker-Ames Visiting Professor with the University of Washington, in 1964. He has also been a Visiting Professor with the Catholic University, Rio de Janeiro, Brazil, the Tokyo Institute of Technology, Tokyo, Japan, the Central China Institute of Science and Technology, Wuhan, China, and the University of Rome, Rome, Italy. In 2003, the University of Rome ("La Sapienza") granted him an Honorary Doctorate, and organized an associated special symposium in his honor. He is a member of the Board of Directors of Merrimac Industries. He has authored over 300 papers, various book chapters, and has coauthored or coedited three books. His research has covered a wide variety of topics in the microwave field including network representations of microwave structures, guided-wave theory with stress on surface waves and leaky waves, waves in plasmas, periodic structure theory, and phased-array antennas. He has made pioneering and fundamental contributions in several of these areas. His interests have also included waveguides for surface acoustic waves and integrated optics, novel leaky-wave antennas for millimeter waves, and leakage effects in microwave integrated circuits. Lately, he has contributed to the topics of metamaterials, and to enhanced propagation through subwavelength holes.

Dr. Oliner is a Fellow of the American Association for the Advancement of Science (AAAS) and the Institution of Electrical Engineers (IEE), U.K. He was a Guggenheim Fellow. He was elected a member of the National Academy of Engineering in 1991. He has been the recipient of prizes for two of his papers: the IEEE Microwave Prize in 1967 for his work on strip-line discontinuities, and the Institution Premium of the IEE in 1964 for his comprehensive studies of complex wave types guided by interfaces and layers. He was President of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), its first Distinguished Lecturer, and a member of the IEEE Publication Board. He is an Honorary Life Member of IEEE MTT-S (one of only six such persons). In 1982, he was the recipient of its highest recognition, the Microwave Career Award. A special retrospective session was held in his honor at the IEEE MTT-S International Microwave Symposium (reported in detail in the December 1988 issue of this TRANSACTIONS, pp. 1578-1581). In 1993, he was the first recipient of the Distinguished Educator Award of the IEEE MTT-S. He was also a recipient of the IEEE Centennial and Millennium Medals. He is also a past U.S. chairman of Commissions A and D of the International Union of Radio Science (URSI), a long-time member of and active contributor to Commission B, and a former member of the U.S. National Committee of URSI. In 1990, he was the recipient of the URSI van der Pol Gold Medal, which is given triennially, for his contributions to leaky waves. In 2000, the IEEE awarded him a second gold medal, the Heinrich Hertz Medal, which is its highest award in the area of electromagnetic waves.