Metamaterials and Metasurfaces—Historical Context, Recent Advances, and Future Directions

I. HISTORY OF METAMATERIALS AND METASURFACES

THE TRAJECTORY of technological progress is ultimately guided by constraints at the physical level. In building a better device or system, we are bound 1) by the properties of the materials available to us and 2) by our understanding of physical phenomena. The physical laws of the universe, immutable as they are, lead us naturally to question whether we may be able to "engineer" raw materials to better allow us to achieve, control, and manipulate natural phenomena for useful purposes. In order to do this, we must first define what we mean by the term "material." The perception that a material must appear homogeneous to the naked eye (i.e., "a uniform goop, with no discontinuous bits and pieces" [1]), natural though it may be, is flawed: surely, all materials may be considered heterogeneous on some level of scale, but more importantly, this perspective is tied specifically to the electromagnetic response of these materials to wavelengths of light that are visible to the human eye. For example, although a diamond displays familiar macroscopic properties such as color, luster, and dispersion when viewed under visible light, illumination using X-rays results in a diffraction pattern that reveals its crystalline structure. Thus, the macroscopic properties of a material, e.g. polarizabilities, permittivity, permeability, refractive index, intrinsic bulk or surface impedance, and so on, are revealed only under illumination by wavelengths of light much longer than the size of its scatterers (i.e., its atoms and molecules) and their spacing (e.g., the lattice constants of a crystal). Therefore, it would seem that engineering such macroscopic properties of materials would require control of scattering at length scales of fractions—say several hundredths or even just tenths—of a wavelength, a prohibitive task if dealing in the nanometers or Angstroms. Fortunately, the reach of the electromagnetic spectrum permits us to examine the long-wavelength condition at frequencies where such length scales become much more accessible, such as the microwave and terahertz. Advances in nanoscale fabrication have extended this reach even further to infrared and visible light. At such scales, it becomes possible to synthesize scatterers to exhibit electric and magnetic responses that may then, in analogy to their natural counterparts, be homogenized to describe effective macroscopic electromagnetic properties apparent under illumination by correspondingly long wavelengths.

A. Artificial Dielectrics

The earliest attempts to synthesize electromagnetic properties artificially go back well over a century to the pioneering work of Bose in 1898 [2] and Lindman in 1914 [3], who explored what today might be called artificial chiral structures in the millimeter-wave and microwave regions, respectively. However, the consolidated pursuit of synthesizing useful electromagnetic properties artificially was established in the seminal study of the so-called "artificial dielectrics" in the 1940s, 1950s, and 1960s (see, for example, [4]–[8]). The resulting philosophy was succinctly encapsulated by Kock in his stimulating work on metallic delay lenses, in which he noted that any artificial dielectric material may be "arrived at by reproducing, on a much larger scale, those processes occurring in the molecules of a true dielectric …[this involves] arranging metallic elements in a three-dimensional array or lattice structure to simulate the crystalline lattices of the dielectric material. Such an array responds to radio waves just as a molecular lattice responds to light waves" [4].

B. Engineering New Material Properties

The early artificial dielectrics sought to reproduce known material parameters for such purposes as creating lightweight materials (e.g., conducting scatterers suspended in a foam host medium) for RF/microwave wavelengths where the use of natural dielectrics would be superfluous. It was only a matter of time (several decades, in fact) before the pursuit was extended to material properties that transcend those found in nature. These efforts were motivated by ideas put forth in the late 1960s in an obscure Russian work by Veselago, who examined solutions to Maxwell's equations in hypothetical media exhibiting simultaneously negative isotropic permittivity and permeability [9]. This, Veselago found, results in a negative refractive index—a property that had been considered in general terms as far back as the turn of the 20th century [10], [11] and more seriously thereafter [12], [13], and which predicts several intriguing consequences such as counter-directed phase velocity and power flow, reversed Čerenkov radiation, and focusing at flat interfaces between positive- and negative-index media. Negative permittivity is a well-known property of cold plasmas below their plasma frequencies; in fact, the ground work for positive permittivities below that of free space had already been laid out in the study of artificial microwave plasmas (i.e., wire arrays) in the artificial-dielectrics community [8] and was resurrected by Pendry *et al.* [14] in the late 1990s to report their negative-permittivity properties. However, negative permeability had no known natural analog and remained elusive until the discovery of the split-ring resonator (SRR) in 1999, also by

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.
Digital Object Identifier 10.1109/TAP.2020.2969732

Pendry [15]. In 2001, researchers at UCSD combined wire and SRR arrays to demonstrate, for the first time and at microwave frequencies, a property not yet seen in natural materials: a negative refractive index [16].

C. Introduction of Metamaterials

Here roughly begins the story of "metamaterials": artificial materials engineered to exhibit electromagnetic phenomena not available or not readily available in nature. The term is said to have been introduced by R. Walser at a 1999 DARPA Workshop on composite materials, where the prefix "meta" was chosen to convey that such composites transcend the properties of natural materials [17], [18]. Although definitions abound and continue to evolve, metamaterials may generally be described as (typically periodic) structures consisting of subwavelength arrangements of metallic and/or dielectric inclusions engineered to effect exotic or otherwise inaccessible macroscopic properties not found in the natural materials that comprise them.

Expectedly, the first demonstration of negative refraction ignited a flurry of activity. The field was inherently multidisciplinary, combining concepts from solid-state physics and materials science to microwave engineering and optics to plasmonics and nanotechnology. As such, it attracted immediate and sustained interest from several communities, each emboldened by the essentially limitless possibilities of discovering one or another new property or application thereof. This frenetic pace was periodically energized by the continued contributions of Pendry, in particular, the revelation that a properly designed negative-index flat lens could offer theoretically infinite resolution, breaking the classical diffraction limit [19], and his later suggestion that metamaterials could be used to alter optical space (i.e., bend light) in just the right way as to render objects invisible [20]–[22], both of which were ultimately proved in experiments [23]–[26]. This era of discovery also evolved several metamaterial implementations beyond the wire/SRR medium (e.g., planar and volumetric transmission-line metamaterials [27]–[31], complementary-SRR-based metamaterials [32], plasmonic metamaterials, magnetodielectric metamaterials, all-dielectric metamaterials, and the so-called metatronic metamaterials [33]–[34], to name a few) and was also punctuated by practical applications benefiting from or inspired by metamaterial properties, such as leaky-wave antennas capable of back-fire to endfire radiation through broadside [35]–[37], ultraminiaturized efficient antennas [38], [39], and ultracompact phase shifters, power dividers, and other components [40], [41].

D. Introduction of Metasurfaces

Their intriguing wave-manipulation properties notwithstanding, 3-D metamaterials presented several challenges, including complex fabrication and large insertion losses. It was therefore natural to ask whether similarly intriguing properties and applications could be realized using 2-D arrangements of engineered scatterers, now widely known as "metasurfaces." Although several works had, by this time, described surfaces that could have rightly been considered metasurfaces (e.g., the seminal early work of Kildal on artificial hard surfaces [42], later implementations of impedance surfaces such as [43], [44], and indeed most planar optical metamaterials), various sources trace the first published use of the term to a 2003 work by Sievenpiper *et al.* appearing in these very IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION (hereafter, the *Transactions*) [45]. However, the term only truly established itself in the last decade, which saw a concerted development of the theory and applications of metasurfaces both inside and outside the antennas and propagation community. The pioneering works of Capasso and Shalaev in the area of gradient metasurfaces [46], [47], based on the manipulation of the amplitude and phase of the impinging wavefront with engineered nanostructures, have jumpstarted a remarkable interest in the control of the optical wavefront with ultrathin engineered devices. This flurry of interest has not been without controversy: while the engineering community has pointed out how the concepts of phased arrays, reflect-arrays, and transmit-arrays, based on analogous principles have been around for decades [48], the optics community has also noticed that analogous concepts had been developed in the context of diffraction gratings [49]–[51]. It is, however, clear that these recent activities have spurred exciting technological developments of scientific and commercial value and further enhanced the visibility and interest around metamaterials and metasurfaces.

II. METAMATERIALS AND METASURFACES TODAY

By any metric, research into metamaterials and metasurfaces have experienced explosive growth over the last two decades. Special sessions on metamaterials and metasurfaces are now commonplace at the main international meetings in several communities, and entire conferences are devoted to the subject (e.g., the *Metamaterials* conference is now remarkably in its fourteenth edition). At present, there are several hundreds of research groups actively pursuing "meta" research programs worldwide, and several institutional networks and funding mechanisms have been established solely for the purpose of advancing this science and technology. Several tens of thousands of articles have been published at a truly astonishing rate in the leading journals in several research communities. At the time of writing (December 2019), a search of the terms "metamaterials" or "metasurfaces" in titles, abstracts, and keywords for all articles indexed by the Scopus database (www.scopus.com) produces over 43 000 documents distributed across 120 journals, with roughly half of these documents contributed by research groups in the United States and China. Indeed, the actual number is certainly much higher if the search is expanded to include full text and non-indexed journals. It is noteworthy that the *Transactions* occupies the largest fraction of these papers among engineering journals (677 in total). A search of the full text of all *Transactions* papers using IEEE Xplore (https://ieeexplore.ieee.org/Xplore/home.jsp) yields 1319 papers including the term "metamaterial" and 421 papers including the term "metasurface" (these numbers exclude "Early Access" papers not yet assigned to issues, including those included in this Special Issue). Figure 1 shows the growth of papers in these two categories by year of publication in the *Transactions*.

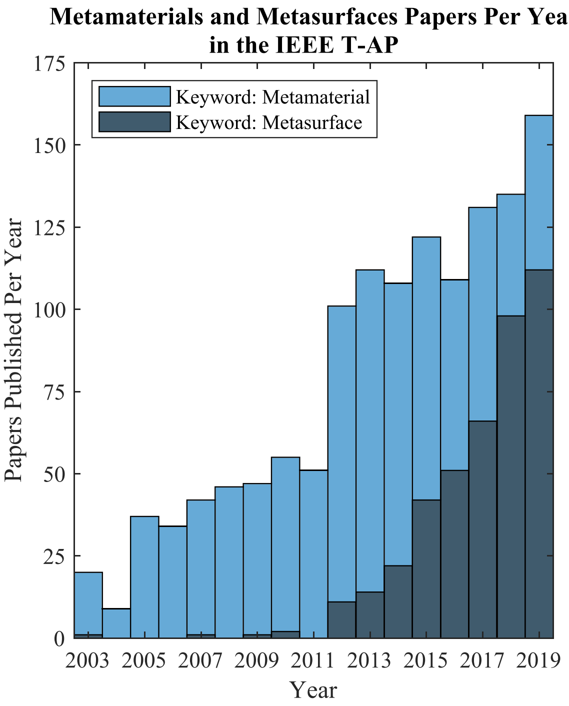

Fig. 1. IEEE Transactions on Antennas and Propagation papers containing the terms "Metamaterial" and "Metasurface," by publication year.

The first special issue on metamaterials, to the best of our knowledge, was commissioned by the Optical Society of America for *Optics Express* and fittingly guest edited by Pendry in 2003 [52]. The same year saw the publication of the first IEEE special issue on the subject, appearing in these *Transactions*, and guest edited by Ziolkowski and Engheta [53] (an excellent review of the field and the important early contributions that appeared in that special issue are provided in the review paper by Ziolkowski and Engheta appearing as the first article in the present special issue, p. 1232). In the over 16 years since, the fields of metamaterials and metasurfaces have evolved tremendously. The field has become significantly more interdisciplinary, expanding in scope from the more traditional solid-state physics, microwave engineering, optics, and materials science principles to include mechanics, acoustics, thermal engineering, and quantum concepts. Hundreds of novel metamaterial-/metasurface-infused devices have been proposed in fields ranging from biomedicine to aerospace/defense to telecommunications. This trend has necessitated concurrent advances in computing and fabrication technology, which have enabled investigations that may have previously been considered out of reach; as such, artificial intelligence, machine learning, and micro- and nanotechnologies are expected to be integral facets of future metamaterials/metasurfaces research.

III. THIS SPECIAL ISSUE

A. Goal

Although the unified pursuit of "holy grails" like the superlens and invisibility cloak has largely subsided, the pace of metamaterials/metasurfaces research today remains frenetic in 1) the continuation of long-standing fundamental pursuits including theoretical studies of unusual wave interactions with metamaterials and metasurfaces, homogenization techniques, applications of extreme or near-zero material parameters, efforts in miniaturization of devices and antennas, and enabling new electromagnetic-bandgap structures, as well as 2) several new pursuits including nonreciprocal/time-varying, nonlinear, and active/non-Foster varieties, parity-/time-symmetric structures that exploit gain and loss to achieve special properties and dispersion characteristics, topological structures, scattering-cancellation and low-profile cloaking metasurfaces, as well as metamaterials/metasurfaces that can perform various digitally coded imaging functions and possess tunable radiation properties. There is also a large push toward application-driven research, with the end goal of dispelling the hyperbole accumulated over the years and engendering real confidence in their practical application as viable alternatives to established, more mainstream technologies.

The purpose of this special issue is to draw attention to the evolution of metamaterials and metasurfaces and provide to our community a snapshot of the latest progress in this active and fertile area of research. In doing so, we hope to identify an emerging roadmap for the certainly solid future of this exciting field (a detailed discussion on our views of the future prospects of metamaterials and metasurfaces is provided in Section IV).

B. Composition

In soliciting contributions to this special issue, there was a deliberate effort to cast a wide net, so that the issue would be reflective of the growing interdisciplinarity of the field, but also to recognize the universality of antennas and propagation concepts in their applicability to all such disciplines. A total of 61 papers appear in this special issue. Of these, 34 were invited, and we are pleased to have received an additional 27 excellent contributed papers, making this one of the largest special issues (if not the largest special issue) in the recent history of the *Transactions*.

We thank Profs. Rick Ziolkowski and Nader Engheta, guest editors of the original 2003 *Transactions* special issue, for providing, as the first article of this special issue (p. 1232), an excellent recap of the seminal contributions in that special issue and their views on the evolution of the field since. Also appearing in this issue are an intriguing review on metasurfaces and their distinctions versus related concepts in antenna arrays (Wang *et al.*, p. 1332), a review on metasurface antennas for computational imaging and pattern synthesis (Imani *et al.*, p. 1860), as well as a timely two-part review on space–time metamaterials (Caloz *et al.*, p. 1569 and p. 1583). Of the remaining papers, over half are focused on metasurfaces, followed in decreasing order by metamaterials, metagratings, and metamaterial-inspired structures. Geographically, approximately one-quarter of the papers are from the United States, followed in decreasing order by China, Italy, Canada, and a handful of other countries.

In accordance with the immense growth of the field and its diversity, this special issue covers a wide variety of topics, including both theoretical and experimental work, exploring fundamental aspects as well as application-oriented scenarios, studying phenomena and devices across the electromagnetic spectrum: from low frequencies (LF), via microwaves and millimeter waves, to the terahertz (THz) and optical regimes. Generally speaking, the collection of papers can be seen as a representative snapshot of current areas of interest for the Antennas and Propagation community within this field of research. In describing these papers below, the following general metamaterial/metasurface categories have been used: 1) antenna enhancement and radar cross section (RCS) reduction; 2) wavefront transformations; 3) active and time-modulated devices; 4) unconventional waveguiding and scattering; and 5) modeling, synthesis, and analysis techniques. Of course, this partition is not strict, and many of the papers include elements relevant to more than one category.

1) Antenna Enhancement and RCS Reduction: Naturally, a large number of manuscripts focus on antenna devices, harnessing metamaterial and metasurface concepts to enhance their performance and introduce new functionalities. With modern applications in mind (e.g., 5G cellular networks, automotive radars, and low-earth-orbit (LEO) satellite communication systems), beam steering and bandwidth considerations receive special attention, finding use in various, very different, classes of antennas. For instance, in the work of Wu *et al.* (p. 1238), a twist on electrically small metamaterial-inspired Huygens dipole antennas enables pattern reconfigurability. Interestingly, Huygens' sources are also used by Dorrah *et al.* (p. 1249), this time as peripheral excitation elements in a large-aperture perforated Huygens' box, facilitating an alternative scheme for diverse dynamic beamforming. In addition, two reports propose paths for embedding these extended capabilities into modulated metasurface leaky-wave antennas: wideband operation is enabled by designating different active regions on the metasurface for radiation at different frequencies (Faenzi *et al.*, p. 1261), while multibeam functionality is achieved by introduction of multiple feeds and a judicious numerical design algorithm (Bodehou *et al.*, p. 1273). Another leaky-wave antenna by Liu *et al.* (p. 1282) utilizes a helical-tape waveguide and offers switchable radiation patterns controlled by the polarization handedness of the excitation, while the one by Sengupta *et al.* (p. 1289) demonstrates efficient generation of a 2-D-collimated broadside beam, relying on a cross-shaped aperture to reduce grating lobes in this periodic leaky-wave antenna. The classical short backfire antenna also receives an efficiency boost with the addition of carefully designed anisotropic metasurfaces to its cavity walls (Binion *et al.*, p. 1302), enabling dual-band operation with exceptionally high aperture efficiency.

Antenna devices can also benefit from the possibility of implementing metamaterials with prescribed, smoothly varying propagation constants, traditionally associated with effective refractive indices. Indeed, this feature is used by Papathanasopoulos *et al.* (p. 1312) in forming a collapsible 3D gradient-index lens for space-borne lens antennas, while Zetterstrom *et al.* (p. 1322) utilize its 2-D analog to form a prism for surface waves, reducing the beam-squint of a leaky-wave antenna designated for mm-wave point-to-point high-throughput communication.

In many cases, metasurfaces and metasurface-inspired structures are used as antenna superstrates, promoting desirable aperture fields by proper engineering of local phase shifts or resonant mode profiles, as can be seen in the work by Liu *et al.* (p. 1348) and Li *et al.* (p. 1356) Flat lenses and phase-gradient metasurfaces are widely used manifestations of this ability; although these are rather well-established concepts, the increasing demands of next-generation communication systems require their further development and evolution. Accordingly, two papers, by Shunli Li *et al.* (p. 1366) and Teng Li *et al.* (p. 1378), demonstrate integration of metasurface lenses in different multibeam systems to enhance their massive MIMO performance, and Singh *et al.* (p. 1389) propose optimization of phase-gradient metasurfaces to reduce the sidelobe level in an antenna with 2-D mechanical beam steering. Phase-gradient metasurfaces are further utilized by Lv *et al.* (p. 1402) for the design and implementation of planar phased arrays with extended scanning range.

Reflective and absorptive superstrates can be useful also for reducing the RCS of antenna devices; the ability offered by metasurfaces and metamaterials to tune the reflection and absorption coefficients for each polarization across a range of frequencies on a subwavelength scale makes them excellent candidates to perform this task. These qualities are harnessed in the papers by Cheng *et al.* (p. 1411), Han *et al.* (p. 1419), and Guo *et al.* (p. 1426) to reduce the RCS of various antennas. Metasurfaces for RCS reduction of dihedral corner reflectors (Modi *et al.*, p. 1436), single-layer dual-band metafilms for polarization-selective shielding (Baladi *et al.*, p. 1448), and multiband metamaterial absorbers for crowd estimation (Tofigh *et al.*, p. 1458) are demonstrated as well, emphasizing the usefulness of these concepts for an even wider range of applications.

2) Wavefront Transformations: Another significant portion of this special issue is dedicated to metasurfaces intended for wavefront transformations. This functionality is closely associated with the perspective according to which locally homogenized metasurfaces form equivalent spatially varying boundary conditions, which can be engineered to convert a given incident field into a desired scattered waveform. Related work includes novel configurations for meta-atoms, used to deflect incoming plane waves into preferable directions, manipulate their polarization state, and generate special beams. Among these, bilayer Huygens' meta-atoms developed by Xue *et al.* (p. 1468) enable broadband focusing via a metasurface lens; omega-bianisotropic asymmetric wire-loop meta-atoms proposed by Chen *et al.* (p. 1477) facilitate reflectionless wide-angle refraction; and self-complementary metasurfaces for frequency-controllable polarization rotation at THz frequencies are synthesized and analyzed by Sayanskiy *et al.* (p. 1491) At THz as well, Miao *et al.* (p. 1503) utilize a folded-reflector configuration to generate 2-D Airy beams. More on the special-beams front, Wang *et al.* (p. 1514) design and demonstrate an efficient FSS-based vortex beam generator, and Abdipour *et al.* (p. 1523) investigate the lateral (Goose–Hänchen and Imbert–Fedorov) shifts undergone by Gaussian beams upon reflection by a homogenized metasurface.

An additional way to efficiently implement controlled beam deflection that has been attracting increased attention lately relies on the concept of metagratings. In contrast to metasurfaces, metagratings typically consist of sparsely distributed polarizable particles and do not adhere to the conventional homogenization approximation. However, by judicious engineering of the supercell, effective wave rerouting can be obtained. Three papers in this special issue report advances in this field, focusing on printed-circuit-board (PCB) realizations at microwave frequencies: Popov *et al.* (p. 1533) describe the design procedure and experimental characterization of reflective-type metagratings; Casolaro *et al.* (p. 1542) introduce means for dynamic beam steering, in both reflection and transmission, alongside a suitable model; and Rabinovich *et al.* (p. 1553) formulate and verify experimentally a scheme to realize arbitrary diffraction engineering with multilayered multielement metagratings.

3) Active and Time-Modulated Devices: Recently, there has been growing interest in active and time-modulated metamaterials and metasurfaces in the electromagnetics and photonics communities. These concepts, with inherent possibilities for frequency conversion/generation and nonreciprocal operation, are identified as powerful degrees of freedom that are yet to reveal their full potential. Furthermore, as many classical limits were derived with linear, static, and passive systems in mind, breaking these underlying assumptions is expected to lead to interesting wave phenomena and unprecedented performance of radiators, scatterers, and waveguides.

Not surprisingly, this emerging topic receives substantial consideration in this special issue. In particular, time-modulated transmissive metasurfaces demonstrated by Wu *et al.* (p. 1599) implement serrodyne frequency translation, while Ramaccia *et al.* (p. 1607) use such modulation in reflective metasurfaces to induce an artificial Doppler effect. Temporal variation in the metasurface response may also pave the path for alternative communication methodologies. Dai *et al.* (p. 1618) follow this idea to realize multimodulation schemes with time-domain digital-coding metasurfaces at microwaves, whereas Salary *et al.* (p. 1628) propose to use time-modulated conducting oxide metasurfaces for adaptive multiple access optical communication. Related theoretical framework for analyzing soft temporal switching of transmission line properties is derived and illustrated by Hadad *et al.* (p. 1643), e.g., for ultra-wideband impedance matching for short pulse signals.

Diverse perspectives of active devices are addressed as well in the frame of this issue. In a theoretical work, Chen *et al.* (p. 1655) shed light on the capabilities and limitations of active scattering-cancellation cloaking, considering both bandwidth and stability aspects. Stability is also an important factor in the work of Vincelj *et al.* (p. 1665), which designs, manufactures, and tests a self-oscillating non-Foster unit cell, envisioned as a building block for future active metasurfaces. On the antenna front, Li *et al.* (p. 1680) propose and demonstrate an interesting concept to convert dc voltage to RF radiation using an active metasurface, with potential for electronic beam steering.

4) Unconventional Waveguiding and Scattering: As reviewed in Section I, the concept of versatile engineered complex media has, from the very early days of metamaterials research, led to continuous challenging of the boundaries of traditional optics and electromagnetics. Ideas such as negative index of refraction, epsilon/mu-near-zero, hyperbolic dispersion, focusing beyond the diffraction limit, and cloaking, to name a few, have led to new perspectives and driven the development of new devices across all disciplines of wave physics. Similar trends (perhaps with respect to different ideas) are still very much present in today's metamaterial and metasurface communities, forming points of intersection between researchers from different fields of study. As such, this special issue contains several related studies, exploring complex media configurations that support unconventional wave propagation, waveguiding, or scattering phenomena. In a work that corresponds with the contemporary notion of "bound states in the continuum," Cuesta *et al.* (p. 1689) theoretically and experimentally investigate pairs of passive metasurfaces that form a nonscattering system to an external observer, while having the ability to strongly modulate the fields between them. Special scattering properties are also the focus of the analysis by Moccia *et al.* (p. 1704), considering a plane wave impinging a core-shell cylindrical structure possessing non-Hermitian constituents (i.e., combining gain and loss). The work studies the spectral singularities associated with such structures, pointing out possibilities to utilize them to control (potentially dynamically) the cylinder scattering pattern. Vellucci *et al.* (p. 1717) also address scattering control, applied in their work to provide waveform selectivity to a wire antenna. Specifically, they propose to load a mantle cloak with nonlinear diode-based circuits, making the antenna "invisible" for pulse signals while allowing normal receive/transmit operation for continuous wave signals.

As denoted above, exotic wave propagation and waveguiding properties associated with certain metamaterial and metasurface designs are considered in this special issue as well. Among these, Zangeneh-Nejad *et al.* (p. 1726) show how a metamaterial crystal can be engineered to possess nonreciprocal properties at the subwavelength unit-cell level, relying on an externally biased magnetic material to break time-reversal symmetry. Magnetic bias, albeit in-plane, is utilized to break reciprocity in the work of Yu *et al.* (p. 1733) as well, where a one-way waveguide is formed by removing a row of elements from a metasurface positioned above a ground-plane-backed ferrite, owing to the formation of accidental Dirac cones; attempts to launch the wave in the opposite direction results in leakage to the waveguide cladding. Nonreciprocity also features in the analysis by Mazor *et al.* (p. 1739), where space–time modulation facilitates one-way propagation of surface waves on hyperbolic metasurfaces. On hyperbolic metamaterials, Campione *et al.* (p. 1748) present an experimental evidence that such composites exhibit a Lorentz-like effective medium resonance, made observable by engineering strong coupling to a plasmonic metasurface and suitable measurements at mid-infrared frequencies. Hyperbolic response also plays a major role in the investigation by Silva *et al.* (p. 1755), shedding light on the comb-like dispersion curves associated with modes supported by a double wire medium slab. The dispersion of compact metamaterial-based electromagnetic bandgap structures is engineered in the work of Barth *et al.* (p. 1761) using the theory laid out therein to realize dual-band microstrip networks. In the paper by Ma *et al.* (p. 1773), original parallel-plate waveguides formed by a pair of penetrable metasurfaces are studied, and the associated guided mode dispersion is theoretically derived and analyzed.

5) Modeling, Synthesis, and Analysis Techniques: As can be inferred from the diverse nature of the devices and physical effects explored so far, metamaterials, metasurfaces, and other related forms of complex media possess numerous degrees of freedom available for their design. In fact, this explosion of opportunities is one of the most prominent characteristics of the metamaterial "philosophy." In view of this intrinsic design complexity, this special issue would not be complete without reporting advances in synthesis and analysis techniques of artificial electromagnetic media. Such tools and models are instrumental to the further development of the field: not only are they essential for the transfer of theoretical ideas to practical prototypes, but, many times, they reveal promising research directions and trigger paradigm shifts.

Within this group of papers, Yakovlev *et al.* (p. 1786) develop an equivalent ABCD matrix formalism, useful for analysis of scattering off finite-thickness nonlocal wire media structures with terminating surfaces. On the modeling of complex media, Monti *et al.* (p. 1799) derive analytical expressions for the homogenized (electric and magnetic) surface impedances of metasurfaces composed solely of dielectric spheres and demonstrate their potential for the synthesis of all-dielectric reflectors. Metasurface synthesis is also addressed in the work by Brown *et al.* (p. 1812), where they present an inverse design algorithm based on surface-susceptibility representations and utilize it to design planar and spherical surfaces with prescribed scattering performance in the near or far-field. Graphene is a promising platform for achieving tunability in metadevices, especially at high frequencies (THz and beyond); to enable effective design and optimization of such active devices, Prokopeva *et al.* (p. 1825) propose a computationally efficient and physically meaningful surface conductivity model for both time and frequency domain analyses, replacing time-consuming direct numerical integration of Kubo's integral formulas. Salucci *et al.* (p. 1836) use a Schwarz-Christoffel mapping to extend the transformation electromagnetics formulation such that it allows synthesis of metamaterial lenses with holes or forbidden regions, typical in applications such as mast-mounted cellular base stations and radar antennas. For shaping radiation patterns of patch antennas, Barbuto *et al.* (p. 1851) formulate a unique synthesis scheme based on topological principles, enabling pattern diversity by exciting a combination of vortex beams.

Finally, beyond the variety of radiating, scattering, and guiding devices considered above, additional articles in this special issue illustrate how the incorporation of metamaterial and metasurface elements can facilitate novel routes for tackling other, perhaps less obvious, applications. These include microwave imaging (Imani *et al.*, p. 1860), dielectric material characterization and defect detection (Gil *et al.*, p. 1876), and wireless power transfer (Brizi *et al.*, p. 1887).

IV. OUTLOOK: FUTURE PROSPECTS FOR METAMATERIALS AND METASURFACES

The phenomenal and continued interest in metamaterials and metasurfaces over the past 20 years has been driven by the idea that any phenomenon, technique, or device based on the properties of its constituent materials may be open to reexamination, for it may possess a "meta" counterpart with paradigm-shifting implications, useful new attributes, or improved performance. As a result of the attention garnered by metamaterials in the academic community, there has also been a growing recognition of their potential commercial value in industry. Thus, metamaterials research has arrived at a crossroads, at which multiple academic disciplines and industries must be brought together to initiate a mass transition from proof-of-concept to practical applications in real-world problems, so as to encourage their adoption as commercially viable alternatives to existing mainstream technologies.

In this context, several exciting trends have been emerging in the recent metamaterials/metasurfaces research, opening important opportunities for a wide range of technologies. While it is certainly not possible to review here the several open directions in their entirety, a good starting point is the collection of articles contained in this special issue, which indeed sample recent examples of excellent research from the leaders in this field. In the following discussion, we summarize a few promising directions toward which the metamaterials/metasurfaces community appears to be pointing.

Gradient metasurfaces [46], [54] and their various applications from optics (meta-lenses, meta-holograms) to radio waves have been driving the community to more applied directions. Commercial interest in these efforts has been growing fast, and this field of technology promises tremendous opportunities for real-life impact on the near future.

One missing component in this growing field is the possibility of real-time reconfigurability of the functionality encoded in metasurfaces. Reconfigurable ultrathin surfaces providing *ad hoc* wavefront transformations to the impinging waves [55]–[58], ideally responding in real time to changes in the environment, may form the basis for smart surfaces with significant impact on nearly any electromagnetic and photonic application, from classical to quantum photonics, from radar to wireless technology.

Tunable components with sufficient speeds open other exciting opportunities for metamaterials and metasurfaces, beyond simple reconfigurability. Time-varying elements can break fundamental limitations of passive metastructures, including reciprocity constraints and passivity. Time-varying metamaterials and metasurfaces have been recently investigated for their nonreciprocal properties [59], [60] and for the possibility to provide energy to the impinging signal through parametric phenomena [61]; yet, significant challenges remain, especially in the framework of translating these concepts to higher frequencies.

Active metasurfaces may be employed to break the bandwidth limitations of passive structures, realizing non-Foster dispersion [62], but important challenges are associated with the stability of these components and to the difficulty in providing sufficient gain at high frequencies. In the context of active media, a particularly interesting class of metamaterials is the one satisfying parity-time symmetry in the context of non-Hermitian physics, opening the way to a plethora of exotic phenomena of great interest [63]–[67]. Parity-time symmetry requires a balanced distribution of gain and loss in a geometrically asymmetric structure, supporting quite unusual responses, including negative refraction [68], [69] and cloaking [70], [71] without the bandwidth and efficiency limitations of passive metamaterial structures.

Metamaterials and metasurfaces with giant nonlinear responses are also a very active research area, which we expect to further grow in the coming years with improved technological and nanofabrication processes. Conventional nonlinear optics relies on phase matching and electrically large structures, yet metamaterial concepts can realize extreme nonlinear phenomena at the subwavelength scale, potentially opening groundbreaking opportunities in nonlinear optics and electromagnetics [72]–[74]. Finally, it is important to mention the field of topological metamaterials, a rapidly growing area which has translated the concept of topological phases of matter from condensed matter physics into the field of artificial materials, facilitating breakthroughs in engineered photonics and electromagnetics [75]–[78]. These concepts are particularly interesting for metamaterials because they endow them with unusual robustness to disorder and fabrication errors, as their exotic properties stem from topological features that do not change upon continuous variations of the geometry.

We cannot safely predict which of these directions, or if other equally exciting opportunities that we did not cover in this editorial, will take over in the future of metamaterials/metasurfaces research. However, we can confidently say that metamaterials and metasurfaces have evolved into a vibrant and multidisciplinary research field, with solid foundations and a bright future ahead of further growth and expansion, in which the Antennas and Propagation community will continue to play a leading role.

ACKNOWLEDGMENT

We extend our gratitude to all authors in this special issue, who range from pioneers (many of whom contributed to the original 2003 *Transactions* special issue) to new entrants making “waves” in the field. We also apologize to the authors of several other excellent papers that could not be accommodated, many of which have been directed to upcoming regular issues of the *Transactions*. We must also thank Prof. Danilo Erricolo, Editor-in-Chief of the *Transactions* for entrusting this special issue to us, as well as his administrative assistant Ms. Sunny Tse, IEEE Transactions/Journals Production Manager Ms. Sharon M. Turk, and Editorial Support and Production Assistant Ms. Lauren Briede for fielding so many of our questions. Finally, we thank the 125 reviewers whose competent and constructive comments have ensured a high-quality final product.

ASHWIN K. IYER, *Guest Editor*
Department of Electrical and Computer Engineering
University of Alberta
Edmonton, AB, Canada
iyer@ece.ualberta.ca

ANDREA ALÙ, *Guest Editor*
Photonics Initiative
CUNY Advance Science Research Center
New York, NY, USA
aalu@gc.cuny.edu

ARIEL EPSTEIN, *Guest Editor*
Andrew and Erna Viterbi Faculty
of Electrical Engineering
Technion—Israel Institute of Technology
Haifa, Israel
epsteina@ee.technion.ac.il

REFERENCES

[1] S. Cripps, “Metamaterialism,” *IEEE Microw.*, vol. 7, no. 6, pp. 32–37, Dec. 2006.
[2] J. C. Bose, “On the rotation of plane of polarisation of electric wave by a twisted structure,” *Proc. Roy. Soc. London*, vol. 63, pp. 146–152, Dec. 1898.
[3] I. Lindell, A. 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.
[4] W. E. Kock, “Metallic delay lenses,” *Bell. Syst. Tech. J.*, vol. 27, no. 1, pp. 58–82, Jan. 1948.
[5] W. Kock, “Metal-lens antennas,” *Proc. IRE*, vol. 34, no. 11, pp. 828–836, Nov. 1946.
[6] R. N. Bracewell, “Analogues of an ionized medium: Applications to the ionosphere,” *Wireless Eng.*, vol. 31, pp. 320–326, Dec. 1954.
[7] J. Brown and W. Jackson, “The properties of artificial dielectrics at centimetre wavelengths,” *Proc. IEE-B, Radio Electron. Eng.*, vol. 102, no. 1, pp. 11–16, Jan. 1955.
[8] W. Rotman, “Plasma simulation by artificial dielectrics and parallel-plate media,” *IRE Trans. Antennas Propag.*, vol. 10, no. 1, pp. 82–95, Jan. 1962.
[9] V. G. Veselago, “The electrodynamics of substances with simultaneously negative values of ϵ and μ,” *Soviet Phys. Uspekhi*, vol. 10, no. 4, pp. 509–514, Jan.-Feb. 1968.
[10] A. Schuster, *An Introduction to the Theory of Optics*. London, U.K.: Edward Arnold, 1904.
[11] H. Lamb, “On group-velocity,” *Proc. London Math. Soc.*, vol. 2, no. 1, pp. 473–479, 1904.
[12] V. E. Pafomov, “Transition radiation and Cerenkov radiation,” *Sov. Phys. JETP*, vol. 36, no. 6, pp. 1321–1324, Dec. 1959.
[13] L. I. Mandel’shtam, “Group velocity in a crystal lattice,” *Zhurnal Eksperimentalnoi Teoreticheskoi Fiziki*, vol. 15, pp. 475–478, Jan. 1945.
[14] J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, “Extremely low frequency plasmons in metallic mesostructures,” *Phys. Rev. Lett.*, vol. 76, no. 25, pp. 4773–4776, Jul. 2002.
[15] J. Pendry, A. Holden, D. Robbins, and W. Stewart, “Magnetism from conductors and enhanced nonlinear phenomena,” *IEEE Trans. Microw. Theory Techn.*, vol. 47, no. 11, pp. 2075–2084, Nov. 1999.
[16] R. A. Shelby, “Experimental verification of a negative index of refraction,” *Science*, vol. 292, no. 5514, pp. 77–79, Apr. 2001.
[17] R. W. Ziolkowski, “Metamaterials: The early years in the USA,” *EPJ Appl. Metamat.*, vol. 1, p. 5, Jul. 2014.
[18] J. S. Derov, R. Hammond, and I. J. Youngs, “The history of the early years of metamaterials in USA and UK defense agencies,” *J. Opt.*, vol. 19, no. 8, Aug. 2017, Art. no. 084002.
[19] J. B. Pendry, “Negative refraction makes a perfect lens,” *Phys. Rev. Lett.*, vol. 85, no. 18, pp. 3966–3969, Jul. 2002.
[20] J. B. Pendry, “Controlling electromagnetic fields,” *Science*, vol. 312, no. 5781, pp. 1780–1782, Jun. 2006.
[21] U. Leonhardt, “Optical conformal mapping,” *Science*, vol. 312, no. 5781, pp. 1777–1780, Jun. 2006.
[22] A. Alù and N. Engheta, “Achieving transparency with plasmonic and metamaterial coatings,” *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 72, no. 1, Jul. 2005, Art. no. 016623.
[23] A. Grbic and G. V. Eleftheriades, “Overcoming the diffraction limit with a planar left-handed transmission-line lens,” *Phys. Rev. Lett.*, vol. 92, no. 11, Mar. 2004, Art. no. 117403.
[24] A. K. Iyer and G. V. Eleftheriades, “Free-space imaging beyond the diffraction limit using a Veselago-Pendry transmission-line metamaterial superlens,” *IEEE Trans. Antennas Propag.*, vol. 57, no. 6, pp. 1720–1727, Jun. 2009.
[25] D. Schurig *et al.*, “Metamaterial electromagnetic cloak at microwave frequencies,” *Science*, vol. 314, no. 5801, pp. 977–980, Nov. 2006.
[26] D. Rainwater, A. Kerkhoff, K. Melin, J. C. Soric, G. Moreno, and A. Alù, “Experimental verification of three-dimensional plasmonic cloaking in free-space,” *New J. Phys.*, vol. 14, no. 1, Jan. 2012, Art. no. 013054.

[27] 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 Techn.*, vol. 50, no. 12, pp. 2702–2712, Dec. 2002.

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

[29] A. K. Iyer and G. V. Eleftheriades, “A multilayer negative-refractive-index transmission-line (NRI-TL) metamaterial free-space lens at X-band,” *IEEE Trans. Antennas Propag.*, vol. 55, no. 10, pp. 2746–2753, Oct. 2007.

[30] A. K. Iyer and G. V. Eleftheriades, “A three-dimensional isotropic transmission-line metamaterial topology for free-space excitation,” *Appl. Phys. Lett.*, vol. 92, no. 26, Jun. 2008, Art. no. 261106.

[31] S. M. Rudolph and A. Grbic, “Volumetric negative-refractive-index medium exhibiting broadband negative permeability,” *J. Appl. Phys.*, vol. 102, no. 1, Jul. 2007, Art. no. 013904.

[32] F. Falcone, T. Lopetegi, J. Baena, R. Marques, F. Martin, and M. Sorolla, “Effective negative-ε stopband microstrip lines based on complementary split ring resonators,” *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 6, pp. 280–282, Jun. 2004.

[33] N. Engheta, A. Salandrino, and A. Alù, “Circuit elements at optical frequencies: Nanoinductors, nanocapacitors, and nanoresistors,” *Phys. Rev. Lett.*, vol. 95, no. 9, pp. 095504-1–095504-4, Aug. 2005.

[34] N. Engheta, “Circuits with light at nanoscales: Optical nanocircuits inspired by metamaterials,” *Science*, vol. 317, no. 5845, pp. 1698–1702, Sep. 2007.

[35] A. Grbic and G. V. Eleftheriades, “Experimental verification of backward-wave radiation from a negative refractive index metamaterial,” *J. Appl. Phys.*, vol. 92, no. 10, pp. 5930–5935, Nov. 2002.

[36] A. K. Iyer and G. V. Eleftheriades, “Leaky-wave radiation from a two-dimensional negative-refractive-index transmission-line metamaterial,” in *Proc. URSI Int. EM Theory Symp.*, Pisa, Italy, May 2004, pp. 891–893.

[37] S. Lim, C. Caloz, and T. Itoh, “Metamaterial-based electronically controlled transmission-line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth,” *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 12, pp. 2678–2690, Dec. 2004.

[38] R. W. Ziolkowski and A. Erentok, “Metamaterial-based efficient electrically small antennas,” *IEEE Trans. Antennas Propag.*, vol. 54, no. 7, pp. 2113–2130, Jul. 2006.

[39] A. Erentok and R. W. Ziolkowski, “Metamaterial-inspired efficient electrically small antennas,” *IEEE Trans. Antennas Propag.*, vol. 56, no. 3, pp. 691–707, Mar. 2008.

[40] M. Antoniades and G. Eleftheriades, “Compact linear lead/lag metamaterial phase shifters for broadband applications,” *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 103–106, 2003.

[41] G. V. Eleftheriades and R. Islam, “Miniaturized microwave components and antennas using negative-refractive-index transmission-line (NRI-TL) metamaterials,” *Metamaterials*, vol. 1, no. 2, pp. 53–61, Dec. 2007.

[42] P.-S. Kildal, “Artificially soft and hard surfaces in electromagnetics,” *IEEE Trans. Antennas Propag.*, vol. 38, no. 10, pp. 1537–1544, 1990.

[43] S. Linden, “Magnetic response of metamaterials at 100 terahertz,” *Science*, vol. 306, no. 5700, pp. 1351–1353, Nov. 2004.

[44] H. Mosallaei and K. Sarabandi, “Antenna miniaturization and bandwidth enhancement using a reactive impedance substrate,” *IEEE Trans. Antennas Propag.*, vol. 52, no. 9, pp. 2403–2414, Sep. 2004.

[45] D. Sievenpiper, J. Schaffner, H. Song, R. Loo, and G. Tangonan, “Two-dimensional beam steering using an electrically tunable impedance surface,” *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, pp. 2713–2722, Oct. 2003.

[46] N. Yu *et al.*, “Light propagation with phase discontinuities: Generalized laws of reflection and refraction,” *Science*, vol. 334, no. 6054, pp. 333–337, Oct. 2011.

[47] X. Ni, N. K. Emani, A. V. Kildishev, A. Boltasseva, and V. M. Shalaev, “Broadband light bending with plasmonic nanoantennas,” *Science*, vol. 335, no. 6067, p. 427, Jan. 2012.

[48] R. Bansal, “Bending snell’s laws [AP-S turnstile],” *IEEE Antennas Propag. Mag.*, vol. 53, no. 5, pp. 146–147, Oct. 2011.

[49] Z. Bomzon, G. Biener, V. Kleiner, and E. Hasman, “Space-variant Pancharatnam-Berry phase optical elements with computer-generated subwavelength gratings,” *Opt. Lett.*, vol. 27, no. 13, pp. 1141–1143, Jul. 2002.

[50] E. Silberstein, P. Lalanne, J.-P. Hugonin, and Q. Cao, “Use of grating theories in integrated optics,” *J. Opt. Soc. Amer. A, Opt. Image Sci.*, vol. 18, no. 11, p. 2865, Nov. 2001.

[51] P. Lalanne and P. Chavel, “Metalenses at visible wavelengths: Past, present, perspectives,” *Laser Photon. Rev.*, vol. 11, no. 3, May 2017, Art. no. 1600295.

[52] J. B. Pendry Ed, “Focus issue: Negative refraction and metamaterials,” *Opt. Express*, vol. 11, no. 7, p. 639, Apr. 2003.

[53] R. Ziolkowski and N. Engheta, “Metamaterial special issue introduction,” *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, pp. 2546–2549, Oct. 2003.

[54] A. V. Kildishev, A. Boltasseva, and V. M. Shalaev, “Planar photonics with metasurfaces,” *Science*, vol. 339, no. 6125, Mar. 2013, Art. no. 1232009.

[55] Y. Ra’di and A. Alù, “Reconfigurable metagratings,” *ACS Photon.*, vol. 5, no. 5, pp. 1779–1785, May 2018.

[56] K. Chen *et al.*, “A reconfigurable active Huygens’ metalens,” *Adv. Mater.*, vol. 29, no. 17, May 2017, Art. no. 1606422.

[57] X. Zhao *et al.*, “Electromechanically tunable metasurface transmission waveplate at terahertz frequencies,” *Optica*, vol. 5, no. 3, p. 303, Mar. 2018.

[58] A. Karvounis, B. Gholipour, K. F. Macdonald, and N. I. Zheludev, “All-dielectric phase-change reconfigurable metasurface,” *Appl. Phys. Lett.*, vol. 109, no. 5, Aug. 2016, Art. no. 051103.

[59] Y. Hadad, D. L. Sounas, and A. Alù, “Space-time gradient metasurfaces,” *Phys. Rev. B, Condens. Matter*, vol. 92, no. 10, Sep. 2015, Art. no. 100304.

[60] A. Shaltout, A. Kildishev, and V. Shalaev, “Time-varying metasurfaces and Lorentz non-reciprocity,” *Opt. Mater. Express*, vol. 5, no. 11, pp. 2459–2467, Nov. 2015.

[61] H. Li, A. Mekawy, and A. Alù, “Beyond Chu’s limit with Floquet impedance matching,” *Phys. Rev. Lett.*, vol. 123, no. 16, Oct. 2019, Art. no. 164102.

[62] S. Hrabar, “First ten years of active metamaterial structures with ‘negative’ elements,” *EPJ Appl. Metamater.*, vol. 5, p. 9, Oct. 2018.

[63] H. Hodaei, M.-A. Miri, M. Heinrich, D. N. Christodoulides, and M. Khajavikhan, “Parity-time-symmetric microring lasers,” *Science*, vol. 346, no. 6212, pp. 975–978, Nov. 2014.

[64] R. Fleury, D. Sounas, and A. Alù, “An invisible acoustic sensor based on parity-time symmetry,” *Nature Commun.*, vol. 6, Jan. 2015, Art. no. 5905.

[65] L. Feng, R. El-Ganainy, and L. Ge, “Non-Hermitian photonics based on parity-time symmetry,” *Nature Photon.*, vol. 11, pp. 752–762, Dec. 2017.

[66] R. El-Ganainy, K. G. Makris, M. Khajavikhan, Z. H. Musslimani, S. Rotter, and D. N. Christodoulides, “Non-Hermitian physics and PT symmetry,” *Nature Phys.*, vol. 14, no. 1, pp. 11–19, Jan. 2018.

[67] M.-A. Miri and A. Alù, “Exceptional points in optics and photonics,” *Science*, vol. 363, no. 6422, Jan. 2019, Art. no. eaar7709.

[68] R. Fleury, D. L. Sounas, and A. Alù, “Negative refraction and planar focusing based on parity-time symmetric metasurfaces,” *Phys. Rev. Lett.*, vol. 113, Jul. 2014, Art. no. 023903.

[69] F. Monticone, C. A. Valagiannopoulos, and A. Alù, “Aberration-free imaging based on parity-time symmetric nonlocal metasurfaces,” *Phys. Rev. X*, vol. 6, Oct. 2016, Art. no. 041018.

[70] A. Kord, D. L. Sounas, and A. Alù, “Active microwave cloaking using parity-time symmetric Satellites,” *Phys. Rev. A, Gen. Phys.*, vol. 10, no. 5, Nov. 2018, Art. no. 054040.

[71] D. L. Sounas, R. Fleury, and A. Alù, “Unidirectional cloaking based on metasurfaces with balanced loss and gain,” *Phys. Rev. Appl.*, vol. 4, no. 1, 2015, Art. no. 014005.

[72] N. Nookala *et al.*, “Ultrathin gradient nonlinear metasurfaces with giant nonlinear response,” *Optica*, vol. 3, no. 3, pp. 283–288, Mar. 2016.

[73] J. Lee *et al.*, “Giant nonlinear response from plasmonic metasurfaces coupled to intersubband transitions,” *Nature*, vol. 511, no. 7507, pp. 65–69, Jul. 2014.

[74] S. Liu *et al.*, “An all-dielectric metasurface as a broadband optical frequency mixer,” *Nature Commun.*, vol. 9, Jun. 2018, Art. no. 2507.

[75] S. Raghu and F. D. M. Haldane, “Analogs of quantum-Hall-effect edge states in photonic crystals,” *Phys. Rev. A, Gen. Phys.*, vol. 78, no. 3, pp. 033834-1–033834-21, Sep. 2008.

[76] Z. Wang, Y. Chong, J. D. Joannopoulos, and M. Soljačić, “Observation of unidirectional backscattering-immune topological electromagnetic states,” *Nature*, vol. 461, no. 7265, pp. 772–775, Oct. 2009.

[77] M. Hafezi, E. A. Demler, M. D. Lukin, and J. M. Taylor, “Robust optical delay lines with topological protection,” *Nature Phys.*, vol. 7, no. 11, pp. 907–912, Nov. 2011.

[78] X. Ni, D. Purtseladze, D. A. Smirnova, A. Slobozhanyuk, A. Alù, and A. B. Khanikaev, “Spin- and valley-polarized one-way Klein tunneling in photonic topological insulators,” *Sci. Adv.*, vol. 4, no. 5, May 2018, Art. no. eaap8802.

Ashwin K. Iyer (Senior Member, IEEE) received the B.A.Sc., M.A.Sc., and Ph.D. degrees in electrical engineering from the University of Toronto, Toronto, ON, Canada, in 2001, 2003, and 2009, respectively, with a focus on the discovery and development of the negative-refractive-index transmission-line approach to metamaterial design and the realization of metamaterial lenses for free-space microwave subdiffraction imaging.

He is currently an Associate Professor with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada, where he leads a team of graduate students investigating novel RF/microwave circuits and techniques, fundamental electromagnetic theory, antennas, and engineered metamaterials, with an emphasis on their applications to microwave and optical devices, defense technologies, and biomedicine. He has coauthored a number of highly cited articles and book chapters on metamaterials.

Dr. Iyer is a member of the IEEE AP-S Education Committee and a Registered Member of the Association of Professional Engineers and Geoscientists of Alberta. He was a recipient of the IEEE AP-S R. W. P. King Award in 2008, the IEEE AP-S Donald G. Dudley Jr. Undergraduate Teaching Award in 2015, the University of Alberta Provost's Award for Early Achievement of Excellence in Undergraduate Teaching in 2014, and the University of Alberta Rutherford Award for Excellence in Undergraduate Teaching in 2018. His students are the recipients of several major national and international awards for their research. He serves as the Co-Chair for the IEEE Northern Canada Section's award-winning Joint Chapter of the AP-S and MTT-S societies and a Technical Program Committee Co-Chair for the 2020 AP-S/URSI International Symposium. From 2012 to 2018, he was an Associate Editor of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION and currently serves as a Track Editor.

Andrea Alù (Fellow, IEEE) received the *Laurea*, M.S., and Ph.D. degrees from the University of Rome Tre, Rome, Italy, in 2001, 2003, and 2007, respectively.

He is the Founding Director of the Photonics Initiative at the Advanced Science Research Center (ASRC) with Graduate Center, City University of New York (CUNY), New York, NY, USA. He is also the Einstein Professor of physics with the CUNY Graduate Center, a Professor of electrical engineering with the City College of New York, New York, an Adjunct Professor and a Senior Research Scientist with the University of Texas at Austin, Austin, TX, USA. From 2002 to 2008, he was periodically working at the University of Pennsylvania (UPenn), Philadelphia, PA, USA, where he developed significant parts of his Ph.D. and postgraduate research. After spending one year as a Postdoctoral Research Fellow at UPenn, in 2009, he joined the Faculty of the University of Texas at Austin, where he was the Temple Foundation Endowed Professor until 2018. He is the coauthor of an edited book on *Optical Antennas*, over 500 journal articles and over 35 book chapters. He has been a Highly Cited Researcher from Web of Science since 2017. His current research interests span over metamaterials and plasmonics, electromangetics, optics and nanophotonics, acoustics, scattering, nanocircuits and nanostructures, miniaturized antennas and nanoantennas, and RF antennas and circuits.

Dr. Alù is a full member of URSI and a fellow of NAI, OSA, AAAS, SPIE, and APS. Over the last few years, he has received several research awards, including the IEEE Kiyo Tomiyasu Award in 2019, the ICO Prize in Optics 2016, the Edith and Peter O'Donnell Award in Engineering in 2016, the NSF Alan T. Waterman Award in 2015, the IEEE MTT Outstanding Young Engineer Award in 2014, the OSA Adolph Lomb Medal in 2013, and the URSI Issac Koga Gold Medal in 2011. He was the Technical Program Chair for the IEEE AP-S symposium in 2016, and the program chair, and the general co-chair for several Metamaterials conferences. He is currently an Associate Editor of *Applied Physics Letters* and serves on the Editorial Board of *Physical Review B*, *Advanced Optical Materials*, *EPJ Applied Metamaterials*, and *ISTE Metamaterials*. He has guest edited special issues for the IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, the PROCEEDINGS OF IEEE, the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, *Nanophotonics*, the *Journal of Optics*, the *Journal of the Optical Society of America B*, *Photonics and Nanostructures: Fundamentals and Applications*, *Optics Communications*, *Metamaterials*, and *Sensors* on a variety of topics involving metamaterials, plasmonics, optics, and electromagnetic theory. He has been a Simons Investigator of physics since 2016. He has been serving as the President of the Metamorphose Virtual Institute for Artificial Electromagnetic Materials and Metamaterials, a member of the Administrative Committee for the IEEE Antennas and Propagation Society, an OSA Traveling Lecturer since 2010, an IEEE AP-S Distinguished Lecturer since 2014, and the IEEE Joint AP-S and MTT-S Chapter for Central Texas.

Ariel Epstein (Senior Member, IEEE) received the B.A. degree in computer science from the Open University of Israel, Ra'anana, Israel, in 2000, and the B.A. degree in physics and the B.Sc. and Ph.D. degrees in electrical engineering from the Technion—Israel Institute of Technology, Haifa, Israel, in 2003 and 2013, respectively.

From 2013 to 2016, he was a Lyon Sachs Post-Doctoral Fellow with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada. He is currently an Assistant Professor with the Andrew and Erna Viterbi Faculty of Electrical Engineering, Technion—Israel Institute of Technology, where he is leading the Modern Electromagnetic Theory and Applications (META) Research Group. His current research interests include utilization of electromagnetic theory, with an emphasis on analytical techniques, for the development of novel metasurface- and metagrating-based antenna and microwave devices, and investigation of new physical effects.

Dr. Epstein was a recipient of the Young Scientist Best Paper Award in the URSI Commission B International Symposium on Electromagnetic Theory (EMTS2013), Hiroshima, Japan, in May 2013. Since 2018, he has been serving as an Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION.