Anthony Grbic Stefano Maci

EM Metasurfaces

Metasurfaces (MTSs) [1]–[5] are the surface equivalent of metamaterials (MTMs): artificial materials composed of subwavelength inclusions embedded in a host medium tailored to exhibit unconventional electromagnetic (EM) properties. In contrast to MTMs, which are characterized in terms of homogenized material parameters, the EM responses of MTSs are often characterized by homogenized boundary conditions (BCs). MTSs can be designed to exhibit abrupt amplitude and phase discontinuities to perform extreme wavefront transformations. Classical "surface EMs" [3] took on fresh and exciting research directions with MTSs, revealing fascinating phenomena and new applications.

In their modern form, MTSs have been around for just over a decade and have attracted enormous interest in the antennas and propagation community. Even though the word *metasurface* began to appear in the literature around 2010, the fundamental physics and related applications have been investigated much earlier in the community. In the 1970s and 1980s, the properties of frequency-selective surfaces (FSSs) [6]–[9] were heavily explored and exploited. FSSs are periodic arrays of conducting patches or apertures in a conducting screen. They have been used to control the reflection and transmission of incoming plane waves in terms of frequency and angle of incidence. FSSs have found applications as frequency-dependent mirrors or transmissive screens as well as dichroic filters in space antennas. The understanding of FSSs evolved from optical diffraction gratings, discovered by Rittenhouse in the 18th century [10].

Although FSSs may be loosely regarded as MTSs, their periodic elements are on the order of a half-wavelength at the operating frequency. Only years after FSSs were introduced was there an effort to reduce the electrical size of their elements and increase their density so that homogenization could be applied. In parallel with the advancements in FSSs, the antenna community also began to develop reflectarrays [11]. These arrays of printed elements are designed to modify the phase of the local reflection coefficient to produce prescribed radiation patterns. The reflectarray concept was first introduced in 1963 [12] and evolved significantly in the 1990s thanks to the development of numerical analysis tools [13]. The concept of microwave transmitarrays followed in those same years [14].

FSSs, reflectarrays, and transmitarrays were composed of resonant-length scatterers that were not homogenizable and therefore could not be represented with continuous BCs. The first systematic description of a homogenized sheet impedance BC was introduced by Kuester in 2003 [15]. However, homogenized BCs were used in 1988 by Kildal to introduce artificially soft and hard surfaces [16]. During this time, Yablonovitch and John elaborated on the idea of EM band gaps (EBGs) in artificial materials [17], [18], opening several research directions in optics and microwaves. Together, Yablonovitch and Sievenpiper introduced the idea of bandgaps for surface waves (SWs) and artificial magnetic surfaces with mushroom-type surfaces [19]. Subsequently, this idea was linked to Kildal's soft surfaces [20].

In their book [21], Yang and Rahmat-Samii proposed several applications of EBGs for printed dipoles and patch antennas. In addition, MTSs known as *partially reflective surfaces* were used to improve the directivity of dipoles [22]. Even though the term *metasurface* was not yet circulating in the community, the concepts of magnetic conductors, artificial surfaces [20], and holographic artificial impedance surfaces [23] generated numerous antenna applications in the years 2000–2010. Therefore, this period of research can be considered as the first generation (1G) of MTSs (Figure 1). In those years, MTSs consisted of periodic arrangements of subwavelength printed elements. Notable exceptions were two categories of aperiodic MTSs: holographic artificial impedance surfaces [23], [24] and near-field plates [25]–[27]. Holographic impedance surfaces were introduced for far-field radiation control and eventually became

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known as *metasurface antennas*, while near-field plates were introduced for tailoring the EM near field.

In the 2G of MTSs (2010–2020), aperiodic MTSs were systematically designed with BCs that vary in space to control reflection/transmission, the surface/plasmonic wave propagation, and the leaky-wave (LW) radiation in a point-by-point manner. The BCs are modified by spatially changing the shape, orientation, or characteristic dimensions of the electrically small inclusions while maintaining a uniform periodic lattice. It is possible to identify two classes of these nonuniform MTSs: 1) MTSs for space-wave control and 2) MTSs for in-plane SW and LW control. The study of MTSs of type 1 was ignited by the seminal article by Capasso's group [28] that introduced optical phase-gradient MTSs for optical beam deflection. The beam deflection was explained with the use of a generalization of the geometrical optics (GO) Snell's law for MTS-imposed BC.

Today, leveraging the developments within the 2G, we are facing a transition to a 3G of MTSs, where the BCs of MTSs change in space and time, becoming controllable and intelligent.

Beam-deflecting MTSs were further explored and led to the development of "Huygens' MTS" (HMS) [29]–[33]. These MTSs were inspired by the Huygens' principle, or its vector form known as the *surface equivalence principle*. HMSs are transparent MTSs that can transform the wavefront of the incident space-wave field into a prescribed transmitted wave. Thin lenses, beam deflectors, beam splitters, polarizers, and multifunctional devices can be realized using HMSs. From a physical point of view, HMSs implement through MTSs the surface equivalence principle in a generalized physical optics framework. This is in contrast to the GO framework of gradient MTSs presented in [28]. The transparency of an HMS is enabled by the presence of electric and magnetic current densities that coexist within the same surface, as prescribed by the surface equivalence principle. Coupling these currents to the EM fields at the MTS boundary

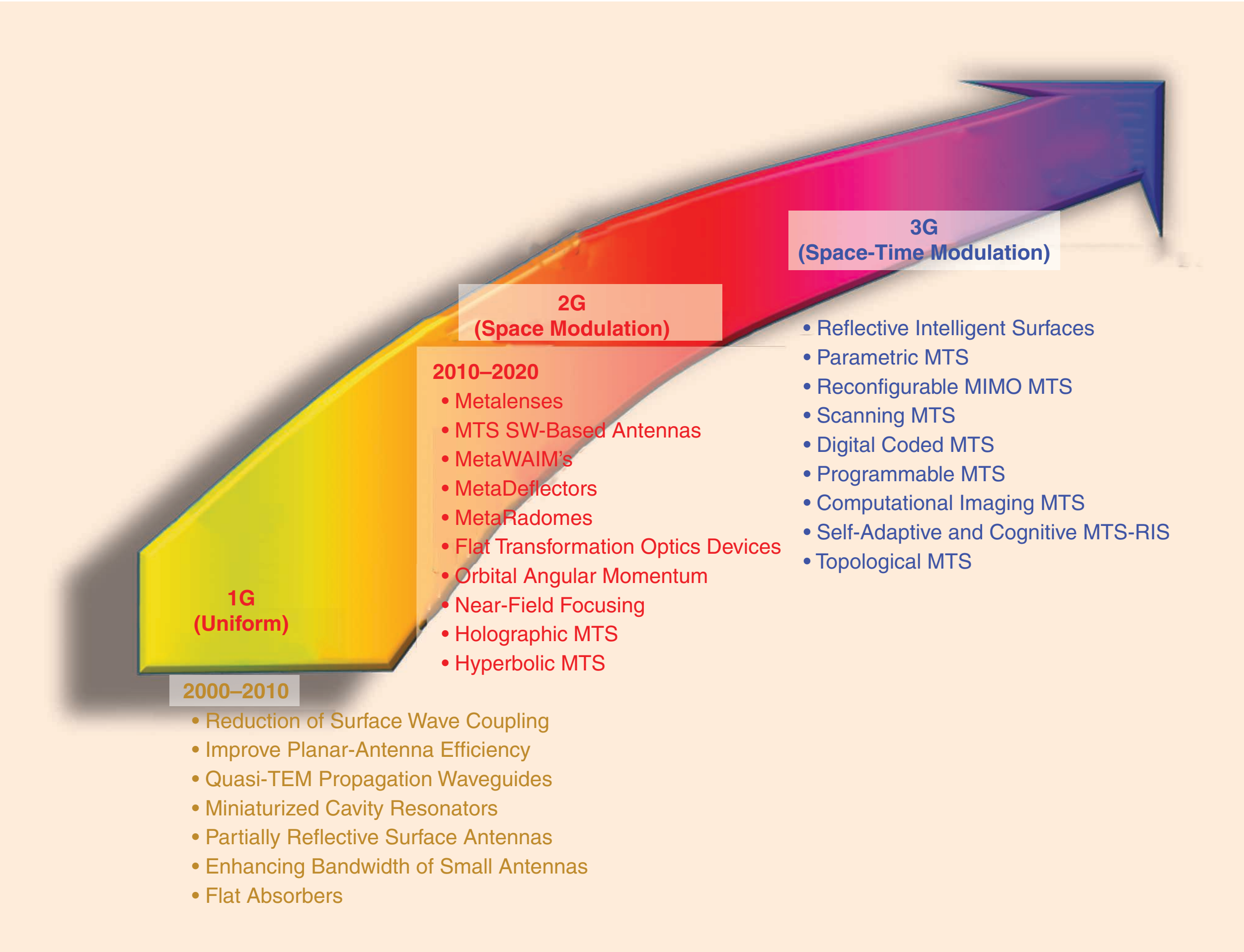

FIGURE 1. The generations of MTSs. MIMO: multiple-input, multiple-output; RIS: reconfigurable intelligent surface; TEM: transverse EM; MetaWAIMs: MTSs for wide-angle impedance matching.

generally results in bianisotropic tensor-impedance BCs [34]–[38].

Nonuniform MTSs of type 2 [39], [40] control surface/plasmonic wave propagation paths and wavefronts and transform SWs to LWs [40]–[46]. These MTSs shape the wavefront through propagation. It is similar to what happens in 3D transformation optics but for bounded waves. Planar lenses, cloaking devices, and general metastructured beamforming networks belong to this category. Their behavior can be analyzed in a number of ways. It can be analyzed through an analogy to GO in equivalent graded-index materials, through a planar version of transformation optics [47], [48], or through local control of phase and power flow on the MTS [41]. On the other hand, a transition between SWs and LWs can be obtained by using a periodic macromodulation of a tensor impedance. This has led to a class of LW-based MTS antennas [44], [49]–[56] in which the beamforming network is realized by the MTS itself and the feed is a simple monopole in the middle of the surface. The physical limits of aperture efficiency [57], [58], bandwidth gain [59]–[61], and multibeam [62] of MTS antennas have been investigated, thus leading to a variety of new high-performance models and prototypes [63].

Today, leveraging the developments within the 2G, we are facing a transition to a 3G of MTSs, where the BCs of MTSs change in space and time, becoming controllable and intelligent. MTS reconfigurability can be achieved by using electronics, time-varying materials, or multiple switchable feed points distributed over the MTSs. The possibility of independently controlling the individual elements gave rise to traveling-wave modulated MTSs exhibiting nonreciprocity, frequency conversion, and parametric amplification [64]–[66]. It also led to the concept of "digital-coding MTSs," [67], [68] which evolved into "programmable MTSs" to control different MTS functionalities based on different digital states of the elements [67], [69]. This concept can be further extended to self-adaptive and cognitive MTSs [70], [71].

Finally, the article by Wang and Caloz presents space-time MTSs modulated by pseudorandom sequence waveforms.

This special issue contains 10 articles written by some of the internationally renowned leaders in the field. The articles discuss how to prescribe MTS parameters to obtain exotic EM functionalities, how to physically implement them, and how to apply them in the microwave and antenna domains. The articles also cover recent advances in modeling and design and new trends in the 3G of MTSs.

The first two articles deal with the modeling and design of MTS antennas based on the transformation of a cylindrical SW into a tailored LW wavefront. In particular, Bodehou et al. show a synthesis method based on the direct numerical solution of the surface-integral equation enforcing homogenized BC. The method has been extended to generate multibeams and perform multifunctional operations. The obtained designs are implemented as distributions of small patches, based on an efficient periodic method-of-moments solver. For the same type of antennas, Faenzi et al. explore and compare three simple approaches to diplex two beams with orthogonal polarizations. The first method is based on exciting both a transverse electric and a transverse magnetic SW mode on the same modulated impedance. The second method exploits the concept of impedance modulation sharing. Here, distinct modulations, designed to radiate different polarizations when illuminated by distinct feed points, are superimposed onto the same aperture. A third method involves duplexing an outward (radially diverging) and an inward (converging to the center) SW. Simple analytical formulas are presented for the synthesis of the impedance that allows for the control of the inward/outward waves.

The article by Singh et al. deals with the SW-MTS interaction and the exploration of different physical mechanisms and applications. It is shown that MTS symmetry can be used to create propagation modes immune to backscattering for a certain class of discontinuities. Similar modes can also be obtained by chiral channels in homogeneous materials. Exciting new applications are also reviewed, including nonreciprocal structures, self-collimating waves based on diffusive transport, defect-based amorphous structures, and time-modulated MTSs.

The next couple of articles deal with MTS antennas for beamforming and beam steering. The article by Szymanski et al. presents an experimental realization of a multiple-input, multiple-output (MIMO) metastructure for antenna beamforming based on MTSs that control SWs. The MTS is obtained by an inverse design procedure that significantly reduces the required time and computational resources needed in design. It circumvents full-wave simulations by analyzing the MTS using a circuit solver that cascades admittance matrix representations of the unit cells to solve for the fields. The MIMO metastructure is built and interfaced with a 3D-printed horn to form a multibeam switchable antenna and, experimentally verified. Various MIMO functionalities and linear operators could be realized using the proposed approach. The article by Ataloglou et al. reviews recent advances in HMSs for antenna beam steering. It is shown how it is possible to realize HMS-based antenna beamforming without feeding networks and how it is possible to use HMS radomes to extend the scan range of phased arrays. Finally, several strategies are described for realizing reconfigurable HMS by means of electronic control.

The article by Díaz-Rubio et al. presents the use of reconfigurable intelligent surfaces (RISs) for the optimization of propagation channels: an enabling technique for the next generation of wireless communications systems. Reflective and refractive MTSs are used to control both reflection and transmission in a smart communication environment. The theories of diffraction gratings and physical optics are used to design and analyze finite-size MTSs mounted on partially reflecting walls that are illuminated by both plane waves and directive antennas.

The next couple of articles review the concept of coding and digital MTSs. This concept breaks the boundaries between the traditional analog and digital devices to bridge the physical and information worlds. The article by Ma et al. presents methods to digitize the local geometry and the MTS BCs. Within this framework, a broad variety of field manipulations and functionalities are explored. These include beam tailoring, holograms, and amplitude and polarization modulations. It is also shown how the integration of switching elements renders these MTSs "programmable." Furthermore, by integrating sensors and artificial intelligence algorithms, self-adaptive and smart MTSs can be conceived for automatic sensing and reactive functionalities. The article emphasizes selected research directions and their possible evolution and perspectives. The article by Venkatesh et al. presents an example of a digital MTS platform for multifunctional millimeter-wave and terahertz communication. The MTS consists of tiled silicon chips, each controlling a subarray of meta-elements, which are individually addressable and reconfigurable at GHz speed. The technique allows large-scale, reconfigurable, millimeter-wave, and terahertz MTSs at low cost.

The article by Sleasman et al. reviews the evolution of MTS antennas for computational microwave imaging. The system comprises dynamic printed MTS cavities as modular building blocks. These MTS cavities can generate a multitude of spatially diverse, voltage-controlled illumination patterns and can encode the EM scattering from a scene into a set of measurements that can be postprocessed to produce an image. The individual MTS cavities act as transmitters and/or receivers and can be combined to create an electrically large aperture. High-quality imaging can be produced with a reduced frequency bandwidth.

Finally, the article by Wang and Caloz presents space-time MTSs modulated by pseudorandom sequence (PRS) waveforms. In contrast to their harmonically modulated counterparts, these MTSs spread the frequency and spatial spectrum. These MTSs are assumed to operate in the "slow modulation" regime, which allows a safe separation of the time-variance and frequency-dispersive effects of the system. Thanks to the special properties of the modulation, the space-time-modulated PRS can perform spectrum spreading, interference suppression, and cell selection. These properties, combined with modern microwave CMOS technologies, will allow applications such as EM scattering control, secured communication, the direction of arrival estimation, and spatial multiplexing.

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