Received 9 November 2021; revised 21 December 2021; accepted 21 December 2021. Date of publication 27 December 2021; date of current version 5 January 2022.

Digital Object Identifier 10.1109/OJAP.2021.3138617

Intelligence Enabled by 2D Metastructures in Antennas and Wireless Propagation Systems

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This work was supported by the frame of the activities of the Project MANTLES, funded by the Italian Ministry of University and Research through the PRIN 2017 Program under Grant 2017BHFZKH.

ABSTRACT The development of the next generation of wireless systems is bringing renewed attention to the physical layer of the communication link. Indeed, the new low-latency requirements cannot be satisfied relying only upon the extreme virtualization of the hardware functions. Moreover, conventional wireless systems with fixed characteristics and functionalities are not appropriate to modern electromagnetic environments, which undergo continuous and fast variations. Embedded smartness is a required feature for widening the range of the possible electromagnetic responses to support advanced and novel functionalities. In this paper, we show how the combination of 2D metastructures with conventional antennas and reflectors enables an unprecedented electromagnetic behavior, which is at the basis of new properties, capabilities, and applications. In particular, we propose an emerging design approach based on the shifting of the reconfigurability, adaptivity, sensing, and power management of a wireless system at the physical level, thanks to the use of properly designed 2D metastructures to be coupled with standard antennas and reflectors.

INDEX TERMS Smart antennas, smart electromagnetic environment, metasurfaces, reconfigurability.

I. INTRODUCTION

Wireless systems are evolving faster and faster in the last years to satisfy the ever-growing demand for high data rates, low latency, extremely low power consumption, and autonomy. In this framework, the required enhancement was not limited to the capability of the system to transfer wirelessly the information between two or more users with the best performances, but also to provide new functionalities related to sensing, powering, and identification, taking into account also the rapid variation of the surrounding environment [1]. Currently, adaptive, multiple, MIMO antennas [2], and anomalous reflectors [3] have been proposed for providing high data-rate in the congested environments of mobile communications and increased coverage of the wireless signal, respectively. In these systems, the "smartness" is enabled by the use of advanced signal processing techniques aimed at tracking the mobile users and focusing the signal on them, whilst their physical layer is still realized through conventional antennas and reflectarrays with fixed functionalities [4]. The possibility to enable more than one functionality at the hardware level is, thus, an essential element for further improving the performance of the next-generation wireless systems.

Until recently, reconfigurability in electromagnetic systems has played a crucial role in expanding the functionalities of energy radiating, capturing, and storing structures. For example, as for the antenna systems, several interesting designs have been proposed in the literature for achieving frequency reconfigurability [5]–[7], polarization control [8], [9], or radiation pattern shaping [10], [11] using electrical or mechanical switching mechanism [12], [13], PIN diodes [14], [15], varactor diodes [16], [17], or micro-electromechanical systems [18], [19]. In these systems, the reconfigurability has been achieved mostly by connecting and disconnecting metallic or dielectric parts of the radiating or reflecting antenna element, modifying its layout to change its performance.

In this work, instead, we discuss about the shifting paradigm of "intelligence-by-material" where the reconfigurability, adaptivity, sensing, and power management are shifted at the hardware-level thanks to the use of properly designed 2D metastructures to be coupled with standard antennas and reflectors. In particular, by reviewing some of our latest results about this topic, we show that unprecedented wireless functionalities can be enabled by loading the radiating device or conventional metallic reflector with ultra-thin metasurfaces or electrically small metamaterial inclusions.

The manuscript is organized as follows. In Section II, we show how the use of non-linear metasurfaces allows making the response of an antenna dependent on the amount of the electromagnetic power interacting with it. In Section III, we report a new class of metasurface loaded antennas whose scattering and/or radiating characteristics are made dependent on the waveform of the received/transmitted signals making the radiators selective on both frequency- and time-properties of the electromagnetic radiation interacting with them. Then, in Section IV, we present an advanced approach based on engineered vortex modes to manipulate electromagnetic radiation, enabling fast radiation pattern synthesis and reconfigurability in antenna systems. In Section V, we propose the design of non-reciprocal radiating systems enabled by spatio-temporal modulated meta-particles and metasurfaces, highlighting the tremendous impact they can have in smart electromagnetic environments. Finally, in Section VI, we show that by using time modulation a cavity made by a standard metallic reflector and a metasurface can be used to store wireless power, creating a free-space battery to be employed in zero-power wireless systems.

II. NON-LINEAR METASURFACES FOR POWER-DEPENDENT ANTENNAS

A. MODELING AND WORKING PRINCIPLE

As a first example of metasurfaces featuring advanced functionalities [20], we focus our attention on non-linear structures and, in particular, on the possibility to make the behavior of a metasurface sensitive with respect to the level of the impinging power [21]–[26].

This effect can be achieved by periodically loading the metasurface with non-linear elements. To better explain this point, we have considered a very simple–yet widely used–metasurface geometry, consisting in an array of vertical strips with width equal to w_1 and periodicity a. When excited by a normally-impinging plane wave, whose electric field is perpendicular to the strips, the un-loaded metasurface behaves as an equivalent capacitor [27]–[29]. Its homogenized surface impedance can be approximated as:

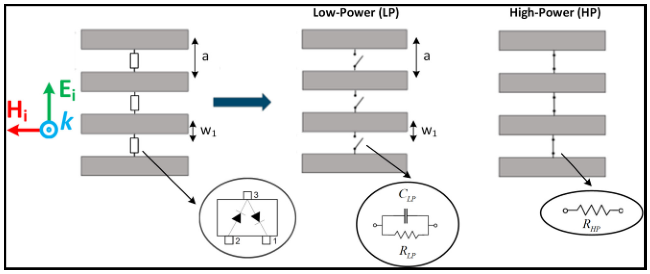


FIGURE 1. Strip-based metasurface loaded with non-linear elements whose response depends on the level of the impinging power.

$$Z_s^{TE} = -j\frac{\pi\eta_0}{2k_0 a}\ln^{-1}\left[\csc\left(\frac{\pi w_1}{2a}\right)\right], \tag{1}$$

A possibility to make the response of this metasurface power-dependent is based on the use of a periodic electronic load, as shown in Fig. 1. In this case, each pair of consecutive strips are connected by an anti-parallel diode pair, whose response depends on the level of the impinging electromagnetic power.

The effect of the anti-parallel diode pair in the homogenized response of the metasurface can be easily accounted for by using the two equivalent circuit models shown in the insets of Fig. 1. In particular, in the low power (LP) scenario, the diode can be effectively described by a RC parallel circuit, where the value of the capacitance C_{LP} and R_{LP} are, respectively, low and high. In the high power (HP) case, instead, the equivalent circuit is represented by a simple low resistance R_{HP}. The two load impedances introduced by the diode pair in the LP and HP case are, thus:

$$Z_{LP} = \left(\frac{1}{R_{LP}} + \frac{1}{j\omega C_{LP}}\right)^{-1}, \quad Z_{HP} = R_{HP} \tag{2}$$

Consequently, the surface impedances of the loaded metasurface in the two scenarios can be written as the parallel combination of the unloaded surface impedance (1) and the load impedance (2), i.e.,

$$Z_{s,LP}^{TE} = \left(\frac{1}{Z_s^{TE}} + \frac{1}{Z_{LP}}\right)^{-1} \quad Z_{s,HP}^{TE} = \left(\frac{1}{Z_s^{TE}} + \frac{1}{Z_{HP}}\right)^{-1}, \tag{3}$$

respectively. The effectiveness of this simple model–even considering commercial electronic elements–has been checked through a proper full-wave co-simulation routine in [24], while appropriate metasurface geometries for obtaining similar effects for inductive metasurfaces have been described in [26].

For the sake of simplicity, let us now assume the use of ideal diodes without parasitics. In this case, each diode pair can be considered as an open-circuit when the voltage between the metallic parts of the metasurface is not enough to turn the diodes on (i.e., $Z_{LP} \to \infty$); on the contrary, it behaves as a short-circuit when the power impinging onto the metasurface overcomes a specific threshold (i.e., $Z_{HP} \to 0$).

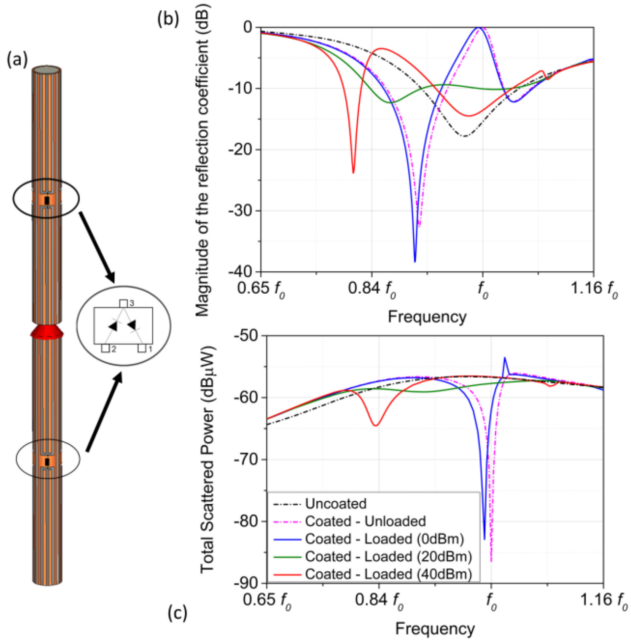


FIGURE 2. **(a) Half-wavelength dipole antenna surrounded by an inductive metasurface designed to cancel its overall scattering at its resonance frequency. The metasurface is periodically loaded with non-linear elements that make its response power-dependent. (b) Reflection coefficient at the antenna input port for different levels of the input power. (c) Total scattered power by the antenna for different levels of the input power. In (b) and (c), the case of the dipole when the metasurface is not applied ("uncoated") is also reported for comparison.**

Therefore, in the ideal case, the response of the metasurface reduces to:

$$\overline{Z_{s,LP}^{TE}} \approx Z_s^{TE} \qquad \overline{Z_{s,HP}^{TE}} \approx 0, \tag{4}$$

Eq. (4) reveals that the loaded metasurface shown in Fig. 1 behaves as a conventional capacitive strip metasurface for LP signals, whereas it switches to a PEC-like behavior for strong signals. Remarkably, the power threshold in which this transition occurs can be tuned by properly selecting the diode pair used to load the metasurface.

In the next Sections, we will discuss how these power-dependent response of the metasurface can be exploited for designing antenna systems with unconventional features.

B. POWER-DEPENDENT ANTENNAS

As a first application of non-linear metasurfaces, we discuss the design of a non-linear antenna being almost invisible to LP signals, whilst keeping its capability to efficiently transmit HP electromagnetic fields.

To reduce the overall scattering of a linear antenna, we rely on the concept of electromagnetic cloaking [30]–[34], which has been widely investigated in the context of low-signature antennas [35]–[38] and antenna co-siting [39]–[49]. The antenna system considered in this work is shown in Fig. 2 and consists of an half-wavelength dipole surrounded by a strip-based metasurface loaded with non-linear circuit elements. The unloaded metasurface has been designed to hit the invisibility condition of the antenna [36] at its own resonance frequency. This can be achieved using inductive metasurfaces based on vertical strips and slightly correcting the original geometry to engineer the flow of the currents. More details can be found in [26].

The periodic loading of the metasurface with an anti-parallel diode pair makes its response power-dependent, as can be appreciated form the results shown in Fig. 2 achieved through a commercial full-wave simulator [50]. In particular, for LP signals, the metasurface exhibits its original unloaded response and behaves as a cloaking metasurface. As a consequence, the antenna scattering cross section is dramatically reduced compared to the one of the bare dipole (Fig. 2(c)). However, the reduction of the scattering cross section is also accompanied by an important mismatching of the antenna with its source (Fig. 2(b)), as dictated by the optical theorem [26].

On the contrary, when the power level of the signal impinging onto the antenna system is such that the voltage across the strips overcomes the diode threshold, the metasurface becomes a simple conductive shell surrounding the dipole, with minimal effects on its performances. Indeed, as shown in Fig. 2, the original impedance matching of the dipole, as well as its original scattering cross section, are completely restored in the HP scenario. The power threshold at which this transition appears strictly depends on the choice of the non-linear element used to load the metasurface (e.g., for this example, we have considered a Hitachi HVM14S diode and the transition can be observed between 0 and 10 dBm). More details on the co-simulation scheme exploited for performance evaluation can be found in [24], [26].

The proposed system, thus, behaves as a non-linear antenna whose electromagnetic signature and impedance matching depends on the level of the impinging power. Indeed, the antenna is truly invisible to LP signals, such as the ones emitted by a detector placed remotely. Still, the antenna can be used as an efficient radiative system using signals whose power is such to activate the diodes loading the metasurface. It is worth noticing that this behavior cannot be achieved using conventional linear metasurfaces: indeed, as discussed above, an antenna whose scattering has been drastically reduced with an invisibility device is intrinsically mismatched with its source and, as such, cannot be used as an efficient transmitting device. The use of non-linear metasurfaces, sensitive to the level of the impinging power, allows discriminating the antenna response depending on the specific applications. Further improvements of the performance of these devices in terms of scattering suppression, maximum size of the concealed object and operation bandwidth may be achieved by relying on high-order metasurfaces [51], [52] or multilayer cloaks [53], [54].

C. POWER-DEPENDENT ANTENNA ARRAYS

In this Section, we discuss another interesting application of non-linear metasurfaces for antenna arrays. We consider two different cases: in the first one, the non-linear metasurfaces

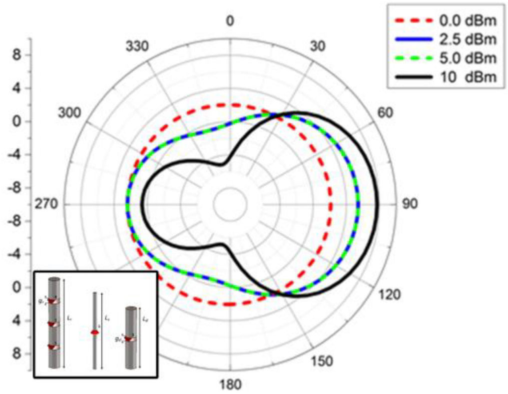


FIGURE 3. Directivity on the horizontal plane of the parasitic array shown in the inset. The radiative system consists of a three-element Yagi-Uda antenna in which the two parasitic elements are surrounded by a capacitive metasurface to make them invisible at the resonance frequency of the driven dipole. The metasurface is periodically loaded with non-linear elements able to switch the metasurface cloaking behavior off for HP signals.

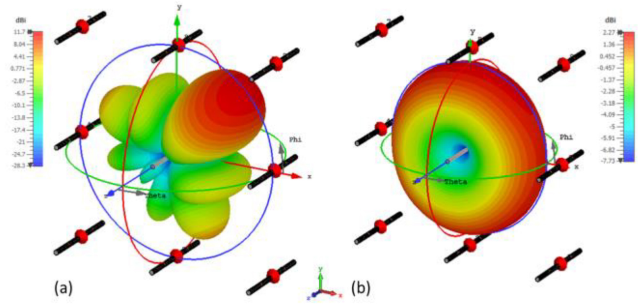


FIGURE 4. Radiation diagram of a conceptually-new phased array composed by half-wavelength dipoles for (a) HP signals and (b) LP signals. The peripherical elements of the array are surrounded by non-linear inductive metasurfaces able turning their electromagnetic visibility on/off depending on the level of the impinging power. In the HP scenario, the array behaves as a regular phased array, whereas in the LP scenario the radiation diagram of the array coincides with the one of its central element as if it were isolated.

are applied to parasitic arrays to achieve a power-dependent electromagnetic visibility of the passive elements; in the second one, instead, the non-linear metasurfaces are applied to the peripherical elements of a phased array.

The first scenario is depicted in the inset of Fig. 3: the parasitic array we have considered is a three-element Yagi-Uda antenna. The two parasitic elements of the radiator (i.e., the director and the reflector) are covered by capacitive metasurfaces, designed to dramatically reduce their overall scattering signature at the operative frequency of the antenna itself [48], [49]. As it can be appreciated in Fig. 3(a), the capacitive metasurfaces are periodically loaded with anti-parallel diode pairs that make their response depending on the antenna input power. In particular, the parasitic elements of the antenna are invisible to the driven dipole in the LP scenario. As such, the behavior of the overall antenna system is expected to coincide with the one of the isolated half-wavelength dipole. In the HP case, instead, the capacitive metasurfaces resemble simple conductive shells and the original effect of the parasitic elements on the antenna system is restored. Therefore, the antenna system is expected to work as a conventional three-element Yagi-Uda array.

The directivity of this antenna system on the horizontal plane for different levels of the impinging power is reported in Fig. 3. These results have been obtained using a full-wave co-simulation routine, which includes the measured response of the non-linear element used to load the metasurface (Hitachi HVM14S). As it can be appreciated, the radiation diagram of the antenna is progressively transformed as the antenna input power is increased. In particular, in the LP case the radiation diagram of the array coincides with the one of a conventional half-wavelength dipole. Conversely, in the HP case the radiation diagram resembles the one of the unload three-element Yagi-Uda antenna. The antenna impedance matching keeps always below -10 dB at the working frequency (not shown here).

The described non-linear Yagi-Uda array can be used to design a passive repeater able receiving HP signals from a given direction and broadcasting (omnidirectionally) LP version of them. Similarly, this system can be used for designing peripherical base stations able receiving LP signals from the distributed users, while establishing a directive radio-link with other base-stations using HP signals.

The second scenario we consider here is shown in Fig. 4. In this case, we have a 3×3 phased array of half-wavelength dipoles. The idea is to exploit this system as an omni-directional receiving antenna for LP signals, while keeping the steering capability of the array for HP ones. For achieving this goal, all the elements of the array but not the central one are covered by non-linear cloaking metasurfaces. In the LP case, the metasurfaces behave as cloaking devices and make all the peripherical elements of the array invisible to the central radiator. As such, the response of the system is the one of a conventional half-wavelength dipole (see Fig. 4(b)). Conversely, in the HP case, the cloaking metasurfaces become ineffective and the system keeps working as a conventional phased array able to steer the beam in a desired direction depending on the excitation phases (Fig. 4(a)).

The described system represents an innovative power-dependent antenna array whose diagram is omni-directional for LP signals and directive for HP ones. It may find applications, for instance, in radar system, to illuminate selectively a given angular region using HP signals, while being able to receive LP return signals from all the directions [55].

III. WAVEFORM-DEPENDENT DEVICES FOR FREQUENCY- AND TIME-DOMAIN SELECTIVE ANTENNAS

In the last decades, the ever-growing demand for different wireless services has increased electromagnetic noise and clutter. Due to spectrum congestion, the wireless devices receive not only useful signals but also unnecessary electromagnetic noise, with the high risk of a significant deterioration of the quality of the communication environment. Thus, the possibility to increase the degree of freedom

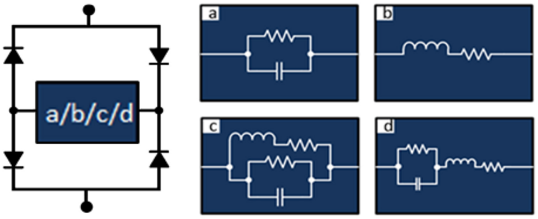


FIGURE 5. Schematic of the waveform-selective circuit composed by a diode bridge rectifier and (a) parallel RC circuit, (b) series RL circuit, (c) parallel RC circuit connected in parallel with a series RL circuit, or (d) parallel RC circuit connected in series with a series RL circuit.

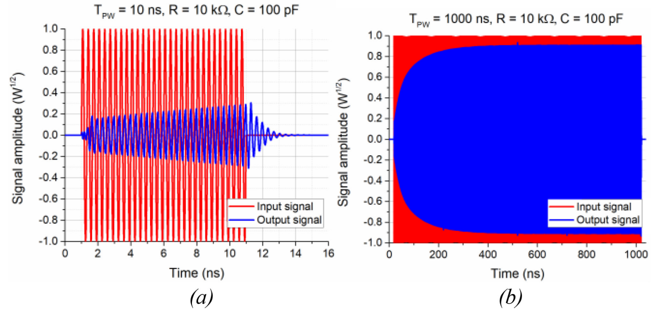


FIGURE 6. Signal amplitude at the input and output ports of the waveform-selective circuit in the case of a parallel RC loading circuit, for different temporal pulse widths (TPW) of a signal at 3 GHz: (a) TPW = 10 ns, (b) TPW = 1000 ns. Commercial circuit simulator results.

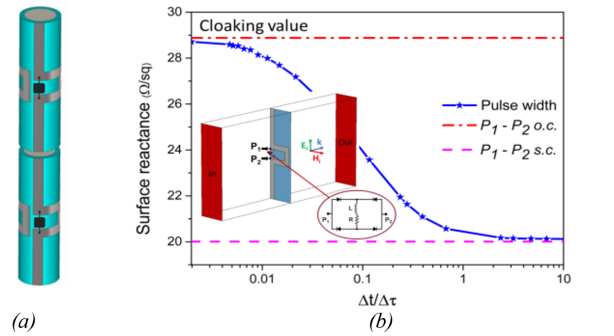


FIGURE 7. (a) Half-wavelength dipole antenna coated by a meandered inductive metasurface loaded by a waveform-selective circuit. (b) Retrieved surface reactance of the loaded metasurface for different values of the illuminating signal pulse width (Δt), normalized to the loading circuit time constant ($\Delta\tau$). In the inset, the schematic of the retrieval setup is reported.

for discriminating the useful signal from the environmental noise is a highly desirable feature.

In the previous Section, we have shown the possibility of designing power-dependent devices, whose functionalities depend on the power level of the impinging wave. Here, we further explore the possibility of designing antenna systems whose behavior depends on specific characteristics of the signal even at the same frequency. In particular, we present radiating devices exhibiting different responses depending on the waveform of the transmitted/received waves.

A. WAVEFORM-SELECTIVE CIRCUIT

Waveform-selectivity can be achieved by exploiting the lumped elements circuit reported in Fig. 5, discussed for the first time in [56]. Indeed, the peculiar response of the circuit allows adding time-domain selective properties to the device loaded by this circuit [57].

The lumped-element circuit uses a full diode bridge rectifier and passive elements like resistors (R), capacitors (C), and inductors (L). The diode bridge is loaded by a shunt or series combination of RLC elements, as shown in Figs. 5 (a)–(d). When a signal is at the input port, thanks to the presence of the diode bridge, it is rectified and most of the energy is converted to zero frequency (i.e., DC) and applied to the RLC element. Thanks to the different time-domain responses of the RLC elements, the circuit behaves differently in presence of a short-pulsed waveform signal (PW) or a long pulse or a continuous waveform (CW).

In presence of a RC parallel circuit (Fig. 5(a)), in fact, a strong current initially flows in the circuit, as shown in Fig. 6(a), and the circuit itself behaves as a low-impedance component (i.e., $Z_{in} \rightarrow 0$). However, since the capacitor charges over time, after a while the circuit behaves as a high-impedance element, finally blocking the current flow and acting as an open-circuit (i.e., $Z_{in} \rightarrow \infty$), as shown in Fig. 6 (b). Therefore, in presence of a short pulse, the signal can flow along the circuit, whilst for a long pulse, the signal is blocked. Short and long are referred to the time constant of the circuit.

Remarkably, the dual behavior can be achieved using a series RL element (Fig. 5 (b)), while by properly combining RC and RL circuits (Figs. 5 (c)–(d)), bandpass or notched-band time-domain characteristics could be designed [58].

This unprecedented functionality can be thus exploited to extend the degree of freedom in antenna design, by properly loading the radiating element with this waveform-dependent circuit and making the antenna dependent not only on the frequency of the incoming signal but also on its time-domain properties. In the following, we present some of this waveform-selective antenna system showing how they can further extend the antenna capability.

B. WAVEFORM-SELECTIVE CLOAKS FOR ANTENNAS

The antenna cloaking functionalities discussed in the previous Sections can be expanded by exploiting cloaking metasurfaces loaded by waveform-selective circuits. We can make the cloaking effect depending not only on the frequency of operation but also on the pulse width of the signal. Thus, it is possible to conceive an antenna system that is invisible to a detecting pulsed radar, whilst the antenna visibility is automatically restored in presence of a longer pulse or a CW [59].

This functionality can be realized by exploiting the cloaking metasurface reported in Fig. 7(a). Here, a half-wavelength dipole antenna is coated by a cloaking metasurface implemented through meandered metallic strips, where the throat of the meander is loaded with the waveform-selective circuit. The unloaded metasurface has been designed to suppress the scattering signature of the antenna at its own resonance frequency $f_0 = 3$ GHz, when exhibiting a surface reactance $X_s = 29\ \Omega/\text{sq}$.

By loading the cloaking metasurface with a waveform-selective circuit characterized by a series RL, we can make the surface reactance of the metasurface dependent on the ratio between the pulse width of the imping signal (Δt) and the time constant of the circuit ($\Delta\tau = \text{L/R}$) (see Fig. 7(b)). For a short pulse ($\Delta t << \Delta\tau$), the value of the surface impedance of the metasurface is the one needed to obtain the cloaking effect. Conversely, for longer pulse width ($\Delta t >> \Delta\tau$), the surface reactance results in a lower value, being the throat of the meander short-circuited. Further details on the retrieval technique used to get the surface reactance values can be found in [60].

This behavior drastically modifies the scattering response of the antenna and its matching characteristics. In Fig. 8(a) the scattering signature of the antenna is reported, whilst in Fig. 8(b) the reflection coefficient at the antenna input port is shown. It is worth noticing that these results have been obtained using a numerical routine based on both full-wave and circuit simulations that allows taking into account the non-linear effects and the higher-order harmonics generation introduced by the loading circuit [50], [61].

As can be appreciated, in presence of a short pulse (PW) the toral scattering signature of the coated antenna is reduced at f_0. At the same time, the reflection coefficient at the antenna input port is very high, disabling the antenna functionalities. On the contrary, when a signal with a large pulse width (CW) is received by the antenna, due to the variation of the surface reactance, the cloaking resonance is shifted towards higher frequencies. The matching properties of the antenna, thus, are restored, and it can receive/transmit efficiently.

Therefore, by using waveform-selective cloaks, we can introduce "intelligence" to the antenna system, making it sensitive to both the frequency- and time-domain properties of signals in the environment and enabling autonomous reconfigurability of its radiating/scattering characteristics. Indeed, such an antenna could be placed in front of a radar system scanning the environment through short pulses without affecting its performance, thanks to the antenna capability of hiding itself only when the radar is receiving or transmitting. This waveform-selective cloaking solution introduces unprecedented possibilities in the design of radiating systems, broadening the range of functionalities available for antenna designers in terms of antennas self-reconfigurability depending on the frequency, polarization, waveform characteristics of the surrounding environment.

C. WAVEFORM-SELECTIVE FILTERING MODULES FOR ANTENNAS

Waveform-selective devices can be used not only to improve cloaking functionalities in antenna systems, but they can also be integrated into conventional filtering modules for introducing frequency- and time-domain filtering functionalities, making the device less sensitive to noise and interference.

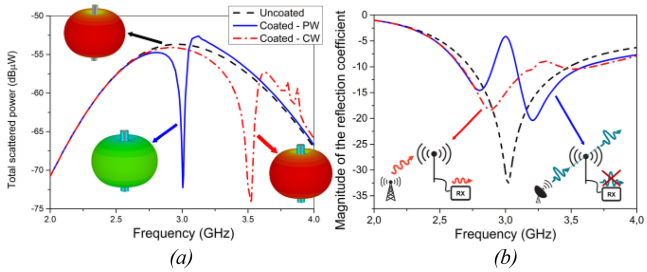


FIGURE 8. (a) Total scattered power by the coated antenna for an incoming pulsed waveform signal (PW) or continuous signal (CW). For comparison, the scattering response of the bare antenna is also reported. (b) Magnitude of the reflection coefficient at the antenna input port for the same scenarios.

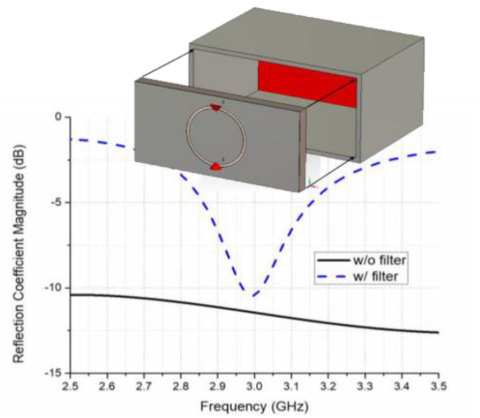
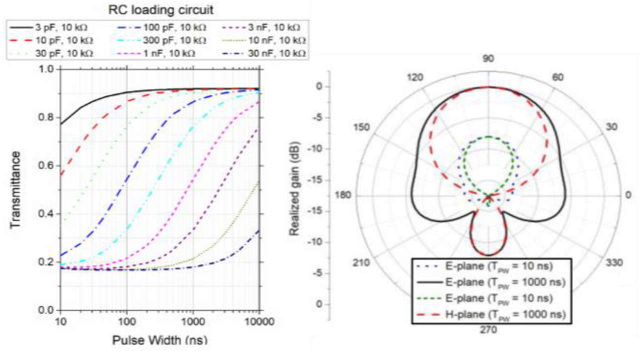


FIGURE 9. Reflection coefficient magnitude of the waveguide aperture antenna (in the inset) with and without the capping frequency- and time-domain filtering iris.

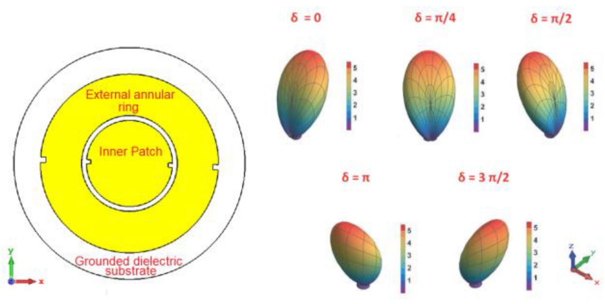
In the inset of Fig. 9, the design of an aperture antenna integrating such functionalities is depicted. An open-ended rectangular waveguide is capped by a metallic plate with an integrated annular slot. As known [62], [63], this filtering module can be used to introduce a frequency-domain filtering effect on the antenna. In fact, in Fig. 9 when comparing the magnitude of the reflection coefficient at the antenna input port with and without the iris, the filtering effect is immediately clear: thanks to the resonance nature of the loading particle, a band-pass behavior is introduced, and the signal can be received just around the resonance frequency [64]. Indeed, by modifying the iris shape, the frequency response, as well as the polarization state of the transmitted field can be controlled [65]–[69].

Still, the iris is not able to distinguish between two signals within the band-pass spectrum, even though their time-domain responses are different. To introduce this functionality, the iris can be loaded with a waveform-selective circuit. Here, the annular slot is loaded in two points by the lumped element circuit (red arrow in the inset of Fig. 9). Since the circuit behaves as a high- or low-impedance load, depending on the pulse width of the incoming signal, these two points can be short- or open-circuited and the iris is transformed from a conventional filtering annular slot to a metallic plate. In the latter, in fact, a strong current flows



(a) (b)

FIGURE 10. (a) Transmittance of the overall system for a parallel RC-based circuit (left) and a series RL-based circuit (right). Different values of the reactive elements are considered.



(a) (b)

FIGURE 11. (a) Geometrical sketch of the proposed structure for generating composite vortex patterns and (b) beam-steering capabilities of patch antennas enabled by composite vortex properties.

along with the connecting points of the slot, short-circuiting them and reflecting the signal. More details can be found in [70].

The magnitude of the transmission coefficient of an equivalent rectangular waveguide filled with the same filtering module loaded by an RC waveform-selective circuit is reported in Fig. 10(a). As can be appreciated, depending on the pulse width of the input signal full- or zero- transmission is enabled. Moreover, by judiciously controlling the value of the loading capacitor the transmittance level for a specific pulse width can be tuned.

Finally, in Fig. 10(b) the polar plot of the realized gain of the designed aperture antenna on the E- and H-planes is reported. The patterns have been evaluated at the central frequency of operation of the radiating system. It can be observed that, for very short pulse (10 ns), the antenna has poor radiation performance thanks to the short circuiting of the filtering iris. On the contrary, for signals characterized by longer pulse width (> 1000 ns), radiation performance strongly improves due to the open-circuit condition of the iris.

The proposed structure is just an example of a new class of radiating systems that can be made extremely robust to interference from the external environment thanks to the integrated frequency- and time-domain filtering functionality, being the antenna specifically designed for working with a given waveform in a given bandwidth. Finally, it is worth mentioning that, being these devices equipped with non-linear diode, they are inherently power-dependent devices and their time-dependent filtering functionalities could be disabled, particularly if receiving too low powered signal. Indeed, it has been demonstrated that more complex circuit solutions relying on the use of operational amplifiers can dramatically mitigate this issue [71].

IV. ANTENNA RECONFIGURABILITY ENABLED BY COMPOSITE VORTEX PROPERTIES

As discussed in the previous Sections, the possibility of structuring metasurfaces on a subwavelength scale allows manipulating the electromagnetic field with a larger number of degrees of freedom and precision. Metamaterial /metasurface lenses [72] allow overcoming the diffraction limit of conventional lenses, in which the resolution is limited to half the wavelength of the light source. This limit, however, applies to the focusing of light and, thus, on the minimum distances between two distinguishable bright regions. On the contrary, dark regions produced by phase singularity points [72] (i.e., points where the phase of an electromagnetic field is undefined) can be arbitrarily localized and subwavelength spaced [74]. Phase singularity points can be thus exploited for tailoring an electromagnetic field with deep precision and wide flexibility [75].

In this regard, several antennas radiating electromagnetic fields with phase singularity points have been proposed, which are based on the possibility of generating vortex modes [76]–[80]. In fact, a vortex beam is characterized by the presence, in the centre of the beam itself, of an amplitude null and a singularity point surrounded by a spiral-like phase variation. However, for structuring the overall field according to the possibility of controlling the number and position of phase singularity points, different vortex modes should be superimposed for creating a composite vortex pattern [81].

For this purpose, we have recently proposed a simple structure consisting of concentric patches etched on a common grounded dielectric substrate [82]. In particular, as shown in Fig. 11(a), the proposed structure consists of an inner circular patch antenna surrounded by an annular metallic ring. By properly selecting their radii, the two patches can be designed for radiating different resonant modes [83]. Moreover, as demonstrated in [78], these modes effectively act as vortex beams if a circular polarization operation is properly implemented. In this way, an overall composite vortex pattern can be radiated, where the position of the phase singularity points can be simply controlled by acting on the amplitude and phase of excitation of the two constituting beams [82].

In particular, in the simple case of a vortex mode of the first order superimposed to a vortex-free mode, the overall pattern has a single phase singularity and, thus,

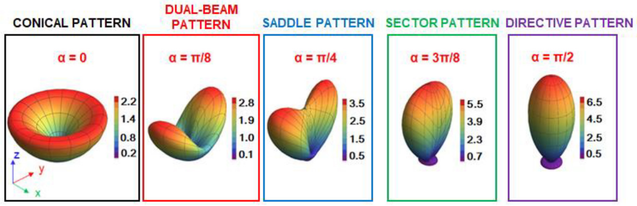


FIGURE 12. Possible radiation patterns of the structure reported in Fig. 11, when the two radiating elements are designed for radiating a vortex mode of the second order superimposed to a vortex-free component. Here, α dictates the amplitude ratio between the two modes, as described in [85].

a single amplitude null, whose position can be analytically determined [82], [84]. In this way, the overall structure exhibits a directive pattern with a pointing direction that can be finely controlled by acting on the phase shift δ between the feeding ports of the two patches, as shown in Fig. 11(b).

These preliminary results, obtained through a proper set of full-wave numerical simulations [50], suggested to further investigate the possibility offered by composite vortex properties in radiation pattern synthesis and reconfigurability. Thus, a more general analysis was carried out in [85], where the superposition between any two different vortex modes radiated by a patch antenna was considered. This analysis confirmed that phase singularity points of vortex modes and, thus, their amplitude nulls, can be exploited as a new design strategy for tailoring, almost at will, the radiation pattern of patch antennas. In fact, by properly choosing the order modes of the two radiating patches, the number of phase singularity points can be selected. Once fixed the number of this new degrees of freedoms, their positions can be engineered for shaping and pointing the overall radiation pattern.

For demonstrating the effectiveness of the proposed approach, some radiation pattern shapes of practical interests were reported. In particular, as shown in Fig. 12, a two-element patch antenna can be reconfigured in real-time to exhibit very different radiation patterns, such as conical, dual-beam, saddle, sector or directive patterns, whose shapes found practical applications in mobile or satellite communication systems. Please note that these different patterns are typically obtained by designing a specific antenna structure for each one of them. Instead, the flexibility enabled by composite vortex property allows reaching these different patterns by using a single radiating structure. Moreover, an electronic switching between the different patterns can be implemented by simply varying the amplitude ratio (here dictated by α) between the two constituting beams, thus enabling the possibility to adapt in real-time the antenna properties to the operative environment.

Finally, we remark here that, by also acting on the phase shift between the two constituting beams, the radiation patterns, reported in Fig. 12, can be also easily rotated. Therefore, the proposed approach can be considered as a promising strategy for implementing reconfigurable planar devices with possible applications in next generation wireless systems.

V. ANTENNA NON-RECIPROCITY ENABLED BY SPATIO-TEMPORAL MODULATION

As it is well-known from antenna theory, the radiation pattern of an antenna describes the radiation intensity radiated in all directions [86]. Due to reciprocity, the radiation pattern in transmission mode also describes the effectiveness with which the antenna can capture electromagnetic energy from the surrounding space. Indeed, typically, the transmission and reception gains, $G_{TX}(f_0, r_0)$ and $G_{RX}(f_0, r_0)$, are identical for a given operation frequency f_0 and direction r_0 [87], [88]. Therefore, the antennas are not able to intelligently select the radiated/captured waves, to avoid, for example, that the echo of a transmitted signal, or any interfering signal coming from the same direction is perceived.

The conventional technologies for breaking reciprocity are typically based on bulk magnets or non-linear devices that are not compatible with required compactness of antenna systems or linearity of the system response, respectively. Therefore, more recently, the original concept of reconfigurability of metamaterial and metasurfaces has been extended to achieve fast dynamic modulation of the properties of a system in real-time. Starting from the first attempts of tunability of the metasurfaces [86]–[92], recently, it has been demonstrated that faster modulation can be also applied [93]–[94], and several exotic space–time scattering phenomena never observed before have been observed. In the following, we present and discuss some unprecedented antenna responses enabled by space-time metamaterials and time-varying metasurfaces. Among them, the possibility to break the reciprocity constraint of a passive system and generate/control frequency harmonics in the scattered field represents the most appealing functionality [95]–[99].

In the next sub-sections, we focus our attention on the use of space-time modulated meta-particles and metamaterials [100]–[103] for enabling different radiating performances in TX and RX modes, resulting in an additional degree of freedom for antenna designers, leading to independently tailoring the transmitting and receiving radiation patterns for specific applications. As a side effect, the antenna is capable of selecting autonomously the signal to be received and transmitted according to the propagation direction, frequency, and/or polarization state, showing an embedded intelligence not presented before.

A. NON-RECIPROCAL FILTERING HORN ANTENNA

Reciprocity in antennas may represent a limit in the case of radiators operating in a dual-link scenarios, such as in satellite communications. If both uplink and downlink narrowband channels are considered, it would be preferable that only one polarization, for example the LHCP, is used in the uplink frequency band, but the same is not received by the antenna. Conversely, in the downlink frequency band, the same polarization can only be received, but not transmitted. This is not achievable through a conventional orthomode transducer (OMT), because it would work only in the case of uplink and downlink operating at the same frequency

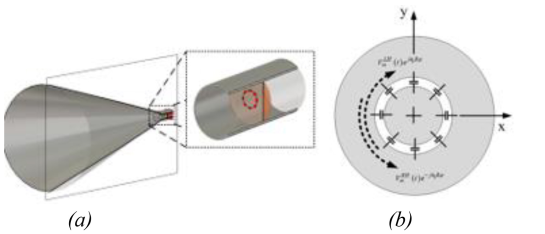


FIGURE 13. Schematic and performances of non-reciprocal horn antenna enabled by spatio-temporal modulation. (a) Perspective view of the antenna. (b) Representation of the voltage waves propagating on the annular aperture in presence of the time variable capacitors.

and orthogonal polarizations. Such an antenna, exhibiting self-filtering properties and dual-band operation is obviously non-reciprocal and can relax the requirements of the diplexer that is necessary to connect after the antenna to separate the uplink and downlink bands.

Recently, we addressed this issue by proposing a standard high-gain horn antenna loaded with a spatio-temporal modulated filtering particle inserted between the antenna and the feeding waveguide [104]–[106], as shown in Fig. 13a.

When the resonant particle is not modulated, it behaves as a pass-band filter, allowing the energy passing through it only in a limited range of the spectrum. In case of a ring aperture, the current distribution at the resonant frequency f_0 is a standing wave that can be represented as a superposition of two oppositely propagating waves with the same amplitude, carrying the same energy. The two opposite waves travel with the same wavenumber $k^{RH} = k^{LH} = k_1$, leading to a reciprocal response for the particle. The symmetry of oppositely traveling current waves can be broken by introducing angular-momentum biasing, driven by a set of time-modulated varactor mounted across the aperture (see Fig. 13(b)). A spatio-temporal modulation of the effective permittivity function as $\varepsilon_r(t, \varphi) = \varepsilon_{r0} + \varepsilon_m \cos(2\pi f_m t - p\varphi)$ is imposed by the varactors to the annular aperture, where ε_{r0} is the background permittivity, the permittivity modulation amplitude, f_m the modulation frequency, and p the angular-momentum order.

Due to the presence of the time-varying periodic perturbation of the effective permittivity function, the traveling current waves with opposite handedness experience a local Doppler effect and each of them perceives the ring to have a different electrical length. As demonstrated in [104], the spatio-temporal modulated annular ring exhibits four separate resonant states, two for each circular polarization state, i.e., LHCP and RHCP. In Fig. 14(a), we report the resonant eigenstate of the modulated particle as a function of the modulation frequency f_m. It is worth noticing that when the modulation frequency is zero, the effective permittivity function is only spatially modulated with a periodicity imposed by the angular momentum order p. Being the spatial period of the modulation twice than the periodicity of the travelling wave on the ring aperture, the local electromagnetic field generated by the currents flowing along the ring edges perceive a local Bragg grating and no resonant eigenstate is obtained at the original resonant frequency f_0. However, the annular inclusion can still support a resonant state that is at a different frequencies, i.e., $f_0^{\pm} = f_0(1 \pm 0.5\kappa_m)$, where κ_m is the resonant mode coupling factor evaluated as reported in [95]. In this scenario, however, the particle is still reciprocal, being the LH/RHCP states resonating at the same frequencies $f_0^{\pm}$.

When the modulation frequency f_m increases, the local Doppler effect induced by the modulation is perceived by the travelling waves on the apertures. The eigen solutions of the resonant LH/RHCP states split and the particle exhibits different resonant frequencies according to the polarization stare of the illuminating wave. In particular, considering Fig. 14(a), It is worth noticing that two main resonant states, in the solid lines, and two secondary resonant states, in the dashed lines, are excited. The main states exhibit a stronger resonant response with respect to the secondary ones. For sake of generality, the curves in Fig. 14a are not specified for a specific spatio-temporal modulated annular ring, allowing to catch the important role of the modulation regardless the particles characteristics (please, see [104] for the analytical expression of the curves reported in Fig. 14a). The two main resonant states are symmetrically located with respect to the original resonant frequency of the unmodulated particle and approach it for higher modulation frequencies. Indeed, for very fast modulation, the travelling waves are not able to perceive the modulation and the annular aperture resonates again at the original frequency. However, for modulation frequencies lower than one order of magnitude with respect to f_0, the non-reciprocal response is clearly achieved as shown in Fig. 14(b). The transmission coefficients in terms of S_{21} and S_{12} scattering parameters as a function of the frequency have been evaluated though a proper set of numerical co-simulation between CST Microwave Studio [50] and Advanced Design System [61]. The modulation frequency is just 0.05 f_0. The red and blue line represent the transmission coefficient for the same polarization in transmission and reception. It is clear that more than 10 dB of isolation can be achieved when the operative frequency coincides with the maximum transmission level for one direction. However, for opposite handedness of the illuminating wave, the transmission is maximum. This allows enabling an intelligent selection of the wave to be transmitted and rejected not only according to the frequency, but also according to the polarization state.

B. NON-RECIPROCAL ANTENNAS ENABLED BY CORE-SHELL COVERS

In the previous Section, we discussed the possibility to break reciprocity of an horn antenna by using space-time modulated meta-particles. Such an approach is clearly applicable to only aperture antennas, since the radiated and captured field can interact directly with the modulated particle. However, the concept of metamaterial-based non-reciprocity can be extended to any antenna system if a proper space-time

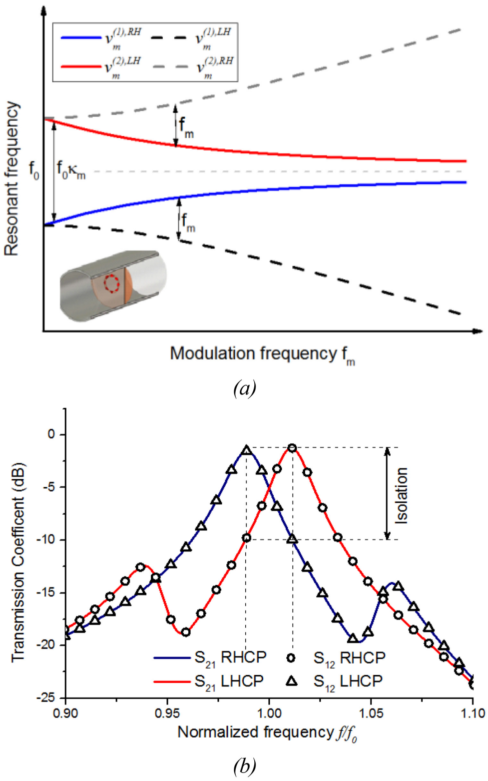


FIGURE 14. **(a) Resonant frequencies of the modulated annular aperture as a function the modulation frequency. (b) Magnitude of the transmission coefficient of the modulated annular aperture when the spatio-temporal modulation is present.**

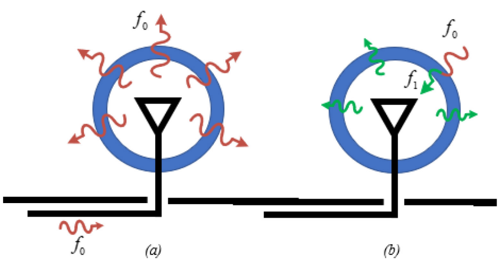


FIGURE 15. **A properly designed space-time varying cloak covering the antenna keeps the transmission performance unaltered (a), but drastically reduces the reception of the in-band interfering signals (b), shifting them out of the antenna operational band and, thus, making their presence undetectable.**

varying (STV) cover is designed around it, as proposed in [107]–[110].

In Fig. 15, we report the operative principle of the spatio-temporally modulated cover for antennas. The cover exhibits a radially modulated permittivity profile, making its response isotropic and, thus, independent of the type of antenna and corresponding radiation diagram. The cover can be designed to keep the outgoing radiation unaltered (Fig. 15(a)) but changes drastically the received radiation (Fig. 15(b)) at the operative frequency of the antenna, significantly modifying its realized gain.

Let us consider the antenna system shown in Fig. 16(a) consisting of a resonant dipole antenna operating at frequency f_0 covered by a STV cloaking shell with

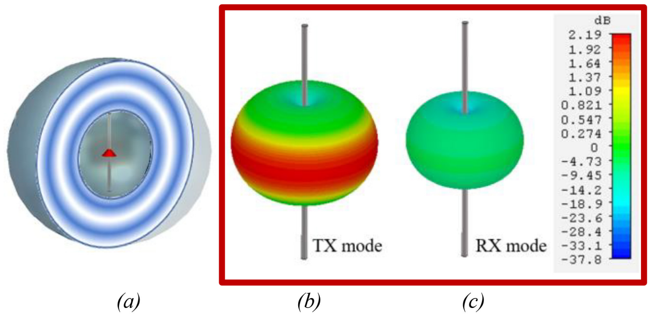


FIGURE 16. **(a) Perspective 3D view of the space-time varying metamaterial shell surrounding a resonant electric dipole. The permittivity of the shell is modulated to appear in motion in inward direction. (b)-(c) Realized gain patterns exhibited by a dipole antenna in presence of a STV metamaterial shell in (b) TX mode and (c) RX mode.**

thickness $d = a_2 - a_1$, where $a_{1,2}$ are the inner and outer radius of the shell, respectively. The shell is made of a radially modulated dielectric material, whose electric permittivity changes in space and time in the range $a_1 \leq r \leq a_2$ according to the modulation profile $\varepsilon_r(r, t) = \varepsilon_{r_0} + \delta\varepsilon \cos\left[2\pi f_m t \pm k_m r\right]$, where ε_{r_0} is the static electric permittivity of the dielectric, $\delta\varepsilon$ is the modulation amplitude and (f_m, k_m) are the temporal frequency and wave-number of the modulation profile, respectively. The sign "±" defines the moving direction of the permittivity wave within the shell: if positive, the permittivity wave is moving inward direction and it is used for changing the receiving radiation performances with respect to the unmodulated case; on the contrary, if negative, the radiating performances in transmitting mode are modified, whereas the antenna is still able to receive as if the shell were static. The non-reciprocity of the spatio-temporal cover, therefore, is enabled by the different capability of the shell to interact with the propagating wave, radiated or captured, according to its propagation direction.

Indeed, let us consider a STV shell with inward moving permittivity profile. If the antenna operates in transmitting mode, the interaction with the permittivity wave is *contra-directed* in any direction, i.e., the two waves move in different directions. A phase matching between radiated wave and permittivity wave is not possible, and the frequency conversion of the radiated signal is identically zero [111]. As shown in Fig. 16(b), the realized gain pattern of the dipole antenna at the operating frequency f_0 in TX mode coincides with the unmodulated one. The patten has been obtained properly combining the results obtained though Finite Difference Time Domain simulations and CST Microwave Studio [50].

On the contrary, when the antenna is operating in receiving mode, the *co-directed* permittivity travelling wave interacts with the incident field at frequency f_0 and it is modulated, distributing the energy of the received signal on a set of harmonics located at the frequencies $f_{n\pm} = f_0 \pm n f_m$, as demonstrated in [101]. This is clearly shown in Fig. 16(c), where the realized gain pattern of the dipole antenna at the operating frequency f_0 in RX mode is reported. The maximum gain is significantly reduced, making the antenna unable to capture the signal anymore.

A similar effect can be also obtained using a properly engineered system based on time-varying metasurfaces [112]–[115], instead of bulk metamaterials. In [116], [117] we recently proposed an isolating non-reciprocal system based on time-varying metasurfaces. They are at the opposite side of a generic filtering structure, that let the signal pass through or stop according to the propagation direction of the illuminating signals. Indeed, the two metasurfaces impart opposite frequency conversion (up- and down-conversion) of the incident wave by exploiting the linear modulation of their phase properties [98], [112]. In this case, the signal is shifted within the pass-band frequency range of the filter or moved in the stop-band region according to which of the two metasurfaces is illuminated first. This approach would relax the requirement of a modulated permittivity function, simplifying the implementation.

VI. 2D RECEIVING AND STORING FOR WIRELESS POWER TRANSFERRING SYSTEMS

The increasing demand of wireless systems has always provided numerous challenges connected to energy transfer, that brought recently to a new generation of energy storing and transfer devices, that is, Wireless Power Transfer (WPT) systems. Energy transfer applications have been exploited in far and near field systems, ranging from microwave power transmission [119], [120] to short-range WPT applications exploiting inductive coupling and resonant coupling [121]–[123]. Among those, virtual effects [123]–[125], and energy storing based on virtual coupling [126]–[127] have recently attracted our community, introducing electromagnetic light confinement in lossless systems [128]: energy is neither reflected, transmitted nor absorbed but stored within the system and is lately released at will. This is achieved by approaching electromagnetic scattering zeros of the system, that correspond to absorbing modes. However, being the system lossless, energy will be only accumulated. The absorbing mode is related to a time-varying excitation, that allows energy accumulation and the zero-scattering condition.

In this frame, we have recently proposed metasurface based systems able to store electromagnetic energy in resonant cavities [129]–[131]. This is achieved by leveraging a semi-bounded cavity consisting of a metasurface and a perfect conducting mirror. The scattering complex plane is explored and the frequency zeros that grant virtual perfect absorption are found as a function of the metasurface reactance and the cavity dimensions. A generalization of the perfect virtual absorption phenomenon in a metasurface cavity for any incidence angle and polarization of the impinging wave has been modelled and numerically demonstrated. A metasurface extended design with reactance expressions for any incidence angle and polarization of the impinging wave has also been settled.

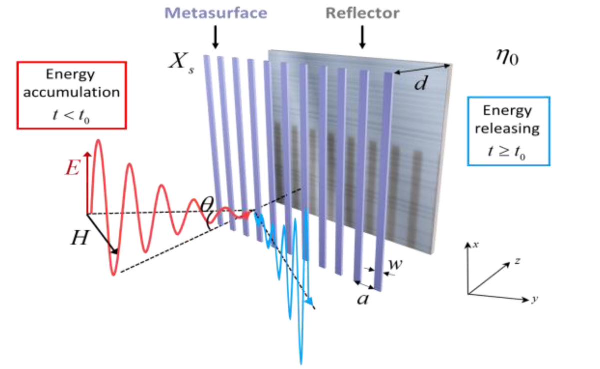


FIGURE 17. Two-dimensional metasurface cavity backed by a reflector, illuminated by a TE plane wave impinging with incidence angle θ. The metasurface consists of a dense array of metallic strips aligned along the x-direction. Energy is stored before the kick-off instant t_0 and is released after it.

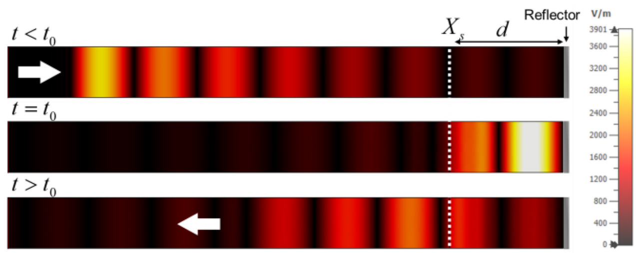


FIGURE 18. Snap-shot in time of the electric field during illumination, storing, and releasing of energy (upper, middle, and bottom figure, respectively) of a metasurface bounded cavity for a normal incidence illumination.

The metasurface bounded cavity is composed, as depicted in Fig. 17, by a dense array of strips, which show an overall reactance of $X_s = 580\Omega$, spaced from the reflector by the distance $d = 0.9\lambda$ at $f_0 = 5GHz$in free space that is $\eta = \eta_0$.

The reactance exhibited by the array has been defined by geometrical strip width and their periodicity through eq. (1). Exploiting the equivalent transmission line model of the system, the reflection coefficient at the metasurface interface can be expressed, and seeking for its zeros leads to the zero scattering complex frequencies:

$$\omega_0 = \omega_r + i\omega_i = \frac{c}{d\cos\theta}\left[\pi n - \frac{1}{2}\log\left(1 - 2i\frac{X_s}{\eta_0}\right)\right] \quad (5)$$

where n is the index of the cavity mode responsible for storing the incident electromagnetic energy. The zeros in eq. (5) are complex quantities and can be found on the scattering complex frequency plane, where they lay in the lower half plane and are periodic along the real frequency axis, according to the cavity order n, so they have the same imaginary frequency ω_i. Exciting the metasurface cavity with one of these zeros brings to the virtual perfect absorption, as showed by full-wave simulated time-snapshots of the electric field in Fig. 18, obtained by using CST Microwave Studio [50]. Here, it is proved that the signal is completely accumulated inside the metasurface cavity, as far as the designed complex frequency excitation holds, that is, up to the kick-off instant t_0. When this condition is not fulfilled anymore, the

TABLE 1. Metastructures for antennas and wireless propagation systems.

Metastructure	Properties	Applications	References
Non-linear cloaking metasurfaces	*Power-dependent*	*Invisible antennas; Non-reciprocal antennas; Array for sensing applications.*	[24],[25], [26],[55]
Waveform-selective metastructures	*Frequency- and Time-domain dependent*	*Waveform-selective cloaking devices*; *Waveform-selective filtering modules for antennas.*	[59],[60], [70]
Vortex-mode engineering metastructures	*Structured fields*	*Antenna radiation pattern engineering.*	[78]-[80], [82], [84]-[85]
Spatio-temporal metastructures	*Spatio-temporal modulated antennas*	*Non-reciprocal antennas; Spatio-temporal invisibility cloaks.*	[101][104] [107]
Metasurface cavities	*Virtual absorption*	*Energy storing; Energy transfer enhancement.*	[124][129] [132]

signal is released back as a superposition of cavity modes. During the zero scattering excitation, the signal is completely accumulated inside the free-space cavity and no reflections occur as far as the proper temporally shaped signal excites the structure.

We have then demonstrated that virtual perfect absorption can occur under peculiar conditions that are related to values of the metasurface surface reactance and the cavity input reactance [132], [133]. First of all, the two reactances have to show an opposite electric behaviour, that is, $sgn[X_{cavity}] = -sgn[X_{metasurface}]$, so they must circuitally behave as an inductance and a capacity or viceversa. Last, to get complex scattering zeros, the related inductance and capacitance emulating the reactance behaviour at the operative frequency f_0 must fullfill the condition: $L/C < 4\eta_0^2$. Otherwise, scattering zeros will be purely imaginary; this condition cannot lead to free-space propagation, since the signal is static and exponentially growing [132]. This approach, instead, can be used to guided propagation, paving the way to energy storing in circuital purely reactive loads [134]–[136].

The intriguing technique of time-varying excitation has been also used to get virtual perfect absorption for enhancing energy transfer, by locally controlling energy accumulation and enabling metasurfaces as key parameter to make steps forward in the research on wireless power transfer systems [123], [137].

VII. CONCLUSION

In this paper, we have reviewed some recent applications of metasurfaces in antenna and reflector systems. In particular, we focused on non-linear, waveform-selective, topologically-inspired, time-varying, reconfigurable and energy storing structures, which have been exploited to add reconfigurability to standard designs, as well as, conceive new radiating systems with awareness capabilities on the operational environment. A resume Table illustrating the fundamental properties, target applications, and reporting relevant references for each of the discussed metastructure devices is reported in Table 1.

With the reported practical examples of innovative antenna systems, we have shown that metasurfaces and, more in general, 2D reconfigurable structures, can be of paramount importance to overcome existing limitations on the physical layer of a communication link and, thus, can be very attractive for implementing next-generation wireless systems. Indeed, some challenges are still open before a full establishment of the proposed technologies, and the main research efforts in the near future will be focused to overcome the performance limitations arising from the presence of electronic elements in the metastructure design.

Compared to passive metastructures, whose technological maturity has been widely demonstrated and led to the commercialization of several devices, active metastructures exhibit more severe frequency limitations caused by the loading electronic devices. This issue is strongly related to the class of electronic devices used. For instance, applications relying on the use of PIN diodes are expected to be applied in a broader range of frequency due to their availability up to very high microwave frequencies. Indeed, more complex circuit systems or frequency modulators can be more easily affected by limitations coming from the available current technology, although the recent effort of the community towards the design of spatio-temporal modulated structures is quickly boosting the technology in the field.

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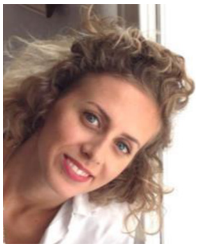
MIRKO BARBUTO (Senior Member, IEEE) was born in Rome, Italy, on April 26, 1986. He received the B.S., M.S., and Ph.D. degrees from "Roma Tre" University, Rome, Italy, in 2008, 2010, and 2015, respectively.

Since September 2013, he has been the "Niccolò Cusano" University, Rome, where he currently serves as an Associate Professor of Electromagnetic Field Theory, as the Director of the Applied Electromagnetic Laboratory, and as a Member of the Doctoral Board in Industrial and Civil Engineering. He is currently the author of more than 90 papers in international journals and conference proceedings. His main research interests are in the framework of applied electromagnetics, with an emphasis on antennas and components at RF and microwaves, cloaking devices for radiating systems, metamaterials and metasurfaces, electromagnetic structures loaded with non-linear or non-foster circuits, topological properties of vortex fields, and smart antennas for GNSS and communication technology.

Dr. Barbuto was the recipient of the Outstanding Reviewers Awards assigned by the Editorial Board of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION (for six consecutive years, from 2015 to 2020) and by the Editorial Board of the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS (for three consecutive years, from 2017 to 2019). In 2017, he has been selected as one of the Best Reviewers by the Editorial Board of *Radioengineering Journal*. He has been serving as an Associate Editor for IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS (since 2019) and for this role, he has been awarded for the exceptional performance from 1 January to 31 December 2020. He has been a member of the Editorial Board of the *Radioengineering Journal* (since 2019), the Technical Program Committee of the International Congress on Artificial Materials for Novel Wave Phenomena (since 2017), and of secretarial office of the International Association METAMORPHOSE VI (the Virtual Institute for Artificial Electromagnetic Materials and Metamaterials). He serves as a Technical Reviewer of the major international conferences and journals related to electromagnetic field theory and metamaterials. He has been Technical Program Coordinator (Track "Electromagnetics and Materials") for the 2016 IEEE Antennas and Propagation Symposium and he served as the Guest Editor of three special issues on metamaterials and metasurfaces. Since 2015, he has been the Proceeding Editor for the annual International Congress on Engineered Material Platforms for Novel Wave Phenomena—Metamaterials and in 2019, he was appointed as the General Chair of the 39th EUPROMETA Doctoral School on metamaterials held in Rome, Italy. He is currently a member of the Italian Society on Electromagnetics, of the National Inter-University Consortium for Telecommunications, of the Virtual Institute for Artificial Electromagnetic Materials and Metamaterials (Metamorphose VI AISBL), and of the Institute of Electrical and Electronics Engineers (IEEE).

ZAHRA HAMZAVI-ZARGHANI was born in Shiraz, Iran. She received the B.Sc. degree in electrical engineering from Shiraz University, Shiraz, Iran, in 2010, the M.Sc. degree in electrical engineering from Tarbiat Modares University, Tehran, Iran, in 2014, and the joint Ph.D. degree from Shiraz University and Politecnico di Torino, Turin, Italy, in 2020. She is currently a Postdoctoral Researcher with Roma Tre University, Rome, Italy, where she is working on electromagnetic and acoustic metasurfaces. Her research interests include metamaterial and metasurfaces, electromagnetics and acoustics, imaging, scattering manipulation and cloaking, transmitarray and reflectarray antennas, graphene, and tunable applications.



MICHELA LONGHI received the B.S. and M.S. degrees *(summa cum laude)* in electronic engineering from the Università Politecnica delle Marche, Ancona, Italy, in 2012 and 2014, respectively, and the Ph.D. degree from the University of Tor Vergata, Rome, Italy, with European Label in 2019.

In 2014, she joined the European Space Agency, Noordwijk, The Netherlands, for the master thesis project. In 2015, she was Research Fellow with Group of Engineering for Health and Weelbeing, Consiglio Nazionale delle Ricerche (CNR-IEIIT), Milan, Italy. In 2019, she was hosted by the ETH Zurich, Switzerland, for Ph.D. internship. She worked as a RF and System Engineering with MVG Italy, Pomezia, Italy, from 2019 to 2021. She is currently a Postdoctoral Researcher with the Niccolò Cusano University, Rome, Italy. Her research interests include beam array antennas, deep transcranial magnetic simulation, radiofrequency identification devices, drones, antennas designd, tests and measurements and recently, AI applications for metamaterials design. He is currently a member of the Italian Society on Electromagnetics, of the National Inter-University Consortium for Telecommunications, and of the Virtual Institute for Artificial Electromagnetic Materials and Metamaterials (Metamorphose VI AISBL).

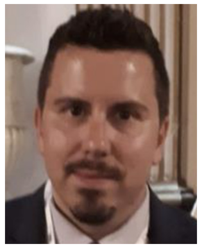
ANGELICA VIOLA MARINI (Student Member, IEEE) was born in Rome, in 1992. She received the M.M. degree in piano performance from Conservatorio di Musica Santa Cecilia, Rome, Italy, in 2012, the B.S. and M.S. degrees in electronics and ICT engineering from ROMA TRE University, Rome, in 2014 and 2017, respectively, and the Ph.D. degree with the Department of Applied Electronics, ROMA TRE University, Rome.

She made an internship as an Engineer in Wind Tre S.p.A. for 5G deployment experimentation in 2017. Her research fields are time-modulated phenomena and structures, and anomalous electromagnetic propagation enabled by metasurfaces and microwave components. She has received the Honorable Mention and resulting Finalst at the Student Paper Context at Marinaforum 2021. She is a member of the Virtual Institute for Artificial Electromagnetic Materials and Metamaterials (METAMORPHOSE VI, the International Metamaterials Society). She served as a Member of local organizing committee of Congress Metamaterials'2019, held in Rome, Italy, in 2019, and local organizing committee of XXXVIII and XXXIX Euprometa Doctoral schools, held in Rome, Italy in 2017 and 2019.

ALESSIO MONTI (Senior Member, IEEE) was born in Rome, Italy, in 1987. He received the B.S. degree in electronic engineering *(summa cum laude)*, the M.S. degree in telecommunications engineering *(summa cum laude)* and the Ph.D degree in biomedical electronics, electromagnetics and telecommunications engineering from ROMA TRE University, Rome, Italy, in 2008, 2010, and 2015, respectively.

From 2013 to 2021, he was with the Niccolò Cusano University, Rome, since November 2021, he has been the ROMA TRE University, where he serves as an Associate Professor of Electromagnetic Field Theory. His research activities resulted in over 100 papers published in international journals, conference proceedings, and book chapters. His research interests include varied theoretical and application-oriented aspects of metamaterials and metasurfaces at microwave and optical frequencies, the design of functionalized covers and invisibility devices for antennas and antenna arrays and the electromagnetic modeling of micro- and nano-structured artificial surfaces.

Dr. Monti has been the recipient of several national and international awards and recognitions, including the URSI Young Scientist Award in 2019, the Outstanding Associate Editor of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION under 2019 and 2020, the Finmeccanica Group Innovation Award for Young People in 2015, and the 2nd Place at the Student Paper Competition of the conference Metamaterials' in 2012. He is a member of the secretarial office of the International Association METAMORPHOSE VI, and has been the Editorial Board of the journals *EPJ Applied Metamaterials* (since 2016) and IEEE TRANSACTION ON ANTENNAS AND PROPAGATION (since 2018). In 2019, he has been appointed as the General Chair of the International Congress on Artificial Materials for Novel Wave Phenomena–Metamaterials and he has been serving as the Chair of the Steering Committee of the same Congress series since 2017. He has been also a member of the Technical Program Committee (TPC) of the IEEE International Symposium on Antennas and Propagation, from 2016 to 2019 and of the International Congress on Advanced Electromagnetic Materials in Microwaves and Optics-Metamaterials from 2014 tp 2016 and has been the guest-editor of five journal special issues focused on metamaterials and nanophotonics. He has also been serving as a Technical Reviewer of many high-level international journals related to electromagnetic field theory, metamaterials and nanophotonics and he been selected as one of the Top Reviewers by the Editorial Board of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION from 2014 to 2019.



DAVIDE RAMACCIA (Senior Member, IEEE) received the B.S. *(summa cum laude)* and M.S. *(summa cum laude)* degrees in electronic and ICT engineering and the Ph.D. degree in electronic engineering from ROMA TRE University, Rome, Italy, in 2007, 2009, and 2013, respectively.

Since 2013, he has been with the Department of Engineering from 2013 to 2021 and has been the Department of Industrial, Electronic, and Mechanical Engineering (since, 2021), ROMA TRE University. He has coauthored more than 100 articles in international journals, conference proceedings, book chapters, and holds one patent. His main research interests are in the modeling and design of (space-)time-varying metamaterials and metasurfaces, and their applications to microwave components and antennas, and the analysis of anomalous scattering effects in temporal metamaterials.

Dr. Ramaccia was the recipient of a number of awards and recognitions, including the Electromagnetics Academy Young Scientist Award in 2019, the Seven Outstanding Reviewer Award by the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION from 2013 to 2021, the IET Prizes for the Best Poster on Microwave Metamaterials in 2013, and the IET Award for the Best Poster on the Metamaterial Application in Antenna Field in 2011. He has been serving the scientific community, by playing roles in the management of scientific societies, in the editorial board of international journals, and in the organization of conferences and courses. He is currently the General Secretary of the Virtual Institute for Artificial Electromagnetic Materials and Metamaterials (METAMORPHOSE VI, the International Metamaterials Society) and is an Elected Member of the Board of Directors of the same association from three consecutive terms (since 2014). He serves as an Associate Editor for the IEEE ACCESS (since 2019), a Scientific Moderator for IEEE TechRxiv (since 2019), a Technical Reviewer of the major international journals related to electromagnetic field theory and metamaterials. He was also as Guest Co-Editor of three special issues on metamaterials and metasurfaces. Since 2015, he serves as a member of the Steering Committee of the International Congress on Advanced Electromagnetic Materials in Microwaves and Optics—Metamaterials Congress. He has been the General Chair and the Local organizer of the 39^{th} and 42^{nd} EUPROMETA doctoral School on metamaterials held in Rome, Italy, in 2019 and 2021, respectively. He has been the Technical Program Coordinator (Track "Electromagnetics and Materials") for the 2016 IEEE Antennas and Propagation Symposium. He is a member of the Technical Program Committee of the International congress on Laser science and photonics applications—CLEO 2022. He has also been elected as a Secretary of the Project Management Board of the H2020 CSA Project NANOARCHITECTRONICS (from 2017 to 2018).

STEFANO VELLUCCI (Member, IEEE) received the B.S. and M.S. *(summa cum laude)* degrees in electronic engineering, and the Ph.D. degree in applied electronics from ROMA TRE University, Rome, Italy, in 2012, 2015, and 2019, respectively.

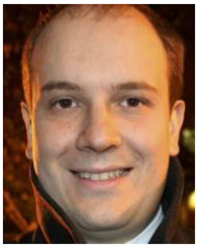
He is currently a Postdoctoral Research Fellow with the Department of Industrial, Electronic, and Mechanical Engineering, ROMA TRE University.

In 2014, he was an Intern with MBDA, Missile Systems, Rome, Italy, and in 2015, he was an Antenna Engineer with ELT Elettronica S.p.A. Rome, Italy, where he designed, modeled, and optimized antennas for military applications. From 2019 to 2020, he was a Postdoctoral Researcher with the ELEDIA Research Center, University of Trento, Trento, Italy, involved in the study and development of metasurfaces for space and terrestrial applications. His current research interests include the design and applications of artificially engineered materials and metamaterials to RF and microwave components, non-linear and reconfigurable circuit-loaded metasurfaces for radiating structures, analysis and design of metasurface-based cloaking devices for antennas. He was the recipient of some national and international awards, including the IEEE AP-S Award of the Central-Southern Italy Chapter in 2019, the Outstanding Reviewers Award assigned by the IEEE Transactions on Antennas and Propagation in 2018, 2019, and 2020, the Leonardo-Finmeccanica Innovation Award for "Young Students" in 2015, and was the Finalist in the Telespazio Technology Contest in 2021. He is currently serving as Associate Editor for the *EPJ Applied Metamaterials Journal*, has been the guest-editor of two journal special issues focused on microwave, photonic, and mechanical metamaterials, and is a member of the Virtual Institute for Artificial Electromagnetic Materials and Metamaterials (METAMORPHOSE VI), the Institute of Electrical and Electronics Engineers (IEEE), and the Italian Society on Electromagnetics (SIEM). In 2019, he was a Local Organizing Committee Member of the International Congress on Artificial Materials for Novel Wave Phenomena—Metamaterials, and since 2016, he has been serving as a Technical Reviewer of many high-level international journals and conferences related to electromagnetic field theory, metamaterial, and metasurfaces.

ALESSANDRO TOSCANO (Senior Member, IEEE) was born in Capua, in 1964. He received the graduation degree in electronic engineering from Sapienza University of Rome in 1988, and the Ph.D. degree in 1993.

Since 2011, he has been a Full Professor of Electromagnetic Fields with the Engineering Department, Roma Tre University. He carries out an intense academic and scientific activity, both nationally and internationally. From April 2013 to January 2018, he was a Member of Roma Tre University Academic Senate. From October 2016 to October 2018, he is a member of the National Commission which enables National Scientific Qualifications to Full and Associate Professors in the tender sector 09/F1—Electromagnetic fields. Since 23rd January 2018, he has been the Vice-Rector for Innovation and Technology Transfer. He is the author of more than one hundred publications in international journals indexed ISI or Scopus; of these on a worldwide scale, three are in the first 0.1 percentile, five in the first 1 percentile and twenty-five in the first 5 percentile in terms of number of quotations and journal quality. His scientific research has as ultimate objective the conceiving, designing and manufacturing of innovative electromagnetic components with a high technological content that show enhanced performance compared to those obtained with traditional technologies and that respond to the need for environment and human health protection. His research activities are focused on three fields: metamaterials and unconventional materials, in collaboration with Prof. A. Alù's Group at The University of Texas at Austin, USA, research and development of electromagnetic cloaking devices and their applications (First place winner of the Leonardo Group Innovation Award for the research project entitled: *Metamaterials and electromagnetic invisibility*) and the research and manufacturing of innovative antenna systems and miniaturized components (First Place Winner of the Leonardo Group Innovation Award for the research project entitled: *Use of metamaterials for miniaturization of components*—MiniMETRIS).

Prof. Toscano is currently a member of the Board of Director of Radiolabs (a non-for-profit Research Consortium), of the steering committee of the National Competence Center on Cyber 4.0, and of the scientific council of CIRIAF (Interuniversity Research Center on Pollution and the Environment). In addition to his commitment in organizing scientific events, he also carries out an intense editorial activity as a member of the review committees of major international journals and conferences in the field of applied electromagnetics. He has held numerous invited lectures at universities, public and private research institutions, national and international companies on the subject of artificial electromagnetic materials, metamaterials and their applications. He actively participated in founding the international association on metamaterials Virtual Institute for Advanced Electromagnetic Materials—METAMORPHOSE, VI. He coordinates and participates in several research projects and contracts funded by national and international public and private research institutions and industries.



FILIBERTO BILOTTI (Fellow, IEEE) received the Laurea and Ph.D. degrees in electronic engineering from ROMA TRE University, Rome, Italy, in 1998 and 2002, respectively.

Since 2002, he has been with the Faculty of Engineering (2002–2012), the Department of Engineering (2013–2021), and the Department of Industrial, Electronic, and Mechanical Engineering (since, 2021) at ROMA TRE University, where he serves as a Full Professor of electromagnetic field theory (since, 2014) and the Director of the Antennas and Metamaterials Research Laboratory (since, 2012). His main research contributions are in the analysis and design of microwave antennas and arrays, analytical modelling of artificial electromagnetic materials, metamaterials, and metasurfaces, including their applications at both microwave and optical frequencies. In the last ten years, his main research interests have been focused on the analysis and design of cloaking metasurfaces for antenna systems, on the modeling and applications of (space and) time-varying metasurfaces, on the topological-based design of antennas supporting structured field, on the modeling, design, implementation, and application of reconfigurable metasurfaces, on the concept of meta-gratings and related applications in optics and at microwaves, on the modeling and applications of optical metasurfaces. The research activities developed in the last 20 years has resulted in more than 500 papers in international journals, conference proceedings, book chapters, and three patents.

Prof. Bilotti was the recipient of a number of awards and recognitions, including the elevation to the IEEE Fellow Grade for contributions to metamaterials for electromagnetic and antenna applications in 2017, the Outstanding Associate Editor of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION in 2016, the NATO SET Panel Excellence Award in 2016, the Finmeccanica Group Innovation Prize in 2014, the Finmeccanica Corporate Innovation Prize in 2014, the IET Best Poster Paper Award (Metamaterials 2013 and Metamaterials 2011), and the Raj Mittra Travel Grant Senior Researcher Award in 2007. He has been serving the scientific community, by playing leading roles in the management of scientific societies, in the editorial board of international journals, and in the organization of conferences and courses. In particular, he was a Founding Member of the Virtual Institute for Artificial Electromagnetic Materials and Metamaterials—METAMORPHOSE VI in 2007. He was elected as a member of the Board of Directors of the Same society for two terms from 2007 to 2013 and as the President for two terms from 2013 to 2019. He currently serves the METAMORPHOSE VI as the Vice President and the Executive Director (since 2019). He served as an Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION from 2013 to 2017 and the *Metamaterials* from 2007 to 2013 and as a member of the Editorial Board of the *International Journal on RF and Microwave Computer-Aided Engineering* from 2009 to 2015, *Nature Scientific Reports* from 2013 to 2016, and *EPJ Applied Metamaterials* (since 2013). He was also the Guest Editor of five special issues in international journals. He hosted in 2007 the inaugural edition of the International Congress on Advanced Electromagnetic Materials in Microwaves and Optics—Metamaterials Congress, served as the Chair of the Steering Committee of the same conference for eight editions (2008–2014, and 2019), and was elected as the General Chair of the Metamaterials Congress for the period from 2015 to 2018. He was also the General Chair of the Second International Workshop on Metamaterials-by-Design Theory, Methods, and Applications to Communications and Sensing in 2016 and has been serving as the Chair or a member of the technical program, steering, and organizing committee of the main national and international conferences in the field of applied electromagnetics.