Time-varying metamaterials and metasurfaces for antennas and propagation applications

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Abstract. In this contribution we present the most recent results from our group about the opportunities offered by time-varying metamaterials and metasurfaces for conceiving antenna systems and devices exhibiting artificial non-reciprocity, frequency conversion, energy accumulation and temporal electromagnetic scattering. Such artificial metastructures are characterized by constitutive parameters (permittivity, permeability and/or surface impedance) that are modulated in time through an external control or requires modulated excitation signal for enabling anomalous scattering behaviour. Here, we briefly describe the physical insights of the unusual interaction arising between the electromagnetic field and such metamaterials and metasurfaces, and then we present some antennas and propagation applications, showing the performances of non-reciprocal antenna systems, magnet-less isolators, Doppler cloaks, temporal devices and metasurface-based virtual absorbers.

1. Introduction

Thanks to the advent of metamaterials and metasurfaces, the RF/microwave antennas and components have been redesigned to fully exploit the new opportunities offered by them in controlling almost at will the scattering [1–3], wavefronts [4], and frequency response [5–7] from such engineerable artificial structures. However, in the last few years a new degree of freedom has been exploited for increasing the possibilities offered by metamaterials and metasurfaces in the design of novel microwave/RF antenna systems and devices: the temporal modulation of the material and surface properties [8]. In this contribution, we review the most recent antenna systems and components proposed by our group based on time-varying metastructures. Here, we focus our attention on four classes of systems and devices: magnet-less non-reciprocal antenna systems [9–11], the Doppler cloaks [12–14], the temporal devices [9,19], and, finally, the metasurface-based virtual electromagnetic absorbers [20–22].

2. Time-varying metamaterials and metasurfaces applications

2.1. Non-reciprocal antennas and components

Electromagnetic reciprocity is one of the fundamental properties of any passive and linear electromagnetic system that forces the response in transmission to be always identical to the one in reception. However, it represents a strong limit in case an isolation between transmitter and receiver is needed. In Fig. 1a and Fig. 1e, we report two different strategies for achieving magnet-less non-reciprocal antenna systems based on space-time modulated metamaterials.
Figure 1. Devices based on space-time and time-varying metamaterials and metasurfaces: (a) non-reciprocal horn antenna with angular-momentum biased filtering inclusion [15,16]; (b) Doppler cloak realized through space-time modulated metamaterial [12]; (c) Time-varying reflective metasurface for frequency conversion and doppler cloaking [13,17]; (d) metasurface-based electromagnetic isolator [18]; (e) space-time modulated covers for antenna non-reciprocity [11]; (f) time-domain components achieved with temporal slabs and multilayered structures [9,19]; (g) metasurface-based virtual absorbers excited by complex frequencies [20–22].

The first one (Fig. 1a) is based on a filtering particle to be placed in the throat of a conventional horn antenna, whose filling material is modulated in both space and time for inducing an artificial Zeeman effect. The opposite propagating circular-polarized fields with the same handedness experience different transmission levels due to the particle modulation. The second one (Fig. 1e) is based on space-time modulated covers to be placed around the antenna. According to the modulation scheme of the material properties of cover, it can induce a frequency conversion for the received (transmitted) signals, while the transmitted (receiving) signals are let passing unaltered, realizing a non-reciprocal antenna system. Finally, in Fig. 1d we report an electromagnetic isolator based on time-varying metasurfaces with opposite frequency modulation capabilities. The two metasurfaces are located at the opposite side of a conventional and passive reciprocal filtering structure, realizing a local Doppler shifting in the volume where the filtering structure is located. This simply realizes an asymmetric transmission when illuminated from opposite sides.

2.2. Frequency conversion and Doppler cloaking

A space-time modulated metamaterial is an artificial material whose permittivity and/or permeability are modulated over space and time, realizing a propagating medium wave within the metamaterial. As shown in Fig. 1b, during the propagation of the electromagnetic wave within such a metamaterial, a frequency and wavevector shift is always induced and, according to the propagation direction of both electromagnetic and medium waves, the excitation of new modes can take place or not. This allowed to engineer the material properties to induces a desired frequency and wavevector shift such that the final modes emerging from the material can compensate the actual Doppler shifting.
induced by the motion. This allowed to design the first Doppler cloaking device based on space-time modulated metamaterial. More recently, a more compact version based on time-modulated metasurfaces has been designed (Fig. 1c). It exploits the temporal modulation of the reflection coefficient by exploiting the properties of a high-impedance surface modulated by a set of varactors. They shift periodically the resonant frequency of the high-impedance surfaces before and after its operative frequency, inducing an apparent Doppler shift for the reflected wave.

2.3. Temporal devices

Matching networks, Fabry-Perot resonators and multilayered electromagnetic devices exploits the scattering from their interfaces and the propagation delay within the materials for tailoring the overall scattering response in transmission and reflection. Temporal devices have been recently conceived by using the temporal dimension instead of the spatial one. The temporal device consists of a cascade of abrupt switching of the material properties where the wave is propagating, as shown in Fig. 1f. The material properties and timing of the switching must be properly selected to achieve the desired overall scattering response from the device, in full analogy with the spatial counterparts. In Fig. 1f, the transmission and reflection coefficient as a function of the temporal thickness of a temporal slab are reported showing that is possible to design temporal Fabry-Perot cavities and matching layers. Multilayered structures benefit of an higher number of degree of freedoms for the synthesis of more complex responses and devices.

2.4. Metasurface-based virtual absorbers

Finally, we present the design of metasurface-based virtual absorbers, which consist of a partially open cavity bounded by a metasurface and a metallic reflector. Such kind of structure always exhibits a reflection when illuminated by a monochromatic uniform plane wave, that can be interpreted through the strong mismatched between the equivalent reactive input impedance exhibited at the metasurface location and the real wave impedance of the free space where the wave is propagating. However, the system may exhibit zero-reflection when it is illuminated by a time-modulated plane wave with a specific complex frequency. As long as the excitation is applied, the system does not transmit or reflect, but store the electromagnetic energy within its cavity volume, realizing a virtual absorption effect, as shown in Fig. 1g. Such a concept has been applied also to microwave circuits, showing not only that it is possible to achieve perfect virtual matching for reactive loads fed by lossless transmission lines, but we have derived the operative bounds for such a system for a given metasurface reactance and electrical dimension of the cavity.

Conclusions

To conclude, this contribution focused its attention on the most recent results from our group about the opportunities offered by time-varying metamaterials and metasurfaces for conceiving antenna systems and devices. In particular, we have presented some applications of time-varying metamaterials, showing how it is possible to design non-reciprocal antenna systems, magnet-less isolators, Doppler cloaks, temporal devices and virtual absorbers.

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References

[1] Alù A 2009 Mantle cloak: Invisibility induced by a surface Phys. Rev. B 80 245115
[2] Ramaccia D, Arcieri S, Toscano A and Bilotti F 2017 Core-Shell Super-Spherical Nanoparticles for LSPR-Based Sensing Platforms IEEE J. Sel. Top. Quantum Electron. 23 380–
[3] Ramaccia D, Toscano A and Bilotti F 2017 Scattering and absorption from super-spherical nanoparticles: analysis and design for transparent displays [Invited] J. Opt. Soc. Am. B 34 D62

[4] Epstein A and Eleftheriades G V. 2016 Huygens’ metasurfaces via the equivalence principle: design and applications J. Opt. Soc. Am. B 33 A31

[5] Ramaccia D, Di Palma L, Ates D, Ozbay E, Toscano A and Bilotti F 2014 Analytical Model of Connected Bi-Omega: Robust Particle for the Selective Power Transmission Through Sub-Wavelength Apertures IEEE Trans. Antennas Propag. 62 2093–101

[6] Ramaccia D, Bilotti F, Toscano A and Vegni L 2013 Dielectric-free multi-band frequency selective surface for antenna applications COMPEL - Int. J. Comput. Math. Electr. Electron. Eng. 32 1868–75

[7] Ramaccia D, Toscano A, Colasante A, Bellaveglia G and lo Forti R 2011 Inductive tri-band double element FSS for space applications Prog. Electromagn. Res. C 18 87–101

[8] Engheta N, Kiasat Y, Mencagli M J, Nahvi E and Edwards B 2019 4D Metastructures: Merging Spatial and Temporal Metamaterials 2019 13th International Congress on Artificial Materials for Novel Wave Phenomena, METAMATERIALS 2019 pp 76–7

[9] Ramaccia D, Toscano A and Bilotti F 2020 Light propagation through metamaterial temporal slabs: Reflection, refraction, and special cases Opt. Lett. 45

[10] Ramaccia D, Sounas D L, Alù A, Bilotti F and Toscano A 2015 Nonreciprocal Horn Antennas Using Angular Momentum-Biased Metamaterial Inclusions IEEE Trans. Antennas Propag. 63 5593–600

[11] Ramaccia D, Sounas D L D L, Alu A, Bilotti F and Toscano A 2018 Nonreciprocity in antenna radiation induced by space-time varying metamaterial cloaks IEEE Antennas Wirel. Propag. Lett. 17 1968–72

[12] Ramaccia D, Sounas D L, Alù A, Toscano A and Bilotti F 2017 Doppler cloak restores invisibility to objects in relativistic motion Phys. Rev. B 95 075113

[13] Ramaccia D, Sounas D L, Alu A, Toscano A and Bilotti F 2020 Phase-Induced Frequency Conversion and Doppler Effect with Time-Modulated Metasurfaces IEEE Trans. Antennas Propag. 68 1607–17

[14] Ramaccia D, Sounas D., Alu A, Toscano A and Bilotti F 2017 Spatio-temporal modulated Doppler cloak for antenna matching at relativistic velocity 2017 11th International Congress on Engineered Materials Platforms for Novel Wave Phenomena (Metamaterials) (IEEE) pp 277–9

[15] Ramaccia D, Sounas D L, Alù A, Bilotti F and Toscano A 2015 Nonreciprocal Horn Antennas Using Angular Momentum-Biased Metamaterial Inclusions IEEE Trans. Antennas Propag. 63

[16] Ramaccia D, Bilotti F and Toscano A 2014 Angular Momentum-biased metamaterials for filtering waveguide components and antennas with non-reciprocal behavior 2014 8th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (IEEE) pp 250–2

[17] Ramaccia D, Sounas D L, Alu A, Toscano A and Bilotti F 2018 Metasurface-based Doppler cloaks: Time-varying metasurface profile to achieve perfect frequency mixing 2018 12th International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials) (IEEE) pp 331–3

[18] Ramaccia D, Sounas D L, Marini A, Toscano A and Bilotti F 2020 Electromagnetic Isolation Induced by Time-Varying Metasurfaces: Non-Reciprocal Bragg Grating IEEE Antennas Wirel. Propag. Lett. 1–1

[19] Ramaccia D, Alù A, Toscano A and Bilotti F 2021 Temporal multilayer structures for designing higher-order transfer functions using time-varying metamaterials Appl. Phys. Lett. 118 101901

[20] Marini A V, Ramaccia D, Toscano A and Bilotti F 2020 Metasurface-bounded open cavities supporting virtual absorption: free-space energy accumulation in lossless systems Opt. Lett. 45 3147–50
[21] Marini A V, Ramaccia D, Toscano A and Bilotti F 2021 Metasurface virtual absorbers: Unveiling operative conditions through equivalent lumped circuit model *EPJ Appl. Metamaterials* 8

[22] Marini A, Ramaccia D, Toscano A and Bilotti F 2020 Perfect matching of reactive-loaded transmission lines through complex excitation *14th European Conference on Antennas and Propagation, EuCAP 2020* (Institute of Electrical and Electronics Engineers Inc.)