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Functionalized Metasurfaces enabling Frequency and Radiation Pattern Reconfigurability for Intelligent Antennas

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Abstract

In the next generation of wireless communications, the antenna systems are expected to undergo continuous and fast variations of the communication links characteristics. Due to the extreme performance requirements, conventional radiators with fixed properties and functionalities cannot represent a reliable solution. A new paradigm change in antenna design where the radiator characteristics are made reconfigurable at the physical layer is thus required. Here, we show how conformal metasurfaces wrapped around conventional wired antennas enable unprecedented electromagnetic behaviors, for achieving frequency, scattering, and pattern tunability, in view of the designs of intelligent antennas whose properties can be shaped on demand depending on the characteristics of the functionalized coating metasurface.

1. Introduction

The 5G and beyond-5G communications are facing several new challenges, such as massive capacity requirements, ultra-high reliability, and almost-zero latency [1],[2]. These issues cannot be easily addressed through the virtualization of the functions at the software level, as is currently done in telecommunication technology based on MIMO systems, software-designed networks, or network virtualized functions. Indeed, the hardware virtualization would require a giant increase in the number of access points and, more importantly, a massive improvement of the computational resources and elaboration time.

In this frame, metasurfaces [3] can be a key enabling technology, thanks to the possibility of adjusting the characteristics of the electromagnetic (EM) field and improving the performances of EM components and devices at the physical level. Recently, reconfigurable, tunable, programmable, and time-modulated metasurfaces have shown the unprecedented possibility of controlling the wireless electromagnetic environment, making it actively contributing to the communication system and allowing for the conception of a "smart" EM environment [4]. Still, in these systems, communication is enabled by conventional radiating devices with fixed functionalities. Although "smartness" in the antenna system has been introduced in the last decades by means of advanced signal processing, antennas with fixed characteristics are still mainly used [5]. 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.

Here, we discuss the new possibility enabled by metasurfaces wrapped around conventional antennas, such as dipoles and monopoles, in shaping their electrical and radiation characteristics. These new degrees of freedom in antenna design are an essential feature for conceiving radiating devices whose properties can be configured on-demand, enabling "intelligence" in antennas at the hardware level [6].

Indeed, recently, conformal cylindrical metasurfaces wrapped around wire antennas have become a new powerful tool for tailoring their scattering characteristics, making them invisible at specific frequencies [7]. A simple sketch of a typical cloaking metasurface is reported in Figure 1 (a). The metasurface usually consists of a patterned metallic sheet wounding the antenna, characterized by a homogeneous scalar surface impedance value Z_s. The cloaking functionality is enabled for specific values of Z_s and the ratio between the metasurface and cylinder radius $a_c/a = \gamma$, for which the surface current scatter with the same amplitude but opposite phase compared to the field scattered by the antenna. Hence, the so-called scattering cancellation principle is exploited [7],[8].

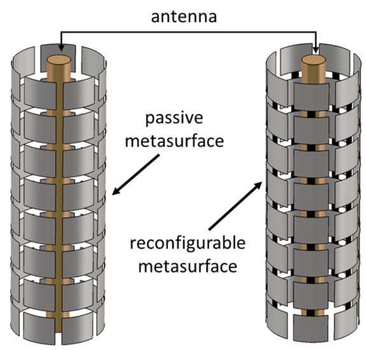

Figure 1. Fig. 1. Sketch of passive metasurface and loaded with electronic elements typically used for cloaking applications in wire antenna systems.

Thanks to the ease of fabrication, many interesting applications exploiting these cloaking devices have been developed in antenna scenarios, ranging from antenna co-siting for terrestrial [9]-[10] and satellite applications [11],[12], to the design of compact array systems [13],[14]. More recently, it has been shown that the cloaking functionalities can be even more enriched by loading the metasurface with electronic elements, making the antenna power-dependent [15], or allowing for sensing array systems [16], or antennas whose visibility level depends on the frequency- and temporal-characteristics of the incoming signal [17].

This newly explored field of coating metasurface loaded with electronic elements allows conceiving antenna systems whose properties can be adapted employing a functionalized coating metasurface, as sketched in Figure 1 (b), in view of applications in next-generation communications. Indeed, the coating metasurface is expected to be able to modify not only the antenna scattering characteristics but also its electrical and radiation properties. In this frame, we report our recent findings in the development of coating metasurfaces for achieving antenna frequency and radiation pattern reconfigurability, further expanding the potentialities for antenna designers.

2. Frequency Reconfigurability Through Coating Metasurfaces

In this section, we focus on the possibility of reconfiguring the resonant frequency of a dipole antenna by tuning the EM characteristics of a wrapping metasurface coat. The scenario under consideration is reported in Figure 2 (a). A conventional half-wavelength dipole antenna is wounded by an isotropic metasurface sheet. The metasurface is assumed lossless so that the Z_s reduce to jX_s. The antenna is designed to work at t he resonant frequency f_0 when loaded to a conventional 50 Ω source.

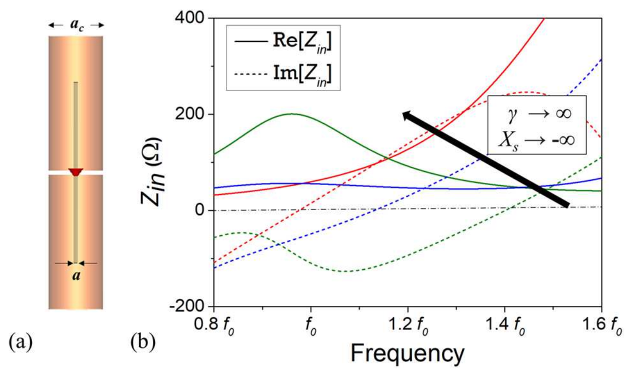

Figure 2. (a) Sketch of a dipole antenna wrapped by a cylindrical metasurface. (b) Complex antenna input impedance for different values of the ratio between the metasurface and antenna radius (γ), and of the surface reactance (X_s).

Thanks to the possibility of tailoring the secondary current induced onto the antenna and generated by part of the waves radiated back, the antenna resonance can be properly modified. Indeed, as shown in Figure 2, the complex input impedance of the antenna can be engineered by a proper combination of the X_s and γ. In particular, in the uncoated antenna scenario (*red lines*), the conventional behavior of a dipole antenna where the imaginary part of the impedance is zero at f_0 whilst the real part reaches the standard 75 Ω can be recognized. In the wounded antenna case, instead, for large values of the metasurface radius (*i.e.*, $\gamma \to \infty$) and for low capacitive values of X_s, (*i.e.*, $X_s \to -\infty$), the zero value of the imaginary part is shifted towards higher frequencies. Remarkably, the real part is also flattened towards the load value. Hence, the antenna input impedance can be tailored accordingly to the values of the X_s and the metasurface radius. Indeed, when reducing γ and increasing the X_s (*green lines*), the zero value of the imaginary part is shifted towards higher frequencies and, still, the real part assumes a value around 50 Ω.

Therefore, dipole antenna resonant frequency can be tuned accordingly without changing the antenna length. In Figure 3 is reported the behavior of the antenna reflection coefficient (Γ). It can observe that, as expected, the antenna resonance can be shifted in a broad frequency range thanks to the possibility of tuning both the imaginary and real part of the input impedance.

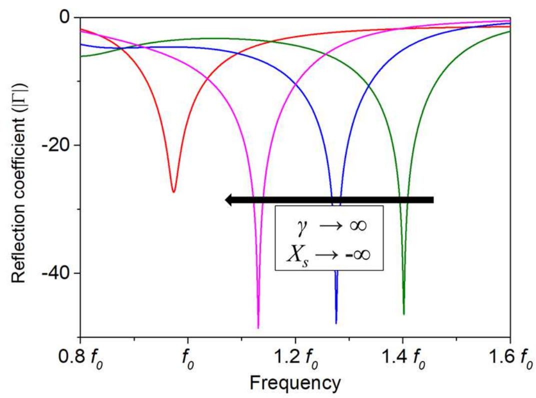

Figure 3. Magnitude of the reflection coefficient at the antenna input port *w/* and *w/o* the covering coat for different values of the metasurface radius and surface reactance.

This peculiar covering metasurface functionality allows for dynamic control of the antenna resonance once the coating metasurface is made reconfigurable through the use of varactor diodes. In Figure 4 (a), a realistic design of the setup is shown. The coating structure is made of a three-layer metasurface implemented through metallic rings able to synthesize a capacitive value of the X_s . The gaps of the rings are loaded by the varactor diodes, where the varactors on the same layer are characterized by the same equivalent capacitance (C_A, C_B, C_C, from inner to outer), making the metasurface still homogeneous. As shown in Figure 4 (b), by judiciously adjusting the varactors' equivalent capacitance the antenna resonance can be tuned, within a 50% fractional bandwidth when considering a commercial varactors model [18]. It is worth noting that the distinct resonances cover adjacent bandwidth of operations, allowing for the use of the system, particularly in cognitive and sensitive radio scenarios. Finally, it is worth remarking that the antenna exhibits a stable omnidirectional pattern at all the frequencies of operations [18].

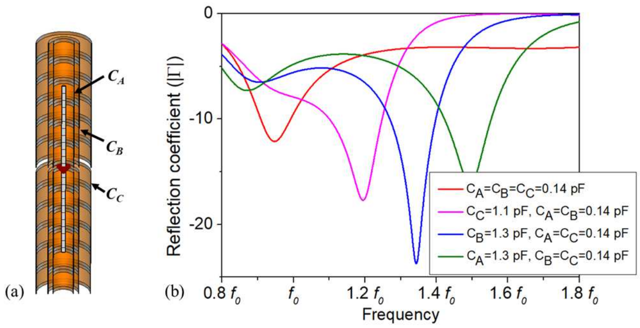

Figure 4. (a) Sketch of the dipole antenna coated by the realistic multi-layered metasurface enabling frequency reconfigurability (b) Magnitude of the antenna reflection coefficient for different values of the junction capacitance of the varactors loading the metasurface layers.

3. Radiation Pattern Reconfigurability Through Coating Metasurfaces

In this section, we report some preliminary results showing the possibilities enabled by coating metasurfaces for shaping the antenna radiation pattern.

The scenario under consideration is still the one reported in Figure 2 (a). However, in this case, the metasurface is assumed inhomogeneous, *i.e.,* with a gradient distribution of the amplitude and phase profile across its surface [19]. Here, the wrapping metasurface is used to properly tailor the phase profile of the field radiated by the dipole antenna. Since the antenna exhibits an omnidirectional pattern on the H-plane, the phase of the radiated field is almost constant along the metasurface cylindrical profile. Indeed, the phase insertion of the coating metasurface can be functionalized to compensate for the cylindrical phase profile and having the antenna radiating towards a specific direction, making it directive.

The metasurface is implemented through Huygens meta-cells guaranteeing the unitary value of the transmission coefficient and introducing the desired phase insertion [20]. In particular, a sketch of the setup is reported in Figure 5. The dipole antenna is surrounded by a gradient-index metasurface divided into four equal sectors, with the same phase insertion distribution. The metasurface is inhomogeneous and implemented through three-layered Huygens cells, as shown in the inset of Figure 5. The cells consist of three ideal impedance sheets characterized by a purely reactive behavior and separated by three identical dielectric layers. The metasurface is also anisotropic since the cells exhibit the same characteristics along the vertical axis. The phase insertion profile is thus introduced just on the antenna H-plane.

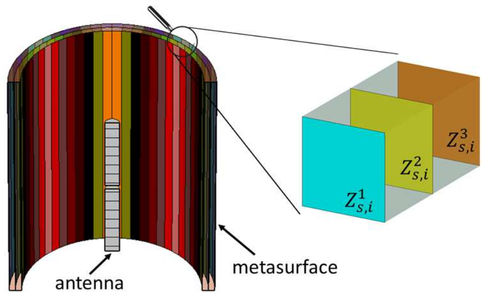

Figure 5. Sectional view of a dipole antenna coated by a cylindrical metasurface enabling radiation pattern shaping. The gradient-index metasurface is implemented through three-layered Huygens cells, as shown in the inset.

In Figure 6, the gain polar plots on the H-plane of the bare dipole antenna and once surrounded by the functionalized gradient-index metasurface are reported. The results have been evaluated through full-wave numerical simulations. As can be appreciated, thanks to the proper phase insertion introduced by the coating metasurface, four different beams can be identified. It is worth noticing that the number of directive beams depends on the number of sectors identified during the gradient-index metasurface design.

We also emphasize that this new design possibility allows the conception of a wire antenna whose radiation pattern can be made selective on-demand through the use of a reconfigurable metasurface whose gradient-index phase profile is made tunable.

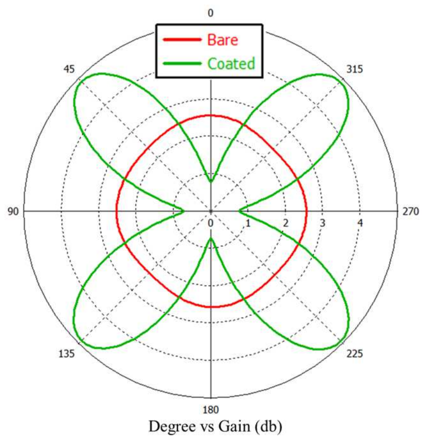

Figure 6. Polar radiation diagram of the gain on the antenna H-plane for the scenarios of the bare dipole, and coated by the cylindrical gradient-index metasurface.

4. Conclusions

In this contribution, we have discussed new possibilities enabled by metasurfaces covering wire antennas. Based on our previous experience in designing cloaking metasurfaces for dipoles/monopoles, we have explored the opportunity to expand the metasurface functionality for introducing frequency and pattern reconfigurability. We have briefly discussed the working principles for achieving such peculiar functionalities, and then some preliminary configurations have been reported in view of the possibility to make the systems reconfigurable by means of tunable metasurfaces. These findings confirm the suitability of covering metasurfaces as a promising solution for implementing antennas made frequency, scattering, and polarization reconfigurable, in view of intelligent antenna systems for next-generation telecommunications.

More details about the designed antennas working principle, the implementation of the metasurface coats, and of the further covering metasurface applications will be discussed at the Conference.

5. Acknowledgements

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