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Multi-layered Metasurfaces Enabling Frequency Reconfigurability in Wire Antennas

S. Vellucci* (1), D. De Sibi (1), A. Monti (2), M. Barbuto (2), A. Toscano (1), and F. Bilotti (1)
(1) ROMA TRE University, Department of Engineering, Via Vito Volterra 62, 00146, Rome, Italy
(2) Niccolò Cusano University, Via Don Carlo Gnocchi 3, 00166, Rome, Italy

Abstract

A new approach for designing frequency reconfigurable wire antennas is proposed. In particular, it is shown that the antenna input impedance and reflection coefficient can be tuned by properly engineering the radius and the surface impedance of a coating metasurface. This mechanism is exploited to design a reconfigurable dipole antenna coated by multi-layered metasurfaces loaded with varactor diodes. By tuning the capacitance of the varactors, the operative frequency band of the antenna can be dynamically and continuously shifted within a broad range of frequencies, while still preserving a stable omnidirectional radiation pattern and not perturbing the antenna gain.

1 Introduction

In the last decade, several different coating metasurfaces have been proposed to modify the scattering characteristics of wired antennas [1]. Thanks to the possibility of describing the scattering problem from a coated elongated object trough a rigorous analytical model [2],[3] and the formulation of the mantle cloaking approach [4], several fascinating devices based on dipole, monopole, or strip antennas coated by ultrathin metasurfaces have been designed, providing an unprecedented degree of freedom to the antenna designer.

For instance, conformal metasurface coatings have been proposed and experimentally demonstrated to allow for the reduction of the blockage effects in antennas placed in close proximity [5]-[7]. This intriguing possibility has been exploited for designing highly dense telecommunication systems equipped with a large number of antennas within a limited space [8],[9], to mitigate the problem of interferences in an overcrowded platform for mobile communications [10], or enabling for new co-siting strategies for multiple antennas installed in small nanosatellites [11]. The possibility to reduce the total scattering from an object through the use of conformal metasurfaces allowed to hide structural or passive objects placed nearby of a radiating element, for both terrestrial [12],[13], and satellite applications [14]. More recently, the antenna functionalities have been further expanded through metasurface coats loaded with electronic lumped elements, allowing for the design of antenna systems with different radiating and scattering characteristics depending on the antenna power level [15],[16]. At the same time, the use of lumped-element circuits loaded onto passive metasurfaces has enabled the design of antennas with both frequency- and time-domain selective properties able to selectively hide or show themselves depending on the waveform of the received signal [17].

These antenna applications are mostly based on the idea of engineering the scattering response of the coated antenna while, arguably, there are very few studies aiming at tailor its impedance matching characteristic. In this frame, some effort has been put into exploiting metasurface coat to broader the matching bandwidth of wired antennas [18],[19]. Here, instead, we show an unprecedented feature of coating metasurfaces, *i.e.*, how they can be exploited to tailor the impedance matching characteristic of an antenna and tune its resonant frequency. Moreover, the design of a realistic multi-layered coat equipped with varactor diodes for enabling multi-band reconfigurability of a wire antenna is proposed.

2 Frequency Reconfigurability trough Coating Metasurface

In this section, we show that a coating metasurface can be used not only to tailor the scattering response of an antenna but also to modify its input impedance in a quite broad frequency range. Let's consider a dipole antenna working at f_0 = 1 GHz ($a = \lambda_0/100$, $l_a = \lambda_0/2.27$) coated by an ideal metasurface ($a_c = \gamma a$) characterized by a surface reactance X_s (Figure 1 insets). As well known, without the coating metasurface, the real part of the complex antenna input impedance reaches at f_0 the standard 50 Ω value, while its imaginary part is almost zero. However, as shown in Figure 1, as the radius of the coat is progressively reduced (*i.e.*, $\gamma \rightarrow 1$) and the metasurface response is made more capacitive, the zero value of the imaginary part of the input impedance is gradually shifted towards higher frequency. At the same time, its real part is flattened in a broad frequency range around 50 Ω.

Accordingly, the antenna resonance moves towards higher frequencies for $\gamma \rightarrow 1$ and for a strong capacitive value of the surface reactance, whilst large values of γ and a strongly inductive metasurface slightly perturb the original antenna resonance, which approaches f_0 (Figure 2). This is due to the metasurface layer, which reflects part of the field radiated back to the antenna, inducing a secondary current. Depending on the values of X_s and γ, the interference between the flowing currents can be engineered to tune the antenna input impedance and, thus, its resonance frequency. Remarkably, the possibility to tune both the imaginary and real parts without changing the length of the dipole is a major advantage compared to conventional matching techniques. The coating metasurface, thus, behaves as a complex matching transmission-line network that can be designed by acting on its surface impedance and/or its diameter. This unusual functionality allows, in principle, to reconfigure the antenna resonant frequency within a quite broad frequency range just acting on the metasurface characteristics. Although the metasurface surface reactance can be easily controlled by an electric tuning mechanism, modifying its radius would possibly require a mechanical system. However, in the next section, we show how to avoid the latter limitation, by replacing the single-layer metasurface with a multi-layered structure.

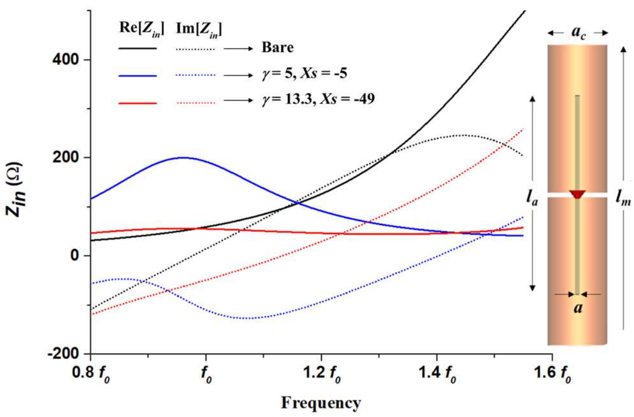

Figure 1. Complex input impedance of the metasurface coated antenna as a function of the metasurface parameters $\gamma = a_c/a$ and X_s [Ω/sq]. In the insets, design of the metasurface coated antenna.

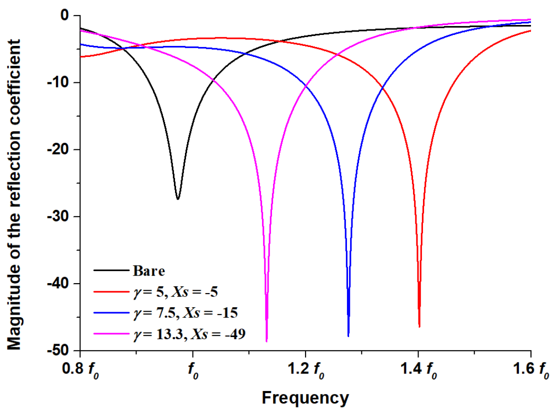

Figure 2. Magnitude of the reflection coefficient of the metasurface coated antenna in Figure 1, as a function of the metasurface parameters $\gamma = a_c/a$ and X_s [Ω/sq].

3 Design of a Multi-band Reconfigurable Antenna

A possible solution, exploiting the approach discussed in the previous section, for designing a multi-band reconfigurable wire antenna whose characteristics are tuned employing tunable multi-layered coating metasurface is reported in Figure 3. The radiating device consists of a dipole antenna resonating at f_0, coated by a three-layer metasurface (from inner to outer $a_A = \gamma_A a$, $a_B = \gamma_B a$, $a_C = \gamma_C a$, with $\gamma_A = 5$, $\gamma_B = 7.5$, and $\gamma_C = 13.3$). The metasurfaces are engineered to return a large capacitive value of the surface reactance [20] and are implemented trough conformal metallic rings ($g = \lambda_0/26$ and $w = \lambda_0/60$) printed on a thin dielectric substrate ($t = 0.0004\lambda_0$, $\varepsilon_r = 2.9$, $\tan\delta = 0.0025$).

To equip the system with reconfiguration capabilities, the metallic rings have been loaded with four varactor diodes (GC15006 *Microsemi*) for each of the three metasurface layers (C_A, C_B, C_C). The equivalent circuit schematic of the metasurface unit-cell is depicted in Figure 3 (b), where C_{MTS} is the equivalent capacitance of the metasurface unit-cell, Cj is the varactor variable junction capacitance (Cj = 0.14-2 pF), $R_s = 2.65$ Ω is its series resistance, and $L_{pkg} = 0.4$ *nH*, and $C_{pkg} = 0.08$ *pF* are the parasitic package reactances. Thus, increasing the value of the C_j allows reducing the value of the metasurface surface reactance, offering the opportunity to dynamically tune the coated antenna resonance. In particular, distinct resonances appear depending on the different combinations of C_A, C_B, C_C, as shown in Figure 4.

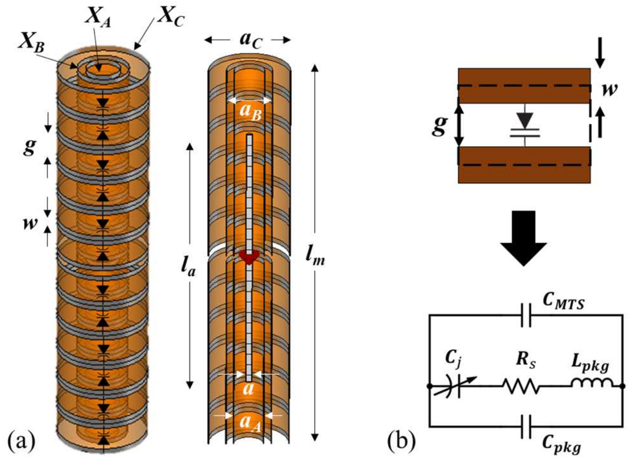

Figure 3. (a) Design of the multi-layered metasurface coated dipole antenna when the metasurfaces gaps are loaded trough varactors diodes. (b) Equivalent circuit schematic of the metasurfaces unit-cells.

The fundamental resonance of the dipole antenna at f_0 is excited when all the loaded varactors exhibit the lowest possible value for C_j (*i.e.*, from the varactor datasheet $C_A = C_B = C_C = 0.14$ pF) and the metasurfaces exhibit a large surface impedance that, from an equivalent transmission-line point of view, appears in parallel to the antenna input impedance. Therefore, the metasurfaces behave almost as transparent layers and do not affect the antenna reflection coefficient at the input port. As demonstrated in the previous section, the metasurface coupling effect comes

into place just for a specific value of the X_s. Therefore, for a precise value of C_j.
In particular, the antenna resonance f is shifted to $f = 1.2f_0$ when the outer metasurface layer is effective (*i.e.*, for C_C = 1.1 pF) while the middle and inner layers appear transparent (*i.e.*, $C_A = C_B$ = 0.14 pF). When the middle layer couples with the radiated field and the other layers are transparent (*i.e.*, C_B = 1.3 pF and $C_A = C_C$ = 0.14 pF), the antenna resonance f further moves toward higher frequency ($f = 1.35f_0$) and, finally, the higher possible resonant frequency $f = 1.5f_0$ is achieved coupling the inner layer (*i.e.*, C_A = 1.3 pF and $C_B = C_C$ = 0.14 pF).

It is worth mentioning that the four distinct resonances exhibited by the device cover adjacent frequency bands, which is a particularly desired feature in cognitive radio systems. More importantly, the antenna gain is not deteriorated by the presence of the coating structure on the E- plane, as shown in Figure 5.

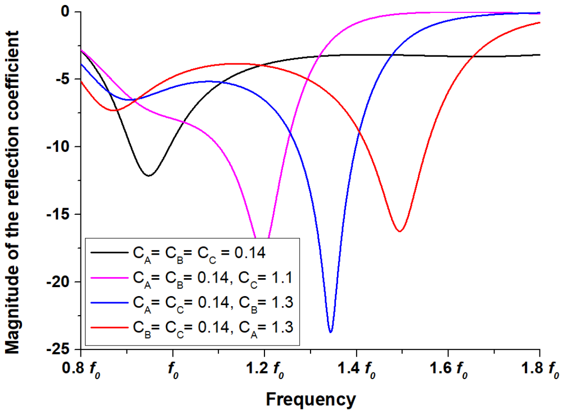

Figure 4. Magnitude of the reflection coefficient of the multi-layered metasurfaces coated dipole antenna in Figure 3, for different combinations of the varactors junction capacitances C_A, C_B, C_C [pF].

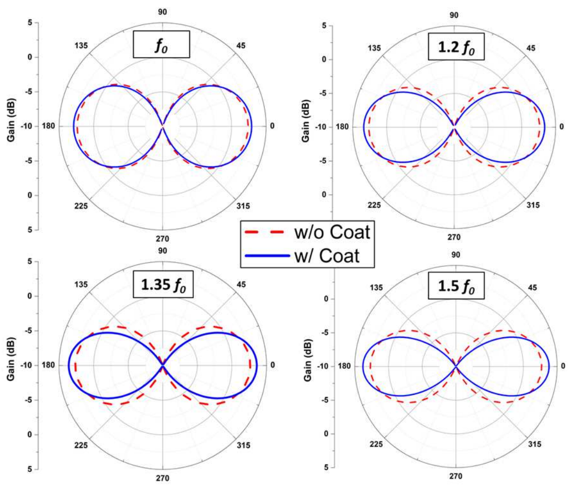

Figure 5. Gain plots on the E- plane of the uncoted dipole antenna and when coated by the varactor-loaded multi-layered metasurface, evaluated at the four different resonant frequencies.

4 Conclusions

The design of a multi-band frequency reconfigurable dipole antenna coated by multi-layered metasurfaces loaded by varactor diodes has been proposed. The surface impedance values of the multi-layered metasurfaces are tuned by the varactors in order to engineer the surface currents induced by the reflected waves and modifying the antenna input impedance accordingly. Indeed, this intriguing impedance matching mechanism allows to tailor both the real and imaginary parts of the antenna input impedance and, thus, may represent an efficient alternative to the conventional matching network, without requiring large values of the reactive ad resistive loadings.

Further details and comments will be discussed at the conference.

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