Advanced Cloaking Metasurfaces for Wire Antennas

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Abstract

We provide a review of our results on the design of mantle cloaking devices for antenna applications with an emphasis on our recent investigations in designing advanced cloaking metasurfaces. It is shown how such cloaking devices allow increasing the degrees of freedom in the design of conventional antennas with a significant enhancement of their functionalities. Several examples of antennas whose conventional functionalities are enriched using cloaking metasurfaces loaded with electronic circuits are reported, and the most significant applications in view of a new generation of intelligent antennas are discussed.

1 Introduction

In the mantle cloaking approach [1], an object can be hidden by covering it with one or more thin metasurfaces able to cancel out the dominant terms in the multipole expansion of its scattered field. Invisibility is thus achieved when the electromagnetic fields scattered by the cloak and by the object are equal in magnitude and out-of-phase. Since a mantle cloak allows to not isolate the concealed volume from the surrounding environment [2], and the coating metasurfaces are usually thin and conformal, the mantle cloaking technique is particularly suited for sensing and antenna applications [3].

In the last decade, several mantle cloaking devices have been designed for different antenna scenarios. For instance, cloaking metasurfaces have been used to hide structural or passive objects placed nearby of a radiating element [4], to increase the absorption efficiency of wired antennas [5], or to design compact radiating systems where the antennas are placed at extremely small electrical distances [6]-[8].

Interestingly, in these applications, passive and linear cloaking structures have been used. However, recently, the functionalities enabled by mantle cloaking devices have been further enhanced breaking the linear assumption by loading the cloaking metasurfaces with electronic lumped elements/circuits.

Here, we propose a short survey on our recent research results on the design of cloaking metasurface for antenna applications with a particular focus on advanced devices obtained when loading the cloaking metasurface with electronic elements.

2 Linear Cloaking Metasurfaces

Linear cloaking metasurfaces are usually made of thin metallic patterns printed on dielectric support [9] and, thus, offer inherent advantages in terms of feasibility and flexibility of the cloak design when dealing with an elongated object. In this frame, one of the more common cloaking strategies for antenna systems is based on the use of a coating device placed around an object obstructing a radiating element. In [4], the scenario of an array of metallic roads placed in front of a pyramidal horn antenna at the order of a fraction of the operative wavelength was analyzed, and it was shown that mantle cloaks were able to massively suppress the blockage and to restore the original antenna performances. Indeed, the designed mantle cloak was engineered to cloak the roads for both the TM and TE polarization, enabling a dual-polarization cloaking functionality.

Mantle cloaking has also enabled unprecedented possibilities in nano-satellite scenarios [10],[11]. Here, in fact, the interfering effects arising between the telecommunication system and the payload on board may represent a major challenge due to the limited dimension of the platform. In [10], the case of CubeSat for weather measurement was considered (Figure 1(a)). The nanosatellite was equipped with sensors mounted on metallic booms, perturbing the radiation characteristics of the cross-dipole antenna system once deployed after the launch. The booms introduce strong nulls in the radiation pattern (Figure 1(b)) and, as such, the satellite link-budget becomes strongly dependent from its orientation. However, equipping the metallic booms with properly designed mantle cloaks allows restoring the original almost-isotropic radiation pattern (Figure 1(c)), enabling the nanosatellite functionalities.

Mantle cloaks can be also equipped directly onto an antenna to mutually hide radiating elements placed at small electrical distances. This approach has been exploited to tightly pack together antenna systems operating at different frequencies. For instance, in [6], a compact telecommunication platform made of two monopole antennas for UMTS and LTE mobile communications was designed (Figure 1(d)). This extremely compact design has been enabled by the possibility to conceal the larger LTE antenna at the UMTS frequencies and, thus, allowing the antenna to operate as if it was isolated (Figure 1(f)). This design approach has been experimentally validated in

[6],[7] and extended to non-symmetric radiating devices such as strip antennas in [8].

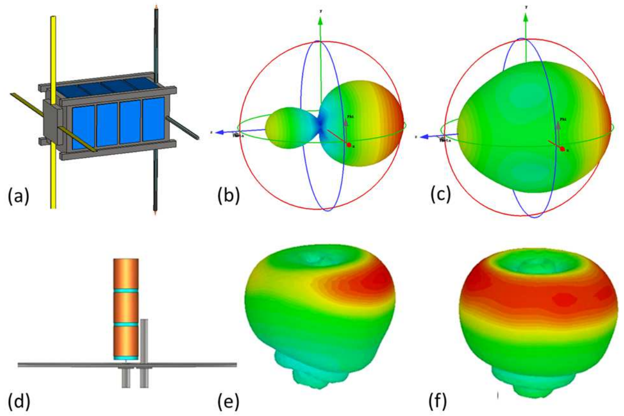

Figure 1. Examples of antenna applications of passive-linear cloaking metasurfaces. (a) CubeSat nanosatellite for weather measurement equipped with cloaked metallic booms and UHF cross-dipole antenna for communication with the radio base station. (b) Cross-dipole antenna radiation pattern in the (b) uncloaked and (c) cloaked booms scenarios. (d) Compact mobile platform made of two monopole antennas for UMTS and LTE communications. (e) UMTS antenna radiation pattern in the (e) uncloaked and (f) cloaked LTE antenna scenarios.

3 Non-linear Cloaking Metasurfaces

Recently, in [12],[13], it has been shown that the cloaking functionalities can be enriched by loading a metasurface with diode pairs. Exploiting the mantle cloaking unit-cells reported in Figure 2 for either designing capacitive or inductive metasurfaces and loading them with non-linear lumped elements, the behavior of the cloak can be made dependent on the impinging power level. Indeed, the ON/OFF switching functionality of the diode pairs allow to dynamically transform the topology of the metasurface unit-cell.

For instance, in the capacitive scenario (Figure 2(a)), for low power levels (LP) the diodes are in the OFF state and the strips of the metasurface are all open-circuited (Figure 2(b)), whilst for high power levels (HP) the diodes are in the ON state and some of the strips of the metasurface are short-circuited, changing the electromagnetic response of the metasurface. Therefore, the metasurface can be designed such that for LP signals the equivalent surface impedance assumes the cloaking value, whilst for HP signals the surface impedance value does not achieve the cloaking condition. The same concept can be applied to inductive cloaking metasurface (Figure 2(d)-(f)).

The operation principle described above has been used in [12] to develop a power-dependent Yagi-Uda antenna whose radiation pattern is tuned by the input power level of the antenna. In particular, by loading the reflector and the director passive element of the device with a power-dependent mantle cloak exploiting the configuration in Figure 2(a), the Yagi-Uda behaves as a directive antenna for HP signals thanks to the de-activation of the cloaking effect. In this case, the director and reflector of the Yagi-Uda are electromagnetically visible and concur to the overall radiation diagram of the antenna. Conversely, for LP signals, the cloaking effect is activated, and the director and the reflector become invisible to the central element which, thus, behaves as a standard dipole.

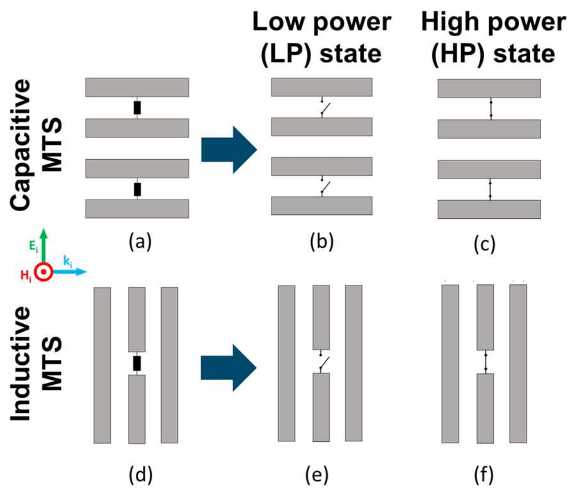

Figure 2. Topology of capacitive (a, b, c) or inductive (d, e, f) non-linear cloaking metasurface unit-cells loaded by diode pairs. (b) Equivalent configurations of the capacitive metasurface for (b) low-power (LP) and (c) high-power (HP) signals. (d) Equivalent configurations of the inductive metasurface for (e) low-power (LP) and (f) high-power (HP) signals.

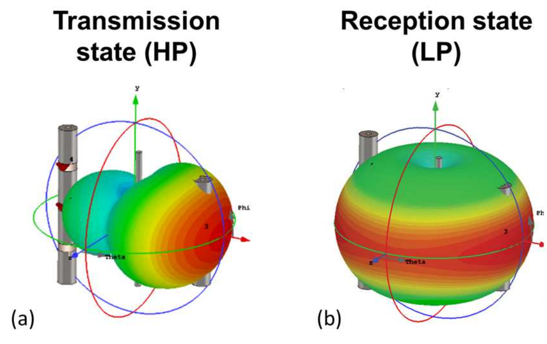

Figure 3. Radiation pattern of a power-dependent Yagi-Uda antenna for HP (a) and LP (b) signals.

A similar design concept can be exploited for conceiving a power-dependent phased array system for detecting applications [13] able to scan selectively the surrounding environment, whilst receiving LP scattered signals from all directions of space. As can be appreciated from Figure 4(b), due to the mutual coupling between neighboring radiators, the embedded element factor of each radiator is usually non-omnidirectional even though the individual radiating element is omnidirectional when operating in free-space. However, this limitation can be circumvented by coating the peripheral elements of the array with non-linear mantle cloaks such that in transmitting mode (*i.e.,* for HP signals) the cloaking effect is turned OFF and the array behaves normally. Conversely, in receiving mode (*i.e.,* for LP), the cloaking effect is turned ON and the peripheral elements of the array are concealed to the central element, whose embedded element factor is, thus, omnidirectional. It is worth noticing that in this case, differently to the Yagi-Uda scenario, the mantle cloaks should be designed to reduce the *in-band* scattering of the radiating elements, making the design of the cloak more sophisticated [13].

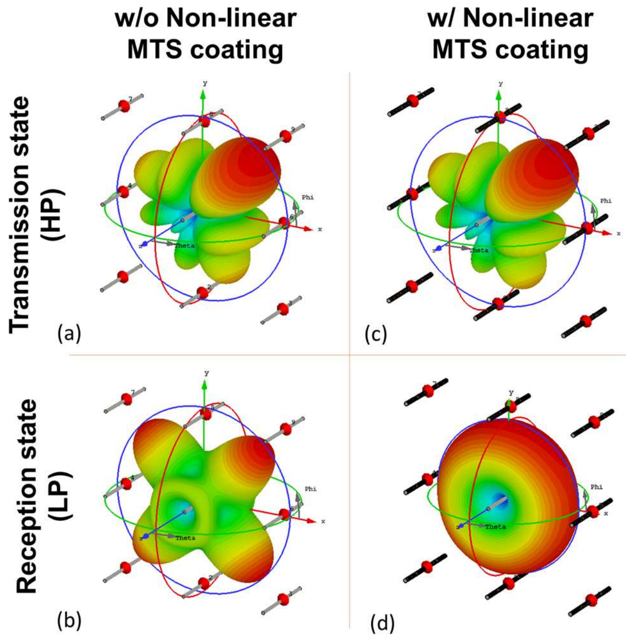

Figure 4. A phased array of dipole antennas excited to focus the main beam in a given direction. (a) Radiation pattern when transmitting HP signals. (b) Embedded central element pattern when receiving LP signals. (c), (d) Same as (a), (b) when the peripheral elements of the array are coated by non-linear cloaking metasurfaces.

4 Waveform Selective Cloaking Metasurfaces

By loading the cloaking metasurface with lumped element circuits, other fascinating antenna applications may be conceived. For instance, in [14], the design of a so-called waveform-selective cloak achieving a different cloaking behavior depending on the temporal waveform of the impinging signal has been discussed (Figure 5).

As demonstrated in [14]-[17], a waveform-selective metasurface can be designed using peculiar lumped-element circuits, exploiting a diode bridge and electronic passive elements like resistors (R), capacitors (C), and inductors (L) (Figure 5 (c)). Here, the diode bridge rectifies the incoming signal at zero frequency and the rectified signal is applied to the RLC elements. In particular, in the case of an RL series circuit as the one depicted in Figure 5(c), the circuit switches from an open-circuit to a short-circuit condition as a function of the waveform of the impinging signal. Due to the loading inductor, for a short-pulsed signal (PW a strong electromotive force appears and opposes the flow of currents in the circuit. The circuit behaves, thus, as a high-impedance bipolar component. Conversely, this opposing effect is weakened after some time and, thus, for a continuous wave (CW), a current can flow in the circuit short-circuiting the input and output ports [16].

By loading this circuit onto a cloaking metasurface a wire antenna can be designed to hide itself to a pulsed signal (Figure 5(a)), whilst show itself to continuous wave and efficiently transmit/receive ((Figure 5(b)). This feature can be used in several different antenna applications, such as selectively hiding antennas to short-pulsed signals coming from a detecting radar and, at the same time, allowing communication with a base-station through continuous waveform signals.

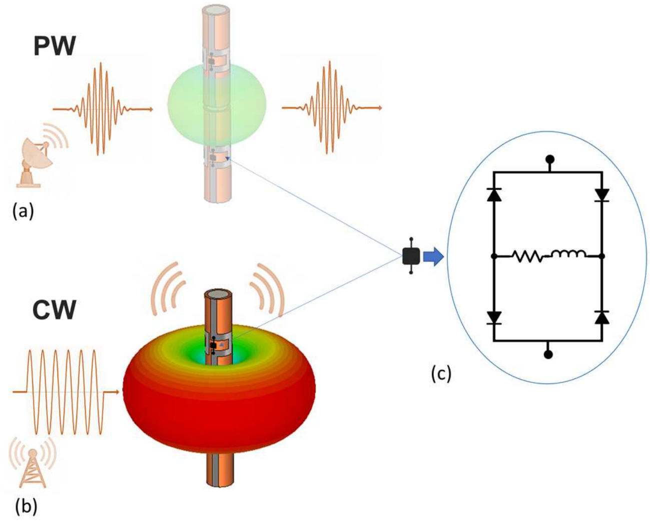

Figure 5. Waveform-selective cloaking applied to a dipole antenna. (a) When the antenna is illuminated by a pulsed signal (PW) the cloaking effect switches ON and the antenna becomes invisible. (c) When the antenna is illuminated by a continuous signal (CW) the cloaking effect switches OFF and the antenna operates in the usual way in both reception and transmission. (c) Waveform-selective circuit loading the cloaking metasurface.

5 Conclusions

In this contribution, we have reviewed our research results on cloaking metasurfaces used to cover wired antennas with a particular emphasis on the recent outcomes in designing advanced cloaking devices exploiting metasurfaces loaded by lumped-element circuits. In particular, we have discussed some of the possible antenna applications that can be achieved using linear metasurface, non-linear cloaking devices, and waveform-selective mantle cloaks, and we have described their possible impact in the next-generation of intelligent antenna systems.

Further details and examples of antenna applications will be shown at the conference.

6 Acknowledgements

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