URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Artificially moving meta-reflectors: Doppler effect achieved through time-varying surface impedance

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Abstract

In this contribution, we present a time-modulated meta-reflector able to shift the frequency content of a normally impinging electromagnetic plane wave. The frequency shifting is proportional to the modulation frequency of the meta-reflector, allowing to control the spectrum of the reflected wave. For an external observer, the meta-reflector acts as a conventional metallic reflector moving at a certain velocity towards or away from the observer, generating de facto an artificial Doppler frequency shift. The frequency conversion is achieved by a dynamic control of the reflection phase, which emulates the phase advance (phase delay) of the field when reflected by a scatterer moving towards (away from) the source. The proposed metasurface can be used for realizing electrically thin Doppler cloak, which can restore the source illumination frequency of a moving object, as if it were not in motion.

1 Introduction

Metasurfaces and metamaterials offer nowadays a high number of possibilities in the control of a propagating field. This has significantly changed the wave-matter interactions, allowing to achieve the desired behavior by just designing the effective macroscopic surface and bulk properties of the artificial metasurface and metamaterial, respectively [1]. This has enabled the conception of a multitude of novel devices and applications [2]–[4], being possible tailoring the transmitted and reflected fields in amplitude, phase, and propagation direction with extraordinary precision [5].
Recently, the concept of temporal modulation of the metasurface and metamaterial properties has opened the door to a new degree of freedom in the control of the propagation of the electromagnetic waves. In particular, metamaterials whose permittivity function is modulated in both space and time have been proposed for changing also the temporal characteristics of an electromagnetic field, i.e., its frequency content [6]–[8]. The space-time modulated metamaterials can couple two or more modes supported by the system and perform a perfect energy transfer from the original frequency f_0 of the incident signal to the shifted frequencies $f_\pm$ of the transmitted (or reflected) field. This property has been explored for conceiving the Doppler cloak [9], a bulk dielectric cover with modulated dielectric characteristics, able to restore the source illumination frequency. It has been used for cancelling the Doppler effect from the movement of the object [9], and for breaking the reciprocity of any narrow-band antenna [8] In this contribution, we report our results on time-varying electrically thin surfaces able to emulate the same frequency shift observed in space-time modulated metamaterials.

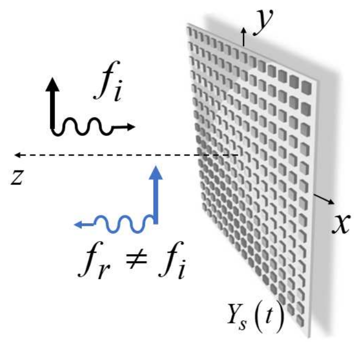

Figure 1. A time-varying meta-reflector with surface admittance $Y_s(t)$. A plane-wave at frequency f_i normally impinges the metasurface. A field at different frequency f_r is reflected back.

2 Artificial moving meta-reflector

The proposed metasurface is shown in Fig. 1 [10]: a planar metasurface consisting of a dense periodic array of subwavelength elements, whose electromagnetic response varies periodically in time. Being the size of the elements much smaller than the operating wavelength, we can model the surface response though its effective surface admittance Y_s. If the artificial metasurface is not frequency dispersive, its surface admittance will exhibit only the temporal dependence as $Y_s = Y_s(t)$. Moreover, the metasurface is fully reflective, i.e. a meta-reflector, and no transmitted fields will be present beyond the metasurface. In this scenario, the time-domain reflection coefficient is function of the instantaneous incident and reflected field at the meta-reflector location as follows:

$$\Gamma(\omega_i, t) = \frac{\underline{E}_r(z=0,t)}{\underline{E}_i(z=0,t)} = \frac{\underline{E_{0.r}}}{\underline{E_{0.i}}} e^{j(\omega_r - \omega_i)t} \qquad (1)$$

However, the incident and reflected fields are also related to each other by the time-varying complex reflection coefficient:

$$\Gamma(t) = \frac{Y_0 - Y_s(t)}{Y_0 + Y_s(t)} \quad (2)$$

where $Y_0 = 1/120\pi$ is the free-space admittance. Combining (1) and (2), it is possible to demonstrate that the metasurface admittance is imaginary with an inductive or capacitive behavior according to the sign of the tangent function. The normalized surface admittance Y_s/Y_0 over a modulation period $T_m = 2\pi/\omega_m$ is shown in Fig. 2. For each modulation period, the surface admittance assumes all possible values following a tangent function profile, spanning from $Y_s = 0$ to $Y_s \to \pm\infty$. In particular, these two extreme values correspond to the case of a perfect magnetic and a perfect electric conductor, respectively.
Moreover, considering eq. (1), the reflection coefficient turns to be a simple time-varying phase, spanning the 2π range with angular frequency $\omega_r - \omega_i$, *i.e.* the modulation frequency ω_m of the meta-reflector. This result is in line with the frequency shift resulting from the Doppler effect in presence of a moving reflector [34]. Indeed, when a reflector moves away from the source with constant velocity, the distance between the source and the reflector increases linearly, decreasing the phase of the reflection coefficient due to the higher the phase delay. Here, the reflector is stationary, but the continuous reduction of reflection phase can emulate the motion of the reflector away from the source and, consequently, inducing an artificial Doppler shift. Similarly, a reflector approaching the source can be emulated by continuously increasing of the reflection phase.

This effect has been validated though a realistic implementation of a time-modulated meta-reflector consisting of a high impedance surface, whose response is modulated through a set of voltage-controlled varactors. In Fig. 2 we report the normalized energy spectral density of reflected field by the time-varying metasurfaces when the up-conversion is induced by the driving signal, clearly showing that the frequency conversion is achieved.

3 Conclusions

In this contribution, we have numerically demonstrated that an electrically thin metasurface with time-varying reflection properties is able to realize a frequency shift for an illuminating electromagnetic wave. Differently from the space-time modulated metamaterials, here, the frequency-shift is achieved by emulating the phase advance (phase delay) of the fields when reflected by a scatterer moving towards (away from) the source. The proposed metasurface exhibits a time-varying reflection phase controlled by a set of varactors, biased in turn by a low-frequency modulating signal. The biasing network is designed to achieve a simultaneous control of the reflection coefficient for both polarizations, realizing a polarization independent time-varying metasurface. Even considering material losses, real models of varactors and parasitic circuit elements in the full-wave numerical simulation, the metasurface performs an almost perfect frequency shift for an illuminating signal, demonstrating that a bi-dimensional version of Doppler cloaks is feasible.

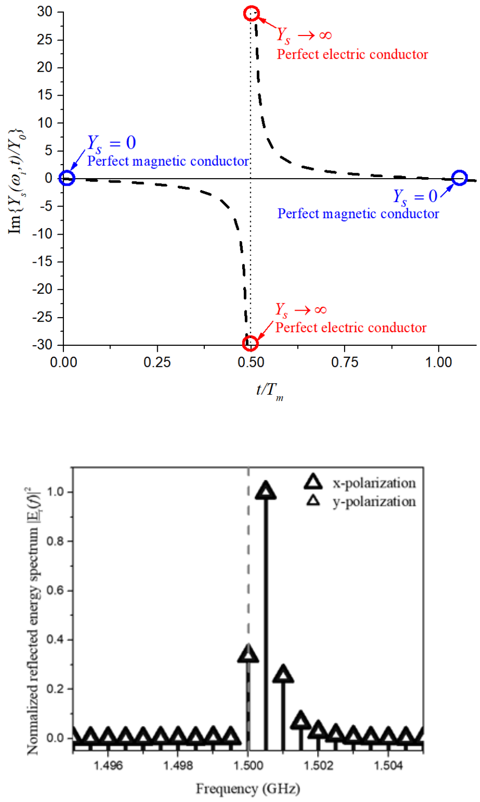

Figure 2. (top) Perspective view of time-varying metareflector operating a 1.5 GHz consisting of square metallic patches loaded by varactors printed on a FR-4 substrate. (bottom) Normalized energy spectral density of reflected field for both polarizations [10].

4 Acknowledgements

The work has been developed in the framework of the activities of the research contract MANTLES, funded by the Italian Ministry of Education, University and Research as a PRIN 2017 project (protocol number 2017BHFZKH).

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