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Material-based high-impedance surfaces for infrared photonic technologies

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Abstract
Metamaterial high-impedance surfaces (HISs) are characterized by a boundary condition close to that of a perfect magnetic conductor (PMC). This property has enabled a variety of antenna systems such as low-profile antennas, electromagnetic absorbers and anti-radar systems. Here, we push forward the concept of material-based high-impedance surfaces (MatHISs), where a high-impedance boundary is directly obtained from the material properties of doped semiconductors and polar dielectrics at infrared frequencies. Technological advantages of MatHISs such as fabrication simplicity, large-area deployment and integrability into conformal devices suggest multiple applications for infrared photonic technologies, including dynamical thermal emitters, optoelectronic devices and basic research on atomically-thin materials.

Key terms
High-impedance surfaces; thermal emission; optoelectronic devices; epsilon-near-zero-media

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1. Introduction

High-impedance surfaces (HISs) consist of metamaterial constructs exhibiting a band-gap and high values for their surface impedance on a limited frequency range [1]. The interest on HISs lies in their ability to suppress the propagation of surface waves [1, 2], as well as in their behavior as a magnetic wall, i.e., a perfect magnetic conductor (PMC) [3, 4]. In other words, the tangential electric(magnetic) field is maximized(minimized) at the boundary of a HIS, reversing the behavior of a conventional metallic mirror. Based on this popular concept, a variety of antenna systems have been demonstrated, including low-profile antennas [5, 6], beamsteering devices [7, 8], electromagnetic absorbers [9, 10, 11], anti-radar surfaces [12, 13] and chip-less RFID [14], to name a few.

Most realizations of HISs consists of: (i) a periodic metallic structure located in the proximity of a ground plane, (ii) a subwavelength dielectric spacer, (iii) optionally, the metallic structure and the ground plane are connected with metal pins or vias. The degrees of freedom in the metamaterial geometry enable tuning the frequency of operation, the bandwidth, as well as the angular and polarization responses of HISs.

In this vision, we push forward the idea that HISs can be directly obtained from the material properties of polar dielectrics and doped semiconductors at infrared (IR) frequencies. These material-based HISs (MatHISs) have technological advantages in terms of fabrication simplicity, large-scale deployment and integrability in conformal devices, pointing to multiple applications at IR frequencies such as thermal emitters and optoelectronic devices. We believe our vision is a good example of the far-reaching legacy of metamaterials research. The thrive of metamaterial concepts brought novel forms of engineering light-matter interactions. Interestingly, some of these ideas can be revised from the perspective of "actual materials", even if they were initially inspired by the design flexibility offered by metamaterials with a complex geometry.

2. Material-based High-Impedance Surfaces

Conceptually, the idea behind material-based high-impedance surfaces (MatHISs) is very simple. The medium impedance of an isotropic nonmagnetic material with dispersive relative permittivity $\varepsilon(\omega)$ is given by $Z(\omega) = Z_0/\sqrt{\varepsilon(\omega)}$. It is clear from this simple expression that good conductors with $|\varepsilon| \gg 1$ are characterized by a low impedance $Z \to 0$. In contrast, a medium with a near-zero permittivity $\varepsilon \to 0$, commonly

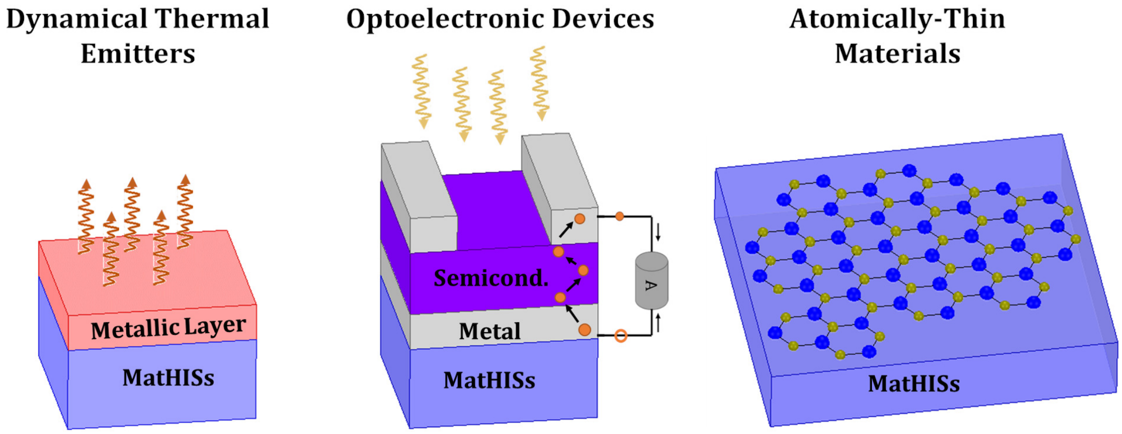

Figure 1: Technological applications of material-based high-impedance surfaces (MatHISs)material at infrared frequencies.

known as epsilon-near-zero (ENZ) media [15], exhibits a large impedance $Z \to \infty$. With this simple observation, MatHISs can be easily integrated in any technological platform in which a "natural" ENZ material is available.

MatHISs pose a number of technological advantages with respect to metamaterial HISs, particularly for IR photonic technologies. First, MatHISs eliminate the need of any complex nanofabrication process. Since a HIS is directly obtained from the material properties of the substrate, there is no need to fabricate nanometer-scale resonators on its surface . Removing the need of any photolithography and/or etching process simplifies the deployment of this photonic technology for large-area, large-scale applications. In addition, MatHISs do not suffer from the levels of spatial dispersion characteristic of metamaterials. In this manner, a high-impedance boundary of a MatHIS is observed for any direction of the indicent wave, and even for near-field interactions with emitters. Moreover, the "unit-cell" of a MatHIS is at the atomic scale. Therefore, the size of the unit-cell does not limit the geometry of the system, which can easily adapted to conformal substrates. Thus MatHISs can be integrated even in complex geometries containing curvature radius much smaller, comparable and/or larger than the wavelength of operation.

Naturally, MatHISs have their own disadvantages. For example, the frequency of operation is limited by the availability of a high-quality ENZ material. Moreover, unavoidable material losses limit the highest value of impedance that can be attained. Fortunately, there is a variety of materials with an ENZ response across the electromagnetic spectrum. These include metals [16, 17, 18] and semi-metals [19] (e.g., transition-metal nitrides) at visible and ultraviolet spectral frequencies, doped semiconductors [20] (e.g., doped oxides such as Al:ZnO, ITO, In:CdO) at near-infrared frequencies, and phononic materials [21] (e.g., SiC, AlN,InP) and mid-infrared frequencies. Moreover, the possibility of engineering a HIS with two-dimensional (2D) and transdimensional materials remains largely unexplored [22, 23].

Finally, MatHISs based on doped semiconductors enable the design of the frequency of operation via doping concentration [24], as well as their electrical [25] and optical [26] tunability. MatHISs, based on polar dielectrics have a more restrictive frequency of operation, but their properties can also be tuned via optical excitation [27]. Therefore, doped semiconductors and polar dielectrics enable the deployment of MatHISs across the entire IR spectrum, and open the possibility of exploring reconfigurable and time-varying systems.

The manufacturing simplicity and the optical properties of MatHISs resonate with a number of technological applications at IR frequencies, as schematically depicted in Fig. 1. In analogy with microwave electromagnetic absorbers, MatHISs provide the possibility of concentrating the absorption of IR radiation into ultra-thin metal layers, with synergies with dynamic and light-weight thermal emitters, as well as for related applications like thermal camouflage. Concentrating the absortion into a thin metal layer is also very relevant for optoelectronic devices and hot electron chemistry, where only the absorption taking place within an thin metal body is of interest. To finalize, absorption of IR radiation by atomically-thin materials is of fundamental scientific interest, and potential technological applications due to their unusually large photothermal effects and tunability.

In a recent work [28], we have already experimentally demonstrated a MatHIS based on SiC that efficiently concentrates absorption into a nanometer-thin metallic film. In our experiment, the emissivity of the sample in the entire atmospheric window is dominated by a spectral feature corresponding to the absorption of the metal layer around the MatHIS wavelength. In another recent work, a Schottky photodiode based on an Al:ZnO substrate acting as MatHIS has been demonstrated [29]. In both systems, the geometry simply consists of an optical coating on top of a substrate. We believe that these are only the first examples of IR devices that can be developed by using a material approach towards HISs.

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