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Comments

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Self-dual systems for backscattering cancellation

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ABSTRACT

Using carefully arranged electric and magnetic components, we have recently demonstrated that backscattering from otherwise arbitrarily shaped two- and three-dimensional structures can be fully eliminated. Here, first we investigate the possibility of creating self-dual microwave absorbers that may provide advantages compared to typical commercial magnetoelectric absorbers. Next, we demonstrate that the self-duality condition is not limited to homogenous structures and may be extended to effective material properties, opening the door to realistic implementation of these structures at microwave and optical frequencies.

Keywords: Impedance matching, absorption, duality, self-duality, backscattering cancellation, magnetic materials, wave funneling

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1. INTRODUCTION

Scattering from an arbitrary object strongly depends on its geometrical shape and constituent materials. Consequently, predicting (or designing) the scattering signature of an object is not straightforward, unless by relying on computational or experimental methods [1]. Recently, we have demonstrated [2], that certain geometrical and electromagnetic symmetries (i.e., self-duality where the object is dual with the $\pi/2$-rotated version of itself: $\mu(\varphi+\pi/2)=\varepsilon(\varphi)$) can guarantee an interesting scattering signature, namely zero backscattering or backscattering null. If such symmetry conditions are satisfied, the total scattering in the direction of the source will vanish, resulting in a large class of arbitrarily shaped impedance-matched objects. In theory, it is possible to create two-dimensional self-dual structures (such as metasurfaces [2], [3], waveguides [4], and waveguide elements [5], [6]), as well as three-dimensional self-dual scatterers (i.e., generalized kerker particles [7]). In addition, zero backscattering may be achieved through similar symmetry conditions also relying on careful arrangement of electric and magnetic properties of the object [8].

Under self-duality condition, a scattering null is always present in the back direction (i.e., toward the source), so these structures provide an interesting platform for creating inherently matched, anti-reflective surfaces and absorbers. In addition, through careful engineering of the object, it is possible to create wave funnels where the entire incident energy is transmitted through subwavelength apertures. These properties can be valuable to a wide range of applications in sensing, nonlinear optics, optical trapping, and applied electromagnetics. Here, we will study two practical aspects of the application and implementation of self-dual structures. First, and in section 2.1 we investigate the possibility of using self-dual arrangement of absorbing materials to better suppress unwanted scattering and enhance the matching of electromagnetic absorbers. Next, and in section 2.2 we focus on practical implementation of self-dual structures. In this section we demonstrate the important possibility of implementing self-dual objects by metamaterials where effective properties of the medium satisfies the self-duality condition.

2. RESULTS AND DISCUSSION

2.1 Self-dual absorbers

Commercial electromagnetic absorbers rely on a variety of techniques (such as gradient impedance matching) to reduce unwanted reflections over broad bandwidths. Magnetic microwave absorbing materials typically show high levels of

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permittivity and moderate permeability as well as intrinsic material losses [9]. Higher permeability materials are also used for improved absorption [10]. To investigate the performance of a self-dual arrangement of absorbers, we consider two different arrangement of absorbing materials in form of a thin slab with fixed thickness of $\lambda_0/5$: I: dielectric absorber with $\varepsilon_r = \alpha, \mu_r = 1$ and II: self-dual arrangement of two materials with $\varepsilon_{r1} = \alpha, \mu_{r1} = 1$, $\varepsilon_{r2} = 1, \mu_{r2} = \alpha$ where $\alpha = 30 - 5j$ (While typical material properties are chosen [9], [10], material dispersion is not considered). We note that the reflection from structure II is identically zero as it is self-dual. In Figure 1, the total absorption from these structures is plotted vs normalized frequency. As it can be seen, self-dual arrangement of electric (high permittivity, low permeability) and magnetic (high permeability, low permittivity) absorbing materials creates higher levels of absorption compared to electric-only (or magnetic-only) materials. It is worth noting that other techniques such as gradient impedance matching or creating balanced electric and magnetic response can also improve matching (i.e., reduce reflection) and improve absorption.

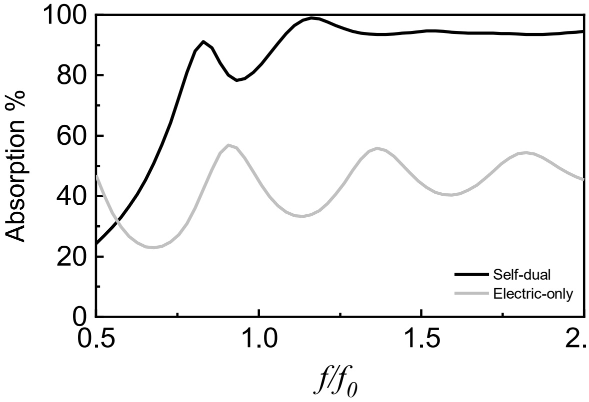

Figure 1. Comparison between absorption of a lossy self-dual slab (black) and a lossy dielectric thin slab (grey).

2.2 Ideas for realistic implementation of self-dual structures

Taking advantage of the exciting properties of self-dual structures (such as creating subwavelength funneling effect) requires access to both electric and magnetic materials [2]. However, natural materials provide only a limited range of material properties and especially at higher frequencies, natural magnetic responses are rare. Metamaterials, on the other hand, have been shown to be able to create *effective* electric and magnetic properties across high frequencies [11]. Self-duality relies on an exact geometrical and material symmetry in the structure, and consequently, it is not clear whether zero backscattering can be preserved if the self-dual structure is implemented with metamaterials (which are non-homogenous). To demonstrate the possibility of using metamaterials in a self-dual arrangement (and achieve zero backscattering), we consider layered uniaxial metamaterials to create hyperbolic metamaterials with different effective parameters. Here, as reported in Figure 2, we consider two cases: silicon/air layered metamaterial operating at 3 micrometers, and silver/silicon dioxide layered metamaterial operating at 633 nm. Using the Nicolson–Ross–Weir method, first we retrieve the effective permittivities of these structures (as reported in the caption of Figure 2). Then, these metamaterials are arranged in a self-dual form with two blocks of homogenous magnetic materials where the relative permeability of the magnetic portions are swept to find the point of minimum reflection. The minimum reflection is used as an indicator of getting close to the self-duality condition. As it can be seen in Figure 2a, self-duality is achieved when permeability of the homogenous blocks is close to the approximately driven effective permittivity of the metamaterial blocks, indicating the possibility of replacing these elements with metamaterials. In the second case (as shown in Figure 2b), the minimum reflection point is deviated from the retired permittivity, raising the possibility of the presence of effective magnetic response in the plasmonic layered metamaterials which is not captured with NRW method. While we replaced the dielectric sections with metamaterials, we note that these results indicate that magnetic sections can also be replaced with metamaterials, albeit requiring a more accurate material retrieval method to correctly calculate the effective permeabilities [11].

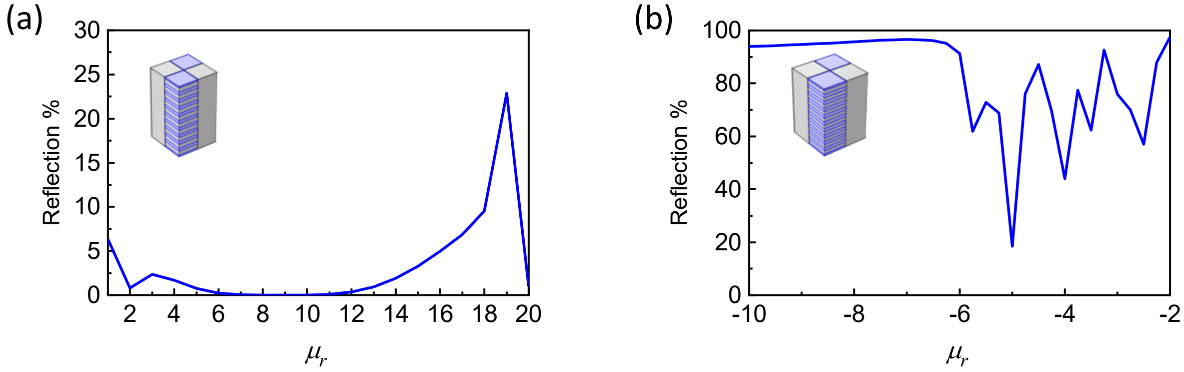

Figure 2. Reflection from checkerboard-type periodic surfaces with metamaterial segments (effectively dielectric) plotted versus the relative permeability of the dual homogenous sections: (a) Silicon/Air layered metamaterials with approximate effective permittivity of $\varepsilon_{eff} \approx 8$ at 3 micrometers, (b) Silver/Silicon dioxide layered metamaterials with approximate effective permittivity of $\varepsilon_{eff} \approx -8$ at 633 nanometers. The schematic of one unit cell of the self-dual surface is shown in the inset of each panel with incident wave propagating from top to bottom. Blue and grey colors indicate the alternating materials in the layered metamaterial.

3. CONCLUSION

Self-dual arrangement of absorbing materials is shown to outperform electric-only absorbers as they provide inherent matching to the incident wave. In addition, realistic approaches for the implementation of self-dual structures at higher frequencies are explored. Layered metamaterials consisting of high/low index layers or plasmonic/dielectric layers are suggested as potential candidates for implementation of these structures at higher frequencies.

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