Isotropic metamaterial perfect absorbers

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Abstract

Here we theoretically study a perfect absorbing surface which does not depend on the polarization state and the incidence angle. Electric and magnetic surface currents allow for the cancelation of the field at the back of the surface while no reflection is scattered into the front of the surface.

1. Introduction

During the first years of Metamaterials, losses were usually considered undesirable for the most of envisioned applications. Oppositely, in 2008 a paper titled "Perfect Metamaterial Absorbers" just took advantage of the losses [1]. A perfect absorber was built as a 2D periodical array of resonant particles responding to both the electric and magnetic field. Just at the resonance frequency a narrow band of quasi-perfect absorption appears. An important drawback is that this absorber is polarization dependent and very sensible to the incidence angle. Subsequent papers [2]-[3] addressed this problem by using as unit cell a metallic cross or a metallic square over a metallic plane. However, these structures are almost opaque for frequencies far from the perfect absorption. Recently, it has been demonstrated that the perfect absorption can also been obtained in a relatively broadband. The same plausible explanation was given in all these papers: in order to avoid any reflected power, the effective medium impedance was must match to that of vacuum and, in order to reduce the transmitted power, the imaginary parts of ε and μ must be high enough, so that most of the power is dissipated inside the slab. However, it is hard to justify the use of this theory of effective medium parameters because the sample thickness was only one unit cell. In this work, instead of using the effective medium approach, we develop a new theory based on surface electric and surface magnetic currents. Besides we give the steps to design isotropic perfect absorbers that absorb all radiation in a sharp frequency region and are almost transparent outside that band.

2. Theory

Let us imagine a 2D array of a certain resonant isotropic particle which is sensible to electric and magnetic fields at the same time. For simplicity we firstly ignore any magnetoelectric coupling. If the unit cell is designed much smaller than the resonance wavelength, then this array can be approximated as an infinitesimally thin surface. In Fig. 1(a) the array is represented by the blue surface. This figure shows the situation of perfect absorption: in the left semi-space the total field is equal to the incident field, while in the right semi-space the total field is zero.

In the linear approximation, the electric and magnetic dipoles are proportional to the local fields applied over the particle, $\mathbf{E}_{loc}$, $\mathbf{H}_{loc}$, what can be written as follows:

$$\mathbf{p} = \varepsilon_0 \alpha_e \mathbf{E}_{loc} \approx \varepsilon_0 \alpha_e \mathbf{E}_1 / 2 \qquad \mathbf{m} = \alpha_m \mathbf{H}_{loc} \approx \alpha_m \mathbf{H}_1 / 2 \tag{1}$$

where α_e and α_m are the electric and magnetic polarizabilities, respectively, and the local field has been roughly approximated as the average of the total fields on the left side ($\mathbf{E}_1$ y $\mathbf{H}_1$) and the right side ($\mathbf{E}_2 = 0$ y $\mathbf{H}_2 = 0$). To justify this approximation, we can decompose the total field into two parts: the field produced by a small disk and the field due to the complementary hole and external sources. On the left side we have $E_1 \approx E_{loc} + \Delta E$ and on the right side $E_2 = 0 \approx E_{loc} - \Delta E$. Since the increments of the field due to the surface current on the disk must be odd, then the addition of both relations carry us to $E_{loc} \approx E_1 / 2$. By a similar reasoning, the local magnetic field is $H_{loc} \approx H_1 / 2$. However, it is worth to note that this is a rough first approximation because the coupling with near neighbors (the "granularity") has been neglected. The polarization of all particles can be consider as an homogeneous distribution of surface polarization $\mathbf{P}_s = \mathbf{p} / a^2$ and surface magnetization $\mathbf{M}_s = \mathbf{m} / a^2$ where a is the reticular parameter. As usual, these can be replaced by effective electric and magnetic surface currents, $\mathbf{J}_s$ and $\mathbf{K}_s$, which can be approximated as

$$\mathbf{J}_s = j\omega \mathbf{P}_s \approx j\omega \frac{\varepsilon_0 \alpha_e}{2a^2} \mathbf{E}_1 \qquad \mathbf{K}_s = j\omega \mu_0 \mathbf{M}_s \approx j\omega \frac{\mu_0 \alpha_m}{2a^2} \mathbf{H}_1 \tag{2}$$

Since the fields on the right side are zero, there must be suitable surface currents over the surface able to account for the discontinuity of the tangential components of the fields. Usually the jumps of the tangential fields are expressed as follows:

$$\hat{\mathbf{n}}_{21} \times (\mathbf{H}_2 - \mathbf{H}_1) = -\hat{\mathbf{n}}_{21} \times \mathbf{H}_1 = \mathbf{J}_s \qquad \hat{\mathbf{n}}_{21} \times (-\mathbf{E}_2 + \mathbf{E}_1) = \hat{\mathbf{n}}_{21} \times \mathbf{E}_1 = \mathbf{K}_s \tag{3}$$

By introducing here the effective surface currents of (2) and taking out from (3) the x component of the first equation and the y component of the second one, we get

$$H_1 \approx j\omega \frac{\varepsilon_0 \alpha_e}{2a^2} E_1 \qquad E_1 \approx j\omega \frac{\mu_0 \alpha_m}{2a^2} H_1 \tag{4}$$

And using (4) and the vacuum impedance $E_1 / H_1 = \sqrt{\mu_0 / \varepsilon_0}$, we achieve

$$\alpha_e = \alpha_m \approx -j \frac{2a^2}{\omega} \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = -j \frac{2a^2 c}{\omega} = -j \frac{a^2 \lambda}{\pi} \tag{6}$$

Therefore, the unit cell must be designed to be balanced (in the sense that its electric and magnetic polarizabilities are equals) and have pure imaginary polarizabilities. Besides, since the electrical size must be small to allow for a homogenization procedure, the last term of Eq. (6) also means that the magnitude of the polarizabilities must be much greater than the volume, what can be easily satisfied by resonators. Namely, if a Lorentzian resonator is used as unit cell, then the design frequency should correspond with the resonance frequency where the real part of both polarizabilities is cancelled out while the imaginary parts take their maximum values.

3. A few ideas for implementation

At the present moment we are working on numerical simulations of realistic implementations of this idea with two different candidates for the unit cell: the bi-isotropic cube of Fig. 1(b) for absorbing microwaves and the plasmonic nanosphere of Fig. 1(c) for absorbing optical signals. The bi-isotropic cube was already proposed for a different purpose: to make a chiral left-handed medium [5]. It was argued that it is isotropic due to some rotation symmetries (namely it is invariant under the tetrahedral, T, subgroup of the cube symmetries). However, an apparent drawback of this particle would be that it presents magnetoelectric coupling. In principle, it should be added into equations (1) as additional terms $\alpha_{em} \mathbf{H}_{loc}$ into the formula for $\mathbf{p}$ and $\alpha_{me} \mathbf{E}_{loc}$ for $\mathbf{m}$. Anyway, under normal incidence, it will not affect to the theory below (3) because when we went from (3) to (4) we took only one Cartesian component of the vector product what left any cross effect out. Although the structure of Fig. 1(b)

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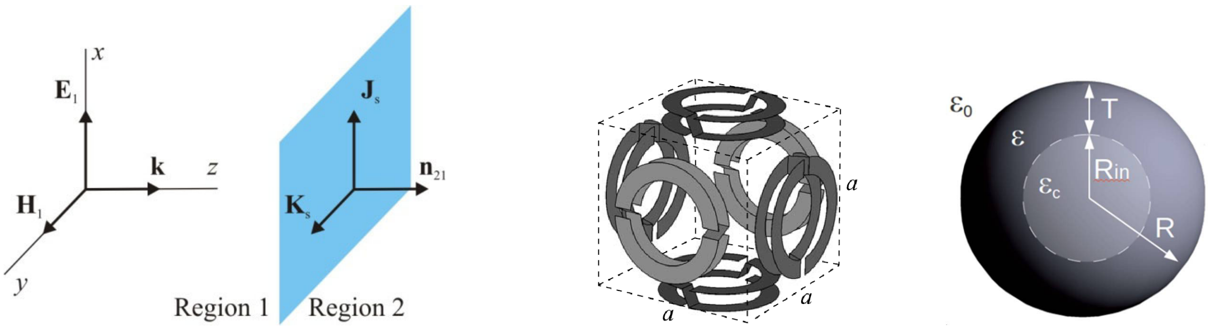
could be manufactured for samples absorbing in the RF or microwaves regions, it is actually challenging, if not impossible, to scale it down up to reach optical frequencies. For this reason, we are also investigating the candidate of Fig. 1(c) which was already studied in Ref. [6]. It is filled inside the core with some plasmonic material with negative permittivity while the outer shell is made with some dielectric with positive permittivity. It was demonstrated that this particle resonates under electric and magnetic excitation and can be designed to be balanced, i.e. with electric and magnetic polarizabilities having the same value. Of course, due to the spherical shape the isotropy is assured. Besides, since there is also inversion symmetry any magnetolectric coupling is forbidden and the simplified theory shown here in (1)-(6) is completely valid.



(a) (b) (c)

Fig. 1: (a) The model of surface currents for a perfect absorber. (b) A candidate as unit cell for perfect absorbers in RF or microwaves. (c) A candidate as unit cell for perfect absorbers in the optical range.

4. Conclusion

In this paper we theoretically design a perfect absorbing surface. The main advantage of this idea, in front of other previous proposals [1-4], is that its reflection coefficient out of the narrow perfect absorption band is almost zero. The exposed idea is quite easy and is based in the use of small metamaterial resonators creating effective electric and magnetic surface currents which allow the cancelation of the incident field into the back side of the surface while no reflection is scattered back into the front side. Although the theory was mounted for normal incidence, we expect that, due the isotropy of the proposed unit cells, the stability of the shape of the absorption coefficient will be good respect to different polarization states and off-normal incidence within a limited range of angles. From the practical point of view, this idea can be used for designing thin absorbers in comparison with conventional microwave absorbers, since the used resonators are much smaller than the wavelength.

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