Cloaking dielectric spheres by a shell of metallic nanoparticles

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Abstract

We describe a metamaterial made of randomly arranged silver nanospheres that is placed as a shell around a dielectric sphere with the purpose of cloaking it. The device is studied rigorously by full wave simulation and approximately by treating the shell of silver nanospheres within the Maxwell-Garnett theory. By both means it is concisely shown that such a metamaterial shell significantly reduces the visibility of the dielectric sphere. Advantages and disadvantages of such a cloak when compared to other implementations are disclosed.

1. Introduction

In 2000 Sir John Pendry showed that a slab of negative refractive index could focus light in a special manner: it promises to overcome the well-known Abbe resolution criterion [1]. And since then, research on metamaterials gained momentum among the optics and acoustics communities; giving rise to many applications. The most intriguing outcome is possibly the invention of invisibility devices that hide objects from external observers by *forcing* light (or any other type of waves) to travel along curved trajectories [2]. Implementation of such cloaks came in sight by relying on metamaterials that provide extreme values of the permittivity and permeability. In the same vein, Alù *et al.* proposed another technique based on scattering cancelation which consists of coating the object to be cloaked by plasmonic layers to cancel the total scattered field [3]. In this contribution, we build upon this latter work, and further suggest to use a bottom-up metamaterial designing of such cloak instead of homogenous plasmonic layers. The advantages are a more efficient cloaking efficiency at higher frequencies, a possibly better tunability that avoids metallic shells with a minuscule thicknesses, and a back-up of a wide range of technologies for its implementation based on colloidal nanochemistry. On top of reproducing the cloaking functionality using plasmonic shells, our work contributes to pave the way to consider metamaterials in the design process of functional devices. That is possible because the functionality of the cloak can be analyzed using full wave simulations, which take into account all the details of the individual metallic nanoparticles forming the shell, but also by considering them as an effective medium. It will be shown that in the plasmon resonance of the particles deviating results are encountered whereas at the operational frequency of the cloak, which is off-resonant, predictions by both methods perfectly agree.

2. Numerics

To design a cloak on the base of the scattering cancellation technique the shell is required to have either a small positive (i.e. larger than zero but smaller than one) or a negative permittivity [3]. A single shell

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only allows to cancel the scattering contribution form an electric dipole. It therefore has to be the leading order in the scattering response of the sphere to be cloaked. Equation (1) shows the relation between the permittivity of the cluster coating ε_c, the one of the sphere to be cloaked ε_s and γ, being the ratio between the radii of the sphere and the shell [3].

$$\gamma^3 = \frac{[\varepsilon_s(\omega) - \varepsilon_b]\,[2\varepsilon_s(\omega) + \varepsilon_c]}{[\varepsilon_s(\omega) - \varepsilon_c]\,[2\varepsilon_s(\omega) + \varepsilon_b]} \tag{1}$$

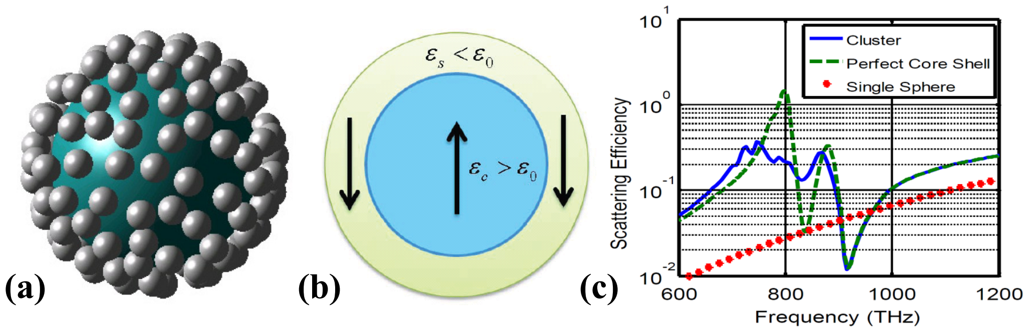

Fig. 1: Schematic of the dielectric sphere to be cloaked surrounded by metallic nanoparticles (a) forming an effective invisibility shell (b) described by its effective permittivity ε_s and effective polarization vector. (c) Numerical calculation of the total scattering efficiency for $\varepsilon_c = 8$ as a function of frequency .

Instead of using a homogenous shell we propose a shell composed of many small metallic nanoparticles, schematically shown in Fig. 1 (a). The shell of Fig. 1 (a) could be described by an effective medium with effective permittivity given by the Maxwell-Garnett formula as sketched in Fig. 1 (b):

$$\varepsilon_{\text{eff}}(\omega) = \varepsilon_m \frac{\varepsilon_i(\omega)[1 + 2f] - \varepsilon_m[2f - 2]}{\varepsilon_m[2 + f] + \varepsilon_i(\omega)[1 - f]} \tag{2}$$

The metamaterial formed from such a material exhibits a Lorentzian resonance in the effective permittivity which shows strong dispersion around the localized plasmon polariton resonance frequency. At larger frequencies it mimics a metal [$\text{Re}(\varepsilon_{\text{eff}}) < 0$] whereas at smaller frequencies it behaves as a dielectric [$\text{Re}(\varepsilon_{\text{eff}}) > 0$). According to the solution of Eq. (1), the regime of interest to design a cloak for the core sphere is the dielectric one far off-resonance where ε_{eff} is less than one but larger than zero. In addition we require moderate losses at the frequency of operation [$\text{Im}(\varepsilon_{\text{eff}}) << \text{Re}(\varepsilon_{\text{eff}})$]. Both requirements are suitably matched for the given filling fraction at a frequency slightly exceeding 900 THz.

In Fig. 1 (c) the scattering response of the cloak is shown for the frequency range between 600 and 1200 THz and for $\varepsilon_c = 8$. In order to test the validity of our effective medium approach, we used two different methods for these calculations: the first one is completely rigorous and is based on multiple scattering for a large number of spheres (the dielectric core sphere of radius 35 nm surrounded by 131 small silver spheres amorphously distributed on its surface with a filling fraction of f = 0.34). In a second simulation the scattering response of the core-shell system was calculated in describing the shell as an effectively homogeneous medium with a permittivity according to the Maxwell-Garnett formula with the appropriate filling fraction (2). It can be clearly seen that in a finite frequency range an excellent scattering reduction may be achieved. The scattering efficiency of the particle to be cloaked is reduced by approximately 70% and the cloaking behavior is equally well predicted by the approximate treatment.

Figure 2 gives the amplitude distribution of the electromagnetic field scattered by the spherical obstacle with [Fig. 2 (a) and (c)] and without ([Fig. 2 (b) and (d)]) the plasmonic shell . When it is surrounded by the cloak, the scattered amplitude is close to zero everywhere in space in contrast to the uncloaked

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case. As already explained, the reduction of scattering is due to the proper choice of the permittivity function of the plasmonic cover. This is consistent with the scattering reduction predicted in Fig. 1 (c). The upper panel of Fig. 2 represents simulations done with FEM (finite element method) using a commercial software and for a homogeneous coating while those of the lower panel are based on the multipole method and both methods show a good scattering reduction.

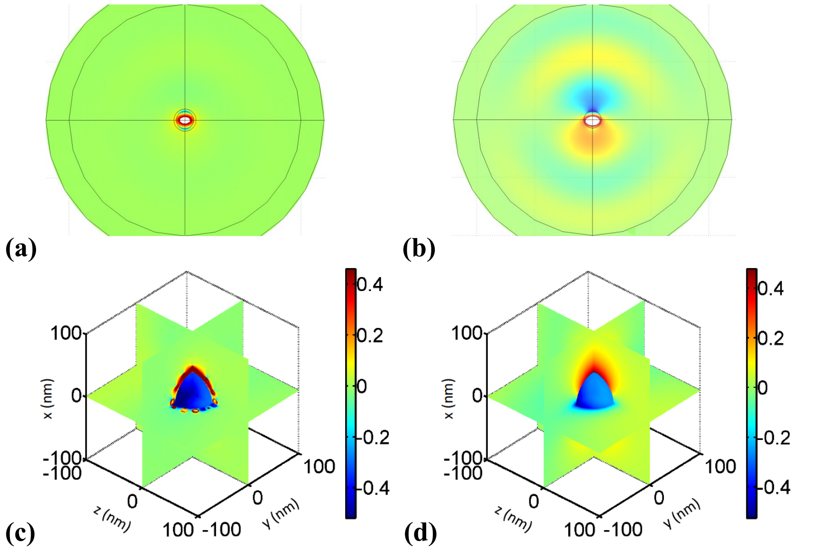

Fig. 2: Time averaged field distributions in a logarithmic scale of a dielectric sphere of $\varepsilon_c = 8$ which is cloaked by the nanoparticles (a), (c) and on its own for comparison (b), (d). The structures are illuminated with a unit amplitude plane wave (909.5 THz) propagating in the z-direction and being polarized in the x-direction. The simulations of the upper panel were performed using FEM and represent the field amplitude in the y-z plane for comparison.

3. Conclusion

We have proposed here a realistic design for cloaking 3D objects by canceling their scattering response in the electric dipole limit. This technique is based on the well-known plasmonic cloaking and requires the shell to have a small permittivity. We propose to extend this idea by allowing the core sphere to be covered by a finite number of plasmonic spheres in order to extend the range of frequencies where cloaking is allowed and to gain new degrees of freedom on controlling the device properties [4]. This will be presented in more detail at the conference.

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