Limitations of Plasmonic Cloaking at Microwave and Optical Frequencies

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Abstract

Here we describe our recent findings on our proposed technique to employ metamaterials and plasmonic structures to design cloaks. After showing how the total scattering cross section of a given dielectric or conducting object may be drastically reduced by surrounding it with a suitably designed plasmonic material or metamaterial, we underline the main inherent limitations of this technique, compared with other metamaterial cloaking methods. The concepts that we present remain valid also when multiple particles are considered and they may be extended to multi-frequency operation, presence of ground planes or reflectors, larger objects and realistic loss and dispersion. Here we review our recent results on this problem and we provide some physical insights into this cloaking mechanism in different frequency regimes.

1. Introduction

Recent technological advancements have encouraged many researchers to concentrate their works on theoretical and experimental aspects of artificial materials and metamaterials composed of molecular-like electrically small inclusions that may interact with the electromagnetic wave at different frequencies in an anomalous fashion. The attention of the media and of the general public for these materials has been mainly attracted by some potentially breakthrough applications, like the possibility of making a given object "invisible" [1-23]. Following our seminal contribution on the topic [1], interest in metamaterial and plasmonic cloaking has been steadily increasing in the technical literature. Our subsequent papers [2-4], exploring and extending several aspects of our original proposal and their potential applications, as well as many other different approaches and solutions to the problem [5-23], have appeared.

The interest of the electromagnetic and physics community in invisibility and cloaking indeed dates back several decades. Already at the beginning of last century, specific and properly designed distributions of oscillating sources with no radiation were predicted [24], and the concepts of "invisible" particles, sources and antennas have been investigated for several decades in a variety of scientific fields [25-30]. Our proposal to apply metamaterials and plasmonic materials to cloaking [1-4] is based on the local negative polarizability of materials with a low or negative effective permittivity. When these materials surround a dielectric or conducting object, the overall scattering from the system may, under proper conditions, be designed to become extremely low -- orders of magnitude lower than that of the uncloaked object by itself. This effect relies on a scattering cancellation, for which the wave scattered from the cloak may cancel the one from the object to be cloaked, leaving an external observer with a very low residual scattering that makes the system practically invisible around the design frequency. This cancellation is very distinct from, and in many ways potentially advantageous to, other cloaking techniques, being independent of the form and polarization of the illuminating source. Moreover, we have shown how this technique is inherently non-resonant [2], and consequently it is fairly robust to variations in the shape, geometry and frequency of operation of the cloak and/or of the object to be covered. This effect may be achieved with naturally available plasmonic materials at THz, infrared and optical frequencies, since it may be based on simple isotropic and homogeneous covers, or it may be realized, at different frequencies, with metamaterials, as we have suggested in a specific geometry at microwave frequencies [3].

Other interesting solutions have recently been proposed in the framework of metamaterial cloaking [5-23]. Of particular interest, two alternative general ways of cloaking may be underlined: the possibility of applying conformal transformations and space distortions in order to tailor and design a metamaterial cloak capable of isolating a given region of space from the surrounding, and the possibility of applying anomalous localized resonances for inducing an anomalous overall cloaking of an object. Both solutions may involve materials with resonant elements, and consequently exhibit strong sensitivity on frequency and on the geometrical and electromagnetic parameters of the cloak. Moreover, at present stage they have been mainly envisioned for 2D geometries and for complex anisotropies and inhomogeneity profile for the involved materials.

In the following, we provide some numerical results on our solution for plasmonic cloaking, underlining the potentials of this solution in terms of cloaking effectiveness and scattering reduction, with particular attention to the inherent limitations that the use of metamaterials in these setups may imply. These results may have important potential applications requiring reduction in scattering, and also for low-noise measurements and non-invasive probing in medicine, biology and optics.

2. Numerical Results

Figure 1 reports a numerical simulation, based on full-wave Mie scattering theory, for the case of an impenetrable/conducting sphere of radius $a = \lambda_0 / 10$ illuminated by a plane wave traveling from bottom to top of the figure. Following our theoretical results in [1-4], we may design different covers to cancel or drastically suppress the scattering from the sphere. One design, corresponding to Fig. 1a, has permittivity $\varepsilon_0 / 10$ and thickness $a_c = 1.1a$, whereas the second design, corresponding to Fig. 1b, has permittivity $\varepsilon_0 / 20$ and $a_c = 1.05a$. The figure reports the total magnetic field distribution (amplitude) on the E plane, but similar results are obtained also on the other plane of polarization. This clearly shows the drastic scattering reduction that the plasmonic cloaks may provide, as compared with the case of a bare sphere (Fig. 1c) or of a conducting sphere occupying also the cloak region (Fig. 1d). Quantitatively, the scattering cross section is reduced by over 95% with this simple design.

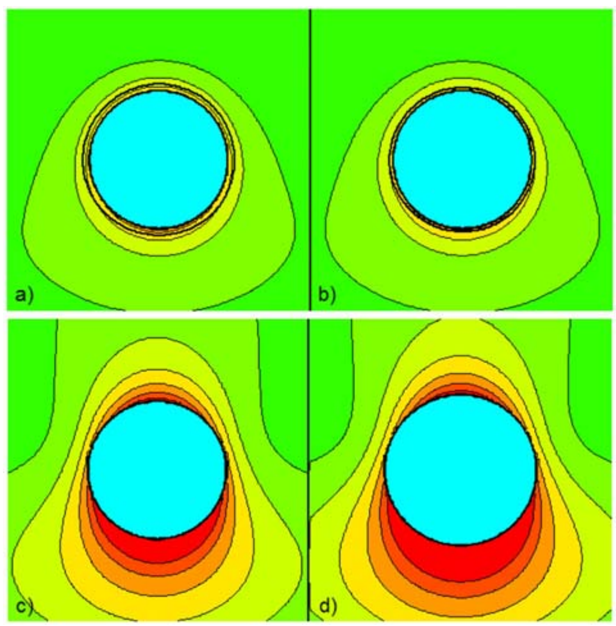

Figure 1 - Magnetic field distribution (amplitude) in the E plane for the four cases of: (a) $\varepsilon_c = \varepsilon_0 / 10$ and $a_c = 1.1a$; (b) $\varepsilon_c = \varepsilon_0 / 20$ and $a_c = 1.05a$; (c) $\varepsilon_c = \varepsilon_0$, (d) $\varepsilon_c = -j\infty$ and $a_c = 1.08a$. Brighter colors correspond to larger values of the field. For better comparison, the color scale is the same in the four plots. The geometry of the four spheres is depicted in black in the figures.

Compared to other available techniques that employ metamaterials for the same purposes [5-23], this solution does not involve the use of particularly complex material profiles, and it is effective in 3D and for an arbitrary polarization and wave front of the impinging wave. Moreover, we have recently extended these concepts to the case of multiple neighboring objects to be cloaked, possible presence of a ground plane and larger systems, as well as to multi-frequency operation. It is noticed that the present simulations involve an impenetrable perfectly conducting object, which may also model a conducting spherical hollow cavity. Since the wave cannot penetrate into the cavity, and its total scattering cross section may be made very small using this cloak, it may be possible to fill the cavity with any object without perturbing the present results. In this way, we may envision the modeling of a cloaking system, composed of the combination of the designed cloak and a spherical hollow cavity, which is totally independent of the specific object(s) to be cloaked.

It is interesting to underline that, despite the outstanding reduction of scattering produced by the cloak in Fig. 1a and Fig. 1b, and in particular of the shadow on the back of the object caused by the presence of an impenetrable obstacle, the geometry under analysis requires some inherent limitations on its overall bandwidth of operation. From a general point of view, requiring that an impinging signal is indeed rerouted around an impenetrable obstacle through the (passive) cloak region implies an inherent delay in the cloak response [20]. This is directly associated with a limitation in the bandwidth of operation, which becomes more stringent for larger systems. As we have noticed in [2], the technique that we have discussed here is quite robust in this sense, allowing geting closer to the inherent limitations required by causality, which are also projected in the required frequency dispersion of metamaterials. Compared with other techniques [5-23], the plasmonic cloaks presented here may have a relatively larger bandwidth of operation, in particular when dielectric and penetrable objects are considered, for which in this design the electromagnetic wave may also penetrate the object, without being necessarily rerouted around it.

3. Conclusions

The sample numerical results presented here (and more will be presented in our talk) fully confirm our previous works on the possibility of cloaking impenetrable and dielectric objects with plasmonic materials with low permittivity. The discussion on the inherent limitations of this phenomenon forecasts promising applications of this cloaking technique, which may be relatively more robust than other metamaterial cloaking techniques. These results may pave the way to novel exciting applications for cloaking, camouflaging and low-noise sensing.

4. References

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