Design of invisibility cloaks using surface integral equation method

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Abstract

Plasmonic and metamaterial cloaking is a scattering cancellation technique consisting of covering the scatterer by an invisibility cloak made up of single or multiple layers of homogeneous plasmonic, metamaterial, and/or dielectric materials. A suitable selection of the cloak geometry and materials allows dramatically reducing the overall scattered field from the cloaked object. In this work, we propose a novel cloaking optimization technique based on the application of surface integral equation (SIE) formulations and optimization techniques.

1. Introduction

The possibility of making an object invisible is one of the oldest hopes of man, once the Wright brothers made their feat. Indeed, writers such as Jules Verne, H.G. Wells already wrote about this possibility in the nineteenth century. In recent years, with the advent of nanoscience and nanotechnology and the unprecedented ability of nanometallic (plasmonic) structures to concentrate light into deep-subwavelength volumes it may be feasible to cloak an isolated dielectric or conducting object by wrapping it with a well-designed plasmonic material cloak [1]-[3], making this one of the most exciting applications that can be engineering with this exciting materials.

An object is detected by receiving the electromagnetic radiation scattered surface when illuminated by an external source. Therefore, an object is invisible if it does not reflect waves back to the source and in addition it does not scatter waves in other directions, and, furthermore, it does not appear any shadow created by the absorption of energy that can be detected. In other words, the object does not disturb the incident fields over its surface. In terms of the theory of scattering of electromagnetic waves, to cloak an object means to reduce its total scattering cross section (SCS). The total scattering cross section is defined as the ratio of the total scattered power to the incident power density.

Nowadays, there are three different techniques to achieve this minimization, transmission-line technique, coordinate transformation technique and scattering cancellation technique. A great review of these techniques is shown in [4]. This work focuses on the scattering cancellation technique, i.e., the scattering from an object is mitigated by adding the scattering of other object which is complementary with respect to the principal scatterer. This minimization can be achieved covering the main scattering object by single or multiple layers of plasmonic materials or metamaterials (which can be homogeneous and isotropic) as was shown in [1]-[3].

Up to now, metamaterial/plasmonic cloaks have been designed using analytical formulations, which limit the object to be cloaked to canonical geometries. Arbitrary geometries have also been successfully cloaked, but for the case of small objects (below approximately half wavelength). To overcome this problem we propose the design of metamaterial/plasmonic cloaks based on the application of surface integral equation (SIE) formulations.

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Although not yet widespread in optics, SIE formulations, based on the method of moments (MoM) [5], bring important advantages for the rigorous analysis of penetrable plasmonic bodies. Since only the surfaces and interfaces between materials have to be modelled, the total number of unknowns for a given problem (and thereby the computational resources) can be dramatically reduced compared with the volumetric approaches usually available in most commercial suites. This enables the possibility of designing invisibility cloaks using optimization algorithms, where different parameters can be conveniently handled, such as number of layers, geometry and material restrictions.

2. Optimization using Surface Integral Equations

In previous works we have demonstrated the accuracy and versatility of the aforementioned SIE-MoM formulations when dealing with plasmonic and metamaterials media, both for homogeneous and piecewise homogeneous objects [6], [7].

In this work, the SIE-MoM method is combined with a genetic algorithm (GA) for the design of multilayer invisibility cloaks. Both layer thickness and material composition are optimized to minimize the SCS of the cloaked object. The SCS of the different individuals at each generation in the GA is calculated from the equivalent electric and magnetic currents on the object and layer boundary surfaces and interfaces, where the equivalent currents are provided by the SIE-MoM approach. In this case, we have used the PMCHWT [8] formulation, as it has proven to be very accurate when dealing with plasmonic problems [9]. Regarding the genetic algorithm, we built on GAlib library [10], modifying it appropriately to include parallelization possibilities using MPI and OpenMP standards. We are currently carrying out optimization procedures using the Finis Terrae supercomputer (installed in the Supercomputing Center of Galicia, CESGA) and the LUSITANIA supercomputer (installed on the Supercomputing Center of Extremadura, CénitS).

3. Numerical Simulations

In order to demonstrate the feasibility of this approach for the engineering of invisibility cloaks, two examples are shown next. The first one is a metallic microscope probe, which has been covered with a two-layer invisibility cloak. Fig. 1: shows the total electric near field for the uncloaked (left) and cloaked (right) probe. It can be seen from Fig. 1: (right) that the electric field for the cloaked probe hardly suffers variation despite the presence of the object, which contrasts with the strong dispersion pattern shown in Fig. 1: (left).

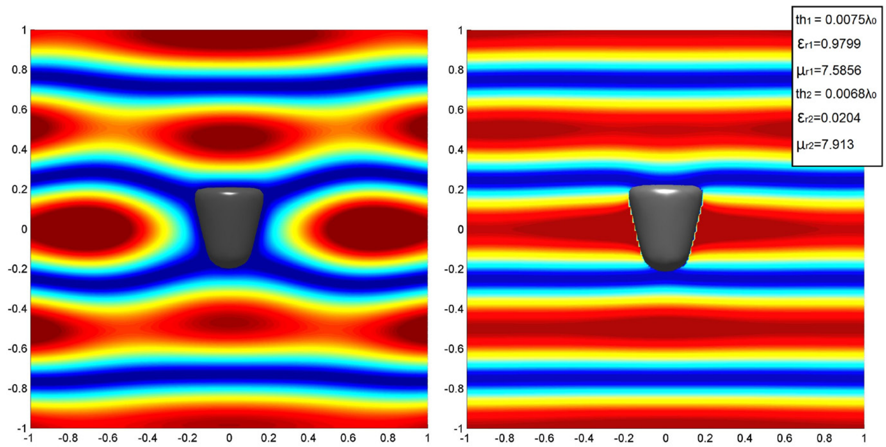

Fig. 1: Total electric near field produced by a plane wave impinging from the bottom on a microscopic probe (left) uncloaked (right) cloaked by a two-layer shell (th1= thickness inner layer, th2= thickness outer layer).

While interest in the first example is the shape of the object, the interest of the second example is its size. In this case, a metallic sphere with λ_0 diameter (λ_0 being the exterior region wavelength) has been cloaked by a properly optimized three-layer shell. Fig. 2: shows the total electric near field for the uncloaked (left) and cloaked (right) sphere, where it can be clearly seen the effectiveness of the designed invisibility cloak.

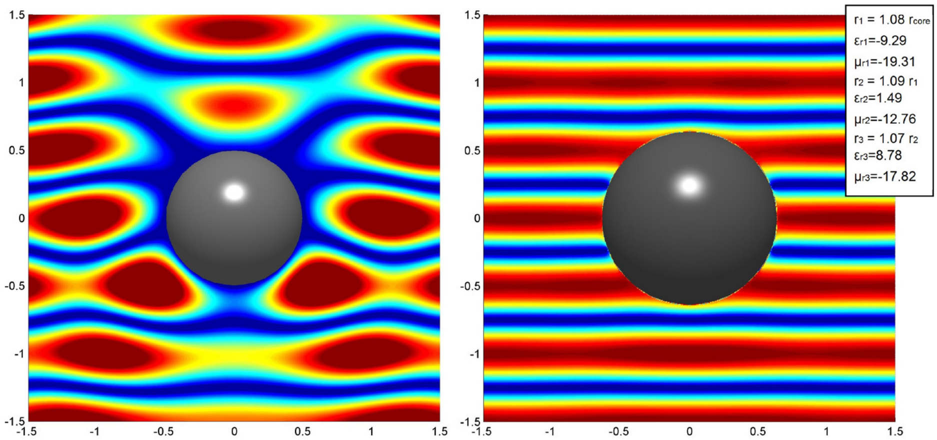

Fig. 2: Total electric near field produced by a plane wave impinging from the bottom on a metallic sphere with a diameter d=λ_0 (left) uncloaked (right) cloaked by a three-layer shell.

4. Conclusions

In view of the results obtained we can confirm the validity and versatility of the proposed cloaking optimization technique using GA and SIE-MoM formulations. The proposed procedure enables the design of multilayer invisibility cloaks for arbitrary shaped objects of moderate size. It also brings the ability to easily include different shape and/or material constraints on the cloak design, which indeed is of great interest for manufacturing purposes.

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