Available online at www.sciencedirect.com
ScienceDirect
Metamaterials 4 (2010) 149–152
Metamaterials
www.elsevier.com/locate/metmat

Resonant cloaking and local density of states

R.C. McPhedran [a,*], N.A. Nicorovici [a], L.C. Botten [b]

[a] ARC Centre of Excellence for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS), School of Physics, University of Sydney, A28, Camperdown, Sydney, NSW 2006, Australia
[b] CUDOS and Department of Mathematical Sciences, University of Technology, Sydney, PO Box 123, Broadway, NSW 2007, Australia

Received 24 November 2009; received in revised form 1 February 2010; accepted 15 February 2010

Abstract

We discuss methods for hiding of objects from detection by electromagnetic waves (cloaking), and also ways by which cloaked objects may be detected. The possibility of detection by means of thermal radiation emitted when electromagnetic energy is resonantly absorbed motivates the calculation of local density of states (LDOS), which controls the ability of a source inside a structured system to radiate. We give the first results of an investigation of the LDOS for systems which cloak by resonant interaction with electromagnetic fields.

Keywords: Metamaterials; Cloaking; Density of states; Green's functions

1. Introduction

The demonstration of the cloaking or hiding of a metal cylinder from detection by electromagnetic waves by Schurig et al. [1] launched a new subfield of wave science. Since then, cloaking has been actively researched for objects in one, two and three dimensions, and for electromagnetic waves in various frequency ranges, as well as sound and water waves. A variety of cloaking mechanisms have been investigated, of which the most usual is based on the methods of transformation optics [2,3], and guides electromagnetic waves around a central cavity by refraction, in much the same way as a mirage is created through refractive index profiling. This is a type of what may be called *internal cloaking*, in that what is to be hidden is to be placed in a cavity inside a shielding structure.

There also exists *external cloaking*, in which the object to be hidden lies in a special region outside the shielding structure. We will discuss here external cloaking due to resonant interaction, in which a hollow cylinder provides the cloaking system. The core of the cylinder has the same dielectric permittivity as the external region, while the shell of the cylinder is made of a material which, at the wavelength of interest, has a dielectric permittivity as close as possible to -1. This wavelength permits resonant electromagnetic interactions, evident in the form of strong surface waves which run along interfaces between the material and free space. Such surface wave effects are at the heart of the perfect imaging by plane interfaces of Pendry [4], as well as the phenomenon of resonant external cloaking [5,6]. There exist other recently-developed approaches to external cloaking, e.g. finite-wavelength scattering minimization using multiple plasmonic layers coating cylinders [7], a technique based on active cancellation of incoming waves by sensing and appropriate counter-radiation [8], and a cancellation technique based on cutting a hole in

* Corresponding author.
E-mail address: ross@physics.usyd.edu.au (R.C. McPhedran).

1873-1988/$ – see front matter
doi:10.1016/j.metmat.2010.02.001

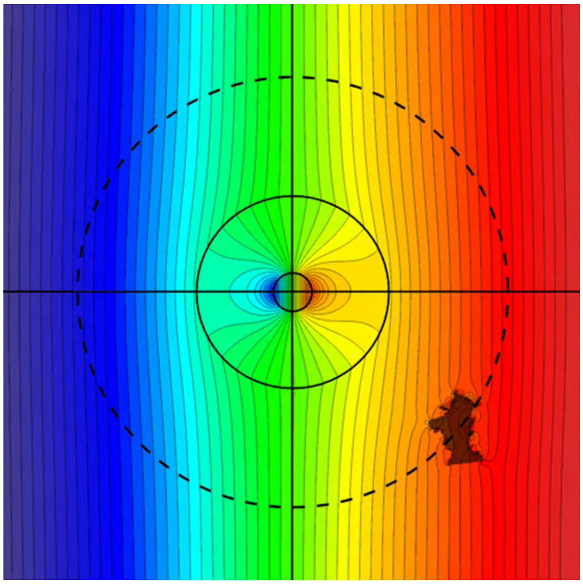

Fig. 1. One frame of the first accompanying animation. The silhouette is outlined by polarizable dipoles, whose strength diminishes as the cloaking region marked by the dashed circle is entered. The cloaking coated cylinder (at centre) is placed in a uniform applied field.

the cylinder shell complementary to the external object to be cloaked [9].

We illustrate resonant external cloaking in Fig. 1, which is one frame of the first animation accompanying this article. The cloaking system is a hollow cylinder with inner radius 0.8 μm and outer radius 4.0 μm. The material between these radii has the complex dielectric constant $-1+i0.585$, corresponding to silver used at 0.337 μm. The cloaking cylinder is placed in a uniform electric field, and a test object which has the form of a familiar silhouette outlined by polarizable dipoles approaches the cylinder. The opacity of the region inside the silhouette represents the total strength of the induced dipoles. When the test object enters the cloaking region, the reaction field due to the cloaking system is such as to cancel out increasingly well the total field acting on each polarizable dipole, leading to a fading of the filling colour until the silhouette disappears at the middle of the animation. We stress that the cloaking illustrated in Fig. 1 is for Laplace's equation, rather than the full Maxwell equations considered by Alú and Engheta, but that the demonstration which is seen to work so well here is for the actual measured data of silver at its optimal wavelength (note the substantial imaginary part ε_i of the complex dielectric constant given above). Given the very low quality factor corresponding to the value of ε_i, the cloaking effect shown in Fig. 1 has reasonable bandwidth.

2. Detecting cloaked objects

For any system conceived to cloak or hide objects from detection by electromagnetic means, there will be counter systems devisable to unmask the cloaked object. For example, if an object is perfectly concealed at a given wavelength, we might use swept-wavelength probe beams to detect it. If the object were concealed using a scheme which worked over a wide range of wavelengths, but relied on knowing the direction of the incoming probe wave, then multi-static detection systems incorporating several antennas illuminating at several quite different angles would be effective in revealing the object.

Another way of detecting cloaked object is particularly relevant to cloaking methods which generate resonant fields in lossy materials (such as those shown in Fig. 1). Those intense local fields, in general, would radiate excess infrared radiation as a consequence of ohmic heat generation, and that radiation could be detected using a passive sensing method. Similarly, structured material systems incorporating metals and other absorptive materials would in general alter the radiation rates of atoms or molecules inside or close to them, thus again enabling passive detectability.

We might define an *ideal cloaking system* as one capable of hiding objects from any means of electromagnetic detection, whether active or passive. Necessary conditions for such an ideal system would then be cloaking over a wide range of frequencies and angles, and also no excess emission of thermal radiation, and no alteration of radiation rates of sources in its vicinity.

In order to investigate the third and fourth types of detection, one convenient tool is the Local Density of States (LDOS) [10]. This quantifies the effect of structuring electromagnetic media on the radiation properties of sources within or close to them. It may be used in semi-classical treatments of radiation processes, where quantum mechanics is used for the atom or molecule, but classical electromagnetism determines the density of available states into which radiation can occur. Technically, one way of calculating the LDOS is through the electromagnetic Green's function, or Green's tensor, which depends on the source point and the field point. The LDOS is given by the imaginary part of the Green's function, or the trace of the transverse part of the Green's tensor, as the field point tends to the source point:

$$\rho(\mathbf{r};\omega) = \frac{2\omega}{\pi c^2} Im[\lim_{r'\to r} \operatorname{Tr}\mathbf{G}(\mathbf{r},\mathbf{r}')] \tag{1}$$

The prefactor in Eq. (1) is for sources in two dimensions, for which the LDOS in a homogeneous,