Broadband Electromagnetic Cloaking of Long Cylindrical Objects

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Electromagnetic cloaks are devices that make objects undetectable for probing with electromagnetic waves. The known realizations of transformational-optics cloaks require materials with exotic electromagnetic properties and offer only limited performance in narrow frequency bands. Here, we demonstrate a wideband and low-loss cloak whose operation is not based on the use of exotic electromagnetic materials, which are inevitably dispersive and lossy. Instead, we use a simple structure made of metal layers. In this Letter, we present an experimental demonstration of cloaking for microwaves and simulation results for cloaking in the visible range.

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The question of the technical possibility of making objects invisible to the eye or for radar has attracted the attention of researchers for a long time. Recently, possibilities to design cloaking devices capable of hiding physical objects from waves of different nature have been studied very actively. Most of the attention has been given to designs based on the coordination transformation technique [1,2] (see also earlier theoretical results [3–5]). The physical realization of electromagnetic cloaks using this principle requires lossless anisotropic materials with some components of the effective relative permittivity and permeability smaller than unity and going to extreme values of zero. Because of fundamental limitations on the properties of passive media, it is not possible to realize materials with such properties in a wide frequency band and with low losses. Alternatively, the total scattering cross section can be reduced using cancellation of scattering from different parts of an object [6,7], which can be potentially designed for multiple frequencies utilizing multiple shells around the cloaked object [8]. The known experiments [9,10] use metamaterial composite structures to realize anisotropic effective media behaving in accordance with the transformational-optics design. The required magnetic properties can be realized only using resonant inclusions [9] and required electric properties can be realized with plasmonic materials [11]. Because of dispersion and associated losses in these materials, realized prototypes demonstrate only limited reduction of object visibility in rather narrow frequency bands. There are relatively broadband solutions based on artificial surfaces, but they work only for a certain fixed direction of incident waves [12]. Also, cloaking objects located near a reflective surface does not require extreme material parameter values [13] and can be realized as dielectric structures with spatially variable permittivity [14–16], but this simple approach is unfortunately not applicable to hiding volumetric objects in free space.

Broadband cloaking was demonstrated for cylindrical structures at microwaves, both by simulations and experiments [17]. That design is not based on the transformation electromagnetics approach. Instead, the electromagnetic energy of incident waves is squeezed into a network of transmission lines going through the cloaked volume [18]. The volume between the transmission lines is cloaked because there is virtually no field. However, the applicability of that approach is limited to hiding objects that allow building of a transmission-line network through its volume. Here, we show how that limitation can be overcome and demonstrate that cylindrical objects can be effectively cloaked from a wide spectrum of electromagnetic radiation using simple structures made of conducting layers. The cloaking effect is experimentally demonstrated in a rectangular waveguide, where a metal structure in the center of the waveguide is made "invisible" when surrounded by the cloak. Although reasonably broadband designs are realizable, we would like to note that no perfect cloaking for broadband signals is possible due to causality restrictions [19].

The geometry of the proposed cloaking device is shown in Fig. 1. An electrically or optically long cylindrical object (for example, a conducting cylinder) strongly scatters if it is illuminated by an electromagnetic wave whose electric field is polarized along the cylinder axis. In our design, a cylinder of diameter D is cloaked by a set of annular metal layers (the outer diameter L_1). The layers form a periodical (along the cylinder axis z) set of parallel-plate waveguides with the height smoothly varying from H to h.

When a plane electromagnetic wave propagates in free space, its propagation is not disturbed if we place a set of parallel perfectly conducting sheets so that the sheets are orthogonal to the electric field vector. Thus, an interface between free space and such a set of conducting sheets is perfectly matched for this polarization of plane waves. Furthermore, this property does not depend on the distance between the conducting sheets. The idea of the proposed cloak design is to gradually reduce the volume occupied by the fields of propagating waves by gradually decreasing the

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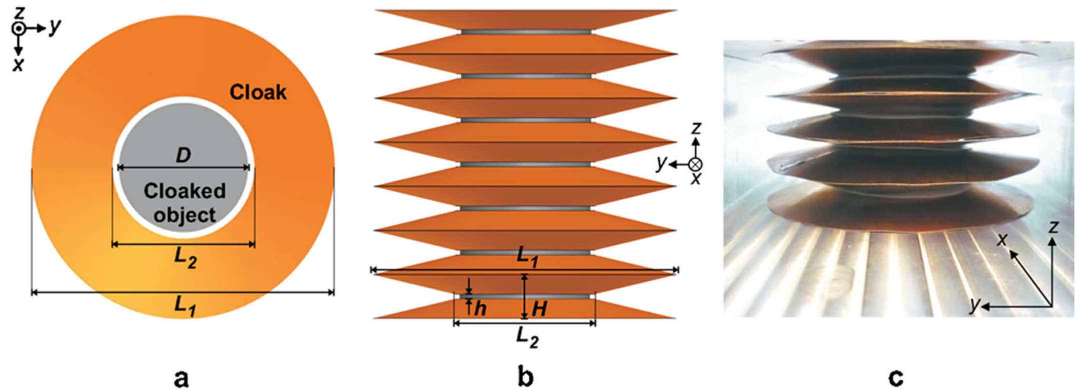

FIG. 1 (color online). Geometry of the cloak in (a) xy and (b) yz planes. (c) Photograph of the measurement setup enclosing the cloak. In numerical simulations, the cloak is assumed to be periodically infinite along the z axis.

distance between the plates in each pair. Because the matching between free space and a set of conducting plates does not depend on the distance between the plates, we expect that electromagnetic waves will propagate inside the structure with negligible reflections, provided the distance between the plates is changing enough smoothly. Because the height of the parallel-plate waveguides is reduced towards the center, the amplitudes of both electric and magnetic fields become higher close to the cloaked volume approximately in the same proportion. Although for the waves everywhere inside the cloak the structure remains impedance-matched to free space, waves practically do not penetrate inside the cloaked volume because the field distribution of the wave inside the cloak in the vicinity of the inner interface is dramatically different from that of a plane wave in free space: The fields inside the cloak are concentrated in tiny openings between the sheets. Instead of propagating into the cloaked volume, waves travel around the central opening because the structure is locally isotropic and has the same wave impedance for all propagation directions in the cloak plane. In other words, for a wave traveling towards the cloaked volume, it is not possible to continue inside the central opening, but in the direction around the object, there is an equivalent transmission line, which is also matched with free space.

The above simple explanation of the device operation does not take into account reflections and slightly varying phase velocity of waves in waveguides of varying height, as well as small reflections near the inner interface. These effects lead to smooth variations in the cloak performance over the operational frequencies. At some frequency, we observe the optimal performance, when the phase delay for waves traveling through the cloak is the same as that of waves which would travel through the same space in the absence of both the cloaked object and the cloak, but the operational bandwidth is still extremely large as compared to known realizations of transformational-optics cloaks.

First, we present a design of a microwave cloak. Results of numerical simulations, conducted with the Ansoft HFSS software, are shown in Fig. 2(a) for the following dimensions: $L_1 = 70$ mm, $L_2 = 32$ mm, $H = 9.2$ mm, $h = 1$ mm, $D = 30$ mm (following the notations of Fig. 1). The cloak consists of copper layers of the thickness of 10 μm, and the cloaked object is a copper cylinder. The cloaking effect is characterized by computing the scattering cross section of the cloaked object, normalized by that

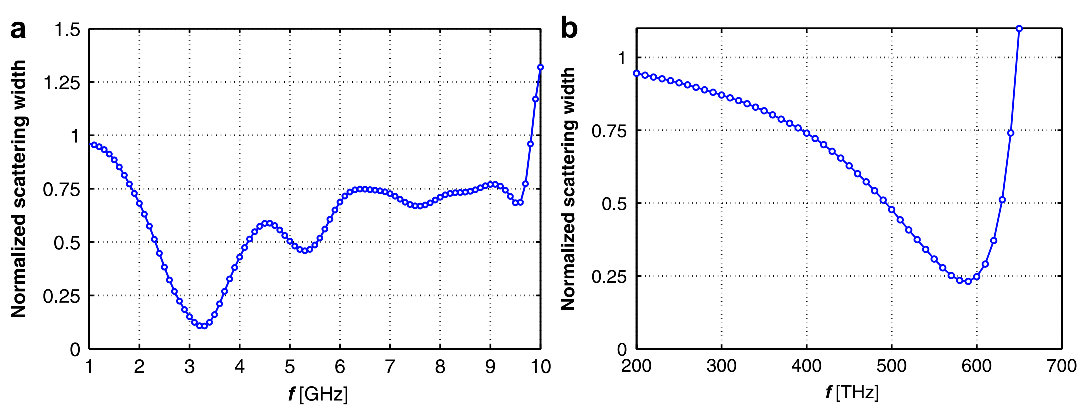

FIG. 2 (color online). Frequency dependence of the total scattering width of the cloaked cylinder normalized by the total scattering width of the same cylinder without the cloak. (a) Microwave cloak. (b) Optical cloak.

of the uncloaked object. In the present case of an infinite cylinder, we calculate parameters per unit length, that is, the scattering width. The total scattering width is calculated integrating the scattering width over all the angles in the xy plane. For these dimensions, the optimal cloaking effect is observed at the frequency of 3.2 GHz, where the total scattering width of the cloaked object is about 90% smaller than the same parameter of the same object but without the cloak. The bandwidth in which the total scattered power is reduced at least by 50% is approximately from 2.3 to 4.2 GHz. The operational principle is illustrated by Fig. 3, where we can see how the electric field and the Poynting vector of the electromagnetic wave are distributed inside the cloak structure.

The experimental setup which we have used to demonstrate the cloak performance is similar to the one described previously [17]. A metal cylinder (the object that we want to cloak) is positioned in the middle of a rectangular waveguide section and connected to both wide walls of the waveguide. The waveguide section is connected to the network analyzer via two coaxial probes. The cloak consists of four periods depicted in Fig. 1 (i.e., eight cone-shaped copper plates in total) with the dimensions given above. The gaps between the adjacent copper plates ($h = 1$ mm) are realized by placing dielectric layers around the inner boundary of the cloak (Rohacell, $\epsilon_r = 1.05$), as shown in Fig. 1(c). The waveguide dimensions are $435 \times 86.36 \times 36.8$ mm^3 (length × width × height), and, together with the coaxial probes, the section is designed to have a wide passband around 3 GHz [17]. The measured results are presented in Fig. 4. The metal cylinder in the middle of the waveguide creates a short circuit and strongly reflects waves back to the source, but with the cloak structure around the object, the reflection coefficient is quite close to that of the empty waveguide section. As expected, close to the design frequency of 3.2 GHz, the phase of the transmitted wave is the same as for a wave transmitted through the empty waveguide, despite the presence of the metal cylinder.

The cloak design is scalable for various frequency ranges. This we demonstrate by numerically simulating a cloak structure which is operational in the visible. In this case, we replace the set of thin metal layers by a silver cylinder with etched cylindrical grooves, forming the same external shape as shown in Fig. 1. The simulated dependence of the reduction of the total scattering width is shown in Fig. 2(b) for the following dimensions: $L_1 = 226$ nm, $L_2 = 130$ nm, $H = 13$ nm, $h = 2.5$ nm, $D = 100$ nm. The material of the cloak and the metal cylinder in the middle (the cloaked object) is silver, whose permittivity is modeled according to widely referenced data [20], taking into account material losses. These results lead us to the

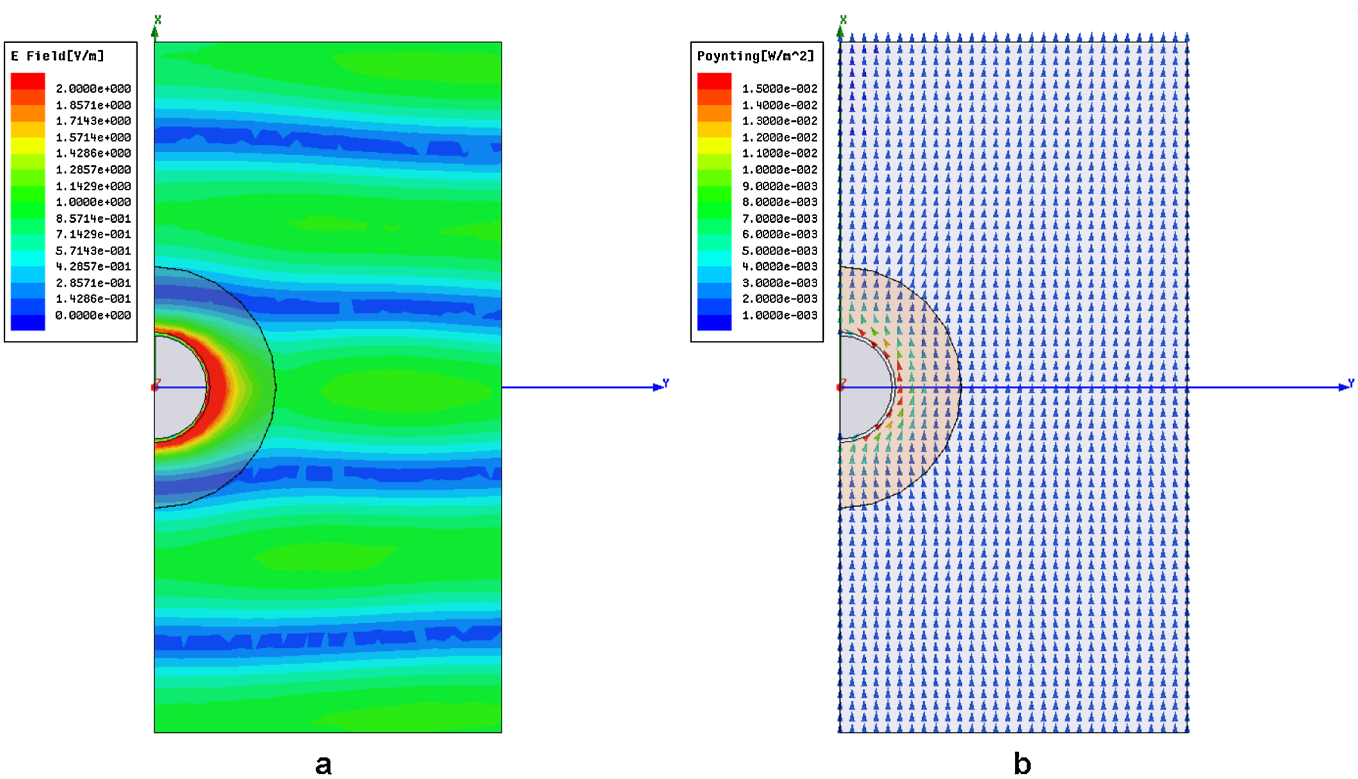

FIG. 3 (color online). Results of numerical simulations of fields in the cloak structure at 3.2 GHz. The pictures show distributions in the xy plane centered between two copper plates of one of the cloak's periods. Because of the symmetry, only one half of the total structure has been simulated. (a) Snapshot of time-harmonic electric field. (b) Poynting vector distribution.

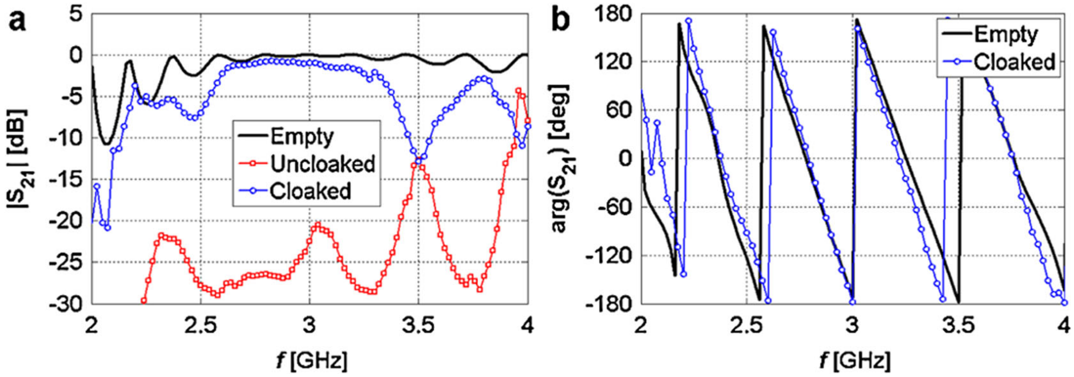

FIG. 4 (color online). Measured transmission coefficients through an empty waveguide section as well as a waveguide section with an uncloaked and a cloaked metal short-circuit post in the middle. (a) Absolute value. (b) Phase.

conclusion that this cloaking solution does not require any exotic materials with extreme parameters, enabling broadband operation. With an appropriate choice of the structure dimensions, the cloak can operate at frequencies from microwaves to the visible light and possibly beyond.

Finally, we note that similar cloaking geometries formed by tapered metal-plate waveguides have been introduced and demonstrated for the orthogonal polarization (electric field parallel to the plates) [21,22]. In that case, the waves inside the cloak become evanescent closer to the structure center [22] or are evanescent in its whole volume [21]. This indicates that there may be a possibility to realize a cloak for both polarizations by properly designing the structure geometry.

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