An infrared invisibility cloak composed of glass

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We propose to implement a nonmetallic low-loss cloak for the infrared range from identical chalcogenide glass resonators. Based on transformation optics for cylindrical objects, our approach does not require metamaterial response to be homogeneous and accounts for the discrete nature of elementary responses governed by resonator shape, illumination angle, and inter-resonator coupling. Air fractions are employed to obtain the desired distribution of the cloak effective parameters. The effect of cloaking is verified by full-wave simulations of the true multiresonator structure. The feasibility of cloak fabrication is demonstrated by prototyping glass grating structures with the dimensions characteristic for the cloak resonators. © *2010 American Institute of Physics*.
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Recent work on transformation optics[1,2] has revealed a path toward creating an invisibility cloak from metamaterials with a prescribed spatial dispersion of effective parameters, in particular, with radial dispersion of the cloak effective permeability/permittivity for transverse-electric (TE)/transverse-magnetic (TM) illumination of cylindrical objects.[3,4] Cloaking effects have been observed for concentric arrangements of metal resonators both experimentally at a microwave frequency,[3] and in simulations.[3,4] The latter works used cloak models consisting of effective material layers with assigned properties instead of actual resonators. Such approach is expected to provide correct results if the medium response is homogenous that is not always true even for conventional metamaterials.[5]

Here we propose a low-loss cylindrical cloak for the infrared range composed of identical nanosized chalcogenide glass resonators, where air fractions are employed to obtain spatial dispersion of the effective permeability. We demonstrate the feasibility of glass cloak fabrication and verify its performance by simulating the true multiresonator structure.

Implementation of an optical cloak from dielectric resonators requires a material with relatively high refractive index. We have chosen a GeSbSe chalcogenide glass composite that exhibits low loss and a dielectric constant (10.5–12) at (1–1.5) μm [Fig. 1(a)].[6] Since dielectric resonators support resonance modes with different field configurations,[5] we determined their optimal shape and dimensions for the formation of magnetic moments along their specific axis at incidence angles ranging between 0° and 90°. When positioned in concentric arrays, such resonators formed radial magnetic moments at plane wave incidence and provided angularly independent radial component of the effective permeability over the cloak. The resonance responses of glass resonators were simulated by using the full-wave software package CST MICROWAVE STUDIO. The best results were obtained for cylindrical resonators with diameters twice as large as their height, which supported magnetic moments along their axes at incidence angles ranging between 15° and 90°. Compared to resonators of other shapes, circular cylinders were also found to produce magnetic resonances with a higher Q and with minimal overlapping between the neighboring modes. The dimensions for the cylindrical resonators were chosen to provide their response for a frequency of about 300 THz

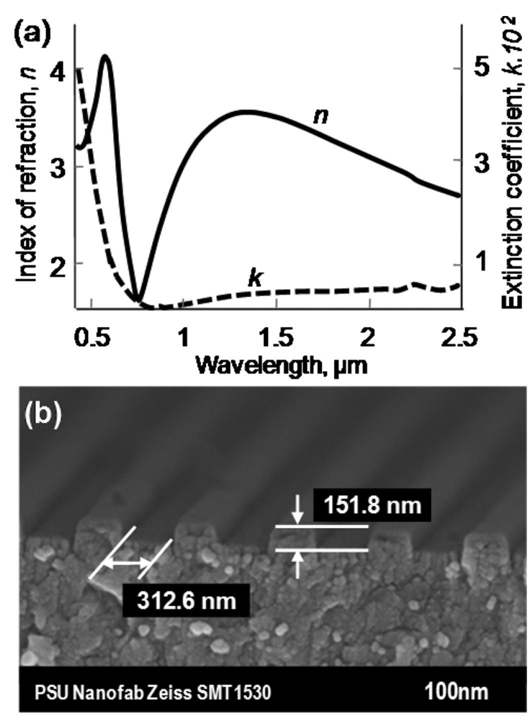

FIG. 1. Spectral behavior of refractive index and extinction coefficient of a GeSbSe thin film (a) and a GeSbSe grating structure fabricated by using e-beam patterning (b).

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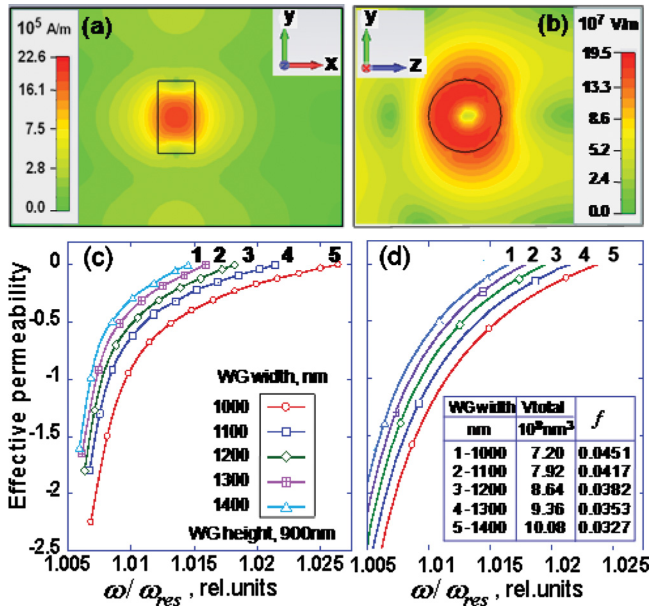

FIG. 2. (Color online) Halos of magnetic (a) and electric (b) fields around cylindrical glass resonator, and frequency dependencies of μ_r^{eff} extracted from simulated scattering parameter spectra for single-resonator unit cells of different widths (c), and analytically calculated for these cells with $V_{\mathrm{halo}}=0.35\times10^8$ nm^3 (d).

(1 μm wavelength in air), i.e., a diameter of 300 nm and a height of 150 nm. Although the dimensions of resonators were larger than $\lambda/10$ because of relatively low permittivity of glass, possible diffraction effects were taken into account by subsequent simulation of the true multiresonator structure. To demonstrate the feasibility of glass resonator fabrication, we have deposited nanosized glass grating structures with characteristic widths of the mesas and trenches of 300 nm and height of the mesas of 150 nm [Fig. 1(b)].

Fabrication tolerance issues at nanodimensions of glass cylinders exclude employment of resonators with slightly different prescribed dimensions for obtaining radial dispersion of the effective permeability μ_r^{eff}.[3] Instead, we used identical resonators throughout the shell, maintained the same quantity of resonators in all concentric arrays, and increased air fractions F_i from the inner to the outer layer of the cloak. In this way, it was possible to achieve the radial growth of μ_r^{eff} from 0 to 1. In order to correctly determine F_i we took into account the formation of field halos around the resonators, i.e., the extension of resonance fields beyond the cylinder bodies [Figs. 2(a) and 2(b)]. Then the air fraction could be expressed through the cloak volume reduced by the total volume of halos. To estimate the halo volume V_{halo} we simulated scattering parameter spectra for several unit cells having different air volume (different size) and then extracted the dependences of μ_r^{eff} on frequency by using the standard retrieval procedure[7] [Fig. 2(c)]. As shown by Pendry *et al.*,[8,9] μ_r^{eff} for a medium composed of resonators and air could be described by the following expression:

$$\mu_r^{\mathrm{eff}} = 1 - \frac{f\omega^2}{\omega^2-\omega_{\mathrm{res}}^2+j\gamma\omega} = 1 - f\mu_r^{\mathrm{res}}, \tag{1}$$

where $f=1-F$ is the resonance-related filling factor related to the interior volume of the resonators, $\mu_r^{\mathrm{res}}=(1-\omega_{\mathrm{res}}^2\omega^{-2}+j\gamma\omega^{-1})^{-1}$, ω is the angular frequency, ω_{res} is the frequency of the magnetic resonance, and γ is the damping factor. Although Eq. (1) is considered in some papers as not casual, no essential differences between this expression and modified expressions for μ_r^{eff} were found.[10] Equation (1) suggests that, when the cell size (and the air fraction F) increases, the plasma frequency ω_p (at which $\mu_r^{\mathrm{eff}}=0$) shifts toward ω_{res}, since $\omega_p=(\omega_{\mathrm{res}}/\sqrt{f})=\omega_{\mathrm{res}}\sqrt{V_{\mathrm{cell}}/V_{\mathrm{res}}}$. We found that the shifts in ω_p predicted by Eq. (1) for the cells of different sizes [Fig. 2(d)] matched similar shifts observed for the dependencies of μ_r^{eff} on frequency extracted from simulations [Fig. 2(c)] at $V_{\mathrm{res}}=V_{\mathrm{halo}}=0.35\times10^8$ nm^3. This value appeared to be about three times as large as the volume of the resonator itself 0.106×10^8 nm^3. We used the obtained value of V_{halo} for estimation of both F_i and the minimal inter-resonator distance $\sqrt[3]{V_{\mathrm{halo}}}$ required to avoid strong overlapping of resonance fields and mode splitting.

The above value of V_{halo} defines the maximum quantity of resonators in the first and, respectively, all other concentric arrays of resonators by the number $N_{\max}=2\pi r/(\sqrt[3]{V_{\mathrm{halo}}})^{-1}$, where r is the inner radius of the cloak. As an example, when $r=6.5$ μm then $N_{\max}=60$. Since the resonance-related filling factor for the first (inner) array of resonators is $f_1=NV_{\mathrm{halo}}/V_1$, where $V_1=\pi h(2r\delta+\delta^2)$ is the volume of the first layer, δ is its thickness, and h is its height (the centers of resonators are located at $r+\delta/2$), then at $h=\delta=\sqrt[3]{V_{\mathrm{halo}}}$ we obtain $f_1=0.11$. Since the resonance response from the first layer should produce $\mu_r^{\mathrm{eff}}=0$, then the operating frequency ω of the cloak within the low-loss approximation (when $\gamma=0$) could be defined by $\omega=\omega_{\mathrm{res}}(1-f_1)^{-0.5}$ resulting in $\omega/\omega_{\mathrm{res}}=1.06$.

At equidistant placement of the resonator arrays in the cloak, the volume of the ith layer is $V_i=\pi hD_i$, where $D_i=2r_1\delta+(2i-1)\delta^2$. Assuming that there is the same quantity of resonators N in each layer, it follows that: $F_i=1-NV_{\mathrm{halo}}/\pi hD_i$, and hence F_i and μ_r^{eff} should increase outward from the center of the cloak. However, this radial growth does not follow the square law prescribed by transformation optics for cylindrical cloaks as follows:[3]

$$(\mu_r^{\mathrm{eff}})_i = \left(\frac{r_i-r}{r_i}\right)^2 = \left(1-\frac{r}{r_i}\right)^2, \tag{2}$$

where r_i is the radius to the center of the ith array. In order to fit the radial dispersion of μ_r^{eff} in the glass cloak to Eq. (2), we gradually decreased the distances between the neighboring concentric resonator arrays from the inner toward the outer layer. Assuming that V_{halo} is the same throughout the cloak, we can express the effective permeability of the ith layer in terms of the ratio of the products δr for the first and the ith layers as: $(\mu_r^{\mathrm{eff}})_i=1-(\delta_1 r_1/\delta_i r_i)$. This expression was used to determine the values of r_i required for fitting Eq. (2). Since the interarray distances $\Delta_i=r_{i+1}-r_i$ should exceed $\sqrt[3]{V_{\mathrm{halo}}}$ to avoid overlapping of halos, the total number of possible layers in the cloak is limited.

After comparing different arrangements of resonators within the arrays, it was found that locating the resonators along radial spokes (Fig. 3) provided better conditions for radial orientation of magnetic dipoles and stronger resonance fields compared to other layouts, where interarray coupling distorted the radial orientation of dipoles. The spoke-type arrangement of resonators is also favorable for fabrication, since the structure could be formed by intermittent deposi-

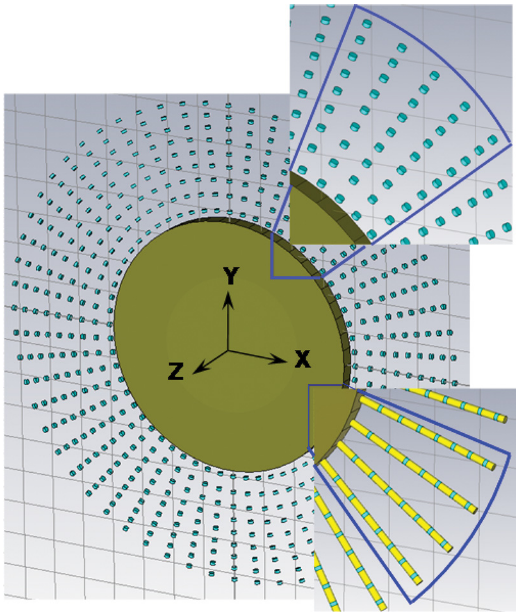

FIG. 3. (Color online) A glass cloak designed to hide a metal cylinder of 15 μm in diameter; upper inset highlights different distances between the resonator arrays; and lower inset depicts cylindrical spokes comprising glass resonators and fused silica spacers.

tion of glass and spacer material (e.g., fused silica) and patterned by using e-beam lithography (Fig. 3).

The performance of the proposed cloak was verified by simulation of the entire multiresonator structure with a hidden metal cylinder inside at TE plane wave incidence. It is worth mentioning that simulations of a true cloaking structure have been recently reported for a terahertz cloak composed of differently sized barium strontium titanate (BZT) resonators.[9] However, no proof of the proper excitation of the magnetic mode in the resonators was presented, simulations were performed at a single frequency, and the size of the hidden object was only a half-wavelength. In comparison, we simulated cloaked objects with dimensions ranging from five to ten wavelengths and visualized the performance of all resonators within the cloak over a wide frequency. We applied periodic boundary conditions to simulate an infinitely long cylindrical cloak. As an example, Fig. 4(a) demonstrates reconstruction of the incident wave front after it passes the object, while Fig. 4(b) shows a "shadow" from the cloak when the cloaking effect disappears. Although the value of the effective permittivity in this design was about 1.2 (smaller than the required value 2.7),[3] this difference did not significantly disturb the cloak's performance. By placing H- and E-field probes in front and behind the cloak we determined that the average transmitted power in the pass band was three times higher than the transmitted power outside this band. In the presented example, the cloaking effect was observed within the 3.5 THz band (1.2% bandwidth), however, this band could be increased up to 8 THz (2.8% bandwidth) for cloaks with larger inner diameters and optimized coupling. Detailed coupling studies will be reported elsewhere.

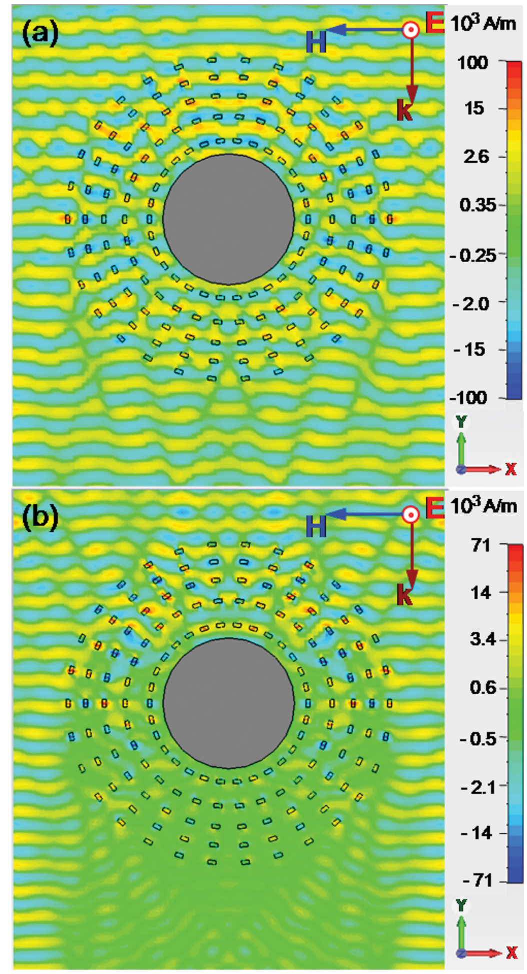

FIG. 4. (Color online) Simulation of TE plane wave incidence on an infinite five layered cloak of 4 μm thickness concealing a metallic object of 5 μm in diameter. The effective permeability values of the first to fifth layers are 0; 0.056; 0.134; 0.2; and 0.257, respectively. Corresponding radii of these layers are 3000, 3925, 4720, 5430, and 6095 nm. Cloaking at 286.3 THz (a) and shadow at 297.1 GHz (b).

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