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. [doi:10.1063/1.3447794]

Recent work on transformation optics1,2 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,7 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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from simulated scattering parameter spectra for single-resonator unit cells of identical resonators throughout the shell, maintained the dependences of $\mu_\text{eff}$ on frequency extracted from simulations [Fig. 2(c)] at $V_{\text{res}}=V_{\text{halo}}=0.35 \times 10^8 \text{ nm}^3$. This value appeared to be about three times as large as the volume of the resonator itself $0.106 \times 10^8 \text{ nm}^3$. We used the obtained value of $V_{\text{halo}}$ for estimation of both $F_i$ and the minimal inter-resonator distance $\delta$ required to avoid strong overlapping of resonance fields and mode splitting.

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

At equidistant placement of the resonator arrays in the cloak, the volume of the $i$th layer is $V_i=\pi h D_i$, where $D_i=2r_i\delta+(2i-1)\delta^2$. Assuming that there is the same quantity of resonators $N$ in each layer, it follows that: $F_i=1-NV_{\text{halo}}/\pi h D_i$, and hence $F_i$ and $\mu_\text{eff}$ 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:

$$\mu_\text{eff} = \left(\frac{r_i-r}{r_i}\right)^2 = \left(1-\frac{r_i}{r_i}\right)^2, \quad (2)$$

where $r_i$ is the radius to the center of the $i$th array. In order to fit the radial dispersion of $\mu_\text{eff}$ 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 $V_{\text{halo}}$ is the same throughout the cloak, we can express the effective permeability of the $i$th layer in terms of the ratio of the products $\delta r$ for the first and the $i$th layers as: $(\mu_\text{eff})_i = 1 - (\delta r_i/\delta r)$. 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 $\delta V_{\text{halo}}$ 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 deposition.

(1 $\mu\text{m}$ 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 by subsequent simulation of the true multiresonator structure.
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. 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), 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.

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