Metal-dielectric metamaterials for transformation-optics and gradient-index devices at visible wavelengths

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Abstract

We theoretically investigate an optical metamaterial consisting of periodically arranged silver spheres embedded in a host medium of PMMA. We demonstrate that this metamaterial can be used to fabricate a cylindrical cloaking device operating at visible wavelengths. The presented metamaterial utilizes the tunability of the plasmonic interactions between the metallic nanoparticles which depend on distance and size. The presented concept is also applicable to gradient-index devices with an isotropic permittivity distribution. We show this for the optical black hole.

1. Introduction

Transformation optics allows controlling the path of light in a desired fashion by adequately tailoring the permittivity and permeability. The most prominent device that can be suggested by transformation optics is an invisibility cloak [1,2]. The emerging field of metamaterials made it possible to realize transformation-optics devices by engineering materials that exhibit the required permittivity and permeability distribution.

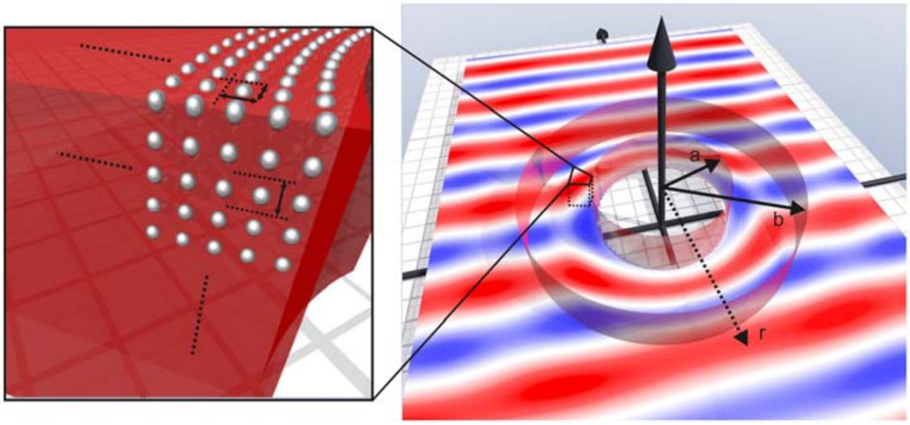

Fig. 1: A cylindrical cloaking shell of inner radius *a* and outer radius *b* guides light around the inner cylindrical core. The inset shows a segment of the cloaking shell consisting of silver spheres periodically placed in a host medium of PMMA.

However, the extraordinary material parameters that need to be obtained make a realization very challenging. For example, a cylindrical cloaking device, which guides light around an object, has up to now only been realized in the microwave regime [3]. In this contribution we give an experimentally realizable approach how to bring the operating frequency of a cylindrical cloak to the visible regime. The presented approach uses silver spheres included in a host medium of PMMA and exploits the

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plasmonic excitations that emerge when the metal spheres are very close together. In contrast to previous work which proposes metal needles of small size that are radially aligned [4], the spherically-shaped inclusions do not need to be specifically orientated in the host medium. Fig. 1 shows a cylindrical cloak together with a segment of the cloaking shell consisting of silver spheres periodically placed in the host medium.

2. Tailoring of the permittivity tensor

The key ingredient of our structure is the tailorability of the plasmonic resonances. Fig. 2(a) exemplarily shows a density plot of the transmission coefficient $|S_{21,r}|$ (the measured transmission T ist defined as $T = |S|^2$) of an array of silver spheres (the diameter was set to d = 12 nm) with respect to the particle distance in radial direction (l_r). It can clearly be seen that the spectral resonance position strongly depends on the particle distance when the particles are very close together (see also Ref. [5]). Selected transmission curves from the density plot along with the corresponding reflection spectra are displayed in Fig. 2(b). Fig 2(c) shows the retrieved permittivity calculated with the retrieval method of Smith and coworkers [6]. The variation of the particle distances increases or decreases the interaction strength of the particles. This results in a shift of the permittivity at a given frequency of interest, enabling us to obtain the permittivity profile that is needed for cylindrical cloaking.

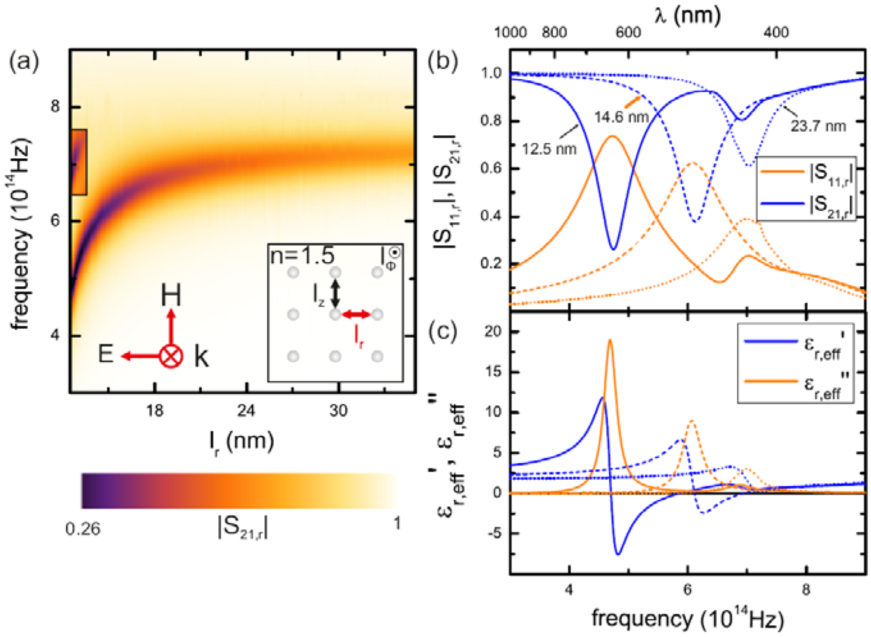

Fig. 2: Tailoring of the permittivity tensor via distance-dependent surface plasmon resonances. (a) Magnitude of the transmission coefficient $|S_{21,r}|$ with respect to frequency and the extension of the particles (d = 12 nm) in r direction. (b) Exemplary $|S_{21,r}|$ curves from the density plot and their corresponding reflection coefficient curves ($|S_{11,r}|$). (c) Retrieved real and imaginary part of the effective permittivity in r direction.

3. Design optimization of the cylindrical cloak and the optical black hole

To examine the validity of our approach we substituted the retrieved permittivities into a commercial full-wave simulation program and compared the electric field pattern with that of a "perfect" cylindrical cloak (Fig. 3(a) and (b)). We find that the cloaking performance of our proposed device is reasonably good. The operating frequency $f = 6.65 \cdot 10^{14}$ Hz (λ = 451.13 nm) is in the visible regime.

The concept of tailored surface plasmon resonances in metal-dielectric composites is also applicable to gradient-index devices which require an isotropic permittivity distribution. We demonstrated this for a so-called optical black hole [7], an omnidirectional light absorber (Fig 3(c)).

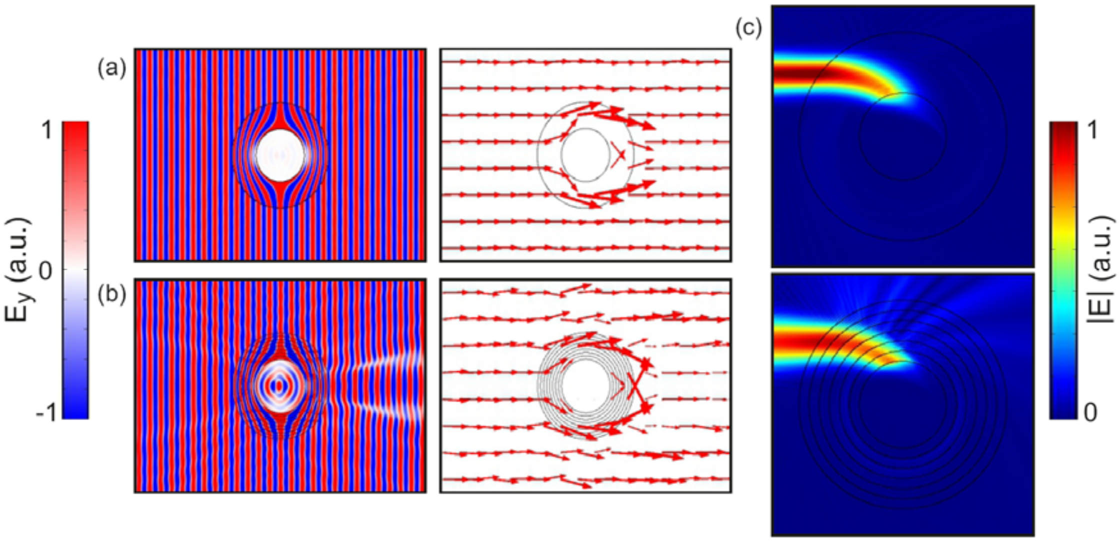

Fig. 3: (a) Simulation of the cylindrical cloaking device with its continuous-ideal parameters. The E_y field and the power flow of a p polarized, plane wave incident on the cloak is displayed. (b) Simulation of the cloak with the retrieved parameters of the metal-dielectric metamaterial (8 layers). In both (a) and (b) the operating frequency is f = $6.65{\cdot}10^{14}$ Hz (λ = 451.13 nm). Material losses have been neglected. (c) shows the simulation of the optical black hole with continuous-ideal (upper) and retrieved parameters (lower, 6 layers). The operating frequency is $f = 3{\cdot}10^{14}$ Hz (λ = 1000 nm).

4. Conclusion

We present a pathway towards the realization of a cylindrical cloaking device at visible frequencies as well as the optical black hole in the near-infrared regime. The necessary permittivity profiles can be obtained by varying the distances between silver spheres in a PMMA matrix and, thereby, changing the surface-plasmon resonance.

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