

Concentric Metawaveguide Cloaking

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Abstract

We introduce here a novel type of cloaking, based on a circular concentric meta-waveguide structure, where the metawaveguides are bent waveguides with porous metasurface walls. In contrast to the cloak implementation reported in [Schurig et al. \(2006\)](#), which only *approximates* the ideally perfect transformation-optics cloak because of prohibitive fabrication complexity, this cloak is designed ab initio for optimal cloaking, and offers therefore largely superior performance. Its combined simplicity and performance arguably makes it the most practical existing cloak reported so far.

1 Introduction

Cloaking is one of the most popular applications of metamaterials. Practical cloaking techniques may be classified in four main categories: 1) transformation optics [Pendry et al. \(2006\)](#), 2) plasmonic scattering cancellation [Alù and Engheta \(2005\)](#), 3) transmission-line matching [Alitalo and Tretyakov \(2009\)](#), and 4) redirection cloaking [Dehmollaian and Caloz \(2020\)](#).

Unfortunately, each of these techniques suffers from some major drawback. Transformation optics cloaking requires a complex nonuniform and bianisotropic medium [Schurig et al. \(2006\)](#), scattering cancellation cloaking is restricted to electrically small objects [Fleury et al. \(2015\)](#), transmission-line matching cloaking implies penetration through the object to cloak [Alitalo and Tretyakov \(2009\)](#), and redirection cloaking is restricted to a specific incidence angle [Dehmollaian and Caloz \(2020\)](#).

The recent spectacular developments in metasurface technology [Achouri and Caloz \(2021\)](#) may offer new avenues for cloaking that would be immune to the issues mentioned above. In this context, we present here a novel form of cloak, formed by a set of circular concentric porous metasurface cavities, or a *concentric metawaveguide cloaking*, which operates in a fundamentally different fashion than the approximation of the transformation optics cloak presented in [Schurig et al. \(2006\)](#).

2 Operation Principle

Transformation optics provides perfect cloaking [Pendry et al. \(2006\)](#). Unfortunately, it involves a complex nonuniform bianisotropic medium whose fabrication is prohibitively challenging. This issue constrained Schurig et al. to sacrifice some of the parameters of the perfect cloak in their proof-of-concept experimental prototype [Schurig et al. \(2006\)](#), and the resulting *imperfect cloak* displayed a forward scattering shadow even in the ideal case of perfect homogeneity [Schurig et al. \(2006\)](#).

Our cloak has the same concentric topology as the imperfect cloak built in [Schurig et al. \(2006\)](#): it is also composed of thin concentric 'metasurfaces'¹. However, its design and operation is fundamentally different. It is indeed designed ab initio for (quasi-)perfect cloaking, and is therefore immune from any approximation imperfection. As a result, as will be shown at the conference, it has different meta-parameters than those of the prototypes in [Schurig et al. \(2006\)](#), and exhibits largely superior performance.

¹At the time of the publication of [Schurig et al. \(2006\)](#), which is already 15 years ago, metasurfaces were in their infancy, and the authors of that paper did not even refer to their concentric structures as metasurfaces.

In fact, our cloak, instead of gradually deflecting waves according to an equivalent curvature of spacetime achieved by nonuniform bianisotropy, guides the illuminating wave around the object to cloak via curved waveguides made of penetrable metasurface walls, which we refer here to as porous or leaky *metawaveguides*, as illustrated in Fig. 1. The metasurfaces are separated by a quarter of the wavelength, so as to form a kind of two-dimensional Fabry-Perot resonator with perfect reflection cancellation, and the wave is perfectly routed to the output of the system thanks to an optimal interplay between local reflection and transmission on each metasurface. Note that the structure is circularly symmetric, i.e., composed of uniform metasurfaces, and therefore omnidirectional, as typical cloaks.

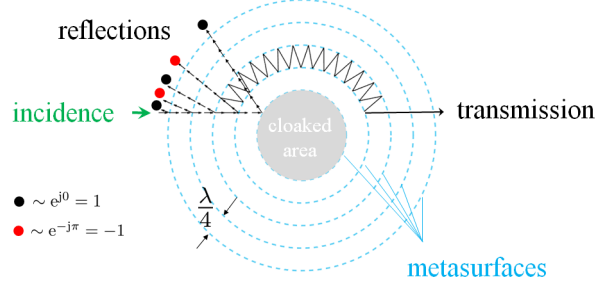


Figure 1: Waveguide routing operation (ray picture) of the proposed concentric metawaveguide cloak.

3 Design

We design the concentric metawaveguide cloak by optimizing the susceptibilities of its metasurfaces for minimal scattering. We assume that the metasurfaces have only *transverse* electric and magnetic surface polarization densities, $\vec{P}_{\parallel}$ and $\vec{M}_{\parallel}$, in which case the harmonic ($e^{j\omega t}$) Generalized Sheet Transition Conditions (GSTCs) reduce to [Achouri and Caloz \(2021\)](#)

$$\hat{n} \times \Delta \vec{E} = -j\omega\mu_0 \vec{M}_{\parallel}, \quad \hat{n} \times \Delta \vec{H} = j\omega \vec{P}_{\parallel}, \quad (1)$$

where $\hat{n}$ is the unit vector normal to the metasurface, $\Delta \vec{E}$ and $\Delta \vec{H}$ are the difference of the fields at both sides of the metasurface, and $\vec{M}_{\parallel}$ and $\vec{P}_{\parallel}$ will be expressed in terms of the average fields at both sides of the metasurface, $\vec{E}_{\parallel, \text{av}}$ and $\vec{H}_{\parallel, \text{av}}$, and of the bianisotropic surface susceptibility tensors $\bar{\chi}_{\text{mm} \parallel}$, $\bar{\chi}_{\text{me} \parallel}$, $\bar{\chi}_{\text{em} \parallel}$, $\bar{\chi}_{\text{ee} \parallel}$?. Let us assume a two-dimensional cloaking structure (perpendicular to the Cartesian coordinate z), composed of N metasurfaces and operating in the TM_z polarization regime. We shall synthesize the metasurface, i.e., determine its surface susceptibilities, by iterative analysis optimization.

To analyse the cloaking structure, i.e., to compute the fields that it scatters for given susceptibilities, we proceed as follows. First, we expand the tangential electromagnetic fields involved in Eqs. (1), namely E_z and H_{ϕ} , within each cloak layer (or metawaveguide) in generalized Fourier series, namely in terms of cylindrical Bessel basis functions and sinusoidal basis functions for the radial and azimuthal dependencies, respectively. Assuming M metasurfaces and $2N$ unknown Fourier coefficients, these expansions include $2MN$ unknown coefficients for the two tangential fields. Then, we insert these expressions for the fields into (1) and use the orthogonality of the sinusoidal basis functions. This results into $2N$ scalar equations at the interface of each metasurface, and the inversion of the related matrix system provides the sought-after field solutions. This is of course an exact analysis technique, which accounts for the exact electromagnetic scattering in the structure.

We next perform the synthesis by iteratively applying the analysis tool described in the previous paragraph for different susceptibility parameters until the scattering cross section falls below a determined threshold. The lossless and gainless susceptibilities found by this synthesis procedure are plotted in Fig. 2.

4 Results and Discussion

Figure 3 presents the main results. Figure 3(a) plots the real part of the total electric field, which reveals an essentially perfect cloaking performance. The scattered power was computed to be as low as 1.7×10^{-5} !

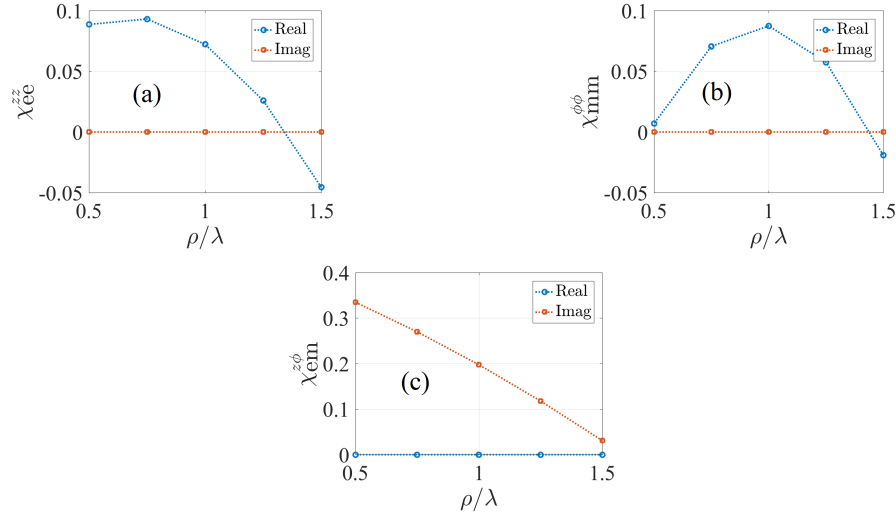


Figure 2: Optimized susceptibilities versus radial distance from the innermost metasurface to the outermost metasurface. (a) χ_{ee}^{zz} , (b) $\chi_{mm}^{\phi\phi}$, and (c) $\chi_{em}^{z\phi} = -\chi_{me}^{\phi z}$ of the 5 concentric metasurfaces.

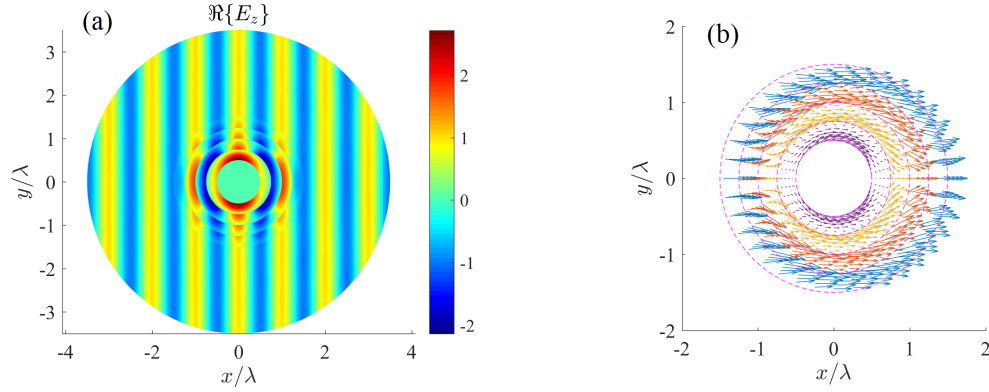


Figure 3: (a) The real part of the total electric field and (b) the Poynting vector inside the metawaveguide cloak.

Figure 3(b) plots the Poynting vector field, which confirms the waveguiding mechanism indicated by the simplified ray picture of Fig. 1.

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