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Polarization-Independent Broadband Bidirectional Optical Cloaking Using a New Type of Inverse Scattering Approach

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ABSTRACT

Since the advent of transformation optics a decade ago [1], the ability to achieve optical cloaking has become a matter of practical realization. However, so far extreme material requirements and large device areas have significantly posed an obstacle to realize compact cloaking schemes that are fully functional. Here, by taking a different approach and by following our recently developed general theorem to control the scattering behaviour of an arbitrary object on a specific demand [2], we show that nearly perfect bidirectional optical cloaking effect can be generated for any type of object with a given shape and size. Contrary to previous approaches, we reveal that such a method is always able to produce local refractive indices larger than one and that neither gain nor lossy materials are required. Furthermore, by means of numerical calculations, we demonstrate a highly tunable broad operational bandwidth of 550 nm (covering 650-1200 nm interval) and an angular aperture of 36° for both directions and polarizations. With these unprecedented features, we expect that the present work will hold a great potential to enable a new class of optical cloaking structures that will find applications particularly in communication systems, defence industry and in other related fields.

Keywords: scattering theory, optical cloaking, invisibility, scattering cancellation, graded-index optics.

1. INTRODUCTION

The idea of cloaking various objects, such that their optical responses mimic the wave propagation in free space, has been a long sought goal. A major breakthrough in this context has been the introduction of transformation optics [1], which has enabled the arbitrarily manipulation of the light path. Following this direction, various cloaking schemes based on conformal or quasiconformal coordinate transformations have been realized so far [3-7]. However such structures come with an inherent problem: the device area that provides the optical cloaking effect is often quite large compared to the cloaked area [8]. For instance, in Ref. [3] the device area is 225 μm^2, whereas the cloaked region has an area of only 1.60 μm^2. Consequently, optical cloaking becomes practically challenging if one aims at the cloaking of objects with large spatial dimensions.

Another powerful and inspirational approach to manipulate the optical response of a medium, other than transforming the geometrical space, has been recently proposed in Ref. [9], where the back-scattered waves have been completely cancelled by relating the real and imaginary parts of the complex permittivity profile by the socalled "spatial Kramers-Kronig" relations. More recently, it has been further shown that such a design can also exhibit a bidirectional cloaking effect at small grazing incidence angles when the so-called "cancellation condition" is satisfied [10]. While such approaches provide a valuable insight to the intimate relation between the material properties and the associated optical behaviour, they suffer from various serious drawbacks. First of all, it is assumed that the complex permittivity profile is infinitely extended in space [9], meaning that there is in fact no particular "object" or even an "interface" that is to be cloaked [10] but rather an infinite permittivity profile. Second, lossy [9] or even gain [10] materials are always required to build the necessary complex permittivity distribution, which brings additional difficulties in terms of practical realizations and instability issues.

In this paper, based on our recent proposal [2], we present a new way to achieve bidirectional cloaking for a *given object* with finite spatial dimensions, by directly manipulating its scattering properties. We first present a short summary of the scattering design approach, which is always able to yield a purely real positive permittivity greater than one. We then evaluate the cloaking effect of a given object by means of numerical calculations. Consequently, we reveal that our cloaking approach has the advantages of providing a potentially highly tunable broadband, polarization-independent and broad-angle operation, while also keeping the index modulation *limited* nearly to the spatial area of the object. It is expected that the presented method will significantly reduce the cloaking device footprint as well as providing a much more realizable optical environment that will have a profound impact in various industrial fields.

2. DESIGN APPROACH AND NUMERICAL ANALYSES

The design method presented here is based on the local filtering of the scattering potential of an arbitrary object to tailor its overall scattering behaviour as explained in Fig. 1. We have recently shown that such a filtering

yields a generalized Hilbert transform (relating the real and imaginary permittivity), of which a detailed explanation and exact analytical solutions can be found in Ref. [2]. Here, to obtain a bidirectional cloaking effect, one must eliminate all scattered waves in all possible directions *except* in the original incident direction. According to the linear diffraction tomography theorem [2, 11], it is apparent that such an elimination is intimately related to "ring" shaped areas inside the scattering potential. That is to say, assuming a weakly scattering potential, the scatterings completely vanish in the case when the scattering vectors on the constant wavevector region [2, 11] are absent. Furthermore, to extend this idea to cover a specific operational bandwidth rather that a single frequency, as shown in Figs. 1a and 1b, a "half-moon" shaped k-area can be employed instead of ring shaped one.
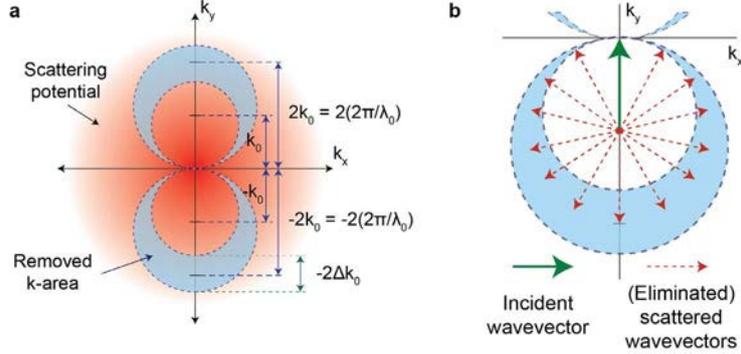

Figure 1: (a) By inverse designing the scattering potential, (b) one can eliminate specific undesired scattered waves completely. The operational frequency can be easily tuned by varying the size of the targeted k-area.

For convenience, we present the case for "half-moon" shaped areas located on the *y* axis (see Fig. 2a), but the areas can be located on any arbitrary region in the wavevector domain [2]. The initial object is shown in Fig. 2b, whose index profile was extracted from a grayscale image of a chair. After filtering the designated "half-moon" shaped areas presented in Fig. 2a from the scattering potential (which can be characterized by the spatial electric susceptibility distribution $\chi(x,y)$) of the initial object, the modified index profile was obtained as in Fig. 2c. We notice here that the resulting profile is locally isotropic and contains only positive index. Another important fact to notice is that some regions have refractive indices lower than one. At first, this may seem as an undesired result concerning the possible fabrication feasibility of the cloaked objects. However, we should notice that the linear scattering approach we have employed does not rely on exact index amplitudes but rather on the relative index differences between different regions [11]. Hence, a possible solution would be to increase the overall index of the cloaked object by a specific constant value so that no region contains a refractive index lower than one. As the local index differences would remain the same in such a case, the object would still exhibit the desired cloaking behaviour.
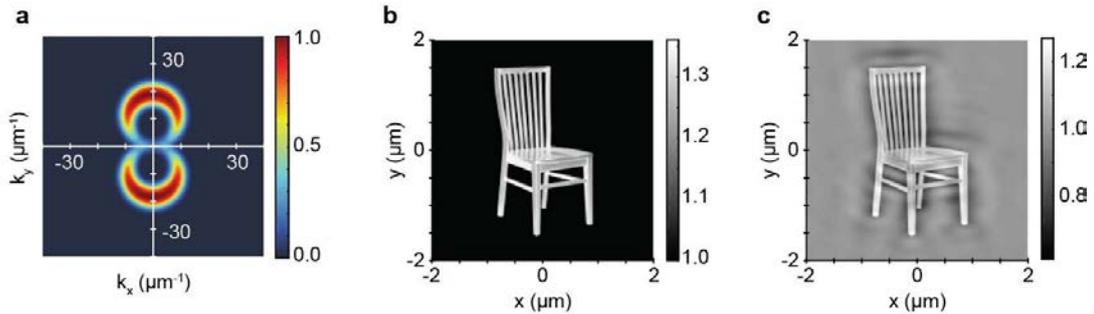

Figure 2: (a) The area that is removed from the scattering potential is shown in wavevector domain. The spatial index distribution of the (b) original and the (c) modified object (exhibiting cloaking effect) is given.

To evidence that the obtained index profile exhibits a bidirectional cloaking effect, numerical analyses were performed using the two-dimensional (2D) finite-difference time-domain (FDTD) method [12]. A transverse magnetic (TM, electric field is perpendicular to the in-plane) plane wave was employed to excite the object and to study its scattering behaviour. For a reference, in Figs. 3a and 3b we first present the spatial field distributions for the initial object exhibiting no cloaking effect (given in Fig. 2b). It is apparent from this figure that the initial object shows a strong scattering behaviour and is, thus, easily detectable by an observer located on both sides. We then present the field distributions of the cloaked object (given in Fig. 2c) as in Figs. 3c and 3d. These figures evidence the remarkable suppression of the field scatterings in both the +*y* and −*y* propagation directions. Here, important to notice is that the shape of the phase fronts and the amplitude of the incident wave are almost perfectly preserved, which are essential criteria for a cloaking operation. Furthermore, numerical results showed that the cloaking is present in a wavelength range of $0.65 - 1.20$ μm, which verifies the broadband operation arising from the envisaged thickness of the "moon-shaped" k-area. Another interesting point that deserves to mention is that the cloaking operation does not only function at normal incidences but also at various grazing incidences. As given in Figs. 3e

and 3f, the object is still cloaked up to an incident angle of 18° with respect to the *y*- axis. Moreover, as the linear scattering theorem does not depend on the type of the polarization of the light, the same object exhibits cloaking also for a transverse electric (TE, electric field is parallel to the in-plane), as provided in Fig. 3g. Last but not least, it is worth questioning whether the same object can be cloaked, if its spatial dimensions were enlarged. In this regard, the size of the original object was scaled up by a factor of three, and the same k-area (given in Fig. 2a) has been employed to obtain index distribution of the resulting cloaked object. Figure 3h shows the FDTD result of such an enlarged cloaked object. It is fascinating to see that cloaking can be achieved for arbitrary sized objects with the given method, whereas for instance in transformation optics based cloaking schemes the requirement of the total device area usually increases drastically with respect to the size of the object to be cloaked [8].
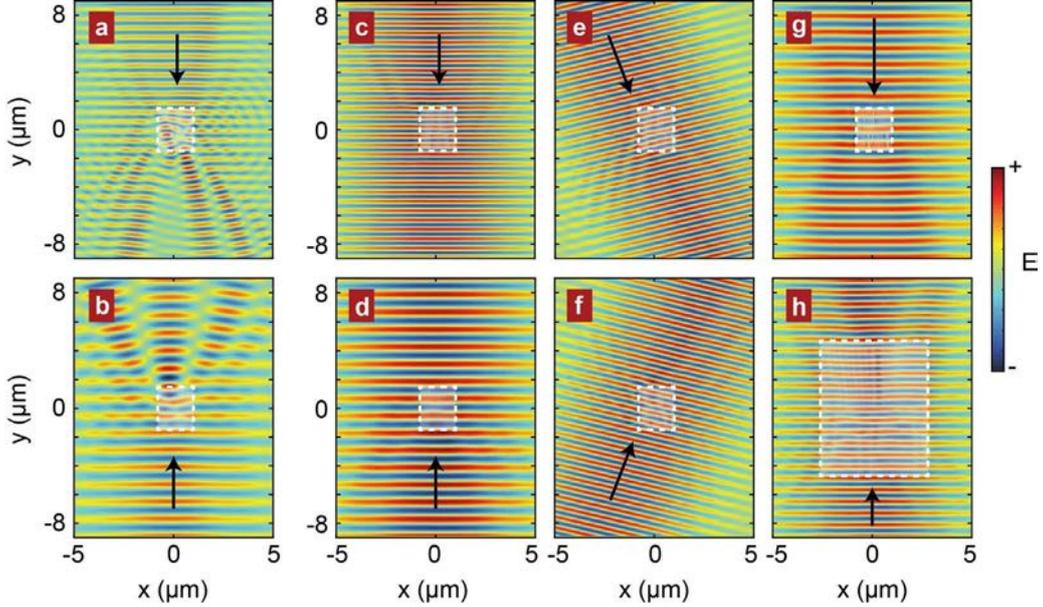

Figure 3. The spatial electric field distributions for various cases are given to illustrate the cloaking effect. The original object causes strong wave scattering and, thus, exhibits no cloaking for both the (a) –y and (b) +y propagation directions. (c, d) The modified object, on the other hand, eliminates nearly all backward and forward scattered waves and displays a bidirectional cloaking effect. (e ,f) The bidirectional cloaking behaviour is still present until to an oblique source incident angle of 18° with respect to normal incidence. (g) The same object exhibits optical cloaking also for a TE polarized source. (h) The optical cloaking effect still survives even if the object is enlarged (in this case, the object is three times larger than in the previous cases). The operational frequencies correspond to 0.65 μm, 1.20 μm, 0.65 μm, 1.20 μm, 0.70 μm, 0.70 μm, 1.10 μm and 0.80 μm for (a),(b),(c),(d),(e),(f),(g) and (h); respectively. The operational frequencies have been chosen so that the figures simultaneously demonstrate the broadband behaviour. Furthermore, the black arrows reveal the direction of the wave propagation and the white dashed lines outline the positions of the "chair" objects.

To reveal a more detailed insight into the magnitude and the phase alteration of the incident radiation directed towards the cloaked object, we give the spatial field magnitude and phase profiles for both the –*y* and +*y* propagation directions in Figs. 4a and 4b, respectively. As it follows from these figures, the magnitude of the incident field is almost perfectly conserved and the phase is nearly unaffected by the cloaked object for both directions. In other words, the incident wave propagates just like as it would propagate in free space, as one would expect from a cloaking operation.
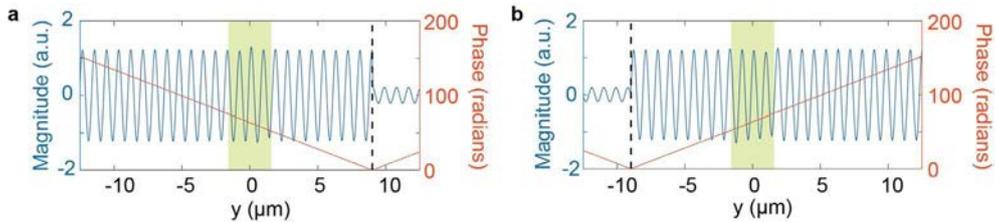

Figure 4. Superimposed magnitude and phase profiles of the electric field along the optical axis, for wave propagation in the (a) –y and (b) +y direction. The green colored areas denote the spatial location of the cloaked object and the black dashed lines show the positions of the sources.

3. CONCLUSIONS

In summary, following our recently proposed general recipe to arbitrary manipulate the field scatterings on a specific demand [2], we have demonstrated a nearly perfect bidirectional cloaking effect that can be extended to any type of object with arbitrary dimensions and shape. The bidirectional cloaking effect has been verified by

means of FDTD calculations, revealing a broad operational bandwidth of 550 nm and an angular aperture of 36°. Furthermore, the cloaking behaviour have been shown to be independent of the type of the wave polarization, thus, the reported results may potentially open wide variety of cloaking schemes that can operate under unpolarized light. Most importantly, the designed cloaked objects does not require any magnetic material responses, negative index structures or gain/loss materials and can be easily constructed by purely conventional dielectric materials and, hence, could outperform various other cloaking schemes based on e.g. transformation optics or PT-symmetric structures that usually require extreme materials. Consequently, the reported cloaking concept can be easily realized to operate in a wide electromagnetic spectrum ranging from the microwave regime down to visible wavelengths (by using e.g. electron-beam lithography [3] or focused ion beam milling [4]). Thus, we expect that the range of realizable optical cloaking devices in the fields of optical communications [3], stealth technology, and in various other optical systems will improve significantly in the near future.

ACKNOWLEDGEMENTS

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