Suppression of Light Scattering with ENZ-metamaterials

Alexander S. Shalin[1,2,3], **Pavel A. Belov**[1], **and Yuri S. Kivshar**[1,4]

[1]ITMO University, St. Petersburg 197101, Russia
[2]Kotel'nikov Institute of Radio Engineering and Electronics of RAS, Ulyanovsk 432011, Russia
[3]Ulyanovsk StateUniversity, Ulyanovsk 432017, Russia
[4]Nonlinear Physics Center, Australian National University, Canberra ACT 0200, Australia

Abstract— Cloaking devices enabling to hide objects from external observers have numerous potential applications but still face challenges in realization, especially in the visible spectral range. In particular, inherent losses and extreme parameters of metamaterials required for the cloaking are the limiting factors. Here, we propose and demonstrate numerically nearly perfect concealing of objects in ENZ-metamaterials (homogeneous and layered realizations) acting alignment-free scattering suppression covers. The suppression of visibility relies on the reconstruction of a plane wavefront after scattering of light by an object placed inside an anisotropic metamaterial with vanishing permittivity along one of the major crystallographic directions (uniaxial ENZ metamaterial). We also consider a realistic realization of the metamaterial as a metal-dielectric multilayer and demonstrate the cloaking in forward and backward directions with perfectly preserved wavefronts and less than 10% absolute intensity change.

1. INTRODUCTION

Numerous approaches for controlling electromagnetic characteristics have been developed and employed in antennas engineering for the enhancement of scattering cross-sections and radiation directivities [1]. While the main technological effort has been focused at the millimeter and radio frequencies ranges where majority of applications are, considerable interest at the optical frequencies has recently emerged. Optical antennas have been already found use in tailoring radiation properties of emitters, solar cells applications, and more [2].

Reduction of scattering cross-sections in a specifically designed material environment leads to reduced detectability of objects, and may, ultimately, result in their invisibility for an external observer. The concept of 'cloaking' was introduced in [3, 4] and gained remarkable attention due to continuous demand to achieve invisibility for radar waves [5] and visible light [6–8]. The general approaches for cloaking rely either on transformation optics concepts [3] or on conformal optical mapping of complex electromagnetic potentials [4]. While the former generally results in the requirements on strongly anisotropic electric and magnetic susceptibilities of a medium of a cloak, the latter approach requires a position-dependent refractive index variation but is restricted for two-dimensional geometries.

One of the main challenges in the development of practical cloaking devices is to minimize demands for permeability and anisotropy and reduce inherent material losses of required materials. The so-called 'carpet cloak' has been proposed and implemented to mitigate these factors by imposing certain geometrical restrictions and utilizing quasi-conformal mapping [9, 10]. Qualitatively different approach to cloaking utilizes epsilon-near-zero (ENZ) metamaterials to suppress a dipolar scattering of a concealed object [11]. While number of the ENZ metamaterial realizations exist in the radio frequency range [12, 13], in optics such an anisotropic response may be achieved through metal-dielectric layered structures [14], semiconductor heterostructures [15], or vertically aligned arrays of nanorods [16].

Here we demonstrate scattering suppression from an arbitrary (not necessarily subwavelength) sized objects placed inside a homogeneous ENZ-metamaterial and its layered metal-dielectric realization. Investigation of the exact numerical model, taking into account material losses and finite dimensions of the metamaterial, shows the possibility of nearly perfect cloaking of arbitrary shaped bodies with the minimal variations of the phase front of the transmitted/reflected optical wave and highly suppressed scattering. The proposed scheme does not require extreme electric and magnetic susceptibilities and can operate in an alignment-free manner. It is worth noting that the proposed approach is qualitatively different from other approaches when the incident light does not interact with a cloaked object being bended around by a material layer (e.g., [3, 5]) or when the scattered field is suppressed with another anti-parallel dipole [11]. Recently, similar scheme for scattering suppression in homogeneous ENZ metamaterial was proposed; however, no practical implementation was given [17].

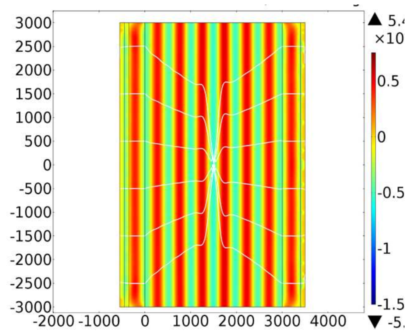

Figure 1: Electric field radiation by the dipole situated inside ENZ-metamaterial. Dipole is oriented along y-axis, wavelength — 540 nm, $\varepsilon_x = 0.004$, $\varepsilon_y = 1.23$. White lines — power flow.

2. HOMOGENEOUS METAMATERIALS

Let us firstly consider a radiating dipole situated inside a homogeneous epsilon-near-zero metamaterial. As the basic leading term in the multipolar decomposition of the scattered field is the dipole, the understanding of dipolar emission inside ENZ metamaterial will enable to analyze scattering from complex structures. Fig. 1 shows the results of electromagnetic modelling of dipolar emission inside the ENZ slab. As may be observed, the y-component (along the vanishing component of the effective permittivity tensor) shows remarkable structure of flat phase fronts, which is substantially different from the classical pattern. The dielectric tensor in this simulation was taken to be $\varepsilon_x = 0.004$, $\varepsilon_y = 1.23$. Consequently, the dipolar scattering from an embedded object supposed to provide similar flat type of fronts of scattered waves.

Figure 2 shows the result of scattering on 2 different objects, embedded in homogeneous ENZ metamaterial — (a) dielectric cylinder (b) cylinder made of perfect electric conductor (PEC). In both cases the distortion of the incident wave front is almost negligible and the y-component of the total electrical field outside the metamaterial is homogeneous. It means that the object, embedded within the metamaterial slab is invisible. It is worth noting the conceptual difference between cases (a) and (b). In the first case the field penetrates the object and obtains the phase lag, while in the second case the field at the interior of the object is identically zero. In both cases, however, the scattered field in the presence of the embedded object and without is the same, making it invisible for an observer, situated either in front or behind the structure. The key effect, responsible for the scattering suppression, is the flat phase fronts of the scattered field. Additional minor scattering takes place along the x axis and this radiation is going to infinity if the ideal ENZ material ($\varepsilon_x = 0$). Furthermore, the remarkable property to be considered is the overall size of the embedded objects — in both cases the cylinder's diameter is comparable to the wavelength of the excitation. The size of the object does not affect the scattering suppression characteristics.

3. METAL-DIELECTRIC MULTILAYERED METAMATERIALS

While the above discussion was based on ideal homogeneous metamaterial, its actual realization could have an impact on the device performance. Hereafter, layered realization was considered. The effective permittivity tensor of layered composites can be directly evaluated from their thickness, periodicity, and optical parameters of the constitutive materials [e.g., 18]. While this approach can predict optical properties of the composites made of low contrast positive epsilon layers, it faces severe challenges once negative permittivity (plasmonic metals) materials are involved. Optical properties of these multilayered composites determined by guided surface electromagnetic modes (surface plasmon polaritons) on metal-dielectric interfaces, and spatial dispersion effects become especially significant in the parameters range where the effective medium theory (EMT) predicts vanishing values of permittivity [18].

The parameters used for analysis of homogeneous structure were obtained with layered realization, while effective medium theory, developed at [18], was used in order to find proper geometrical arrangement of the layers. The metamaterial parameters with the Au layer thickness of $d_g = 20$ nm and air thickness of $d_a = 100$ nm were considered with dispersive Au [19] and nondispersive dielectric. It is worth noting, that layered system, based on practical possible realization, do have optical losses, which were neglected in the homogeneous realization.

Figure 3 shows the results for the scattering on a cylindrical object, placed inside layered metamaterial. The remarkable similarity between ideal homogeneous case and realistic system, could be observed. While the field inside the object obtained relatively curved shape, the total transmitted field maintain its flat nature. Direct calculations show that the minor difference in performance between ideal and layered cases is within the range of 5% in the amplitude. Consequently, layered realization could suppress the scattering exactly in the same way the homogeneous ENZ metamaterial does. Our resent original paper provides detailed description of the phenomena and also addresses issues of strong spatial dispersion in metal-dielectric composites [20].

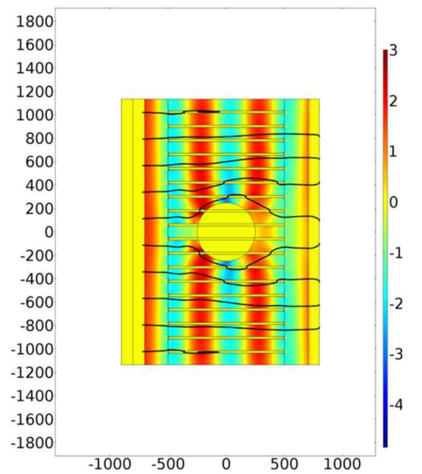

Figure 3: Electric field (y-component) distributions for the plane wave illuminating the multilayered cloak (a) with the 500 nm diameter PEC cylinder inside. Layers are 20 nm gold and 100 nm air. Black lines represent power flow.

4. CONCLUSION

We have shown that ENZ-metamaterials can perform as nearly-perfect scattering suppression devices for the objects of larger than wavelength sizes. The fundamental principle behind this new type of cloaking relies on the flat phase fronts of the scattered radiation. The scattering is controlled by the vanishing component of dielectric tensor along the propagation direction of the incident wave. In this case, the scattered field has flat phase fronts that do not distort the shape of the incident radiation. As the result, the transmitted field is only slightly attenuated with the wavefront maintaining its original profile, making the detection (almost always based on the amplitude and wavefront deformation observations) by a prying observer to be impossible. The same considerations are applicable for observation in reflection with the phased matched cloak (Figs. 2, 3). The proposed type of cloaking may find use not only in the conventional concealing applications but also serve as a platform for 'cloaked detectors' schemes [21] where bulk and alignment free cloaks may significantly reduce the complexity of the realization.

ACKNOWLEDGMENT

This work was partially supported by the Government of the Russian Federation (Grant 074-U01), Russian Fund for Basic Research (project #15-02-01344), and Australian Research Council. The calculation of field distributions has been supported by the Russian Science Foundation Grant No. 14-12-01227.

REFERENCES

1. Stutzman, W. L. and G. A. Thiele, *Antenna Theory and Design*, 3rd Edition, John Wiley & Sons, 2012.
2. Novotny, L. and N. van Hulst, "Antennas for light," *Nature Photon.*, Vol. 5, 83–90, 2011.
3. Pendry, J. B., D. Schurig, and D. R. Smith, "Controlling electromagnetic fields," *Science*, Vol. 312, 1780–1782, 2006.
4. Leonhardt, U., "Optical conformal mapping," *Science*, Vol. 312, 1777–1780, 2006.
5. Schurig, D., J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, "Metamaterial electromagnetic cloak at microwave frequencies," *Science*, Vol. 314, 977–980, 2006.

6. Valentine, J., J. Li, T. Zentgraf, G. Bartal, and X. Zhang, "An optical cloak made of dielectrics," *Nature Materials*, Vol. 8, 568–571, 2009.
7. Gabrielli, L. H., J. Cardenas, C. B. Poitras, and M. Lipson, "Silicon nanostructure cloak operating at optical frequencies," *Nature Photon.*, Vol. 3, 461–463, 2009.
8. Cai, W., U. K. Chettiar, A. V. Kildishev, and V. M. Shalaev, "Optical cloaking with metamaterials," *Nature Photon.*, Vol. 1, 224–227, 2007.
9. Li, J. and J. B. Pendry, "Hiding under the carpet: A new strategy for cloaking," *Phys. Rev. Lett.*, Vol. 101, 203901, 2008.
10. Landy, N. I. and W. J. Padilla, "Guiding light with conformal transformations," *Opt. Express*, Vol. 17, 14872, 2009.
11. Alu, A. and N. Engheta, "Achieving transparency with metamaterial and plasmonic coatings," *Phys. Rev. E*, Vol. 72, 16623, 2005.
12. Edwards, B., A. Al, M. E. Young, M. Silveirinha, and N. Engheta, "Experimental verification of ε-near-zero metamaterial coupling and energy squeezing using a microwave waveguide," *Phys. Rev. Lett.*, Vol. 100, 033903, 2008.
13. Liu, R., Q. Cheng, T. Hand, J. J. Mock, T. J. Cui, S. A. Cummer, and D. R. Smith, "Experimental demonstration of electromagnetic tunneling through an epsilon-near-zero metamaterial at microwave frequencies," *Phys. Rev. Lett.*, Vol. 100, 023903, 2008.
14. Jacob, Z., J. Y. Kim, G. V. Naik, A. Boltasseva, E. E. Narimanov, and V. M. Shalaev, "Engineering photonic density of states using metamaterials," *Appl. Phys. B*, Vol. 100, No. 1, 215–218, 2010.
15. Ginzburg, P. and M. Orenstein, "Nonmetallic left-handed material based on negative-positive anisotropy in low-dimensional quantum structures," *J. Appl. Phys.*, Vol. 103, 083105, 2008.
16. Ginzburg, P., F. J. Rodríguez Fortuño, G. A. Wurtz, W. Dickson, A. Murphy, F. Morgan, R. J. Pollard, I. Iorsh, A. Atrashchenko, P. A. Belov, Y. S. Kivshar, A. Nevet, G. Ankonina, M. Orenstein, and A. V. Zayats, "Manipulating polarization of light with ultrathin epsilon-near-zero metamaterials," *Opt. Express*, Vol. 21, 14907–14917, 2013.
17. Luo, J., W. Lu, Z. Hang, H. Chen, B. Hou, Y.Lai, and C. T. Chan, "Arbitrary control of electromagnetic flux in inhomogeneous anisotropic media with near-zero index," *Phys. Rev. Lett.*, Vol. 112, 073903, 2014.
18. Orlov, A., I. Iorsh, P. Belov, and Y. Kivshar, "Complex band structure of nanostructured metal-dielectric metamaterials," *Opt. Express*, Vol. 21, 1593–1598, 2013.
19. Palik, E. D., *Handbook of Optical Constants of Solids*, Academic Press, 1985.
20. Shalin, A. S., P. Ginzburg, A. A. Orlov, I. Iorsh, P. A. Belov, Y. S. Kivshar, and A. V. Zayats, "Scattering suppression from arbitrary objects in spatially dispersive layered metamaterials," *Phys. Rev. B*, Vol. 91, 125426, 2015.
21. Fan, P., U. Chettiar, L. Cao, F. Afshinmanesh, N. Engheta, and M. Brongersma, "An invisible metal semiconductor photodetector," *Nature Photon.*, Vol. 6, No. 6, 380–385, 2012.