Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 628-629

P-9-16L

A Theoretical Study on Invisibility Devices based on Materials with Negative Refractive Index

T. Ochiai[1] and J.C. Nacher[2]

[1] *Faculty of Engineering, Toyama Prefectural University*
5180 Kurokawa Imizu-shi Toyama, 939-0398, Japan
ochiai@pu-toyama.ac.jp
[2] *Department of Complex Systems, Future University-Hakodate*
116-2 Kamedanakano-cho Hakodate, Hokkaido, 041-8655, Japan
nacher@fun.ac.jp

1 Introduction

A dielectric medium that is able to hide objects from sight is called invisibility device. Here, we present a new design based on negative refraction index that create invisible space. Our device is flexible enough to generate a large variety of bounded orbits for light rays. In particular, we investigated the relationship between the time delay and the maximum size of the invisible space. Our findings indicate that we can simultaneously make the invisible space larger and time delay shorter within some limits.

2 Methods

Recently, some models aimed at creating a perfect illusion of invisibility have ben proposed. The idea is to design a dielectric medium that is able to guide the light around a given object. As the device itself should be invisible, an external observer would not see the object. Although a perfect illusion based on isotropic media is not possible because of the ultimate wave nature of light [1, 2, 3, 4], using anisotropic media these distortions could be significantly reduced if an optimal dielectric device could be designed [3, 4, 5, 6, 7, 8].

Emerging research based on new man-made materials (also known as *metamaterials* is opening up new avenues by exploiting the artificial dielectric media [9]. From telecommunications, radar and optical invisibility in defense areas to medical imaging and microelectronics in industrial sectors, the new emergent electromagnetic features obtained using metamaterials can offer many potential and exciting applications. These material properties emerge as a consequence of their complex and periodic structures rather than their chemical composition. Therefore, engineered materials with pre-designed periodic nanostructures could lead to a large range of refractive indices. This is also true for the recently discovered metamaterials with negative refractive index [9]. A striking property of materials with negative index is that the rays will be refracted on the same side of the normal on entering the material according to the Snell's law.

In this work, we extend the original idea of Leonhardt [3, 4] based on optimal conformal mapping to create dielectric invisibility devices. In this context, we propose a new design for a cloaking device made of a metamaterial with negative refractive index to reduce the time delay and relax the constraints imposed by the requirement for bounded orbits in the Riemann sheet. By following [3, 4], a dielectric medium conformally maps a physical space z onto Riemann sheets given by an analytic function $w(z)$. By using the well-known Joukowski transformation [10, 11], Leonhardt shows a mapping between the physical space described by the complex field z and the analytic function $w(z)$ that represents the mathematical space composed of two Riemann sheets and a branch cut which connects both sheets. As a result any object located at the center of physical space cannot be detected by an external observer.

The most important distortions of invisibility are caused by reflections and time delays [4]. In this work, we investigate how to relax the constraints for designing and manufacturing invisibility devices. In previous works, refractive-index profiles on the interior Riemann sheet should guide the rays around the branch points and should define close loops or trajectories. Therefore, according to classical dynamics [12], the number of potential or index profiles is drastically reduced to a few ones: harmonic-oscillator and Kepler profile. In contrast, our proposed design is able to generate a large variety of bounded orbits for rays using striking properties of negative refractive indices. The refractive-index material we propose is as follows:

The refractive index of the first Riemann sheet in space w is given by

$$n = 1. \tag{1}$$

Next, we divided the second Riemann sheet in space w into four regions as follows:

$$\begin{aligned}
&\text{Region 1 (R1):} \quad (x < 2a \ \text{ and } \ y > 0), \quad (2)\\
&\text{Region 2 (R2):} \quad (x > 2a \ \text{ and } \ y > 0), \quad (3)\\
&\text{Region 3 (R3):} \quad (x > 2a \ \text{ and } \ y < 0), \quad (4)\\
&\text{Region 4 (R4):} \quad (x < 2a \ \text{ and } \ y < 0). \quad (5)
\end{aligned}$$

The refractive index on the second Riemann sheet in space w is given by

$$\begin{aligned}
n &= \sqrt{2E - 2U(x)} \\
&= \begin{cases} \sqrt{2E - 2A(2a - x)} & \text{(R1)} \\ -\sqrt{2E + 2A(2a - x)} & \text{(R2)} \\ \sqrt{2E + 2A(2a - x)} & \text{(R3)} \\ -\sqrt{2E - 2A(2a - x)} & \text{(R4)} \end{cases}
\end{aligned} \tag{6}$$

Based on this designed dielectric medium, we investigated the relationship between the time delay and the maximum size of the invisible space. Even though it may go against intuition, our findings reveal that it is possible to optimize both of them at the same time. Namely, we can simultaneously make the invisible space larger and time delay shorter within some limits. A short time delay is important because it leads to decrease both optical distortions and risk of wave detection. Similarly, a large invisible space could allow to hide from sight objects with higher spatial dimensions.

3 Conclusion

Our proposed design may stimulate theoretical studies for designing and manufacturing cloaking devices using the properties of negative refraction index. Even though the current invisible space is not enough huge to hide extensive objects, our model has proposed a novel use of metamaterials for creating invisibility devices. Additional progress toward three dimensional studies is encouraged together with more experiments based on dielectric media for achieving the complete invisibility illusion.

References

[1] A. I. Nachman, Ann. Math. 128, 531 (1998).

[2] E. Wolf and T. Habashy, J. Mod. Opt. 40, 785 (1993).

[3] U. Leonhardt, Optical Conformal Mapping, Science 312, 1777-1780 (2006).

[4] U. Leonhardt, Notes on Conformal Invisibility Devices, New. J. Phys. 8, 118 (2006).

[5] J.B. Pendry, D. Schuring and D.R. Smith, Science 312, 1780 (2006).

[6] D.R. Smith, J.B. Pendry and M.C.K. Wilshire, Science 305, 788, 788 (2004).

[7] A. Grbic and G.V. Eleftheriades, Phys. Rev. Lett. 92, 117403 (2004)

[8] A.N. Grigorenko et al., Nature 438, 335 (2005).

[9] G.V. Eleftheriades and K.G. Balmain, *Negative-refraction metamaterials* (Wiley Inter-Science, 2006).

[10] Z. Nehari, *Conformal mapping*, (Dover Publications, Inc. New York, 1952).

[11] L.I. Volkovyskii, G.L. Lunts and I.G. Aramanovich, *A collection of problems on complex analysis* (Dover Publications, Inc. New York, 1965).

[12] L.D. Landau and E.M. Lifshitz, *Mechanics* (Pergamon, Oxford, 1976).