Metamaterial Cloaking: Making the Invisibility through the Visible

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Abstract: This paper encapsulates the principles, properties and implementation areas of metamaterial cloaking and electromagnetic invisibliity. They are characterized by having high surface impedance. The geometry of this structure is such that it makes the object invisible for electromagnetic radiation in a particular frequency range. Also, it exhibits negative index of refraction. Thus, opening another new area of implementation such as metamaterial cloaking.

Keywords: AMC (Artificial magnetic conductor), HIS (High impedance surface), frequency selective surface (FSS), ground plane, cloaking.

Introduction

Metamaterials exhibit properties not found in nature, such as negative index of refraction. They are cellular assemblies of multiple elements fashioned from materials including metals and plastics, arranged in periodic patterns. Metamaterials gain their properties not from their constituents, but from their exactingly-designed structures. The structural units of metamaterials can be tailored in shape and size. Their composition, and their form or structure, can be finely adjusted. Their precise shape, geometry, size, orientation and arrangement can affect light or sound in a manner that is unachievable with conventional materials. Inclusions designed can be placed at desired locations in order to vary the function of a given material.For microwave radiation, the cells need to be in the order of several millimeters. Microwave frequency metamaterials are usually constructed as arrays of electrically conductive elements (such as loops of wire) that have suitable inductive and capacitive characteristics. Photonic metamaterials, at the scale of nanometers, can be used to manipulate light at optical frequencies. Plasmonic metamaterials utilize surface plasmons, which are packets of electrical charges that collectively oscillate at the surfaces of metals at optical frequencies. Frequency selective surfaces (FSS) exhibiting subwavelength characteristics are known variously as Artificial magnetic conductors (AMC) or High Impedance Surfaces (HIS). FSS display inductive and capacitive characteristics that are directly related to their subwavelength structure. Negative refractive index is an important characteristic in metamaterial design and fabrication. Reverse-refraction occur when both permittivity ε and permeability μ are negative. Fig 1 shows the conditions to attain negative refractive index.

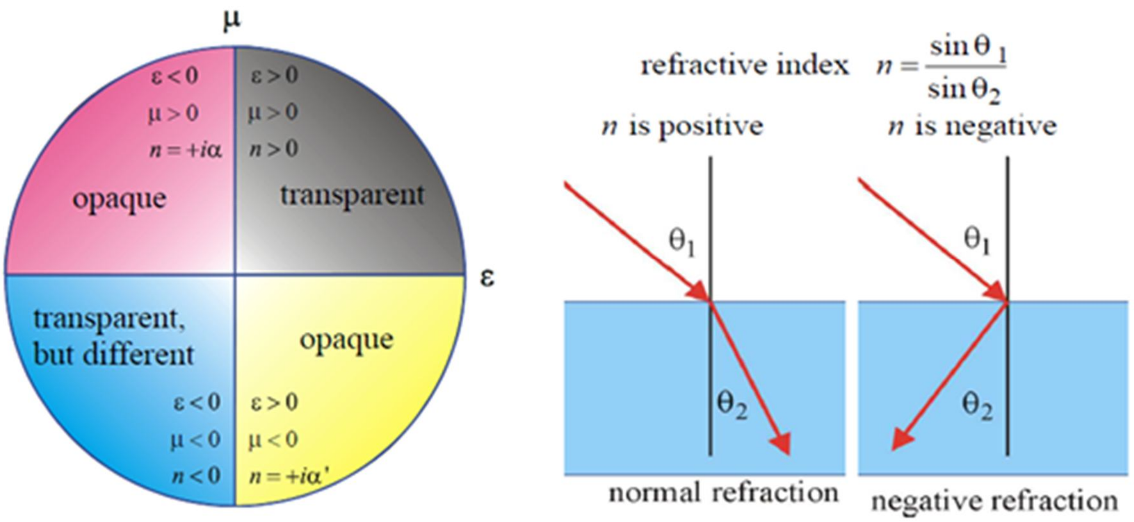

Fig 1. Negative refractive index [1]

For plane waves propagating in electromagnetic metamaterials, the electric field, magnetic field and wave vector follow a left-hand rule. This is a reversal of direction when compared to the behavior of conventional optical materials. Metamaterial antennas are a class of antennas that use metamaterials to improve performance [6][7].They can attain negative permeability which allow for properties such as an electrically small antenna size, high directivity and tunable operational frequency.

Science of Cloaking

Hiding the object from the object detecting device is the prime intent behind metamaterial cloaking. This can be accomplished by making the electromagnetic wave coming out of the cloak to bend over the object rather than being reflected or scattered. Naturally occurring matter exhibits behavior based on the molecules that make it up -- the atomic material that composes the finished product determines what properties the product will have. With metamaterials, the sum of the parts, not the parts themselves, determines how the material behaves. It has been found that by the use of certain materials like gold and copper arranged in certain patterns and shapes can combine the properties of those materials. In other words, unlike natural matter, metamaterials' behavior depends on the properties of the materials that make it up and the way the materials are put together. Metamaterials theoretically can guide light around an object, rather than reflect or refract the light.
If the light waves can be guided by the metamaterials around the object and back to its original course, the object wouldn't cast a shadow, either. Thus, metamaterials can create cloaking devices.
To effectively manipulate an electromagnetic wavelength of any kind, the metamaterial used has to be smaller than the wavelength. Since microwaves' wavelengths are measured in centimeters, metamaterials created are small enough to manipulate them, moving waves around an object [2]. Cloaking is not the same as stealth technology because stealth technologies only minimise the power reflected back to the probing radar by covering the object with absorbing layer or shaping the object in a form which minimises the scattered field towards the direction of illumination.

Metamaterial Cloaking

Metamaterial cloaking is the usage of metamaterials in an invisibility cloak. It is based on transformation optics, thus can direct and control the propagation and transmission of specified parts of the light spectrum. Fig 2 shows the coordinate system transformation to attain metamaterial cloaks.

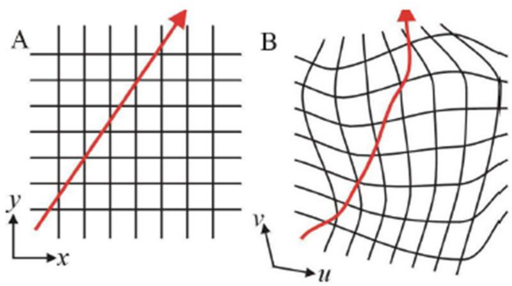

Fig 2. Coordinate system transformation [2]

The artificial structure for cloaking applications is a lattice design – a sequentially repeating network – of identical elements. For microwave frequencies, these materials are analogous to crystals for optics. They are capable of a very strong interaction, or coupling, with the magnetic component of light. The permittivity and permeability tensors of the cloaking device are derived in such a way that its material becomes invariant, inhomogeneous and anisotropic which is the main property required for cloaking. Fig 3 shows how the EM wave travels through cylindrical cloak.

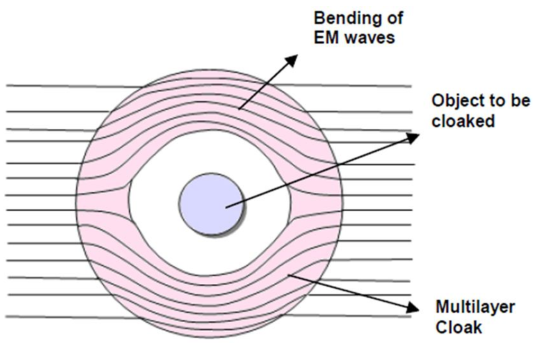

Fig 3. Illustration of cylindrical cloak [1]

Therefore, the range of response to radiated light is expanded beyond the ordinary optical limitations that are described by the sciences of physical optics and optical physics. In addition, as artificially constructed materials, both the magnetic and electric components of the radiated light can be controlled at will, in any desired fashion as it travels through the material. This is because a metamaterial's behavior is typically formed from individual components, and each component responds independently to a radiated spectrum of light. The guiding vision for the metamaterial cloak is a device that directs the flow of light smoothly around an object, like water flowing past a rock in a stream, without reflection, rendering the object invisible.

Metamaterials and Transformation Optics

Transformation optics subscribes to the capability of bending light, or electromagnetic waves and energy, in any preferred or desired fashion, for a desired application. Maxwell's equations do not vary even though coordinates transform. Instead it is the values of the chosen parameters of the materials which "transform", or alter, during a certain time period. So, transformation optics has been developed from the capability to choose the parameters for a given material. Since Maxwell's equations retain the same form, it is the successive values of the parameters, permittivity and permeability, which change over time. Permittivity and permeability are in a sense responses to the electric and magnetic fields of a radiated light source respectively.

For example, A sphere with radius R_1 is chosen as the object to be hidden. The cloaking region is to be contained within the annulus $R_1 < r < R_2$. A simple transformation that achieves the desired result can be found by taking all fields in the region $r < R_2$ and compressing them into the region $R_1 < r < R_2$. The coordinate transformations do not alter Maxwell's equations. Only the values of ε and μ change over time. Fig 4 depicts the transformation optics for electric and magnetic field lines.

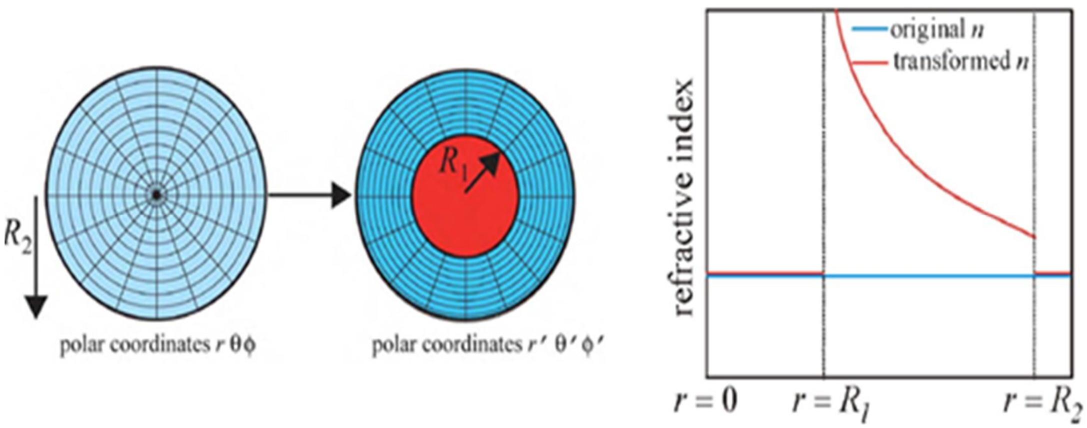

Fig 4. Transformation optics for electric and magnetic field lines [1]

The precise degree of electric and magnetic response can be controlled in a metamaterial, point by point. Since so much control can be maintained over the responses of the material, this leads to an enhanced and highly flexible gradient-index material [3][4][5]. Conventionally predetermined refractive index of ordinary materials instead become independent spatial gradients in a metamaterial, which can be controlled at will. Therefore, transformation optics is a new method for creating novel and unique optical devices.

Design and Simulation Techniques for Metamaterial Cloak

Because of the conformal multilayer structure of the cloaking devices, the analysis using the existing analytical techniques becomes difficult. To devise metamaterial cloaks, numerical simulation techniques such as finite-difference time-domain method (FDTD), finite-element method (FEM), finite-integration technique (FIT), inductor-capacitor representation method (LC-MTM) etc can be used. In FDTD, any new structure to be modelled is reduced to a problem of mesh generation rather than reformulation of an integral equation, thus reducing the complexity. FEM being a numerical technique gives approximate solutions to partial differential as well as integral equations [2][3]. FIT uses spatial discretization scheme to solve electromagnetic field problems both in time and frequency domains. This technique is used for highly flexible geometric modelling and boundary handling problems. The LC MTM method uses the Kirchoff’s voltage and current laws for spatially discretizing Maxwell’s equations. The constitutive parameters can be directly determined with the LC circuit network representation.

Application Fields

Metamaterial in coming future will help to protect a building from earthquakes by bending seismic waves around it. Similarly, tsunami waves could be bent around towns, and sound waves bent around a room to make it soundproof.

Commercially, metamaterials could be used for satellite communications (flat-panel antennas) Wireless charging of devices, is another area which is attracting keen industry attention.

Challenges in Cloaking

Light wavelengths are measured in nanometers (billionths of a meter), and the metamaterials needed to block light must be even smaller than that. Therefore it becomes difficult in reality to manufacture units for metamaterials.Another challenge is that a metamaterial cloaking device would have to be arranged to manipulate light on the entire visible spectrum, because different colors exist on different wavelengths.

Conclusion

The past few years have illustrated the power of the metamaterial approach, because new material responses, some with no analog in usual materials, are now available for exploration. This paper provided a technical overview of the rapidly emerging metamaterial technology offering a wealth of new phenomena in optics and electromagnetism including negative refraction near field focusing, artificial magnetism and optical invisibility. The technology has potential applications, especially in optics, photonics, the science and technology utilizing lights, medicine and telecommunication.

References

[1] Wood, B. and Pendry, J.B. 2007. Metamaterials at zero Frequency. Journal of Physics: Condensed Matter. 19(076208): 1-9.

[2] Islam, S. S., Faruque, M. R. I. and Islam, M. T. 2015. A Near Zero Refractive Index Metamaterial for Electromagnetic Invisibility Cloaking Operation. Materials. 8: 4790-4804.

[3] Schurig, D., Mock, J. J., Justice, B. J., Cummer, S. A., Pendry, J. B., Starr, A. F. and Smith, D. R. 2006. Metamaterial Electromagnetic Cloak at Microwave Frequencies. Science. 314: 977-980.

[4] Cai, W.,Chettiar, U. K., Kildishev, A. V., Shalaev, V. M.(2007a): Optical cloaking with metamaterials. Nature Photonics, vol. 1, pp. 224-227.

[5] Huanyang Chen, Che Ting Chan, "From the perfect lens to anti cloak, superscatter and beyond", Progress In Electromagnetics Research Symposium Abstracts, Beijing, China, March 23-27, 2009.

[6] S.Vladimir, C.Wenshan, Optical Metamaterials: Fundamentals and applications, Springer science,2010.

[7] H. Paudyal , M. Johri and A. Tiwari, " From Left Handed Materials to Invisible Cloak: Recent Advances", The Himalyan physics , Vol.4, No.4, July 2013.