Invisibility cloaks

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To become invisible or make other things invisible has always been a great fantasy for the human mind. Many science-fiction novels or movies revolve around people with powers to become invisible. Modern science is fast converting this fantasy into a reality. Scientists have already developed certain devices which can render things invisible to certain specific electromagnetic waves. Such devices are known as 'invisibility cloaks' or simply 'cloaks'.

A cloaking device can virtually conceal what is placed under it. This device is made up of special metamaterials (MTMs) with variable refractive index which do not allow waves to enter it. The waves falling on the cloaking material are allowed to flow around the cloak undistortedly and then emerge on the other side, while remaining in phase with other waves which do not fall on the cloak, i.e. exactly in the same direction as they began. In this way the cloak allows no reflection of waves as well as casts no shadow. This makes the object inside a cloak to virtually become invisible! That is, one can theoretically see behind the cloaked object.

MTMs used for making cloaks are required to have negative refraction and other electromagnetic properties and are known as left-handed (LH) MTMs. MTMs are a class of artificially engineered composite materials having extraordinary electromagnetic properties (not found in natural materials) which can be altered as desired.

Shelby *et al.*[1] experimentally showed the existence of negative electromagnetic properties (refractive index, permittivity and permeability) at microwave frequencies in a MTM and that such MTMs do not violate any of Maxwell's equations.

J. B. Pendry is the pioneer of the cloaking concept and Pendry *et al.*[2] first illustrated through theoretical simulations, that objects can be cloaked from electromagnetic fields by exploiting coordinate transformations in inhomogeneous and anisotropic MTMs. According to them, electromagnetically inhomogeneous MTMs can be used to control the path of light or electromagnetic waves. They showed that an object can be concealed from electromagnetic detection by placing it in an inhomogeneous MTM design or media having variable values of permittivity and permeability throughout the material. Such electromagnetic MTM design guides the incident radiations to bend around, thus leaving some space electromagnetically empty – called concealment volume or void – which can be used to cloak an object.

Pendry *et al.*[3] constructed a cloak using MTM design and practically achieved electromagnetic cloaking at microwave frequencies concealing a 7 in^3 area from microwave detection.

Seeing the tremendous scope of such cloaks in the future, different groups of researchers are working on this new magical science frontier. Since 2006, research in the cloaking frontier has been mostly concentrated on developing 2D and symmetrical (spherical and cylindrical) cloaks. But recently, Wu *et al.*[4] have shown through simulations that cloaks of arbitrary shape can be designed by using transformation-optical approach.

Transformations used by Pendry *et al.*[2] were of first-order. Recognizing the undesired scattering in the first-order transformation cloaks, Cai *et al.*[5] proposed the use of high-order coordinate transformations to eliminate scattering and to develop cloaks at optical frequencies.

Weder[6] proved that both high-order and first-order transformation invisibility cloaks cannot be detected by any scattering experiment and that such cloaks can actually conceal both active and passive devices. Weder showed these results for transformation media obtained from general anisotropic materials.

Ochiai *et al.*[7] have also forwarded a theoretical blueprint of a perfect invisible cloak. This cloak is made up of five MTMs with different values of refractive index and different index distributions. These materials are combined with one another like building blocks. The distribution of refractive index is such that light is bent around the void/hole, thus making it (or anything placed in it) invisible[7].

Yao *et al.*[8] have recently engineered 3D (bulk) MTMs made of nanowires that show negative refraction at optical frequencies. They demonstrated backward bending of visible and near infrared light by this bulk MTM medium. Researchers[9] at UC Berkeley have reported another similar bulk optical 'fishnet' MTM developed through another approach.

Leonhardt *et al.*[10] have shown the possibility of invisibility in a broader spectrum using transformation optics of a curved, non-Euclidean.

Invisibility cloaks have many future applications. They can be used to hide any unwanted thing which blocks a particular view. They can also be used to redirect light at will for any electromagnetic utility. In military, these can be used to hide tanks, bunkers, submarines, or make warships invisible to radars, etc. These can also be used to route cellphone signals around obstacles or to make the shade/shadow of an object to disappear.

All these advances in this new frontier will take us close to making 3D cloaks for the visible region. And hopefully, a full-spectrum invisibility cloak may soon be a reality.

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