

A Novel Refractive Technique for Achieving Macroscopic Invisibility of Visual Light

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Abstract The theoretical tools of optical transformation and conformal mapping have enabled the transference of the concept of invisibility from the realms of mythology to scientific reality. A number of attempts have been made to achieve invisibility which relied on Nano or micro fabricated artificial composite material with spatially varying electro-magnetic properties. This approach limits the size of the invisibility region to a few wavelengths and is also very costly. Here, we experimentally solve this problem by designing a structure with low cost materials and simple manufacturing techniques based on the principles of refraction and lateral shift. This cloak developed is able to conceal macroscopic object of sizes of at least 3 orders of magnitude larger than the wavelength of light in all three dimensions. This cloak can find huge application in defense and transformation optics.

Keywords: invisibility, optics, refraction, ray tracing

1. Introduction

Invisibility has been believed to be a mere hypothetical concept over the years and was thought to be impossible until a few years ago. Invisibility, though considered to be an extremely difficult phenomenon to achieve, is viewed as a demanding benchmark. It has been used extensively in multiple applications like in transformation optics [1,2,3]. In addition, the increasing defense concerns in the world demand for better concealment of weaponry [4].

A number of attempts have been made in the past to achieve invisibility. Ehrenfest's work on radiation less motions [1] came in 1910, which was a revolution as he made use of radiation to partially achieve invisibility. Scientists have also tried to achieve invisibility through the use of Meta materials in Japan [5]. In addition to this technology, micro wave [6,7,8,9,10], tera-hertz [11] and optical methods [12,13,14,15] have also been used to do the same. Scientists have also put in efforts, in trying to make a perfect invisibility cloak i.e. a cloak which demonstrates zero scattering of light [1].

However, in these experiments "invisibility cloaking" could not be achieved over the entire visible spectrum but was achieved only for a certain range of micro wave frequencies [16], further was applicable only for a two dimensional setting [17]. Several experiments have reported successful invisibility cloaking for microscopic [18,19,20,21,22] and macroscopic [23,24] objects, meta-materials is one such example.

Meta-material are artificially engineered composite structures. These materials contain a large number of elements that are identical in size, electromagnetic

properties, and shape. Meta-materials with negative refractive index serve as the primary reason for invisibility. The elements are to be designed such that they are smaller than the propagating electromagnetic waves. Manufacturing of meta-materials is arduous and time consuming as it involves engineering a large number of elements at atomic level. This paper aims at presenting a convenient method for the attainment of invisibility.

In this paper we report the demonstration of a cloaking device which is able to conceal macroscopic object of sizes of at least 3 orders of magnitude larger than the wave length of light in all three dimensions. The main emphasis of this paper is to achieve near invisibility in the visible range of frequencies. Near invisibility is the invisibility achieved with a small percentage of light scattering. The scattering of light reduces the intensity of the light and sometimes the object to be made invisible may seem transparent if not completely invisible. The design of the cloaking system uses refractive material thereby eliminating the necessity of time consuming and expensive nanofabrication processes and enabling the realization of cloaking at macroscopic scales.

An object is said to be invisible if it does not reflect and absorb light. Hence for an object to be considered invisible, light has to bend around the object and pass on further. This phenomenon of bending the light around the object is approximated in this paper by using the concept of lateral shift produced by the refractive material used to manufacture the cloaking device. The lateral shift produced by the refractive material allows the light to deviate from its original path thereby creating a region void of light rays. This behavior is obtained practically by designing a structure which allows the incident light to refract from it. The lateral shift produced by the incident

light creates a small region in which an object is invisible as the incident light does not enter in this region. The lateral shift produced by the cloaking device can be varied by varying the refractive index of the material used hence the volume of this region depends on the lateral shift produced by the cloaking device. In this paper the cloaking device is made using an acrylic sheet which has a refractive index of 1.49.

The remaining parts of this paper can be classified as follows. The next section mainly emphasizes on the detailed description of the experimental design of the apparatus being used and also the numerical proof of the proposed method. The third section presents the results obtained by using the proposed method. The last section gives the conclusion to the results obtained and also describes the application of invisibility in various fields.

2. Experimental Design

The major focus of the cloak design is to obtain an area inside the structure where ideally no light rays pass as shown in Figure 1. Lateral shift produced by refractive material can be used to make the light rays bend towards the normal of a surface. A region void of light rays can be created exploiting this property. Hence the cloak is constructed using refractive material like acrylic sheet which is readily available in the market and also has a suitable refractive index which is capable of generating a region of invisibility of size of at least 3 orders of magnitude larger than the wave length of light which is one of the main objectives in the experiment.

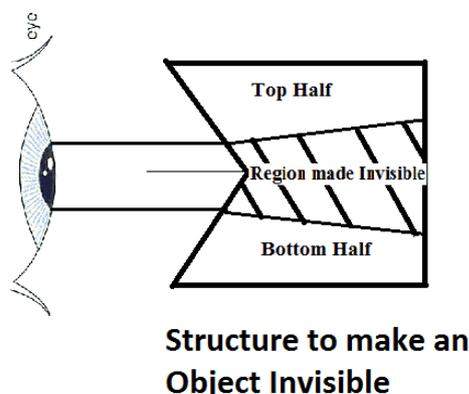


Figure 1. Proposed Structure used to make the object invisible

The proposed structure consists of a triangular face, having an angle of 90 degrees at the apex as shown in Figure 2. Plexi Glass or acrylic sheet is chosen for the manufacture of the structure as it is readily available and is relatively cheap. The refractive index of acrylic sheet is 1.49. The development of the proposed structure on a complete glass slab is quite difficult. While practically cutting the glass slab in the form of the proposed structure, there may be some error in the apex angle obtained i.e. the obtained apex angle may be different from our experimental requirements. This has a great influence on the dimension of the region of invisibility. Hence acrylic sheets are taken for the development of the structure. The two halves of the structure are obtained by gluing the acrylic sheets together using Araldite which is an acrylic adhesive.



Figure 2. Cross sectional view of the apparatus made of acrylic used to make the object invisible

The lateral shift [25] produced in the path of the incident ray occurs when the incident light enters the refractive surface [25,26]. The cloak is designed to make maximum utilization of the lateral shift produced by the upper and lower part of the cloak. The angle at the apex of the structure is kept at 90 degrees for symmetry. The upper and lower parts of the cloak are kept at 45 degrees with respect to the horizontal so that the light rays in the upper half of the cloak are bent towards the roof of the cloak and the light rays in the bottom half of the cloak are bent towards the bottom of the cloak thereby generating an area inside the cloak void of light rays i.e. where the flow of light rays is minimum from the observer's point of view. The lateral shift produced is shown below:

$$\text{Lateral Shift} = t \sin(i - r) \sec(r) \quad (1)$$

where 't' is the thickness of the glass sheets, i is the angle of incidence while r is the angle of refraction.

As can be seen from equation (1) the lateral shift produced by the structure depends upon the number of glass sheets used. If 'n' is the number of glass sheets used to make one half of the structure, the lateral shift produced by that half is n times the lateral shift produced by a single glass sheet. The number of sheets which are to be glued together depends upon the required lateral shift to be produced as shown in Figure 2.

2.1. Numerical Proof

In this section, we give numerical proof to the assumption that a region void of light rays is produced by the proposed structure. In addition, the dimensions of the cloak are also calculated. As seen from the Figure 3 'h' represents the height of the region of invisibility and x represents the distance of the center of the region to the apex of the triangular face.

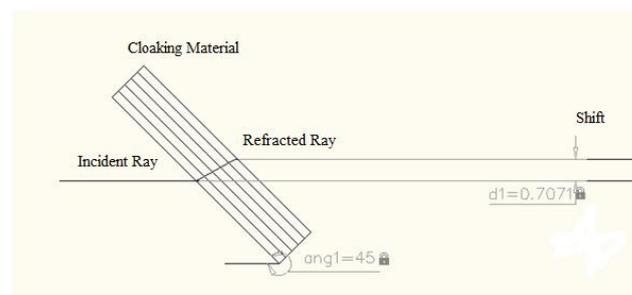


Figure 3. Ray tracing of light through the top half of the system at 532nm

Consider a single ray of light from the source which is at negligible angular distance from the apex of the triangular face. The incident ray of light can be considered parallel to the base of the structure. As the angle at the base of the structure is 45 degrees hence the angle of incidence will be 45 deg. (as alternative angles). According to Snell's law ratio of sine of angle of incidence to sine of angle of refraction is equal to the refractive index of the material (μ)

$$\sin(i)/\sin(r) = \mu \quad (2)$$

Hence,

$$\sin(45 \text{ degrees})/\sin(r) = \mu \quad (3)$$

$$0.707/\sin(r) = \mu \quad (4)$$

As the surface of the cloak is at an angle of 45 degrees with respect to the horizontal, a light ray parallel to horizontal will be at an angle of 45 degrees with respect to the cloak surface. Hence the incident angle made by the light ray is 45 degrees.

$$\tan(\phi) = h/x \quad (5)$$

In the triangle made by the path of light inside the structure, the radius of the area of invisibility 'h', and the distance 'x' from the center of the region of invisibility to the apex of the triangular face the tangent of the angle ϕ is equal to the ratio of the radius 'h' to the distance 'x'. The angle ϕ is the angle made by the refracted ray with respect to the horizontal.

$$\phi + \text{angle } r = 45 \text{ degrees} \quad (6)$$

The sum of angle ϕ and the refractive angle is equal to 45 degrees as the angle made by the refractive surface with the horizontal is equal to 45 degrees.

Substituting equation (4) and (5) in (6) we get,

$$\arctan(h/x) + \arcsin(0.707/\mu) = 45 \text{ degrees} \quad (7)$$

(from equation-(4))

Equation (7) gives the dimensions of the region of invisibility. According to equation (7) by using different refractive materials the dimensions of the area of invisibility can be changed.

3. Experimental Results

This section elaborates the results of the experimentation conducted for testing the success of the proposed methodology in achieving invisibility. This section explains in detail the type of material used for experimentation, the construction of the structure and the nature of results obtained. The relationship between height or radius of the cavity (h) and the distance (x) is obtained as

$$h/x = 0.286888 \quad (8)$$

on substituting the value of refractive index ($\mu=1.5$) in equation 7.

If an object is kept at a distance (x) of 2.45 centimeters from the apex of the structure then substituting the value of x in equation (8) we get h= 0.7 centimeters.

The practical verification of the above theoretically calculated value is obtained by placing a black object on

the white screen. The refractive index of the surrounding media is assumed to be 1.49. Figure 3 represents the ray tracing of light through the cloak system at 532nm. The refractive material used in the system consists of five (n=5) acrylic sheets of thickness 0.4 centimeters arranged as shown in Figure 3. The incident light is incident at an angle of 45 degrees with the normal. The light ray gets refracted, the refractive angle being 28.1255 degrees for the above conditions. A lateral shift, $d_1=0.7071$, is produced due to the refraction of the light ray by the top half of the cloak system as seen from Figure 3. Similarly the bottom half of the cloak system also produces the same lateral shift. This creates a region of height $h=2*d_1$ i.e. $h=1.4$ centimeters in which light rays do not pass. This height constitutes the region of invisibility. It is found that an object of height approximately equal to 1.4 centimeters is made invisible by the apparatus as shown in Figure 4.



Figure 4. Observer's view through the apex

4. Conclusion

It is observed from Figure 4 that the black strip (clearly shown in Figure 4), which was needed to be made invisible, is not visible to the viewer when it is kept in a cavity of radius 1.5 centimeters thereby giving valid proof to the theory used in this paper. The radius of this cavity can be increased by using a material with higher refractive index. But on using a material with higher refractive index the amount of light transmitted through the structure decreases. Any sort of external disturbances can be avoided by surrounding the structure with black walls. This structure can also be used for electromagnetic waves other than that of visible range by using different refractive material.

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