International Journal of Soft Computing and Engineering (IJSCE)
ISSN: 2231-2307, Volume-8 Issue-6, March 2019

Metamaterial Cloaking Designs with Calculation of Far-Field and Near-Field

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Abstract- The cloaking theory is the mother of stealth technology. Now a day as per cloaking theory you can hide anything from the naked eye even satellites, Radars and cameras etc, are operational. The cloaking should guide electromagnetic waves around an object as if nothing were there, regardless of where the waves come from. The cloak could reduce the scattering of waves used for radio and aerospace technology. Mankind has a cloaking concept over several centuries. This paper comprises of different section. The section I is introduction of cloaking and metamaterial. In section II we describe brief history of cloaking. In section III types of cloaking with details. In section IV we describes applications and in V analyses of cloaking types with their beneficial and drawbacks. At the end we discussed conclusion.

Keywords: Communications, Metamaterial, Cloaking, Techniques, Invisibility, Naked eye.

I. INTRODUCTION

The proper concept of cloaking was introduce in 2006 by Nicorovici and Milton [2] and has been enhance by many scientists such as Lintner and Bruno [3], Schweizer and Bouchitte [4], Kohn et al. [6], Nguyen [7]. Ammari et al. [5]. In metamaterials, we want to construct artificial materials with simultaneously pure negative magnetic μ (permeability) and electric ε (permittivity). Schurig et al. [8] enable the first practical in 10 November 2006's on metamaterial at a microwave frequency (8-5 GHZ) and made a copper cylinder wave consisting of split ring resonators which was cloaked. As per Alu and Engheta [8] idea plasmonic or metamaterial reduce the scattering by cancellation effect. Moreover they enhance the idea using plasmonic coating. The object remains invisible from detection by incident waves.

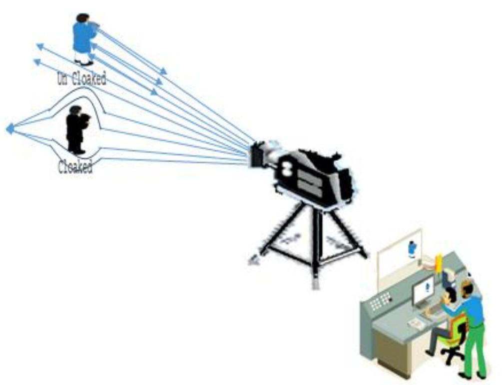

Fig. 1 Black Cloaked Object Not Detected.

Everybody like the idea of hiding to observe what is happening around him without being seen [1].

II. HISTORY OF METAMATERIAL INVISIBILITY CLOAKS

In 2000, four seminar papers of Soymar and Shamonina gave the birth of metamatirials which uses the double negative property. The Russian physicist Vector Veselago [10] introduce that the metamaterial is a left hand material. He elaborated the properties of negative permeability μ and negative permittivity ε. The David Smith first successfully constructed the double negative metamaterial or left-handed medium. In this paper he experience on conducting nonmagnetic split ring resonators continuous wires and periodic array of interspaced. Defined the frequency region for the microwave with effective values of the negative permittivity ε eff(ω) and permeability μ eff(ω) [11]. In 2001 Shelby, Smith and Schultz [12] experimentally show n =√ ε μ the effective index of refraction for microwave frequencies. The effective index of refraction is negative when both ε permittivity and μ permeability are negative [9]. In June 23, 2006's Leonhardt [13] and Pendry et al. [14] their papers which are popular on electromagnetic cloaking issue published in Science magazine. Which is also called transformation optics/electromagnetics [15, 16]. In 2003 mathematicians Green leaf et al. [17, 18, 19] discovered transformation based cloaking for non-delectability [9].

History detail:-

Revised Version Manuscript Received on March 05, 2019.
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S No.	Scientist Name	Country	Year	Work detail
1	Velesago	Russia	1963	Theoretical investigation of negative permittivity and permeability.
2	Vogelius, Sylvester, Uhlmann	USA	1990 till now	Invisibility and Inverse cloaking Problems.
3	Shalaev	USA	2005	Breakthrough in creation of a cloak for microwaves.
4	Leonhardt	UK	2006	Theory of Conformal mapping in electromagnetic.
5	Torrent	ESP	2008	Acoustics, Construction of a bilayered isotropic cloak.
6	Movchan	UK	2009	Elastic waves.
7	Wegener and KIT	Germany	2011	Physics, Lithography of a cloak for electromagnetic field; construction of a cloak for elastic waves.
8	Joseph Choi	USA	2014	Paraxial' cloak
9	Kelly Hodgkins, Boubacar Kante	USA	2015 till now	Dielectric metasurface cloaking.
10	Yang Hao, Luigi La Spada	UK	2016	Acoustic and heat waves.
11	Allison Mills,	USA	2016	Photonic crystals.

III.TYPES OF CLOAKING

There are main two types of cloaking.

A. Passive cloaking

In passive cloaking the metamaterials Guiding the incident waves around the obstacle via transformation or changing the scattering strength. This leads to anisotropic materials (metamaterials) [21] which can be approximated by bi-layered isotropic media. Isotropy is highly relevant for the praxis, scattering cancellation approach Idea, intelligent scattering [20, Chap.10].

B. Active Cloaking

In active cloaking we apply additional wave-sources such that the total field features as the desired Property. These types can be classified in exterior and interior cloaking [22].

C. Cloaking Techniques

The Electromagnetic cloaking is being used for one frequency and one polarisation [23]. Enhancement of electromagnetic cloaking is "carpet cloaking" [24,25]. This technique makes things flat instead of invisible. Further acoustic waves used for non-electromagnetic forms of cloaking [26,27].

D. Transformation Electrodynamics

In this cloaking technique the coordinate grids of space are being stretched. The anisotropy and inhomogeneity background plays the role of geometrical distortion by possessing full control over both permittivity ε and permeability μ.

E. Spherical Transformation Cloak

By using the transformation optics (TO) we are enables to obtain spherical transformation cloaking. Radius R2 of spherical region in free space and map volume into an annulus R1 $<r<$R 2, radius R1 isolated from external electromagnetic, the centre point must be finite. With a hole, transform free space map into a bowed space. Put on this technique to the radial transformation r' = R1 + r(R2 −R1)/R1 we are enables to get spherical transformation cloaking technique [28].

$\mu rr = \varepsilon rr = R2/ R2 - R1. (r - R1)^2 / r2$

$\mu\theta\theta = \varepsilon\theta\theta = R2/ R2 - R1$

$\mu\varphi\varphi = \varepsilon\varphi\varphi = R2/R2 - R1$

Similar equations raise in 2D case for cylindrical cloak. These cloaks give the zero scattering, in these case the wave flow around the volume are being controlled which are insulated from the world electromagnetically [29].

F. Non-Euclidean Transformation Cloaking

A curved non Euclidian transformation is proposed by Leon hardt and Tyc [30] in this method to avoid singularities and infinite expansions one achieved on the surface of a sphere instead on a plane. This approach escapes super luminal propagation. As a result we achieve the broadband cloaking for all angles [31]. This approach added phase delay as a result additional propagation time required in associated curved space. This type of cloaking is for all angles of rays not for waves. For phase velocity without singularities invisibility can be created by this method [32].

G. Carpet Cloaking With Its Variants

The carpet cloaking was presented by Pendry and Li [33], quasi conformal mapping used in transformation optics. The object surrounded by PEC is hides embedded in bump. The graded index profile which give the mirror flat used for transformation.

In this method the incident beam scattered in different directions. Every object appears as a flat when cloak tops the bumps. This technique is used for only 2D geometry this is main drawback of this method. In the 3D, the dump would be detectable. The carpet cloaking was used for microwave frequencies but due to metallic elements losses it was not extendable for optical frequencies [34].

H. Transformation Cloaking At Zero Frequency

This technique is used at zero frequency [35]. By decoupling DC electromagnetic field the DC electric/magnetic fields with permittivity/permeability cloaking associated. These fields elaborated theoretically and experimentally by using superconductors [36, 37]. The resistor network used for fabricating of DC electric [38, 39].

I. Cloaking using Transmission Line Networks

In this method to hide object from electromagnetic waves, we use transmission line networks [59, 60]. The transmission line network due to low scattering cross area allows passing incident wave easily. This technique hides the object which is fit inside the fishnet.

J. Parallel Plate Cloaking

The cloaking in parallel plate [49, 50, 51] can achieve by making parallel metallic fins with adiabatically which decrease separation as a result the incident electromagnetic energy guided around the object. This technique not uses coordinate transformation as in transformation cloaking but the process is same in both methods. The parallel conducting sheets not disturbed the plane electromagnetic wav which are perpendicular to electric field. The sheets become short when thickness increase gradually as a result electromagnetic wave cannot reach to object and cloaking is created. The broadband cloaking can be achieved in conducting cylinder by using this method.

K. Anomalous Resonances

It induces invisibility in a finite region by localized anomalous resonances [52–55]. This technique adventures resonances, such as plasmonic or at the interface resonances between corresponding media.

L. Cloaking Beyond Electromagnetism

The cloaking for non-electromagnetic system like as matter waves, liquid surface waves, acoustic waves and elastic waves are known as cloaking beyond electromagnetism.

M. Elastic And Acoustic Waves

This technique used for acoustic waves in 2D [56], getting single polarization take the equivalence between 2D Maxwell equation and acoustic equations. This technique is not used for 3D case either in the scalar case.

N. Thermal Waves

By controlling the heat flow we are enables to create components like diodes, transistors and rectifier [57]. The thin cloaks made of homogeneous materials of two layers used for 3D thermal cloaking. The object is isolated from heat [58, 59].

O. Quantum Matter Waves

In this method, by using isotropic and homogeneous layers, semiconductors can be cloaked from incident electrons due to high potential [60, 61]. In furtive quantum sensors this method is being used [62, 63].

P. Surface Liquid Waves

This technique can be used to create interface between a gas and liquid [64, 65]. By using this method we can isolate floating bodies from surface waves.

Q. The Scattering Cancellation Technique

This technique use scattering cancellation method and in multi pole expansion of scattered field it only cancels the dominant scattering terms. In this method we hide the conducting (reflective) surface which makes invisible interiors area from any electromagnetic wave. In dominant term an arbitrary object placed at spherical coordinate system (r,θ,ϕ) by scattering of monochromatic $\exp(j\omega t)$ wave propagating with permeability $\mu 0$ and permittivity $\varepsilon 0$ [40]. Because harmonics are orthogonal functions and Maxwell equations are linear. For each harmonic problem are solved separately. The total scattering field can be finds by adding contribution of each multi poles [41]. The coefficients are used to find the presence of object. Invisibility for an object can be induced by cancel the dominant scattering coefficient.

R. Plasmonic Cloaking

This method used scattering cancellation by shells or cloaks made out of isotropic and homogeneous [42, 43]. The cloak is ideal when permittivity below unit, this can be achieved when dispersion (materials with plasma), this is called plasmonic materials. The object will detect when $\varepsilon_c > \varepsilon_0$ in dielectric is double positive sphere (DPS) and an epsilon negative medium (ENG) $\varepsilon_c < \varepsilon_0$ are there. The invisibility will created by cancellation of fields when both positive and negative fields will be combined.

S. Mantle Cloaking

The Mantle cloaking used ultrathin isotropic frequency selective surface instead of homogeneous isotropic layer of the material [44, 45]. The dominant scattering can be cancel from object by tailoring surface impedance. The mantle covers made of sub wavelength elements. The average surface impedance can achieve by tangential electric field $E_{tan} = Zs^{TM}$ Js divided by average surface current density Js. The ultrathin cover is low loss at radio frequencies so $Zs^{TM} = jXs$. We take Zs^{TM} value scalar due to polarization are required. We apply discontinuity of magnetic field and continuity of tangential electric field as a boundary condition.

$$E_{tan}|_{r=a}\pm = Zs^{TM}\, \hat{r}\times(H_{tan}|_{r=a}+ - H_{tan}|_{r=a}-)$$

The correct value surrounding a dielectric sphere of surface cloak of radius a_c can be achieved by repeating this procedure for plasmonic cloak of radius a_c. By defination γ is equal to a/a_c, which we find [46].

$$Xs = 2[2+ \varepsilon-\gamma^3(\varepsilon-1)]/\ 3\gamma^3\omega a\varepsilon_0(\varepsilon-1)$$

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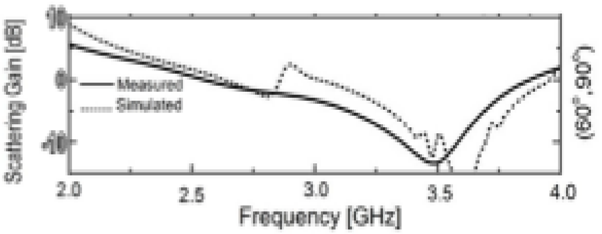
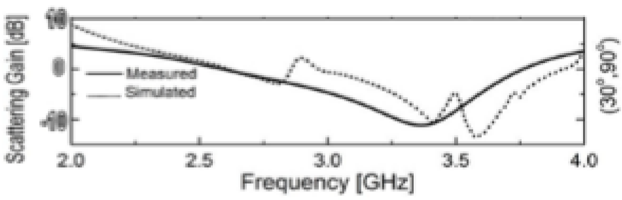
The cloaking for all angles can be achieve by using thin patterned meta surfaces for spherical and cylindrical objects [47, 48].

FAR- FIELD MEASUREMENTS

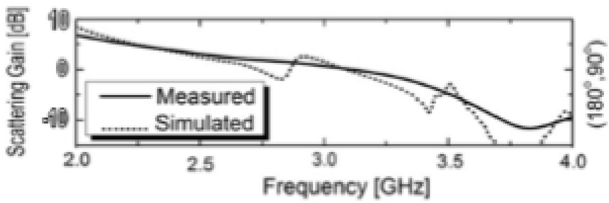
In this technique we obtain radar cross section (RCS) of cloaked and uncloaked objects and also compared with analytical theory and full wave simulations. The distance between transmitter, receiver and target were maintained equally at $R = 16.3\ \lambda_0$. During scanning of position in both azimuthal and elevation planes. We prove that scattering suppressed at observation angles when we change the positions of antenna. The azimuthal bistatic measurements shown in Fig. 2 achieved when the transmitter is positioned at ($\phi = 0^\circ$, $\theta = 90^\circ$) and receiving antenna rotating in azimuth plane. By using time gating and routine background subtraction techniques we remove clutter in this process. We show the radar cross section scattering gain with comparing full wave simulations as cloak RCS to uncloak RCS in Fig. 2. The simulation result show that the low scattering suppression is obtain as −13.6 dB during misalignments of fabrication imperfections of prototype and time gating error for both planes of polarization. Between 3.3 – 3.9 GHz strong scattering suppression has been achieved with around 3.6 GHz optimal performance. When we change the observation angle a little distribution in scattering dip is observed.



(a)



(b)

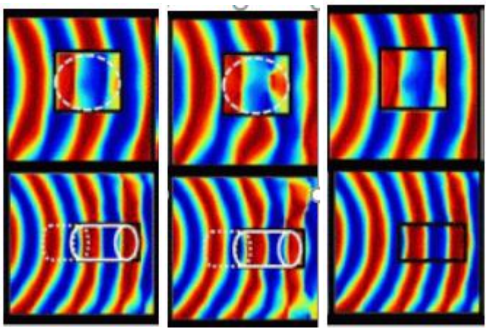


(c)

Fig 2. Scattering measurements of azimuthal bistatic (a) 60°- 90° (b) 30°-90° (c) 180°-90°.

NEAR- FIELD MEASUREMENTS

In this technique the total electric field distributed around the device which is under observation by a 3D programmed scan system. The microwave horn with polarization parallel to the cylindrical axis placed at $2.5\lambda_0$ from the object at frequency $f_0 = 3.5$ GHz approximately $2.3\lambda_0 \times 2.3\lambda_0$ was scanned with sampling resolution $\otimes x = \otimes y = 0.075\lambda_0$. There were considered a case of free space λ_0, cloaked and uncloaked. The constant height 80% of the cylinder height *l* in the azimuthal plane is achieved in each case except during the selected plane disturb the area of under test target. In Fig. 3 the white circle show the rod location and black area present the area where to avoid the collision, near field probe is programmed to examine the object on upper side.



(a) (b) (c)

Fig 3. During measured electric field (a) cloaked (b) uncloaked and (c) free space.

When we comparing free space, cloaked and uncloaked the strong scattering reduction as well as reestablish of real Gaussian phase fronts at 3.3 – 3.9 GHz with good performance 3.6 GHz is obtain, which are shown in measurements of far field during analytical and theoretical effects. These result not limited to far field but exact round the target which combine the field penetration inner side of the cloak object as a result we get 3D invisibility and also provide practical scheme for noninvasive near field sensors of microwave.

IV. CLOAKING APPLICATIONS

The metamaterials are used in radar technology, communications, sensing, invisible cloak devices, sub-waves imaging and data storage. In biological tissue for microwave hyperthermia treatment the metamaterial is used due to its refocusing properties. In array applicator it was difficult to adjust heating spot in tissue by providing heating source around them. But due to metamaterial refocusing, we can control system and overcomes complex deployment. Metamaterial lenses are being used in cancerous tissue for microwave hyperthermia treatment [68]. In general the Sensors disturb the field to measure their presence. A partly cloaking could reduce this affect. In Electromagnetics scenario, the cloaking minimized the effect of metal implantats on electromagnetic measurement. In Acoustics it used for dipole; architekture; automotive industry; better laudspeaker. In Elasticity the cloaking is used for Earthquake resistant buildings [66] In Thermodynamics it used for new cooling system on circuit board, Chip cooling; Routing or focusing of the heat. In Fluiddynamics case it Reduce the turbulences [67]. In medicine it used Acoustic metamaterial superlens for ultrasonic tomography (Shu Zhang, 2009).

In military used for Marine, electromagnetic acoustic, fluid dynamic cloaking used for hiding from Nike eye.

By near zero narrow waveguide the Alu et al. [69] Introduced a dielectric sensing method. To sense material flaws at the wavelength level, a novel microwave non destructive evaluation sensor was urbanised by Shreiber et al. [70]. Labidi et al. [71] Introduced thin film sensors with metamaterials. For high sensitivity strain, chemical sensing and biological, we use flexible metamaterial constructed on photonic device operating in visible-IR rule was proposed by Xu et al. [72]. The superlens made of metamaterials which overcome diffraction limit in optics was proposed in 2000 by Pendry. In this method half wavelength permanently lost in the image. The sharper images can be achieved by enhancing the evanescent waves in superlens.

SECTION: V

Analyses Techniques:-

S. No	Techniques	Advantages / Disadvantages
1.	spherical or cylindrical	The disadvantages of these techniques are having superluminal propagation, as a result to bring invisibility much nearer to actuality.
2.	Carpet Cloaking	The main disadvantage is, it work in 2D. In 3D the object is easily detected due to dump.
3.	Scattering Cancellation	This technique cannot be used for large object due to number of dominant increase fast with the size of target when compare wavelength.
4.	Mantle Cloaking	It provides light weight, broader bandwidths and conformal designs.
5.	Plasmonic	In this method harmonics are orthogonal and Maxwell equations are linear functions. To find scattering is complex process.
6.	Transmission-Line Networks	Only that object can be hide which is inside the fishnet.
7.	Parallel-plate	This technique is not using a coordinate transformation.
8.	Anomalous Resonances	This method is only for a finite region.
9.	Elastic and Acoustic	Acoustic invisibility cannot be achieved in 3D for both vector and scalar cases.
10.	Thermal Waves	This method used for 3D.
11.	Surface Liquid	The stroboscopic effect for the observation can be achieved by this method.

V. CONCLUSION

The waves behind the object emerge from the cloak with their original direction restored, is fundamental idea of cloaking. The metamaterial is used in many techniques of cloaking. The cloak would create the illusion that the light rays have been propagating through empty space, making the object in the middle invisible.

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