International Journal of Technology and Engineering Studies
volume 7 issue 2 pp. 15-23 doi: https://dx.doi.org/10.20469/ijtes.7.10003-2

Invisibility Cloak in Microwave Region Using Double Negative Meta-materials and Their Various Applications

Faiza Ali *
Avionics Engineer,
Department of Aeronautics & Astronautics,
Institute of Space Technology, Islamabad, Pakistan

Mehran Khan
National University of Sciences and Technology (NUST), Islamabad, Pakistan

Muhammad Asif
National University of Sciences & Technology,
Islamabad, Pakistan

Abbas Hussain
National University of Sciences & Technology,
Islamabad, Pakistan

Hafiz Muhammad Saad
National University of Sciences & Technology,
Islamabad, Pakistan

Abstract: Cloaking, camouflage or invisibility in microwave regime can be attained by canceling the electric (E) and magnetic(M) fields created, or by moulding the EM waves about the target. Guiding the EM wave is shifting or creating a change in the coordinate system such that, inside of the cloak remains hollow, at all points down to origin, the EM field will become zero, creating invisibility in the inside shell region. This type of invisibility can be achieved by meta-materials which comprise of negative values of permittivity (G) and permeability (μ) and therefore negative refractive index, hence they are also known as double-negative materials (DNG). They were first analyzed theoretically in 1967 by a Russian physicist, Victor Veselago. These materials are not found naturally as the Greek word meta itself means altered or changed and are supposed to be manufactured artificially. In recent years, a lot of research and theoretical work has been done on the designing, formation, and practical application and implementation of double-negative materials or meta-materials. This paper is a survey type and consists of three parts. In the first part, classification of naturally occurring materials and meta-materials based on permittivity and permeability is done and clear differentiation between naturally occurring and artificially constructed materials is made evident. In the second part, characteristics and designing (unit cell) of meta-materials through the most common or conventional method is done, some of the mathematical aspects are also discussed and compared. In the third part, the vast scope and applications of meta-materials are discussed and mentioned. In the respective research that has been conducted, reliability, convenience and conservation of energy and resources through the usage of meta-materials in various conventional and practical fields is made evident. Complete and ideal designing, and development of a perfect meta-material has not yet been successfully achieved, but day by day, an improvement is made, and the use of these materials in various forms can really make a significant and positive difference in the present and future.

Keywords: *Double-negative meta-materials, cloaking, negative refractive index, artificial materials, negative permittivity and permeability, applications*

Received: 19 June 2021; ***Accepted:*** 23 July 2021; ***Published:*** 24 August 2021

*Correspondence concerning this article should be addressed to Faiza Ali, Avionics Engineer, Department of Aeronautics & Astronautics, Institute of Space Technology, Islamabad, Pakistan E-mail: nasir@pnec.nust.edu.pk

I. INTRODUCTION

Visibility can be elaborated simply by the phenomenon of reflecting back of visible light to our eyes after hitting the object [1, 2]. Various surfaces have their own tendency of reflecting light depending upon their specific range of frequencies [3, 4, 5]. The invisibility cloaks using metamaterials are designed in such a way that they do not allow back reflection rather, they backscatter the light [3, 5, 6].

A perfect cloaking device has the scattering property of vacuum [3, 6].

An invisible cloak in theory, is a stealth device or technology which can make objects or things, such as aircrafts and individuals, to be visible upto some extent or completely vanish in EM spectrum. Although over the whole spectrum, a cloaked object diffracts more as compared to the body that is uncloaked [5, 7, 8].

Cloaking, camouflage or invisibility can be attained by cancelling the electric(E) and magnetic(M) fields created by the object or by molding the EM wave about the object [2, 9]. Guiding the EM wave is shifting or creating a change in the coordinate system such that, inside of the cloak remains hollow, at all points down to origin, the EM field will become zero creating invisibility in the inside shell region [3, 10, 11, 12].

This type of invisibility can be achieved by metamaterials which comprise negative values of permittivity(epsilon) and permeability(mu) and hence negative refractive index, which was first analyzed theoretically in 1967 by a Russian physicist, Victor Veselago [8, 13, 14, 15, 16, 17]. These materials are not found naturally as the Greek word meta itself means altered or changed [3, 18] and are supposed to be manufactured artificially [8, 19, 20]. A real, practical cloaking device can be extended as basic technology used by aircraft cloaking and warship stealth, wireless communications, radar and defense [21].

Metamaterials provide us with the theoretical or fictional probability of electromagnetic rays to pass plainly or move about the cloaked body providing an alternative for optical or active camouflage [22, 21, 23, 24].

II. CONCEPT OF CLOAKING

At present, cloaking has been achieved only with a small frequency range in the electromagnetic spectrum [8]. In microwave region it basically refers to hiding or making an object invisible from radar detection or any other detector. This phenomenon can be attained, when an EM wave which is made incident to an object that is supposed to be concealed, moves out of the cloak without scattering or reflecting i.e., EM field should mould itself around the object [9, 25]. The design and development of the cloak requires transformation optics, in which a transformation of conformal frame of reference is correlated to Maxwell's mathematical equations to obtain a set of fundamental framework, distributed spatially, that defines the invisibility cloak [26]. The permeability and permittivity variables or tensors of the cloaking material are driven in such a way that the material becomes invariant spatially, anisotropic and inhomogeneous, which are the fundamental characteristics to obtain cloaking [27]. Illustration of bending of waves in fig 1, [28].

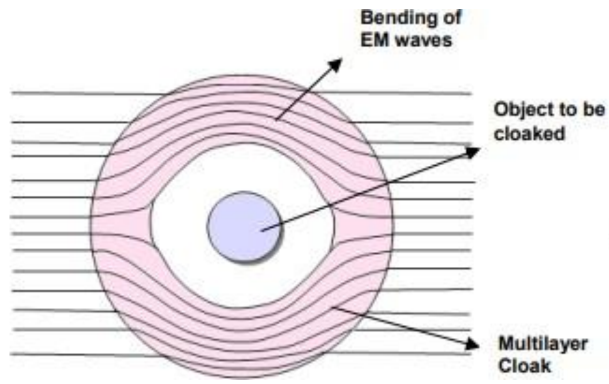

Fig. 1. Bending of waves

III. CATEGORIZATION OF MATERIALS WITH RESPECT TO PERMITTIVITY (S) AND PERMEABILITY (μ)

Classification of materials with respect to (epsilon) (s) and (mu) ((μ) lie within four quads as visible in fig 2 [29].

The first quadrant in which (s) is greater than (>) 0 and (μ) is greater than (>) 0 shows right handed material (RHM), the materials in this quadrant obey the right hand, thumb rule for propagation direction of radiation or wave and are known as double positive (DPS) medium. The propagation of wave occurs in forward direction in the first quadrant. It consists of typical material e. g., dielectrics.

The second quadrant (s) is less than (<) (θ), and (μ) is greater than(>) (θ) constitutes electrical plasmas in certain frequencies ranges supporting evanescent waves in the vicinity of source, they are also called ENG (epsilon negative) materials.

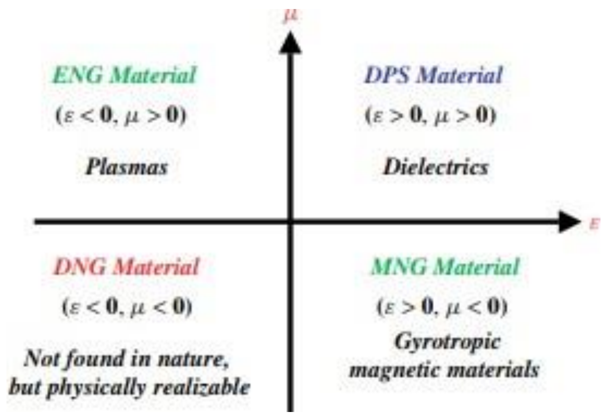

Fig. 2. Classification of materials

Fourth quadrant having (s) is greater than (>) 0 and, (μ) is less than (<) 0 is also supporting evanescent waves, and are known as MNG (mu negative) material, at certain frequencies some gyrotropic material exhibit this phenomenon.

The third quadrant consists of a material with both permittivity(s) and permeability (μ) negative or less than(<) zero. Hence, are called DNG (Double Negative) material, they follow left hand rule because wave propagation takes place in backward direction and are also called left hand materials (LHM), the materials constituting this class can only be manufactured artificially (meta materials) and are not found naturally [5, 8, 29].

IV. SNELLS LAW

Third quadrant comprises of materials consisting of negative Refractive index in the Snells law [13, 29] which describes that an incident wave goes through negative diffraction or refraction as the interfacing ray bends about the inward direction, after being refracted into the medium, which is contradictory, to positive (index) medium. Light is refracted reciprocally for normal right handed materials. Refractive index for metamaterials [8].

$$n = -\sqrt{\mu s} \tag{1}$$

V. DESIGN OF UNIT ELEMENT FOR NEGATIVE PERMITTIVITY AND PERMEABILITY

Design of double negative metamaterial can be achieved by bringing two components in contact, one responsible for negative permittivity and the other for negative permeability. In order to get achieve what we desire we will employ (SRR) split ring resonator, uptill now it has been studied, discussed, and used widely for attaining negative permeability.

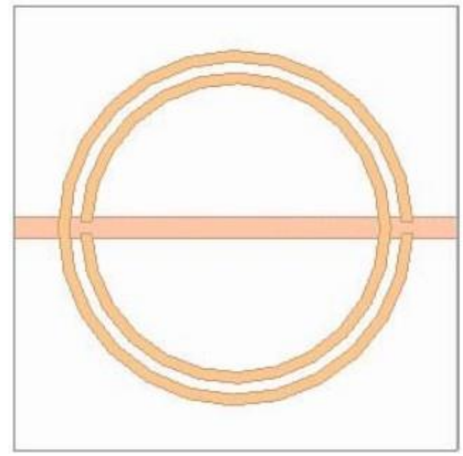

Fig. 3. Unit element structure of double negative material

It consists of two split rings with their splits 180 degrees apart. It behaves as an unnatural or synthetic magnetic doublet or dipole, the empty part between internal and outside rings behaves the way a capacitor does whereas, the ring itself acts the way an inductor does, ultimately giving a resonating LC (inductor, capacitor) circuit, because of this configuration the magnetic doublet generated because of split rings, lag behind the magnetic (H) field by 180 degrees consequently giving negative permeability [30, 31, 32]. Whereas, negative permittivity (s) is attained by the array of tenuous or thin wire which is constructed of metals such as copper, silver, aluminum, gold. Electric dipole will be born due to induced current formed in a result excitation of electric field parallel to plane of wire strip, and hence negative permittivity is induced [30, 31, 32]. The combination of both the objects conclusively provides a double negative material illustrated in fig 3, [30, 33].

VI. THEORETICAL ASPECTS MAXWELLS EQUATIONS

[3, 8]

$$\nabla \times E = -j\omega\mu H \tag{2}$$

$$\nabla \cdot D = \rho \tag{3}$$

$$\nabla \times H = J + j\omega s E \tag{4}$$

$$\sqrt{\nabla} \cdot B = 0 \tag{5}$$

For plane waves [3, 8]:

$$k \times E = \omega\mu H \tag{6}$$

$$k \times H = -\omega s E \tag{7}$$

After negative values of mu and epsilon [3, 8]:

$$k \times E = -\omega\mu H \quad (8)$$

$$k \times H = \omega s E \quad (9)$$

VII. OTHER APPLICATIONS

A. Metamaterials Usage as an Antenna

Metamaterial varnishing or covering has been essentially utilized to upgrade the radiation abilities, furthermore its usage has adjacent effect and increment in the matching property of electrical compact electric and magnetic doublet or dipole antenna. Metamaterial enhance the power radiated and hence the gain. The latest antenna constituting metamaterial proliferate with a percentage of 95, of total signal provided at input in micro or radio frequency. Antennas constituted of metamaterials under test or in experimentation are as compact as 1/5 of a (lambda) wavelength [33, 34, 35].

Directivity has been increased upto a great extent by coating a simple patch antenna with metamaterial film. In a similar way, the directivity of horn antenna has been incremented by keeping its geometry flat and constructing it with metamaterial having zero(0) index. Metamaterial antenna can play a legit crucial role in increasing gain ,directivity and a reduction of a favorable amount of return loss in an antenna [34, 35, 36, 37].

B. Metamaterials Usage as an Absorber

In order to create an absorber that is electromagnetic, metamaterials can be utilized. An absorber constituting metamaterial or completely constructed from it can actually have an improved performance and more significant usage. A metamaterial absorber exploits the components of loss of the complex parameters, mu and epsilon of metamaterial [38, 39, 40, 41].

The first Metamaterial based absorber was designed with near unity absorbance by N. I. Landy in 2008, it utilized three beds, two beds made up of metals and one is dielectric and it gave an excellent result of absorption in simulations that has the accuracy with a percentage of 99 at 11.48 GHz as displayed in 5,[38] . Whereas, through experimentations Landy was capable of achieving an absorptivity comprising of accuracy upto the percentage of 88 as in 4, [38]. The variation in the simulated result and actual tests was because of error generated due to fabrication of the device [3, 38, 41].

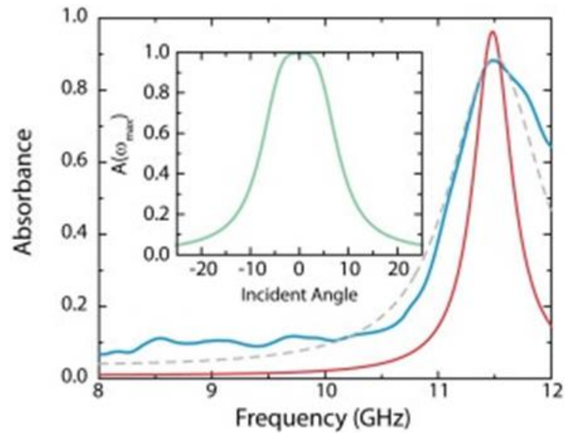

Fig. 4. Fabrication results

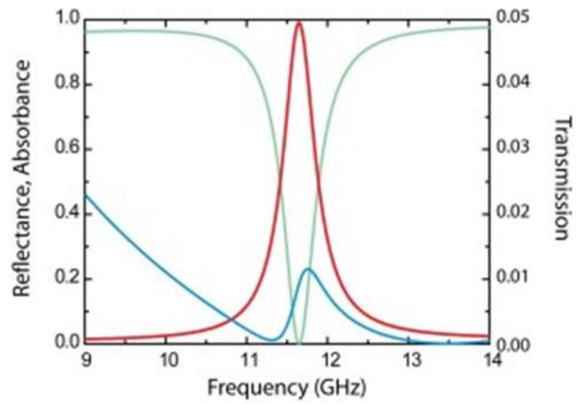

Fig. 5. Simulation results

C. Metamaterials Usage as a Super Lens

In order to overcome the refraction, reflection and diffraction limit, metamaterials can be utilized, due to their capabilites of resolution, they go beyond these limitations. Standard or regular lenses have a limitation of diffraction, this is because the components that are supposedly propagating are only broadcasted from an origin of light. The nondispatching components or the components that do not propagate at all, the evanescent radiations, are not really broadcasted or transmitted. One approach to make the resolution better is to enhance the refractive index which comes with a draw- back of its presence in materials comprising high index. The main purpose of a super lens is retrieving data or essential information from the non propagating (evanescent) radiations which carry the data at a very minute level [39, 42, 43, 44, 45]. A Veselago Pendry lens constructed from metamaterial (left handed medium) shown in 6, [45]. In this arrangement negative refraction is basically used for converging ray from point to a point in order to focus. This helps in formation of a flat surface lens with no optical axis at all, focusing the rays on the same point due to convergence actually gives birth to a lens having a crucial characteristic of zero aberration focus[3, 45, 46].

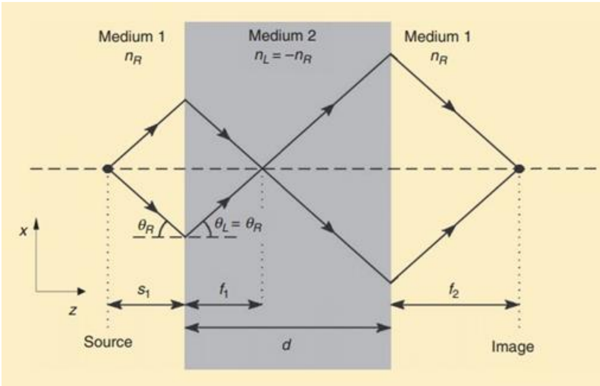

Fig. 6. Veselago pendary super lens

D. MetamaterialJs Usage as Sensors

One of the most advantageous use of metamaterial is creating a sensor of desired sensitivity by specifying the range according to our need. Double negative material can cater with the limits of present sensors by incrementing the resolution, sensitivity and possible range of the sensors upto a fair or significant amount. It plays a crucial role in various practical and conventional fields, e. g., security systems, biosensing and environmental sensing [29, 47, 48, 49].

E. MetamaterialJs Usage for Manipulation of Radar-Signals

Transmitting or broadcasting a microwave coherent beam in air and then orchestrating it is crucial as well as hard work to be done. It is a legit endeavor to avoid inessential scattering of waves in the atmosphere while their transmission that leads to divergence. A class of metamaterials named as VHMMs(Virtual Hyperbolic Meta Materials) is introduced in order to orchestrate or manipulate beam in microwave region, its construction comprises of an assembly (array) of channels consisting of plasma in atmosphere attained by self converging and hence focusing of a laser pulse with high intensity [50, 51, 52, 53].

The formation of such structure can be utilized in order to collocate the laser beam quite efficiently and for shifting or enrouting the signals transmitted from radar around the target or any obstacle [52, 53, 54, 55, 56].

F. MetamaterialJs Usage as a Phase Compensator

The concept of phase-compensation via metamaterials can be made by the phenomenon that occurs when a ray passes through it i.e., when an actual radiation or a wave penetrates through a metamaterial, it acts as a phase compensator, it can be made clear, when a wave passes through a double negative medium (DNG), actually transmitting through a double positive medium (DPS) before entering DNG medium, when the wave moves through a DPS medium, a phase shift is introduced in it, in order to cater it, a DNG medium is placed in its path which generates an opposite phase shift, hence the wave conclusively attained through this arrangement has a resultant phase difference of zero and hence compensation of phase [2, 3, 57, 58].

G. MetamaterialJs Usage in Acoustics

Acoustic metamaterial are metamaterials which comprise of negative relative change in the overall volume of the object as well as negative relative change in the overall density both at the same time, in a legit way of effective medium. Metamaterials in the field of acoustics or more generalized terminology Acoustic metamaterials are man- made or synthetically manufactured and designed materials in order to orchestrate, control, and move sound waves in a desired direction, sound waves can be in various regimes such as infrasonic i.e., below the audible range of frequency (under 20 hertz), ultrasonic i.e., above the higher audible limit of range of frequency (from 20,000 hertz to several giga hertz) and sonic i.e., audible (from 20 hertz to 20,000 hertz) [3, 59, 60, 61].

H. MetamaterialJs Usage in Seismology

Another useful advantage as well as usage of metamaterial is seismic damper, the SM (seismic metamaterial) refashions the soil functioning during earthquake or soil amplification in order to reduce the magnified amplitude and bring the frequency back to resonance level. SMs are metamaterials which are designed to nullify the unfortunate effects of seismic waves (by counteracting upon them) on man-made infrastructures and megastructures [39, 62, 62, 63, 64, 65].

I. MetamaterialJs Usage as a Flat Lens

In order to avoid unwanted diffractions (formation of color or more generalized term flat lens are used. The flat lens fringes) and blurred image, metamaterial lens with flat surface basically eradicate spherical and chromatic aberrations i.e., the formation of the colored border or fringes formed due to non-focused different wavelengths of light at a single point.

Due to this advantage flat lens can be used extensively in manufacturing microscopes and cell phone cameras with way much better results, resolution and aberration free outcomes [66, 67, 68, 69].

J. Miniature Metamaterial

They can also have reversible focus i.e., converging light - beams at sub wavelength focal (convergence or focus point) points. This capability of metamaterials can be of great significance in order to design and manufacture miniscule or miniature objects or structures. The engravement of extremely fine details can be achieved by an ultrafine, coherent light radiation. One of the main and crucial advantage of it is the allocation and containment of the data and information on the optical drives and computer chips upto a comparatively much larger extent. Its application and usage provides us with the dynamic flexibility in sensitivity, miniaturization according to the desired measurements and geometry [50, 69, 70, 71, 72, 73].

VIII. CONCLUSION

The research that has been conducted by us on metamaterials is because of the increasing scope it has in cloaking as well as many other applications regarding various practical and conventional implementations. Complete and ideal designing and development of a perfect metamaterial has not yet been successfully achieved by day by day an improvement is made and the use of these materials in various forms can really make a significant and positive difference in present and future.

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