

Negative Index Materials: Metamaterials

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ABSTRACT

In the past few years, new advances in structured electromagnetic materials have given growth to materials with negative refractive index, which have both negative dielectric permittivity and negative magnetic permeability in some frequency ranges. These negative refractive index materials exhibit exotic properties which are not easily achieved using naturally occurring materials. This awareness of a negative refractive index opens up new theoretical frontiers in optics, electromagnetism, physics, material sciences, nanotechnology, engineering and many other branches of sciences. One much discussed case is the concept of a perfect lens that allows imaging with sub wavelength image resolution. According to researchers, controlling negative refraction will help in the development of superlenses that magnify the objects too small to see with a conventional optical microscope. Here in this paper we review the basic concepts and ideas of a negative refractive index material. First we will present the ideas of Metamaterials, which enable to design the new materials with negative dielectric permittivity, negative magnetic permeability and negative refractive index then we will discuss the various types and applications of metamaterials.

1. Introduction

1.1 What is negative refractive index?

Refractive index is recognized as ratio of the phase velocity of a wave in a reference material (for light, we take vacuum as reference material) to the phase velocity of the wave in any another material. In almost entirely undergraduates and graduate level texts on the topics of optics or electricity and magnetism the refractive index of a material is always expected to be positive. But nature has concealed numerous great secrets from us, first described by Victor Veselago a Russian Physicist in 1967 [1]. Veselago revealed the unusual and interesting property that if material has negative values of both of permittivity ($\epsilon < 0$) and permeability ($\mu < 0$) then refractive index ($n = \sqrt{\mu\epsilon}$) of that material will also be negative ($n < 0$). When a wave travels into a material with a negative refractive index then the direction of the phase velocity of the wave will be opposite to the direction of incident wave.

As we all are conversant with the definition of refractive index, it is the ratio of velocity of light in vacuum to that of velocity of light in any given medium. It is also known that the ray of light bends on the way to the normal as the medium gets denser. When light travels in any usual material medium, its velocity gets slowed down. The amount up to which velocity of light slowed down depends upon the refractive index 'n' of the material. Light wave travelling from air to any ordinary material like water many theoretical calculations and experiments have shown that light ray bent as it enters into a new material, the process is known as refraction.

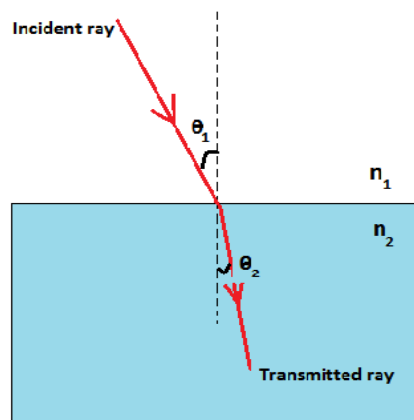


Fig 1: Refraction of light wave through an ordinary medium with positive refractive index.

Here θ_1 and θ_2 are the angles which incident and transmitted rays make with normal to the surface satisfying Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad (1)$$

Snell's law is still contented even when one of the materials has negative refractive index but the direction of light ray is mirror imaged about the normal to the surface as shown in fig given below:

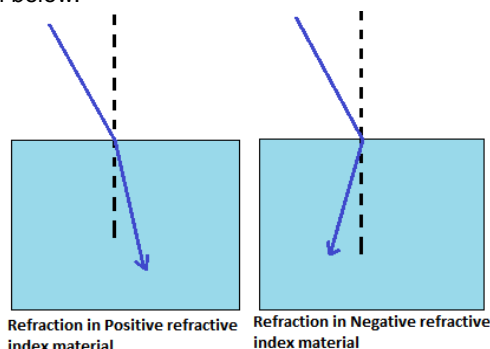


Fig 2: When a ray of light coming from vacuum hits a negative index material (right side), the refractive beam inside the place is on similar aspect of the surface area typical as the event beam. This's unlike the situation for regular positive index materials (left side).

From the fig given below we can see the difference between refraction and negative refraction.

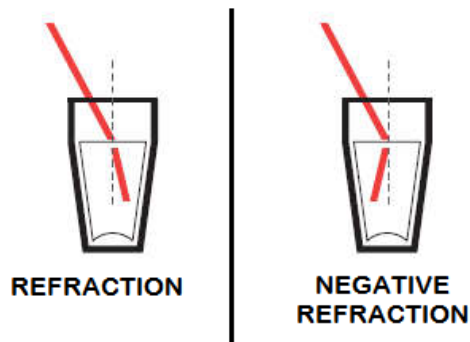


Fig 3: Refraction versus Negative Refraction

1.2 What are negative index materials (NIM)?

Wikipedia defines a metamaterials as follows [2]:

A metamaterial is a material which gains its properties from its structure rather than directly from its composition. To distinguishes metamaterials from other composite materials; the metamaterial label is usually used for a material which has unusual properties.

Meta implies beyond, which the title was given to materials with negative refractive index because these substances are beyond standard materials. The phrase of metamaterial was provided by Rodger M. Walserin 1999, that defined metamaterials as Macroscopic composites having a synthetic, three dimensional, periodic cellular structure created to create an enhanced combination, unavailable in nature, of 2 plus responses. Another means of expressing the significance of the growth is emphasizing the objective of metamaterials, that is achieving material functionality beyond the limits of traditional composites [three]. The very first Metamaterial proficient of bending electromagnetic radiation is made by Dr. Smith and the staff of his at the Faculty of California in 2000. A great deal of current investigations were centered on a brand new category of components referred to as left handed materials or maybe negative index components, and they exhibit extremely uncommon electromagnetic clasp and properties promise for brand new unit uses. This most prominent home and that isn't previously found is damaging refractive index. Negative-index material (NIM) is a metamaterial whose refractive index for an electromagnetic trend has a bad quality over several frequency range. Metamaterials might possess qualities which are a lot more apparent than those found in natural substance with good refractive index. These metamaterials don't happen naturally. They are able to just be fabricated artificially and for this main reason, these substances are called metamaterials. The special qualities of negative refractive index metamaterials aren't influenced by the essential physical qualities of the components of theirs, but by the design Materials and distribution of the precise plans bundled in them. Negative refractive index metamaterials may also be known as Left

Handed Metamaterials (LHM). Metamaterials could be meant to display both magnetic and electric resonances which can be distinctly tuned to transpire in frequency bands from megahertz to terahertz frequencies, along with expectantly on the noticeable area of the electromagnetic spectrum.

Veselago seen that the planar sheet of content of correct material plus thickness parameter with negative refractive index may be utilized as a lens.

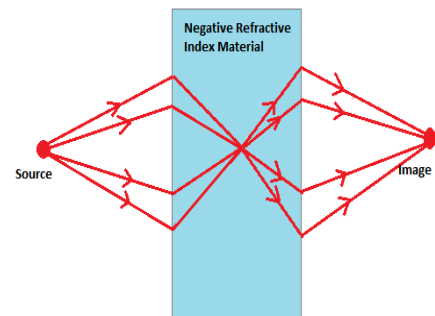


Fig 4: Slab of Negative refractive index material can be used as a perfect lens.

Veselago predicted the electromagnetic plane waves in a medium having simultaneously detrimental permittivity and also bad permeability[4], that propagate in a direction reverse to which of the flow of power. This result follows not from the trend equation that remains unaffected in the absence of options but from the single Maxwell curl equations. The Maxwell curl equation for the electric powered field gives a clear cut "right hand" (RH) principle between the instructions of the electric field 'E', the magnetic induction 'B' and also the path of the propagation vector 'k'. The guidance of energy flow, provided by 'E XH', forms a right handed product just if the permeability is higher compared to zero. When the permeability is unfavorable, the path of propagation is inverted with regard to the direction of electricity flow, the vectors E, H, and also k building a left handed system. Thus, Veselago pointed out such substances as "left handed".

1.3 Types of Metamaterials:

There are various types of metamaterial explained as follows [5]:

1.3.1 Electromagnetic Metamaterials:

Electromagnetic metamaterials are made up of conductive particles and havetraces inside a dielectric matrix. Thesemetamaterials have zero or even negative permeability and/or permittivity. Kymeta, MetamaterialTechnologies, Fractal antenna system, Imperial Universityof and duke Faculty London are definitely the recentfront runner of thethis type of metamaterials. These metamaterials are now being applied to the arena of microwave and also optics including beam steerers, antenna radomes, lenses, microwave couplers, modulators, as well bandpass filters. Electromagneticmetamaterials greatly influence theelectromagnetic waves with little wavelength as opposed to the wavelength of electromagnetic radiation.

1.3.1 (a) Single Negative Metamaterials: These type of electromagnetic metamaterials have either negative permeability or negativepermittivity, but not both.

1.3.1 (b) Double Negative Metamaterial: The metamaterials which have both the negative permittivity and negative permeability with the negative refractive index. These are also recognized as backward wave media.

1.3.1 (c) Photonic Metamaterial: These types of Electromagnetic metamaterials are designed to interact with optical frequencies and are also known as the optical metamaterials. Photonic metamaterials have zero refractive index. These metamaterials are the dynamic area of study in the field of optics.

1.3.1 (d) Bi-isotropic and Bi-anisotropic Metamaterials: Depending on the independent electrical and magnetic responses discussed by the parameters permittivity and magnetic permeability, the electromagnetic metamaterials are classified into double or single negative metamaterials. In numerous instances of electromagnetic metamaterials, the electrical field causes magnetic polarization as well as the magnetic field comes an electric polarization. Such media denoted as bi isotropic metamaterials since it shows magneto electric coupling which is anisotropic and also named as bi anisotropic.

1.3.2 Acoustic Metamaterials: These metamaterials are ready from 2 plus materials with various bulk modulus plus mass density. These types' of metamaterials have negative highly effective mass density as well as bulk modulus. The Faculty of Liverpool and Hong Kong University of Technology and Science is definitely the recent front runner in re-search of Acoustic metamaterials, having excessive interest for their target uses of these metamaterials as vibration damping, Anti sonar, wireless energy transfer and seismic protection. These metamaterials are the artificially designed metamaterial to direct, operate and also regulate sound waves in gases, solids, and liquid. Almost any kind of sound waves could be managed by managing the mass density and also bulk modulus of the acoustic metamaterials.

1.3.3 Mechanical Metamaterials: These are the artificial composite metamaterial which consists of various types of mechanical properties. Mechanical metamaterials have negative Poisson's ratio, negative modulus of elasticity, frictional properties and zero modulus of rigidity and are made up of materials with a precise pored structure or inclusion of secondary materials. The scientists of Harvard University and Northwestern University have a great concern in the new research application of these metamaterials in the area of aerospace and defense.

1.3.4 Tunable Metamaterials: They've power to randomly change the frequency of a refractive index. An incident electromagnetic wave offers varying response with such metamaterials. The framework of these metamaterials can be transformed in real time which helps make it easy to reconfigure an unit during operation [six]. Tuning in the near infrared range is achieved by altering the permittivity of nematic liquid crystal. These metamaterials could be tuned from bad index values, to zero index or maybe good index values, additionally to this particular damaging index values might be enhanced or perhaps decreased.

GREAT thinking is usually both graceful and simple. Such suggestion was produced by Sir John Pendry that an ideal lens [seven], totally free from any type of loss or deformation of info, may be created whether it was probable to construct a material that had specific incredible properties. On November seventeen, 2005 scientists showed an important step towards making such material for visible light. When a ray of light crosses a fringe, like that between air along with a block of glass, then the ray transformed its course. In the situation of cup plus air, the light is bent towards the boundary. This bending, together with utilizing a rounded exterior, is exploited to create the standard lenses utilized in digicams, telescopes and optical microscopes. These traditional lenses can't ever be ideal because they often don't refocus the gentle rays which originate from the item under examination in the form of decaying waves. The image thus can't make up the info about the item toted by these waves.

The range up to that the ray of light is bent is referred to as the material's refractive index. This's partly based on the result of the components on the electrical element of the partially by and light material's reaction to the magnetic component. The refractive index of the cup is approximately 1.4; this's practically solely determined by the power result of the cup. When the light was bent far from the boundary, the material would've a refractive index under a single. When the light was bent back on itself, within the form of a hairpin, the refractive index will be damaging. Sir John discovered that when the refractive index were negative after that it will be easy to create a great lens. His vision was very authentic he received a knighthood for it.

Geometrically, this thought isn't as tough to envisage as shown diagram. In a material with a refractive index of -1, the perspective of refraction of the gentle ray will be comparable to the angle of incidence however in the complete opposite path. The very same thing would occur at the 2nd boundary. A flat slab of material would thus send all of the gentle rays initiating from one point to a mirror image issue on the reverse side of the slab. It will serve as a lens without demanding the specifically curved surfaces that regular lenses require. Furthermore, it wouldn't confront the issues which compel the accuracy of curved lenses therefore may make a great lens.

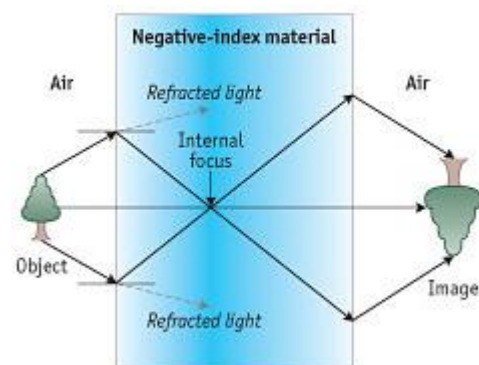


Fig 5: Negative refraction explained- How a perfect lens would bend light

Unfortunately, the only material with a negative refractive index to be developed so far functioned only at wavelengths

Negative Refractive Index Materials as Perfect Lenses:

very much longer than the wavelength of visible light. A team of investigators led by Alexander Grigorenko of the University of Manchester took a step closer towards producing a material with a negative refractive index which works for visible light rays. Their goal was to produce the elusive magnetic response required to turn the refractive index negative.

The scientists covered a small glass plate with little gold pillars, each about 100 Nano meters high. They found that these structures performed like bar magnets when light shone on them, abandoning the magnetic component of the incident light ray. In other words, the material had negative permeability, one of the two factors of a negative refractive index.

Further work is required to produce a material that negatively refracts visible light. But the result is an important step towards generating a perfect lens that could focus imageries to show features smaller than the wavelength of light itself.

Metamaterials to improve the efficiency of wireless transmission:

In modern era, wireless power transmission is one of the transmissions, which is undergoing with lots of investigation and have many applications, including wireless charging of electronic devices, electrical vehicles and powering on of fixed bio medical devices. Wireless power transmission uses magnetically attached resonant circuit to transfer the power without use of any wiring medium. However, efficiency of transmission decreases sharply due to the divergence of magnetic field, specifically under coupled areas. Electromagnetic metamaterial can influence the direction of electromagnetic fields due to its abnormal permittivity or permeability [8].

We live in a world of technological development. New technologies are arising every day to make our lives more comfortable. Despite all these, we still depend on on the conventional wire system to charge our low power machineries such as cell phones, digital camera and digital watches etc. and even the devices with mid power such as laptops. When it comes to charge several devices simultaneously the conventional wire system produces a chaos and It also require a lot of electric sockets and each device has different design for the charging port. At this point a question might arise. —What if only one charger can be used to charge many devices at the same time without the use of wiring system and without producing a chaos in the process? We gave it a thought and came up with an idea. The answer to all these dilemma lies with inductive coupling, a simple and more efficient way of transferring power without use of wires[9][10]. Wireless Power Transmission is the effective transmission of electric power from one point to another through vacuum or an atmosphere. The power can be transmitted effectively with the use of Inductive coupling for short range devices, resonant Induction for mid-range devices and electromagnetic wave

power transfer for high range devices. Wireless transmission of the power can be possible by using metamaterials. Metamaterials can improve the effectiveness by its property through space and charge a chosen low power device. The system using resonant coils can be used to transmit power from an AC line to a resistive load. Investigation of numerous geometrical and physical form factors calculated in order to increase coupling between transmitter and receiver using metamaterials. An achievement in doing this would remove the usage of cables in the charging process hence making it much easier to charge a low energy device. It'd also verify the security of the unit since it'd eradicate the risk of short circuit. Use of metamaterials will in addition earn simple to impose multiple minimal energy devices instantly using a source which could utilize one power outlet [10][11][12]. Metamaterials are produced from musters of several elements created from compound components like plastics or metals. The supplies are generally organized in repeating patterns. The patterns are set up at scales which are smaller compared to the wavelengths on the phenomena that they influence. Metamaterials develop the properties of theirs from their newly created configurations not from the attributes of the starting materials. The accurate figure, geometry, dimension, arrangement and alignment of the metamaterials provides intelligent qualities, that create them proficient in manipulating electromagnetic waves by blocking, absorbing, enhancing, or perhaps bending waves, to achieve advantages that go beyond what's achievable with standard materials. Properly designed metamaterials are able to affect electromagnetic radiation or maybe sound waves in a fashion that isn't observed in standard materials. The supplies which display a bad refractive index for certain wavelengths have fascinated many significant researches. These substances are called negative refractive index metamaterials.

Dr. Shiva Kumar and his staff created metamaterials in 2 shapes with Computer Simulation Technology Suite (CST MWS) software program and after that compared their simulation results [thirteen]. Fig six shows the shapes of square shaped split ring resonator, circular shaped split ring resonator and 2X2 slabs of circular and square split ring resonators respectively that had been created by Dr. Shiva Kumar and the staff of his in 2018 to improve the electrical power transmission. They developed a metamaterial with Square shape and also circular shape short range systems. In their designs metamaterial unit cell was miniaturized deep into the sub-wavelength selection and also a compressed content that comprise of those device cell was fabricated. Experimentations with a reasonable 2 coil power transfer system offered that proficiency increases were achievable no matter if the total separation between the coils were better and also the metamaterial was positioned near the getting and transmitting coil. This could provide considerable latitude within the style of small range wireless power transmission devices and also makes it possible for greatest remedies being discovered within the restraints of exact applications [14].

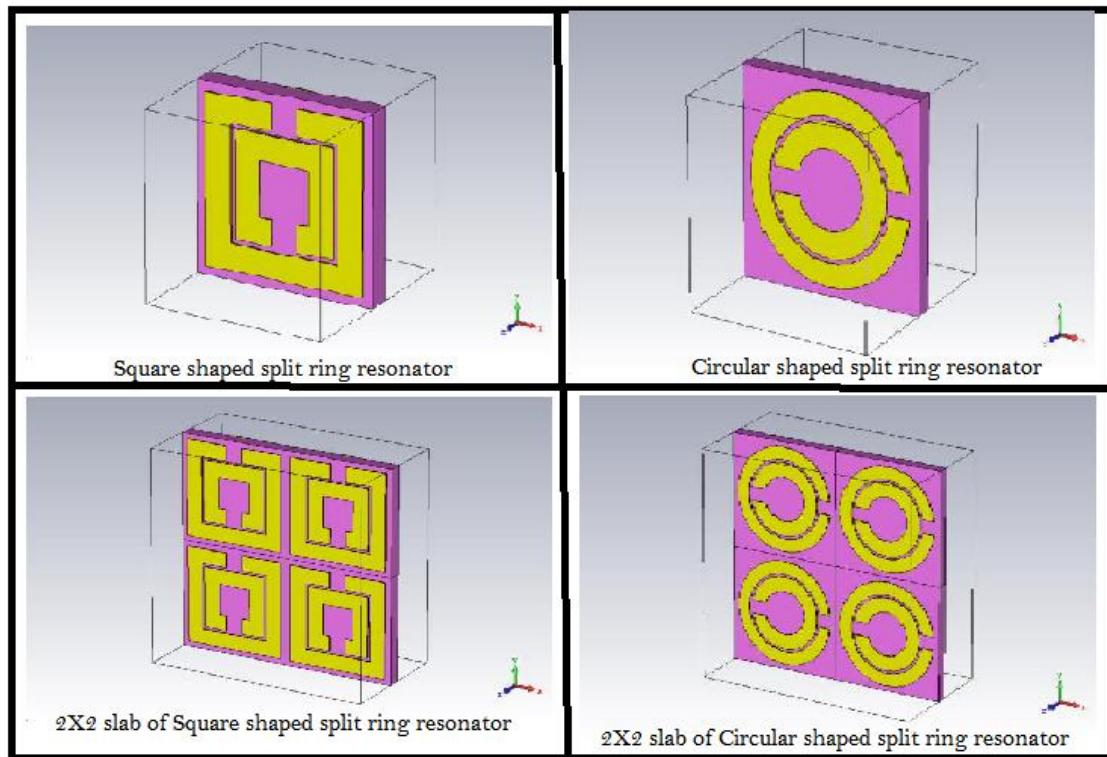


Fig6: Different shapes of metamaterials to increase the efficiency of power transmission system

Dr. Shiva and his staff demonstrated that the Square shaped split ring resonator had far more efficiency than Circular shaped split ring resonator. They found that use of a metamaterial slab might relieve the consequences of coil offsets on system efficacy. Consequently, use of a small metamaterial slab could be a feasible strategy to boost the expertise associated with a wireless power transfer program and also might be useful in applications like wireless charging and powering implantable biomedical devices.

4. Other Applications:

Applications of Metamaterials are discovered in different fields which include public safety, sensor detection, higher frequency battle field communication, enhancing ultrasonic sensors, solar energy management, for increased gain antennas and remote aerospace applications [fifteen].

4.1 WMD Detectors: Army and air Force scientists use metamaterials to sense the presence of chemical explosives, biological agents, and pollution.

4.2 Invisible Subs: The metamaterials could affect the wavelength of sound. It bends sound waves across the submarine making it invisible to enemy sonar. Civilian spinoffs also make use of the metamaterials to create sound proof rooms with great acoustics.

4.3 Biosensor Biosensors: These're really important resources in a number of places, like green monitoring, food security and illness diagnostics within the study of natural phenomena recently metamaterials are employed by researchers in bio sensing technologies due to its detection of label free bio molecules and effective cost.

4.4 Metamaterials Absorber: A metamaterial absorber competently absorbs electromagnetic radiation. Metamaterials absorbers have numerous benefits over traditional absorbers such as for instance supplementary miniaturization, broader adaptableness, and improved effectiveness. To make a high ratio of electromagnetic radiation absorption, it requires highly effective medium design, magnetic permeability and permittivity.

4.5 Metamaterial Antennas: Negative refractive index metamaterials are utilized in antennas to increase the functionality of shrunk antenna systems. The metamaterials antennas are utilized to boost the output of an antenna due to its distinctive band gap characteristics & periodic structures. In little standard antennas the maximum of the wavelength echos the signal to the source whereas the metamaterials antenna has arrangement which re radiates and shops power making the size of its tiny and behaves as bigger antenna. Fig.7 exhibits the Z shaped Metamaterials Antenna.

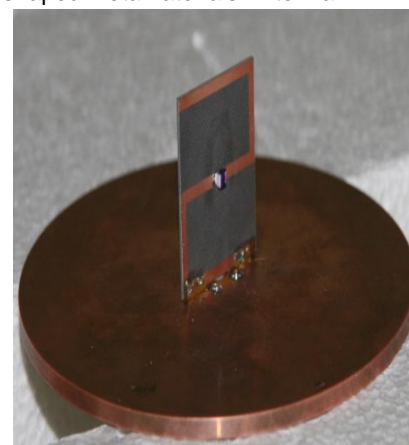


Fig 7: Z- shaped antenna

The application of metamaterials, properly created to increase some prescribed antenna characteristics as impedance matching, competence, increased bandwidth, etc. Several of metamaterials antennas are below:

4.5.1 Zero-Phase-Shift Line Based Antenna: A circumference of 2 working wavelengths at ultra high frequency bands for the near field RFID applications runs on the zero-phase-shift segmented loop antennas since it create a bit larger even magnetic field. A circularly polarized Omni directional antenna design with zero-phase-shift type is utilized for all the apps of wireless neighborhood area network.

4.5.2 Anisotropic High Permittivity Loaded Antenna: To design a multiple input multiple output system a dipole antenna is used and is laden with good permittivity anisotropic metamaterials. In order to reduce the thickness as much as a great level in arrays of cellular base station idea of this style is used.

4.5.3 Mushroom Antenna: The antenna that fashioned with group of many mushroom cells is known as a mushroom type antenna. This kind of antenna is utilized for all the apps of Wi Fi.

4.5.4 Gap Capacitor Loaded Antenna: This antenna is set of a selection of slotted patches with anti phase and also zero order resonance that presents a series gap capacitance at center of the spot and at its radiating edges. This kind of antennas is applicable in L band radar system.

5. Future Scope with Metamaterial:

Metamaterials are artificially created materials getting bad index of refraction and as a result of this the daydream of invisibility cloaks is starting to be possible so the 2 measures

have actually been consumed that specific path. Duke Faculty has already been doing work on changing technology with metamaterials for hiding obstructive structures or even designing invisibility cloaks before year 2020. Metamaterial camera might be created without a lens or even moving parts that uses compressed microwave images. As metamaterials have far better absorption features therefore Units with metamaterials may be made that brings down the size of standard units and can raise the absorption of solar power. This technological innovation utilizing metamaterials might work as energy efficient satellite communication devices for troops on the battleground.

6. Conclusion:

Metamaterials will be the new area of investigation, without any qualm we are able to say that metamaterials is now an incredibly enjoyable investigation area. The area of metamaterials is a turf of investigation with talent. From microwave and optical sciences, acoustics, materials science, nanotechnology and also high performance computing each are intrigued by the metamaterials. Since the start of the century, lots of research papers are written on the subject of Metamaterials. The scientists from many disciplines are now being fascinated towards metamaterials due to its distinctive electromagnetic characteristics. Therefore there's an excellent area of development and study for the producing brand new solutions for future development. In this paper, a brief overview of the metamaterials its many kinds and uses of metamaterials are talked about. The metamaterials have generated incredible advancements in electromagnetic response capabilities which can provide exciting chances of potential look of equipment plus components applying quiet features of metamaterials.

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