Metamaterial: Materials with Exceptional Properties

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Abstract— **Metamaterials are artificial materials with exceptional properties, engineered to have properties that may not be found in nature. They are combination of multiple individual elements shaped from straight microscopic materials such as metals or plastics, but the materials are generally arranged in periodic patterns. Metamaterials get their properties from their firmly-designed structures not from their composition. Their accurate shape, geometry, size, orientation and arrangement can affect the waves of light or sound in an unusual manner, creating material properties which are unattainable with conventional materials. These metamaterials attain desired property by incorporating structural elements of sub-wavelength sizes, i.e. description that is actually smaller than the wavelength of the waves they affect.**

Keywords— Metamaterial, Metals, Plastics, Conventional materials, Snell's Law

I. INTRODUCTION

Materials are composed of atoms and molecules. Material properties arise from molecular constituents and their interactions. It may also arise from macroscopic in-homogeneity. If a wave or disturbance varies on a scale much larger than material in-homogeneity, local response can be homogenised.

So metamaterials are materials that are designed at the atomic level. These materials hold exceptional properties that are not found in natural materials. One such property is negative refractive index. The explanation to metamaterials is based mainly on the arrangement of the constituents rather than their individual properties. The property that is being designed for is a macroscopic property. The essential objective in designing metamaterials is wave manipulation unlike that of a natural material.

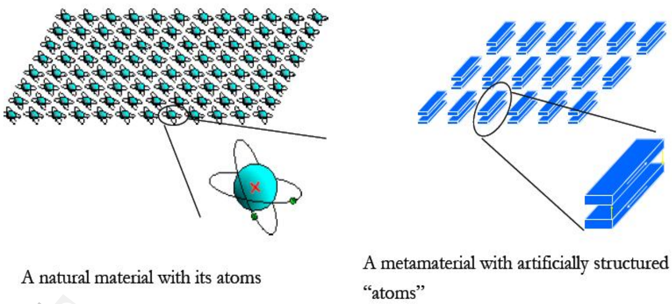


Fig:-Natural material and Metamaterial

Metamaterials are artificial materials. They are assemblies of multiple individual elements formed from predictable microscopic materials such as metals or plastics, but the materials are generally arranged in periodic patterns. Metamaterials gain their properties not from their composition, but from their exactingly-designed structures. Their specific shape, geometry, size, orientation and arrangement can affect the waves of light or sound in an exceptional manner. It can create material properties which are unachievable with conventional materials. These metamaterials get desired effects by incorporating structural elements of sub-wavelength sizes, i.e. features that are actually smaller than the wavelength of the waves they affect

II. WORKING PRINCIPLE OF METAMATERIAL

The fundamental theme of nearly all metamaterials is wave manipulation. Generally, when a wave moves from one medium to another, it refracts according to Snell's Law. Here, the incident ray propagating through one medium and reflecting and refracting when coming in contact with a medium with different refractive indexes. Snell's law is normally assumed to have positive values for both n1 and n2. As seen, the wave will both reflect and refract at the contact surface between the media. Metamaterials have a negative index of refraction and use this property to redirect waves around an object as seen in the lower figure. In the darker figure a metamaterial and the negative refraction of a light wave. Note the degree of refraction is much sharper.

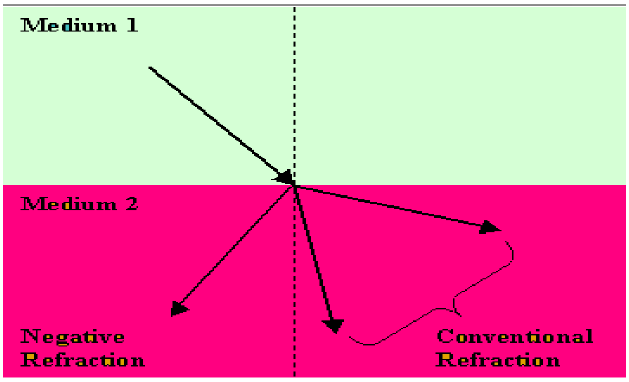


Fig:-Negative Refraction in Metamaterial

For a metamaterial to be effective, it must be taken as a uniform material rather than an array of particles. This means the units that make up the metamaterial must be relatively small compared to the wavelength that is to be manipulated and redirected. This becomes the main limitation of metamaterial advancements

III. TYPES OF METAMATERIALS

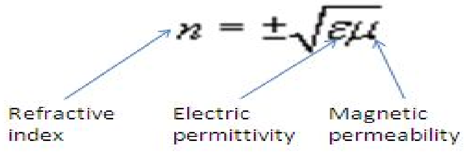
There are two major subcategories of metamaterials; electromagnetic and acoustic. For both categories, the central goal is wave redirection and manipulation. Electromagnetic metamaterials bend and manipulate electromagnetic waves like visible light waves, microwaves, and infrared waves. These are transverse waves. Electromagnetic metamaterials utilize negative electric permittivity and negative magnetic permeability to control wave propagation.

Acoustic metamaterials manipulate longitudinal waves associated with vibrations. A specialized application of this is in seismic metamaterials which, theoretically, can redirect seismic waves. Acoustic metamaterials rely on a negative bulk modulus and negative mass density for operation. The acoustic metamaterials are easier to construct since the wavelengths for acoustic waves are much larger than those of electromagnetic waves.

A. *Electromagnetic Metamaterials*

Negative Refractive Index

Since negative refractive index is central to electromagnetic metamaterials, it is important to understand what negative refraction of electromagnetic waves is. As discussed, normal materials refract waves with positive refractive index as seen in the left image. Shown is the definition of refractive index, n. It is a function of electric permittivity and magnetic permeability which are properties relating to the material in the presence of an electric and magnetic field, respectively. Normally, a positive coefficient is assumed for most media; for a metamaterial, both epsilon and mu are negative. As Veselago theorized, if both parameters are negative, then a negative coefficient must be used. According to the Snell's Law, when a wave encounters a negative index material (NIM), the angle that the refracted wave makes with the normal plane is much greater than that of materials with positive refractive index.



Application of electromagnetic metamaterials that is currently in use are-

1) Antenna: One application of electromagnetic metamaterials that is currently in use is in antennas. The negative refractive index means the wave associated with the antenna is bent to a sharper angle. This effectively increases the radiated power of the antenna and can also double the frequency range. In the figure a normal antenna and its azimuthal gain, and below that the metamaterial slip and a dramatic increase in gain with more uniformity

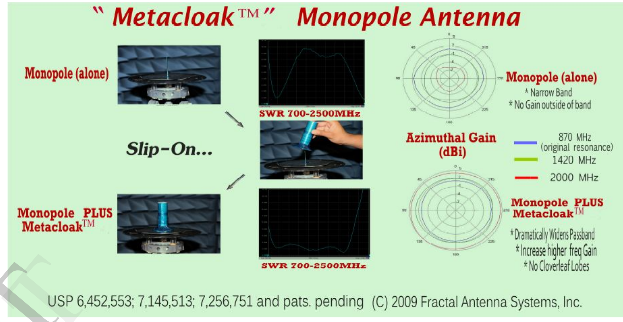


Fig:- Metaclock effect on antenna

2) *Invisibility:* Another application of electromagnetic metamaterials is in a potential invisibility cloak. When light waves travelling through air encounters a naturally occurring material, it is reflected and refracted in a positive sense. In first figure typical object that is encountering electromagnetic waves. The object is impeding the propagation of the wave; that is, light is reflecting off of the object so that it is visible. In the image on the right, the object is being shielded from the electromagnetic waves which are redirected around the object. Based on the propagation of the waves, the object is virtually undetectable. If these waves are light waves, then the object is rendered invisible.

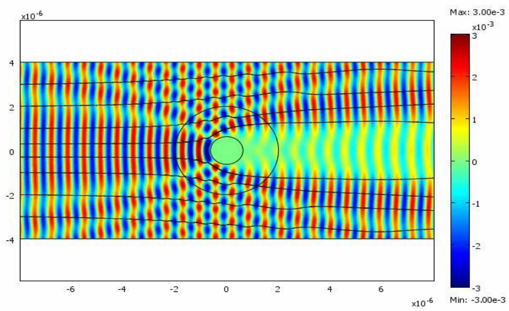


Fig: when clock is off

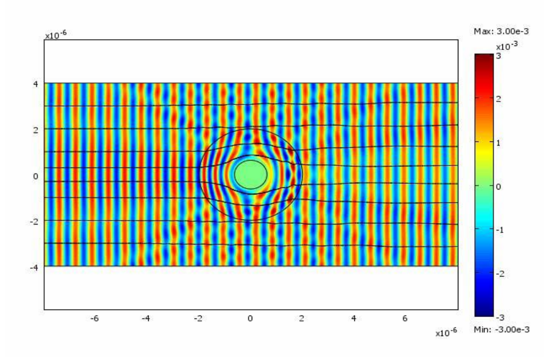
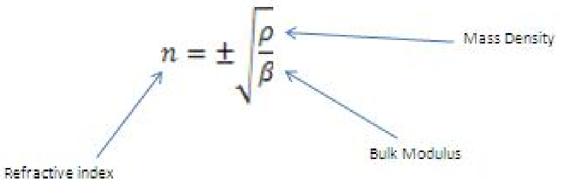


Fig: when the clock is on

B. *Acoustic Metamaterials*

Acoustic waves are longitudinal; the parameters used to describe the wave are pressure and particle velocity. In electromagnetism (EM), both electric and magnetic fields are transverse waves. However, the two wave systems have the common physical concepts as wave vector, wave impedance, and power flow.

$$n = \pm\sqrt{\frac{\rho}{\beta}}$$



For acoustic metamaterials, both bulk modulus and density are component parameters, which define their refractive index. In certain frequency bands, the effective mass density and bulk modulus may become negative. This results in a negative refractive index.

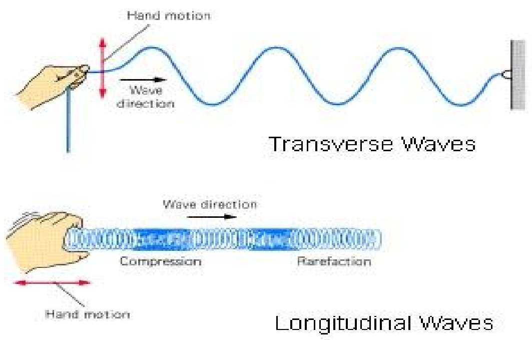


Fig:-Transverse and longitudinal waves

1) Soundproof Room: Conventional technology in soundproofing rooms would require walls 3 meters thick to completely cancel out sound: application of acoustic metamaterials could accomplish the same with walls as thin as a tile. Future applications of acoustic metamaterials designed to cloak objects from sound wavelengths include soundproofing specific sections of buildings

2) Invisible Submarines (Sonar Blocking): A military application is the invisible submarine, which would be invisible to modern sonar technology as it would redirect sonar waves. Currently, however, coating subs in this metamaterial is not viable. Generally, thicker metamaterial can block more wavelengths of sound. A completely "sonar-invisible" sub would be coated in metamaterials too thick and heavy to be economically practical for a submarine.

C. *Seismic Metamaterial*

Seismic waves associated with earthquakes have destructive effects on structures within the same plane along which they propagate. Originally, this posed a peculiar problem as seismic waves are composed of both longitudinally propagating pressure waves and coupled transverse shear waves, making a metamaterial solution difficult to apply beyond a 2D plane. The cylindrical metamaterial cloak proposed would answer this by decoupling the pressure and shear waves, causing them to be dispersed around the cloaked structure without harming it. Modern seismic materials development began in 2009 and is still underway.

D. *Creation of Metamaterials*

Lithography is a process commonly used in the creation of nanomaterials. The process uses a beam that passes through a mask to contact with a surface coated in a substrate called the resist, changing the properties of the hit area of the resist from those of the surrounding substrate. Certain wavelengths of light are used in photolithography, while a beam of electrons is used in e-beam lithography. When a developer solution is then applied to the resist, the changed properties of the resist will cause the affected material to be etched away while the other remains, or vice versa.

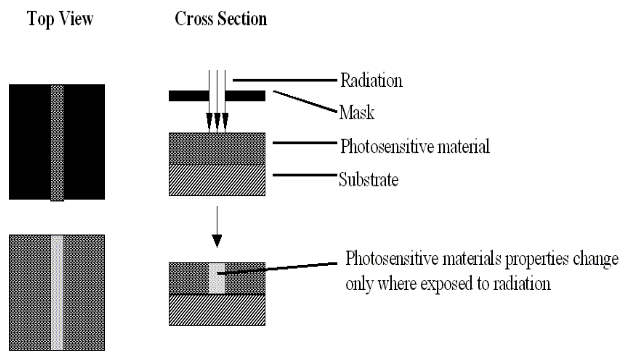


Fig:-Manufacturing of Meta material

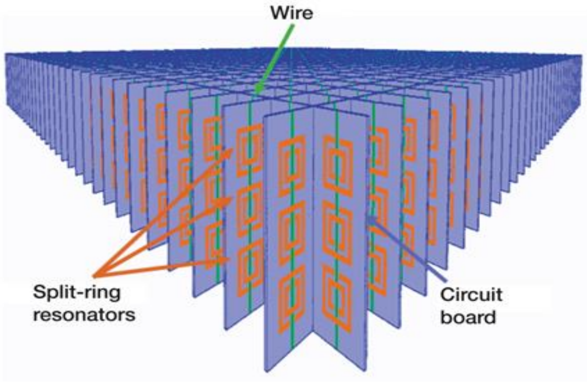
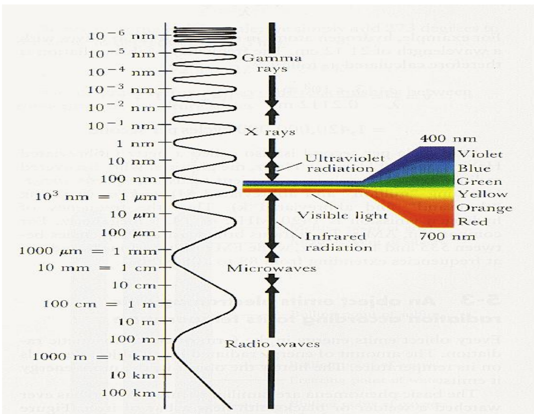


Fig: - Square Split-ring of Meta material

As an example, patterns such as square split-ring shown are created from nonmagnetic materials such as copper and mounted to fiberglass circuit boards.

E. Limitations

Although the theoretical applications of metamaterials are broadening, the intrinsic limitations of the material become more prevalent. As discussed before, the material must be considered a uniform mass and loses effective qualities if this assumption is not met. That is, if the wavelength being manipulated is very small, it becomes very difficult to manufacture units that are small enough to be considered uniform. Researchers have successfully developed metamaterials that can redirect microwaves and infrared radiation that have relatively large wavelengths. Visible light, however, ranges from 400nm to 700nm wavelength. Only the largest of these wavelengths (red light) has successfully be cloaked against in the laboratory.



Another intrinsic limitation of metamaterials is that each metamaterial is designed and tuned to operate with a specific wavelength. That is, only when encountering this specified wavelength can the material redirect and manipulate the waves. This leads to obvious difficulties in cloaking the entire visible light spectrum. For example, an object that is being cloaked in red light will still be visible in violet light. In response to this limitation, researchers have developed a new branch of metamaterials called frequency selective surfaces (FSS). FSS, also called tunable metamaterials, are designed so that they can handle a range of wavelengths. This does not mean that these materials can handle more than one wavelength at a time; rather, they can be tuned to a specific known wavelength within its range of capability.

ACKNOWLEDGMENT

I would like to thank Sir V. G. Veselago and Sir John Pendry. As both of them have done great work in this field. In 1968 Sir Victor Veselago, a Russian physicist, predicted that it is possible to develop a material that acts in the exact opposite manner of natural materials. This was demonstrated in 1999 by Dr. John Pendry who is still a leading figure in metamaterial research in London. Both Veselago on paper and Pendry in the laboratory showed that metamaterials can be developed that have a negative refractive index.

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