# Analysis of Metamaterials –for its Different Properties and Areas of Applications

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***Abstract*— Metamaterials are the artificial structures that are unusual or not found naturally. Metamaterials provides the possibility to synthesize artificial media with the properties not found among natural materials and thus able to open up new fields of application or to improve the existing ones. This paper provides a review in which, firstly the concept of metamaterials in its historical context is given. We then overview its main properties in demonstrating some of the most striking and unusual phenomena, and attempt to assess their real potential towards practical implementations.**

**Keywords**— ***metamaterials; permeability; permittivity; antennas;***

## I. INTRODUCTION

The metamaterial is a combination of word “meta” and “material”, Meta is a Greek word which means something beyond, altered, changed or something advance. The word metamaterial was first coined by Rodger M. Walser [1] who defined it as follows:

“Metamaterials are macroscopic composites having a man-made, 3-dimensional, periodic cellular architecture designed to produce an optimized combination, not available naturally, to a specific excitation of two or more responses”.Many definitions have been suggested, since then, to describe the same term. All definitions show the properties that metamaterials should exhibit [2]:

- not observed in constituent materials.
- not observed in nature.

The possibility of existence of artificial metamaterial is showed by J.C bose in 1898 during conducting microwave experiments on twisted structure [3].Later in 1968,a Russian physicist named Victor Veselago of Moscow’s P.N Lebedev Institute of Physics presented the theoretical investigation on the concepts of Metametarial [4].Metamaterials are artificial media with unusual electromagnetic properties[5].Most unusual property that metamaterial have is probably negative refraction which is achieved when both the permeability and permittivity of a medium are negative [6]. Although first metamaterials were electromagnetic, it involves the research in many fields like electrical engineering, electromagnetics , microwave and antenna engineering, optoelectronics, solid state physics, semiconductor engineering ,and so on [5][6][7].Metamaterials have potential for research in applications[8][9][10][11][12] like remote aerospace, sensor detection and infrastructure monitoring, highly sensitive chemical and biological sensing, nano imaging, subsurface sensing, Dyakonov plasmonics, fluorescence engineering, thermal emission control, smart solar power management, public safety, radomes, high frequency battlefield communication, lenses for high-gain antennas, improving ultrasonic sensors, acoustics, seismic protection, shielding structures from earthquakes, reverberation chambers, radar absorbers, invisibility cloaks[13][14][15][16][17][18].

## II. METAMATERIAL CLASSIFICATION AND THEIR PROPERTIES

Metamaterials can be divided into different classes but the prime focus is on two main properties: permittivity ‘ε’ and permeability ‘μ’, properties that divide metamaterials into four categories [19] are:

### A. *Double Positive(DPS)*

Both ε and μ are positive, they do occur in nature. Examples of such materials are dielectrics.

### B. *Epsilon Negative(ENG)*

ε is negative but μ is positive. This characteristic was observed in many plasmas.e.g- noble metals such silver or gold will exhibit this characteristic in the infrared and visible spectrums.

### C. *Mu Negative (MNG)*

Metamaterials. Gyrotropic or gyromagnetic materials exhibit this characteristic. Joining ENG material and MNG material resulted in properties such as anomalous tunnelling, resonances, transparency, and zero reflection [5].

### D. *Double Negative(DNG)*

Finally, both ε and μ are negative. Materials with simultaneously negative ε and μ are not found in nature. David Smith and Shelly Schultz manufacture the first negatively refracting substance by combining negative permittivity and negative permeability metamaterial in the same structure. They were constructed artificially in 2000 [6]. Artificial materials with the combination of DPS, ENG and MNG properties have been fabricated [20].

### E. *Bi-isotropic and bianisotropic*

Categorizing metamaterials into single or double negative or double positive,assumes normally that the metamaterial has independent electric and magnetic responses described by ε and μ. However in many examples of electromagnetic metamaterials, an electric field causes magnetic polarization, and the magnetic field causes electrical polarization, called as magneto-electric coupling. Such media are denoted as being bi-isotropic. The media which exhibit magneto-electric coupling, and which are also anisotropic (which is the case for many metamaterial structure), are called as bi-anisotropic [21][22].The four material parameters that are intrinsic to magnetoelectric coupling of bi-isotropic media are ε, μ, $\kappa$ and χ or permittivity, permeability, strength of chirality, and the Tellegen parameter respectively[7].

### F. *Chiral*

Chiral metamaterials are constructed from chiral in which the effective parameter $k$ is non-zero. Metamaterials can implement more sophisticated structures, such as chiral ones. The term chiral describes an object that is non-superimposable on its mirror image. The word 'chiral' is a Greek word means 'for hand'. In fact, human hands are an excellent example of chiral. In chemistry, biology and pharmaceuticals, chiral molecules have an important context. Many active biologically molecules, such as naturally existing amino acids, sugars and enzymes, are chiral. A chiral molecule and its mirror image is called as enantiomers, which are often termed as "right-handed" and "left-handed" enantiomer, respectively[23].

### G. *Frequency selective surface based metamaterials*

FSS based metamaterials have become an alternative to the fixed frequency metamaterial. Frequency selective surface-based metamaterials block signals in one waveband and pass those at another waveband [24].

## III. METAMATERIAL APPLICATIONS

Metamaterials have found and are finding lots of applications due to its exciting and unusual features. Some of the achievements of metamaterials are given below.

### A. *Metamaterial Antennas*

Metamaterial antennas are very small and powerful antennas that can be manufactured according to what kinds of capabilities are needed by the application. Metamaterial enables antenna to bend radio frequency waves so that the efficiency is even higher than large kinds of antennas. Metamaterial antenna systems are suited for wireless communication, satellite communication, air planes, space communication, GPS, space vehicle navigation. Metamaterials and their antenna application is very interesting and developing research area in coming years [25], because they support high output and speed, controls broadband frequencies and phase shifting.By using metamaterial in antenna we can increase bandwidth, reduce antenna size, increase radiator efficiency.

Use of metamaterials as antenna substrate shows its specific ability to manipulate and control electromagnetic fields, bandwidth enhancement, sensing and controlling the direction of radiation and reduce antenna size[26][27].

Metamaterial when used as antenna superstrate increases the transmission rate and control of the direction of the transmission which enable one to design high gain directive antennas. Metamaterial superstrates can be applied to conventional antenna to increase both the impedance and directivity bandwidth of the proximity coupled microstrip patch antenna and can also be used to change the polarization state of the antenna. High directive antenna elements can be realized by using metamaterial as superstrates that can improve the radiating efficiency. A dielectric superstrate[27] if placed properly above a planar antenna shows remarkable effects on its gain and radiation characteristics.

Metamaterials can be used to improve the impedance matching of planar phased array antennas over a broad range of scan angles [28]. In recent years metamaterial phase shifters are adopted to fine tune the phase difference between adjacent elements.

Phase-shifting metamaterial lines can be used to develop antenna feed network which can provide broadband, compact and non-radiating, feed-networks for antenna arrays.

Transmission line feed networks based on metamaterial can be used to replace conventional transmission lines based feed-networks which can be bulky and narrowband. The advantage of these feed-networks is being compact in size, and therefore eliminating the need for conventional transmission lines meander lines [34].

Metamaterials can be suitably designed to use as Radome that is used as a covering to protect vehicular antenna from rain, wind, perturbations, aerodynamic drag and other disturbances [29].

Metamaterial ground planes also known as artificial magnetic conducting ground planes are widely used as the planar antenna ground planes in order to enhance the input impedance bandwidth [30]. Metamaterials ground planes find important applications in low profile cavity backing and isolation improvement in microwave components and cavity backed antennas respectively. It also improves isolation between radio frequency or microwave channels of (multiple-input multiple-output) (MIMO) antenna arrays systems. Metamaterial ground planes provides high impedance surface that can be used to improve the axial ratio and radiation efficiency of low profile antennas located close to the ground plane surface and can also increase the gain of antenna as well [31].

Struts in reflector antenna systems are generally mechanical structures supporting the feed in the reflector system.Usually these struts block the aperture and consequently affect the antenna performance, such as a reduction of the antenna gain and an increase of the side lobe levels. [32]. With the advent of metamaterials a new method has been introduced that minimize these effects in the operational directions to nearly zero by guiding and launching the electromagnetic radiation in preferred directions [33].MEMS based reconfigurable metamaterials ,if properly designed ,can bring valuable improvements to antenna systems.MEMS based metasurface designs with reconfigurable reflection properties utilized in reflect arrays and PRS antennas,resulting in dynamic radiation pattern control[35].

### B. *Metamaterial Absorber*

A metamaterial absorber is a type of metamaterial intended to efficiently absorb electromagnetic radiation .A metamaterial absorber manipulates the loss components of metamaterials magnetic permeability and permittivity for the absorption of large amounts of electromagnetic radiation. A Metamaterial absorber introduced by Landy et al. [36] which utilizes the tuning of losses, has two requirements for the effective absorption of electromagnetic waves. One is that the impedance should be matched to the free space: $Z \approx Z0$ to ensure minimum reflection. The other is that the imaginary part of the refractive index should be as large as possible to maximize the absorption of incident waves. In practice, the loss of material is measured by the amount of absorbed electromagnetic power. Intended applications for the metamaterial absorber include sensors, emitters, spatial light modulators, wireless communication, infrared camouflage and use in solar photovoltaics and thermophotovoltaics[37].A practical implementation shows an absorber[38] using metamaterial structure operating at 2.45 GHz exhibited an absorption of approximately 97 % and a half-max bandwidth of approximately 0.16 GHz. A wideband-enhanced double-layer perfect metamaterial [39] absorber has been introduced to reduce the in-band RCS of circularly polarization tilted beam antenna. In [40], double zero metamaterials was investigated as radar absorbing metamaterials for the reduction of reflected power.

### C. Superlenses

When an object scatters light, it generates two types of waves, the *propagating* wave and the *evanescent* wave. The propagating wave travels in space to far distance which can be detected and used for imaging in far field optics such as optical microscopes.[41] In the case of evanescent wave, does not propagate out but stays on top of the surface of an object and decays in the near-field. Conventional lens, which are typical far field imaging methods, cannot capture this kind of waves, and since evanescent waves carry sub-wavelength feature size information, its absence in the image limits the maximum achievable resolution to the order of the propagating wavelength, which is called the “diffraction limit”. A practical superlens or perfect lens, is a type of lens that uses metamaterials to go beyond the diffraction limit.Some practical implementation includes the [42] demonstration of subwavelength imaging from a left-handed metamaterial superlens with the spot size of the image obtained from a five-layer LHM lens is $0.23\lambda$, which is not achievable with any ubiquitous materials. A Experimental verification [43] of broadband superlensing using a metamaterial with an extreme index of refraction demonstrated that a dense array of crossed metallic strips may enable imaging with resolution well below the diffraction limit over a very broad bandwidth and with good transmission efficiency.A simple superlens for microwave spectrum can be realized by the array of parallel conducting wires that was shown to be able to improve the resolution of MRI imaging [44].

### D. Cloaking devices

A cloaking device is a theoretical or fictional stealth technology that can cause objects,[45] to be partially or wholly invisible to parts of the electromagnetic spectrum.[46][47] Since from the beginning of optical sciences, the ability to control the light with materials has been limited to only the most common optical effects, such as ordinary refraction with common diffraction limitations in lenses and imaging. As light consists of an electric field and a magnetic field, ordinary optical materials such as optical microscope lenses have a strong reaction only to the electric field[48][49]. The corresponding magnetic interaction is essentially nil. Through the use of artificially constructed materials like metamaterials, both the electric and magnetic components of the radiated light can be controlled, in any desired fashion as it travels through the material. Therefore, the range of response to radiated light is expanded beyond the ordinary optical limitations and thus we can say metamaterials [20] [51] have the potential to be engineered and constructed with desirable properties that fit a specific need. Hence, metamaterials are applied to cloaking applications for a few reasons. First, the parameter known as material response has broader range. Second, the material response can be controlled at will. Third, optical components, such as lenses, respond within a certain defined range to light. However, [52] [53] metamaterials are limited. Cloaking across a broad spectrum of frequencies has not been achieved, including the visible spectrum. Dissipation, absorption, and dispersion are also current drawbacks, but this field is still in its optimistic infancy.

### E. Acoustic Metamaterials

Acoustic metamaterials are the fabricated materials artificially designed to direct, control and manipulate sound in the form of sonic, ultrasonic waves or infrasonic as these might occur in liquids, solids and gases. The control of various forms of sound waves is mostly accomplished through the bulk modulus $\beta$, mass density $\rho$, and chirality [9] The density and bulk modulus are analogies of the electromagnetic parameters and permittivity. These metamaterials usually gain properties from structure rather than composition, to enact effective macroscopic behaviour.[20][58] Research on acoustic metamaterials began in the year 2000 with the fabrication and demonstration of sonic crystals in a liquid followed by transposing the behavior of the split-ring resonator to research in acoustic metamaterials [54][55].After this double negative parameters (negative bulk modulus $\beta_{\text{eff}}$ and negative density $\rho_{\text{eff}}$) were produced by this type of medium,[56] a group of researchers shows design and tested results of an ultrasonic metamaterial lens for focusing 60 kHz [57].

### F. Seismic Protection

Seismic waves are the waves of energy that travel through the layers of Earth, giving the result in the form of an earthquake or a volcano eruption that gives out low-frequency acoustic energy. The wave’s propagation velocity depends on density and elasticity of the medium. Among the many types of seismic waves, one can distinguish in between *body waves* and *surface waves*. [59][60].Body waves travel through the Earth’s interior whereas surface waves travel across the surface. As particle motion of surface waves is larger than that of body waves, surface waves tend to cause more damage.Seismic metamaterials are designed to counteract the adverse effects of seismic waves on artificial structures. As of 2009, seismic metamaterials were still in the development stage. The idea is proposed that if the metamaterial used as ring around a building foundation then there have possibility that it diverts the most destructive seismic waves around the entire building[50][61][10].

## IV. CONCLUSION

The research work presented in this paper summarizes the recent developments and applications of metamaterials in different fields. This paper has also highlighted the potential of metamaterial technology to exploit the future research directions through practical implementation. We expect that many other fascinating discoveries and application will be found in future and explore the hidden world of metamaterials.

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