Metamaterials: Characteristics, Process and Applications

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Abstract

We present a tutorial paper of distinctive properties of metamaterial, prominently negative index materials (NIM). These have permitted emerging applications, concepts and devices to be developed in the last few years. Since a metamaterial is a material which is having negative permittivity and permeability, it can be regarded as an artificial medium with negative index of refraction. Negative refraction was determined by a Snell’s Law. If Metamaterial is having permittivity and permeability near zero it is called “Zero-index material. Zero-index metamaterials can be used to achieve high directivity antennas. We present Metamaterial as a left-handed material which follows left hand rule. The split ring resonator acts as an artificial magnetic dipole. The gap between inner and outer ring acts as a capacitor while the rings themselves act as an inductor, resulting in an LC resonant circuit. Just below resonance, the magnetic dipole due to the split rings will lag the H field by roughly 180° resulting in negative permeability. Negative permittivity is obtained by the array of thin wire which is made of materials like aluminum, silver, and gold. We can verify the value of ε and μ “theoretically” with the help of mathematics. A review of the progress made in field of electronics and agriculture and applications in telemetry, vehicles, wireless communications etc. By using Metamaterial in antenna we can increase bandwidth, reduce antenna size and increase in radiator efficiency. The most favorite application is Metamaterial absorber which is fastest growing field in the electronics, metamaterial absorber is thin, light weight, doesn’t require use of expensive materials and can be used over a wide frequency range. The same concept can be applied to construct an
absorber functioning at a different frequency. Some other application of the area also discussed in the present paper.

**Keywords:** Components; metamaterials; left-handed materials; negative-index of refraction materials; split-ring, Resonator; absorber

1. **Introduction**

In 1898 J.C. Bose showed the possibility of existence of artificial material by conducting microwave experiment on twisted structure. Later, the physicist Victor Veselgo (1968) presented theoretical investigation and Pendry et al in 1996 used an artificial wired medium whose permittivity is negative to realize artificial electric plasma, followed by this, in 1999 magnetic plasma is realized whose permeability is negative using split-ring resonators (SRR). Smith et al (2004) had realized gradient refractive index medium to bend electromagnetic waves. Metamaterial opened up a new exciting world for the scholars. The concept of negative refractive index is now widely accepted and focus of the research has moved toward applications. The word was first coined by Rodger M. Walser (2001) who gave the following definition

“Metamaterials are defined as macroscopic composites having a man-made, three dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to a specific excitation.”

“Metamaterials are artificial periodic structures with lattice constants that are much smaller than the wavelength of the incident radiation. Therefor providing negative refractive index characteristics”

2. **Theory of Metamaterials**

This word is a combination of “meta” and “material”. Meta is a Greek word which means something beyond, altered, changed or something advance as presented in Sihovola (2007). In a precise way, Metamaterials can have their electromagnetic properties altered to something beyond what can be found in nature. They are typically man made material. Some theoretical study is being presented here.

2.1 **Theoretical Aspects**

Metamaterial can be characterized by using Maxwell equations (DaviBibiano 2010). Transformation of Maxwell equations have a prominent role in describing Metamaterial which is given below

Maxwell equation in time domain:

\[
\mathbf{\nabla} \times \mathbf{E} = -j \omega \mu \mathbf{H} ; \mathbf{\nabla} \cdot \mathbf{D} = \rho \\
\mathbf{\nabla} \times \mathbf{H} = j \omega \varepsilon \mathbf{E} + \mathbf{\nabla} \times \mathbf{D} = 0
\]  \(\text{(2.2a)}\)

For the plane wave these equations can be reduced to

\[
\mathbf{k} \times \mathbf{E} = \omega \mu H \; ; \mathbf{k} \times \mathbf{H} = -\omega \varepsilon \mathbf{E}
\]  \(\text{(2.2c)}\)
Therefore, for positive $\varepsilon$ and $\mu$, $\vec{E}$, $\vec{H}$ and $\vec{k}$ form a right handed orthogonal system. When $\varepsilon$ and $\mu$ are negative the equation (2.2c) changes to,

$$\vec{k} \times \vec{E} = -\omega \mu \vec{H}$$

$$\vec{k} \times \vec{H} = \omega \varepsilon \vec{E}$$

The above case shows left handed materials and their opposite direction and left hand triplet of $\vec{E}$, $\vec{H}$ and $\vec{k}$.

3. Classification and Properties

Materials can be classified on the basis of $\varepsilon$ and $\mu$ in four quadrants as shown in figure 1. The first quadrant $(\varepsilon > 0, \mu > 0)$ represents right handed material (RHM). The forward propagation of wave takes place in the first quadrant. It is commonly used material. It follows the right hand thumb rule for the direction of propagation of wave as described in S. Ramakrishna (2013).

The second quadrant $(\varepsilon < 0$ and $\mu > 0)$ describes electric plasmas which support evanescent waves. It is also called ENG (epsilon negative) material. The fourth quadrant $(\varepsilon > 0$ and $\mu < 0)$ also supports evanescent, corresponding to MNG (mu negative material) $\mu$.

![Diagram](image)

**Fig. 1:** Classification of material on the basis of $\mu$ and $\varepsilon$.

The third quadrant $(\varepsilon < 0$, $\mu < 0)$ represents Metamaterial, also called left handed material or double negative material (DNG). It follows the left handed rule because propagation of wave takes place in backward direction in this medium. Due to negative $\mu$ and negative $\varepsilon$, the refractive index of the medium is calculated to be negative. Thus also termed as NIM (negative index material). Electric vector $E$, electromagnetic vector $H$ and wave vector $k$ forms the left hand triplet as shown in fig. By using the property of third quadrant, the first left handed test
Structure was used which was the combination of material with negative permittivity (thin wire) and negative permeability (SRR).

![First left-handed test structure array made by the San Diego group (courtesy D R Smith).](image)

**Fig. 2:** First left-handed test structure array made by the San Diego group (courtesy D R Smith).

### 3.1 Effect on Snell’s law:
In the third quadrant Refractive index in the Snell’s law is negative. N. Engheta (2006) described that an incident wave faces negative refraction at the interface Ray bends in inside direction after refracting in to medium which is contrary to positive index medium as shown in fig. Light is refracted in a contrary way as compared to the normal “right handed material”.

![Comparison of Snell’s law in different medium.](image)

**Fig. 3:** Comparison of Snell’s law in different medium.

### 4. Structure of Unit Cell
Metamaterial are usually implemented in a periodic structure. It is a soft option to design and fabricate it by recurring structure of unit cells. A unit cell is a combination of SRR and wire structure which is shown in figure. An array of unit cells may be used to get this structure. Rectangular SRR is described below.

![Rectangular SRR and equivalent circuit.](image)

**Fig. 4:** (a) Combination of wire and SRR as unit cell (b) Pendry’s (1999) circular SRR (c) Equivalent circuit of circular SRR
4.1 Realisation of Metamaterials

4.1.1 Negative $\varepsilon$

The metamaterial used as a metallic mesh of thin wires for obtaining negative value of $\varepsilon$. The effective permittivity can be expressed as

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2}$$ (3.2a)

Where $\omega_p$ is the plasma frequency and $\omega$ is the frequency of the propagating electromagnetic wave. From this equation, the effective permittivity is negative when the frequency is below the plasma frequency. When operating at the plasma frequency, the effective permittivity is zero, and hence yields a zero index of refraction. Thin metallic wires of Aluminum, Silver and Gold are arranged periodically as shown in fig 5.

4.1.2 Negative $\mu$

An array of split-ring resonators (SRRs) are arranged periodically. A split ring resonator is constructed by having two concentric metallic rings, with a gap in each ring, and the gaps are 180° apart. The gap between inner and outer ring acts as a capacitor while the rings themselves act as an inductor, resulting in an LC resonant circuit.

![Fig. 5: Combination of thin wires and SRR (courtesy Aos Al-waidh),](image)

5. Applications

5.1 Metamaterial as antenna

Metamaterial coatings have been used to enhance the radiation and matching properties of electrically small electric and magnetic dipole antennas. Metamaterial step up the radiated power. The newest Metamaterial antenna radiate 95% of input radio signal at 350 MHz Experimental metamaterial antenna are as small as one fifth of a wavelength. Patch antenna with metamaterial cover have increased directivity. Flat horn antenna with flat aperture constructed of zero index metamaterial has advantage of improved directivity. Zero-index metamaterials can be used to achieve high directivity antennas. Because a signal Propagating in a zero-index metamaterial will stimulate a spatially static field structure that varies in time; the phase at any point in a zero-index metamaterial will have the same constant value once steady state is reached. Metamaterial can enhance the gain and reduce the return loss of a patch antenna. Metamaterial inspired I shaped antenna comparison is given below and it is done by M.A. Wan Nordin et al (2012).
5.2 Metamaterial as Absorber
The first Metamaterial based absorber by landy (2008) utilizes three layers, two metallic layers and dielectric and shows a simulated absorptivity of 99% at 11.48 GHz as shown in fig7. Experimentally, landy was able to achieve an absorptivity of 88%. The difference between simulated and measured results were due to fabrication errors.
5.3 Metamaterial as superlens
Superlens uses metamaterials to go beyond the diffraction limit. Ramakrishna (2005) showed, it has resolution capabilities that go beyond ordinary microscopes. Conventional optical materials suffer a diffraction limit because only the propagating components are transmitted from a light source. The non-propagating components, the evanescent waves, are not transmitted. One way to improve the resolution is to increase the refractive index but it is limited by the availability of high-index materials. The road to the super lens is its aptitude to significantly enhance and recover the evanescent waves that carry information at very small scales. No lens is yet able to completely reconstitute all the evanescent waves emitted by an object. So the future challenge is to design a superlens which can constitute all evanescent waves to get perfect image.

5.4 Metamaterial as cloaks
Cloaking can be achieved by cancellation of the electric and magnetic field generated by an object or by guiding the electromagnetic wave around the object. Guiding the wave means transforming the coordinate system in such a way that inside the hollow cloak electromagnetic field will be zero this makes the region inside the shell disappear. Metamaterial cloak based on the concept of coordinate transformation is described by Adnan noor (2010).
5.5 Metamaterial as sensor
Metamaterial opens a door for designing sensor with specified sensitivity. Metamaterials provide tools to significantly enhance the sensitivity and resolution of sensors. Metamaterial sensors are used in agriculture, biomedical etc. In agriculture the sensors are based on resonant material and employ SRR to gain better sensitivity. In biomedical wireless strain sensors are widely used, nested SRR based strain sensors have been developed to enhance the sensitivity and described by Goran Kiti et al (2012).

![Fig. 10: Metamaterial unit cells that are used for the sensor (a) Multiple SRR (b) Sierpinski SRR (c) Spiral Resonator](image)

5.6 Metamaterial as Phase compensator
Metamaterial act as a phase compensator, when wave passes through a (double positive) DPS slab having positive phase shift while DNG slab has opposite phase shift so when wave exit from a DNG slab the total phase difference is equal to zero. The concept is described by Adnan Noor (2010).

6. Conclusion
Metamaterial are expected to have an impact across the entire range of technologies where electromagnetic radiation are used and will provide a flexible platform for technological advancement. Among metamaterials, negative refractive index materials or left-handed materials have drawn special attention in microwaves. Metamaterial properties, which allows for the reduction in size as compared to other materials for the multiband operation and reconfigurability of microwave devices and antennas. The most interesting application is as an absorber and also as sensors for humidity, soil moisture measurement etc. It is also true that no progress in metamaterials research
will be possible without further developments in fabrication, however, From the progress and interest in this field it is clear that the future of metamaterials lies in the field of optics and medical. This is closely linked to advancements in nanotechnology.

References