Review of Metamaterials, Types and Design Approaches

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Abstract: Metamaterials are one of the most significant and interesting theme for the Electromagnetic Field Theory in the recent past. Many scientific efforts have been performed and analyzed in this field and concluding that the metamaterials have unique and incredible properties which can be used to increase the key performances of conventional devices. Basically metamaterials are considered in the category which show different behavior under the effect of electric and magnetic field than those materials which are naturally derived. The response of the metamaterials inspired devices at the high frequencies is much better than the devices with conventional materials. Use of metamaterials in various antenna designing and fabrication enhances the gain profile, efficiency and bandwidth requirements. In this paper, we will discuss about the brief history and types of metamaterials, its structure based various properties and approaches.

Keywords: Metamaterials, properties, characteristics, miniaturization, gain, efficiency, directivity.

1. Introduction

In recent years, the electromagnetic metamaterials are considered for the various practical engineering applications. We are known to the terms *electric permittivity (ε)* (i.e. ability of a material to polarize in response to the electric field) and *magnetic permeability (μ)* (i.e. degree of magnetization of a material in response to a magnetic field). These two basic parameters can describe the electromagnetic (EM) properties and effect of induced polarization of any material. In Greek, the word 'Meta' means 'beyond' or 'superior'. This means metamaterials are the artificial structures that possess unusual and superior properties than those materials which derived naturally. Metamaterials are the materials which have electromagnetic and acoustic properties arise from their internal structure rather than the matter of which they are composed. To differentiate metamaterials from other composites, the metamaterial label is usually used for a material which possesses extra-ordinary properties. The meaning of metamaterial can also be expressed in another way, which is "to achieve material response beyond the limitations of conventional composites." And even more, it is emergent in the very meaning of its definition, "the material which gains its properties from its structure" [1].

Behavior of metamaterials in communication field is of great consideration. Metamaterial configured antenna substrate efficiently responds to the high frequencies and provides high gain profile, large bandwidth requirements, increased directivity, high beam-width efficiency, high radiated power, less noise power etc. in results. In case of microstrip patch antenna, as for the selection of substrate, major consideration will be the dielectric constant and loss tangent. High dielectric constant results in smaller patch size but this will generally reduce bandwidth efficiency. By incorporating SRR (Split Ring Resonator) into substrate layer, the directivity can be increased [2]. These unique significant properties of metamaterials are very beneficial for enhancement of antenna designing and antenna fabrication techniques. High directive antenna elements can be realized by introducing a set of metamaterial superstrates that can improve the radiating efficiency [3].By carefully designing the metamaterial unit cells, it is thus possible to construct composites that exhibit effective homogeneous properties unlike those found in naturally occurring materials. For example, it has been experimentally proved [4] that an array of wires and split ring resonators (SRRs) possesses all the non-intuitive properties of negative index material [5]. Metamaterials as an artificial electromagnetic material also possess unique optical properties. Metamaterials based configurations can be made useful for optical frequency ranges [6].

2. Historyof Metamaterials

The concept of metamaterial was mathematically given by Russian theorist Victor G. Veselago in 1967.He gave the statement that the materials with both negative permittivity and negative permeability are theoretically possible[7]. In 1999, Professor John B. Pendry found the practical method to make Left Handed Metamaterials (LHM) which did not obey conventional right hand rule [8]. LHM are the subset of metamaterial and having an antiparallel relation between wave propagation vector (k) and the poynting vector (P), where 'k' represents the direction of propagation of wave and 'P' represents the direction of flow of energy. The value of k can be given as$k = \pm\frac{\omega}{c}\sqrt{\varepsilon\mu}$ and poynting vector P is the vector product of$\vec{E}$and $\vec{H}$vector, where E is representing the electric field and His representing the perpendicular magnetic field.

For the case of Right handed materials, μ and ε both are having positive sign, thedirection of vector k and P both will be in same direction i.e. co-directed (as shown in fig. 1(a)) and the group velocity (v_g) varies linearly with the phase velocity (v_p). But in case of Left handed materials, the values of μ and ε both are having negative sign, here in this case the vector k and P are contra-directional i.e. antiparallel in direction (as shown in fig. 1(b)) and the group velocity and phase velocity will possess inverse relation with each other.

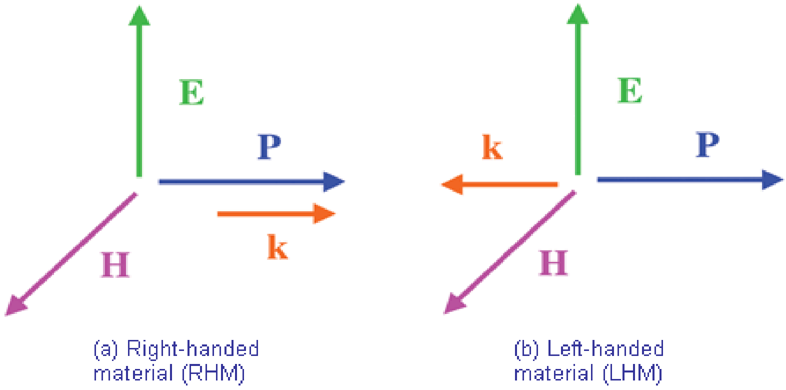

Fig. 1 (a) Vectors k and P are co-directional (b) Vectors k and P are contra-directional

The refractive index (n) will also suffers through the change under these conditions as it is also dependent upon ε and μ by the relation$n = \pm\sqrt{\varepsilon\mu}$, which concludes that for Right handed materials, n is positive ($n > 0$) and for Left handed materials, the value of n is negative ($n < 0$). So, the metamaterials are also known as Double Negative materials (DNG) or Negative Index materials (NIM) or Veselago Medium or Left Handed materials (LHM).Negative-Index material (NIM) were first demonstrated for microwave frequencies, but to design NIMs for optical frequencies has been a challenge due to complex fabrication techniques and high energy dissipation in metals [9].

3. Types of Metamaterials

Before the metamaterials, different techniques and method were used to improve the performance characteristics or reduce the mass and volume of microwave passive devices like defected ground structure (DSG), photonic bandgap structures (PBG), frequency selective surfaces (FSS) etc. But the properties of metamaterials and its behavior towards the electromagnetic RF waves provide a new approach based on the concept of artificial effective media, which is the applicative part of the metamaterials. These artificial structures are composed of unit cells same as the matters are consisting of atoms. The metamaterials represent the next level of structural organization of matter because the size of the unit cells is typically smaller than one tenth of propagating wavelength i.e. same as the atoms.

Consequently, metamaterials can be considered as a continuous medium with effective parameters, namely effective dielectric permittivity and effective magnetic permeability. By a proper choice of the type and geometrical arrangement of constituent unit cells, the effective parameters of metamaterials can be made arbitrarily small or large, or even negative [10]. There are subclasses of the metamaterials based upon the value of permittivity and permeability (as shown in fig. 2), which can be discussed as, Double Negative

Material (the sub class of metamaterials having both the effective parameters i.e. permittivity and permeability negative i.e. ($\mu < 0$) and ($\varepsilon < 0$) in certain range of frequencies), Single Negative Material: the sub class of metamaterials having either permittivity or permeability negative i.e. ($\mu < 0$) or ($\varepsilon < 0$) in certain range of frequencies), Mu Negative Material (the sub class of metamaterials having permittivity as positive i.e. ($\varepsilon > 0$) and permeability as negative i.e. ($\mu < 0$) in certain range of frequencies), *EpsilonNegative Material:* the sub class of metamaterials havingpermittivity as negative i.e. ($\varepsilon < 0$) and permeability as positive i.e. ($\mu > 0$) in certain range of frequencies, are called as Epsilon Negative Materials (ENG).

Based upon the value of permittivity and permeability the metamaterials designing is approached. As with the change of these two effective parameters, the effective electromagnetic behavior and response of the metamaterial varies leading to the different categories of the metamaterials like *electromagnetic* metamaterials, *chiral*metamaterials (arrays of dielectric gammadions or planar metallic on a substrate. When a linearly polarized light is incident on the array, it becomes elliptically polarized upon interaction with the gammadions with the same handedness as the gammadion itself [10]), *photonic* metamaterials (working on optical frequencies), *terahertz* metamaterials (ranging from 0.1-10 THz) etc.

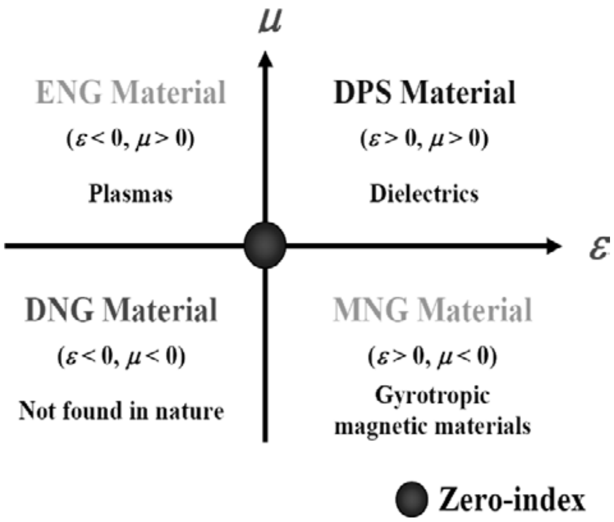

Fig. 2 Classification of materials on the basis of the values of effective parameters i.e. permittivity and permeability

4. Design Approachesfor Metamaterials

The main goals of current research in the field of metamaterials are further miniaturization and performance improvement of the unit cell. Since the LH behavior is obtained due to the resonant nature of the unit cell, the structures based on the applications of SRR are considered in resonant approach. In 2002, three groups of researcher's simultaneous proposed new non-resonant approach to the design of planar LH metamaterials based on the dual transmission line (TL) concept [11]. While the first (resonant) approach results in narrow-banded LH structures, the second one (TL) provides a useful tool for the design of simultaneously low loss and broad bandwidth devices. To aim miniaturization, the third approach is used in which sub wavelength particles from both the resonant and non-resonant approachesare combined into one unit cell. On the basis of different metamaterials structures, some approaches are discussed here.

4.1 Resonant Approach

In this approach the LH behavior of metamaterials is developed, by combining two different particles into a unit cell in such a way that one particle possess negative permittivity and the other possess negative permeability i.e. one should be ENG metamaterial and other should be a MNG metamaterial.This

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approach is based upon the application of SRR (Split Ring Resonator) particles [12]. The functioning of this approach is based upon the principle that when resonant material is exposed to the axial magnetic field, it exhibits the extreme values of effective magnetic permeability in the vicinity of resonance and showing highly positive in the narrow band below the quasi-static resonant frequency and highly negative in the narrow band above the quasi-static resonant frequency of the rings.

This property can be used in filtering operation as an array of SRRs has filtering properties, when properly polarized, can inhibit signal propagation, thusoffering an effective way to reject a frequency band in the vicinity of its quasi-static resonance . A microstrip line loaded with SRRs is a single-negative medium, and therefore exhibits a stop-band characteristic. To improve the coupling, the distance between the line and the rings should be as small as possible. Although having a narrowfrequency range with negative permeability, theconfigurations using SSR have driven a lot of attention [12] [13]. So we can also use SRR approach in waveguides as well to allow only those signals which are propagating below the cut off frequency. This approach no doubt can be successfully applied in the designing of filters and frequency selective surfaces, but it limits the designing for wide frequency ranges.

4.2 Transmission line Approach

TL theory provides a significant tool for analysis and design of conventional (right-handed, RH) materials. The basic idea behind the TL approach to the design of metamaterials is that standard TL theory can be used to analyze and design LH metamaterials using a dual concept [11]. A dual transmission line can be described by an equivalent circuit that is the dual of the circuit that models a conventional transmission line. In the dual case, the capacitors are connected in series, while the inductors are placed in a shunt configuration.

If the unit cells are sufficiently small (much smaller than the propagating signal wavelength), such structure can be regarded homogenous, i.e. effective permittivity and permeability can be calculated. It has been shown that dual transmission line exhibits negative effective permittivity and permeability in a certain frequency range and, therefore, behaves as LH transmission line. LH TL is obviously of high-pass nature, in contrast to the RH TL, which is of low-pass nature [12].

The homogenous CRLH transmission lines do not exist in nature, but it can be constructed by cascading a number of CRLH unit cells, realized by lumped components. Using this approach, number of novel devices has been proposed like couplers, zeroth order resonator, planar lens, leaky wave antenna etc. Comparing the response of these devices, it was concluded that this approach has achieved small dimensions due to the application of LH metamaterial but also giving the relatively high Insertion losses. This drawback has been overcome by novel unit cells called ForeS [15][16] and Super-compact LH unit cells called S-spiral [17]. This proposed structure shows lower insertion loss at resonant frequency and higher quality factor.

4.3 Hybrid Approach

The Hybrid approach combines the concept of both above mentioned approaches i.e. resonant approach and transmission line approach. This approach combines the SRR (Split Ring Resonator) and CSRR (Composite Split Ring Resonator) from one side and gaps and shunted stubs from the other side. Generally, SRRs and gaps are providing negative permeability, while CSRRs and stubs areproviding negative permittivity. Using various combinations of these particles, hybrid LH metamaterials can be designed.

Unit cells that combine shunted stubs and CSRRs which uses the concept of compact ultra-wide band pass filters. The performance of this approach is slightly differing because the pass band obtained in this is not entirely LH in nature. Therefore, it is also possible to design LH lines with more than two particles. The third particle can be used to control the response [17].

5. Conclusion

Metamaterials have attracted the interest of Electronics Engineer as it is an extremely exciting research area. In this paper, a short review of the history of metamaterials, some of its significant features, its various types and different design approaches have been discussed. The metamaterials have resulted in surprising improvements in electromagnetic response functions like high gain profile, efficiency, low loss and satisfied bandwidth requirement that offer exciting possibilities of future design of devices, components and salient properties of metamaterials. We compared the different design approaches which are of great use for designing metamaterial inspired devices.

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