



## A Study of Significance of Metamaterial in Antenna Array Elements Design

Neha Singh, Kamal Kishor Choure, Amandeep Kochar

Department of ECE,  
Poornima Group of Colleges  
Jaipur, Rajasthan, India

Harshavardhan Singh

Department of ECE,  
National Institute of Technology  
Durgapur, India

**Abstract**— *Antenna designing with large bandwidth and desired radiation characteristics is a very challenging task. The manufacturing material of antenna plays a very important role for achieving the desired antenna parameters. It was demonstrated by various experiments that by using a magneto dielectric material antenna performance is enhance. The electromagnetic (EM) properties of any material can be described by its electric permittivity and magnetic permeability. Metamaterials have arisen in an attempt to engineer the electromagnetic properties of natural substances. It has been realized that the emergence of metamaterials has implications to nearly all branches of science and engineering exploiting the EM radiation. In this paper we did a study on the metamaterial from the vision to the realization of various wavelength elements that contribute to varieties of electric and magnetic responses.*

**Keywords**— *electromagnetic, metamaterial, artificial dielectrics, negative-index, right handed medium, left handed medium*

### I. INTRODUCTION

In modern era wireless communication systems, antenna miniaturization with large bandwidth and desired radiation characteristics is very challenging task. The manufacturing materials of elements of array play an important role in the designing of the antenna array and to achieve the antenna parameters. Various experiments explained that antenna performance is significantly increased by using a magneto dielectric material [1]. The electromagnetic (EM) properties of any material can be described by its electric permittivity and magnetic permeability. These two parameters also describe the effects of induced polarization. Designing of EM structures has been important research topic for some time. During 1950s and 1960s, lattices of discrete obstacles, also known as “artificial dielectrics” were extensively studied. These artificial dielectric materials are operating in the long wavelength regime, where the wavelength of radiation is very large as compared to the scattered dimension and periodic spacing. As a result, they can be considered as an effective media when describing EM phenomena at a macroscopic level. EM properties of such structures are expressed in terms of an effective electric permittivity and magnetic permeability. A renewed interest in artificial dielectrics has emerged from recent advances in Electromagnetic microstructures that have extended the range of achievable effective permittivity and permeability values. The recent implementation of a microstructure material with negative magnetic permeability in the gigahertz range has quickly led to the development of a composite medium with simultaneously negative values of permeability and permittivity over a finite frequency range. This composite medium has often been referred to as a negative refractive index metamaterial. This type of material combines an array of metallic wires to attain negative effective permittivity with an array of split-ring resonators to achieve negative permeability. Its realization has launched a new area for research and renewed interest in EM phenomena associated with wave propagation in negative refractive index materials [2].

### II. HISTORY OF METAMATERIAL

In 1968, Veselago theoretically investigated the electrodynamics of a medium with simultaneously negative values of permittivity and permeability. According to his study, these materials are “left handed media” (LHM). These materials are also known as “meta-material” [2]. A meta-material can be created by adding periodic macro pores in the structural layer in which the bulk mode resonator is manufactured [3]. When a lossless metamaterial possessed of negative real permittivity and permeability at certain frequencies, the index of refraction for such a medium is reach at real values. So as theoretically predicted by Veselago, the EM wave can propagate in such a medium [4]. However, for a monochromatic uniform plane wave in such a medium the phase velocity is in the opposite direction of the Poynting vector [5]. In 2000, David Smith and his colleagues, constructed the first LHM, which is based on a periodic array of interspaced conducting nonmagnetic split-ring resonators and continuous metallic wires. In 2001, this group made another LHM for X band and verified the negative index of refraction as predicted by Veselago. In 2002, Mehmet Bayindir studied the transmission properties of LHM in free space; he also verified the existence of negative permeability and permittivity. Stefan Enoch also studied the directive emission of a source embedded in a slab of meta-material in 2002. In 2003, Ran Lixin, Hongsheng Chen of Zhejiang University and their colleagues made the first beam shifting experiment and T-junction waveguide experiment to verify the

negative refraction. We did a survey on the transmission properties, advantages, disadvantages and application of metamaterial [6].

Negative-index metamaterials (NIMs) were first demonstrated for microwave frequencies, but it has been a big challenge to design NIMs for optical frequencies because of significant fabrication challenges and strong energy dissipation in metals. Such type of thin structures is similar to a monolayer of atoms, making it complex to assign bulk properties such as the index of refraction. Negative refraction of surface Plasmon's was recently demonstrated but was confined to a two-dimensional waveguide. Three-dimensional (3D) optical metamaterials have come into picture recently, along with the realization of negative refraction by using layered semiconductor metamaterials and a 3D magnetic metamaterial in the infra-red frequencies; however, neither of these had a negative index of refraction [7]. The exotic and often dramatic physics predicted for metamaterials is under pinned by the resonant nature of their response and therefore achieving resonances with high quality factors is essential in order to make metamaterials performance efficient. However, resonance quality factors demonstrated by conventional metamaterials are often limited to rather small values. This comes from the fact that resonating structural elements of metamaterials are strongly coupled to free-space and therefore suffer significant losses due to radiation. Furthermore, conventional metamaterials are often composed of sub-wavelength particles that are simply unable to provide large volume confinement of electromagnetic field necessary to support high-Q resonances. As evidenced in recent theoretical analysis the high-Q resonances involving dark (or closed) modes are nevertheless possible in metamaterials if certain small asymmetries are introduced in the shape of their structural elements [8].

Realization of metamaterials has been increasing attention for various applications due to its several advantages. Some interesting applications have been more efficient in wireless power transfer [9], super-lensing [10], and radar-absorbing materials [11]. While the demonstrations of such unique properties and their abilities for improving on previous technologies have been widespread, the adoption of metamaterials in industry has been underwhelming. This is primarily due to the barriers in transition from technology to market due to high-cost of fabrication. Cheaper and simpler manufacturing methods might therefore allow metamaterials to see more widespread adoption. Typically metamaterials have been produced by using complex, multi-step processes such as chemical vapor deposition, followed by ion sputtering [12]. While these methods have presented numerous interesting results, they cannot be scaled to large areas where they would carry high costs of implementation. These conflicts with some applications of metamaterials, such as absorbers, require large surface coverage [13].

Lower cost methods are now available which can yield high volume production; specialized ink-jet printers are used to create metamaterials in the THz region. One problem is that the process mentioned above is typically performed in a batch manner under tightly controlled environmental conditions. The ability to "paint-on" metamaterials to a variety of surfaces might allow for a wider range of industrial applications that require large surface area coverage. The idea of metamaterials as a replacement for bulky radar absorbing materials has been widely discussed. The "perfect absorber" device has been at the center of such conversations. It is also noted that creating high levels of absorbency in any given frequency band require that the electromagnetic characteristics of the middle dielectric layer and the top and bottom conducting planes be well matched [13]. Metamaterials, which are operating in the visible light range needed nano-scale patterning resolution less than 390 nm, since these feature sizes are smaller than the wavelength of electromagnetic radiation (light) it interacts with. The fabrication of meta-atom at optical frequencies usually used physical lithography (top-down approach) which on the large scale of fabrication is restricted by the expensive instruments [14].

### **III. PROPERTIES OF METAMATERIAL**

The term meta-materials is generally used for an artificial composites material which have the necessary properties that are absent in the naturally occurring materials. The most important property due to which the development of meta-materials begins is the identification of different electromagnetic property of the materials. For example, it has recently been explained that metamaterials with split ring resonators can have a negative magnetic permeability  $\mu < 0$  in the microwave range and even in terahertz frequency ranges. When additional elements, such as continuous conducting wires, are incorporated into an elementary cell of a meta-material, it shows the negative dielectric permittivity and magnetic permeability [15]. These negative index materials (NIMs) with  $\epsilon < 0$  and  $\mu < 0$  increase the possibility of making a 'perfect' lens with sub-wavelength spatial resolution. NIMs have found a wide range of application in microwave and optical field as well. It's being a challenge to developed NIMs for optical frequency range [16].

As the electromagnetic properties of the metamaterial have a great difference from the electromagnetic properties of the ordinary material and their wide application in microwave and optical range, get attention of the researchers. A metamaterial is a periodic structure of conventional materials forming a composite structure which gives the unique electromagnetic properties when the waves get interact with this periodic structure. Veselago is the first person who discovers the concept of metamaterials in 1967. After detailed research he found an unknown material that has a negative permeability and permittivity in the same frequency range and it shows the abnormal behaviour of electromagnetic properties when the uniform plane-wave propagation was studied [17]. Based on these studies, Veselago regarded this materials as left-handed materials (LHM), because in this the electric field, magnetic field, and direction of propagation are related by a left-handed rule that shows the phase and group velocities of an electromagnetic wave being anti-parallel [18].

With the help of periodic arrangement of metals, the metamaterials produce new electrolytic capabilities, dielectrics, effective circuit elements, and other engineered properties within an arrangement of discrete unit cells. There are many more new radio frequency properties that have been explained, including negative permittivity or permeability, near zero refractive index, and various cloaking and lens structures. Generally, many of these properties are not practically possible because of their high dispersion, and narrow bandwidth. Many metamaterials achieve their unique properties through the

narrow bandwidth which is the result of resonance. This is also the reason to make them highly dispersive. Furthermore, while the idea of cloaking is attractive, if an object must be coated with a material that is on the order of a wavelength thick or more, it will not be useful in the frequency ranges where cloaking is most important [19]. A LHM is having real values of refraction index and wave vectors, and showing extended wave propagation over a frequency band because it is having negative permittivity ( $\epsilon$ ) and permeability ( $\mu$ ) over the same frequency band as its property. Smith performed his initial transmission experiments on a one-dimensional LHM that is composed of an array of unit cells and each cell consisting of one split-ring resonator. A negative group velocity is one of the necessary characteristic marks of an LHM [20].

In such materials, the anti-parallel phase velocity and energy flow, results a new phenomena called 'counterintuitive phenomena'. This is like reversed refraction as well as reversals of the conventional Doppler shift and Cherenkov radiation. J.B Pendry [10]; in his work on perfect lenses; proposed a fact that flat slabs of negative refractive index Metamaterial shows behavior like unconventional lenses with sub wavelength resolving properties. Shelby in his recent experiments uses the array of wires and split-ring resonators to demonstrate a left-handed propagation band and support the work of Veselago which described that LHMs exhibit reversed refraction *i.e.*, an incident beam on an LHM from an ordinary right handed medium (RHM) was shown to refract to the same side of the normal as the incident beam. The metamaterial supports reverse travelling EM waves with phase velocities greater than the speed of light, and when it is compared to the radiated wave from charged particles exceeding the speed of light in a LHM, these waves emit very much like coherent backward wave radiation [2].

As  $E$ ,  $H$ , and  $k$  ( $k$  is wave vector) form a left-handed system, under proper conditions, a propagating plane wave in this media is such that  $k$  is being the wave vector. LHMs have been the subject of intensive research in the past few years. The amazing refractive properties of the metamaterials and, more specifically, the LHMs have excited the imaginations of the researchers, and ideas proposed by Vesalogo are taken up nowadays and extended [21]. In his work, Pendry has proposed LHMs to build perfect lenses that are not limited to the usual wavelength limits but are able to focus even evanescent waves [22]. When it comes about the control of emission, it has two interesting features:

- a. The enhancement of the emission rate
- b. Control of the direction of emission.

Many of solutions have been proposed to these problems, such as photonic crystals that are probably the best candidates to inhibit, enhance, and control emission or micro cavities which have been used to increase spontaneous emission. Regarding this, photonic crystals have been first proposed for the inhibition of the spontaneous emission [21]. Basically a tridimensional photonic crystal is made up of dielectric or periodic metallic structure whose period is of the order of magnitude but smaller than the wavelength for use. The problems encountered to realize these type of periodic structures in the optical domain have decreases the development rate of the applications, but recent researches have prove that they are now available [23].

Photonic crystal provides benefit to the antennas also due to its properties. These crystals have been first proposed by Stefan Enoch [21] as a substrate for planar antennas which help in suppressing the surface modes on a conventional metallic ground plane. The next idea was to design directive antennas by using planar defects in a photonic crystal [24]. The planar cavity works as a Fabry-Perot resonator in that case, and the similitude is even clearer for mono-dimensional photonic crystals similar like classic Fabry-Perot filter realized using dielectric optical thin films. It is generally used as an optical spectral filter [21]. The propagation of pulse through such metamaterials has considerable delay, however much smaller thickness of the structure along the direction of wave propagation allows successive stacking of multiple metamaterial slabs. This shows a significant increase in the normal dispersion band of spectrum, as well as in transmission levels [25]. In case of extreme anisotropy, Meta-materials can have a larger impact on the field of nanophotonics. Meta-materials with extreme anisotropy can, in fact, enable diffraction-free, deep sub-wavelength imaging, deep sub-wavelength beam propagation, as well as deep sub-wavelength beam manipulation [26].

Generally, at RF/microwave frequencies; to illustrate peculiar electromagnetic properties; the artificial effective mediums of metamaterials are electromagnetically ordered array scatters, fulfilling a sufficient long wavelength condition. Electromagnetic community has been trying to utilize the unique properties of metamaterial since the emerging of these materials. Planar left handed (LH) transmission media can be based on loading a hosting transmission line (TL) with series capacitors and shunt inductors; utilizes the properties of metamaterials. In addition to the broad bandwidth, this approach is a non resonant approach and has advantage of compactness. TL can be named as composite right/left-handed (CRLH) TLs [27]. Due to the parasitic shunt capacitor and series inductor effects of the hosting transmission line, this approach has led to development of novel guided and radiated microwave devices and components. Several antenna size enhancement and performance have been introduced by employing different metamaterial LH TL structures. These materials become simpler and inexpensive for fabrication procedures in addition to their simple cascading with active components.

#### **IV. APPLICATION OF METAMATERIAL**

Metamaterial is used in various fields especially for communication. Equipments used in WiMAX may operate at different frequency bands. The main frequency band are; lower WiMAX band at 2.4 GHz, medium WiMAX band at 3.5, 3.65GHz, and higher WiMAX band at 5.2/5.3/5.8 GHz; most commonly used and license free frequencies in RF/microwave frequency range. The challenge is to produce compact equipments that can operate at these different frequency bands simultaneously. A compact triple band metamaterial based antenna is designed to cover all the operating frequencies of WiMAX (2.1-2.6 GHz band, 3.3-3.7 GHz band, and 5.2-5.9 GHz band) in one device discussed in [28]. Dual band antennas was based on using a metamaterial modified LH-TL unit cell. The designed antenna was introduced to operate with the WiMAX lower 2.4 GHz band and upper 5.8 GHz band. A dual band meta-material antenna for WiMAX

applications has been designed too. The designed antenna has the advantages of its compact size (only 2 X 3 cm<sup>2</sup>), the designed patch radiator is only 25% at 2.4 GHz and 60% 5.8 GHz compared to the conventional patch length [29].

The development of a metamaterial has permitted the construction of a very light weight large size lens, weighing only 50 kg which provides easy mobility and installation and also enhance the real-time broadband far field zone and antenna-on-body testing of larger size antennas. As the weight of the lens get reduced, it provides a simplified solution for antenna on body measurements as it can be easily mounted on a robotic arm allowing it to move around an object and provide real-time amplitude measurements [30].

In military application it is used as microwave absorbers to reduce the radar cross-section (RCS) of a conducting target and it also helps in reducing the electromagnetic (EM) interference among microwave components. The use of artificially structured meta-metamaterials (MTMs) provides the advancement in the absorber technology, which creates a high performance absorber for the microwave and terahertz frequency regime. By giving proper tuning of electric and magnetic resonances, an MTM can be impedance-matched to free space which provides 100 % absorbance. Typically, absorbers are usually made with metallic backing plates in order to prevent power transmission through the absorbers, which may cause many problems in stealth applications [31].

Various types of meta-materials has been proposed in THz frequencies [32] and applied to the sensing applications. Since the transmission spectrum of the meta-materials are largely effected by the properties of the meta-materials, the meta-materials can be used as high sensitive sensors by measuring the transmittance change when the particles are adsorbed to the surface of the meta-materials [33].

## V. CONCLUSION

In this paper we have seen how interesting electromagnetic responses can be derived from metamaterials in a desirable way. Metamaterial research is of great importance to terahertz technology, since this new class of material promises strong electromagnetic responses not available from natural materials at terahertz frequencies. Realization of meta-materials has been increasing attention for various applications due to its several advantages. Some interesting applications have been more efficient wireless power transfer, super-lensing, and radar-absorbing materials. Some terahertz devices arising from metamaterial building blocks have been proposed recently. However, improvement of metamaterial performance at this frequency regime has not been fully addressed, and still remains a challenge.

## REFERENCES

- [1] Hossein Mosallaei and Kamal Sarabandi, "Engineered Meta-Substrates For Antenna Miniaturization," URSI EMTS, pp. 391-393, 2004.
- [2] Anthony Grbic and George V. Eleftheriades, "Experimental verification of backward-wave radiation from a negative refractive index metamaterial," Journal Of Applied Physics, Vol. 92, No. 10, 15 November, pp. 5930-5936, 2002.
- [3] R. Jansen, X. Rottenberg, V. Rochus and H.A.C. Tilmans, "Simulations of Thermo-Elastic Losses in a Meta-Material Bulk Bar Resonator," 13th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems, EuroSimE 2012.
- [4] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of  $\epsilon$  and  $\mu$ " (in also in Russian, Usp. Fiz. Nauk., vol. 92, pp. 517-526, 1967), Soviet Phys. Uspekhi, vol. 10, no. 4, pp. 509-514, 1968.
- [5] Nader Engheta, "An Idea for Thin Subwavelength Cavity Resonators Using Metamaterials With Negative Permittivity and Permeability," IEEE Antennas And Wireless Propagation Letters, VOL. 1, pp. 10-13, 2002.
- [6] Q. Sui , C. Li, L. L. Li, and F. Li, "Experimental Study Of  $\lambda/4$  Monopole Antennas In A Left-Handed Meta-Material," Progress In Electromagnetics Research, PIER 51, pp. 281-293, 2005.
- [7] Jason Valentine, Shuang Zhang, Thomas Zentgraf, Erick Ulin-Avila, Dentcho A. Genov, Guy Bartal & Xiang Zhang, "Three-dimensional optical metamaterial with a negative refractive index," NATURE, Vol. 455, 18 September, pp. 376-380, 2008.
- [8] V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis, and N. I. Zheludev, "Sharp dark-mode resonances in planar metamaterials with broken structural Symmetry," Physics.optics, 12 April, 2007.
- [9] B. Wang et al, "Experiments on wireless power transfer with metamaterials," Appl. Phys. Lett. 98, 254101, 2011.
- [10] Pendry, J. B., "Negative Refraction Makes a Perfect Lens," Phys. Rev. Lett. 85, pp. 3966-3969, 2000.
- [11] H. Oraizi, A. Abdolali, and N. Vaseghi, "Application of double zero metamaterials as radar absorbing materials for the reduction of radar cross section," Progress In Electromagnetics Research, Vol. 101, pp. 323-337, 2010.
- [12] X. Liu et al, "Metamaterials on Thin Film Parylene Substrate: Design, Fabrication and Measurements," Applied Physics Letters, 96, 011906, 2010.
- [13] Chris Mutzel, Sam MacNaughton, Sameer Sonkusale, "Paint-On Metamaterial: Low Cost Fabrication of Absorbers at X Band Frequencies," IEEE, 2012.
- [14] M. A. Salim, H. Misran, S. Z. Othman, N. N. H. Shah, N. A. A. Razak and H. Abdullah, "Facile Processing of Si-Cu Core-Shell as Potential Meta-atom Materials," 3rd International Conference on Photonics 2012, Penang, 1-3 October, pp. 159-162, 2012.
- [15] Smith D R, Padilla W J, Vier D C, Nemat-Nasser S C and Schultz S 2000 Phys. Rev. Lett. 84 4184.
- [16] Gennady Shvets and Yaroslav A Urzhumov, "Negative index meta-materials based on two-dimensional metallic structures," J. Opt. A: Pure Appl. Opt. 8, pp. S122-S130, 2006.
- [17] E. Nader and R. W. Ziolkowski. "A positive future for doublenegative metamaterials". IEEE Transactions on Microwave Theory and Techniques. Vol. 53, 1535-1556, 2005.

- [18] H. Benosman and N. Boukli Hacene, "Multi-Band Meta-material Structures Based On Hexagonal Shaped Magnetic Resonators," 24th International Conference on Microelectronics (ICM), 2012.
- [19] Dan Sievenpiper, "Active, Nonlinear, and Anisotropic Artificial Impedance Surfaces," 7th European Conference on Antennas and Propagation (EUCAP), pp.3950, 2013.
- [20] R. A. Shelby, D. R. Smith, S. C. Nemat-Nasser, and S. Schultz, "Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial," Applied Physics Letters, Volume 78, Number 4, January, pp. 489-491, 2001.
- [21] Stefan Enoch, Gerard Tayeb, Pierre Sabouroux, Nicolas Guerin, and Patrick Vincent, "A Metamaterial for Directive Emission," Physical Review Letters, Volume 89, Number 21, November, 2002.
- [22] J. B. Pendry, Phys. Rev. Lett. 85, 3966 (2000).
- [23] Y. A. Vlasov, X.-Z. Bo, J.C. Sturm, and D. J. Norris, Nature (London) 414, 289 (2001).
- [24] M. Thevenot, C. Cheype, A. Reineix, and B. Jecko, IEEE Trans. Microwave Theory Tech. 47, 2115 (1999).
- [25] N. Papasimakis, V. A. Fedotov, and N. I. Zheludev, "A metamaterial analog of electromagnetically induced transparency," Physics Optics, Jan, 2008.
- [26] Peter B. Catrysse and Shan-hui Fan, "Deep sub-wavelength beam propagation, beam manipulation and imaging with extreme anisotropic meta-materials," CLEO Technical Digest, 2012.
- [27] C. Caloz and T. Itoh, "Electromagnetic Metamaterials Transmission Line Theory and Microwave Applications," New Jersey: John Wiley & Sons, 2006.
- [28] Mahmoud Abdalla, Usama Abdelnaby, and Abdelazez A. Mitkees, "Compact and Triple Band Meta-material Antenna for All WiMAX Applications," Proceedings of ISAP, Nagoya, Japan, 2012.
- [29] Mahmoud A. Abdalla, Zhirun Hu, "A Compact Dual Band Meta-material Antenna for Wireless Applications," Loughborough Antennas & Propagation Conference, UK, November 2012.
- [30] Leo Matysine, Pavel Lagoiski and Serguei Matitsine, "Antenna Measurement Using Large Size, Lightweight, Broadband Convex RF Lens," 6th European Conference on Antennas and Propagation (EUCAP), pp. 2271-2274, 2011.
- [31] Hongmin Lee, Hyungsup Lee, "A Backplane-less Microwave Meta-material Absorber (Invited)," IEEE Asia-Pacific Conference on Antennas and Propagation, August 27-29, Singapore, 2012.
- [32] T. Chen, S. Li, and H. Sun, "Metamaterials Applications in Sensing," Sensors 2012, 12, pp.2742-2765
- [33] Takuya Sono, Mitsuhiro Shinomiya, Kenji Sakai, Toshihiko Kiwa, and Keiji Tsukada, "Hydrogen Gas Response of Meta Materials Made From the Catalytic Metal," Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR), 2013.