Volume. No. 1, Issue No. 2, Mar – Jun 2013, ISSN: 2320 - 8996

Metamaterial Antennas Miniaturization and Bandwidth Enhancement – A Review

[1]Deepak Gangwar, [2]R. L. Yadava, [3]Sushrut Das

[1,2]Department of Electronics and Communication Engineering Galgotia's College of Engineering and Technology, Uttar Pradesh, India
[3]Department of Electronic Engineering, Indian School of Mines, Dhanbad, Ranchi, India
er.deepakgangwar@gmail.com

Abstract: *In this review paper, antenna miniaturization and bandwidth enhancement are discussed. We presented a detailed survey upon the most recent research efforts associated with those metamaterial based antennas. It is found that RIS (reactive impedance surface) substrate can be used for both the antenna miniaturization as well as band width enhancement; however periodic magneto- dielectric is basically to maximize the bandwidth of the miniaturized antenna. In this review we have focused on the results found in the literatures on practically realizable artificial magnetic media operating in microwave regime only.*

Keywords: *Patch antenna, metamaterials, split ring resonators and magneto dielectric substrate*

1. INTRODUCTION

Microstrip patch antennas have found extensive application in wireless communication and military systems owing to their advantages such as low-profile, conformability, low- cost fabrication and ease of integration with feed networks. However, the microstrip antennas inherently have a narrow bandwidth and low gain. With the ever-increasing need for mobile communication it is a major challenge to design miniaturized/compact broadband antennas because they hav% mutually conflicting propertie3 and improvement of one of the characteristics normally results in degradation of the other. In order to design a miniaturized patch antenna, high permittivity substrate can be preferred, but the excitation of surface waves lead to pattern degradation causing poor radiation efficiency as well as narrow impedance bandwidth. To overcome the inherent limitation of narrow impedance bandwidth and to increase the radiation efficiency of patch antennas, the coupled patch antennas have been suggested [1-3].

The coupled patch antennas can be made of using two or multiple patch antennas. Gain of coupled patch antennas will be slightly larger than that of a single-layered patch, due to its increased height above the ground plane. The larger the height of the stacked configuration, the higher is the gain. This is an additional benefit of stacking of the patch antennas apart from its broadband impedance bandwidth. However multiple coupled patch antennas can increase both the input impedance bandwidth and the gain significantly [2-6]. Recently, the interest has been growing in the theoretical and experimental study of metamaterials. Metamaterials are artificial materials synthesized by embedding specific inclusions like periodic structures in the host media. Some of these materials exhibit either negative permittivity or negative permeability. If both permittivity and permeability of such materials are negative at the same frequency, then the composite possesses an effective negative index of refraction for isotropic medium. It is referred as a left handed metamaterial [7-10]. This is because the electric field, the magnetic field and the wave vector together form a left-handed system. Due to this extraordinary behavior of metamaterials, they are called as double negative (DNG) or single negative (SNG) materials[11-14]. Metamaterials are sometimes significantly referred as mu negative (MNG) or epsilon negative (ENG)[15-17]. These metamaterials are typically realized artificially as composite structures that are composed of periodic metallic patterns printed on dielectric substrates. The novel characteristics of metamaterials lead to design new devices like planar antennas, frequency selective surfaces, filters and resonators[18-22].

2. METAMATERIAL ANTENNAS

The performance of metamaterial antennas is admired by the antenna and microwave researchers due to their astonishing and extraordinary electromagnetic properties. The applications of metamaterial have improved the performance and novel functionalities of the conventional microwave devices. Antenna has become one of the most exciting applications of metamaterials due to the possibility of significant improvement in their performance. The emergence of new artificial materials such as high impedance surfaces (HIS), reactive impedance surfaces (RIS), magneto-dielectrics and metamaterials provide new ways to achieve higher levels of miniaturization than more conventional techniques. Major advantages of metamaterial antennas are miniaturization, high gain, high directivity and highly efficient [23-27].

In 1990, Pendry reported that an array of split ring resonator caters negative effective magnetic permeability over its resonant frequency range [28]. Further in 2000, Smith et al. performed the experimentation on metamaterials by periodically arranging thin conducting wires and split ring resonator (SRRs) [29]. R.W. Ziolkowski et al. reported that the radiation power of small antennas increase due to metamaterial characteristics [30].

3. REACTIVE IMPEDANCE SURFACE (RIS)

The concept of a novel reactive impedance surface (RIS) as a substrate for planar antennas is proposed by Hossein Mosallaei is shown in fig 1. This can miniaturize the size and significantly enhance the bandwidth along with the radiation characteristics of an antenna. Pure reactive impedance plane with a specific surface reactance can minimize the int%raction between the elementar9 source and its image in the RIS substrate. An RIS can be tuned anywhere between perfectly electric (PEC) and magnetic conductor (PMC) surfaces offering a property to achieve the optimal bandwidth and miniaturization factor. It is demonstrated that RIS can provide performance superior to PMC when used as substrate for antennas [31].

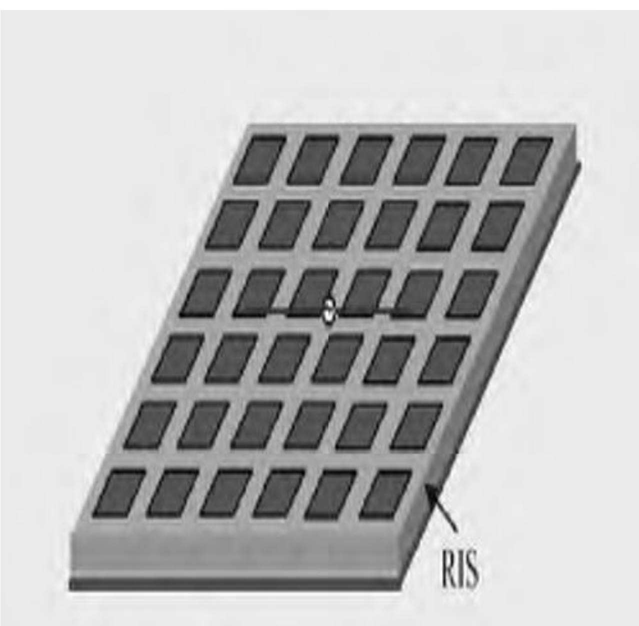

Fig. 1: RIS is a 6X6 finite array of square patches printed on the PEC-backed dielectric material [31]

An approximate circuit model and a full-wave FDTD numerical technique are developed for designing and characterizing reactive impedance surfaces. A miniaturized patch antenna over an RIS substrate was fabricated and tested. It was shown that the antenna over RIS exhibits superior characteristics compared to the conventional patch antenna. The measured relative bandwidth, antenna gain, and radiation efficiency of the RIS patch antenna are respectively BW = 6.7%, G = 4.5dBi and er = 90%. This constitutes the highest bandwidth, gain and efficiency reported for such a small size thin planar antenna [31]

.4.MAGNETO-DIELECTRICMETAMATERIAL

The applications of magneto-dielectric metamaterials are for improving the performance and miniaturization of antenna. The magneto-dielectrics have the dual benefit of improving band-gap rejection levels along with size reduction. This was demonstrated using a magneto- dielectric woodpile structure and its performance was compared with a dielectric woodpile. The magneto- dielectric meta-substrates are also shown to provide a great advantage in the design of miniaturized planar antennas with superior radiation and bandwidth characteristics. Both the dielectric and magnetic materials allow simultaneous ease of antenna impedance matching and miniaturization. A periodic arrangement of dielectric and magneto- dielectric materials is effectively obtained as an engineered substrate. This substrate is utilised for designing a miniaturized patch antenna, which demonstrates a relatively high bandwidth and efficiency [32-33].

The effect of artificial magneto dielectric substrates is systematically studied on the impedance bandwidth properties of microstrip antennas. It has been shown that with artificial magneto dielectric substrates obeying the modified Lorentzian type dispersion for μeff, frequency dispersion cannot be neglected in the analysis. A relation has been derived for the ratio between radiation quality factors of ideally shaped antennas loaded with dispersive magneto dielectrics and dispersion-free reference dielectrics. The result shows that artificial magneto dielectric substrates lead always to larger radiation quality factor if static Re{μeff} = 1. The effect of frequency dispersion has a very fundamental nature, yet this effect is often neglected when studying the impedance bandwidth properties. A common belief is that by selecting the operational frequency of the antenna closer to the substrate resonance, the bandwidth is more effectively retained since Re{μeff} is larger. However, the closer one lies to the substrate resonance, the steeper is the gradient of the dispersion curve, and the stronger is the effect of frequency dispersion to the stored energy. To explain the effect of static permeability and frequency dispersion, it is assume that the antenna is filled with a magneto dielectric material obeying the modified Lorentzian (low-frequency approximation for the Lorentzian model) type dispersion in

$$\mu = \mu' - \mu'' = \mu'(1 - \tan\delta_\mu)$$

$$\mu = \mu(\omega) = \mu_s + \frac{\Lambda\omega^2}{\omega_0^2 - \omega^2 + j\omega\Gamma}$$

Where μ_s is the static permeability, O is the amplitude factor ω_o is the undamped angular frequency of the zeroth pole pair (the resonant frequency of the medium), and 1 is the loss factor [34-36].

An artificial magneto-dielectric material composed of stacks of split ring resonator under the patch has been studied by pekka ikonen. In this work, the effect of size, shape, orientation and the packing density of the rings on the S_{11} characteristics were examined [37].

The novel printed resonator antenna is mainly composed of three parts: 1) the two radiation patches on the top of substrate, 2) the metal vias integrated in the midlayer of the substrate as the metal walls and 3) CPW feed line in the ground plane. The configuration of the SRR-based printed antenna is given in Fig. 2.

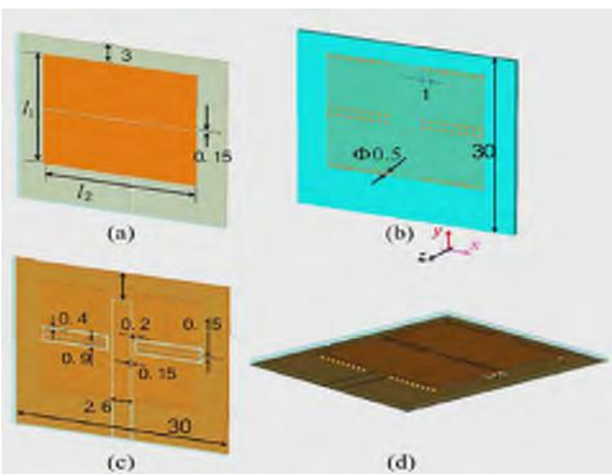

Fig. 2: Geometry of the SRR-based antenna. (a) Top surface. (b) Midlayer. (c) Bottom surface. (d) The overall topology of the antenna (unit: mm) [38]

The SRR-based antenna structures can be considered as a magnetic dipole at the resonance according to the loop- current distributions. The simulated and measured parameters of the SRR-based antenna are shown in Fig. 3. The SRR-based antenna has a reduced electrical size due to the increased capacitance caused by the additional metal vias along the gap. This improvement is similar to increasing the arm length of the conventional SRR so as to reduce the resonant frequency [38].

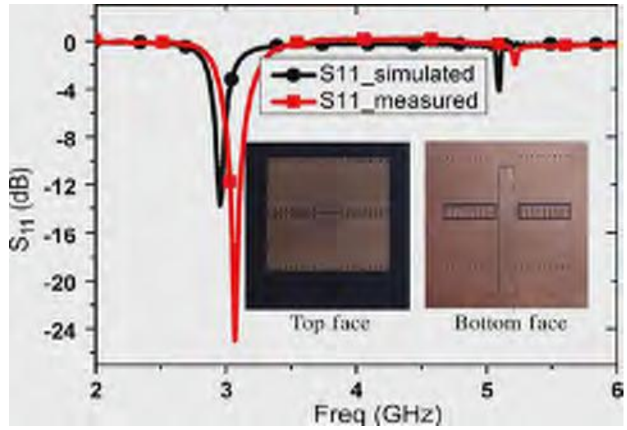

Fig. 3: Simulated and measured S11 parameters of the improved SRR-based Antenna structure [38].

The current distribution in one unit cell is inhomogeneous as shown in Fig. 4. For each unit cell, the electric and magnetic dipoles are simultaneously excited. However, the magnetic dipoles are more effective than the electric ones. At first, magnetic dipole fields do not cancel in the far field because of in plane electrical coupling among the cells on the front and back side as in the case of same direction imaging of the horizontal magnetic dipole on perfect electric plane [39].

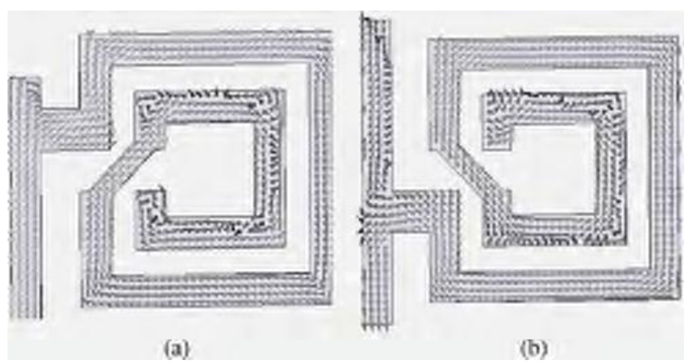

Fig. 4: Surface Eigen current distribution on the (a) front and (b) back side of One unit cell [39].

The antenna is composed of six unit cells of left-handed metamaterial (LHM) and a dipole element. The dipole is directly connected to three of six LHM unit cells, which are arranged in a 2 2 3 antenna array forms as in fig. 5. In this aspect, the proposed antenna is regarded as LHM loaded dipole antenna. The antenna is matched with a stepped impedance transformer and rectangular slot in the truncated ground plane. The coupled LH resonances and simultaneous excitation of different sections of unit cells and dipole result into broad bandwidth [39].

Volume. No. 1, Issue No. 2, Mar – Jun 2013, ISSN: 2320 - 8996

5. MNG METAMATERIAL

The radiation properties of electrically small elliptical patch antennas loaded by MNG metamaterials, have reported some fascinate designs. These designs may enhance the bandwidth of operation and tailor their radiation and polarization properties by combining the two orthogonal sub wavelength modes, contemporarily supported by this geometry despite of its small size. Fig. 6 illustrates the geometry of the elliptical patch antenna under consideration, where the orthogonal elliptical coordinates and the coaxial feed location are defined. The antenna consists of a metallic patch loaded by a grounded inhomogeneous substrate with thickness, consisting of a regular DPS dielectric shell with permittivity and permeability and a magnetic metamaterial core with permittivity and permeability, varying with frequency. The semi major and semi minor axes are denoted by and for the MNG material core, and by and for the surrounding DPS dielectric layer. It follows that the eccentricity of the metallic patch. The filling ratio is defined as the volume of the metamaterial core divided by the total volume underneath the patch [40-42].

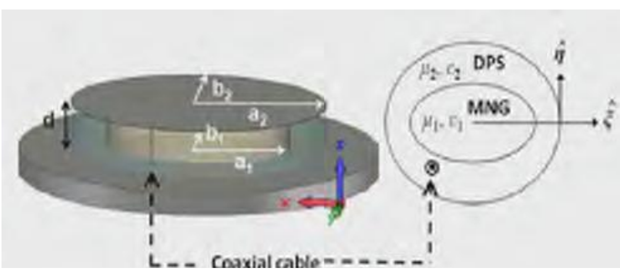

Fig. 5: A broadband planar antenna is proposed by loading a narrowband dipole antenna with six LHM unit cells [39].

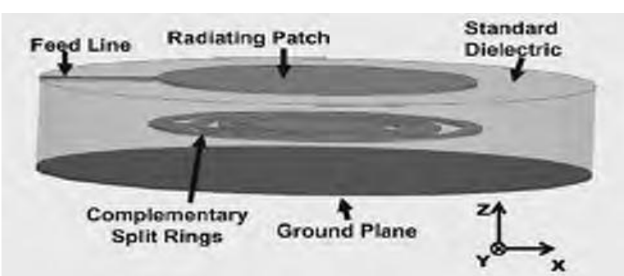

Fig. 6: Geometry of an elliptical patch antenna partially loaded with an MNG metamaterial in the elliptical coordinate reference system. [41]

A novel compact single-fed patch antenna loaded with the RIS and the mushroom-like CRLH resonators has been studied and presented for the CP radiation. It is realized by exciting two orthogonal modes with a 90o phase difference. Based on the similar principle and structure, a dual-band microstrip antenna with different polarizations has also been designed. It is shown that a good CP radiation can be obtained by changing the patch size, the configuration and the position of the embedded mushroom structures [43].

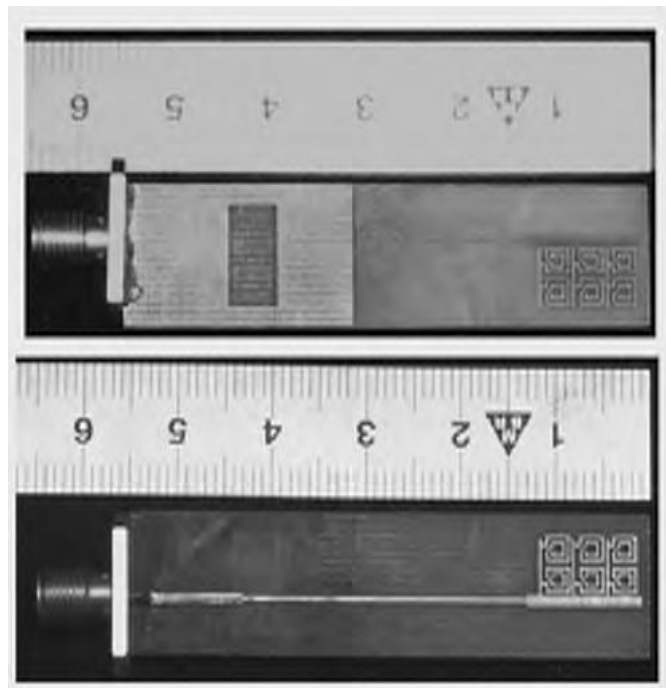

Fig. 7: Configurations of the proposed CP patch antenna loaded with the mushroom- like structure and the RIS. [43]

A magneto-dielectric substrate that can be embedded in the host dielectric substrate is realized. The structure can influence the constitutive parameters of the host dielectric substrate. In this way, the magnetic permeability can be increased to compensate for bandwidth reduction while miniaturizing the antenna. Furthermore, the proposed substrate structure is compatible with planar circuitry. Using the magneto-dielectric substrate, a miniaturized microstrip rectangular patch antenna is realized. The size of the miniaturized antenna is reduced up to about 65% compared to a conventional microstrip antenna. The microstrip antenna is then fabricated, tested, and measured. The measurement results agree well with those obtained from simulations [44].

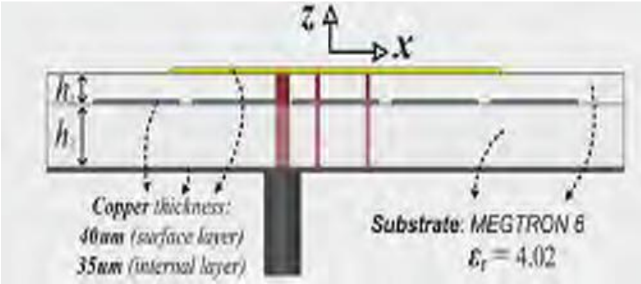

Fig. 8: Geometry of the miniaturized patch antenna [45].

A new design methodology is introduced to produce highly miniaturized patch antennas that are thin, low cost, and easy to fabricate. Importantly, miniaturization is accompanied by a very good impedance match, with a return loss of more than 20 dB in all cases, and without significantly compromising the radiation pattern. At least a 4.5 dB front-to-back ratio is maintained for a 75% size reduction, with excellent isolation between the co- and cross-polarized fields in both the E- and H-planes. There is a tradeoff, however, since increased levels of miniaturization result in a reduction of the bandwidth and radiation efficiency of the antenna. But even with a miniaturization to 1/16 the area of a traditional patch, the reductions in bandwidth and radiation efficiency remain acceptable. Miniaturization is achieved by loading the patch cavity using complementary SRRs (CSRR). By duality with SRRs, these are excited by the vertical electric field of the patch cavity mode, and thus may be oriented horizontally between the patch and the ground plane. The geometry of the CSRR is optimized in place to produce appropriate antenna characteristics at frequencies much lower than the resonant frequency of the unloaded patch cavity. Applications of single negative (SNG) and double negative (DNG) metamaterials have been extensively studied in the miniaturization of sub-wavelength cavity and patch antennas [43-46].

6. REFERENCES

[1]. Balanis, “Antenna theory analysis and design,” Wiley Inter science, New York, 3rd Edition, 2005.

[2]. R. Garg, P. Bartia, I. J. Bahl, and A. Ittipiboon, “Microstrip antenna design handbook’’, Artech House Inc. Norwood, MA, 2001.

[3]. J. R. James and P. S. Hall, “Handbook of microstrip antennas (IEE Electromagnetic Waves Series)”, IET 1989.

[4]. Chen, A. Tulintseff and R. Sorbello, “Broadband two-layer microstrip antenna”, Antennas and Propagation Society International Symposium, pages 251-254, Jun,1984.

[5]. J. P. Damiano, J. Bennegueouche and A. Papiernik, “Study of multilayer microstrip antennas with radiating elements of various geometry”, Microwaves, Antennas and Propagation, Vol.137, Issue 3 , pages 163 – 170, 1990

[6]. M. Sanad, “A compact dual broadband microstrip antenna having both stacked and planar parasitic elements”, Antennas and Propagation Society International Symposium, Vol.1, pages 6-9, 1996.

[7]. R. Smith, W. J. Padilla, D. C. Vier, D. C. Nemal- Nasser, and S. Schultz, “Composite medium with simultaneously negative permeability and permittivity,” Phys. Rev. Lett., Vol. 84, No. 18, May 2000.

[8]. J. A. Kong, “Electromagnetic wave interaction with stratified negative isotropic media,” J. Electromagnetic Waves and Applications, Vol. 15, No. 10, 2001.

[9]. R. A., Shelby, D. R. Smith, and S. Schultz, “Experimental verification of a negative index of refraction,” Science, Vol. 292, April 2001

[10]. P. Markos, and C. M. Soukoulis, “Transmission studies of lefthanded materials,” Physical Review B, Vol. 65, December 2001.

[11]. I.V. Lindell, S. A. Tretyakov, K. I. Nikoskinen, and S. Ilvonen, “BW media—Media with negative parameters, capable of supporting backward waves,” Microwave Opt. Technol. Lett., vol. 31, no. 2, pp. 129–133, 2001.

[12]. R. Marques, F. Medina, and R. Rafii-El-Idrissi, “Role of bianisotropy in negative permeability and left- handed metamaterials,” Phys. Rev. B,Condens. Matter, vol. 65, no. 14, 144440, 2002.

[13]. P. M. Valanju, R. M. Walser, and A. P. Valanju, “Wave refraction in negative-index media: Always positive and very inhomogeneous,” Phys. Rev. Lett., vol. 88, no. 18, 012220, 2002.

[14]. N. Engheta, “Is Foster’s reactance theorem satisfied in double-negative and single-negative media?,” Microwave Opt. Technol. Lett., vol. 39, no. 1, pp. 11–14, Oct. 5, 2003.

[15]. A. Alù and N. Engheta, “Pairing an epsilon-negative slab with a mu-negative slab: Resonance, tunneling and transparency,” IEEE Trans. Antennas and Propagation (Special Issue), vol. 51, pp. 2558–2571, Oct 2003.

[16]. M. G. Silveirinha , “Nonlocal homogenizationmodel for a periodic array of epsilon-negative rods”, Phys. Rev. E., 73,046612,2006

[17]. M. G. Silveirinha and P. A. Belov, “Spatial dispersion in lattices of split ring resonatorswith permeability near

zero", Phys. Rev. B(BR), 77, 233104, 2008.

[18]. M. Gil, J. Bonache, J. Garcia-Garcia, J. Martel, and F.Martin, "Composite right/left-handed metamaterial transmission lines based on complementary split-rings resonators and their applications to very wideband and compact filter design," IEEE Trans. Microw. Theory Tech., vol. 55, no. 6, pp. 1296–1304, Jun. 2007.

[19]. C.-J. Lee, K. M. K. H. Leong, and T. Itoh, "Design of resonant small antenna using composite right/left handed transmission line," in Antennas Propag. Soc. Int. Symp., 2005, vol. 2B.

[20]. H. Iizuka and P. S. Hall, "Left-handed dipole antennas and their implementations," IEEE Trans. Antennas Propag., vol. 55, no. 5, pp. 1246–1253, May 2007.

[21]. M. Gil, J. Bonache, J. Garcia-Garcia, J. Martel, and F.Martin, "Composite right/left-handed metamaterial transmission lines based on complementary split-rings resonators and their applications to very wideband and compact filter design," IEEE Trans. Microw. Theory Tech., vol. 55, no. 6, pp. 1296–1304, Jun. 2007.

[22]. H. V. Nguyen and C. Caloz, "Generalized coupled-mode approach of metamaterial coupled line couplers: Coupling theory, Phenomenological explanation and experimental demonstration," IEEE Trans. Microw. Theory Tech., vol. 55, no. 5, pp. 2007

[23]. F. Capolino, "Theory and phenomena of metamaterials", CRC Press, 2009.

[24]. Sievenpiper, L. Zhang, R. Broas, N. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band", IEEE Trans. Microwave Theory Technol., 47, 2059-2074, Nov. 1999.

[25]. R.F.J. Broas, D.F. Sievenpiper, and E. Yablonovitch, "A high-impedance ground plane applied to a cellphone handset geometry", IEEE Trans. Microw.Theory Tech., 49(7), 1262-1265, July 2001.

[26]. I. Gallina, A. DellaVilla, V. Galdi, V. Pierro, F. Capolino, S. Enoch, G. Tayeb, and G. Gerini, "Aperiodictiling- based mushroom-type high impedance surfaces", IEEE Antennas Wireless Propagat. Lett.,7, 54-57,2008.

[27]. J.B. Pendry, A.J. Holden, W.J. Stewart and I. Youngs, "Extremely low frequency plasmons in metallic mesostructures" Physical Review Letters, Vol. 76(25), pages 4773–76, 1996.

[28]. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat- Nasser and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity", Physical Review Letters, Vol. 84, pages 4184-4187, 2000.

[29]. R.W. Ziolkowski and A. Erentok, "Metamaterial-based efficient electrically small antennas", IEEE Transactions on Antennas and Propagation, Vol.54, No.7, pages 2113-2130, July 2006.

[30]. H. Mosallaei and K. Sarabandi, "Antenna miniaturization and bandwidth enhancement using a reactive impedance substrate", IEEE Trans. on Antennas Propagation, Vol. 52, No. 9, pages. 2403–2414, Sep. 2004

[31]. H. Mosallaei and K. Sarabandi, "Magneto dielectric in electromagnetic concept and application ", IEEE Transactions on Antennas and Propagation, Vol. 52, No. 6, pages 1558–1567, Jun 2004

[32]. A. P. Feresidis, G. Goussetis, S. Wang and J. C. Vardaxoglou, "Artificial magnetic conductor surfaces and their application to low-profile high-gain planar antennas", IEEE Transactions on Antennas and Propagation, Vol. 53, No. 1, pages 209–215, Jan.2005.

[33]. P. M. T. Ikonen, S. I. Maslovski, C. R. Simovski and S. A. Tretyakov, "On artificial magnetodielectric loading for improving the impedance bandwidth properties of microstrip antennas", IEEE Transactions on Antennas and Propagation, Vol. 54, No. 6, pages 1654–1662, Jun. 2006.

[34]. X. M. Yang, Q. H. Sun, Y. Jing, Q. Cheng, X. Y. Zhou, H. Kong and T. J. Cui, "Increasing the bandwidth of microstrip patch antenna by loading compact artificial magneto-dielectrics", IEEE Transactions on Antennas and Propagation, Vol. 59, No. 2, pages 373–378, Feb. 2011.

[35]. P. M. T. Ikonen, K. N. Rozanov, A. V. Osipov,P.Alitalo and S. A. Tretyakov, "Magneto-dielectric substrates in antenna miniaturization: Potential and limitations", IEEE Transactions on Antennas and Propagation, Vol. 54, No. 11, pages 3391–3399, Nov.2006.

[36]. P. M. T. Ikonen, K. N. Rozanov, A. V. Osipov, P. Alitalo and S. A. Tretyakov, "Magneto-dielectric substrates in antenna miniaturization: Potential and limitations", IEEE Transactions on Antennas and Propagation, Vol. 54, No. 11, pages 3391–3399, Nov.2006.

[37]. M. Karkkainen and P. Ikonen, "Patch antenna with stacked split-ring resonators as artificial magnetodielectric substrate", Microw. Opt. Technol. Lett., Vol. 46, No. 6, pages 554–556, 2005.

[38]. M. Li, X. Q. Lin, J. Y. Chin, R. Liu, and T. J. Cui, "A novel miniaturized printed planar antenna using split-ring resonator", IEEE Antennas Wireless Propag. Lett., Vol. 7, pages 629–631, 2008.

[39]. M. Palandoken, A. Grede and H. Henke, "Broadband microstrip antenna with left-handed metamaterials", IEEE Transactions on Antennas and Propagation, Vol. 57, pages 331-338, 2009.

Volume. No. 1, Issue No. 2, Mar – Jun 2013, ISSN: 2320 - 8996

[40]. P. Y.Chen and A. Alu, "Dual-mode miniaturized elliptical patch antenna with mu-negative metamaterials", IEEE Antennas and Wireless Propagation Letters, Vol. 9, pages 351-354, 2010.

[41]. S. Jahani, J. R. Mohassel and M. Shahabad, "Miniaturization of circular patch antennas using MNG metamaterials," IEEE Antennas and Wireless Propagation Letters, Vol. 9, pages 1194-1196, 2010.

[42]. Y. Dong, H. Toyao and T. Itoh, "Compact circularly-polarized patch antenna loaded with metamaterial structure", IEEE Transactions on Antennas and Propagation, Vol. 59, pages 4329-4333, 2011.

[43]. Farzami, K. Forooraghi and M. Norooziarab, "Miniaturization of a microstrip antenna using a compact and thin magneto-dielectric substrate" , IEEE Antennas and Wireless Propagation Letters, Vol. 10, pages 1540-1542, 2011

[44]. R. O. Ouegraogo, E. J. Rothwell, A. R. Diaz, K. Fuchi and A. Temme, "Miniaturization of patch antennas using a metamaterial-inspired technique", IEEE Transactions on Antennas and Propagation, Vol.99,page. 1–1, March 2012.

[45]. Y. Dong and T. Itoh, "Metamaterial based antenna" Proceedings of IEEE, Vol.99, pages 01–15, March 2012.

[46].