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A Survey of Antenna Miniaturization Techniques Using Metamaterials

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Abstract: **- The steadfast growth in wireless technology compels antennas to continue to be electrically small but having appreciable performance in terms of bandwidth and efficiency. Designing of such antennas is a challenge. Metamaterials have encouraged many new designs of electrically small antennas. Metamaterials are engineered materials, made of periodic insertions of conventional materials with manageable electromagnetic properties. This paper discusses the elementary concepts and updated analysis of the diverse methodologies used for small antennas designs using metamaterials.**

***Index Terms*— Composite right/left-handed (CRLH) antenna, metamaterial-inspired antenna, resonant cavity antennas, High impedance surfaces.**

I. INTRODUCTION

Decreasing the size of antennas, without major performance degradation, has been a field of research for decades. Wireless devices are shrinking in size and their design technology has also improved significantly. MIMO (Multi-Input Multi-Output) systems, WiMAX (Worldwide Interoperability for Microwave Access), and other wireless broadband systems, necessitate antennas which reside in small areas. Here the antenna largely governs the performance of the whole system as a shoddily designed antenna leads to a reduced range and lowered efficiency. Established methods for designing electrically small antennas, like folding, slot loading, meandering, and dielectric loading come across difficulties like limited bandwidth and low radiation efficiency. Metamaterials, have opened the way to new heights in antenna size reduction. Metamaterials are characteristically constructed from periodic arrangements of existing material whose electromagnetic properties can be regulated, by suitably designing these artificial materials. Metamaterials have material characteristics with negative permittivity and/or negative permeability. The notion of these type of materials was originally put forward by V. G. Veselago in 1967 [1]. John Pendry demonstrated that a collection of three dimensional inductive wires could accomplish negative permittivity and the use of split-ring resonators creates negative permeability [2]. Experimental confirmation of LHM behavior was done only later by Shelby [3]. Metamaterial technology has significantly assisted in design of miniature antennas. They have helped in enhancing the efficiency and bandwidth of these antennas and also create multiband antennas. The focus of this paper is to provide a summary of some of the noteworthy progresses in antenna miniaturization using metamaterials. The different metamaterial based research methods are presented and discussed in Sections II–IV. Section V, focusses on the future challenges and limitations of metamaterial based small antennas. The focus of this paper is to provide a summary of some of the noteworthy progresses in antenna miniaturization using metamaterials. The different metamaterial based research methods are presented and discussed in Sections II–IV. Section V, focusses on the future challenges and limitations of metamaterial based small antennas.

II HIGH IMPEDANCE SURFACES

Electromagnetic Band Gap (EBG) structures are designed periodic arrangements that demonstrate a band gap characteristics which inhibits the transmission of surface waves in a designated range of frequency [4]. High impedance surfaces (HIS) is a similar kind of structure, which is utilized in wire antennas to reduce the antenna height. In wire antennas, the antennas needs to be placed at a distance h, which is approximately quarter wavelength from the PEC ground plane. If the antenna is placed closer, then the opposite image current hinders the signal from the original antenna, and consequently degrades the radiation efficiency. HIS is a designed metasurface, which can be formed by etching out an array of small ($<< \lambda$) metal areas periodically, in a two dimensional lattice. In a standard mushroom type HIS, as shown in Fig. 1(a), the metallic layer on the top is etched out to form areas that are linked to the ground plane by means of vias. A detailed analysis of these structures can be found in [5]. A practical implementation of the concept described, was first introduced by Sievenpiper [6] and its design methodology is presented in [7]. Here, the capacitance C is due to the space between the neighboring metallic areas and the inductance L due to the vias and ground plane as

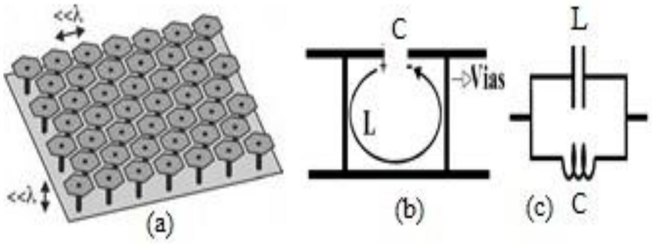

Fig. 1. (a) A mushroom type high-impedance surfaces (b) A cross section of one segment (c) Equivalent circuit [4].

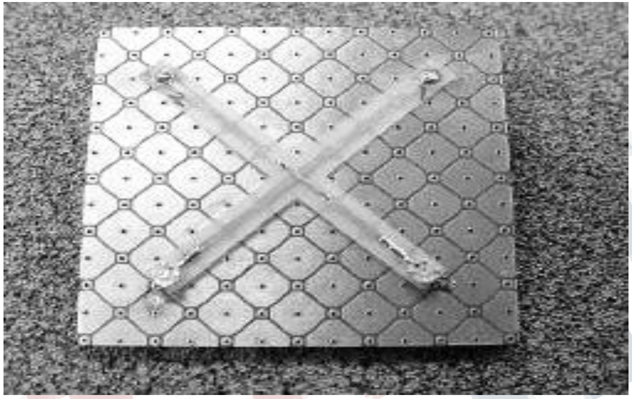

Fig. 2. Top view of orthogonal monopoles antenna with HIS [8].

demonstrated in Fig. 1(b). This arrangement can be described by the model presented in. Fig. 1(c), from which the surface impedance Z_s of HIS can be calculated as

$$Z_s = \frac{j\omega l}{1-\omega^2 LC} \qquad (1)$$

At resonance, ω = $1/\sqrt{LC}$, and the Zs becomes infinite and therefore deters the propagation of surface waves. The structure now behaves like artificial magnetic conductor (AMC). There are abundant employments of metasurfaces like HIS, AMC, used as for constructing low profile antennas [8-18]. In [8], two perpendicular bent wire monopoles, resonating at 1.9 GHz, are placed adjacent to a HIS layer consisting of square metallic patches as shown in Fig. 2. The antenna has a bandwidth of 3.17 % and gain of 3 dBi. The radiation efficiency is about 60 % and a front-to-back ratio of 7 dB is observed. The size of the antenna is λ0/3.2 x λ0/3.2, where λ0 is the operating wavelength. The total height of antenna is diminished from λ0/4 to λ0/50. An AMC ground plane with partially reflective surface (PRS), excited by a patch antenna which resonates at 14.2 GHz as proposed in [11]. The AMC ground surface is made up of square patches and an array of square metal patches forms the PRS superstrate as depicted in Fig. 3 (a) and (b). The profile of these high gain antennas is reduced due to the use of metasurfaces as ground planes. The ground plane is of size 7.1 λ0 x 7.1 λ0. The space between the partially reflective surface and the AMC, is diminished to about half. A representation of this type of antenna is shown in Fig. 3(c). Antennas of λ0/30 to λ0/60 heights have also been implemented in [13]. The profile of the metamaterial based resonant cavity antenna has been reduced to λ0/125 at 12GHz in [16]. Diminishing the profile of resonant cavity has restrictions, because it increases the quality factor of the antennas, resulting in decrease of impedance bandwidth.

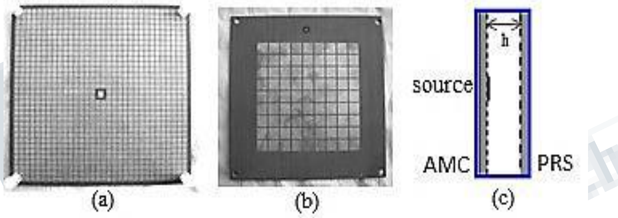

Fig. 3. (a) Patch antenna with AMC ground plane (b) PRS superstrate (c) Model of resonant cavity [11].

III. COMPOSITE RIGHT LEFT HAND TRANSMISSION LINE ANTENNAS.

A fusion of the standard right-handed transmission line (TL) with series inductances and shunt capacitances and engineered left-handed TL with series capacitors and shunt inductors, represents a composite right left hand transmission line (CRLH TL) [19]. The equivalent circuit of this line can be described as shown in Fig. 4 as T and Π model [20]. The dispersion relation of a homogenous CRLH TL is given as

$$\beta = s(\omega)\sqrt{\omega^2 L_{RT}C_{RT} + \frac{1}{\omega^2 L_{LT}C_{LT}} - \left(\frac{L_{RT}}{C_{LT}} + \frac{C_{RT}}{C_{LT}}\right)} \qquad (2)$$

$$s(\omega) = \begin{cases} -1 \; if \;\; \omega < \min\left(\frac{1}{\sqrt{L_{RT}C_{LT}}}, \frac{1}{\sqrt{L_{LT}C_{RT}}}\right) \\ 1 \;\; if \;\; \omega > max\left(\frac{1}{\sqrt{L_{RT}C_{LT}}}, \frac{1}{\sqrt{L_{LT}C_{RT}}}\right) \end{cases} \qquad (3)$$

A CRLH TL of length l, consists of N unit cells of length m. Multiple resonance modes appears, when length l is a multiple of half the guided wavelength λ_g. The CRLH structure assists negative (n < 0), positive (n > 0), and zeroth order resonances (n = 0). A discontinuity or bandgap occurs between the left and the right hand

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ranges because the series resonance ω_{ser} = 1/ LRTCLT and shunt resonance ωshr = 1/CRTLLT are dissimilar as indicated in the dispersion diagram in Fig. 5. However, this gap vanishes when the resonances are made equal and infinite-wavelength propagation is attained at this frequency [19]. The zeroth order resonant mode is obtained when $\beta = 0$ and λ_g becomes ∞ ($\lambda_g = 2\pi/\beta$). The antenna size becomes apparently detached of the working frequency, but in fact, it depends on the extent of space needed by the line. The resonant length of the antenna need not be of the order of $\lambda/2$ as required. The chief benefit of CRLH lines is that the phase constant and impedance can be regulated by using appropriate values of inductance and capacitance. The phase constant β can be controlled to decreasing the resonant frequency. A variety of CRLH resonant antennas have been cited in the literature [21-31], designed for dual band and multiband operation.

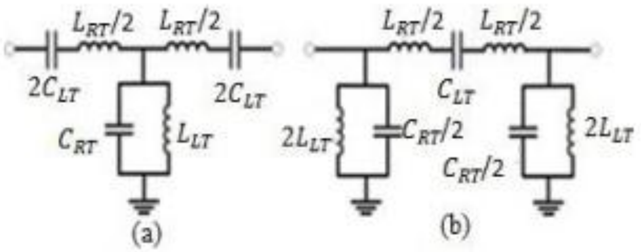

Fig. 4. Equivalent circuits for the symmetrical CRLH unit cells. (a) T type (b) Π -type model [20].

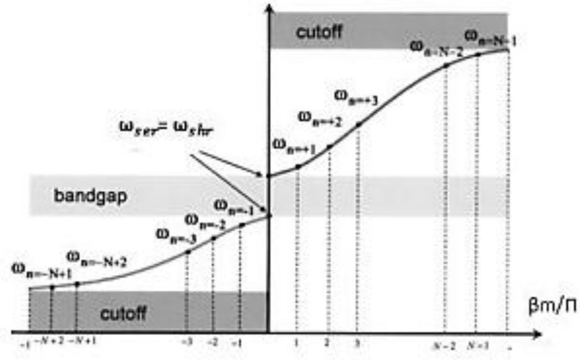

Fig. 5. The dispersion diagram of an N-unit-cell CRLH transmission line.

A CRLH based antenna using the zeroth-order resonance antenna is stated in [21] with a design frequency 4.88 GHz. The antenna consists of four unit cells and each involves an interdigitated capacitor and a parallel meandered inductor. It is attached with a patch as shown in in Fig. 6. There is a 75% reduction in size. The measured reflection coefficient is -11 dB. In [25], unit-cells are constructed on a modified mushroom structure. A CRLH and inductor-loaded transmission line having infinite wavelength is presented in Fig. 7. The inductor loaded TL is formed by sealing the capacitive gap between the cells. The 3.38 GHz antenna are fabricated on Rogers RT/Duroid 5880 of 0.16 λ0 x 0.16 λ0 x 0.018 λ0 dimensions.

IV. METAMATERIAL-INSPIRED ANTENNAS

A metamaterial shell having either negative permittivity or negative permeability when enclosing a dipole antenna can reduce its electrical size, while preserving a high radiation efficiency. This was first investigated by Ziolkwoski et al in [32-33]. A small dipole antenna is confined within an epsilon negative shell, and the whole arrangement behaves like a RLC resonator because the dipole behaves like a capacitor accumulating electrical energy in its near field and the ENG shell behaves inductive in nature because it is packed with a negative permittivity material. By altering the electrical parameters of the shell, resonance can be accomplished, without the need of any external matching circuit. A practical complication with the realization of such a concept is the need of materials having high efficiency. Based on the above concept, are the “metamaterial-inspired antennas”. In these antennas, instead of accomplishing impedance matching by using a employed. When placed near the antenna, resonance occurs in these structures at a lower frequency. Most metamaterial inspired antennas are executed with resonant particles like split ring resonators (SRR) and its dual structure, the complementary split ring resonators (CSRR). The SRR provides negative

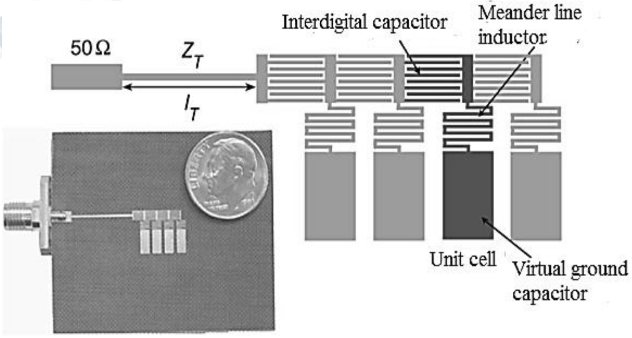

Fig. 6. Zeroth-order CRLH resonator antenna [21].

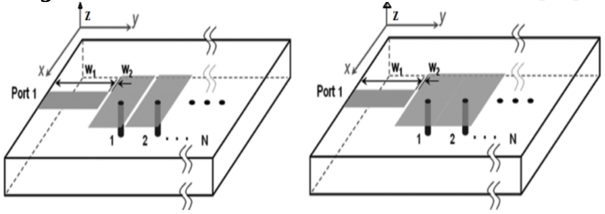

Fig. 7. (a) Mushroom ZOR antenna with CRLHTL unit cell and (b) Inductor loaded TL unit cell implementation [25].

permeability and is driven by a magnetic field [34]. The CSSR, in contrast, exhibits negative permittivity. It was introduced by Falcone et al. in 2004 [35]. CSRRs and SRRs have been applied extensively to dipoles and patch antennas for reducing their sizes [36] – [43]. In [37], a dual band rectangular patch is proposed, by inserting a single CSRR on it, as shown in Fig. 8. The resonant frequencies produced by the CSRR particle and patch are 4.19 GHz and 4.8 GHz respectively. At the first resonance of 4.19 GHz, the gain is -0.1 dB and efficiency is 17.92%. The bandwidth obtained is 0.72%. At the second resonance of 4.8 GHz, the gain is 5.85 dBi, efficiency is 64.83% and -10 dB bandwidth is 0.78%. The decline in the efficiency at the first resonance is accompanied with miniaturization. Multiband behavior and reduction in size can also be obtained by inserting CSRRs in the ground plane as presented in [41]. Dual frequency bands are created by inserting two CSRRs. The two resonances produced are, one due to the patch, at 5.5 GHz and the other due to CSRR at 3.87 GHz. The presence of CSRRs does not change the patch resonant frequency. The maximum gain is 4.7 dBi at lower frequency and 6.2 dBi at higher resonant frequency, thus giving good gains at both operating frequencies. The -10db fractional bandwidth at 3.87 GHz is 0.92%, as compared to the bandwidth of 2.72% at 5.5 GHz. Here the antenna bandwidth has been compromised. In [36], Lee et al, showed that the size reduction of antenna as well as dual band behavior can be achieved by incorporating in the ground plane an 3x5 arrangement of circular complimentary split ring resonators as shown in Fig. 9. The patch was initially designed to resonate at 4.3 GHz, placing the metaresonator structures makes it resonate at 2.96 GHz. At 4.3 GHz, the bandwidth and gain of the patch is 2% and 6.05 dBi respectively. At 2.96 Mhz, the bandwidth and gain is 3.3 % and 2 dBi respectively. Thus bandwidth has enhanced but with a reduction in gain. Resonant particles can also be embedded in the dielectric as described in [43], where the circular CSRR is neither on the patch nor the ground plane, but in the dielectric substrate as shown in Fig. 10. There is a 1/16 reduction in patch size. The radiation efficiency is lowered from 94% to 28.1%. Also the bandwidth is decreased from 1.3% to 0.5%. Here the trade-off is in terms of efficiency and bandwidth

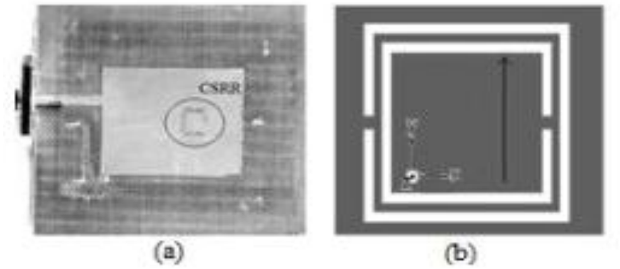

Fig. 8. (a) Photograph of the dual band patch antenna with single CSRR etched in the patch (b) Geometry of CSRR [37].

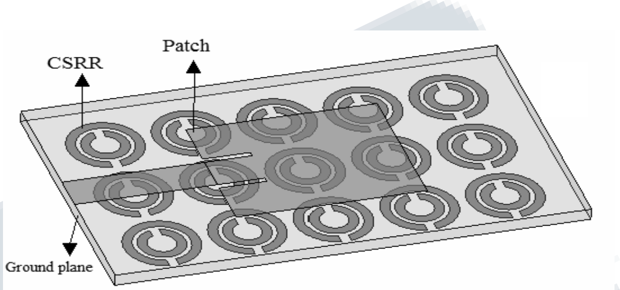

Fig. 9. Configuration of the CSRR loaded microstrip patch antenna [36].

V. CONCLUSION

Metamaterials suggest a methodology to overcome the limitations of conventional small antennas designs due to their readily adapted responses and material properties which can be modified effortlessly. In this paper, numerous procedures for miniaturizing antennas using metamaterials have been examined. It is observed that each design technique is always accompanied with some degradation in the antenna performance, given the fact that for a small antenna, the antenna bandwidth and antenna size are directly related to each other, and also that, as bandwidth increases, the antenna efficiency is lowered. Transmission line metamaterials have a broader bandwidth, as the cut-off frequency of these antennas can be planned by using appropriate LC values by dispersion engineering. Although a decent progress has been made in this field, specific issues facing metamaterial antennas are accomplishing wide operating bandwidth and enhancing their efficiency. Using artificial magneto-dielectric materials, tunable and reconfigurable materials, and employment of low loss materials, are a few remedies to alleviate these problems. Since the use of these antennas for practical applications is still not progressed much, the research solutions need to be converted into realistic antenna engineering designs and also to improve existing small antennas.

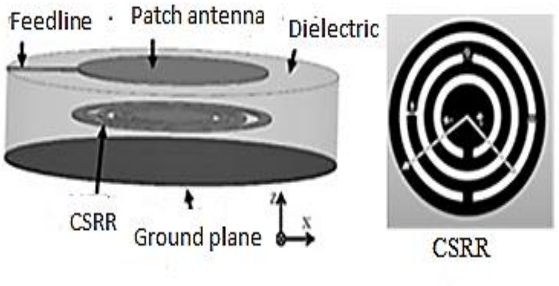

Fig. 10. (a) Miniaturized patch antenna with CSRR in patch cavity. (b) CSRR geometry [43].

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