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Metamaterial Based High Performance Antenna: An Overview

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Abstract— **The low gain and narrow bandwidth are the two major drawbacks of the microstrip patch antenna (MPA) to be employed in wireless communication systems. Even though conventional broadbanding techniques are used to enhance the bandwidth of antenna, lead to the degradation of other antenna radiation characteristics such as gain, efficiency, etc. Recently, metamaterial is found to be better candidate to enhance the bandwidth of MPA without compromising on its gain and efficiency. In view of this, a brief review of the broadband high gain metamaterial based microstrip patch antenna is presented in this paper. This includes the design methodologies for achieving broadband high gain characteristics, methods for the analysis, and fabrication techniques for the metamaterial based microstrip patch antennas. The issues involved in the conventional broadbanding techniques of MPA are also outlined.**

Keywords**—Microstrip antenna, LHM antenna, metamaterial, broadbanding techniques.**

I. INTRODUCTION

The world of communication is mainly dependent on wireless technologies. Various advanced technologies are emerging for improvising the wireless communications, which require antennas with higher gain and wider bandwidth to cater to the requirements of efficient transmission of both voice and data information over scarcely available bandwidth to improve its *quality of service* (QOS). For efficient usage of the channel, the broadband antennas are required. Transceiver section of wireless communication system widely uses the *microstrip patch antenna* (MPA) due to its popular characteristics such as low profile, low cost, low weight, ease of manufacturing, ease of integration with other electronic devices on the same substrate, and its conformability. In spite of these advantages, MPA suffers from serious drawbacks such as narrow bandwidth and low gain. Some techniques that have been implemented to enhance the bandwidth as well as gain are reviewed in this paper.

Several drawbacks of MPA that emerged during the broadbanding of conventional MPA can now be overcome by the use of metamaterial inspired MPA. These metamaterials are not readily available in the nature but they can be realized by introducing structural modifications such as periodic structures, holes, slots etc. The metamaterials were theoretically [1], experimentally [2], structurally [3], and numerically [4] explored to establish that these materials possess peculiar characteristics as opposed to the ordinary material, i.e. *right-handed material* (RHM). It has the Poynting vector and wave vector of electromagnetic wave lie antiparallel thus forming a *left-handed material* (LHM). It was also demonstrated that the adaptation of the ‘split ring structure’ and ‘wire’ together behaves as the small resonant particles invoking the artificial *negative magnetic permeability media* (NMPM). Furthermore, Smith *et al.* [3] demonstrated the use of composite medium and non-magnetic elements to design a left-handed material with negative permeability and permittivity. These LHM could be used in the MPA. Metamaterial inspired microstrip patch antenna can be used to generate the broadband radiation characteristics without compromising on its gain [5]-[7].

The techniques used to imbibe the metamaterial properties to obtain a broadband characteristic have been reviewed in this report. Further it is required to ensure that the metamaterial structure used for microstrip antenna application should show metamaterial properties at resonance, which can be investigated by analytical techniques. The overview of various techniques such as method of moment, transmission line transfer matrix method, cavity model method, and equivalent circuit method employed for the analysis of metamaterial based MPA, are also discussed. The details of the work have been discussed in the following sections.

II. CONVENTIONAL BROADBANDING TECHNIQUES

A microstrip patch antenna is basically consist of two thin sheets of metal forming the patch and the ground separated by a dielectric material (Fig. 1). In spite of several advantages, there are some serious drawbacks such as low gain with a very narrow frequency band that the MPA possess, draws serious attentions to the researchers. In order to improve the gain and bandwidth of MPA, the various techniques have been reported in the open literature as listed below,

- Increasing the substrate thickness
- Reactive loading
- Gap-coupled coplanar parasitic patches
- Stacked or electromagnetically coupled
- Impedance matching techniques
- Genetic algorithm

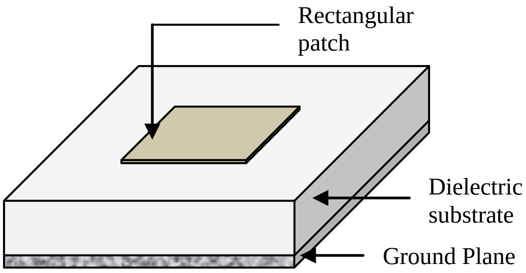


Fig. 1. Schematic of a microstrip patch antenna.

The low gain is mainly due to the lossy dielectric substrate that is being used, which traps the radiating power. The factors that control the bandwidth of a microstrip patch antenna are the reflection loss (input VSWR) and the quality factor (Q-factor) of the cavity beneath the patch. The quality-factor can be reduced by increasing the substrate thickness which increases the effective dielectric constant and hence enhance the bandwidth of the antenna [8]. However, the use of thick substrate introduces other issues such as; (i) surface wave that reduces efficiency of the antenna, and (ii) longer probe feed to excite the antenna introduces additional inductance.

Amongst all the approaches, the coupled resonator approach has been widely adapted for designing the broadband MPA. In this approach, resonators are coupled to the patches by the use of stacked patches or slots, or the combination of slots and patches. Ooi *et al.* [9] demonstrated a stacked E-shaped patch antenna for broadband applications where the use of second patch over the E-shaped patch introduced another resonant point to achieve impedance bandwidth up to 38.41%. The bandwidth as high as 54% was achieved with truncated V-slot [10] and compared to the patch with a U-slot that produced a bandwidth of about 30%. Slots can also be used in combination with other aperture shapes or patches. For instance, stacked U-slots in combination with washer at the probe showed a wide bandwidth of up to 45% [11].

Another technique for enhancing the bandwidth is the introduction of stubs which provides reactive loading to the MPA [12]. The parasitic patches coupled to the radiating edges have also been shown to broaden the bandwidth of patch antenna [13]. Further, Manzini *et al*. [14] demonstrated that the polygonal shaped patch provides multiple resonant points for achieving multiband as compared to the other shaped patches. In order to further enhance the wide bandwidth, Genetic algorithm were widely used to optimize the microstrip patch antenna. For instance, Sun *et al.* [15] employed Genetic algorithm to design the feed line networks of MPA to achieve broader bandwidth.

The predominant issues seen in all these above specified designs for bandwidth widening are achieved at the expense of increased antenna volume. These conventional methods results in low radiation efficiencies, narrow bandwidth, and undesired radiation patterns. Increasing the height of the substrate also increases the complexity (e.g. weight, surface wave, etc.) and suffers from the power loss.

III. DESIGN METHODOLOGIES OF METAMATERIAL BASED HIGH GAIN MICROSTRIP PATCH ANTENNAS

The broadbanding techniques used to improve the broadband capability of conventional MPA as discussed in the previous sections are mainly dependent on increasing the effective dielectric constant of the substrate, trapping large amount of power in the substrate and resulting in reduced gain. Since the requirement is to achieve broadband characteristics without compromising the gain, which can be accomplished by loading the metamaterial to the microstrip patch antenna. The use of metamaterial not only enhances the bandwidth but also improves other antenna properties like reduced return loss, enhanced gain and directivity. In order to achieve such characteristics of printed antenna, the metamaterial can be loaded to the MPA in either of the two ways:

- Inclusions of MTM either in the ground plane/ substrate of antenna or as superstrate
- Loading as transmission line

A. Inclusions of Metamaterial in the Ground Plane or as a Superstrate

Mu negative and epsilon negative properties can be introduced in an ordinary substrate of a MPA by two different methods namely; 2D LHM and 3D LHM structures. In 2D LHM, the rectangular patch is designed on one side of the dielectric material and the metamaterial structure is used as the ground plane with a certain height. Various microstrip patch antennas based on 2D SRR LHM structures have been reported in the open domain [5]-[7]. It is well known that SRR (split ring resonator) behaves as a *LC* resonator circuit with a very high *Q*. These edge coupled SRR resonators are basically concentric rings with gaps located at the opposite sides. The operating frequency can be tuned by changing the split rings dimensions. The cross polarization effect caused by the edge coupled split ring resonator was overcome by the use of broadside coupled SRR [5]. Moreover, SRR can be combined with monopoles to obtain dual-band characteristics. The *complementary split ring resonator* (CSRR), a negative image of SRR, is used in conjunction with the SRR. This complimentary structure provides stop-band effect in the vicinity of the resonance frequency [6], [7]. Further the “interconnected SRR” based MPA was designed at S-band (2-4 GHz) that exhibited a gain and bandwidth (378 MHz) enhancement as compared to the conventional rectangular MPA [16]. Later, Garg *et al.* [17] presented the double E-shaped MPA loaded with *slotted triangular ring resonator* (STRR).

Another classification under LHM is the 3D metamaterial structures, which is basically consisting of unit cell containing the metamaterial structure. These unit cells are arranged in a periodic pattern along three dimensions. These structures form the dielectric substrate over which the microstrip patch is incorporated. Griguer *et al.* [18] demonstrated that the three dimensional metamaterial consisting of symmetrical half ring and a wire as the unit cell structure. This structure formed LHM when arranged in a periodic manner. In another experiment, Ziolkowski [19] used the SRR in combination with *capacitance loaded strip* (CLS) in which strong magnetic field and electric field was produced by the SRR and CLS, respectively. The similar work has also been reported by Li *et al*. [20] and Nordin *et al*. [21]. The combination producing the LHM material was used to improve the gain and the bandwidth of the microstrip patch antenna. Further, the LHM structure was employed as lens in front of the antenna to enhance the gain and the bandwidth of the antenna [22]. Recently, the π-shaped and cross shaped pattern were used at the radiating and ground plane of the MPA, respectively leading to the left handed metamaterial behaviour and achieved ultra-wideband characteristics [23]. Attia *et al*. [24] demonstrated the use of engineered magnetic material as the superstrate on a planar printed antenna to enhance the gain and efficiency.

B. Loading as Transmission Line

A new approach for achieving *negative refractive index* (NRI) at resonance was proposed by Eleftheriades *et al*. [25] by loading a *transmission line* (TL) with capacitor in series and inductor in shunt. The loading of transmission line facilitates the metamaterial cell structure to produce negative effective parameters ensuring a shift towards a high resonant frequency. The parasitic effect found in *Left handed-transmission line* (LH-TL) was overcome by the use of the *composite right-left-handed-transmission line* (CRLH-TL). In view of this, the broadband antenna inspired by transmission line techniques was proposed by Dong and Itoh [26]. The antenna was designed with mushroom structure which is capable of generating three different resonances including the zero, first, and second order resonances, resulting in 36% of bandwidth enhancement.

The broadband characteristics can also be achieved by an antenna resonating at two frequencies closely spaced to each other and merged together to form a single pass-band. This double resonance was realized using two arms of transmission line consisting of spiral inductors which formed the metamaterial loading. With this design, a bandwidth of 100 MHz and an efficiency of 65.8% were obtained at 3.30 GHz [27]. Another TL based metamaterial microstrip antenna was designed with a metamaterial unit cell formed by the combination of interdigital capacitor on the patch and CSRR loaded ground plane [28]. The proposed antenna exhibited high efficiency (96%) and reasonable gain of 3.85 dBi. The bandwidth of the proposed antenna was reported to be three times higher than that of conventional MPA operating at the same frequency band.

IV. METHODS FOR ANALYSIS

Various numerical techniques have been employed in open domain to analyze the metamaterial based microstrip antennas. These techniques have a capability to examine the negative material properties of the structure at resonance and antenna radiation characteristics. Some of these techniques are listed below:

- Equivalent circuit method
- Method of Moment (MoM)
- Transmission line method
- Transfer matrix method
- Cavity model method

The frequency responses of the metamaterial structures are more accurately estimated by using the equivalent circuit model. This approximate equivalent two-port circuit modelling approach is used to evaluate the resonance behaviour of SRR unit cells and SRR arrays. The basic idea behind this technique is to model the individual SRR unit cells by *RLC* circuit and then used to compute the frequency response of the SRR structure. The investigation in this direction suggested that a unit cell can be used to determine the EM characteristics of the structure, which is further extended to an array or multiple cells [19]. The main drawback of equivalent circuit model is that it is unable to predict the frequency responses of the structures accurately at higher frequencies due to Bragg effect [29]. The good approximation of the bandwidth can be achieved by computing the *Q*-factor, which is dependent on the resonance frequency of the individual inclusions. The *quasi-static equivalent circuit models* in terms of *RLC* equivalent circuit was introduced by Bilotti *et al*. [30] that considers the metallic losses as well as the dielectric losses in the analysis. The analysis of various resonators such as multiple split-ring resonator and spiral resonator were carried out. In another study, inter-resonator coupling was modelled in terms of mutual capacitance. It is reported that to accurately describe the complimentary SRR/ microstrip lines gap, it is necessary to consider the electrical parameters of the host line (inductance, *L* and capacitance, *C*) and inter-resonator coupling [29].

Another analytical method is the method of moment (MoM), used for the analysis of metamaterial based MPA where the mixed potential integral equation is converted into matrix. This is a very accurate method to predict the resonant frequency, impedances, etc. [31]. Moreover, this method can be applied to lossy conducting surfaces and dielectrics. In this method, an arbitrarily shaped microstrip patch is modeled as the surface patch dipole modes and Galerkin’s solution is applied for all surfaces of the dipoles except at the edges of the patch to introduce a current basis discontinuity function. The dielectric is modeled as the rectangular volume cells using the volume polarization current theorem [32]. The method of moment can also be used to analyse the conformal shaped MPA [33].

The metamaterial based antenna can also be analysed by *transfer matrix method* (TMM). The original algorithm for the transfer matrix of LHM was developed by Pendry *et al*. [2]. The transfer matrix method enables to find the transmission and reflection matrices of the metamaterial structure which facilitate to estimate the transmission, reflection, and absorption characteristics of the given structure. Due to the periodic structure of the DNM (double- negative material), it is sufficient enough to analyze single unit cell to predict the EM characteristics of entire structure [4]. Further, Fichtner *et al*. [34] used transmission line matrix method along with Genetic algorithm to optimize bandwidth of metamaterial based antenna, where DNM was consisted of an array of thin wire and a periodic arrangement of SRR. Furthermore, TLM were performed as 2D TLM and 3D TLM. The two dimensional

TLM method is used for analyzing the electromagnetic fields associated with TE or TM polarization. In 3D TLM method, the electromagnetic fields are modeled by wave pulses propagating in 3D meshes of lines.

The variations in the fields along the edges of the radiation slot of MPA are ignored by the transmission line model which is a major disadvantage of this approach. This drawback can be overcome by cavity model [35]. The cavity model is an approximate model which in principle leads to reactive input impedance (of zero or infinite value of resonance) and it does not radiate any power. This model is capable of producing normalized electric and magnetic field distributions underneath the patch. The movements of these charges create corresponding current densities from its edges to the top surface of the patch, contributing to the radiation field of the MPA. An analytical model based on cavity model in conjunction with reciprocity theorem was presented by Attia *et al.* [24] to analyze the radiation field of MPA loaded with artificial magnetic superstrate.

Recently, analysis of a microstrip patch antenna loaded with novel metamaterial superstrate was presented using transmission line model and reciprocity theorem [36]. The schematic of proposed antenna is shown in Fig. 2(a), where MTM superstrate consists of cascaded layer of a mu-negative (MNG), a double positive (DPS), and an epsilon negative (ENG).

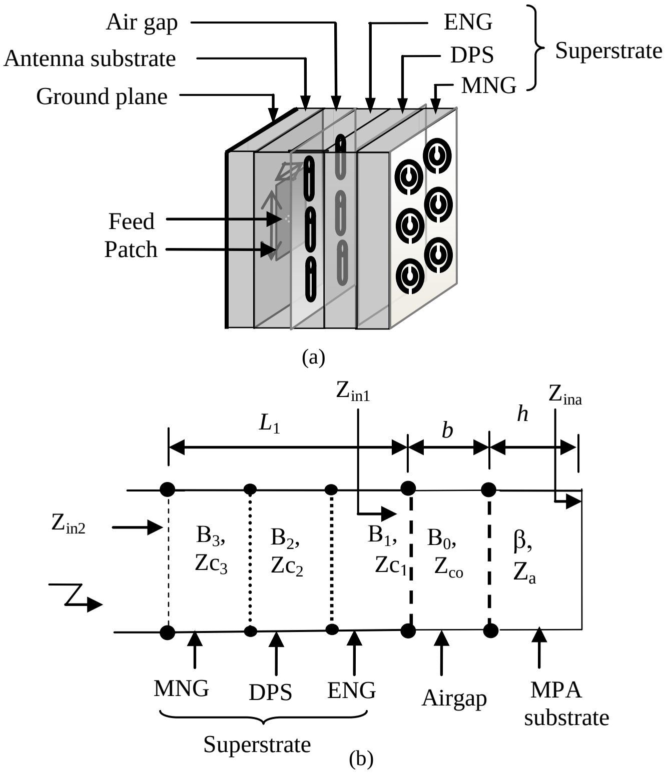
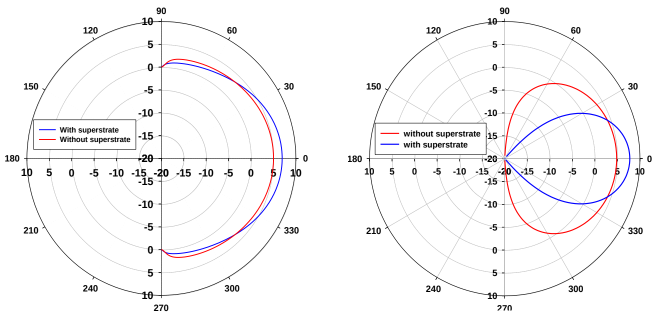


Fig. 2. (a) Schematic of MPA loaded with MTM superstrate, (b) Equivalent transmission line model.



(a) (b)

Fig. 3. Radiation pattern of microstrip patch antenna with and without metamaterial superstrate; (a) E-plane, and (b) H-plane.

The equivalent transmission line model of proposed antenna is shown in Fig. 2 (b), which is basically consist of three sections namely, antenna, superstrate, and airgap between antenna and superstrate. The proposed antenna exhibited a directivity enhancement of 2.5 dB in E-plane as well as in H-plane as compared to conventional MPA by loading the multilayered metamaterial superstrate as shown in Fig. 3.

V. TECHNIQUES FOR THE FABRICATION OF METAMATERIAL BASED MPA

The techniques for fabricating the metamaterial based structures used for different applications are given as follows,

- Hot press technique
- Nano fabrication technique
- EMLC by lithography technique
- Scanning probe nano-lithography

The manufactured metamaterial LHM must possess mechanical stability which is one of the main requirements for the microstrip patch antenna. Hot press techniques is used for manufacturing the *printed circuit boards* (PCB) and also used to fabricate the LHM based patch antenna as it requires mechanical and electromagnetic (EM) stability along with low-loss and wide bandwidth. Ran *et al.* [37] obtained a 5 unit solid state LHM sample with 0.5 dB loss per unit cell and a bandwidth of 2.5 GHz.

Moser *et al.* [38] used the micro-fabrication technique for the first time to produce electromagnetic metamaterial. The lithography based micro and nanofabrication includes the LIGA process (Lithography, Galvanoforming, and Abforming) that was used to fabricate the Pendry's rod and split ring resonator. The SRR were fabricated with nickel or gold and rods in AzP4620 resin matrix with structural details up to 5 microns. These composites exhibit electromagnetic properties in the frequency range of 1-2.7 THz. The electric inductive-capacitance resonator is analogous to a magnetic-*LC* resonator and a single-split ring resonator is analogous to the electromagnetic *LC* resonator, were fabricated using lithography technique by Schurig *et al.* [39]. This electromagnetic *LC* resonator responded the electromagnetic waves in the Ku-band at 15.7 GHz.

The Scanning probe nano-lithography technique is use to produce meta-surfaces in the mid-*Infrared* (IR) region. Based on this technique, a metamaterial structure consisted of double SRR and complimentary double SRR was fabricated to resonate at 100 THz [40]. The z-axis scanner movement was used to sputter silver layers at 20 nm. The line width of about 80-120 nm and a groove depth of 4-80 nm were achieved with this technique.

In general, a metamaterial based microstrip patch antenna can be fabricated as follows: initially the designed patch is screen printed on the substrate layer coated with copper layer. The ground plane is masked to prevent any damage. The substrate is then dipped in dilute solution of ferrous chloride solution. The patch is cleaned after removing from the etchant. To connect the feed, the substrate is drilled and then soldered [41]. In order to fabricate a MTM block, SRR inclusions were etched on the Duroid substrate. However, the MTM structure on original 125 mil Rogers Duroid substrate is very complex to fabricate and expensive. An alternative procedure is suggested by Ziolkowski [19], where a comparatively cheaper, 31 mil 5880-Rogers Duroid was used as the substrate on which the inclusions were etched. The MTM layer thus prepared were cut to the specified thickness and alignment holes were drilled. The individual layers are then stacked by using the polyethylene rod through the alignment holes and finally milled to form a smooth MTM block.

VI. CONCLUSIONS

A brief review of broadband high gain metamaterial based microstrip antenna has been carried out in this paper followed by issues involved in the conventional broadbanding techniques of MPA. It is found that the gain as well as bandwidth of conventional MPA can be enhanced by incorporating the metamaterial structure to it. The various techniques for the design of broadband metamaterial based MPA with high gain characteristics are outlined. The loading of 3-D LHM to MPA is found to be better techniques for the enhancement of bandwidth and gain of MPA. Further the various methods have been discussed for the analysis of metamaterial based microstrip patch antenna. Finally, the techniques for the fabrication of metamaterial based MPA are also outlined briefly.

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