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Proposing a Criss-Cross Metamaterial Structure for Improvement of Performance Parameters of Microstrip Antennas

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Abstract—In this paper, we present the design of a metamaterial based microstrip patch antenna, optimized for bandwidth and multiple frequency operations. A Criss-Cross structure has been proposed. This shape is inspired by the famous Jerusalem Cross. The theory and design formulas to calculate various parameters of the proposed antenna have been presented. The software analysis of the proposed unit cell structure has been validated experimentally thus giving negative response of ε and μ. Following this, a metamaterial-based-microstrip-patch-antenna is designed. A detailed comparative study is conducted exploring the response of the designed patch made of metamaterial and that of the conventional patch. Finally, antenna parameters such as gain, bandwidth, radiation pattern and multiple frequency responses are investigated and optimised and presented in tables and response-graphs. It is also observed that the physical dimension of the metamaterial based patch antenna is smaller than its conventional counterpart operating at the same fundamental frequency. The response of the patch antenna has also been verified experimentally. The challenging part was to develop metamaterial based on some signature structures and techniques that would offer advantage in terms of bandwidth and multiple frequency operation, which is demonstrated in this paper. The unique shape proposed in this paper gives improvement in bandwidth without reducing the gain of the antenna.

1. INTRODUCTION

Low gain and narrow bandwidth are the limitations of conventional microstrip antennas (MSA). The desire to have a compact antenna configuration further deteriorates these two parameters as gain and bandwidth both are directly related to the size of the antenna. Therefore, the most recent design consideration for most of the practical wireless communication applications is size reduction together with gain and bandwidth enhancement. In order to increase the gain, techniques such as loading of high permittivity dielectric substrate [1], inclusion of an amplifier type active circuitry [2] and stacked configuration [3] are used. Bandwidth improves if the substrate thickness is increased, or the dielectric constant is reduced. Use of thick substrates with the help of air or foam along with impedance matching technique [4], suspended microstrip antenna with a dielectric resonator [5], truncating and slotting the patch in C shape, U shape, E shape [6], etc. have raised the bandwidth up to 30%. Use of metamaterials (MM) for further improving the performance of microstrip antennas (MSA) has been the recent trend in this field. Majid et al. have proved that the gain and bandwidth of MSA can be increased by placing an array of left-handed metamaterials (LHM) in front of the patch [7]. Papers as [8, 9] show the integration and analysis of LHM with antennas. Frequency Selective Surface (FSS) and Electronic Band-Gap (EBG) have also been used to increase the gain [10, 11]. This paper lends its contribution to bandwidth enhancement using a unique MM of Criss-Cross shape. The use of this shape for miniaturisation of MSA has been reported in [12].

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2. CROSS METAMATERIALS

For the creation of Double Negative (DNG) medium, both ε and μ should be negative simultaneously. Negative permittivity is often realised by a simple array of wires, capacitively-loaded strips, etc. [13]. However, negative permeability is more difficult to realise as the structure giving negative μ should behave as a 'magnetic plasma'. Such a thing does not exist in nature. SRRs were the first structure to exhibit negative μ, and therefore they are popular till now. SRRs are fully scalable with frequency which has very narrow band. They are also lossy in their resonance region. Several different methods of creating multiband structures have been proposed, which rely on SRRs or SRR like structures. But one main drawback of SRRs based MM is that they are dependent on structure rotation. Cross type structures have overcome this effect [14]. Further replacement of SRRs by JCs has been studied by Katko [15] thus proving that JCs can be used as DNG medium. His work has been referred for analysis of the new shape for MM by the authors.

The Cross metamaterial structure is shown in Figure 1(a), and its effective LC circuit models is shown in Figure 1(b). Likewise, considering the periodicity, this LC circuit model is equivalent to the model described in Figure 1(c). Close to the magnetic resonance regime, the anti-parallel current distribution is shown in Figure 1(c) with arrows, which show the shunt inductances of L_1 and L_2, and the series capacitances of C_1 and C_2. Thus, the total inductance L and capacitance C in the circuit satisfy

$$\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2} \quad \text{and} \quad \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} \tag{1}$$

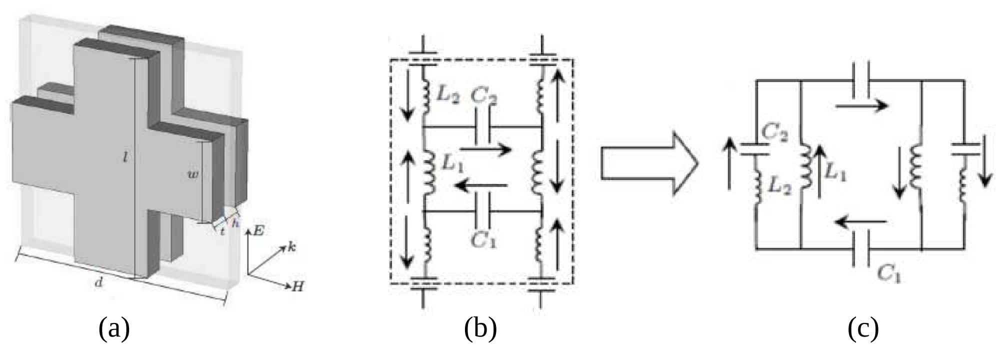


Figure 1. (a) Schematic representation of Cross metamaterials and equivalent circuit.

Then the magnetic resonance frequency of the structure is given by

$$f_m = \omega/2\pi(LC)^{-1/2} \tag{2}$$

Alexander Remely Katko has presented the study of JC very well. He used an effective medium approach for analyzing the material. The results obtained in [15] were reproduced by the authors in order to create a simulation test bench. The next section introduces a new proposed shape namely the signature-Criss-Cross shape. Its parameter extraction was done using the above test bench.

3. DESIGNING OF CRISS-CROSS SHAPE METAMATERIAL

3.1. Mechanical and Material Aspects

In the Criss-Cross shape [16], there are two cross shapes stacked, but electrically separated from each other by 45° as shown in Figure 2(a) and Figure 2(b). The dimension of the unit cell is 6.35×6.35 mm with each of its strip with a width of 1.016 mm made of copper with a thickness of 0.017 mm. The substrate used is FR4 with $\varepsilon_r = 4.4$.

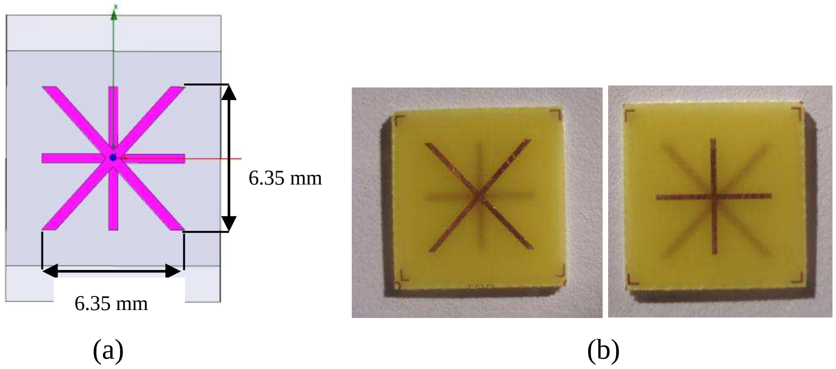


Figure 2. A Criss-Cross shape unit cell with stacked X on both sides of substrate, (a) in HFSS, (b) fabricated model.

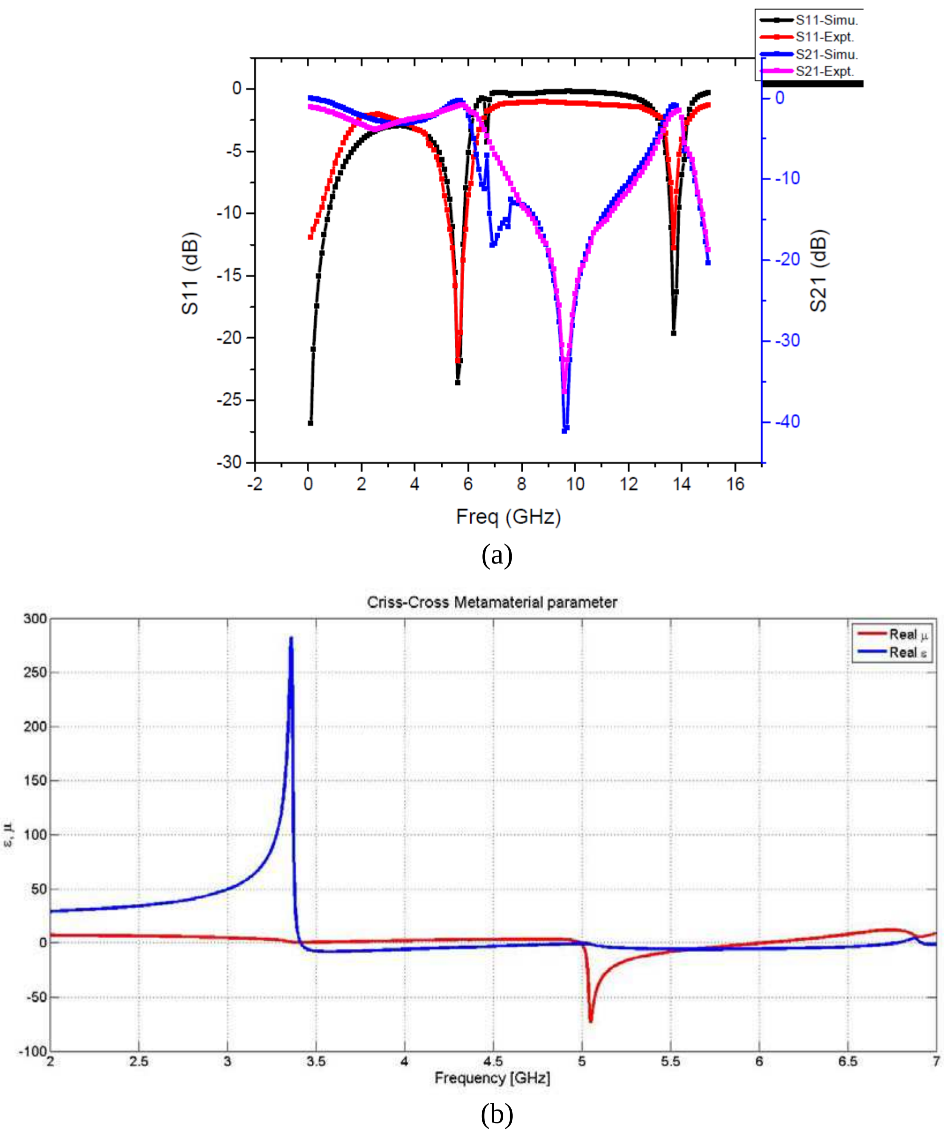


Figure 3. (a) Experimental verification of scattering parameters of Criss-Cross unit cell. (b) Negative ε and μ for the frequency band of 5–7 GHz.

3.2. Simulations and Experimental Responses

The simulations were carried out in HFSS 13. For experimentation, these unit cells were kept inside a standard open ended waveguide. An EM wave in TEM mode was incident on both the open ends of the waveguide, and scattering parameter was measured using Agilent PNA-L Network Analyzer N5230A (10 MHz–50 GHz). The simulation and experimental measurements are shown in Figure 3(a). Figure 3(b) shows that both ε and μ are negative in nature in the frequency band of 5 to 7 GHz, thus can be considered as a effective negative medium band. The negative parameter bandwidth obtained is 33%. The same structure was tested on dielectric materials as Dupont ($\varepsilon_r = 7.8$) and RT Duroid ($\varepsilon_r = 2.2$). The variation in the behaviour of this signature shape has been well presented in [16].

A good matching between simulated and experimental results has been achieved. This motivates the authors to utilize the concept of Criss-Cross metamaterial for improving the performance of a simple patch antenna.

4. DESIGNING OF A CRISS-CROSS METAMATERIAL EMBEDDED MICROSTRIP PATCH ANTENNA

We now present the design aspects related to designing of rectangular microstrip patch antenna on a substrate with metamaterial (signature criss-cross). The metamaterial based patch antenna is compared with the conventional patch antenna that was designed to resonate at 6 GHz as shown in Figure 4(a). The patch on a criss-cross embodied substrate is shown in Figure 5(a). The length of the patch is 14.8 mm, and its width is 19.8 mm. The substrate dimensions are $l = 32.8$ mm and $w = 37.8$ mm with a thickness of 3 mm with $\varepsilon_r = 4.4$ (FR4 has been selected out of the three dielectric materials mentioned earlier). The feed position is $(x, y) = (4, 4)$. The feed position was optimized in an attempt to obtain multi-band response covering a larger frequency bandwidth with a view that the negative medium band after inclusion of MM can be covered by the device. Figures 4(b) & (c) show the return loss response and radiation plot for the conventional patch antenna for $f_0 = 6$ GHz.

Table 1 summarises the results of an optimised conventional MSA. A tri-band response is achieved with good return loss and standard bandwidth. The VSWR is less than 2 in all the three bands. The gain achieved in this case is 2.32 dB.

Table 1. Summary of conventional MSA at $f_0 = 6$ GHz.

Conventional Patch, $l = 14.8$, $w = 19.8$ Gain achieved: 2.32 dB				
Frequency	S_{11} (dB)	f_r (GHz)	Bandwidth (MHz)	VSWR
Band 1	-16.85	4.9	180	1.71
Band 2	-26.95	5.8	300	1.69
Band 3	-10.84	7.8	-	1.36

In the next step, a 3×3 array of Criss-Cross metamaterial was created. This array was embedded in the substrate of the patch antenna as shown in Figure 5(a). The S_{11} response is shown in Figure 5(b). The left shift in frequency is due to change in the effective impedance of the medium due to metamaterial inclusions. The -10 dB band starts from 4.92 GHz to 5.48 GHz. This means that the bandwidth of this antenna configuration is 560 MHz. The bandwidth for a simple patch was 300 MHz, so an enhancement of 86.66% is achieved.

For such a design, the substrate has to be divided into three layers as shown in Figure 5(c). This is because the metamaterial unit cells cannot be dug inside any material. In Figure 5(c), layer 1 shows substrate 1 with ground plane at its bottom face. The second layer is a substrate with 3×3 array of PLUS shape printed on its bottom face and a 3×3 array CROSS shape printed on its top face. The third layer is the substrate with the radiating patch of dimensions 14.8×19.8 mm being printed on its top face. The fabricated model of the same design is shown in Figure 5(d). For fabrication, each substrate layer was 1 mm thick as it was the minimum thickness available with the manufacturer. Thus the thickness

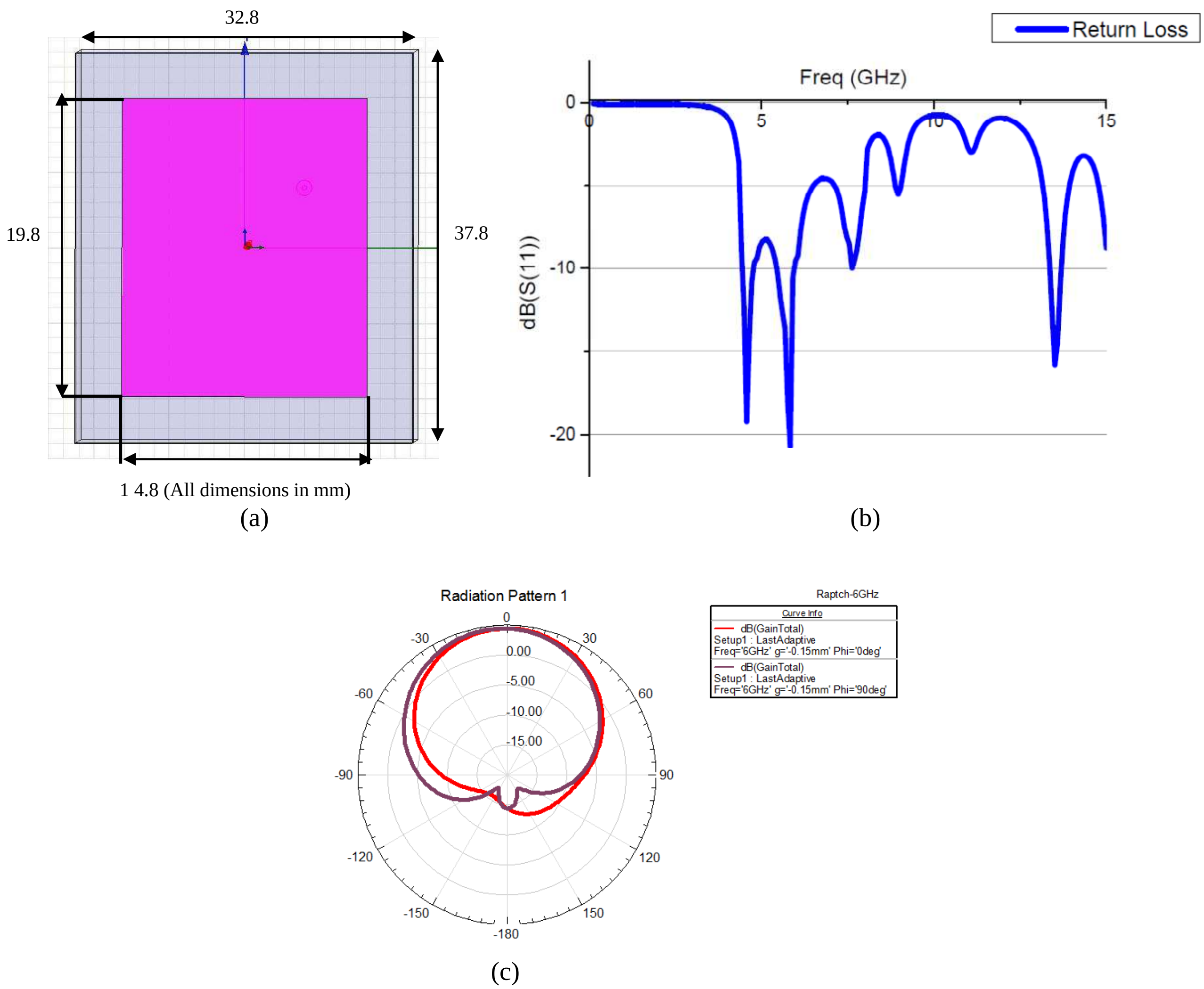


Figure 4. (a) Design for a conventional patch antenna for $f_0 = 6\,\text{GHz}$ with feed position (4,4). (b) S_{11} response of the conventional patch antenna. (c) Gain of 2.32 dB achieved for the conventional patch antenna.

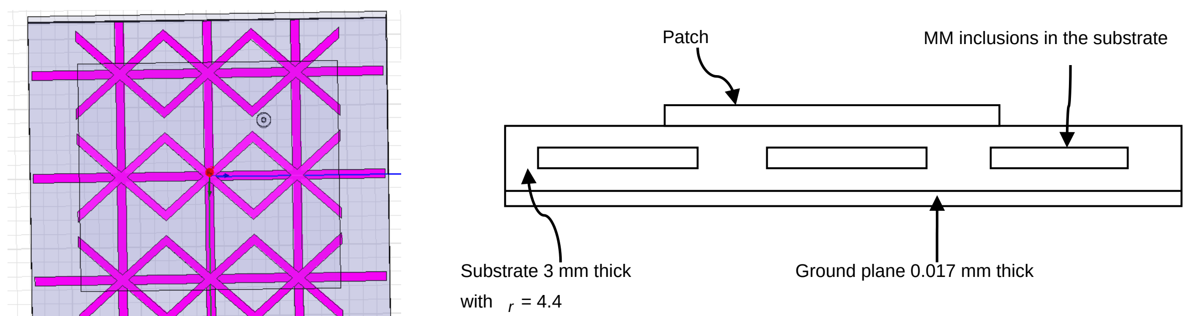
of the patch becomes 3 mm. This modification was incorporated in the simulation once again as shown in Figure 5(e). It is obvious that the response of the fabricated structure will be a changed one as compared to that of 5(b). Thus this response was calibrated for the original response of Figure 5(b) by changing the feed position. After obtaining the optimized feed position through simulation, the design was fabricated.

It is a well-known fact that if the thickness of the substrate of the patch antenna is increased, its bandwidth also improves. But the major disadvantage of increasing thickness is the reduced efficiency since the large portion of the input power is dissipated in the resistor which takes away the available power that can be radiated by the antenna. This drawback of the conventional patch antenna has been overcome by Criss-Cross MMs as inclusions inside the substrate. This effect can be seen in response shown in Figure 5(e) where the calibrated or optimized simulated and experimental results match well. An improvement in gain has also been reported here which is a drawback of conventional patch antenna with thick substrate. Clearly, this credit goes to the Criss-Cross MMs as inclusions inside the substrate.

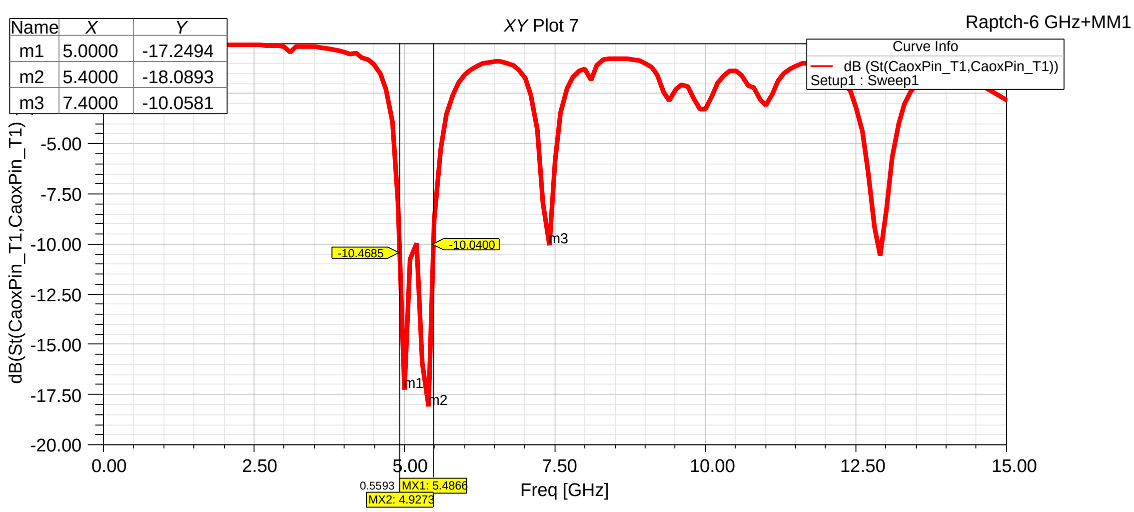
The reason behind the increase in both gain and bandwidth is explained as follows. Each MM cell can be considered as an independent resonating body. Let us consider a single MM cell say M_1 of some shape with a resonating frequency of say f_1. Similarly, other MM cells have resonant frequency

$f_2, f_3, \ldots, f_n$. Now if we place another MM cell say M_2 of same shape and same dimension neighbouring it, then the resonating frequency of M_2 will affect the frequency of M_1. Similarly, if we keep adding cells in some definite arrangement (3×3 array as mentioned in the text or any other arrangement), the equivalent frequency response will be a changed one for that arrangement as compared to that of individual cells. This changed frequency response has been depicted in the paper when unit cells are arranged in 3×3 array shape giving a merged bandwidth. The change in the arrangement of unit cells will lead to change in some other parameters such as gain, VSWR.

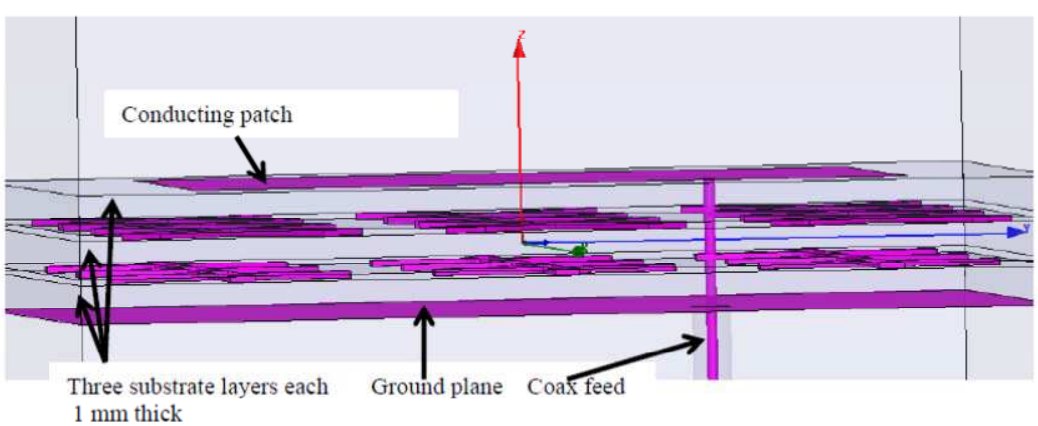
The summary of the results is shown in Table 2. An improvement in bandwidth by 86.66% is achieved here with a gain improvement nearly 2 dB compared to that of conventional patch antenna.



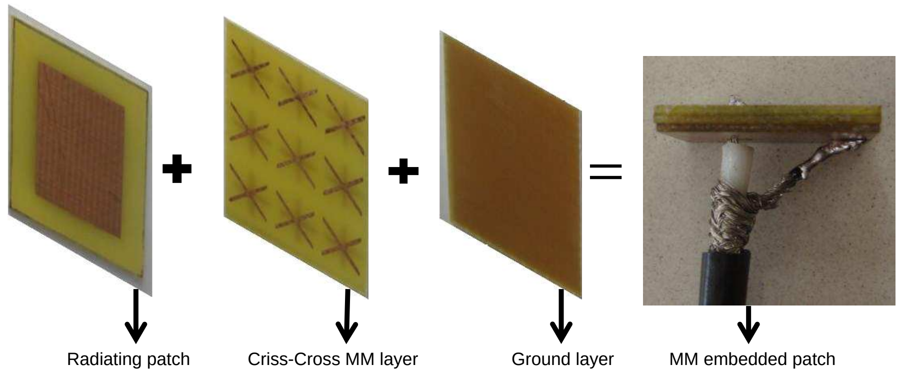
(a)



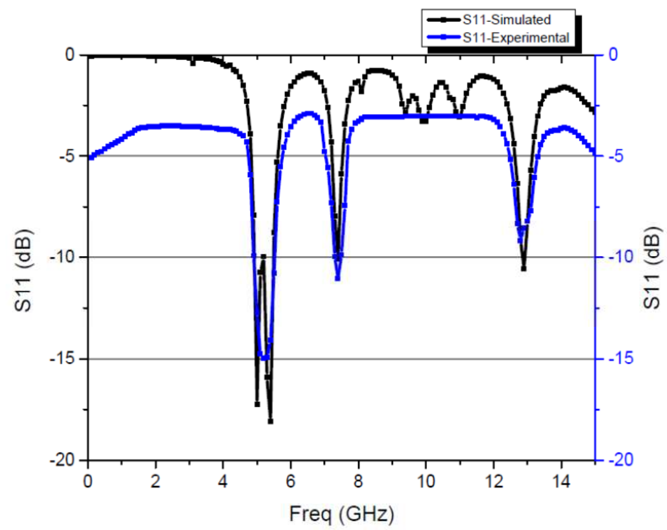
(b)



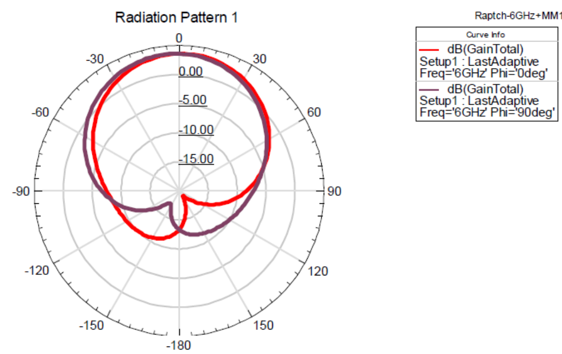
(c)



(d)



(e)



(f)

Figure 5. (a) Design of Criss-Cross metamaterial embedded patch antenna designed in HFSS (top & front view). (b) The S_{11} response for the patch antenna configuration shown in Figure 5(a) in HFSS. (c) The layered structure of the design shown in Figure 5(a) used for fabrication. (d) Fabricated model of the design shown in Figure 5(a). (e) S_{11} response for the Criss-Cross metamaterial embedded patch antenna. (Simulated and Experimental results). (f) Radiation pattern for the Criss-Cross metamaterial embedded patch antenna.

Table 2. Summary of Criss-Cross based MSA at $f_0 = 6\,\text{GHz}$.

MSA on 3×3 criss-cross array, $l = 14.3$, $w = 18.8$ Gain achieved: 4.37 dB				
Frequency	S_{11} (dB)	f_r (GHz)	Bandwidth (MHz)	VSWR
Band 1	-17.24	5	560	1.31
Band 2	-18.08	5.4		1.28
Band 3	-10.05	7.4	-	1.91

5. CONCLUSIONS

This paper presents simulated and experimental results for a new signature — Criss-Cross shaped metamaterial unit cell structure and its application to a radiating patch antenna. It has been shown that the proposed structure exhibits negative values of μ and ε in the region of design-interest. The negative parameter bandwidth obtained for this signature shape (Criss-Cross) is 33.33% which is distinctively higher than Square SRR structure (17–18%) [17] and other reported cross structures (31%) [15]. When our proposed signature — Criss-Cross metamaterial structure is utilized to design a rectangular microstrip patch antenna, multiple band operation was observed with an improvement of bandwidth within the multiple bands along with appreciable improvements in the gain as well, compared to the conventional patch antenna. Summing up, an increase in bandwidth up to 86% along with an increase in gain around 2 dB has been achieved as showcased in the tables, response-graphs and plots. Clearly, the effect of the signature — Criss-Cross MM in terms of improvements in gain, bandwidth and multiple frequency operation is validated for a microstrip antenna. Thus, inspired from the Jerusalem cross, this novel signature — Criss-Cross shaped metamaterial antenna can be strategically utilized to realized microstrip based radiating antennas.

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