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Development of a Miniaturized CPW-Fed Rectangular Microstrip Patch Antenna with L and S Shaped Strips for WLAN, WiMAX and IMT Applications

Asmita Chopra, Jaswinder Kaur

Abstract: ***In this paper, a pioneering CPW-fed compact rectangular microstrip patch antenna having L and S shaped meander strips has been propounded for WLAN, WiMAX and IMT applications. The antenna design has been simulated, fabricated as well as theoretically analysed by transmission and cavity model for setting up a correlation between the frequencies, thus helping in anticipating the frequencies to be calculated on paper. The proposed antenna resonates well below -10 dB covering the required bandwidth of 2.7/3.4/4.4 GHz IMT, 5.1 GHz WLAN and 3.4/5.2 GHz WiMAX standards. A close agreement was obtained while comparing the measured radiation pattern and gain results for the proposed antenna with the simulated ones.***

Index Terms: ***Microstrip patch antenna, multiband, WLAN, WiMAX, IMT.***

I. INTRODUCTION

After the advent of the Printed Circuit Board (PCB) technology, the microstrip patch antenna has proven to be a boon to the wireless industry and since then its popularity has been soaring high because of it being designer and user friendly in terms of its low profile, easy fabrication and embedment with Monolithic microwave integrated circuits (MMIC), light weight and cost which is the ultimate desire of today's end users regarding their appliances. Despite being so much advantageous and a part of umpteen applications be it mobile phones, radio frequency identification (RFID), radio detection and ranging (RADAR) systems, television, aircrafts and spacecrafts etc, it carries a blot of being an antenna with narrow bandwidth, low gain and relatively larger size such that the classical patch antenna has to go through several manipulations in its designs before it can be employed for some application. Such amendments include stacking, etching slots of various shapes like U, C, L, S, usage of coplanar waveguide feed, electromagnetic band gap structures (EBG), cavity backing and lens covering etc. that aid in getting the desired bandwidth and gain. Further the fast growing wireless communication systems continuously desire for an antenna that incorporates the technologies like WLAN, WiMAX, Bluetooth, IMT etc. for which the regular patch antenna has to be designed in a way that it alone caters to all these features. Many researchers have proposed favorable multiband antenna designs for the wireless applications like a compact CPW-fed monopole antenna with a U-shaped strip and a pair of L-slits ground[1], a compact dual-band planar antenna[2], a compact microstrip slot triple-band antenna for WLAN/WiMAX applications[3], novel CPW-Fed planar monopole antenna[4], compact planar monopole antenna with symmetrical U-Shaped slots[5], Compact multiband antenna for GPS, WiMAX and WLAN applications[6], a new triple band CPW-fed monopole antenna for WLAN and WiMAX applications[7], multiband monopole antenna for UMTS, WiMAX and WLAN[8], multiband monopole antenna with complementary split-ring resonators for WLAN and WiMAX applications[9], a compact planar multiband antenna for integrated mobile devices[10], miniaturized asymmetric coplanar strip fed antenna[11], dual band antenna for WLAN/MIMO/WiMAX/AMSAT/WAVE applications[12], and CPW-fed triple band monopole antenna for WLAN and WiMAX applications[13]. Researchers have also put their efforts in exploring multiband, frequency reconfigurable, and metamaterial antennas design techniques[14] and miniaturized circularly polarized coaxial fed superstrate slot antenna for L-band application[15]. In order to understand the behavior of patch antenna after loading it with slots, various rigorous parametric and theoretical studies are carried out which helps in analyzing the birth of the frequencies. In this paper, a classical rectangular patch antenna has been modulated such that the overall design is an amalgamation of L and S shaped meander strips being fed by CPW feed. The region responsible for particular technology has been studied theoretically by equating every strip to a single cavity whose length and width has the onus of giving a particular resonant mode thus making the entire structure multi-band. Furthermore, the simulated and fabricated results are matched with the theoretical results to understand the extent to which theory helps in estimating the frequencies.

II. ANTENNA DESIGN

The geometrical configuration of the proposed antenna as designed and realized using three dimensional electromagnetic simulator Computer Simulation Technology Microwave Studio Version 14.0 (CSTMWS V14.0) is outlined with its complete dimensions in Fig.1(a) and the photograph after its fabrication been performed is illustrated in Fig.1(b).

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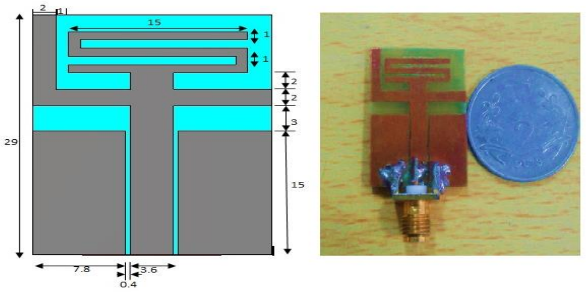
The proposed antenna is having a compact size of the order of 29 × 20 mm^2. The antenna has been fabricated on a 1.524 mm thick FR-4 substrate having relative permittivity 4.4 and loss tangent 0.0024. The thickness of radiating patch and ground is taken as 0.07 mm for this proposed antenna design. The antenna has been fed by 50-Ω coplanar waveguide feed having 3.6 mm wide strip along with a pair of 0.4 mm wide gaps between the strip and CPW ground plane. At a low value of characteristic impedance like 50-Ω, this CPW feeding mechanism being lossy results in lesser Q factor value, thus providing higher bandwidth as desired.



(a) (b)

Fig.1. Geometry of proposed antenna (a) Simulated View (b) Fabricated view

To ensure the effectiveness and practicality of designing, we must consider the dielectric substrate thickness and finite coplanar waveguide structure. The antenna feed structure is calculated from the following equations (1) to (7).

$$Z_0 = \frac{30}{\sqrt{\varepsilon_{eff}}}\frac{K(k_0')}{K(k_0)} \quad (1)$$

$$\varepsilon_{eff} = 1 + \frac{\varepsilon_r - 1}{2}\frac{K(k_1)K(k_0')}{K(k_1')K(k_0)} \quad (2)$$

$$G = 2s + W \quad (3)$$

$$k_0 = \frac{W}{G} \quad (4)$$

$$k_0' = \sqrt{1 - k_0^2} \quad (5)$$

$$k_1 = \frac{sh(\pi w/4h)}{sh(\pi G/4h)} \quad (6)$$

$$k_1' = \sqrt{1 - k_1^2} \quad (7)$$

In the above equations h, ε_r, ε_{eff}, W and s are the notations corresponding to the thickness of the dielectric substrate, the substrate relative permittivity, the effective dielectric constant substrate, the width of CPW-fed wire and the gap between CPW-fed wire and the ground respectively. K(k_0), K(k_1), K(k_0'), K(k_1') are the first complete elliptic integral functions and its complement functions.

The proposed antenna consists of the coalition of L and S shaped meander strips which together let the antenna resonate for Wireless Local Area Network (WLAN), Worldwide Interoperability for Microwave Access (WiMAX) and International Mobile Telecommunication (IMT) band applications. In this structure, both the L and S shaped strips are controlling the occurrence of all the 2.7/3.4/4.4 IMT bands. The S-shaped strips are controlling the operation of 5.1 GHz WLAN and 5.2 GHz WiMAX and a few portion of S is responsible for 3.4 GHz WiMAX operation with a center frequency at 3.5 GHz. Further the regions responsible for particular resonances are analyzed theoretically using the transmission line and cavity model which give an approximate insight and idea about the probable behavior of every section of the design having a particular length and width. It is done by dividing the whole structure into fragments/subsections such that each sub-portion acts as a cavity in its own, thus resulting in multiple cavities in a single structure, each responsible for contributing for a particular resonance according to the following general design equations (8) to (11) from transmission line model. We could realize the birth of the final resonant frequencies of the complete antenna structure using these equations. Every single section of the whole structure i.e. the 'L' part, 'S' part and the ground plane, was taken as a separate sub-cavity and for the sake of this only, the basic equations have been mentioned with the subscript "sub" indicating every subsection.

$$L_{eff(sub)} = L_{sub} + 2\Delta L_{sub} \quad (8)$$

where $L_{eff(sub)}$ is the effective length of each subsection of patch and ΔL_{sub} specifies the respective increase in length of each subsection due to fringing process in the patch which is given by:

$$\frac{\Delta L_{sub}}{h} = 0.412\frac{\left(\varepsilon_{reff(sub)} + 0.3\right)\left(\frac{W_{sub}}{h} + 0.264\right)}{\left(\varepsilon_{reff(sub)} - 0.258\right)\left(\frac{W_{sub}}{h} + 0.8\right)} \quad (9)$$

where, W_{sub} specifies the effective width of the subsection and $\varepsilon_{reff(sub)}$ is the effective dielectric constant for the respective subsection with given effective length and width and is given by:

$$\varepsilon_{reff(sub)} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W_{sub}}\right)^{-1/2} \quad (10)$$

Thus dividing the whole patch area into different subsections of particular length and width with specific effective epsilon with each subsection accountable for particular frequency depending upon the mode becomes the basis for the presence of multiple resonant frequencies in a slotted patch antenna structure according to the following formula for f_{mn} i.e.

$$f_{mn} = \frac{c}{2\sqrt{\varepsilon_{reff(sub)}}}\sqrt{\left(\frac{m}{L_{eff(sub)}}\right)^2 + \left(\frac{n}{W_{(sub)}}\right)^2} \quad (11)$$

where, m and n specify the number of half cycle field variations across effective length and width of the sub-cavity. Thus with the help of equations given above, the resonant frequency and S-parameter value for every sub-cavity was calculated & a rough graph showing some correlation to the simulated results was drawn as shown in the succeeding section with S_{11} on y-axis and frequency on x-axis.

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III. ANALYSIS, SIMULATED AND MEASURED RESULTS AND DISCUSSIONS

In order to understand the behavior of the proposed antenna design, the antenna has been theoretically studied, simulated, fabricated and then tested using some major equipments available in Antenna Research Lab, Electronics and Communication Engineering Department, Thapar Institute of Engineering and Technology, Patiala, Punjab, India. The reflection coefficient and radiation pattern was measured using Agilent's Vector Network Analyzer (VNA) E 5071 C series and Anechoic chamber upto 18 GHz respectively. As per the theory, the regions mainly responsible for the resonance are shown in Fig.2.

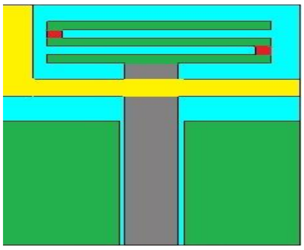
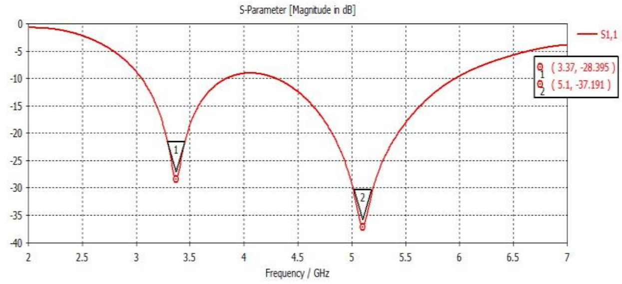
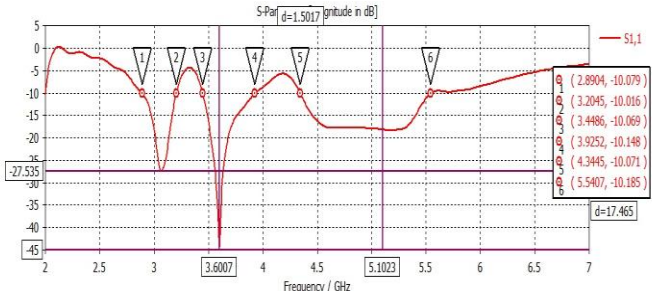


Fig.2. Regions responsible for resonance

The yellow colored L strip constitutes the first region of interest. The green colored strips of S and the ground plane as per their dimensions together constitute the second region from which resonance is expected. Now taking the first region into consideration, the length and width of L strip being 11×20 mm^2 such that w_{sub}> L_{sub}> $L_{sub}/2$ >h causes TM_{01} mode to be dominant resulting in a frequency of 3.7 GHz theoretically. This theoretical frequency gets approximately justified by the presence of a resonance at 3.37 GHz as shown in the simulated S_{11} parameter results of Fig. 3(a) when only L-strip is made. Also the surface current distribution at this resonance does prove that the region mainly responsible for this resonance is the L shaped strip as can be justified via Fig. 4(a). Also the coplanar ground plane being dimensionally equal to 15×15.6 mm^2 with w_{sub}> L_{sub}> $L_{sub}/2$ > h has TM_{01} as its dominant mode and according to this it should provide a resonance near to 4.8 GHz theoretically. The resonance at 5.1 GHz as illustrated in Fig. 3(a) and its surface current distribution in Fig.4(b) somehow give an indication that the region responsible for this resonance is the ground plane. The final structure is formed upon the introduction of S-shaped meander strip, along with the already present L-shaped strip, each arm of which has equal dimensioned length and width of 1×15mm^2 with w_{sub}> $w_{sub}/2$ > w_{sub}>h thus having TM_{01} mode as the dominant one. As per its dimensions the single arm of S-shaped strip should result in a resonance of about 5.6 GHz theoretically. Also during simulation, it is observed that when all the arms of S-shaped meander are being constructed the bandwidth around 5.1 GHz central frequency starts increasing owing to an increase in the electrical length of the region responsible for this resonance. Hence as per the theory, it can be said that all the arms of S-shaped meander should collectively be responsible for giving a wideband around 5 GHz approximately, which is supported by the presence of the wideband generated around the central frequency of 5.1 GHz, which had occurred previously because of the ground plane. But practically, this antenna structure gives a very strong resonance at 3.6 GHz as can be seen in Fig.3(b) about which the theory does not point about. Also as the S-shaped meander is formed, the resonance at 3.37 GHz due to the L-shaped strip gets shifted towards left to a value of 3.06 GHz in the final structure which is due to the increase in the inductance value about which the multi cavity model is unable to predict.



(a)



(b)

Fig.3. Simulated S_{11}-Parameters for (a) partial antenna design consisting of only L strip and ground plane (b) final antenna design consisting of L strip, ground plane and S strip

The simulated results for the proposed antenna are shown in Fig.3(b). It shows the excitement of various resonant modes at 3.06 GHz, 3.6 GHz and an extreme wideband centered about 5 GHz which contribute in covering the frequency range for WLAN, WiMAX and IMT band applications. The frequency bands contributing to IMT, WLAN and WiMAX applications include 2.8-3.2 GHz with 400 MHz bandwidth, 3.4-3.9 GHz with 500 MHz bandwidth, 4.3-5.5 GHz with 1200 MHz bandwidth with a promising return loss of -27.53 dB, -44.227 dB and an average return loss of -17 dB over the wideband respectively. The demand for WiMAX applications is catered by the 3.4-3.69 GHz and 5.25-5.85 GHz band, 2.4-2.484 GHz and 5.1-5.35 GHz frequency bands serve for WLAN application and 2.7-2.9 GHz, 3.4-4.2 GHz and 4.4-4.9 GHz serve for IMT application. The resonant frequencies so obtained are analyzed using transmission line model and cavity model as has been described and discussed by the equations (8) to (11) in the previous section. Likewise, the resonant frequencies for each and every sub-cavity have been calculated theoretically, in a similar way the S-parameter value for every sub-cavity is calculated & a theoretical graph showing some correlation to the simulated results is drawn with S_{11} on y-axis and frequency on x-axis. Thus with S_{11} & frequency value calculated manually for each sub-cavity, a theoretical graph has been plotted between both the parameters stating the multi resonant behavior of the whole structure arising from each sub-section.

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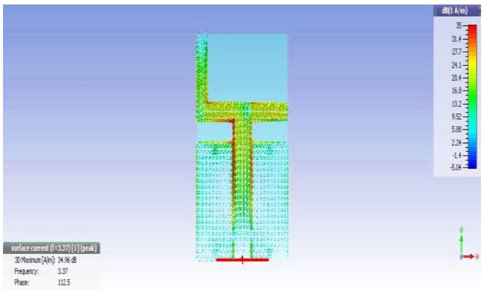
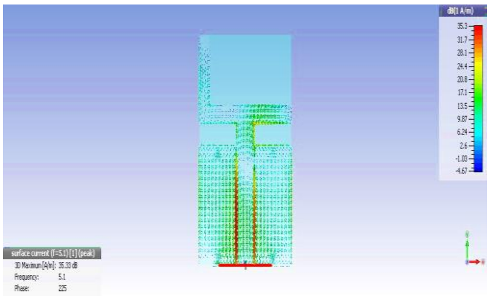
The theoretical analysis helped in getting an approximation of the multi-resonant behavior of the antenna & an attempt to set some parallelism between the theoretical & practical results has been made. Also the inability to get an approximate for the resonant frequency left states that 100% prediction of the practical behavior is not possible. There is a bridge between theory and practical world which needs to be covered further using higher models.

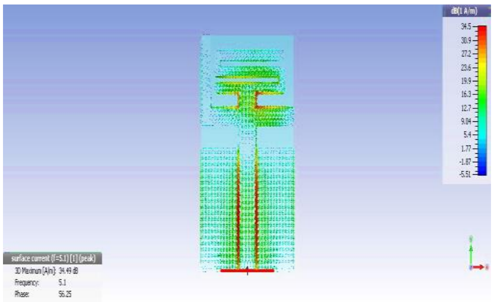


(a)

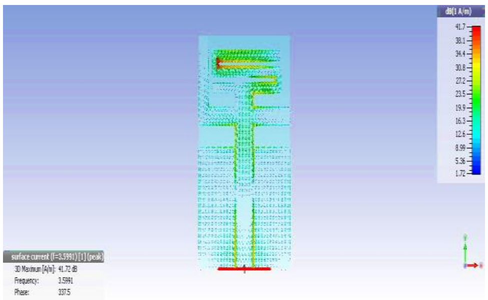


(b)

Fig.4. Current distribution for partial antenna design consisting of only L strip and ground plane at (a) 3.37 GHz, (b) 5.1 GHz



(a)



(b)

Fig.5. Current distribution for final antenna design consisting of L strip, ground plane and S strip at (a) 5.1 GHz, (b) 3.5 GHz

As per the current distribution simulated results shown in Fig. 5(a) and (b), only the lower portion of the S-shaped meander strip and the ground plane are responsible for contributing to the wideband occurring around the 5.1 GHz frequency and the upper portion of the S-shaped strip is actually contributing for the 3.5 GHz resonance. Hence an inference can be drawn here that with the help of transmission line and multi-cavity model, one can easily get a rough estimation of the frequencies that will result from the sub-sections of the antenna thus helping in the rapid optimization of the parameters for getting desired frequency bands. Fig.6 shows the comparison between the theoretical, simulated and the measured results. The measured results do support the simulated results and are in good agreement with the simulated ones. The minor deviations between the simulated and the measured results may occur due to the snags that arise during fabrication and soldering processes. Also looking at the theoretical results that have been drawn by calculating S_{11} parameter values at required frequencies, one can say that, prediction of 65-70% of the behavior of the antenna is possible on paper.

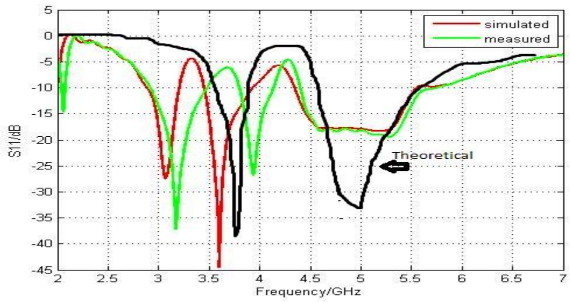
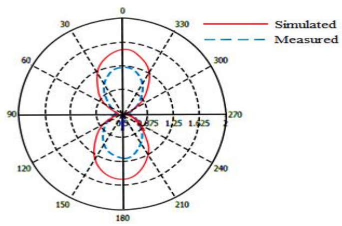
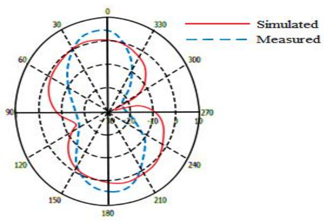


Fig.6. Comparison of theoretical, simulated and measured results of the proposed antenna

Fig.7-9 depict the simulated and measured E (elevation) and H (azimuthal) plane radiation pattern of the antenna defining its radiation characteristics as a function of space at the resonating frequencies of 3.06 GHz, 3.6 GHz and 5.1 GHz. A bidirectional elevation radiation pattern and nearly omni-directional azimuthal radiation pattern is observed at 3.06 GHz, 3.6 GHz and 5.1 GHz. Fig. 10 illustrates the simulated and measured peak gain values for the three respective frequency bands of the proposed antenna. The graph clearly indicates that both the simulated and measured peak gains are relatively closer to each other which justify the commercial application of antenna.



(a)



(b)

Fig.7. Simulated and Measured Radiation Pattern at 3.06 GHz (a) E-plane, (b) H-plane

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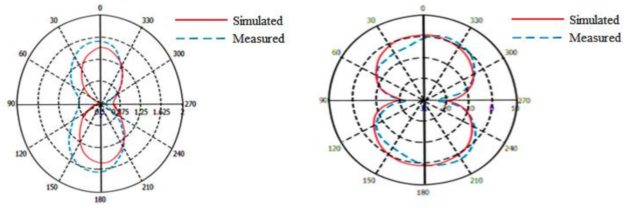
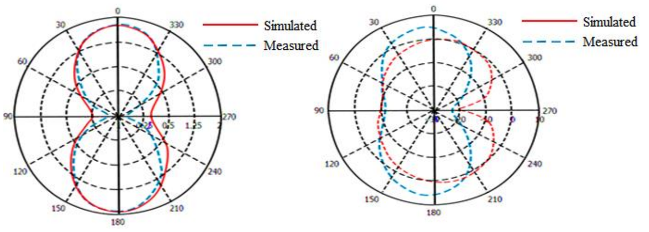


(a) (b)

Fig.8. Simulated and Measured Radiation Pattern at 3.6 GHz (a) E-plane, (b) H-plane



(a) (b)

Fig.9. Simulated and Measured Radiation Pattern at 5.1 GHz (A) E-plane, (B) H-plane

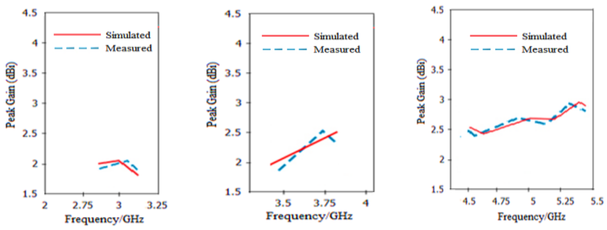


Fig.10. Simulated and Measured Gain (dBi) vs Frequency

IV. CONCLUSION

A compact microstrip patch antenna with L and S shaped meander strips has been simulated, theoretically analyzed, fabricated and tested for proving the sanctity of the results. Coplanar waveguide feed is used to exploit its ability of providing wide bandwidth. The proposed antenna has a very wide scope of being employed for the purpose of WLAN, WiMAX and IMT band applications offering very good impedance bandwidths. Almost perfect impedance matching has been achieved with VSWR values very close to one at the resonating frequencies. Also a good approximation for the behavior of the antenna is observed by theoretically analyzing the antenna with the help of transmission line and multi-cavity model. It is observed that the multi-resonant behavior of the antenna is because of the different sub-sections of the design acting as a cavity in their own thus giving a resonance as per their effective length and width. The small size of the antenna makes it a favorable candidate for its integration in the hand-held devices. Some further manipulations can be done to increase the gain of the antenna at the specified wireless applications.

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