Design and implementation of slotted metamaterial stacked microstrip patch antenna for broadband applications

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Abstract: The design of stacked patch antenna integrated with metamaterial for broadband applications to achieve appreciable gain, directivity and low return loss is presented in this article. It mainly focuses on optimization and easy adaptation in MMIC technology. The antenna is designed to carry out by combining two Microstrip patch antenna in a stack manner and Metamaterial is implemented by Complementary Split Ring Resonator (CSRR) technique on both side of the patch antenna and slots are introduced at four corners of the patch and adjacent to the metamaterial. The designed antenna is capable of maintaining its performance over wireless system at C band (4–8 GHz) frequency range. The substrate used is FR-4 with thickness of 0.8mm and permittivity is 4.2. It is simulated using Advanced Design System (ADS) and it is resonated around 6 GHz. It yields a VSWR of about 1.014 (6.25 GHz), 1.022 (5.829 GHz) and 1.015 (6.522 GHz) under simulation and 1.25 (6.03 GHz), 1.119 (5.74 GHz) and 1.247 (5.36 GHz) in measurements respectively. Thus the antenna becomes a necessity for many applications in recent wireless communications such as RADAR and space applications.

Keywords: Microstrip, Metamaterial, Gain, Directivity and C-band.

1. Introduction

An antenna plays a vital role in communication systems. An antenna is an element / component / device used transmit / receive electromagnetic wave in free space. An antenna provides and satisfies property known as reciprocity, which means an antenna will retain the same characteristics regardless if it is transmitting or receiving. Most antennas are resonating in a microwave frequency band based on the applications, which operate competently over a relatively tapered frequency band. The special type of antennas that is attractive more trendy in recent years is microstrip antenna. The microstrip antenna is also called as patch antenna or printed antenna or Microstrip patch antenna (MSA). As the MSA are directly printed on to the circuit boards, in the modern epoch of mobile phone souk there is a no other best view than MSA and attractive very extensive within the mobile phone souk. MSA are becoming ever more useful because they can be printed directly onto a circuit board. Patch antennas are low cost, have a low profile and are easily fabricated. MSA have found extensive applications in wireless communication system following to their advantages such as low profile conformability, low cost and ease of fabrication [8]. On the other hand, traditional MSA suffers from much tapered bandwidth with respect to the center frequency. To overcome this, slot antenna have been considered a good aspirant in compliance to these trends. In order to diminish the size of the antenna, recent research has been suggested for miniaturization technique with slot antennas. Wherever the fields are radiated there is an opening that is called as slot antenna. The shape and size of the slot, as well as resonant frequency, determine the radiation pattern. It is based on Babinet’s Principle which states that the slot is having the same radiation pattern as dipole. An extension of Babinet’s principle, which includes polarization and the more realistic conducting screens, was introduced by Booker. The main
advantages of slot antenna are its size, design simplicity, robustness and convenient adaptation to mass production using Printed Circuit Board (PCB) technology. To provide appropriate impedance matching between the cable and slot antenna a patch feed is used and a slot antenna of \( \lambda/2 \) length is preferred. When the slot is perpendicularly polarized, it gives parallel waves. When the slot is parallel polarized, it gives perpendicular waves. The shapes of the slot not essentially have to be rectangular but it can have any expedient shape. Rectangular and circular shapes are desirable because they can be made without difficulty and are simple to analyze. The slot antennas are very constructive in numerous applications like high speed aircraft. Many slots has its balancing form in wires or strips that can be used in predicting patterns and impedances of the analogous slots. The width of the slot must be more than \( \lambda/2 \) to broadcast energy, but it should be less than \( \lambda \) to hold back higher order modes. The transmission mode of the slot antenna is TE\(_{10}\) mode. The length to width of the slot ratio is about 3. For a compact slot antenna design, greater than ever the length of the slot or adjusting the shape of the slot is needed [14]. By implanting diversity shapes of the slots, the antenna size can be reduced for a given operating frequency. By using slot antennas, extensive bandwidth can be obtained, without increasing the thickness or area of the antenna [9]. In order to reduce antenna size, recent research has anticipated many miniaturization techniques for slot antennas. The important parameters of an antenna are impedance, bandwidth and return loss [8]. The S band defined by an IEEE standard with frequencies 2 to 4 GHz. Odd multiple of wavelength (33 \( \lambda \)) increases the radiation pattern of antenna. The C-band applications such as Satellite communication, RADAR devices, Terminal Air traffic control, Long-Range weather and Marine RADAR.

2. Literature Survey

The MSA is designed with the help of alumina and paper substrate at a resonant frequency of 2.4 GHz which is used for Wi-Fi application. The recital of the antenna having diverse substrates is analyzed on the basis of comparison of gain, directivity, VSWR, BW and return loss. A dual-band antenna is operated to over free space for Wi-Fi and ultra-low power radar applications, which is designed in Ansoft high frequency structure simulator (HFSS). The designed antenna is fictitious through commercialized Dimatix material inkjet printer by using silver nano-particle conductive ink on 50\( \mu \)m PET substrate. The results show that the proposed antenna is appropriate for simple communication and ultra-low power radar applications [1]. A novel multiple slitted and circular stacked microstrip patch antenna with high gain has been proposed. The composite effect of employing slots and stacking provides better return loss (dB), high gain (dB), and directivity (dBi). The proposed antenna is designed and employs FR4 material as a substrate having dielectric constant 4.4. The proposed antenna design has been simulated in CST Microwave Studio 2014, successfully fictitious and experienced using measurement devices [2]. The proposed antenna design can be efficiently used for public safety purposes (4.94 GHz - 4.99 GHz). The design of MSA with high gain that can be used in tetra hertz frequencies. In the proposed antenna design, the substrate of material FR4 which possess the dielectric constant of 4.4 has been used. The microstrip feed line is used in the proposed antenna design [3]. The proposed antenna design is the high gain MSA that has the resonant frequency of 0.125 THz. The parameters through which the performance of the antenna can be measured are impedance bandwidth (THz), return loss (dB), directivity, gain (dBi), VSWR and impedance (ohms). The propounded antenna design can be used for biomedical application for the uncovering of various diseases. The antenna simulation has been performed by using HFSS [4]. The propounded antenna design has been devised and simulated in CST Microwave Studio 2014. This antenna resonates at frequency of 7.94 GHz with the negligible return loss of -81.25 dB, high gain of 8.5 dB and directivity of 8.12dBi. The proposed antenna has been designed using Flame Retardant 4 (FR4) substrate of dielectric constant, \( \varepsilon_r = 4.4 \) sandwiched between copper patch and ground plane. The designed antenna has a opaque area and operating bandwidth of 560MHz (7.67GHz-8.22GHz). The antenna has been fictitious and efficaciously tested using Vector Network Analyzer (VNA). The specified frequency ranges of 7.68 GHz – 8.22 GHz can also be employed for military satellite, weather satellite and radio-determination purposes. A novel structure of metamaterial is proposed so as to miniaturize U-shaped microstrip patch antenna. The methodology uses inter digital capacitor provided on one arm of U-shaped patch antenna. The reflection coefficient is less than 10dB for a frequency range of 3.1GHz to 5.1GHz. The proposed rectangular patch antenna has been devise using Glass Epoxy substrate
(FR4) with dielectric constant \( \varepsilon_r = 4.4 \), loss tangent (tan \( \delta \)) equal to 0.02. The rectangular patch is keyed up using transmission lines of particular length and width. The simulation of rectangular patch antenna was made by HFSS, it was found that the band is acceptable comparing to the typical bandwidth which ranges 3 to 5 GHz; the resonant frequency is 4.3 GHz and return loss \( S_{11} \) equal to -30dB. The design of 16\( \times\)16 array of MSA has been done for X band application at 10GHz frequency. The design and simulation of array consisting of 256 elements using HFSS was done. Array of antenna introduced and deployed using microstrip feeding method. The basic structure and behavior along with simulated and measured result of proposed 16\( \times\)16 MSA array is demonstrated. A compact slotted circle Microstrip patch antenna is presented for the ultra-wideband applications and other multiple wireless communications. The antenna, consisting of a slotted partial ground and a slotted circular patch, covers wider frequency band than the Ultra-wideband (UWB). The prototype is fabricated on an FR4 substrate having a thickness of 1.60mm with the relative permittivity of 4.6 and dielectric loss tangent of 0.02. The antenna yields 10dB return loss (VSWR \( \leq 2 \)) from 4.0 GHz to 19.80 GHz with 132.77% fractional bandwidth. The antenna shows a reliable radiation pattern with 2.85dBi of typical gain [7]. As the antenna covers a wide bandwidth, it can be used in the high fidelity short pulse applications. In addition, the antenna can be used in UWB communications along with supplementary communication channel such as WiMax, WI-Fi, ISM and wireless communication systems. The design of four element microstrip patch antenna array with rectangular slots is simulated and analyzed in detail by using Mitered bend feed network which is used in wireless application in ISM frequency bands. Improved Gain, Directivity and Bandwidth in contrast with declined Reflection coefficient and VSWR together with multiband frequency responses are the characteristics of slot antenna. The paper represents Terahertz microstrip antenna employing FR4 material as a substrate with permittivity of 4.4 and thickness of 1.62µm. The slotted substrate and stacked ground plane has been used in antenna design. The ground, patch and feed line are made up of copper. Slotting in substrate is done to augment the antenna parameters. The proposed terahertz microstrip patch antenna has an impedance bandwidth of 0.077THz with resonant frequency of 4.11THz, thus creation it appropriate for narrowband applications [8]. The proposed antenna has a return loss of -42.00 dB with operating frequency range of 4.07THz-4.15THz. It has gain of 5.73dB and directivity of 555dBi at resonant frequency of 4.11THz. It has input impedance of 50.62 ohms that is required for minimal antenna return losses. The proposed antenna design can be used for uncovering of plastic explosive SX2 at resonant frequency of 4.11 THz. The design of Sierpinski Gasket Antenna use FR4 glass epoxy substrate with relative permittivity of 4.4 and 1.6mm thickness. In cut sierpinski gasket slots on a MSA having 20 x 20mm of size. By this design we get higher bandwidth, gain, thin profile, light in weight, inexpensive, easy to fabricate and compact antenna. The proposed antenna can also be used for single, multiband and various engineering applications such as PCs, Bluetooth, WLAN, Wi-Fi etc, as well as communication system. These parameters are plays vital role while designing RF circuit design: bandwidth, return loss, voltage standing wave ratio, input impedance. This antenna is simulated with transmission line feed technique.

3. Methodology

The proposed rectangular patch antenna comprises on dual FR-4 substrate with air gap and excited with patch feed. The Substrate reduces both the electric field attention on lossy epoxy and the effectual dielectric constant of the radiating plane. Hence a low loss and high gain antenna is obtained. The purpose of using patch feed is to achieve better reliability compared to other feeding techniques [17]. The proposed antenna can be designed by ADS software and it is fictitious and tested by using VNA which helps to obtain the analysis of antenna parameters such as efficiency, VSWR, directivity, return loss, gain and relation between them. The antennas are intended by using FR4 substrate with permittivity \( \varepsilon_r \) is 4.2, and thickness is 0.8 mm. The size of the substrate is fixed with the dimension width 15.5 mm and length 12 mm. With help of equation (1 - 4), the antenna design parameters are calculated and shown below.

Frequency

\[
 f_0 = \frac{c}{\lambda} = 6 \text{ GHz} \quad (1)
\]
Thickness

\[ h \geq \frac{0.06 \lambda}{\sqrt{\varepsilon_r}} = 0.8 \text{mm} \quad (2) \]

Width

\[ w = \frac{c}{2 f_0} \cdot \frac{\sqrt{2}}{\sqrt{\varepsilon_{r+1}}} = 15.5 \text{ mm} \quad (3) \]

Length

\[ L = \frac{c}{2 f_0 \sqrt{\varepsilon_r}} = 12 \text{ mm} \quad (4) \]

The patch feed antenna explained in the foregoing section is next loaded with two pairs of CSRR’s. According to the principle, the resonant frequency of the CSRR’s towards design technique to be vividly different. The design equations for a CSRR with two turns are as below. The Resonant Frequency of the CSRR is given by

\[ \omega_o = \frac{1}{\sqrt{L_C C_C}} \quad (5) \]

\[ L_C = \frac{4.86}{z} \mu_0 (L - w - s) \left[ \ln \left( \frac{0.98}{\rho} + 1.84 \rho \right) \right] \quad (6) \]

\[ \rho = \frac{w + s}{L - w - s} \quad (7) \]

\[ C_C = (L - 1.5(2 + d)C_{pul}) \quad (8) \]

Where ‘w’, ‘L’, ‘s’ represents the width & length of the outer ring and space between rings.
respectively. $\rho$ is the filling factor and $C_{\text{pul}}$ is Per unit capacitance. By using equation (1 – 4), the antenna fundamental parameters are calculated. Equation (5) is common for both the cases of ‘n’ being two or three. Equation (6 – 8) used to design number turns being two for CSRR. The above set of equations was suitably employed to obtain the design dimensions of the CSRR’s. The figure1 shows the design of stacked MSA resonated around 6 GHz. Basically the antenna consist of three layers like ground plane, substrate and patch. In the figure 1 the two layers of an antenna are placed in stack manner. In figure 2, the metamaterial is integrated in stacked MSA and it consists of CSRR technique in both layer of an antenna. In figure 3, the stacked MSA integrated with metamaterial CSRR technique and slots are placed in four corners of the patch and three adjacent sides of the metamaterial. The slots are placed in four corners of the patch and three adjacent sides of metamaterial as shown in figure 7 (c). The antenna parameters are plays a vital role in the designing. Length and width are the basic parameters that affect the antenna performance [16].

4. Design and Simulated Results of MSA

The MSA design was simulated using ADS software and results for the different stages are shown in figure 4, 5, and 6 respectively. The resonant frequency for stacked MSA integrated with metamaterial and slot on both layers was higher compared to the other stage of antenna.

![Figure 4(a). Return Loss for Stacked MSA](image1)

![Figure 4(b). VSWR for Stacked MSA](image2)

![Figure 4(c). Gain, Directivity and Efficiency for Stacked MSA](image3)

The stacked MSA was designed in a stacked manner. The simulated results were obtained and shown in figure 4 (a), (b) & (c). In figure 4 (a) it shows the return loss of stacked MSA antenna and it gives -43.273 dB. Normally the return loss should minimum of -20 dB. Hence the stacked MSA yields maximum return loss around -43.273 dB. In practical, the microwave devices have VSWR in the range of 1.0 – 2.0. The stacked MSA yields VSWR of 1.014 at resonant frequency of 6.03 GHz and it is shown in figure 4 (b). The stacked MSA gives maximum gain of 7.229 dBi and directivity of 8.175
dBi as shown in figure 4 (c).

Figure 5(a). Return loss for Stacked MSA with Both Layers as Metamaterial (b). VSWR for Stacked MSA with Both Layers as Metamaterial

The MSA was arranged in stacked manner and integrated with metamaterial CSRR technique on both layers in order to achieve negative refractive index, magnetism at optical frequencies. The simulated results are shown in the figure 5 (a), (b) & (c). In figure 5 (a) it shows the return loss of stacked MSA antenna with metamaterial gives -39.376 dB and it yields VSWR of 1.022 at frequency of 5.74 GHz as shown in figure 5 (b). The antenna has directivity of 9.195 dBi with minimum gain of 3.483 dBi as shown in figure 5 (c).
The MSA was arranged in stacked manner and integrated with metamaterial inbuilt with slots on four corners of patch and adjacent to metamaterial in order to increase the efficiency, gain, return loss and it is shown in figure 7 (c). Slots are used to increase the gain, efficiency & directivity [17]. The simulated results are tabulated & shown in table 1. From figure 6 (a), derive the return loss value of –42.407 dB for stacked MSA integrated with metamaterial and slot. Figure 6 (b) shows the VSWR value as 1.015 with maximum gain of 6.667 dBi and directivity of 8.096 dBi as shown in figure 6 (c). From table 1 it is easily conclude that, while using the metamaterial on the stacked MSA the parameter results are gain, directivity and radiation efficiency gets down. In order to increase the antenna parameters like gain, directivity and efficiency slots are introduced with stacked MSA. Hence it proves that the results get increased as tabulated in table 1.

### Table 1. Simulated Results

| Description                          | Frequency (GHz) | VSWR  | Return Loss (dB) | Gain (dBi) | Directivity (dBi) | Radiation Efficiency (%) |
|--------------------------------------|-----------------|-------|------------------|------------|-------------------|--------------------------|
| Stacked MSA                          | 6.03            | 1.014 | -43.273          | 7.229      | 8.175             | 80.42                    |
| Stacked MSA with Metamaterial        | 5.74            | 1.022 | -39.376          | 3.483      | 9.195             | 26.84                    |
| Stacked MSA with Metamaterial and Slot| 5.36            | 1.015 | -42.407          | 6.667      | 8.096             | 72.048                   |
5. MSA Implementation (Tested Measurements)

![Images](7 (a), 7 (b), 7 (c))

Figure 7 (a). Stacked MSA (b). Stacked MSA with Both Layers as Metamaterial (c), Stacked MSA Integrated with Metamaterial and Slot on Both Layers

The implementation and fabrication of stacked MSA has successfully done with FR4 substrate with dielectric constant of 4.2, substrate thickness of 0.8mm and dimension of 12 * 15.5 mm. The return loss is a measurement from which we can predict how much amount of power is reflected by the antenna. The radiation properties of the antenna as a function of space coordinate. Radiation pattern is an indication of radiated field strength around antenna. It is different for different antennas and is affected by the location of antenna with respect to ground. The tested results value of stacked MSA is tabulated and shown in table 2.

| Description                        | Frequency (GHz) | VSWR | Return Loss (dB) |
|------------------------------------|----------------|------|-----------------|
| Stacked MSA                        | 6.03           | 1.250| -19.46          |
| Stacked MSA with Metamaterial      | 5.74           | 1.119| -26.65          |
| Stacked MSA with Metamaterial and Slot | 5.36          | 1.247| -20.35          |

In different stages, the antenna yields VSWR varies from 1 – 2. Voltage Standing Wave Ratio (VSWR) must lies in the range of 1.0 - 2.0. Then only the proposed RF devices yields maximum output and appreciable results. Hence the statement proves here for Stacked MSA. The result statement of the stacked MSA is obtained, tabulated and shown in table 3. It shows that the simulated and tested results are very nexus to each other and the stacked MSA is resonated around 6 GHz. The present work has been successfully investigated.

| Description                        | Simulated Results | Tested Results |
|------------------------------------|-------------------|----------------|
| Stacked MSA                        | Frequency (GHz)   | VSWR | Return loss (dB) | Frequency (GHz) | VSWR | Return loss (dB) |
| Stacked MSA with Metamaterial      | 6.25              | 1.25 | -43.273          | 6.03            | 1.25 | -19.46          |
| Stacked MSA with Metamaterial and Slot | 5.829           | 1.119| -39.376          | 5.74            | 1.119| -26.65          |
| Stacked MSA with Metamaterial and Slot | 6.522           | 1.247| -42.07           | 5.36            | 1.247| -20.35          |

| Description                        | Simulated Results | Tested Results | Existing Results | [7] |
|------------------------------------|-------------------|----------------|------------------|-----|
| Stacked MSA                        | Freq (GHz) | VSWR | Return loss (dB) | Freq (GHz) | VSWR | Return loss (dB) | Freq (GHz) | VSWR | Return loss (dB) |
| Stacked MSA                        | 6.25              | 1.25 | -43.273          | 6.03            | 1.25 | -19.46          | 2.45              | 1.41 | -24.96          |
| Stacked MSA with Metamaterial      | 5.829              | 1.119| -39.376          | 5.74            | 1.119| -26.65          | 2.45              | 1.35 | -34.02          |
| Stacked MSA with Metamaterial and Slot | 6.522           | 1.247| -42.07           | 5.36            | 1.247| -20.35          | --                 | --   | --              |
| Stacked MSA with Metamaterial and Slot | 5.468           | 1.022| -40.78           | --              | --   | --              | --                 | --   | --              |
The proposed structure was designed on FR4 Substrate integrated with metamaterial and slots it gave the appreciable gain and directivity. Finally, the proposed stacked MSA is tested using vector network analyzer and results are obtained and tabulated. Table 4 shows that comparative result statement with existing technique, simulated and tested results. Finally, the proposed antenna yields maximum results and resonated over 4 – 8 GHz.

6. Conclusion

The comparative analysis for different MSA has been experimented and investigated successfully. The result shows that the designed antenna contributes to augmentation of antenna performance and all at once without distressing the antenna resonant frequency. The proposed antenna is also suitable to incorporate with other device or component to act as dual-performance. Since the range of the resonant frequency is 4 to 8 GHz, it is widely used for C band applications. Finally the experimental outcome seems very nexus with the simulated and tested results.

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