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Modified Patch and Ground Plane Geometry with Reduced Resonant Frequency

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Abstract—A higher degree of miniaturization technique is presented based on frequency reduction method for a rectangular patch antenna by introducing a slot on the radiating patch with unchanged antenna configuration. To realize the frequency reduction technique, a rectangular patch is designed to operate at the fundamental frequency. Then a slot on the radiating patch is introduced, and as an effect of slot, fundamental resonant frequency is shifted to the left side of reflection coefficient plot. The percentage of reduction resonant frequency is 65.80% where 2.31 GHz is the fundamental frequency, and 790 MHz is the operating frequency of slot integrated patch geometry. In addition, we introduced another similar slot on the ground plane, and as a result, resonant frequency shifted from 790 MHz to 729 MHz caused by 68.44% reduction in resonant frequency with unchanged antenna dimension. To verify the simulated theory, prototypes are fabricated and complied with measured results.

1. INTRODUCTION

We are standing at the edge of modern wireless systems where next generation internal circuit boards are also getting connectivity through the chip integrated RF microwave platform. Nowadays, public transport systems extensively use GPS based technology to provide their users a better experience for tracing vehicles, avoiding collisions, and security purposes. Drones are also used to transport goods for customer door-to-door services. Unlike the conventional loop, dipole, and helical antenna, the patch antenna has low profile, low cost, good conformability, and ease of manufacturing facility. It is readily incorporated with microstrip or coaxial probe feeding. The patch can be circular, rectangular, triangular, or any geometrical and arbitrary shapes. The patch antenna has several attractive advantages, including broadside radiation characteristic that permits it to be integrated into two dimensional arrays. The antennas are most widely used for radar, missiles, aircraft, satellite communications, and mobile communications.

However, the typical size of a patch is about half of free space wavelength, which is too large to be integrated into wireless devices. So, there is the need in the current situation to develop a miniaturized antenna to prescribe the new heights on performance of those advanced wireless devices.

A patch antenna over a reactive impedance surface (RIS) [1] substrate has been proposed and fabricated for $\lambda_0/10$ size reduction compared with the conventional patch. Moreover, the patch antenna for tunable miniaturization factor has been illustrated in [2]. In addition, the literature survey shows that the uses of magneto-dielectric meta-substrate [3], meta-surface [4, 5], hybrid optimization [6], proximity effect [7], ceramic materials [8], meta-materials [9, 10], and shorting pin [11] are effective ways for antenna miniaturization. Many different techniques for microstrip antenna miniaturization has been illustrated in [12]. Henceforth, several useful techniques for slot antenna miniaturization have been described in [13–16]. A compact rectangular patch antenna loaded with a half-U-slot and rectangular slot on the

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edges of the patch for broadband applications has been shown in [17]. A study on different types of slots loaded triangular patch antennas has been presented in [18]. Triangular patches with circular, triangular, rectangular, star slots, and folded rectangular slot produce 18.86%, 27.35%, 27.77%, 29.8%, and 43.47% size reduction, respectively, compared with a conventional patch antenna, but air substrate reduces antenna robustness for space applications. In [19], a T-shaped slit loaded patch antenna obtains 44.65% size reduction for portable GPS handsets. The size reduction of a patch antenna using curved edges has been reported in [20].

In summary, the reported works provide promising approaches to realize compact patch antennas, but problems still exist including limited size reduction, difficulty in fabrication, multilayers, etc. Therefore, it is time to redevelop the miniaturization techniques in higher degree along with minimum modification with the antenna geometry. And this techniques will allow the antenna to integrate with package or platform of advanced wireless systems that are emerging.

However, miniaturization techniques are well recognized concept for last two decades. Therefore, it is imperative to further explore the techniques for realizing higher degree of miniaturization with good antenna performances. This higher degree of miniaturized antenna will allow integration with the package or platform of small wireless devices that are emerging. It is known that the resonance of any antenna is directly linked with the antenna size. Any approach to reducing the size of an antenna can affect the return loss, radiation pattern, and efficiency, and the antenna with reduced size is unable to radiate properly. Then it would be a difficult work for antenna engineers to design a higher degree of miniaturization with minimum effect on antenna performances.

In this current paper, a rectangular microstrip patch antenna has been designed to resonate at 2.31 GHz. We introduced a slot on the radiating patch antenna. As a results, the miniaturization is 65.80%. Then similar slot is also introduced on ground plane to achieve miniaturization from 65.80% to 68.44%. The antenna dimensions for conventional patch and proposed antennas are identical. The paper is organized as follows. The conventional patch and modified patch geometry with reduced resonant frequency are described in Section 2. In addition, equivalent circuit analyses for both topologies are also attached. The modified path geometry is further modified by introducing a slot on ground plane which is presented in Section 3 with a comparative study on recently reported work. Finally, conclusion is drawn in Section 4.

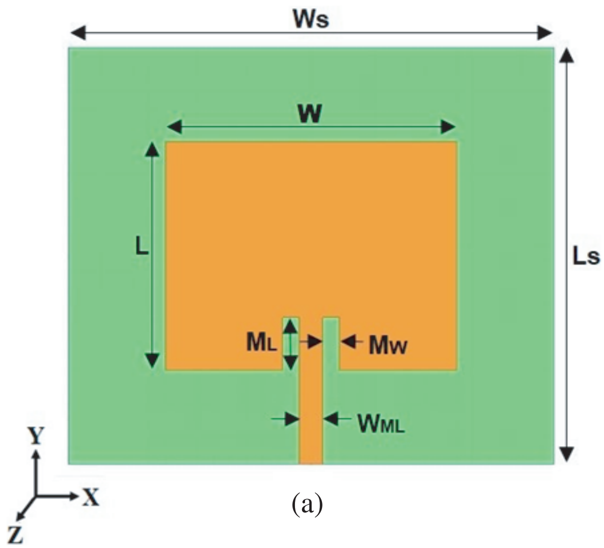
2. DESIGN AND ANALYSIS OF A SIMPLE RECTANGULAR PATCH ANTENNA WITH MODIFIED PATCH

Considering first a patch antenna oriented on top of the dielectric substrate to ground plane on the bottom of the substrate and a 50 Ω microstrip line feed to excite the patch. The top view of patch antenna is shown in Figure 1(a) whose parameters are $Ls = 51\,\text{mm}$, $Ws = 60\,\text{mm}$, $L = 28\,\text{mm}$, $W = 36\,\text{mm}$, $W_{ML} = 2.95\,\text{mm}$, $M_W = 3.20\,\text{mm}$, and $M_L = 6.44\,\text{mm}$. It is well known that this patch can resonate in its fundamental frequency when patch length is about half the free space wavelength. We note that dielectric material throughout this paper is chosen as FR-4 with its known material parameter: $\varepsilon_r = 4.4$, $\tan\delta = 0.021$, and thickness $= 1.58\,\text{mm}$. The software simulation was performed using finite element method based Ansys High Frequency Structure Simulator (HFSS) [21]. The simulated resonant frequency is 2.31 GHz whereas measured value is 2.40 GHz. The little discrepancy between the measurement results can be related to lossy FR_4 dielectric materials and additional ohmic loss normally generated while soldering the SMA connector on fabrication. For better comparison with resonant frequency reduction, the antenna in Figure 1(a) is considered a conventional antenna. The equivalent circuit for patch antenna is extracted from Figure 14.9, Chapter 14 [22]. The transmission line is replaced by series connection of resistance and inductance. The circuit diagram is shown in Figure 1(b). The numerical simulations of equivalent circuits and their optimizations were carried out using NI AWR [23]. The resonant frequency is

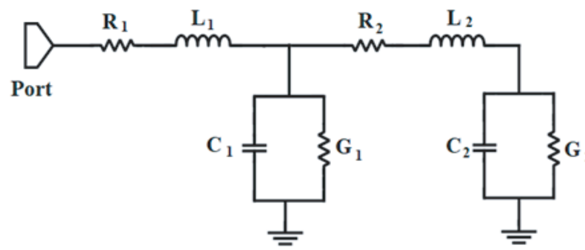
$$F = \frac{1}{2\pi\sqrt{(LC)}}$$

where symbols are standard.

The simulated and measured reflection coefficients of the conventional patch are illustrated in Figure 2 with a reasonable agreement between them. The −10 dB bandwidth for conventional patch



(a)



(b)

Figure 1. (a) Geometry of simple rectangular microstrip antenna. (b) Equivalent circuit model of microstrip patch antenna (The values are $R_1 = 0.815\,\Omega$, $R_2 = 0.738\,\Omega$, $L_1 = 10.69\,\text{nH}$, $L_2 = 1.532\,\text{nH}$, $C_1 = 3.49e\_06\,\mu\text{F}$, $C_2 = 0.262\,\mu\text{F}$, $G_1 = 0.00025510204\,\text{S}$, $G_2 = 1.11\,\text{S}$).

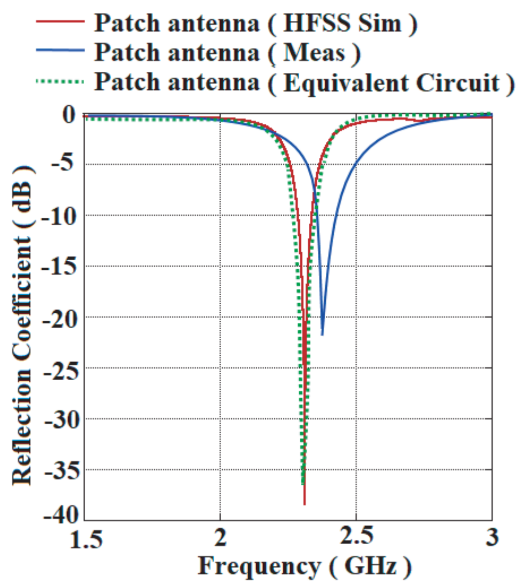


Figure 2. Reflection coefficient of patch antenna.

antenna is 2.18%. The simulated resonant frequency 2.31 GHz also exactly matches the equivalent circuit response. We introduced a slot on radiating patch as shown in Figure 3(a) keeping the patch antenna dimension unchanged. The parameter values are $Ls = 51\,\text{mm}$, $Ws = 60\,\text{mm}$, $L = 28\,\text{mm}$, $W = 36\,\text{mm}$, $W_{ML} = 2.95\,\text{mm}$, $M_W = 2\,\text{mm}$, $M_L = 11\,\text{mm}$, $W_1 = 2\,\text{mm}$, $W_2 = 2\,\text{mm}$, $W_3 = 2\,\text{mm}$, $W_4 = 1.52\,\text{mm}$, $L_1 = 1\,\text{mm}$, $L_2 = 20\,\text{mm}$, and $L_3 = 3\,\text{mm}$. The slot always produced an inductive environment over the transmission line [22]. This inductive environment is placed in parallel with the radiating patch. So, we modified our equivalent circuit diagram by placing an inductor to the patch. The equivalent circuit diagram is shown in Figure 3(b) with corresponding components. The reflection coefficient of the equivalent circuit is exactly matched with the simulated antenna response. The reflection coefficient plot of modified patch antenna is shown in Figure 4. After the introduction of a slot, resonant frequency

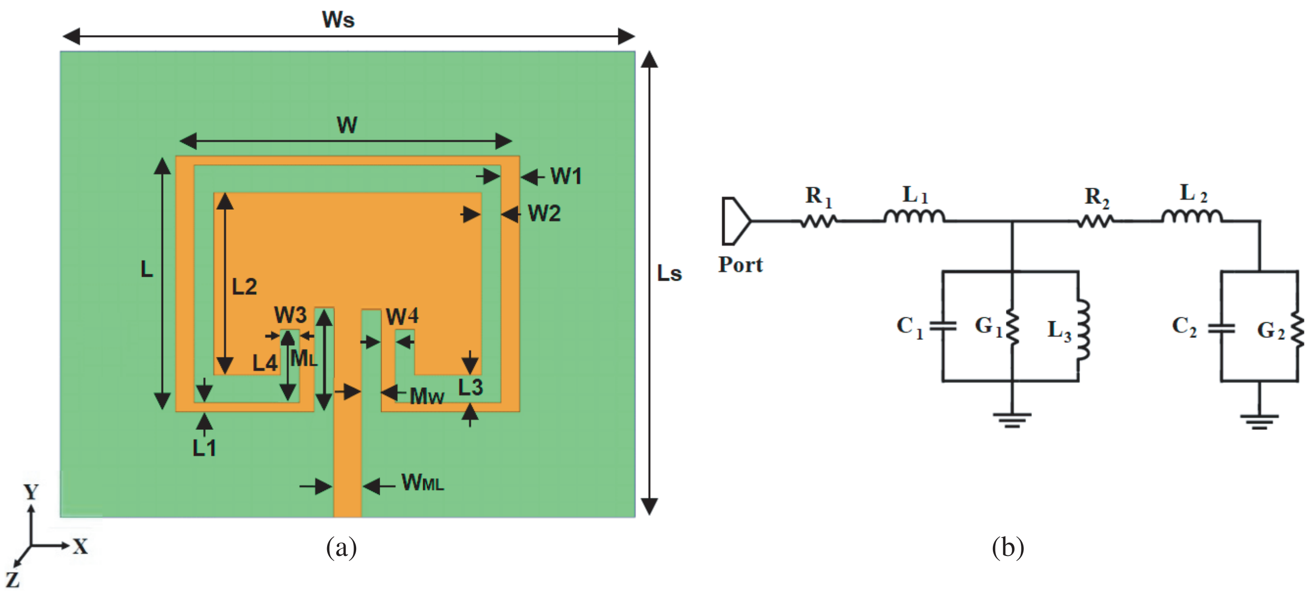


Figure 3. (a) Microstrip patch antenna with slot on the patch. (b) Equivalent circuit model (The values are $R_1 = 0.1\,\Omega$, $R_2 = 182\,\Omega$, $L_1 = 22.8\,\text{nH}$, $L_2 = 0.25\,\text{nH}$, $C_1 = 1.001e\_05\,\mu\text{F}$, $C_2 = 1e - 09\,\mu\text{F}$, $G_1 = 0.05316176895\,\text{S}$, $G_2 = 0.01\,\text{S}$).

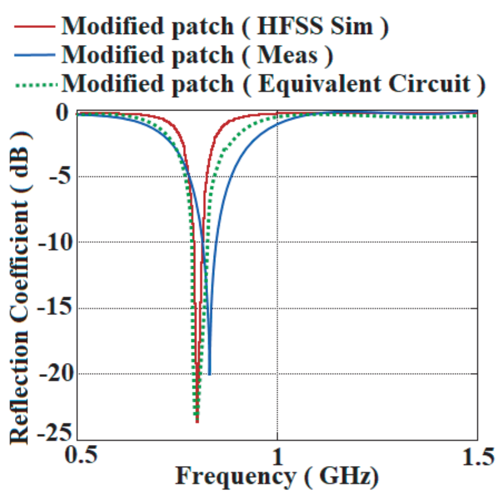


Figure 4. Reflection coefficient of modified patch.

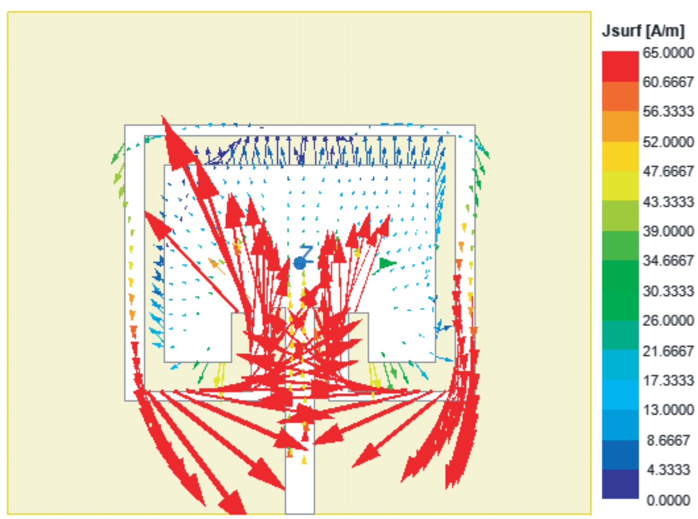
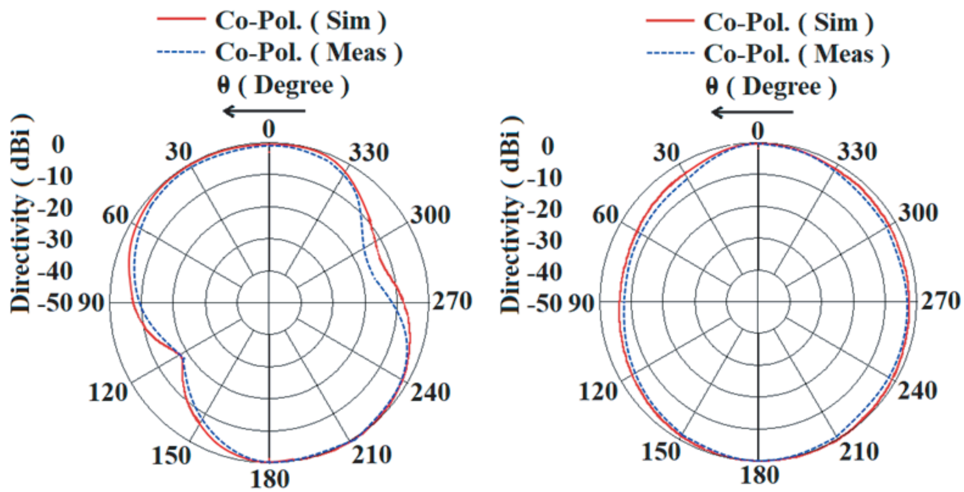


Figure 5. Current distribution of modified patch at 790 MHz.

is shifted from 2.31 GHz to 790 MHz. The percentage of reduction of resonant frequency is 65.80. The measured value is 811 MHz. The bandwidth for modified patch antenna is 2.65%. Generally, the slot on radiating patch surface creates an additional effective surface current path [18] on that patch which lowers resonant frequency. Here, we introduce a large slot in the patch surface in such a way to create maximum current path with minimum modification of conventional rectangular patch, thus making this antenna highly miniaturized. The current distribution of proposed antenna is depicted in Figure 5. The gain of conventional patch antenna is 1.88 dB whereas the gain of modified patch is −15.06 dB.

The far-field E and H plane radiation patterns of modified patch geometry at resonance frequency are shown in Figure 6. The agreement between measurement and simulation radiation characteristics is



(a) (b)

Figure 6. (a) E-plane radiation pattern. (b) H-plane radiation pattern for modified patch antenna.

pretty good. The simulated efficiency of conventional patch antenna is 51.24%, whereas the efficiency of modified patch antenna is 36.25%. The slot excites the patch in such a way that the patch allows high level back radiation which is a unique property for the proposed antenna. This omnidirectional radiation characteristic for patch antenna is widely applied as conformal antennas in aircraft communication system due to low cost, weight and profile and short range communications system at present.

3. DESIGN AND ANALYSIS OF A SIMPLE RECTANGULAR PATCH ANTENNA WITH MODIFIED PATCH AND GROUND PLANE

In modified patch, we have achieved 65.80% miniaturization with unchanged antenna dimensions and substrate properties. Now we introduce the slot on ground plane of modified patch which is identical in dimension placed on top of the radiating patch. Figures 7(a) & 7(b) show the top and bottom views of antenna topology. After the introduction of a slot on ground plane of the modified patch (Figure 3(a)), the resonant frequency shifted from 790 to 729 MHz. As a result, the miniaturization of modified patch is shifted from 65.80 to 68.44%. The equivalent circuit diagram is shown in Figure 7(c). The reflection coefficient of modified patch with modified ground plane is shown in Figure 8. As seen in these plots, the agreement between the measured and simulated results is excellent. The value of simulated frequency is 729 MHz. The bandwidth is 4.14%. The gain of modified patch and ground plane is -16.79 dB.

Impedance is a complex value having resistive and reactive parameters. The real part of this complex value is radiation resistance, while the imaginary part is known as the loss of the antenna. The real and imaginary parts of input impedance versus frequency plot of the proposed antenna are shown in Figure 9. The real part is near 50 Ω with an imaginary part of almost nil, so it indicates that the impedance is well matched. Hence, it can be said that input impedance characteristics are not affected due to higher degree of miniaturization.

The simulated and measured far-field radiation characteristics of the antenna at the resonant frequency of 729 MHz are plotted in Figure 10. The measured characteristics are in good agreement with the simulated ones. It is noticeable that its radiation pattern has maintained omnidirectional behavior. The efficiency of modified patch and ground plane antenna is 34.25%.

The parametric variation of slot width (W_1 & W_2) and position (L_1 & L_3) are shown in Figure 11 for modified patch and ground geometry. Figure 11(a) clearly shows that when $W_1 = 2$ mm, the proposed antenna resonates at 729 MHz with 4.14% bandwidth, but has a poor reflection coefficient when $W_1 = 1$ mm. The antenna was unable to produce a maximum reduction in resonant frequency for W_1 value of 2 mm. For Figure 11(b), we verified the width W_2 for the three consecutive values again

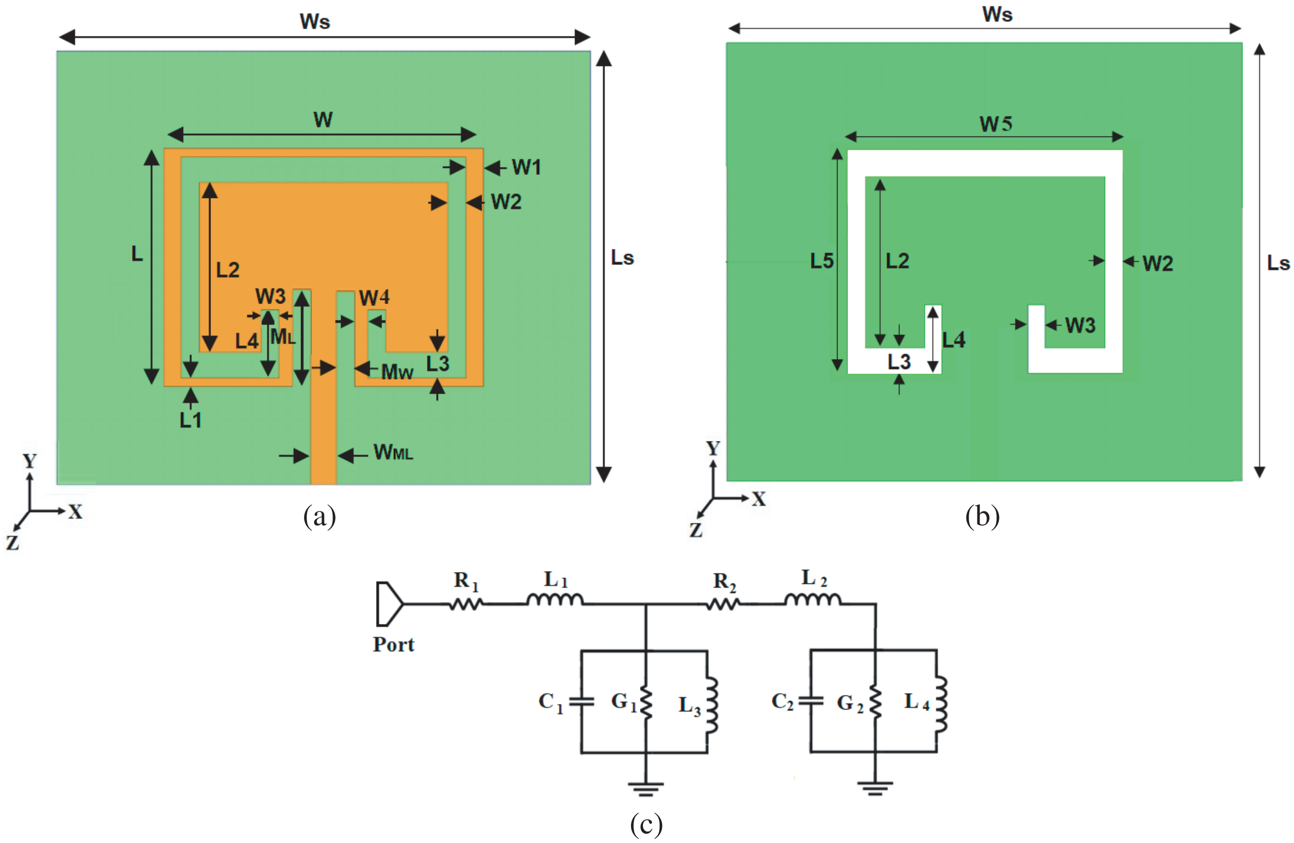


Figure 7. (a) Modified patch on top of the substrate. (b) Modified ground plane on bottom of the substrate. (c) Equivalent circuit model (The values are $R_1 = 0.1\,\Omega$, $R_2 = 182\,\Omega$, $L_1 = 21.6\,\text{nH}$, $L_2 = 0.25\,\text{nH}$, $C_1 = 1.191e\_05\,\mu\text{F}$, $C_2 = 1e - 09\,\mu\text{F}$, $G_1 = 0.05316176895\,\text{S}$, $G_2 = 0.01\,\text{S}$).

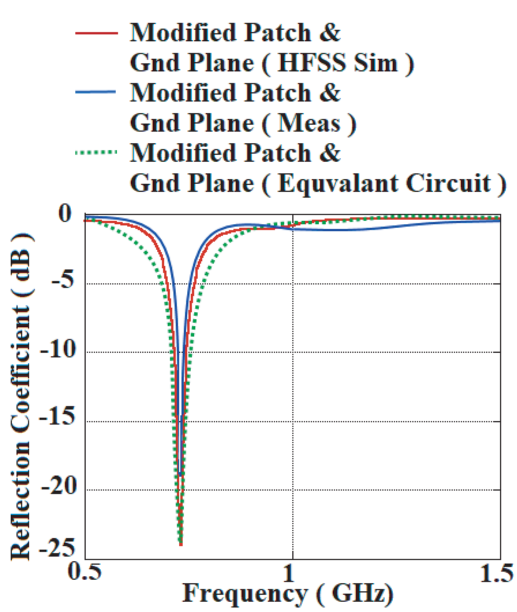
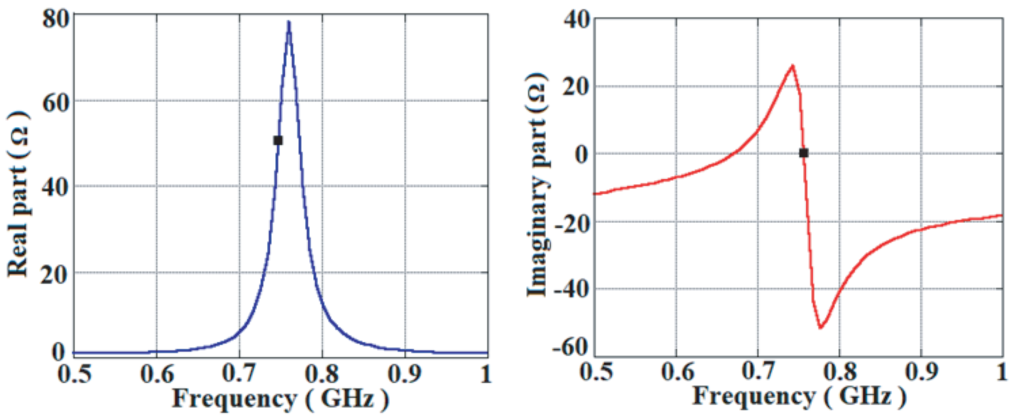
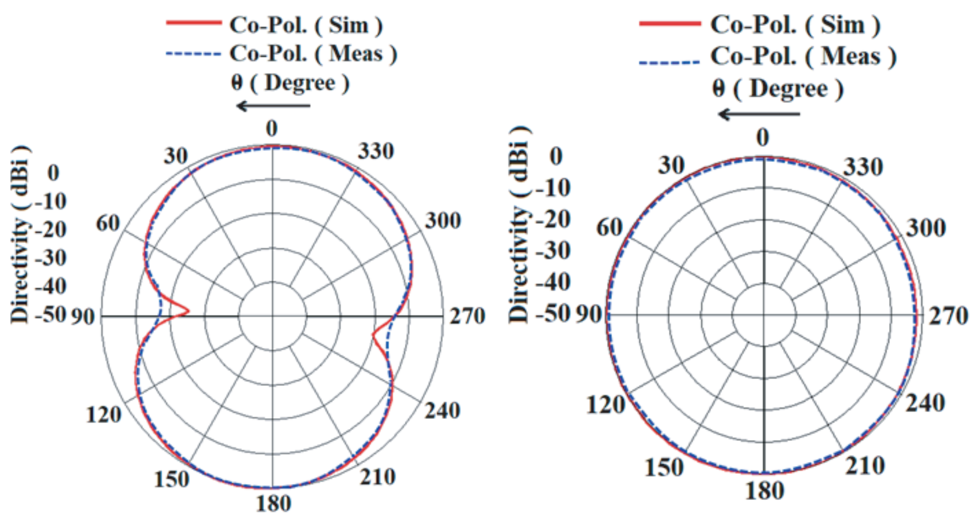


Figure 8. Reflection coefficient of the modified patch with modified ground plane.



(a) (b)

Figure 9. Input impedance of modified patch with modified ground plane. (a) Real part. (b) Imaginary part.



(a) (b)

Figure 10. (a) *E*-plane radiation pattern. (b) *H*-plane radiation pattern for modified patch with modified ground plane.

and obtained a measured value of 2 mm, which is acceptable in comparison to the other two values. Figure 11(c) depicts a variation for L_1 in which the slot position varies from 1 mm to 3 mm. It is justified that when we have taken the width of 1 mm, we get an acceptable value compared to the other two width values. Accordingly, we consider the case for L_3 in Figure 11(d) where four consecutive measured values are taken from 1 to 4 mm and get a better result for 3 mm than the other corresponding values.

Moreover, Table 1 compares the proposed antenna with the reported miniaturized patch antennas and indicates that the proposed antenna provides a higher degree of miniaturization in very simple and easy-to-implementable way. Note that two layers of dielectric material are required to construct the proposed antenna for inter-embedded metasurface structure [5], portable GPS handset antenna [19], and curved edges approach [20]. The comparative complex approaches for miniaturization, rather than introducing a slot, are hybrid topology optimization [6] and material unit cell [10]. The fabricated photo type is shown in Figure 12.

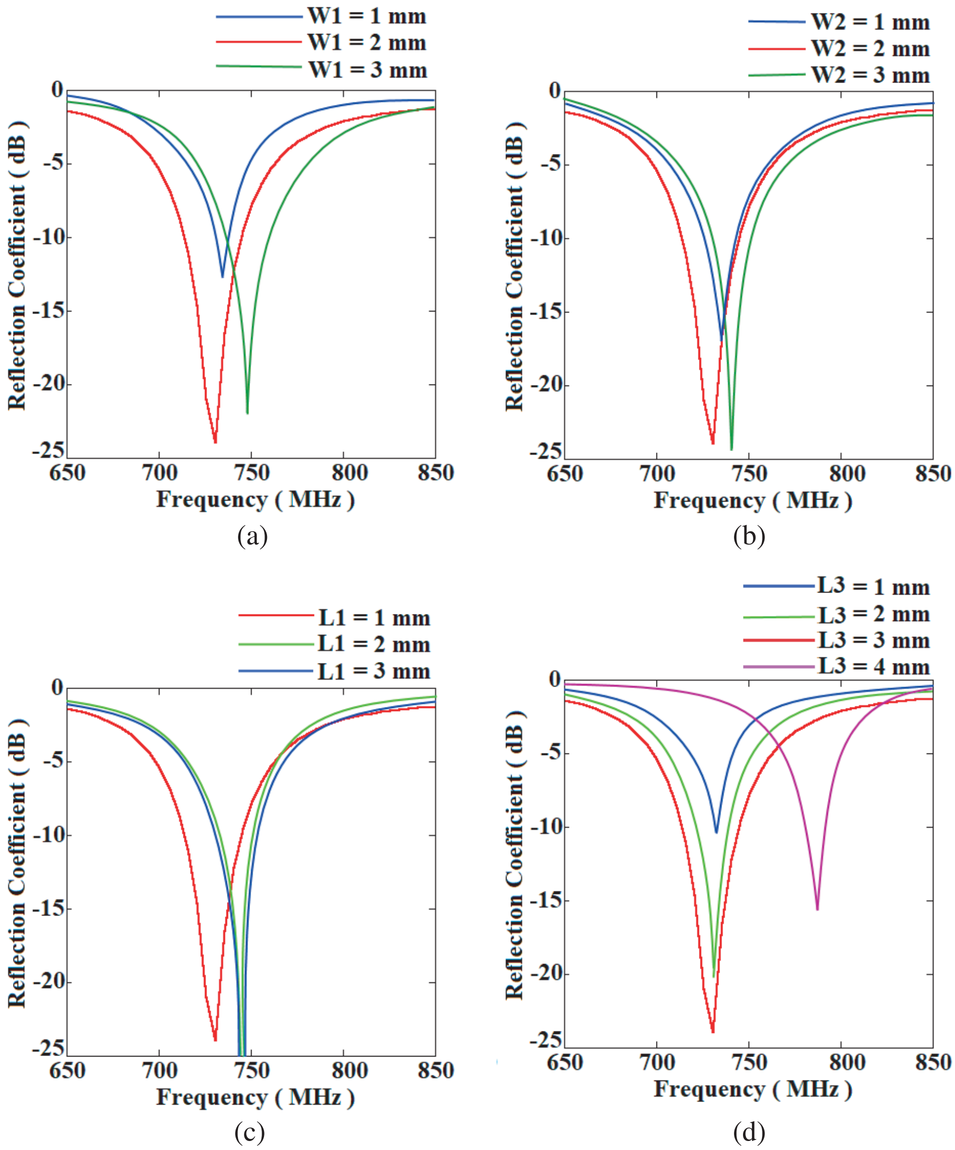


Figure 11. Parametric study of slot on patch for proposed modified patch and ground geometry.

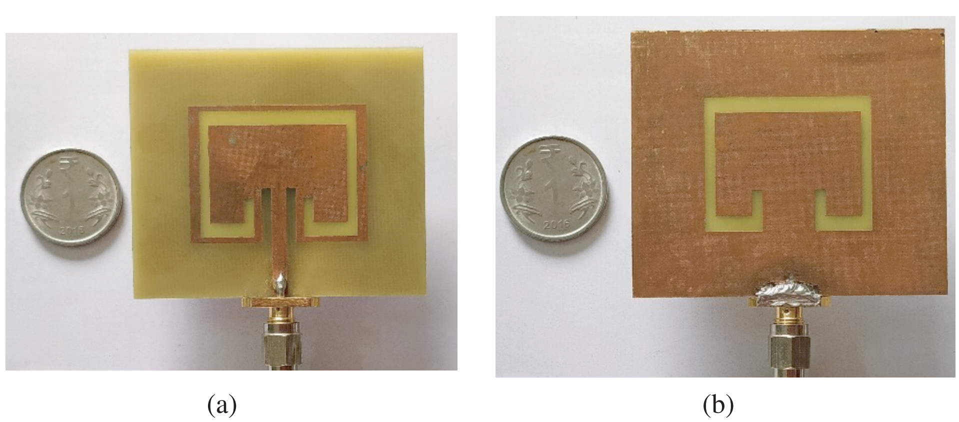


Figure 12. Fabricated photography of modified patch and ground plane. (a) Top View. (b) Bottom view.

Table 1. Comparison table with recent work.

Ref. & Year	Resonance frequency	Size reduction	Design complexity
[5], 2020	6.67 GHz	42%	Complex
[6], 2020	2.6 GHz	63%	Complex
[10], 2017	3.15, 5.28 GHz	60%	Moderate
[18], 2014	2.41 GHz	43.47%	Moderate
[19], 2003	1.575 GHz	44.65%	Complex
[20], 2020	10 GHz	63.5%	Moderate
This work	**0.729 GHz**	**68.44%**	**Simple**

4. CONCLUSION

A higher degree of rectangular patch antenna miniaturization technique is presented based on frequency reduction method by introducing a slot on the radiating patch. As a result, the miniaturization is 65.80%. Then a similar slot is also introduced on ground plane to achieve miniaturization from 65.80% to 68.44%. The antenna dimensions for conventional patch and proposed antennas are identical. The proposed antenna can be used as conformal antennas in aircraft communication systems due to low cost, weight and profile and short-range communications system.

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