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AN INTEGRATED WIDEBAND MULTIFUNCTIONAL ANTENNA USING A MICROSTRIP PATCH WITH TWO U-SLOTS

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Abstract—In this paper, a multifunctional microstrip antenna is designed, fabricated and experimentally verified for operation in AWS, GSM, WiMAX and WLAN bands. This microstrip patch antenna has two U-shaped slots to achieve the dual wideband operation required to meet these specifications. The dimensions and locations of the U-slots are designed appropriately. The thick substrate used here helps in integrating the antenna with the existing aircraft panel material while achieving wide bandwidths. Experimental results of this single feed antenna indicate that it meets all current requirements for in-cabin wireless communication needs.

1. INTRODUCTION

Modern life depends so much on wireless technologies that one can no longer afford to be off-line for long, even during flights. Although present regulations do not allow the use of wireless devices, the aircraft industry has already begun efforts to introduce in-flight wireless connectivity [1, 2]. Although the antenna requirements for these access points within the cabin are not as stringent as antennas placed outside the aircraft, an ideal possibility in this regard would be to integrate the antenna with structural panel materials used typically in cabins. In this context, we present a study that investigates the possibility of designing an integrated wireless antenna catering to various wireless applications using the cabin panel material as the antenna substrate.

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Planning of wireless access points in this scenario, even for mobile phone access, is complicated by the fact that the aircraft, particularly the long-haul ones, are expected to conform to wireless standards currently existing in different parts of the world. It is even more intricate to integrate access points for wireless technologies such as AWS, GSM and various WiMAX and WLAN bands operating at 1.710–1.755 GHz, 1.805–1.880 GHz, 1.900–1.990 GHz, 2.110–2.170 GHz, 2.4–2.5 GHz, 5.15–5.35 GHz, and 5.45–5.85 GHz.

The above operational frequency requirements could be conveniently met with an antenna having two wideband ranges 1.7–2.5 GHz, (BW $\sim$ 38%) and 5.15–5.85 GHz (BW $\sim$ 14.5%). Some approaches for such dual wideband operation at these frequencies are available in literature. One such design proposes a planar monopole antenna for wireless handsets [3]. Some of the other dual-wideband monopole antennas use a modified half-Sierpinski fractal gasket [4], Minkowski fractal geometry [5] and a modified fractal slot fed by cpw [6]. All these configurations are bidirectional antennas and hence cannot be integrated with panels to provide a uniform coverage within the cabin. Backside radiations reflected from the metallic body of the aircraft would seriously degrade the antenna performance.

Microstrip patch antennas on the other hand have unidirectional radiation pattern and are widely considered suitable for many wireless applications. Microstrip antennas have compact size, low weight and low cost [7]. Various shapes of patches and feed mechanisms have been studied for these antennas to improve their bandwidth or to make them operate at multiple frequencies [8]. Yet none of the existing approaches cater to the design of a multi-functional conformal antenna with the two widebands of operation required here. It is clear that two, individually challenging modifications may have to be combined for designing a microstrip antenna with dual-frequency characteristics and wideband operation [8].

Several broad-banding techniques for microstrip antennas are widely known, prominent among them use stacked [9] or parasitic patches [10]. Stacked patch antennas have multilayer structure which is disadvantaged by the overall thickness and fabrication issues related to aligning various layers precisely. Use of shorting pins though reduces the size, the achievable bandwidth is limited [11].

Other relatively simpler approaches include using a thick, low dielectric constant substrate and/or using slots in the patch [8, 12]. Usually a U-shaped slot is used [13–15]. Such broad banding techniques are suitable only for single wideband operation. Design of dual- and multi-band microstrip antennas even with narrow bandwidths is challenging [7]. Patches with suitably designed slits or slots are useful in this context [8].

A double-U-slot antenna has been proposed for operating bands of 3.5–4 GHz and 5.8–6.3 GHz [16]. However, the bandwidth is not wide enough for the current application. Dimensions of these slots are individually fine-tuned for the specified performance. The feed location is moved away from the center to compensate for the probe inductance at the high frequency band. The proposed design has two wideband operational bands centered at 2.1 GHz and 5.4 GHz to meet the requirements. The antenna geometry and design are introduced in Section 2. Discussion of results is done in Section 3 followed by experimental validation in Section 4. Swept frequency radiation pattern measurements in the E- and H-plane are obtained to estimate the field distribution characteristics of the antenna and their variation with frequency and angle are studied experimentally.

2. ANTENNA GEOMETRY AND DESIGN

2.1. Basic Configuration

The proposed antenna consists of a rectangular patch with two U slots as shown in Fig. 1, supported by a customized substrate. The substrate used here has a three layer internal structure. The outer skin layers have a dielectric constant $\varepsilon_r = 3.5$ and thickness of 0.6 mm. The sandwiched honeycomb layer in the middle has permittivity of 1.05 and is 8.5 mm thick. Such sandwich structures are typically employed in aircraft parts and cabin panels to reduce weight and cost. The quasi-static permittivity of this configuration was calculated numerically using IE3D v12, a method of moments(MoM) solver. The procedure involves approximating a patch by a transmission line whose length is nearly half a wavelength at the center frequency. The quasi-static permittivity calculated was 1.13. The height of the substrate T, has to cater to the needs of both the resonant center frequencies namely 2.1 GHz and 5.4 GHz. The thickness of the three layer cabin panel used as the substrate here is 9.7 mm. The thick panel material used in the present study helps to split the resonant modes at the low frequency band to increase the bandwidth there. A rectangular patch antenna is designed to operate in the lower frequency band. Based on standard formulae for patch width and length [17] the dimensions of a patch for 2.1 GHz on the customized substrate are 68.4 mm (W) and 54.8 mm (L). This is further optimized using numerical simulations after inserting the U shaped slots.

2.2. Design of the U Slots

The basic patch is designed to resonate at 2.1 GHz. To introduce a wide operational band about this frequency an additional resonance is brought in by incorporating a U-slot whose length $(2l_{s1} + b_{s1})$ is equal to the slot wavelength at a frequency close to the resonant frequency of the patch. Using the integrated approach for a patch with a single U-slot [12], the dimensions of the patch and the U-slot for broadband operation are obtained by IE3D simulations.

The dual band characteristic of the proposed antenna is achieved by incorporating another U-shaped slot inside the outer U-slot. The center frequencies of these bands are controlled by the electrical length of these slots. In the absence of a complete analytical approach for the design of such an antenna configuration with two U slots,parametric studies are conducted to arrive at the desired performance. The design uses equal arm lengths to retain symmetry in co-polarization patterns. In addition to other factors, the thick multi-layer substrate

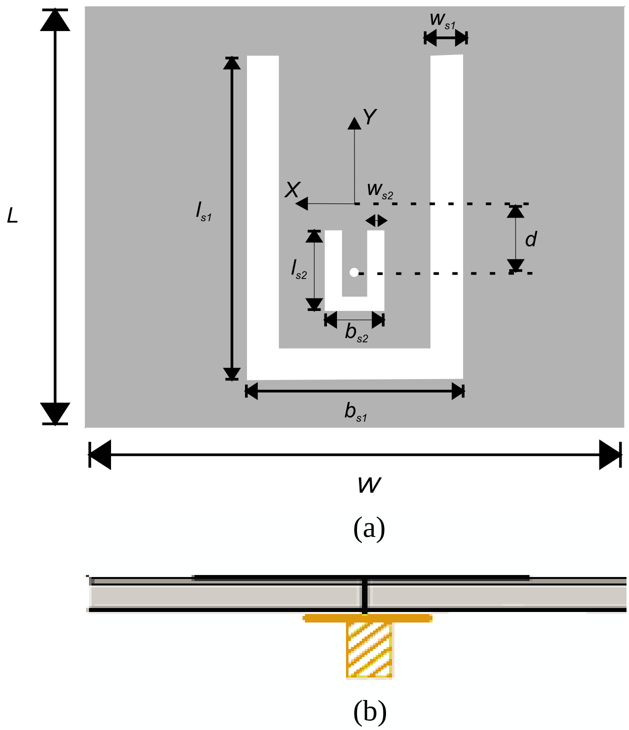


Figure 1. Geometry of the patch antenna with two U-slots. (a) Top view of the patch. (b) Cross sectional view.

helps in achieving the required bandwidth. U-slots used in this patch introduce capacitance which is cancelled by the probe inductance at the respective bands to bring in an additional resonance close to the patch resonance. Thus an effective broadening of the operational band results at two distinct ranges of frequencies. The dimensions of the antenna are shown in Table 1. The parametric variation of S_{11} with the length of the outer slot is shown in Fig. 2. The required bandwidth (1.7 GHz–2.2 GHz and 2.4–2.5 GHz) is obtained for a total length of 90 mm.

By adjusting the width of the outer slot w_{s1}, impedance matching can be further improved. It also affects the broad band characteristics to an extent. It is observed that a slot with a thickness of 4 mm is optimal. As the slot width is decreased the impedance loop becomes more inductive. On the other hand a wider slot is used to introduce larger capacitive loops in the smith chart and thus aids in both matching and broadband characteristics. The parametric variation of S_{11} with width of the outer slot is shown in Fig. 3.

A similar procedure is followed for the design of the inner slot, within the small patch created by the outer slot. A parametric study is done to arrive at the exact slot length that creates a resonance at center frequency of 5.4 GHz. The undesired operation below 4 GHz is removed, and an operational band ranging from 5.15 to 5.85 GHz is obtained when the total length of this slot is 30 mm. As shown in Fig. 4, this design causes the S_{11} below -6 dB in this band. As before, the inner slot width w_{s2} marginally affects the impedance matching.

Table 1. Geometrical parameters of the antenna as labeled in Fig. 1 [all dimensions in mm].

Parameter	Dimension
Patch length (L)	52
Patch width (W)	71
Length of vertical outer slot (l_{s1})	36
Length of horizontal outer slot (b_{s1})	18
Width of outer slot (w_{s1})	4
Total length of outer slot ($2l_{s1} + b_{s1}$)	90
Length of vertical inner slot (l_{s2})	13
Length of horizontal inner slot (b_{s2})	4
Width of inner slot (w_{s2})	1
Total length of inner slot ($2l_{s2} + b_{s2}$)	30
Feed offset (d)	9

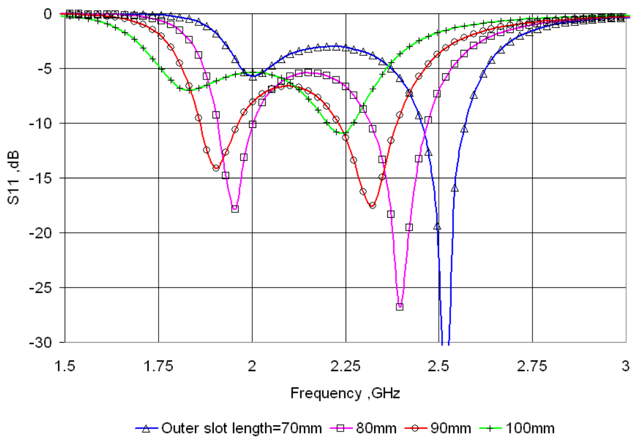


Figure 2. S_{11} variation as the total length of the outer slot is varied from 70 mm to 100 mm. Other dimensions of the antenna are in Table 1 [18].

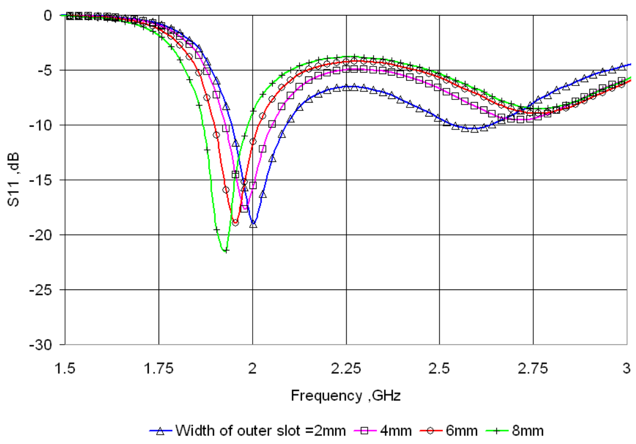


Figure 3. S_{11} variation as the outer slot width alone is varied from 2 mm to 8 mm. Other dimensions of the antenna are in Table 1.

The width of the inner slot is varied from 1 mm to 3 mm as in Fig. 5. As the width is decreased the bandwidth appears to increase. An increase in width also causes the spectrum to shift to the higher side. A width of 1 mm is seen to be optimal for the required bandwidth. For the inner slot, the width does not seem to affect the matching much. The width of the inner slot is limited by fabrication limitations. So a trade-off has to be made. The gain is uniformly ≥ 3 dBi for the 5.15–5.85 GHz band when the width is 1 mm. It is seen that the pattern at this frequency band, is smooth without nulls when the width of the slot is 1 mm.

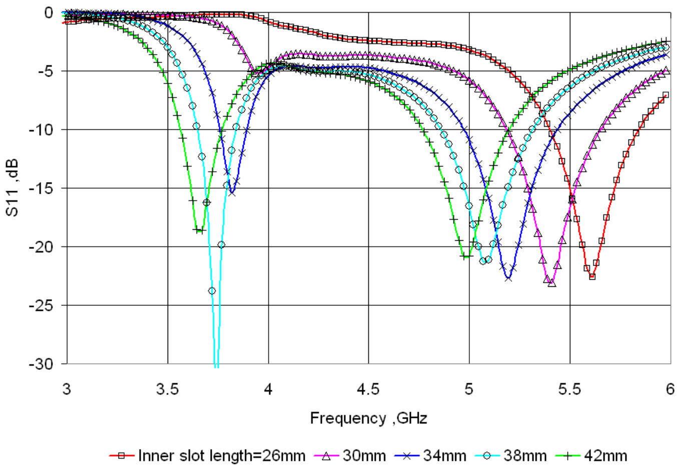


Figure 4. S_{11} variation as the total length of the inner slot is varied from 26 mm to 42 mm. Other dimensions of the antenna are in Table 1 [18].

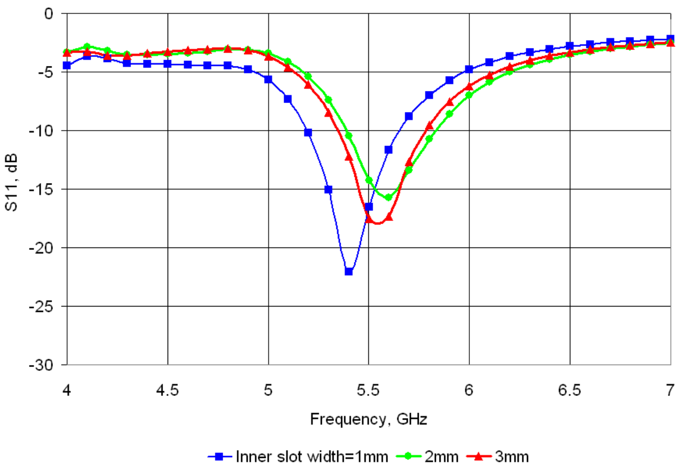


Figure 5. S_{11} variation as the inner slot width alone is varied from 1 mm to 3 mm. Other dimensions of the antenna are in Table 1.

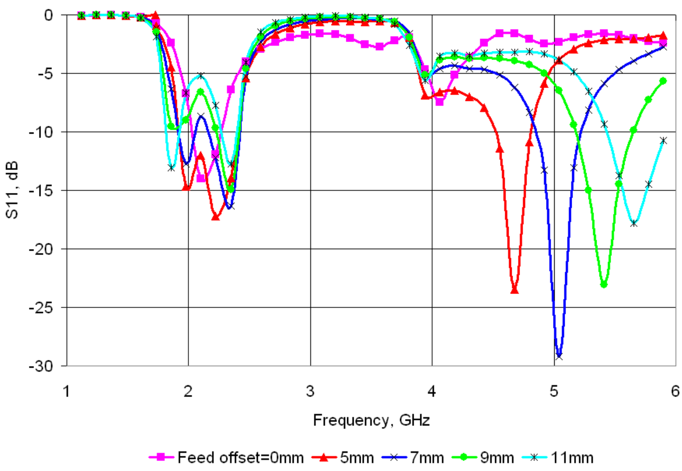


Figure 6. S_{11} variation as the feed offset from center, is varied from 0 mm to 11 mm. Other dimensions of the antenna are in Table 1.

Incidentally, a small stand-alone single U-slot patch whose dimensions fit within the outer U-slot,when simulated independent of the outer U-slot results in a similar return loss characteristic above 5 GHz.

2.3. Feed Position

Another parameter which affects the design is the feed position. The feed location is moved from the center of the geometry to get the best possible impedance match and radiation characteristics for the antenna. It is seen that offset of feed position from the center controls the center and width of the operational band. The S_{11} variation with offset from center is shown in Fig. 6. The feed as is seen from the parametric variation has to be surrounded by a slot. It can be seen in Fig. 6 that at offset lengths of 0 mm and 5 mm for which the feed is not surrounded by inner slot, placement of the feed outside the slot leads to poor matching and narrow bands. The slots are located symmetrically inside the patch to achieve compactness.

3. ANALYSIS AND DISCUSSION OF RESULTS

Though there has been a wide use of U slots in the literature for many applications, there is no complete analytical approach entailing the design of such a U slot. The ones that are available for the design of a single U slot are empirical in nature [12]. Therefore extensive parametric studies were carried out to arrive at the present design.

A double-U-slot antenna has been proposed for operating bands of 3.5–4 GHz and 5.8–6.3 GHz [16]. However this antenna has a fractional bandwidth of 6.2% at the lower band and about 10% at the higher frequency band. Additionally one may also notice that the ratio of mid-frequencies of operating bands is only 1.4. These fall significantly short for the current requirement of an antenna with about 40% bandwidth at the lower band and 15% at the higher band. Furthermore, the first frequency of operation required is almost half as much as reported in [16] and hence the proposed design is significantly modified. Furthermore the proposed antenna is integrated onto existing panel materials.

The proposed antenna works on the basis of multiple resonances established due to the U slot on the patch. The resonances can be analysed based on surface current distribution. Two individual lower band resonances combine together to give a wideband from 1.7 GHz to 2.5 GHz.Additionally there is a higher band resonance at 5.4 GHz with a wideband from 5.15 to 5.85 GHz. The current distribution of the proposed antenna obtained using IE3D 12 is shown in Fig. 7 at 1.9 GHz.

At frequency of 1.9 GHz it can be said that the current distribution is that of TM_{01} mode strongly perturbed by the presence of two U slots. The surface currents originate behind the outer U slot and are strong towards the outer edges of the outer slot and slightly towards the vertical edges of the patch. The presence of two U slots forces the surface currents of the TM_{01} mode to travel around the U slots. The current paths are symmetric around the slots and on the patch. This also explains the symmetrical radiation patterns seen in the lower band.

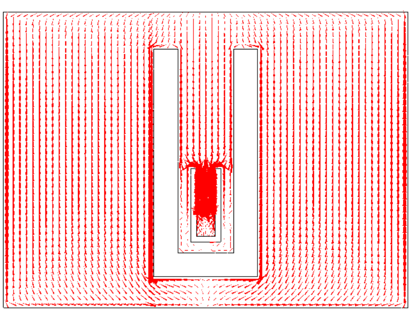


Figure 7. Current vector distribution on the patch at 1.9 GHz.

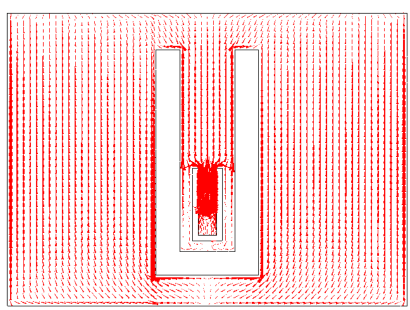


Figure 8. Current vector distribution on the patch at 2.3 GHz.

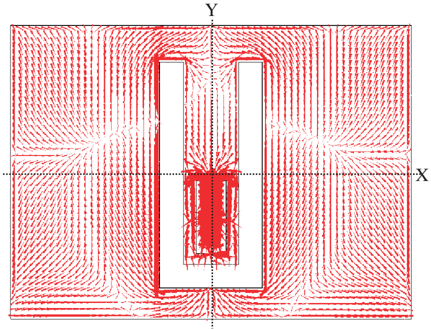


Figure 9. Current vector distribution on the patch at 5.4 GHz.

Figure 10. Photograph of the fabricated antenna with two U-slots.

As seen from Fig. 8, there is not much difference between the antenna behaviour at 1.9 GHz and at 2.3 GHz. The mode remains TM_{01}.

The surface current distribution at 5.4 GHz is different from the other two frequencies as seen in [Fig. 9]. At 5.4 GHz the inner slot is active and creates variations in surface currents. The surface currents emanate from multiple points on the patch. They are very strong around the inner slot perimeter. Based on these TM_{11} mode of operation can be concluded. The radiation pattern at 5.4 GHz has a null at a point near to the boresight, which can be attributed to the asymmetric paths of the currents w.r.t the X axis. The null is not seen in the H plane as the currents travel in symmetry w.r.t the Y axis.

4. EXPERIMENTAL VALIDATION

A prototype antenna is fabricated on the customized three layer substrate. The patch is etched on a copper sheet of 50 μm thickness and attached to one face of the three layer substrate using glue. On the opposite face a copper sheet is pasted to act as the ground. A hole is drilled through the probe mark on the patch to meet the copper ground on the opposite face. An SMA Female connector with 4 hole panel mount and extended dielectric and solder post is used for the RF connection. The ground of the long pin SMA connector is soldered onto the copper sheet ground. A photograph of the fabricated antenna with dimensions in Table 1 is shown in Fig. 10.

The antenna is characterized using Agilent PNA (N5230A) Network Analyzer for S_{11}. The simulated and measured S_{11} are compared in Fig. 11. It may be seen that in the 1.7 to 2.5 GHz band and in the 5.15 to 5.85 GHz band there is a very good agreement between the simulated and measured results.

The radiation pattern of the antenna geometry was simulated using CST Microwave Studio 2009 to account for the finite ground and dielectric. The simulated antenna pattern agrees well with that of the measured pattern. The pattern for frequencies at center of the two widebands are shown in Fig. 12. The radiation pattern was measured in a microwave anechoic chamber.

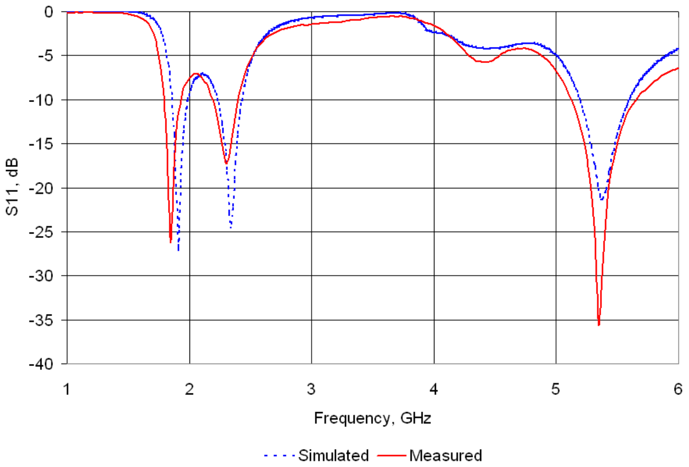
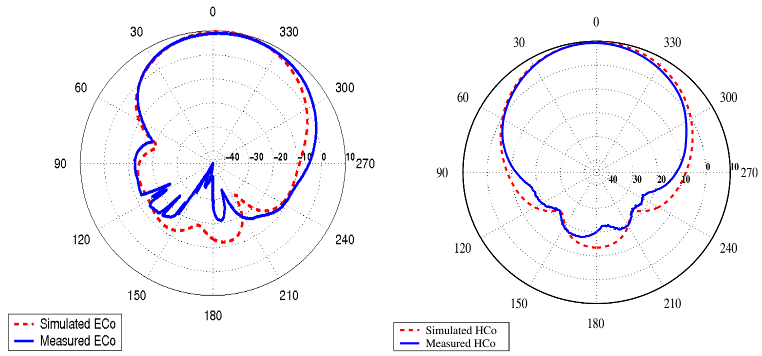


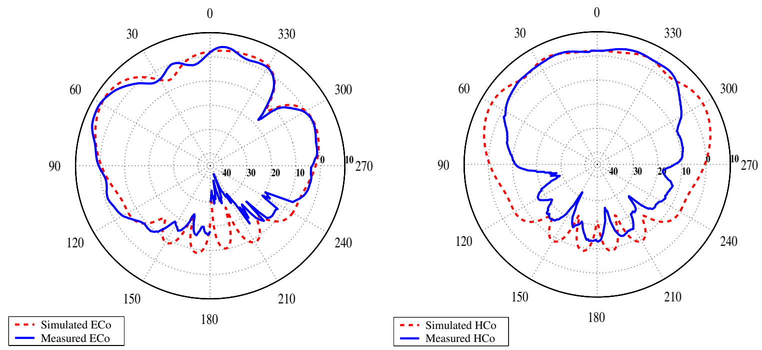
Figure 11. Simulated and measured S_{11} characteristic of the antenna.

Table 2. Range of various antenna parameters in the different wireless bands of interest.

Wireless band (MHz)	Average S_{11} (dB)	Average peak gain (dBi)	Average beamwidth E plane (Deg)	Average beamwidth H plane (Deg)
1710–1755	7.1	2.0	125	132
1805–1880	16.8	7.1	124	134
1900–1990	9.4	8.1	119	132
2110–2170	8.7	8.4	113	129
2400–2500	8.8	7.1	112	130
5150–5350	17.3	6.9	146	196
5450–5850	10.9	5.7	143	185



E and *H* plane radiation patterns at 2.1 GHz



E and *H* plane radiation patterns at 5.4 GHz

Figure 12. Measured and simulated radiation patterns at various frequencies.

A 3D plot showing the measured field distribution plotted vs angle and frequency of operation is shown in Fig. 13. The field measurement is done in an anechoic chamber with swept frequency measurement. Two identical antennas were used to measure the characteristics. These plots made after the necessary corrections show the field distribution along the aisle and along the row for an antenna located in the cabin ceiling. It can be seen from the plots that these patterns have a marginal variation within each of the wireless bands of interest. These plots are also consistent with the symmetry of the patch geometry. Table 2 shows the average values of S_{11}, peak gain, boresight gain, and 10 dB beamwidth in the various wireless bands of interest.

Additional measurements are planned for the antenna inside an aircraft. These would be useful in characterizing the actual propagation parameters.

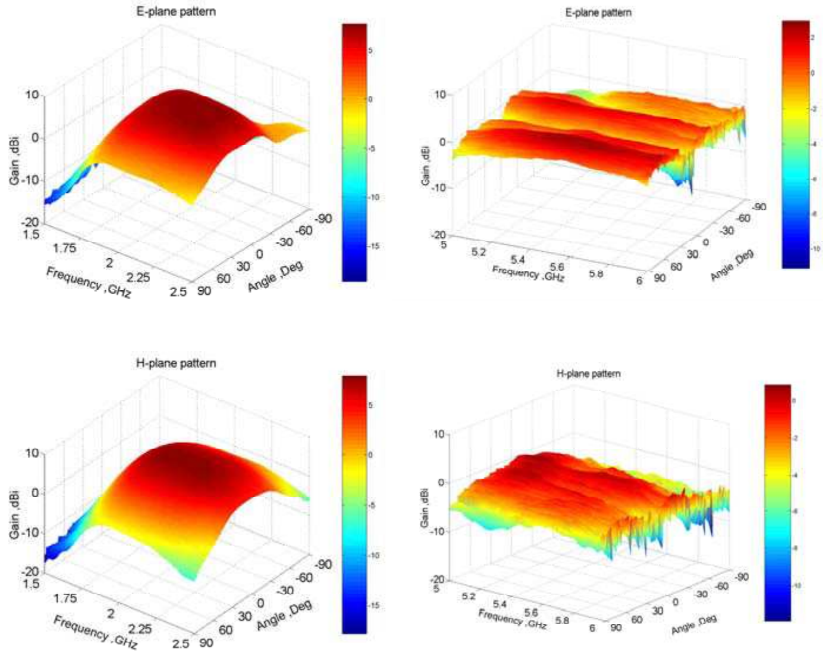


Figure 13. Measured 3D patterns at two bands plotted vs. frequency and angle.

5. CONCLUSIONS

The design of a microstrip patch antenna to operate for several wireless bands with frequency ranges of 1.7–2.2 GHz, 2.4–2.5 GHz, 5.15–5.35 GHz, and 5.45–5.85 GHz is proposed here. The antenna uses panel materials currently used in air plane cabin and hence can be easily integrated and deployed. The primary advantage of this approach is the ease of fabrication as the design does not require alignment between multiple layers of dielectrics and metals. Two U-slots are included to provide the above operating frequency bands. By adjusting the dimensions of the patch, of the slots and the offset of the feed location from the centroid, the desired bandwidths can be obtained for the antenna on this thick substrate. The radiation characteristics have been measured and its variance with angle and frequency studied. The bandwidths and signal strengths are within sufficient tolerances for commercial use. The designed antenna will be tested inside an aircraft cabin which would be useful for characterizing the actual propagation parameters.

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