CHAPTER 5

SLOT ANTENNA FOR 2.4 GHz WLAN AND UWB OPERATIONS

In this chapter, two more slot antennas are developed for 2.4 GHz WLAN and UWB applications, by using stepped stub and corrugated stub structures. These stub structures improve the impedance matching for the multifunctional communication systems. Various design parameters are studied and their effects on the performance characteristics are investigated.

5.1 SLOT ANTENNA WITH STEPPED STRUCTURE

5.1.1 Antenna Design

The geometrical configuration of the proposed antenna is shown in Figure 5.1. This antenna is fabricated on one side of the FR4 substrate with a thickness \( h \) of 1.6 mm and relative dielectric constant \( \varepsilon_r \) of 4.4. The main structure of the proposed slot antenna has a wide rectangular slot size of \( (L \times W) \) mm and the dimension of the dielectric substrate is \( (L_g \times W_g) \) mm. At first, the periphery of the rectangular slot at the lower frequency end \( (f_l) \) is obtained from

\[
2(L+W) \text{ mm} = \left(\frac{300}{f_l\sqrt{\varepsilon_r}}\right)
\]

where, \( f_l \) - is the lowest operating frequency of the proposed antenna in GHz. Then by optimization technique, exact dimension of the slot is derived. Using
computer simulation, the size of the ground plane is increased to a certain size (29 x 32) mm for better radiation pattern.

This antenna is excited by a CPW feed with a stepped stub (SS) structure and the coplanar waveguide is designed to be 50 Ω in order to match the characteristic impedance of transmission line. The SS structure is placed at the center of the rectangular slot to couple maximum energy from feed line to the slot. ‘Ls’ is the length of the SS structure whereas, ‘Ws’ is its width. The dimensions of the rectangular slot (W and L), the parameters of the tuning stub (Ws and Ls) and the spacing(S) affect the broad band operation of

Figure 5.1 Geometry of the antenna with stepped stub structure
the slot antenna, which means that the operating bandwidth is limited by matching between the feed and the wide rectangular slot in the ground plane. In fact, the size of the feed along with the stub is about one third of the rectangular slot size (L x W) mm. The optimized values of the parameters provide the widest bandwidth from 2.3 to 11.8 GHz (without slot) (Figure 5.8). Therefore, the rectangular slot in the ground plane is known to be a radiating slot. To explore the band-notched characteristic for 5 GHz WLAN, a slot is embedded inside the stepped stub structure too. The length of the slot is varied to obtain the desired notch-band function. The slot introduced inside the tuning stub destroys the surface current on the ground plane. Therefore, it gives maximum attenuation due to reflected power at the notched frequency. The optimum value is L = 16.5 mm, which is found to be nearly equal to the half wavelength at notch band center frequency i.e. 5.5 GHz. This is obtained by using the equation

\[ \lambda/2 = c / 2f\sqrt{\varepsilon_{\text{eff}}} \]  \tag{5.2} 

where, \( \varepsilon_{\text{eff}} = (\varepsilon + 1)/2 \), \( \varepsilon \) = relative dielectric constant

Since the slot is almost \( \lambda/2 \) at the notch frequency, it transforms short circuit at the slot to open circuit at the antenna feeding point. This leads to the desired high attenuation and impedance mismatching around the notch frequency. Therefore, the stub slot is known to be a notch band slot.

A parametric study has been carried out to understand the effects of the dimensional parameters and to optimize the performance of the final design. The optimum parameters are summarized in Table 5.1. In all the parameters study, one parameter is varied keeping the other parameters constant as shown in the Table 5.1.
5.1.2 Effect of Rectangular Slot size

A wide rectangular slot is used in the proposed slot antenna to achieve a high level of Electromagnetic energy coupling from the feed line. Therefore, varying the slot size will change the coupling property and thus the operating bandwidth is limited. As shown in the Figure 5.2(a), when the width (W) of the slot is varied from 22 mm to 26 mm, there is a shift in the edge of low frequency from 2.76 GHz to 2.2 GHz.

Figure 5.2 Simulated VSWR values for (a) width (b) length of the slot in the ground plane
But, the edge of high frequency band is slightly affected with the increase in the width. Similarly, when the length (L) of the slot is varied from 10 mm to 12 mm, low frequency edge is shifted from 2.2 GHz to 2.45 GHz. But, a slight shift is there in the high frequency edge (Figure 5.2(b)). Therefore, the slot size of the proposed antenna greatly affects the low frequency edge than the high frequency edge. From the Figures, the optimum value of the slot size is found to be (10 x 26) mm.

5.1.3 **Effect of Steps in the Stub**

In this parameter study, the size of the steps in the tuning stub is consecutively reduced and its effect on the impedance matching is investigated. The length of the first step is taken to be 9 mm (i.e. $W_s = 9$ mm) and its width is 2.2 mm. The simulated VSWR curves of the CPW fed slot antenna for the change in the tuning stub size with step are illustrated as in Figure 5.3. This means that the stub size increases with increase in length of the stub ($L_n$).

![Figure 5.3 Effect of steps in the tuning stub](image)
As shown in the Figure 5.3, the curves for different size of the tuning stub have similar shape but variation trend. As such when the number of step is increased from 3 to 5, there is a shift in the low frequency edge from 2.46 GHz to 2.2 GHz. The high frequency edge is shifted slightly towards the lower frequency. Therefore, in order to lower down the low frequency edge for the proposed 2.4 GHz antenna, a stepped stub structure with 5 steps is chosen. The optimized value of 'L_s' which corresponds to 5 steps is 6.7 mm. Apart from this, there is a significant fluctuation in the 6.9 GHz to 8.71 GHz band. A smoothing performance of the impedance characteristic at this band is achieved by making a small slit cut(1x11) mm in the ground plane as shown in Figure 5.1(on the feed side). This structure further improves the impedance matching and the low frequency edge is shifted to 2.1 GHz (Figure 5.4).

![Figure 5.4 Effect of small slit cut in the ground plane](image-url)
5.1.4 Effect of Slot on the Tuning Stub

The influence of slot embedded on the SS structure is also investigated for notch band function. Figure 5.5 shows the simulated VSWR values of the proposed antenna with different length ‘$L_t$’ of slot (its width is kept at 0.4 mm). From the Figure, it is observed that the length of the slot line in the stub determines the frequency range of the notched band. As ‘$L_t$’ increases, the centre frequency of the notched band shifts towards the lower frequency. With the increasing of ‘$L_t$’ from 16.2 mm to 16.8 mm, the center frequency shifts from 5.57 GHz to 5.48 GHz. Therefore, when ‘$L_t$’ is equal to 16.5 mm, the notch band is from 5.1 to 5.9 GHz centered at 5.5 GHz. From this, it can be concluded that the rejected band can be easily obtained by tuning the length of the slot introduced inside the stub. The optimum value is $L_t = 16.5$ mm, which has been obtained after performing an optimization and is identified in Table 5.1.

![Figure 5.5 VSWR values of the antenna in terms of slot length '$L_t$'](image)
Table 5.1  Optimal parameters values of the CPW fed slot antenna with stepped Stub structure

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$L_g$</th>
<th>$W_g$</th>
<th>L</th>
<th>W</th>
<th>$L_f$</th>
<th>$W_f$</th>
<th>$G$</th>
<th>S</th>
<th>$L_s$</th>
<th>$W_s$</th>
<th>$L_t$</th>
</tr>
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<tr>
<td>Optimal values(mm)</td>
<td>29</td>
<td>32</td>
<td>10</td>
<td>26</td>
<td>16.8</td>
<td>2.8</td>
<td>0.5</td>
<td>1.8</td>
<td>6.7</td>
<td>9</td>
<td>16.5</td>
</tr>
</tbody>
</table>

5.1.5  Performance Analysis

Simulation and measurement results of VSWR, input impedance, radiation patterns, current distributions and gain of the proposed antenna are investigated in this section. The performance of the proposed antenna has been analyzed and optimized by using Advanced Design System software which is based on the method of moments (MOM) and CST microwave studio which is based on the finite integration technique (FIT). To verify the proposed design, a prototype of the antenna based on optimized dimensions has been fabricated (Figure 5.6) and the measurement was carried out with HP8722ES Vector Network Analyzer (Figure 5.7).

Figure 5.6 Prototype of the proposed antenna
The simulated and measured VSWR against frequency for the proposed antenna are plotted and compared as in Figure 5.8. Result of the antenna without slot inside the SS structure is also given for comparison.

Figure 5.7 Experimental setup for antenna measurements using VNA

Figure 5.8 Comparison of simulated and measured VSWR results of the antenna
As shown in this Figure 5.8, the proposed rectangular slot antenna yields a wide bandwidth ranging from 2.1 GHz to 11.6 GHz for VSWR less than 2, which covers the 2.4 GHz WLAN and UWB bands with notch-band from 5.1 to 5.9 GHz. This is also verified from the simulated input impedance curve on the Smith chart (Figure 5.9). The curve inside the VSWR = 2 circle indicates that out of the notch band, the antenna has perfect impedance matching. But, over the notch band from 5.1 GHz to 5.9 GHz the antenna has high input impedance which prohibits the current flow due to reflected power, giving maximum attenuation. This maximum attenuation is shown by the impedance curve outside the VSWR circle. Due to the effect of improper soldering of SMA connector and fabrication error, there is a minor shift between the measured and simulated results. However, the measured bandwidth is relatively equal to the simulated impedance bandwidth.

![Simulated input impedance on smith chart](image)

**Figure 5.9 Simulated input impedance on smith chart**

The radiation patterns of the proposed antenna were measured in anechoic chamber. For a linearly polarized antenna, performance is often described in terms of the E and H-plane patterns. Figure 5.10 shows the
normalized radiation patterns of E-plane (x-z plane) and H-plane (x-y plane) measured at the selective frequencies 2.1 GHz, 3.7 GHz and 8.3 GHz respectively.

Figure 5.10 Radiation patterns at (a) 2.1 GHz (b) 3.7 GHz (c) 8.3 GHz
As shown in this Figure, the E-plane patterns are bidirectional and the H-plane patterns are nearly omni directional which is required to receive information signals from all directions. Due to the symmetry of the antenna geometry, cross polarization level is significantly reduced. It is obvious from these results that the radiation patterns are acceptable over the 2.4 GHz WLAN and UWB bands. It is also observed that the radiation patterns at different frequencies out of the notch band are similar, which is expected from a wideband antenna. Moreover, the H-plane pattern shows more cross-polarization than E-plane pattern.

**Figure 5.11 Simulated current distribution of the antenna at 2.1 GHz**

The surface current distribution has been studied using ADS simulation tool. The simulated current distributions at 2.1 GHz and 5.5 GHz frequencies are presented as a typical example. At frequency 2.1 GHz, the maximum current flow occurs as shown in Figure 5.11 and the antenna radiates signal. But, at the notch band centre frequency 5.5 GHz, current is concentrated around the edge of the slot on the SS structure and it prohibits
the current flow due to reflected power, giving maximum attenuation. Therefore, there is no radiation at 5.5 GHz (Figure 5.12).

![Simulated current distribution of the antenna at 5.5 GHz](image)

**Figure 5.12  Simulated current distribution of the antenna at 5.5 GHz**

Measured antenna gain against frequency is shown in Figure 5.13. The antenna gain is seen to decrease sharply in the notched frequency band. But, for other frequencies out of the notched frequency band, the peak gain is nearly constant from 2.1 GHz to 11.6 GHz because, outside the notched band, antenna gain with a variation of less than 1.5 dBi is achieved. Thus, the antenna exhibits nearly stable gains across the operation band. Gain of the antenna without slot on the stub is also included for comparison. Peak gain variations of the antenna with and without stub slot demonstrate the band notched function of the proposed antenna.
5.1.6 Time Domain Study

UWB systems typically transmit very short duration pulses, unlike the traditional communication schemes. Therefore, antenna pulse distortion must be kept to a minimum. The linear phase response of the radiated field as well as stable group delay response is desirable for not distorting the shape of the transmitted electrical pulse. Time domain characteristics of the proposed antenna are studied using CST Microwave Studio. It is found that the proposed antenna has good performance in transmitting UWB signals with minimum distortion. Figure 5.14 shows the measured group delay in the time-domain. In the group delay study, a pair of identical antennas served as the transmitting and receiving antennas, which were connected to the double ports of the analyzer in the face to face orientations, with a distance of 50 cm between them. In order to validate time domain performance of the antenna, Gaussian pulses are selected to be the source waveforms and applied to the proposed antenna. As can be seen from Figure 5.14, the variation of the group delay is within 1.5 ns in UWB bands and in the notched band, the maximum group delay is more than 5 ns. Hence, it can be concluded that there is a small
acceptable pulse distortion and the proposed antenna is suitable for UWB impulse radio communication.

![Measured group delays of the antenna](image)

**Figure 5.14 Measured group delays of the antenna**

5.2 SLOT ANTENNA WITH CORRUGATED STUB

5.2.1 Antenna Design

The configuration of the proposed antenna is shown in Figure 5.15. The substrate used for this design is FR4 with relative permittivity of 4.4 and thickness of $h = 1.6$ mm. A corrugated stub is connected at the end of the CPW feed line and a wide rectangular slot with dimension $(L \times M)$ mm is etched in the ground plane to obtain wide bandwidth. The CPW feed with corrugated stub strongly influences the performances of wide slot antenna. The characteristic impedance of the CPW feed line is $50 \, \Omega$. By choosing a suitable slot shape, stub shape and tuning their dimensions, the desired operating bandwidth is obtained in our design. Also, two slits are introduced in the ground plane to improve the impedance matching for 2.4 GHz WLAN. The slits lengthen the surface current to lower the antenna’s fundamental resonant frequency.
In the parametric study, the width ‘$W_s$’ and length ‘$L_s$’ of the corrugated stub are varied and their effects on the impedance matching are investigated. The simulated VSWR curves of the CPW fed slot antenna for various values of ‘$L_s$’ and ‘$W_s$’ are illustrated as in Figures 5.16(a) and 5.16(b). From the Figures, it is seen that curves for different values of ‘$L_s$’ and ‘$W_s$’ have similar shape and variation trend. But, the optimum value is $L_s = 7.1$ mm and $W_s = 9$ mm which has been found after performing an optimization because, it provides the widest impedance bandwidth (2.2 GHz – 11.6 GHz) for 2.4 GHz WLAN and UWB operations.
The wide bandwidths are due to the resonances introduced by the combination of the rectangular slot and the corrugated stub. When proper dimensions ($L_s$ and $W_s$) are selected, the resonant modes are shifted close to the antenna’s fundamental resonant mode, resulting in high impedance bandwidth for 2.4 GHz WLAN and UWB systems.

**Figure 5.16** Simulated VSWR values of the antenna in terms of (a) $L_s$ and (b) $W_s$
In order to improve the impedance matching further, two slits are also made in the ground plane so that the antenna covers (2 GHz – 11.4 GHz) bandwidth. Each slit is 12 mm in length parallel to the CPW feed line. The influence of slot embedded on the corrugated stub is also investigated for notch band function. Figure 5.17 shows the simulated VSWR of the proposed antenna with different length ‘L_t’ of slot (its width is kept at 0.4mm).

![Simulated VSWR values of the proposed antenna in terms of slot length 'L_t'](image)

Figure 5.17  Simulated VSWR values of the proposed antenna in terms of slot length 'L_t'

From this Figure, it is observed that the length of the slot line in the stub determines the frequency range of the notched band. As ‘L_t’ increases, the centre frequency of the notched band shifts toward the lower frequency. With the increasing of L_t from 16.4 mm to 16.7 mm, the center frequency shifts from 5.57 GHz to 5.4 GHz. Therefore, when ‘L_t’ is equal to 16.55 mm, the notch band is from 5.1 GHz to 5.9 GHz centered at 5.5 GHz. From this, it can be concluded that the rejected band can be easily obtained by tuning the length of the slot introduced inside the stub. Finally, the antenna covers a wide bandwidth between 2 GHz and 11.4 GHz. All the dimensions are summarized in Table 5.2.
Table 5.2  Optimal parameters values of the CPW fed slot antenna with corrugated stub structure

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lg</th>
<th>Wg</th>
<th>L</th>
<th>W</th>
<th>Lf</th>
<th>Wf</th>
<th>G</th>
<th>S</th>
<th>Ls</th>
<th>Ws</th>
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<td>29</td>
<td>32</td>
<td>10</td>
<td>26</td>
<td>16.9</td>
<td>2.8</td>
<td>0.5</td>
<td>1.9</td>
<td>7.1</td>
<td>9</td>
<td>16.5</td>
<td>12</td>
</tr>
</tbody>
</table>

5.2.2  Performance Analysis

The designed antenna is modeled and simulated using momentum software package of the Advanced Design System and CST microwave studio. The proposed antenna was constructed as shown in Figure 5.18 and VSWR vs. frequency of the antenna was measured by a HP8722ES vector network analyzer.

Figure 5.18 Photograph of the antenna

Figure 5.19 shows the measured VSWR which is compared with the simulated result. Result of the antenna without slot in the stub is also
given. Simulation and measurement results show that the proposed antenna performs well over the required frequency bands, i.e., it yields a wide bandwidth ranging from 2 GHz to 11.4 GHz for VSWR less than 2, which covers the 2.4 GHz WLAN and UWB bands with notch-band from 5.1 GHz to 5.9 GHz. Hence, basic agreements are achieved between the simulated and the measured results. The differences between them may be caused by the fabrication error and soldering effects of SMA connector.

Figure 5.20 shows the input impedance of the proposed antenna over the operating frequency from 2 GHz to 12 GHz. It confirms the impedance matching performance between 2 GHz and 11.4 GHz with notch band function from 5.1 GHz - 5.9 GHz.

![Graph showing VSWR results](image)

**Figure 5.19** Comparison of simulated and measured VSWR results of the antenna
Figure 5.20 Simulated input impedance on smith chart

The radiation patterns and gain measurements are performed in anechoic chamber of Antenna Laboratory. The radiation characteristics of the antenna were experimentally investigated across the impedance bandwidth of 2 GHz - 11.4 GHz. Figure 5.21 shows the measured radiation patterns at 2.4 GHz, 4 GHz, and 9 GHz in the two principal planes, namely the x-z and x-y planes. As shown, a figure of eight pattern in the E-plane and nearly omni directional pattern in the H-plane is obtained. In the patterns, both co-polarization (solid line) and cross polarization (broken line) are shown. Radiation patterns are acceptable over the whole 2.4 GHz WLAN/UWB bandwidth. Also, it is observed that radiation patterns at other frequencies out of the notched frequency band are about stable, suggesting the usefulness of the antenna in the entire band.
Figure 5.21 Radiation patterns at (a) 2.4 GHz (b) 4 GHz and (c) 9 GHz
Figure 5.22 shows the measured gain vs. frequency of the proposed antenna. Gain of the antenna without slot on the stub is also included for comparison. For the antenna without slots, the peak gain is relatively constant over the band from 2.3 GHz to 11.8 GHz. But, for the proposed antenna, a sharp gain decrease occurs in the vicinity of 5.5 GHz due to the frequency notched function and the peak gain is nearly constant outside the notched band from 2 GHz to 11.4 GHz. The peak gain variation is between 2.5 dBi and 4 dBi. Thus, the antenna exhibits almost stable gain across the operation band. These factors demonstrate the band notched function of the proposed antenna.

![Figure 5.22 Measured peak gain of the proposed antenna](image)

5.2.3 Surface Current Distribution

The surface current distribution has been studied using ADS simulation tool. Figure 5.23 shows the simulated current distributions of the proposed antenna at frequencies 2.4 GHz and 5.5 GHz. At frequency 2.4 GHz, the maximum current flow occurs and the antenna radiates signal. But, at the notch band centre frequency 5.5 GHz, current is concentrated around the edge of the slot on the corrugated stub while there is almost no current at the feeding point. Therefore, it prohibits the current flow at that frequency, giving maximum attenuation. Hence, there is no radiation at all (Figure 5.23b).
Figure 5.23 (a) Radiation at 2.4 GHz and (b) No radiation at 5.5 GHz
5.3 SUMMARY

Two rectangular slot antennas fed by a 50 Ω CPW for wideband applications were presented. With the use of stepped stub structure, corrugated stub and slot in the stub, a wide impedance bandwidth for 2.4 GHz WLAN and UWB systems with 5 GHz band-notched characteristics has been achieved. A prototype antenna has been designed, optimized and measured. The measured results well agree with the simulated results. Moreover, the antennas exhibit constant radiation pattern and has a favourable field gain, small group delay variations across the matching band except for the notched band, as a desirable feature for wideband applications.