Chapter 4

The Semi Elliptic Slot Antenna

A slot antenna comprises of a slot of appropriate shape on a thin flat sheet of metal and the slot radiate on both sides of the sheet when excited by a voltage source. The electric field distribution in the slot can be obtained from the relationship between the slot and complementary wire antennas, as established by Booker [Booker, 1946]. The electric field distribution (magnetic current) in the slot is identical to the electric current distribution on a complementary wire. The electric field everywhere is normal to the surface of the slot antenna except in the region of the slot. The radiation of the currents in the sheet can be deduced directly from the distribution of the electric field in the slot. Consequently, the radiated field of an elementary magnetic dipole within the slot boundaries should include the contribution of the electric current flowing on a metal surface.

To broadband microstrip patch antennas, aperture coupling method is deployed where coupling between a near resonant slot and the patch broaden the bandwidth to about 30 percent or higher. Another preferred location for the slot is the patch surface itself. A U-shaped slotted patch was experimentally investigated in [Huynh T., 1995] and an impedance bandwidth of 27% from 1.565 to 2.065 GHz was obtained. Several researchers have attempted similar approaches with microstrip patch antennas, a detailed account of which has been compiled in [Wong, 2002] and [Godara, 2002].

Another technique is to excite a narrow rectangular slot with a simple microstrip feed line as in [Yoshimura, 1972] and [Pozar, 1986]. In [Yoshimura, 1972], the feed point is shifted from the center of the slot and is short circuited through the dielectric substrate with the slot side, which is located further from the
CHAPTER 4. THE SEMI ELLIPTIC SLOT ANTENNA

feed input. A similar technique of feed point shifting close to the slot end was used in [Pozar, 1986]. In both cases, the offset of the feed point lead to perfect impedance matching in a narrow frequency band and the impedance bandwidth is approximately 20%.

As the width of the slot increases, radiation resistance of the slot also increases and this leads to impedance mismatch between the slot and microstrip feed line. This in turn reduces the impedance bandwidth of the antenna [Kahrizi M., 1993]. In [Shaun S. M., 1995] the possibility of increasing the bandwidth of the wide rectangular slot antenna by terminating the open end of the feed line within the width of the slot has been shown even though substantial bandwidth improvement could not be achieved.

In [Myung Ki Kim, 2000], a wide rectangular aperture is excited by a T-shaped microstrip tuning stub to realize a wide bandwidth from 1.5–3.2 GHz, approximately 58% which is considerably wider than the narrow rectangular slot antenna. In [Wen-Shan Chen, 2000], it is shown that a modification of the shape of the slot can also result in broadband operation. The authors used a semi-circular slot and a protruding square shape to realize a bandwidth of 46%, which is about three times that of a corresponding printed wide rectangular slot antenna.

In [Jia-Yi Sze, 2001], a wide aperture is excited by a fork like tuning stub to realize wide band width. A 1 : 1.5 VSWR band width of 1 GHz is achieved at operating frequencies around 2 GHz, which is nearly ten times that of a conventional microstrip-line-fed printed wide-slot antenna.

In [Jang, 2001], the wide aperture is excited by an inverted T-shaped microstrip tuning stub. Reported bandwidth of the antenna is from 1.877–5.638 GHz which is approximately 114% (VSWR ≤ 2).

In [Lei Zhu, 2003], a novel broadband microstrip-fed slot antenna with double rejection zeros is proposed and developed by constructing simultaneously a wide-slot radiator and a quarter-wavelength microstrip line resonator. Experimental results exhibit that significant increase in the bandwidth of the proposed antenna, up to 32.0% as compared to 9.0% of its traditional counterpart.

In the wide square aperture, conducting strips are incorporated on each corners diagonally in [Jyh-Ying, 2003] to improve the bandwidth greater than 60%, about two times that of a simple CPW-fed wide slot antenna. The broad band circularly
polarized antenna proposed in [Jia-Yi Sze, 2003] followed a similar approach. In this design, broadband circular polarization operation is achieved by protruding a T-shaped metallic strip from the ground plane toward the slot center and feeding the square slot antenna using a 50-Ω CPW with a protruded signal strip at 90° to the T-shaped strip. The 3-dB and 1-dB axial-ratio bandwidths are as large as 18% and 13% respectively.

The designs in [Xianming Qin, 2003; Chair R., 2004] incorporated a microstrip feed line with a fork-shaped tuning stub to excite a rectangular slot on the ground plane to achieve ultra wide bandwidth. The complete study of this antenna in the frequency and time domains is carried out in [Gino Sorbello, 2005]. The same antenna has been studied in [Marchais C., 2006] giving emphasis to the direct time domain measurement.

The broadband design in [Wen-Shan Chen, 2004] used a triangular slot and a small rectangular slot protruded from this to create a new resonant mode in the vicinity of the fundamental resonant mode of the triangular slot. A good impedance matching of both the fundamental and the new mode lead to an enhanced bandwidth of 84% for the proposed antenna.

In [Lin Y. F., 2004], the feed-slot combination and the feed gap width are studied for ultra wide band behavior of the antenna. For the study, an antenna with an arc-shape slot and a square-patch feed and an antenna that has a triangular-shape slot and an equilateral triangular-patch feed are used. Widths and lengths for both feeds are about one third of the slot size and their lengths are close to but less than the quarter wavelength measured at the lower frequency edge. The lengths are shorter than a printed monopole at the same frequency, because the slot edge acts as a capacitive load to the monopole. With these antennas, almost 100% bandwidth could be achieved.

Further research interests in the above design has resulted in [Shi-Wei Qu, 2006] where rounded corners are used to improve the bandwidth to 158%. A relatively simple version of the above antennas was proposed in [T. A. Denidni, 2006] wherein the authors used circular slot and a circular tuning stub to realize an antenna with as much as 110% bandwidth. A band notch is realized in this antenna using a pie-cut in the tuning stub [Chin-Ju Pan, 2006]. In [Mohamed A. Habib, 2006], the authors explored the use of stubs other than the circular one to excite the circular slot. Their findings reveal that slots and stubs of
similar geometry can result in the widest possible bandwidth of all the possible combinations. Details of a similar study can be found in [Fabrizio Consoli, 2006] which include a detailed time domain analysis.

In [Evangelos S. Angelopoulos, 2006a], the authors have studied the use of ellipses of various ellipticity ratios for the ground as well as the tuning stub. Their studies propose the use of an elliptical design if PCB space is the concern and a circular design for wider bandwidth. The antennas proposed in this paper are able to cover the FCC UWB with good radiation characteristics. The authors have also shown that a modified design of this antenna will suit the KU-band satellite communication application and designed a wide band 1x8 array in [Evangelos S. Angelopoulos, 2006b]. The paper [Jicen Ding, 2007] explored the possibility of using split ring resonators of various dimensions to result in multiple band notch in the circular slot antenna.

The UWB antenna designs using fork-like stubs require relatively large apertures and contain many parameters for the complex geometry. The design proposed in [Yi-Cheng Lin, 2006] used a rectangular stub to constrict the slot aperture to an area of 13x23 mm². The authors have discussed the correlation between the mode-based field distributions and radiation patterns. Further, three advanced band notch designs are also proposed in this paper. In [Wen-jun Lui, 2007], a modified version of this design has been studied for UWB applications. The authors have proposed the use of a square ring resonator inside the rectangular stub to achieve a sharp band notch and has investigated the time domain performance of the antenna also in this paper. An offset fed square slot antenna with a rectangular stub can also result in UWB as demonstrated in [Horng-Dean Chen, 2006]. In [Aliakbar Dasranj, 2008], an E-shaped slot is excited using a microstrip feed having E-shaped stub to achieve a percentage bandwidth of 120.

In [Jiao J. J., 2007], a wide square slot is excited using a 50Ω feed line without terminating the end with a stub. An additional rectangular slot beneath the microstrip line connected to the wide square slot so as to form a T-shaped aperture, aid in the wideband operation of the antenna. By this approach, overall size of the antenna could be reduced by 26% compared to the wide slot antenna and the bandwidth is about 121%. The antenna design in [Jia-Yi Sze, 2008], where a wide square slot is excited using a 50Ω feed line without terminating
the end with a stub, uses a hat shaped back-patch to result in UWB. A rejected frequency band within this band is produced by embedding a pair of U-shaped slot lines in the back-patch.

In [Tharaka Dissanayake, 2008], two wide band antennas are reported to operate in the upper half of the direct sequence spread spectrum UWB. One L-slot antenna has a planar ground plane and the other modified L-slot antenna has a ground plane consisting of a planar section and two sidewalks. The highlight of this paper is the detailed performance analysis from impedance matching to pattern stability. Wide band radiation characteristics and the pattern stability of these antennas are investigated with the help of pattern stability factor (PSF).

In [Aidin Mehdipour, 2008], the authors evolved a UWB slot antenna from the basic design of an elliptical dipole antenna. A circuit model of the antenna has been used to analyze the input impedance of the antenna. The paper is complete with detailed parametric and time domain analysis of the antenna.

The LTCC based slot antenna in [Ooi B. L., 2008] adopted the waveguide technology, instead of the aperture technology, to improve wide band matching. The multi-layer antenna is excited by a microstrip line feed with a V-shaped tuning stub. To create an electric wall, two rectangular slots at different layers are connected together by vias. Wider bandwidth is obtained by placing diagonal strips along the four corners of the rectangle slots. This design offers a percentage bandwidth of 133 and cover the 3.2 – 10.6 UWB.

The compact UWB slot antenna in [Jorge R. Costa, 2009] is based on a combination of two crossed exponentially tapered slots and a star-shaped slot to produce a stable radiation pattern with very stable polarization over the 3.1–10.6 GHz FCC assigned band. The antenna diameter is only 35 mm (0.3 \( \lambda_0 \) at 3.1 GHz) and can be easily re-designed for MIMO systems with very low mutual coupling. This antenna is especially attractive since it combines the UWB concept with diversity and MIMO strategies to enhance link capacity and improve range, which is constrained by the FCC power emission mask for UWB.

In [Chen & Lin, 2009] a monopole-slot hybrid antenna is proposed for UWB applications. Even though antenna is compact, the radiation patterns have been affected at higher frequencies due to the asymmetry associated with its design.

The design details of a wide aperture slot antenna with geometry optimized for wireless dongle applications can be found in [Deepti Das Krishna, 2009]. Dongle
antennas are required to be constrained to an area of 23x70 mm$^2$ along with omnidirectional radiation and ground independence. Compact geometry of the present antenna is due to multiple matching techniques employed and it has also shown that the effect of ground plane on the radiation characteristics are minimal.

For applications that require unidirectional radiation in addition to wide impedance bandwidth, cavity backed slot antennas were proposed as in [Quan Li, 2002a,b]. An optimized rectangular cavity at the back of these antennas creates an additional resonance to enhance the bandwidth. In [Quan Li, 2002a], design of a single slot with 22% bandwidth and in [Quan Li, 2002b], a cavity backed slot array with 43% bandwidth and improved gain is proposed. Even though the percentage bandwidth is only 24%, the antenna derived from [Quan Li, 2002b] and reported in [Weihua Gao, 2007] offers high gain compared to its predecessor. In [Boyu Zheng, 2005], the authors investigated the effect of a finite ground plane on microstrip-fed cavity-backed slot antennas by the uniform geometrical theory of diffraction. It is demonstrated that the finite ground plane has a small effect on a slot antennas radiation performance, indicating their superiority for use in mobile terminals compared to microstrip patch antennas.

In this chapter, design of a semi-elliptic slot antenna with wide impedance band width of $\sim$150% is presented. The ground plane and patch is shaped as semi-ellipse to minimize any pernicious reflections inside the structure. Resonances in the antenna are due to different modes excited in the slot geometry which can be accounted mathematically, that facilitate it’s design on any microwave laminate. A band notch mechanism suitable for the present design is also proposed and the antennas are characterized in the frequency domain.

### 4.1 Antenna Geometry, Design and Optimization

#### 4.1.1 Geometry

Fig. 4.1 shows the geometry of the proposed semi-elliptic slot antenna. The ground plane of the antenna is shaped as a semi-ellipse near the patch with $a_1$ and $b_1$ as major and minor radii. The patch is also semi-elliptic with major and minor radii $a_2$ and $b_2$ respectively. The patch is displaced from the ground plane by a distance $d$. The ground plane extends beyond the patch to form an 'L' shaped section of length $l_1 + l_2$. 
4.1. ANTENNA GEOMETRY, DESIGN AND OPTIMIZATION

Figure 4.1: Geometry of the semi-elliptic slot antenna

Figure 4.2: Surface current distribution (Intensity) and aperture electric field (vector) at (a) 3.2 GHz (b) 8.5 GHz (c) 12 GHz.
Table 4.1: Computed and optimized geometric parameters of Semi-Elliptic Slot Antennas (also see Table 3.2)

<table>
<thead>
<tr>
<th>Parameter (mm)</th>
<th>Antenna-1 (Rogers 5880)</th>
<th>Antenna-2 (FR4 Epoxy)</th>
<th>Antenna-3 (Rogers RO3006)</th>
<th>Antenna 4 (Rogers 6010LM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Computed</td>
<td>Optimized</td>
<td>Computed</td>
<td>Optimized</td>
</tr>
<tr>
<td>$a_1$</td>
<td>17.43</td>
<td>19.36</td>
<td>14.1</td>
<td>16</td>
</tr>
<tr>
<td>$b_1$</td>
<td>4.9</td>
<td>5.45</td>
<td>3.96</td>
<td>4.48</td>
</tr>
<tr>
<td>$a_2$</td>
<td>10.39</td>
<td>11.52</td>
<td>8.18</td>
<td>9</td>
</tr>
<tr>
<td>$b_2$</td>
<td>7.43</td>
<td>8.27</td>
<td>5.84</td>
<td>6.44</td>
</tr>
<tr>
<td>$t$</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$l_1$</td>
<td>10.55</td>
<td>11.73</td>
<td>8.31</td>
<td>9.5</td>
</tr>
<tr>
<td>$l_2$</td>
<td>8.3</td>
<td>9.25</td>
<td>6.53</td>
<td>7</td>
</tr>
<tr>
<td>$d$</td>
<td>0.26</td>
<td>0.26</td>
<td>0.44</td>
<td>0.48</td>
</tr>
<tr>
<td>$t$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$L_xB (mm^2)$</td>
<td>36.95 x 26</td>
<td>40.65 x 30</td>
<td>30.13 x 23</td>
<td>34 x 25</td>
</tr>
<tr>
<td>$f_1,f_2 (GHz)$</td>
<td>3.4, 9.46</td>
<td>3.18, 8.6</td>
<td>3.5, 9.23</td>
<td>3.2, 8.57</td>
</tr>
</tbody>
</table>
4.1.2 Design

As shown in the intensity distribution in Fig. 4.2(a), the curved path OA is approximately half a wave long at the first resonance, i.e.,

\[ \frac{p_1}{4} + l_1 + l_2 - g - \frac{s}{2} \approx \frac{\lambda_{g,1}}{2} \]  

(4.1)

where \( p_1 \) is the perimeter of the ellipse in the ground plane given by,

\[ p_1 \approx 2\pi \sqrt{a_1^2 + b_1^2} \]  

(4.2)

The path O/A’ in the antenna as shown in Fig. 4.2(b) is responsible for the second resonance. From the field distribution in Figure 4.2(b), it can be arrived that,

\[ \frac{p_2}{2} \approx \frac{\lambda_{g,2}}{2} \]  

(4.3)

where \( p_2 \) is the perimeter of the ellipse with \( a_2 \) and \( b_2 \) as the major and minor radii. Here, \( \lambda_{g,i} \) is the wavelength in the dielectric which is computed from the free space wavelength \( \lambda_{0,i} \) as,

\[ \lambda_{g,i} = \frac{\lambda_{0,i}}{\sqrt{\varepsilon_{re}}} \cdot i = 1, 2 \]  

(4.4)

and \( \varepsilon_{re} \) is the effective permittivity of the substrate. In designing the antenna proposed in this paper, the first resonance is designed to fall in the lower UWB (3.1 - 5.1 GHz) and the second resonance in the upper UWB (5.825 - 10.6 GHz). From the vector distribution of the aperture field shown in Figure 4.2, it can be seen that the modes excited resemble the fundamental modes of typical aperture antennas [Yi-Cheng Lin, 2006], namely \( TE_{01} \) and \( TE_{11} \) at the first and the second resonances. The lower and upper resonances are fixed at 3.2 and 8.5 GHz respectively and a smooth transition between them is obtained by adjusting the spacing \( d \). Extensive simulation studies indicate that the optimum ellipticity values \( (a_1 : b_1) \) and \( (a_2 : b_2) \) are at 3.55 and 1.4 respectively. It is observed that the parameter \( t \) does not contribute to the resonances or the bandwidth of the antenna. Hence in the proposed design, a thin strip of width 1 mm is employed.
4.1.3 Optimization

Based on the observations aforementioned, a design procedure for the semi-elliptic antenna can be framed as explained in this section.

1. Design a 50 CPW line on a substrate with permittivity $\varepsilon_r$ and thickness $h$. Calculate $\varepsilon_{re}$ using the $s$ and $g$ values of the CPW line.

2. Design the ground to create the first resonance ($f_1$) using $l_1 = \frac{\lambda_{g,1}}{6}$
   \[ l_2 = \frac{\lambda_{g,1}}{9} \]
   and then compute $b_1$ and $a_1$ using,
   \[ b_1 = 0.12(\lambda_{g,1} + s + 2g) - 0.24(l_1 + l_2) \]
   \[ a_1 = 3.55b_1 \]

3. Design the patch at the second resonance ($f_2$) using
   \[ b_2 = 0.26\lambda_{g,2} \]
   \[ a_2 = 1.4b_1 \]

Using the parameters so computed, the antenna was studied on substrates with different permittivity, described in Table 3.2. Figure 4.3(a) shows the return losses of the antennas with the computed geometric parameters given in Table 4.1. Resonances of these antennas show slight deviation from the designed values but there is impedance match throughout the band. The reason for this is that the effective permittivity computed for the CPW line does not hold for the radiating
4.2 BAND NOTCH DESIGN

part of the antenna where the CPW line can be considered as flared. This value of \( \varepsilon_{re} \) is lower than that computed. Hence, the parameters are optimized using CST to have resonances at 3.2GHz and 8.5GHz. The \( S_{11} \) plots of these antennas are shown in Figure 4.3(b).

4.2 Band notch Design

To this design, a 'T' section is appended, as in Figure 4.4(a) that results in the required band notch. The parameters for this section are \( l_s \) and \( t_s \) and \( w_s \) as indicated whose variation studies are given in Figure 4.5.

To design the slot resonator for band notch, the equation to be followed is

\[
l_s + t_s = \lambda_{g,5.5}/4
\]

where \( \lambda_{g,5.5} \) is the guide wavelength computed at 5.5 GHz as in 3.6. The optimum values for these parameters are, \( l_s = 6.45 \text{mm}, t_s = 0.9 \text{mm} \) and \( w_s = 0.4 \text{mm} \).

4.3 Experiment results

A prototype of the antenna was fabricated on a substrate of \( \varepsilon_r = 4.4 \) and \( h = 1.6 \text{mm} \) with the optimized parameters in Table 4.1. Return loss measurements indicate a wide band width from 2.85 - 20 GHz, in agreement with the simulation as shown in Figure 4.6(a). The slight deviation from the simulation at higher frequencies could be due to the SMA connector which is not accounted in the simulation. Since the antenna is for use in the 3.1- 10.6 GHz band, this can be ignored. VSWR measurement of the band notch antenna is shown in Figure 4.6. Radiation patterns of the antenna in the X-Y, X-Z and Y-Z planes for three different frequencies are shown in Figure 4.7. The patterns are stable throughout the band and resembles that of a monopole: omnidirectional in the H-plane (X-Y) and bidirectional in the E-planes (Y-Z and X-Z). Polarization of the antenna is along the Z direction. Measured gain of the antenna is compared with the simulated one in Figure 4.9(a) and (b) which shows reasonable agreement throughout the band. Average value of gain when slot resonator not incorporated
Figure 4.4: Semi elliptic slot antenna with slot resonator for band notch (a) design parameters (b) current distribution along the periphery of the slot

Figure 4.5: VSWR vs. Frequency of the band notch semi elliptic slot antenna for different (a) slot lengths while $t_s = 0.9\,mm$ and $w_s = 0.4\,mm$ (b) widths $w_s$ while $t_s = 0.9\,mm$ and $l_s = 6.45\,mm$ (c) slot width $t_s$ while $l_s = 6.45\,mm$ and $w_s = 0.4\,mm$
Figure 4.6: Measured and simulated (a) $S_{11}$ of the UWB semi elliptic slot antenna (b) VSWR of the band notch antenna

in the design is found to be 3.64 dBi. The antenna has adequate radiation efficiency as shown in the same figure.

4.4 Conclusion

A compact slot antenna with minimum insidious reflections is proposed for UWB operation. The antenna features wide impedance bandwidth from 2.85–20 GHz and stable radiation patterns and gain across its entire operating band. As the Square Monopole Antenna in Chapter 3, this antenna too can be easily fabricated on any commercially available substrates since a reliable empirical design guideline
Figure 4.7: Radiation patterns of the UWB semi elliptic slot antenna in the (a) x-y plane: 3.75, 8, 13 GHz, 17 GHz (b) y-z plane: 3.75, 8, 13 GHz, 17 GHz (c) x-z plane: 3.75, 8, 13, 17 GHz
Figure 4.8: Radiation patterns of the semi-elliptic slot antenna with band notch at 5.5 GHz (a) x-y plane (b) y-z plane (c) x-z plane

Figure 4.9: Measured and simulated peak gains and radiation efficiency of the semi-elliptic slot antenna (a) without band notch resonator (b) with band notch resonator

is provided. A tunable band notch feature can be integrated into the antenna to limit radiation in the WLAN band.
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