A PERSONAL OVERVIEW OF THE DEVELOPMENT OF PATCH ANTENNAS

Part 2

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City University of Hong Kong
## Schedule

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5. Broadbanding Techniques

5.1 Bandwidth limitations of the basic patch antenna geometry
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5.1 Bandwidth Limitations of the Basic Microstrip Patch Antenna

- The input impedance (antenna impedance) at resonance is dependent on the feed position. A match with the feedline impedance can be obtained by choosing the feed location properly and using thin substrates (thickness $t \leq 0.03 \lambda_0$) to minimize the feed inductance.
5.1 Bandwidth Limitations of the Basic Microstrip Patch Antenna

- The antenna bandwidth is governed by the impedance bandwidth (SWR ≤ 2), which is typically 2-3% for the basic geometry.

Fig. 2.2
5.1 Bandwidth Limitations of the Basic Microstrip Patch Antenna

- For most frequencies of interest:
  - $\Delta f$ increases as thickness $t$ increases
  - $\Delta f$ increases as $\varepsilon_r$ decreases
  - For $t \leq 0.03\lambda_0$, the reactance $X_r$ is very small and $\Delta f$ essentially represents the bandwidth
    - \( \text{BW} \uparrow \text{as } t \uparrow \)
    - \( \text{BW} \uparrow \text{as } \varepsilon_r \downarrow \)

Fig. 2.3
5.1 Bandwidth Limitations of the Basic Microstrip Patch Antenna

- However, when \( t \geq 0.03\lambda_0 \), the length of the probe (inner coax conductor) has a significant inductance (\( X_r \) is no longer small).
- This causes a large mismatch between the antenna and the feedline so that even at the resonant frequency, the SWR \( \geq 2 \).

Fig. 2.4
5.1 Bandwidth Limitations of the Basic Microstrip Patch Antenna

- Thus one cannot obtain wide bandwidth (> 6 %) just by increasing the thickness $t$. Also, there is a lower bound on the value of $\varepsilon_r$ namely, unity (air or foam). As shown in the Table in the next slide, applications in wireless communication require bandwidths larger than those that can be provided by basic geometry patch antennas.

- A detailed study illustrating the bandwidth limitation by increasing the substrate thickness was reported in a paper by Chen, Lee and Lee (1993) using a sophisticated full-wave moment method analysis.

**NARROW BANDWIDTH IS THE MAJOR PROBLEM ASSOCIATED WITH THE BASIC FORM OF MICROSTRIP PATCH ANTENNA**
<table>
<thead>
<tr>
<th>System</th>
<th>Operating frequency</th>
<th>Overall bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Mobile Phone Service (AMPS)</td>
<td>Tx: 824-849 MHz</td>
<td>70 MHz (8.1%)</td>
</tr>
<tr>
<td></td>
<td>Rx: 869-894 MHz</td>
<td></td>
</tr>
<tr>
<td>Global System for Mobile Communications (GSM)</td>
<td>Tx: 880-915 MHz</td>
<td>80 MHz (8.7%)</td>
</tr>
<tr>
<td></td>
<td>Rx: 925-960 MHz</td>
<td></td>
</tr>
<tr>
<td>Personal Communications Service (PCS)</td>
<td>Tx: 1710-1785 MHz</td>
<td>170 MHz (9.5%)</td>
</tr>
<tr>
<td></td>
<td>Rx: 1805-1880 MHz</td>
<td></td>
</tr>
<tr>
<td>Global System for Mobile Communications (GSM)</td>
<td>Tx: 1850-1910 MHz</td>
<td>140 MHz (7.3%)</td>
</tr>
<tr>
<td></td>
<td>Rx: 1930-1990 MHz</td>
<td></td>
</tr>
<tr>
<td>Wideband Code Division Multiple Access (WCDMA)</td>
<td>Tx: 1920-1980 MHz</td>
<td>250 MHz (12.2%)</td>
</tr>
<tr>
<td></td>
<td>Rx: 2110-2170 MHz</td>
<td></td>
</tr>
<tr>
<td>Universal Mobile Telecommunication Systems (UMTS)</td>
<td>Tx: 1920-1980 MHz</td>
<td>250 MHz (10.2%)</td>
</tr>
<tr>
<td></td>
<td>Rx: 2110-2170 MHz</td>
<td></td>
</tr>
</tbody>
</table>
5.2 General principles of broadbanding

Beginning in the mid-1980’s and throughout the 1990’s, a lot of research was devoted to broaden the bandwidths of patch antennas. The methods developed for efficient wideband patch antenna design are based on one or more of the following principles:

A. Thick substrates of low permittivity are used.
B. A scheme is devised to reduce the mismatch problem associated with thick substrates.
C. By means of parasitic elements or slots, either new resonances are introduced close to the main resonance or existing resonances are brought close to one another so that an overall broader band response is obtained.
The designs developed include:

- Annular gap probe compensation
- Patch with coplanar parasitic elements
- Stacked patches
- Aperture coupled patches
- The U-slot patch
- The L-probe fed patch
- Patch fed by meandering probe
According to two recent Antenna Handbook Chapters, authored by J. Huang and L. Shafai respectively, the most significant, and probably most widely used and most widely cited, broadbanding methods are:

- Stacked patches (Sabban 1983; Chen et al. 1984; Lee, Lee, Bobinchak 1987)
- Aperture coupled patches (Pozar, 1985; Croq & Papiernik 1990; Targonski et al. 1998)
- The U-slot patch (Huynh and Lee, 1995; Lee et al. 1997; Tong et al. 2000)
- The L-probe fed patch (Luk, Mak, Chow and Lee, 1998; Mak et al. 2000; Guo et al. 2001)

Fig. 2.5 shows the above designs. We will discuss each design individually.
Fig. 2.5 Geometries of various wideband patch antennas.

Stacked parasitic patch

- Parasitic patch
- Fed patch
- Ground plane
- Substrate 1
- Substrate 2
- Coaxial feed

Seldom exceeds 20% BW;
More than one layer

U-shaped slot

- U Slot
- Patch
- Ground plane
- Substrate
- Coaxial feed

Single-layer, single patch;
Easily achieve 30% BW;
Thick substrate \( \sim 0.08 \lambda_0 \);
High cross pol in H-plane
36 % BW High cross-pol in one plane.

Fig. 2.5 Geometries of various wideband patch antennas.
(d) About 10% BW for non-resonant slot; about 20% for resonant slot – high back lobe radiation

Fig. 2.5 Geometries of various wideband patch antennas.
Fig. 2.5 Geometries of various wideband patch antennas.

(e) 40-50% BW achievable; More than one layer; High back lobe radiation
5.3 Stacked Parasitic Patches

- The stacked patch arrangement, consisting of one fed patch on one layer and a parasitic patch on another layer, is one of the most popular wideband microstrip antenna. The parasitic patch introduces a second resonance. Many authors have contributed to the study of this design [A. Sabban, 1983; C. H. Chen et al. 1984; Lee, Lee and Bobinchak, 1987; Barlatey et al. 1990; Tulintseff at al. 1991].


This paper, the first Journal paper on the subject, reported an experimental study of the geometry shown in Fig.2.6. A patch antenna with a parasitic patch is sometimes known as an electromagnetically coupled patch antenna. The experiment was performed at NASA Lewis Research Center (later renamed Glenn Research Center) by my MS student J. Bobinchak, in collaboration with Dr. R. Q. Lee of NASA.
Dr. Kai Fong Lee and Dr. Richard Q. Lee at NASA Lewis Research Center, Summer 1986
5.3 Stacked Parasitic Patches

Fig. 2.6 Geometry of rectangular electromagnetically coupled patch antenna.

- substrate with permittivity $\varepsilon_r$
- spacer
- substrate with permittivity $\varepsilon_r$
- ground plane
- coaxial feed
- rectangular patches $a \times b$
- air
- t, s, t
## 5.3 Stacked Parasitic Patches

Table 2.2 Characteristics of a rectangular electromagnetically coupled patch antenna.

<table>
<thead>
<tr>
<th>Spacing s (cm)</th>
<th>$f_{01}$ (GHz)</th>
<th>Pattern shape</th>
<th>3 dB Beamwidth</th>
<th>Estimated Gain</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.9</td>
<td>normal</td>
<td>95° x 73°</td>
<td>5.7</td>
<td>9.0</td>
</tr>
<tr>
<td>0.0508</td>
<td>9.95</td>
<td>normal</td>
<td>75° x 65°</td>
<td>7.3</td>
<td>13.0</td>
</tr>
<tr>
<td>0.102</td>
<td>10.10</td>
<td>normal</td>
<td>75° x 70°</td>
<td>7.0</td>
<td>10.5</td>
</tr>
<tr>
<td>0.152</td>
<td>10.45</td>
<td>normal</td>
<td>75° x 70°</td>
<td>7.0</td>
<td>10.5</td>
</tr>
<tr>
<td>0.204</td>
<td>10.46</td>
<td>normal</td>
<td>75° x 70°</td>
<td>7.0</td>
<td>10.5</td>
</tr>
<tr>
<td>0.254</td>
<td>10.48</td>
<td>normal</td>
<td>70° x 70°</td>
<td>7.2</td>
<td>3.4</td>
</tr>
<tr>
<td>0.305</td>
<td>10.46</td>
<td>normal</td>
<td>73° x 78°</td>
<td>6.6</td>
<td>2.9</td>
</tr>
<tr>
<td>0.356</td>
<td>10.46</td>
<td>normal</td>
<td>75° x 85°</td>
<td>6.1</td>
<td>2.9</td>
</tr>
<tr>
<td>0.406</td>
<td>10.40</td>
<td>normal</td>
<td>85° x 90°</td>
<td>5.3</td>
<td>2.6</td>
</tr>
<tr>
<td>0.457</td>
<td>10.37</td>
<td>abnormal</td>
<td>—</td>
<td>—</td>
<td>1.5</td>
</tr>
<tr>
<td>0.508</td>
<td>10.37</td>
<td>abnormal</td>
<td>—</td>
<td>—</td>
<td>1.5</td>
</tr>
<tr>
<td>0.610</td>
<td>10.34</td>
<td>abnormal</td>
<td>—</td>
<td>—</td>
<td>1.4</td>
</tr>
<tr>
<td>0.762</td>
<td>10.30</td>
<td>abnormal</td>
<td>—</td>
<td>—</td>
<td>1.3</td>
</tr>
<tr>
<td>0.864</td>
<td>10.30</td>
<td>abnormal</td>
<td>—</td>
<td>—</td>
<td>1.3</td>
</tr>
<tr>
<td>0.914</td>
<td>10.28</td>
<td>normal</td>
<td>90° x 37°</td>
<td>8.9</td>
<td>1.3</td>
</tr>
<tr>
<td>0.965</td>
<td>10.28</td>
<td>normal</td>
<td>90° x 37°</td>
<td>8.9</td>
<td>1.3</td>
</tr>
<tr>
<td>1.016</td>
<td>10.28</td>
<td>normal</td>
<td>85° x 37°</td>
<td>9.2</td>
<td>1.3</td>
</tr>
<tr>
<td>1.118</td>
<td>10.30</td>
<td>normal</td>
<td>70° x 37°</td>
<td>10.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Single patch**

10.20 GHz, normal, 110° x 70°, 5.3 dB, 2.3%

$a = 1.5$ cm, $b = 1$ cm, $\varepsilon_r = 2.17$, $t = 0.254$ mm
5.3 Stacked Parasitic Patches

Fig. 2.7 Patterns of a rectangular electromagnetically coupled patch antenna.

\[ a = 1.5 \text{ cm}, \quad b = 1 \text{ cm}, \quad \varepsilon_r = 2.17, \quad t = 0.0254 \text{ cm}, \quad s = 0.0508 \text{ cm} \text{ (region 1)}, \ 0.61 \text{ cm} \text{ (region 2)} \text{ and } 0.9 \text{ cm} \text{ (region 3)}. \]

Patterns of a single patch are also shown (solid curves).
5.3 Stacked Parasitic Patches

- Depending on the spring \( s \), the characteristics of the antenna can be separated into three regions.

- In region 1, occurring when \( s \) is between 0 and 0.406 cm \(( \approx 0.14 \, \lambda_0 )\), the patterns show good broadside features. The bandwidth rises to 13 % at \( s = 0.0508 \, \text{cm} \) \(( \approx 0.017 \, \lambda_0 )\) and the gain is about 7 dB. At the upper boundary of this region \(( s = 0.406 \, \text{cm} )\), the bandwidth and the gain are about the same as the single patch.

- In region 2, occurring when \( s \) is between 0.457 cm and 0.864 cm, the \( E \) plane patterns show a dip at broadside and the bandwidth is less than 2 %. Little advantage is gained in operating the antenna in this region.

- In region 3, which begins at 0.914 cm \(( \approx 0.31 \, \lambda_0 )\), the patterns return to the “normal” shape and the gain increases to 8.9 dB. This high-gain region may be utilized in applications where narrow bandwidth is not a disadvantage.
5.3 Stacked Parasitic Patches


Subsequent to the 1987 paper, my student W. Chen developed a full-wave moment method analysis and a computer program for multi-layer microstrip antennas. Using this program, representative design guides for the configuration of Fig.35, operating at the center frequency of 5 GHz, are shown in Table 3. In Table 3, design 1 gives the parameters which achieve a bandwidth of 12% for the case when there is no superstrate (dielectric cover). When a superstrate of thickness 0.26 mm and relative permittivity of 2.2 is placed on the top of the parasitic patch, the parameters which yield 12% impedance bandwidth are given in design 2. Design 3 provides the antenna parameters which result in a bandwidth of 15% when no superstrate is present. If the center frequency is changed, it is only necessary to scale the length parameters accordingly (patch dimensions, substrate and superstrate thickness, feed location).

The patterns of stacked patches are stable across the impedance bandwidth. Typical E and H plane half-power bandwidths are 76° and 86° respectively. This is to be compared with 92° and 86° for the single patch. The gain of the stacked patches is about 6.0 dBi and that of the single patch is about 5.2 dBi.
5.3 Stacked Parasitic Patches

Table 2.3 Design examples for stacked electromagnetically coupled patch antennas at the center frequency of 5 GHz.

<table>
<thead>
<tr>
<th>BW (VSWR = 2)</th>
<th>12%</th>
<th>15%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Set 1</td>
<td>Set 2</td>
</tr>
<tr>
<td>$\epsilon_1$</td>
<td>1.0</td>
<td>2.2</td>
</tr>
<tr>
<td>$\epsilon_2$</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>$\epsilon_3$</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>$h_1$ (mm)</td>
<td>0.0</td>
<td>0.26</td>
</tr>
<tr>
<td>$h_2$ (mm)</td>
<td>3.580</td>
<td>3.630</td>
</tr>
<tr>
<td>$h_3$ (mm)</td>
<td>0.493</td>
<td>0.486</td>
</tr>
<tr>
<td>$a_1$ (cm)</td>
<td>2.296</td>
<td>2.198</td>
</tr>
<tr>
<td>$b_1$ (cm)</td>
<td>1.275</td>
<td>1.465</td>
</tr>
<tr>
<td>$a_2$ (cm)</td>
<td>2.000</td>
<td>2.027</td>
</tr>
<tr>
<td>$b_2$ (cm)</td>
<td>1.111</td>
<td>1.351</td>
</tr>
<tr>
<td>$F$ (cm)</td>
<td>0.928</td>
<td>0.940</td>
</tr>
</tbody>
</table>

Fig. 2.8 Stacked electromagnetically coupled patch antenna with superstrate
5.3 Stacked Parasitic Patches

Fig. 2.9 Impedance loci for a stacked EMCP antenna with the parameters given by Set 1 of Table 2.3. Bandwidth = 12 %.
5.3 Stacked Parasitic Patches

Fig. 2.10 Impedance loci for a stacked EMCP antenna with the parameters given by Set 2 of Table 2.3. Bandwidth = 12 %.

Fig. 2.11 Impedance loci for a stacked EMCP antenna with the parameters given by Set 3 of Table 2.3. Bandwidth = 15 %.

- Stacked patch designs seldom exceed 20 % BW.
References on section 5.1-5.3


References on stacked patches


5.4 Aperture Coupled Patches

5.4.1 Introduction

- This feeding method was proposed by Pozar (1985). The feed consists of an open-ended microstrip that is located on a dielectric slab below the ground plane. The microstrip antenna is formed on a separate dielectric slab above the ground plane and the two structures are electromagnetically coupled through an electrically small aperture in the ground plane between them. In the original paper by Pozar, the aperture was in the form of a small circular hole (Fig.2.12). Subsequently, a more common shape of the aperture was in the form of a narrow rectangular slot.

Professor D. M. Pozar
University of Massachusetts
Amherst
5.4 Aperture Coupled Patches

Fig. 2.12 Side view (a) and top view (b) of a rectangular microstrip antenna aperture coupled to a microstripline.
5.4 Aperture Coupled Patches

5.4.2 General Remarks

(a) One advantage of this feeding method is that the feed network is isolated from the radiating element by the ground plane, which prevents spurious radiation.

(b) Another advantage is that active devices such as phase shifters and amplifiers can be fabricated in a feed substrate with high dielectric constant, such as gallium arsenide ($\varepsilon_r = 12.8$), while the radiating patch can be mounted on a low dielectric constant substrate in order to increase bandwidth and radiation efficiency.

(c) The coupling slot can be resonant or non-resonant. The advantage of using a non-resonant slot is small backlobe radiation. The bandwidth obtained is typically 6-7% but can be as large as 10-13% by utilizing thick substrates, since the problem of probe impedance is not applicable here. By using a resonant slot, which introduces a second resonance, around 20% bandwidth can be obtained. However, a resonant slot gives rise to strong backlobe radiation, which is a disadvantage since it reduces the gain of the antenna.

(d) As in the case of coaxial feed, a stacked parasitic patch can be introduced to further increase the bandwidth.
5.4 Aperture Coupled Patches

5.4.3 Example of a Wideband Aperture Coupled Patch Antenna

By using a resonant slot and relatively thick foam substrate for the patch, Croq and Papiernik (1990) reported a VSWR < 1.5 impedance bandwidth of 22%. The antenna geometry and the antenna dimensions are shown in Fig. 2.13. Note that there was a dielectric cover (radome) protecting the patch.

Fig. 2.13 Aperture coupled patch antenna
The measured and computed impedances showed that, in the frequency range 4.85 to 6.1 GHz, the VSWR was less than 1.5, corresponding to a bandwidth of about 22%. The antenna gain was found to be about 8 dB for the entire bandwidth. The maximum back to front level was about -14 dB at the frequency of 5.6 GHz and was about -12 dB over the band. The strong back radiation is a major disadvantage of a resonant slot aperture coupled patch antenna.
References on aperture coupled patches


5.5 The Wideband U-Slot Patch Antenna

5.5.1 General Remarks

- The U-slot design was first introduced in a rather obscure conference “International Conference in Radio Science (ICRS)” in Beijing in August 1995 under the invited paper “Progress in the Search of Wideband Microstrip Antennas” by K. F. Lee and T. Huynh. The geometry is shown in Fig. 2.14.

![Diagram of U-Slot Patch Antenna]

Fig. 2.14 Geometry of the U-Slot Patch Antenna
Tan Huynh and K. F. Lee, AP meeting, Seattle, WA 1994

• A number of studies followed (Lee et al. 1997; Tong et al. 2000; Clenet and Shafai 1999; Weigand et al. 2003; Lee et al. 2010). It was firmly established that the U-slot patch antenna can provide impedance bandwidths in excess of 30% for air/foam substrate of thickness about $0.08\lambda_0$ and in excess of 20% for material substrates of similar thickness.
5.5.2 Air/foam substrate

• In the original study of Huynh and Lee, the wide-bandwidth characteristics of the antenna was demonstrated experimentally. It was pointed out in their paper that the factors contributing to the wideband behavior were (1) the air substrate; (2) a relative thick substrate (about 0.08 \( \lambda_0 \)); (3) the capacitance introduced by the U-slot, which countered the feed inductance; and (4) the additional resonance introduced by the U-slot, which combined with the patch resonance to produce a broadband response.

• I was at City University of Hong Kong in the summer of 1995. Prof. Luk assigned K. F. Tong to study the U-slot antenna. In those days, commercial simulation softwares were not available. After trying out many dimensions, he settled in two versions to study experimentally. He also developed a FDTD code for the antenna. The results of one of the antennas are summarized below.
K. F. Tong’s U-slot patch antennas, summer 1997
5.5.2 Air/foam Substrate

Fig. 2.15 VSWR of the U-slot patch antenna with dimensions: W=36 mm, L=26 mm, F=13 mm, \( W_s = 12 \) mm, \( L_s = 20 \) mm, a= 2mm, b=4 mm, \( c_x = c_y = 2 \) mm, and h=5 mm. (x measured, — computed)
5.5.2 Air/foam substrate

- The impedance bandwidth was about 30%.

- The measured patterns (not shown here) were stable across the band. The E and H plane beamwidths were about 70° and 65° respectively. The gain of the antenna was around 7.5 dBi, about 2 dB higher than the traditional patch antenna.

- While the above mentioned studies, as well as others, have shown that more than 30% impedance bandwidth can be obtained when an air-substrate thickness of about 0.08 $\lambda_0$ is used, it should be pointed out that some applications do not need such a wide bandwidth. For example, 8.1% is sufficient for Advanced Mobile Phone Services (AMPS) while only 8.7% is needed for Global System for Mobile Communications (GSM). While such bandwidths cannot be realized by the traditional patch antenna, it has been shown (Lee et al. 2010) that these can be met by a U-slot patch only 0.033 $\lambda_0$ thick, which has a 12% bandwidth.
5.5.3 Material Substrate

• Although the first series of studies used an air or foam substrate, subsequent investigations have confirmed that the U-slot wideband design can also be implemented with material substrates. As expected, the bandwidth of a patch on a material substrate is smaller than one on an air or foam substrate.

• Tong et al. (2000) presented both experimental study and FDTD analyses of two U-slot patches with relative permittivity $\varepsilon_r=2.32$. The dimensions of one of the antennas are shown in Table 2.4. The operating frequencies and bandwidths of this antenna are shown in Table 2.5. The 3 dB-gain bandwidths were about the same as the impedance bandwidths, and the average gains of the antennas were about 7 dBi across the matching band.
Table 2.4. Dimensions of antenna in millimeters

<table>
<thead>
<tr>
<th>$\varepsilon_r$</th>
<th>$W$</th>
<th>$L$</th>
<th>$W_s$</th>
<th>$L_s$</th>
<th>$b$</th>
<th>$F$</th>
<th>$c_x$</th>
<th>$c_y$</th>
<th>$h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.33</td>
<td>36.0</td>
<td>26.0</td>
<td>14.0</td>
<td>18.0</td>
<td>4.0</td>
<td>13.0</td>
<td>2.0</td>
<td>2.0</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Table 2.5. Operating frequencies and bandwidth of the antenna in Table 7

<table>
<thead>
<tr>
<th></th>
<th>$f_1$(GHz)</th>
<th>$f_0$(GHz)</th>
<th>$f_a$(GHz)</th>
<th>BW (GHz)</th>
<th>BW (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computed</td>
<td>2.87</td>
<td>3.28</td>
<td>3.69</td>
<td>0.82</td>
<td>25.0</td>
</tr>
<tr>
<td>Measured</td>
<td>2.76</td>
<td>3.16</td>
<td>3.56</td>
<td>0.80</td>
<td>25.3</td>
</tr>
</tbody>
</table>
5.5.4 Variations of the U-slot patch and the E-patch

- The U-slot design has been found to yield wideband characteristics for other patch shapes such as the circular and the triangular patches.

- Other shapes for the embedded slot (e.g. V, circular arc, omega) were found to increase the impedance bandwidth also.

- By letting the width of the horizontal slot go to zero and extending the two vertical slots to the edge of the patch, an E-patch results (Ooi et al. 2000; Yang et al. 2001). This geometry is shown in Fig. 2.16. As in the U-slot the parallel slots provide an additional path for the currents, giving rise to a second resonance. The parallel slots can also introduce a capacitance which compensates for the probe inductance, thus enabling the use of relatively thick substrate. In Yang et al. 2001, impedance bandwidths of about 30% were obtained for E patches operating at the center frequency of around 2.4 GHz, using air substrate of about 0.08\(\lambda_0\). The antenna parameters for one such antenna are listed below, in mm: \(L=70\), \(W=30\), \(h=15\), \(X_f = 35\), \(Y_f = 6\), \(L_s = 40\), \(W_s = 6\), \(P_s = 10\). Ground plane size = 14 cm x 21 cm.
Fig. 2.16 Geometry of the E-patch
References on the U-slot patch


5.6 The L-Probe Fed Patch

5.6.1 The L-Probe Fed Patch, Mak et al. (1998)

- This design, shown in Fig.44, was first introduced by Luk, Mak, Chow and Lee (1998). The parallel arm of the probe, being an open line less than a quarter of a wavelength, presents a capacitance. This capacitance allows the use of thick substrate because it counteracts the probe inductance. In conjunction with the inductance of the perpendicular portion of the probe, a second resonance is created. This is to be contrasted with the conventional probe, which acts only as an inductor which causes a mismatch and degrades the bandwidth performance of the antenna.

- Similar to the U-slot patch, this design has only one patch and one layer. Using foam substrate between 0.08 to 0.1\( \lambda_0 \), it achieves 30% or more matching bandwidth.

- Experimental results for the dimensions shown in Fig. 2.17 are given in Figs. 2.18-2.21.
C. L. Mak in Columbia, Missouri; the other student is John Hawkins
5.6 The L-Probe Fed Patch

5.6.1 The L-Probe Fed Patch, Mak et al. (1998)

Fig. 2.17 Structure of the L-shaped probe fed patch antenna.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>W/mm</th>
<th>L/mm</th>
<th>H/mm</th>
<th>b/mm</th>
<th>a/mm</th>
<th>D/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>30mm</td>
<td>25mm</td>
<td>6.6mm</td>
<td>10.5mm</td>
<td>5.5mm</td>
<td>2mm</td>
</tr>
<tr>
<td>λ₀</td>
<td>0.44λ₀</td>
<td>0.37λ₀</td>
<td>0.098λ₀</td>
<td>0.156λ₀</td>
<td>0.082λ₀</td>
<td>0.03λ₀</td>
</tr>
</tbody>
</table>
5.6 The L-Probe Fed Patch

5.6.1 The L-Probe Fed Patch, Mak et al. (1998)

Fig. 2.18 Measured gain and SWR against frequency.

36% (SWR<2)
5.6 The L-Probe Fed Patch

5.6.1 The L-Probe Fed Patch, Mak et al. (1998)

Fig. 2.19 Measured input impedance against frequency.
SWR and gain

Figure 2.20  Measured gain and SWR against frequency

36% (SWR<2)
Radiation patterns

Figure 2.21 Measured radiation patterns at (a) 4GHz (b) 4.53GHz (c) 5.34GHz

5.6 The L-Probe Fed Patch

5.6.2 Subsequent studies

- The paper by Mak et al. (1998) was followed by a more detailed paper on experimental results (Mak et al. 2000) and by a FDTD analysis by Guo et al. (2001), both of which provided some design guides.

- Similar to the U-slot patch, this design is not limited to the rectangular patch. Wideband circular and annular ring patch antennas with L-probe feed have been reported. Two related designs are the L-strip and the T-probe fed patches. A patch fed by a L-strip attained a VSWR <2 bandwidth of 49% while a T-probe fed patch achieved a bandwidth of 40%.
Disadvantage of L-shaped probe feeding mechanism

Figure 2.22 Source of high cross polarization
5.6.3 The M-Probe/Strip Fed Patch Antenna

5.6.3.1 The M-Probe Fed Patch Antenna (Lai and Luk 2006)

One method to reduce crosspolarization is to modify the L-probe into a meandering probe as shown in Fig.2.23.

![Diagram showing the geometry of the meandering probe fed patch antenna.]

**Fig. 2.23** Geometry of the meandering probe fed patch antenna.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>L</th>
<th>W</th>
<th>H_p</th>
<th>G_L</th>
<th>G_W</th>
<th>g_1=g_2</th>
<th>h_1=h_2</th>
<th>s_1=s_2</th>
<th>t_s</th>
<th>w_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value/mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mm)</td>
<td>60</td>
<td>70</td>
<td>17.5</td>
<td>300</td>
<td>200</td>
<td>1.5</td>
<td>9.5</td>
<td>20.5</td>
<td>0.2</td>
<td>9.5</td>
</tr>
</tbody>
</table>
With Dr. H. W. Lau and Dr. H. Wong
Paris, October 2005
Current Distribution

Low cross polarization level

→ 180° phase difference of the current on the Meandering probe

Figure 2.24  Side view of the current vector density
5.6.3.1 The Meandering Probe Patch Antenna

Fig. 2.25 Simulated and Experimental results of SWR and gain against frequency of the meandering probe fed patch antenna of Fig. 49.

Impedance bandwidth (SWR<1.5) of 24%
Gain = 9dBi
5.6.3.1 The Meandering Probe Patch Antenna (Lai and Luk, 2006)

(i) 1.56GHz

(ii) 1.82GHz

(iii) 2.12GHz

X-pol level < -18dB
Front-to-back → 18dB
Stable radiation pattern

Fig. 2.26 Measured radiation patterns of meandering probe fed patch antenna of Fig. 49.
5.6.3.2 The Meandering Strip Fed Patch Antenna (Lai and Luk 2008)
The fabrication process is simplified if the meandering feed is fabricated on a printed circuit board, forming a printed meandering strip (PMS).

![Diagram of the meandering strip fed patch antenna](image)

**Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>W</th>
<th>L</th>
<th>H_p</th>
<th>d_L</th>
<th>H</th>
<th>g</th>
<th>h</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values/mm</td>
<td>70</td>
<td>(0.427λ_0)</td>
<td>60</td>
<td>(0.366λ_0)</td>
<td>16.5</td>
<td>(0.101λ_0)</td>
<td>40</td>
<td>(0.244λ_0)</td>
</tr>
</tbody>
</table>

**Fig. 2.27** Geometry of the printed meandering strip fed patch antenna.
5.6.3.2 The Meandering Strip Patch Antenna

Fig. 2.28 Simulated and experimental results of SWR and gain against frequency of the printed meandering strip fed patch antenna of Fig. 53.

22%
5.6.3.2 The Meandering Strip Patch Antenna

Fig. 2.29 Radiation patterns of printed meandering strip fed patch antenna at 1.8GHz.

- Measured
- Simulated

X-pol level < -28dB
Front-to-back ➔ 20dB
Stable radiation pattern
Section 5.6 references


6. Full wave analysis and CAD formulas

As mentioned previously, the cavity model was limited to the basic structure of a single patch of regular shape on a grounded substrate. It became inaccurate for substrate thickness exceeding about 0.03 free space wavelength and is unable to analyze many practical geometries such as patch with dielectric cover, patch with slots, or multiple patches in single or multi-layers. These have to be handled with full wave analysis, i.e. solving Maxwell’s equations subject to the boundary conditions at hand. While papers based on full wave analysis were being published from mid-1980’s through mid-1990’s, simulation softwares, as as IE3D, HFSS etc were not commercially available until the late 1990’s. Graduate students, under the direction of their professors, often had to develop full wave equations and computer programs for their problem at hand.
6. Full wave analysis and CAD formulas

6.1 Full wave analysis developed in house

Under Prof. K. M. Luk

W. Y. Tam, T. M. Au, S. M. Shum: Moment method

Problems studied: Stacked patches, both fed by coax and by aperture coupling

K. F. Tong: FDTD

Problem studied: U-Slot Patch

Y. X. Guo: FDTD

Problem studied: L-probe patch
6. Full wave analysis and CAD formulas

6.1 Full wave analysis developed in house

Under Prof. K. F Lee

Wei Chen: Moment method

Problems studied: Patch on thick substrate; Wideband stacked patches, Coplanar parasitic patches; Patch on multi-layer dielectrics; CAD formula for resonant frequencies of equitriangular patch

Zhibo Fan: Moment method

Problems studied: Patch with air gap; Dual-frequency stacked patches; Patch with dielectric cover
Wei Chen and Zhibo Fan at University of Toledo, summer 1993

Dr. Jian Zheng and Dr. Zhibo Fan of Zeland Software, Inc. 8-2-06
Some of our papers using full wave analysis


Some of our papers using full wave analysis (continued)


● K. F. Lee and Z. Fan, CAD formulas for resonant frequencies of TM$_{ll}$ mode of circular patch antenna with or without superstrate, Microwave and Optical Technology Letters, Volume 7, No. 12, pp. 570-573. 1994.
Some of our papers using full wave analysis (continued)


6.2 Microstrip Antenna Development Procedure with the aid of Commercially available simulation softwares

The main motivation of the full wave analysis and softwares developed by Prof. Luk’s group and my group were to verify the measured results of the patch antennas we studied – stacked patches, U-slot patch, L-probe fed patch etc., configurations which cannot be analyzed using the cavity model. Other groups were doing similarly work. In the late 1980’s and early 1990’s, two Ph.D. graduates of the University of Colorado marketed their simulation softwares commercially. Doris Wu marketed “Ensemble” through her company “Boulder Microwaves” (later sold to Ansoft). Jian Zheng marketed “IE3D” through his company “Zeland”, which were later sold to “Mentor Graphics”. Zhibo Fan, who wrote many papers with me, worked in Zeland and is still with Mentor Graphics.

At present, there are numerous electromagnetic simulation softwares in the market.
Table 2.6 Some commercially available microstrip antenna CAD tools

<table>
<thead>
<tr>
<th>Software name</th>
<th>Theoretical model</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ensemble</td>
<td>Moment method</td>
<td>Ansoft</td>
</tr>
<tr>
<td>IE3D</td>
<td>Moment method</td>
<td>Mentor Graphic/Zeland</td>
</tr>
<tr>
<td>Momentum</td>
<td>Moment method</td>
<td>HP</td>
</tr>
<tr>
<td>EM</td>
<td>Moment method</td>
<td>Sonnet</td>
</tr>
<tr>
<td>PiCasso</td>
<td>Moment method / Genetic</td>
<td>EMAG</td>
</tr>
<tr>
<td>FEKO</td>
<td>Moment method</td>
<td>EMSS</td>
</tr>
<tr>
<td>PCAAD</td>
<td>Cavity model</td>
<td>Antenna Design Associates, Inc.</td>
</tr>
<tr>
<td>Micropatch</td>
<td>Segmentation</td>
<td>Microstrip Designs, Inc.</td>
</tr>
<tr>
<td>Microwave Studio (MAFIA)</td>
<td>FDTD</td>
<td>CST</td>
</tr>
<tr>
<td>Fidelity</td>
<td>FDTD</td>
<td>Zeland</td>
</tr>
<tr>
<td>HFSS</td>
<td>Finite element</td>
<td>Ansoft</td>
</tr>
</tbody>
</table>
6.2 Microstrip Antenna Development Procedure with the aid of commercially available simulation softwares

- **Design Specifications**
  - **Antenna Designer**
    - **Preliminary Design Specifications**
      - **Commercial or Self-Developed Electromagnetic Simulation Software**
        - **Simulation Results**
          - **Do the simulation results agree well with design specifications?**
            - No → **Feedback correction**
            - Yes → **Design**
              - **Fabrication**
                - **Measurement Results**
                  - **Do the measured results agree well with design specifications?**
                    - No → **Feedback correction**
                    - Yes → **Final Design**