A PERSONAL OVERVIEW OF THE DEVELOPMENT OF PATCH ANTENNAS

Part 2

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Schedule

Part 1 (Hour 1)	Part 2 (Hour 2)	Part 3 (Hour 3)	Part 4 (Hour 4)
1. How I got into patch antenna research 2. Basic geometry and basic characteristics of patch antennas 3. Our first topic 4. Our research on topics related to basic studies	5. Broadbanding techniques 6. Full wave analysis and CAD formulas	7. Dual/triple band designs 8. Designs for circular polarization	9. Reconfigurable patch antennas 10. Size reduction techniques 11. Concluding remarks and some citation data

5. Broadbanding Techniques

5.1 Bandwidth limitations of the basic patch antenna geometry

5.2 General principles of broadbanding

5.3 Stacked patches

5.4 Aperture coupled patches

5.5 The U-slot patch

5.6 The L-probe fed patch

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 $t \le 0.03\ \lambda_0$) to minimize the feed inductance.

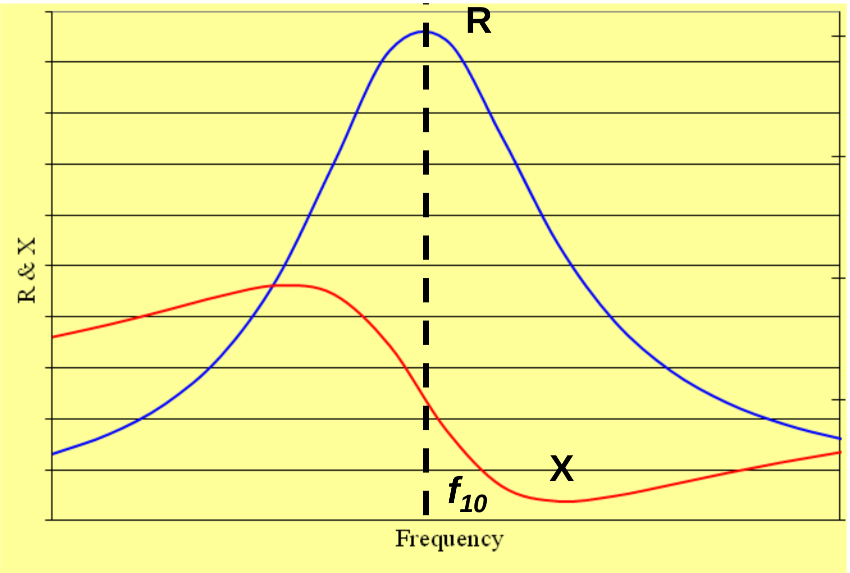


Fig. 2.1

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.

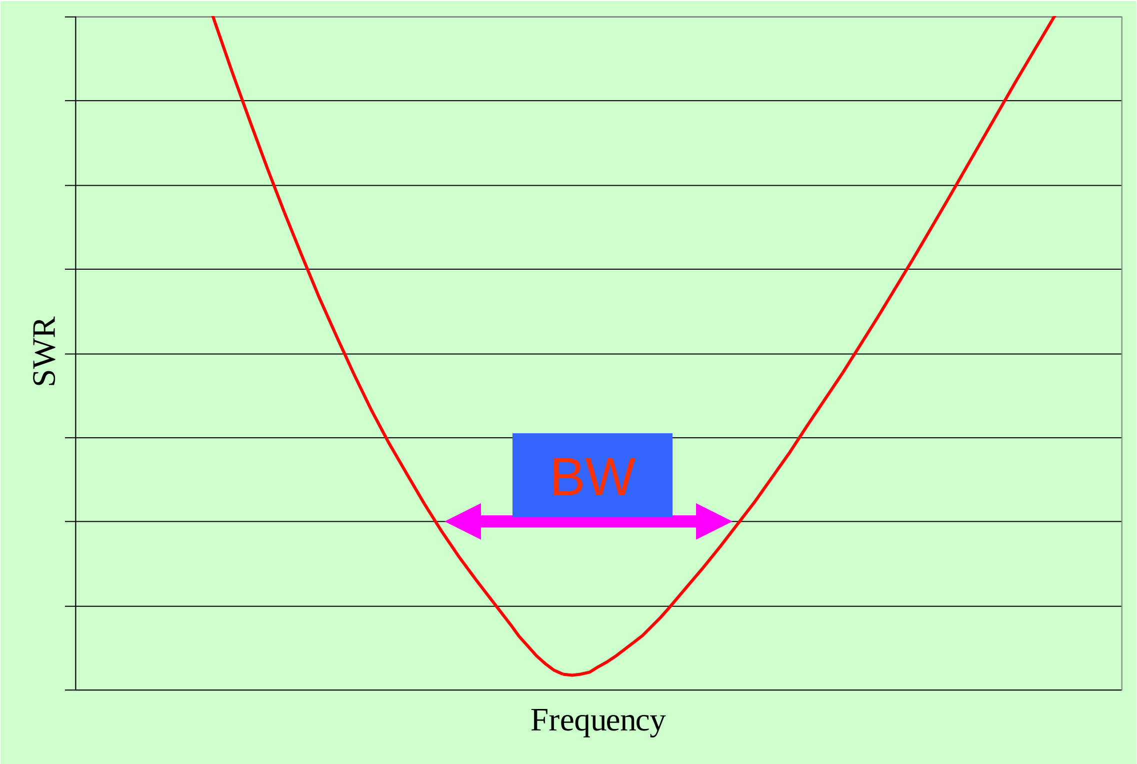


Fig. 2.2

5.1 Bandwidth Limitations of the Basic Microstrip Patch Antenna

- For most frequencies of interest:
  - Δf increases as thickness t increases
  - Δf increases as εr decreases
  - For $t \leq 0.03\lambda_0$, the reactance $\boldsymbol{X_r}$ is very small and Δf essentially represents the bandwidth
    - BW ↑ as t ↑
    - BW ↑ as ε_r ↓

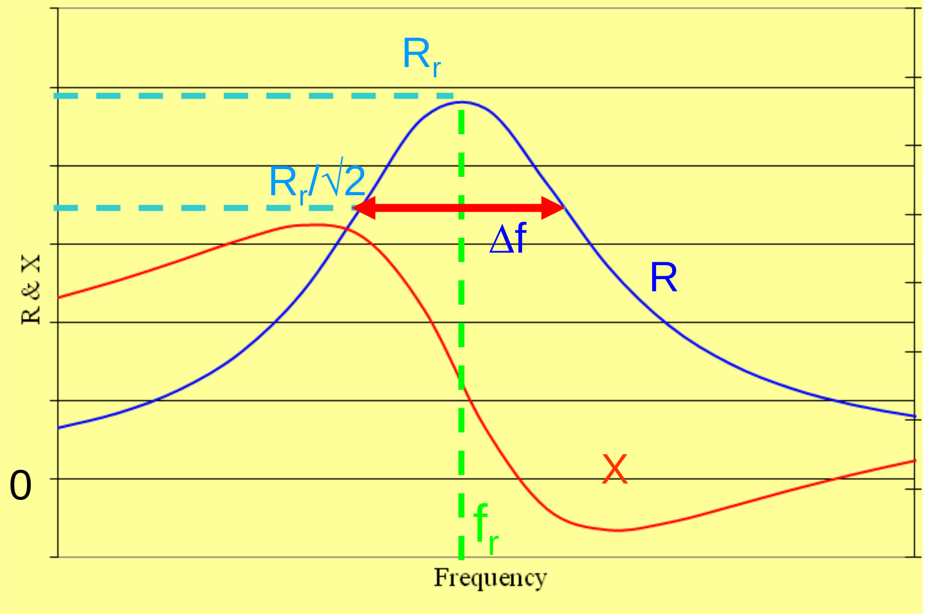


Fig. 2.3

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 ≥ 2.

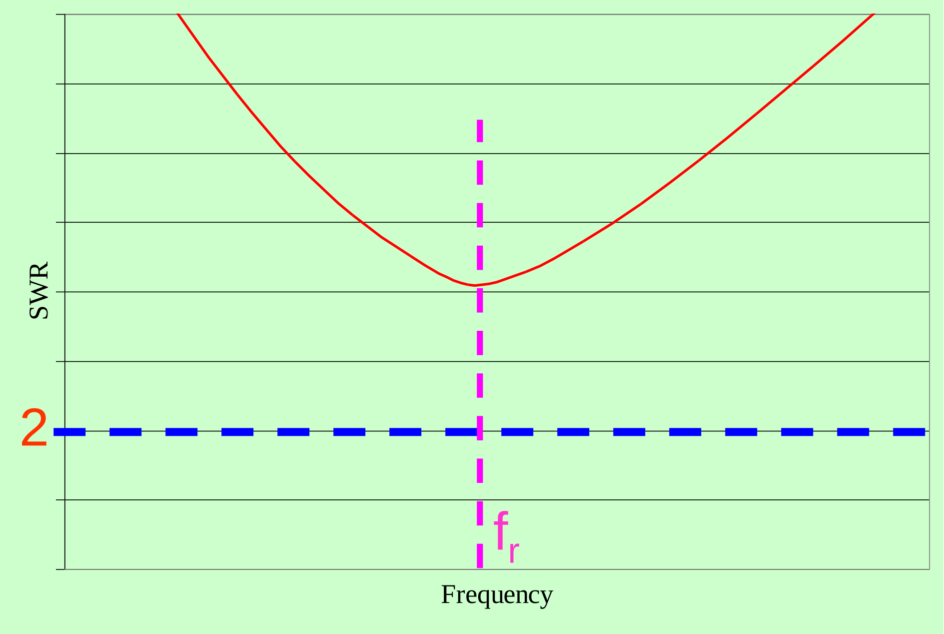


Fig. 2.4

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 ε_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 2.1 Frequencies and Bandwidth Requirements of Several Wireless Communication Systems

System	Operating frequency	Overall bandwidth
Advanced Mobile Phone Service (AMPS)	Tx:824-849 MHz Rx:869-894 MHz	70 MHz (8.1%)
Global System for Mobile Communications (GSM)	Tx:880-915 MHz Rx:925-960 MHz	80 MHz (8.7%)
Personal Communications Service (PCS)	Tx:1710-1785 MHz Rx:1805-1880 MHz	170 MHz (9.5%)
Global System for Mobile Communications (GSM)	Tx:1850-1910 MHz Rx:1930-1990 MHz	140 MHz (7.3%)
Wideband Code Division Multiple Access (WCDMA)	Tx:1920-1980 MHz Rx:2110-2170 MHz	250 MHz (12.2%)
Universal Mobile Telecommunication Systems (UMTS)	Tx:1920-1980 MHz Rx:2110-2170 MHz	250 MHz (10.2%)

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.**

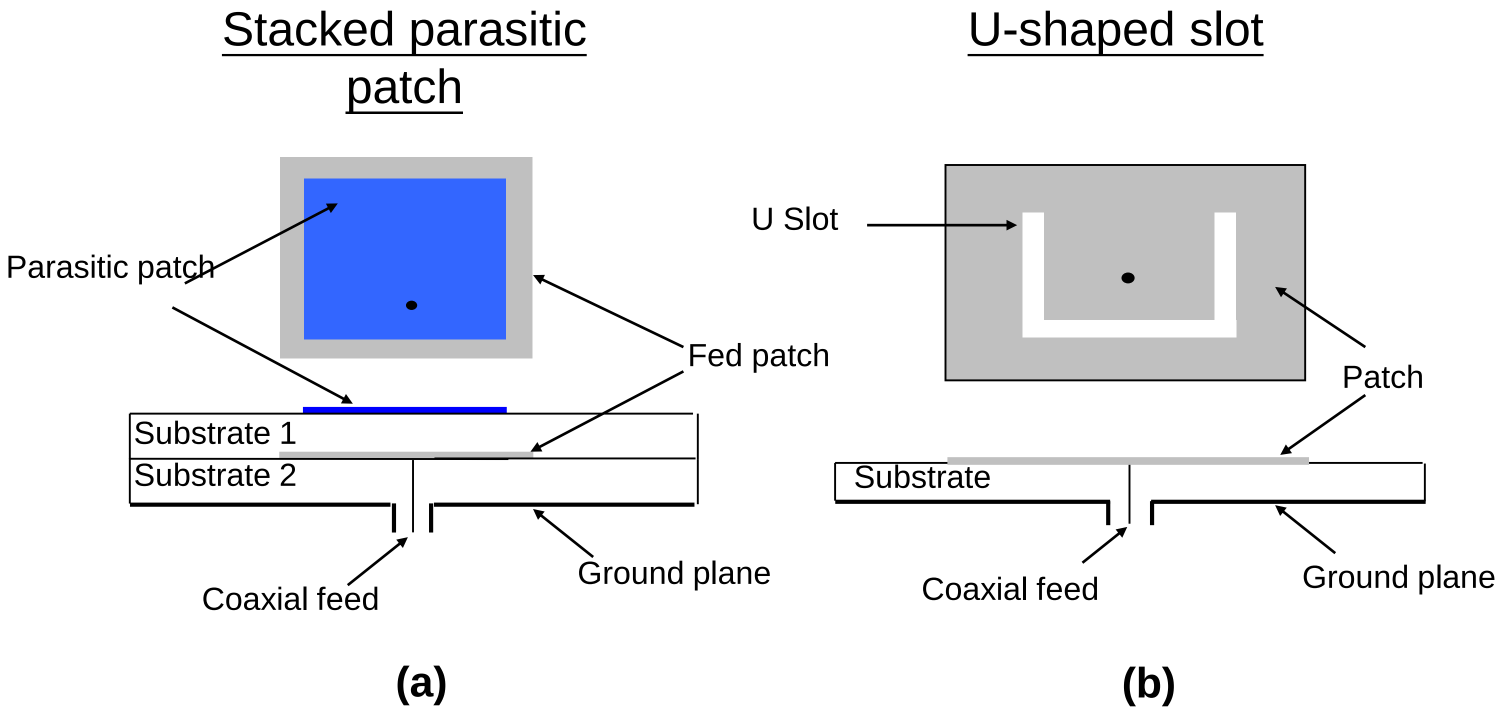
The designs developed include:

- 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.



Stacked parasitic patch

U-shaped slot

(a)

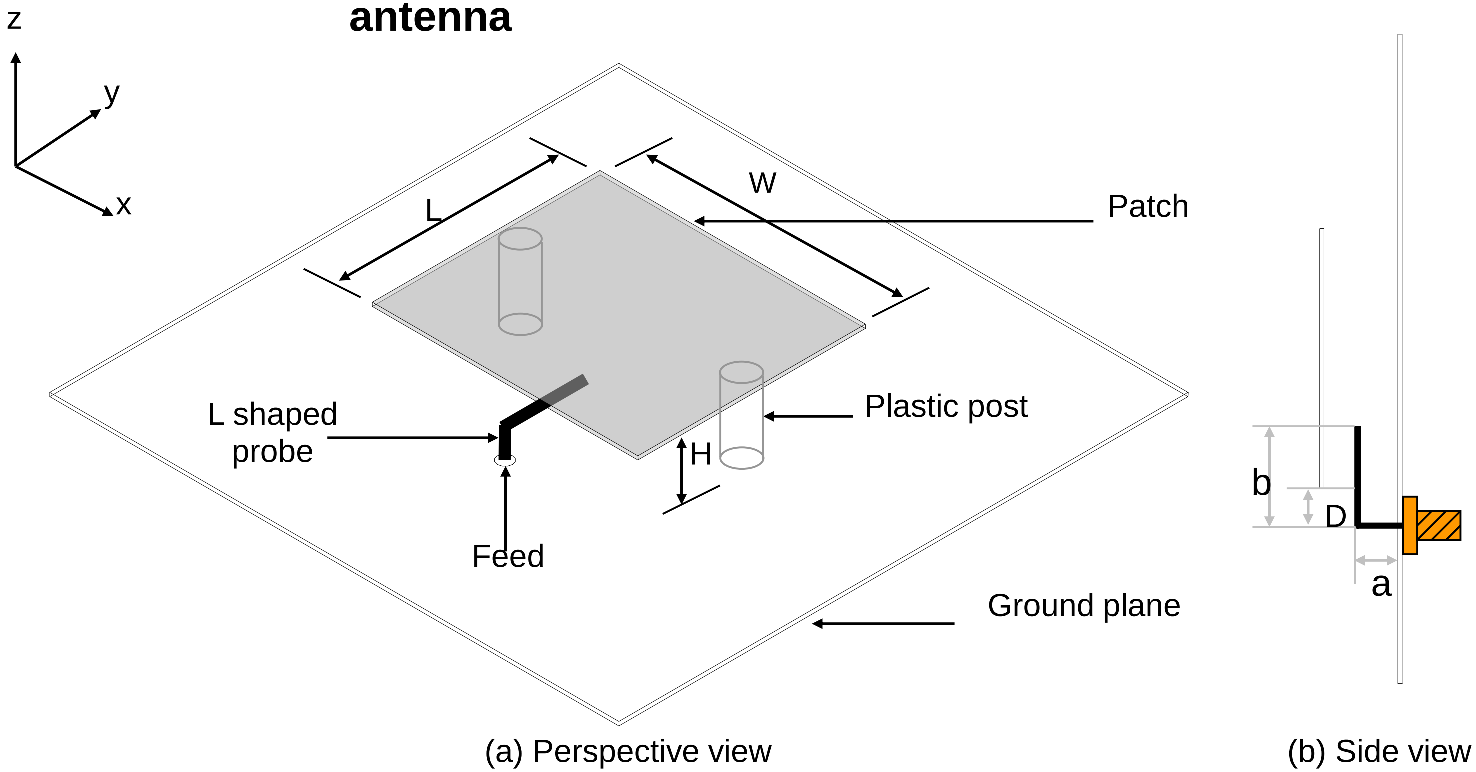
(b)

Seldom exceeds 20% BW;
More than one layer

Single-layer, single patch;
Easily achieve 30% BW;
Thick substrate ~ 0.08 λ_0 ;
High cross pol in H-plane

Fig. 2.5 Geometries of various wideband patch antennas.

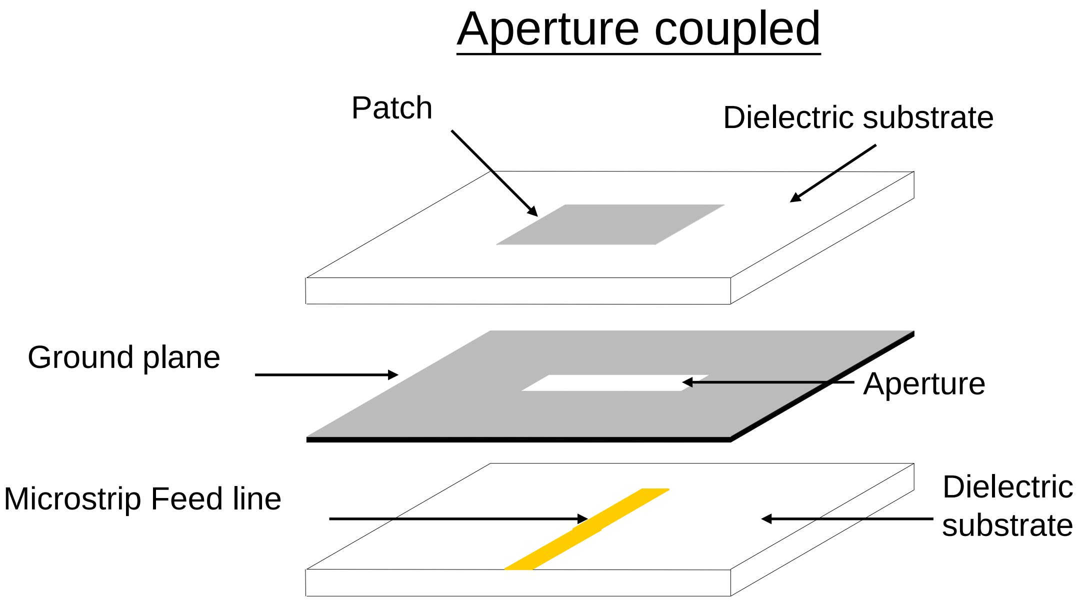
(c) L-probe coupled patch antenna



36 % BW High cross-pol in one plane.

Fig. 2.5 Geometries of various wideband patch antennas.

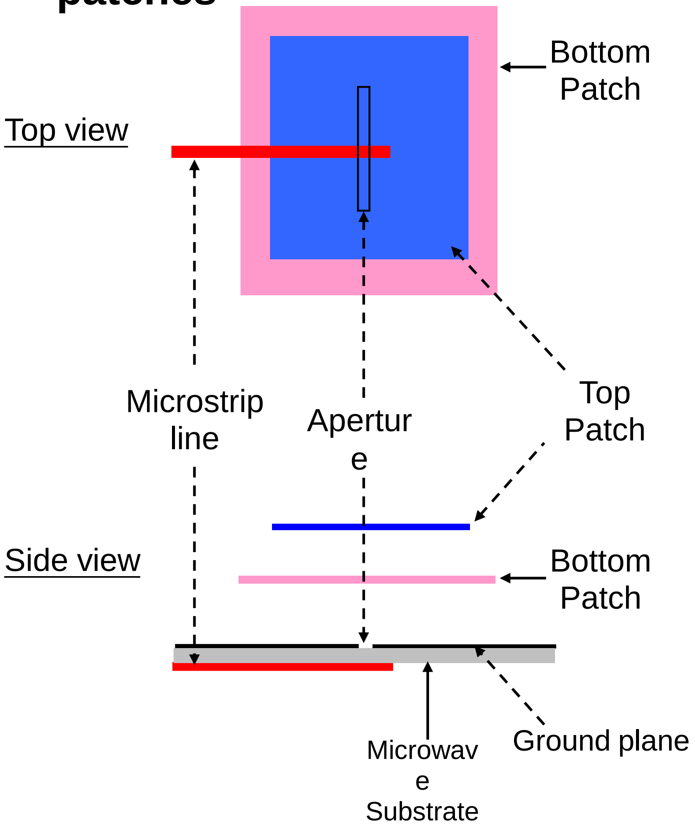
Aperture coupled patches



(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.

Aperture coupled stacked patches



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

Fig. 2.5 Geometries of various wideband patch antennas.

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].
- Example 1: R. Q. Lee, K. F. Lee, J. Bobinchak, *Electronics Letters*, Vol. 23, pp. 1070 – 1072, 1987.

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

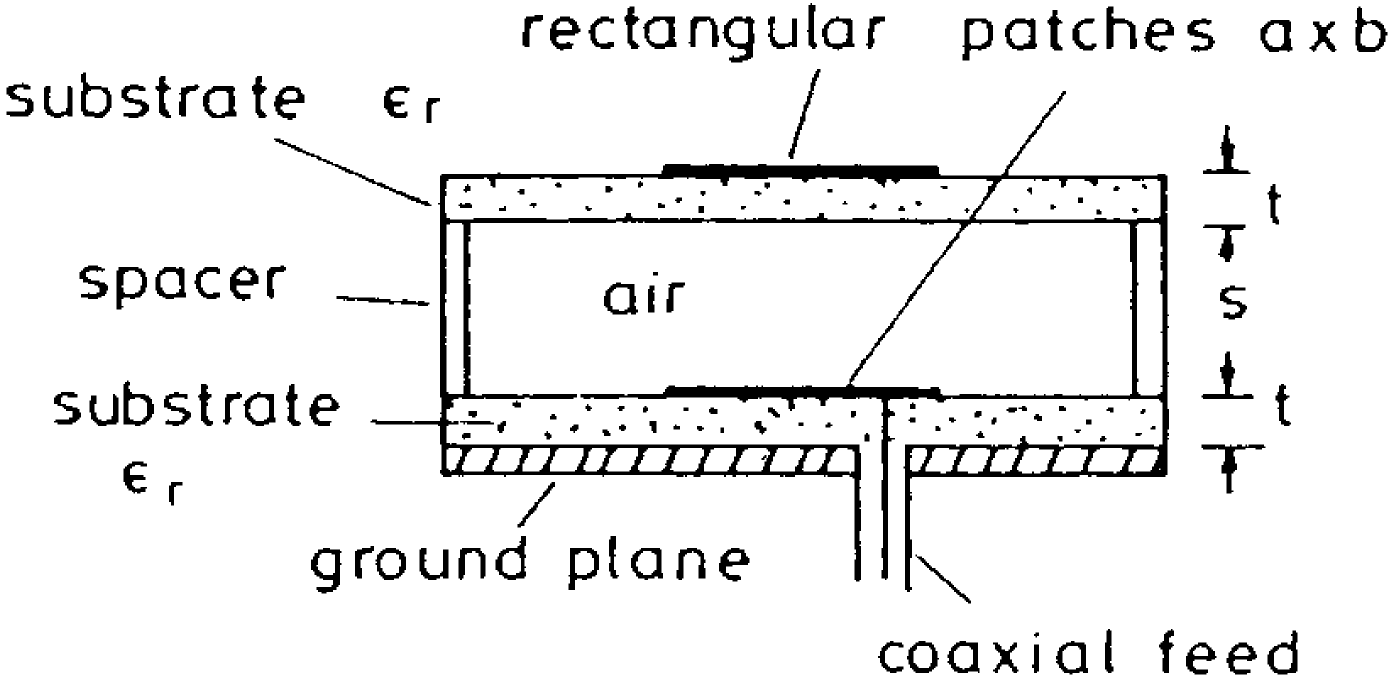
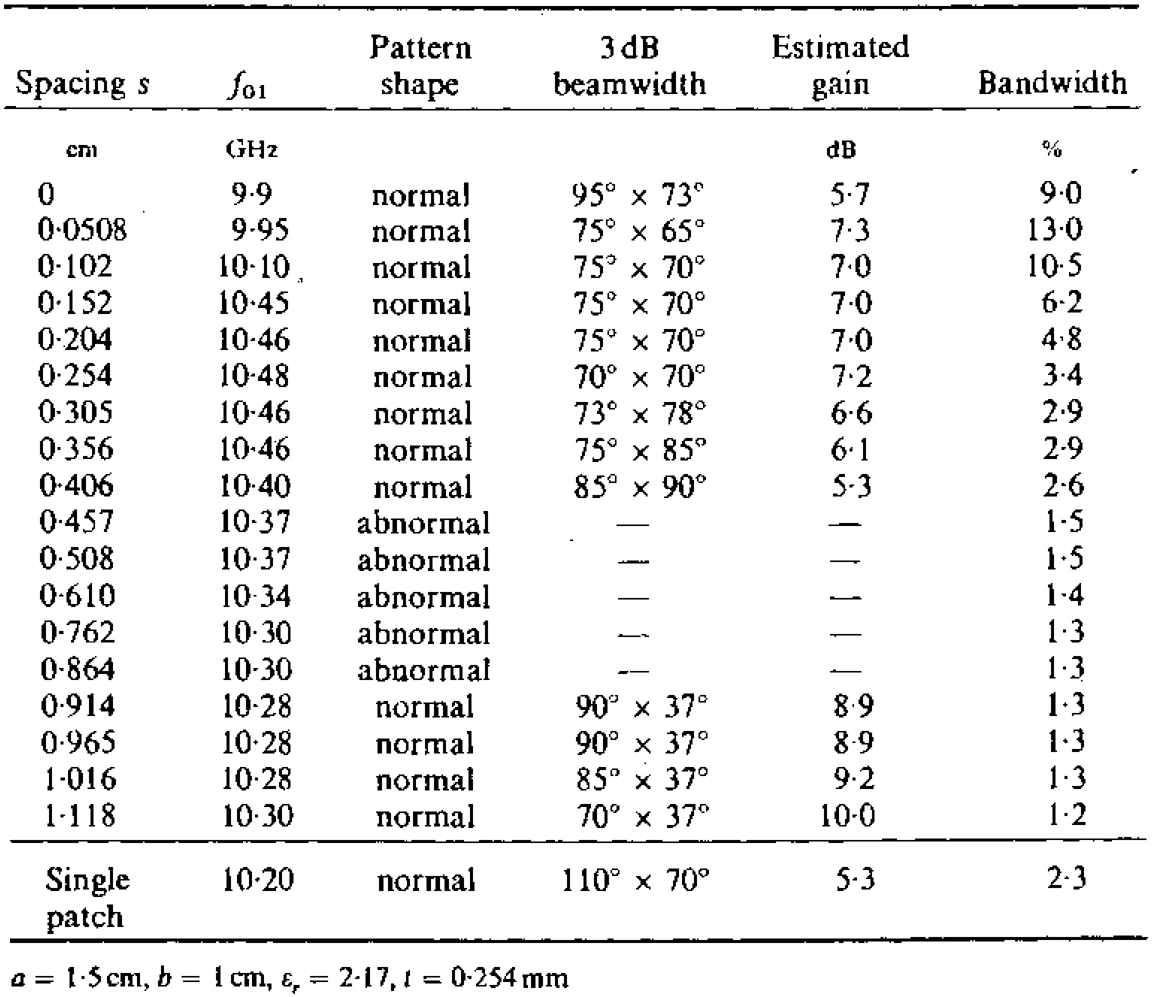


Fig. 2.6 Geometry of rectangular electromagnetically coupled patch antenna.

5.3 Stacked Parasitic Patches

Table 2.2 Characteristics of a rectangular electromagnetically coupled patch antenna.



Spacing s	f_{01}	Pattern shape	3 dB beamwidth	Estimated gain	Bandwidth
cm	GHz			dB	%
0	9·9	normal	95° × 73°	5·7	9·0
0·0508	9·95	normal	75° × 65°	7·3	13·0
0·102	10·10	normal	75° × 70°	7·0	10·5
0·152	10·45	normal	75° × 70°	7·0	6·2
0·204	10·46	normal	75° × 70°	7·0	4·8
0·254	10·48	normal	70° × 70°	7·2	3·4
0·305	10·46	normal	73° × 78°	6·6	2·9
0·356	10·46	normal	75° × 85°	6·1	2·9
0·406	10·40	normal	85° × 90°	5·3	2·6
0·457	10·37	abnormal	—	—	1·5
0·508	10·37	abnormal	—	—	1·5
0·610	10·34	abnormal	—	—	1·4
0·762	10·30	abnormal	—	—	1·3
0·864	10·30	abnormal	—	—	1·3
0·914	10·28	normal	90° × 37°	8·9	1·3
0·965	10·28	normal	90° × 37°	8·9	1·3
1·016	10·28	normal	85° × 37°	9·2	1·3
1·118	10·30	normal	70° × 37°	10·0	1·2
Single patch	10·20	normal	110° × 70°	5·3	2·3

$a = 1·5$ cm, $b = 1$ cm, $\varepsilon_r = 2·17$, $t = 0·254$ mm

5.3 Stacked Parasitic Patches

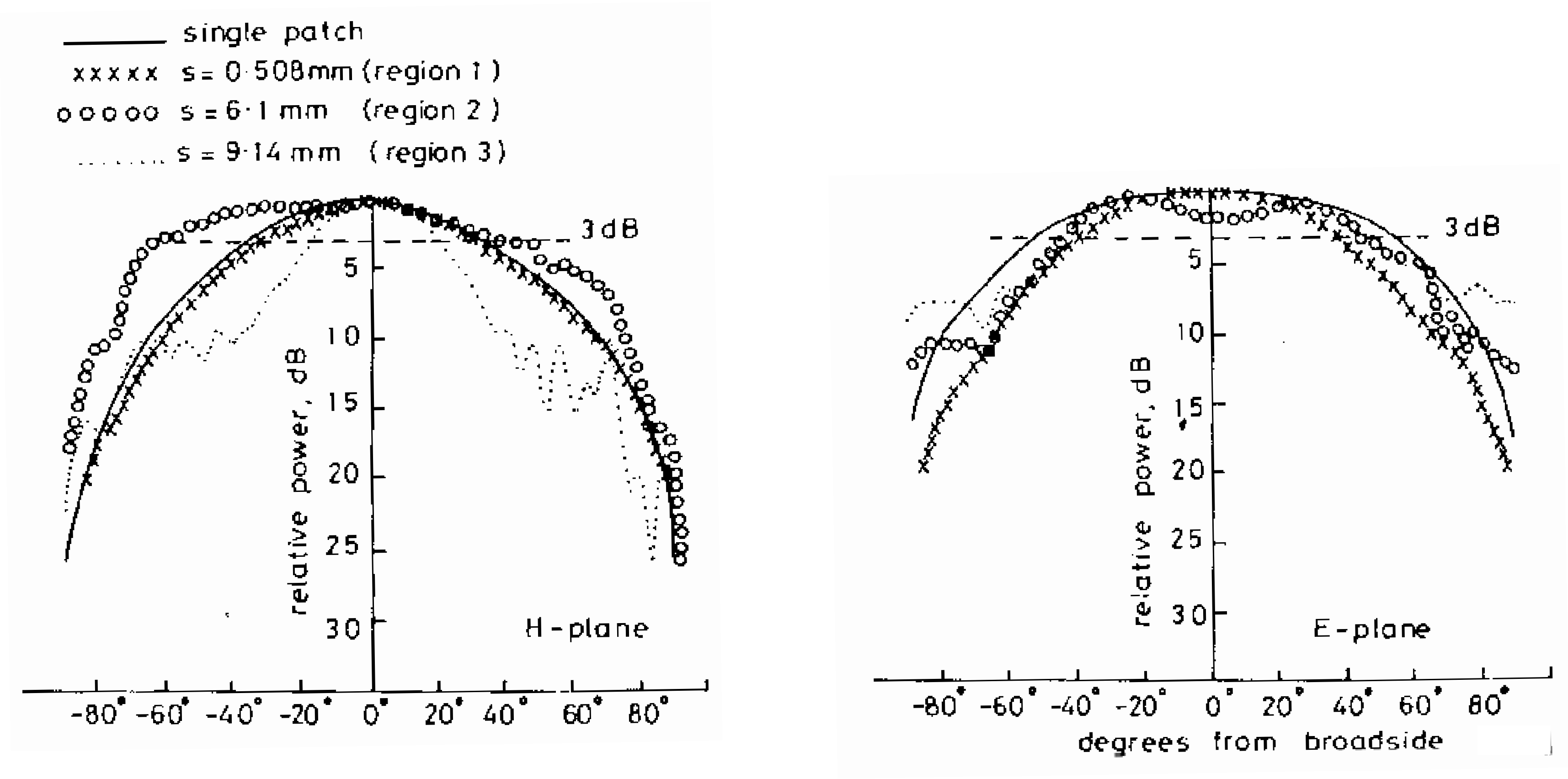


Fig. 2.7 Patterns of a rectangular electromagnetically coupled patch antenna.

***a* = 1.5 cm, *b* = 1 cm, ε_r = 2.17, *t* = 0.0254 cm, *s* = 0.0508 cm (region 1), 0.61 cm (region 2) and 0.9 cm (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 ($\cong 0.14\ \lambda_0$), the patterns show good broadside features. The bandwidth rises to 13 % at ***s*** = 0.0508 cm ($\cong 0.017\ \lambda_0$) and the gain is about 7 dB. At the upper boundary of this region (***s*** = 0.406 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 ($\cong 0.31\ \lambda_0$), 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

- Example 2: K. F. Lee, W. Chen, R. Q. Lee, *Microwave and Optical Technology Letters*, Vol. 8, No. a, pp. 212 – 215, 1995.

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 76^0 and 86^0 respectively. This is to be compared with 92^0 and 86^0 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

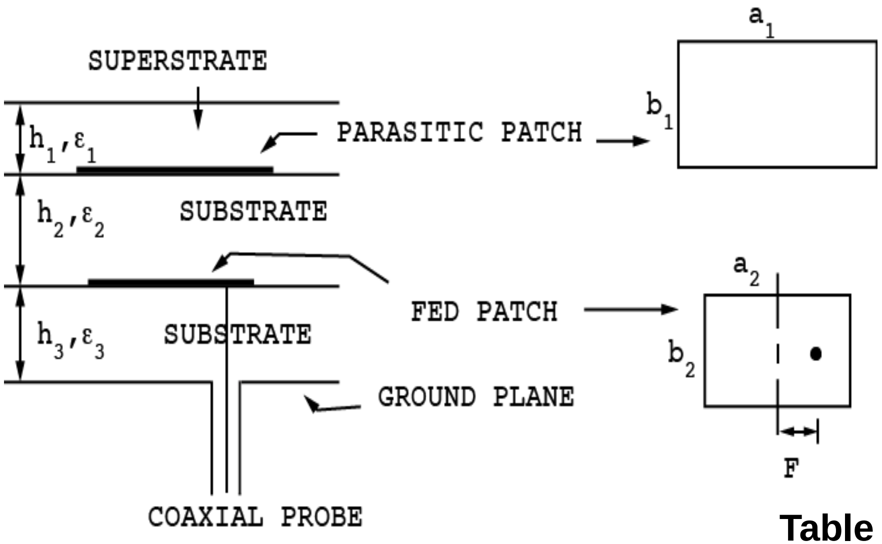
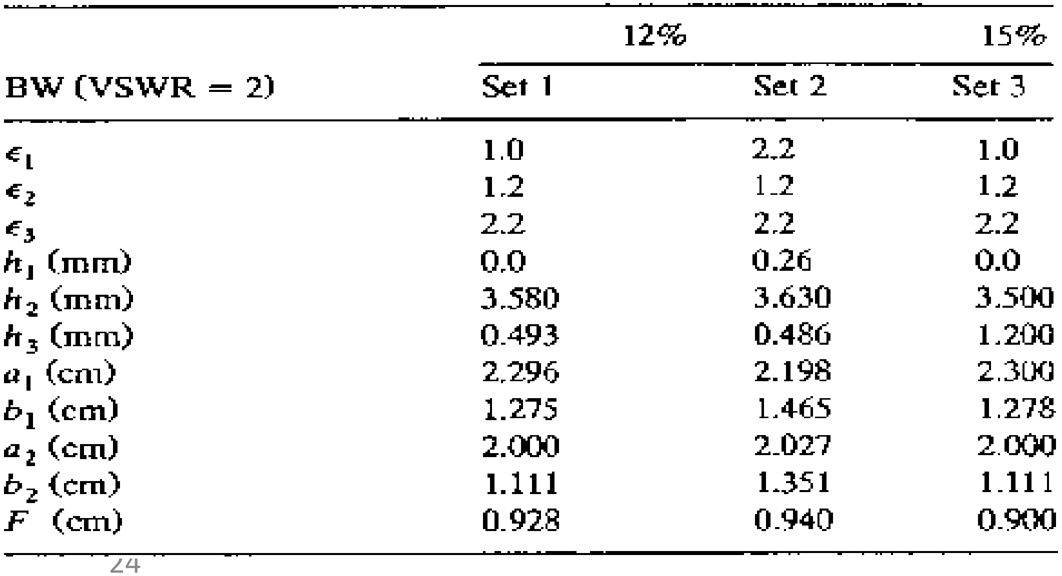


Fig. 2.8 Stacked lectromagnetically coupled patch antenna with superstrate

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



	12%		15%
BW (VSWR = 2)	Set 1	Set 2	Set 3
ϵ_1	1.0	2.2	1.0
ϵ_2	1.2	1.2	1.2
ϵ_3	2.2	2.2	2.2
h_1 (mm)	0.0	0.26	0.0
h_2 (mm)	3.580	3.630	3.500
h_3 (mm)	0.493	0.486	1.200
a_1 (cm)	2.296	2.198	2.300
b_1 (cm)	1.275	1.465	1.278
a_2 (cm)	2.000	2.027	2.000
b_2 (cm)	1.111	1.351	1.111
F (cm)	0.928	0.940	0.900

5.3 Stacked Parasitic Patches

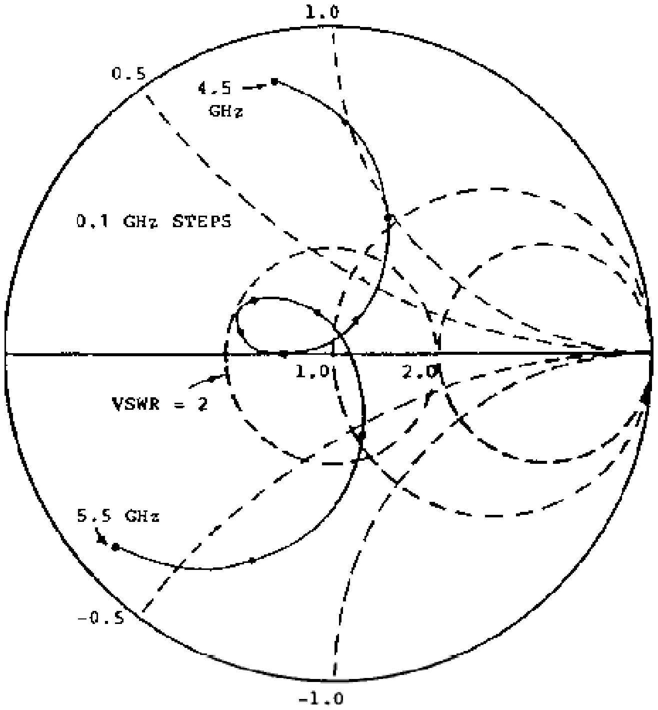


Fig. 2.9 Impedance loci for a stacked EMCP antenna with the parameters given by Set 1 of Table 2.3. Bandwidth = 12 %.

5.3 Stacked Parasitic Patches

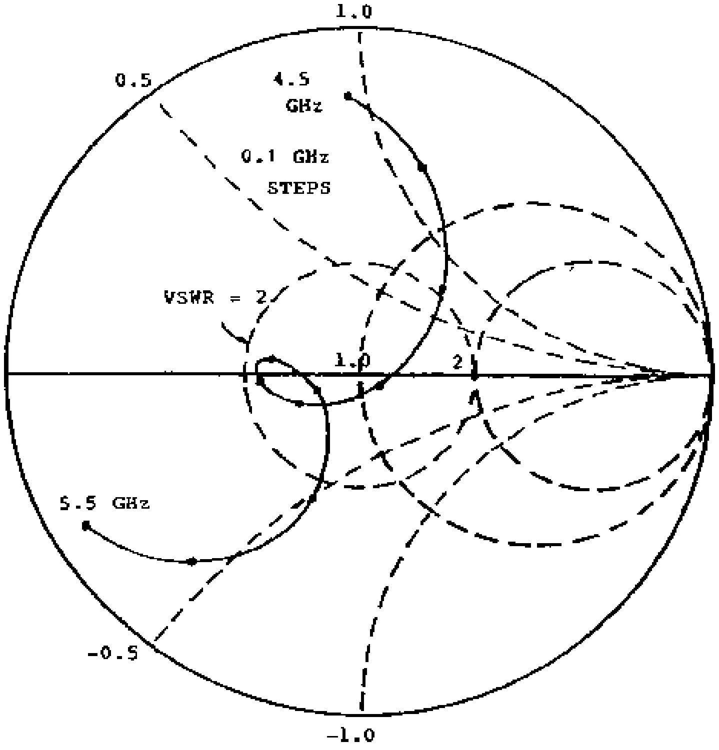


Fig. 2.10 Impedance loci for a stacked EMCP antenna with the parameters given by Set 2 of Table 2.3. Bandwidth = 12 %.

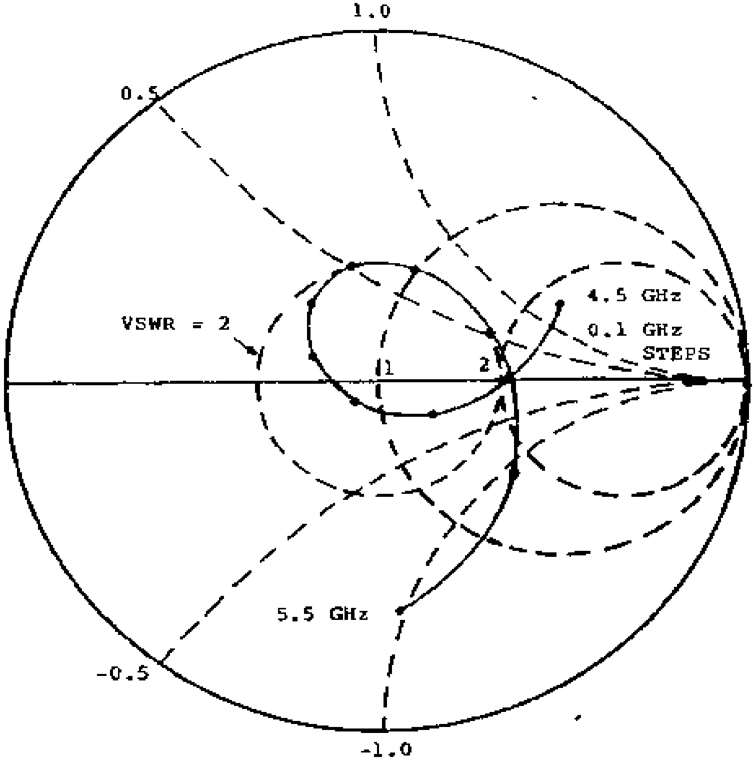


Fig. 2.11 Impedance loci for a stacked EMCP antenna with the parameters given by Set 3 of Table 2.3. Bandwidth = 15 %.

- Stacked patch designs seldom exceed 20 % BW.

References on section 5.1-5.3

- W. Chen, K. F. Lee and R. Q. Lee, "Input Impedance of Coaxially Fed Rectangular Microstrip Antenna on Electrically Thick Substrate," *Microwave and Optical Technology Letters*, Vol. 6, No. 6, pp. 387-390, 1993.

- W. Chen, K. F. Lee and R. Q. Lee, "Spectral-Domain Moment-Method Analysis of Co-planar Microstrip Parasitic Subarrays," *Microwave and Optical Technology Letters,* Vol. 6, No. 3, pp. 157-163, 1993.

- C. Wood, "Improved Bandwidth of Microstrip Antennas Using Parasitic Elements," *IEE Proc., Pt. H*, Vol. 127, pp. 231-234, 1980.

- J. R. Mosig and F. Gardiol, "The Effect of Parasitic Elements on Microstrip Antennas," *IEEE AP-S International Symposium Digest*, pp. 397-400, 1985.

- C. K. Aanandan, P. Mohanabm, and K. G. Nair, "Broad-Band Gap Coupled Antenna," *IEEE Trans. Antennas Propagat*., Vol. AP-38, No. 10, pp. 1581-1586, 1990.

- K. C. Gupta, "Multiport Network Approach for Modelling and Analysis of Microstrip Patch Antenna and Arrays," *in J. R. James and P. S. Hall (Editors), Handbook of Microstrip Antennas, Peter Peregrinus*, London, 1989.

References on stacked patches

- A. Sabban, “New broadband stacked two-layer microstrip antenna,” *IEEE AP-Symposium Digest*, pp. 63-66, 1983.

- L. J. Barlately, J. R. Mosig, and T. Sphicopoulos, “Analysis of stacked microstrip patches with a mixed potential integral equation,” *IEEE Trans. Antennas Propagat*., Vol. AP-38, pp. 608-615, 1990.

- R. Q. Lee, K. F. Lee, and J. Bobinchak, “Characteristics of a two-layer electromagnetically coupled rectangular patch antenna,” *Electronics Letters*, Vol. 23, No. 20, pp. 1070-1073, 1987.

- A. N. Tulintseff, S. M. Ali and J. A. Kong, “Input impedance of a probe-fed stacked circular microstrip antenna,” *IEEE Trans. Antennas and Propagat*., Vol. AP-39, pp. 382-390, 1991.

- K. F. Lee, W. Chen, R. Q. Lee, “Studies of stacked electromagnetically coupled patch antenna,” *Microwave and Optical Technology Letters,* Vol. 8, No. 4, pp. 212-215, 1995.

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

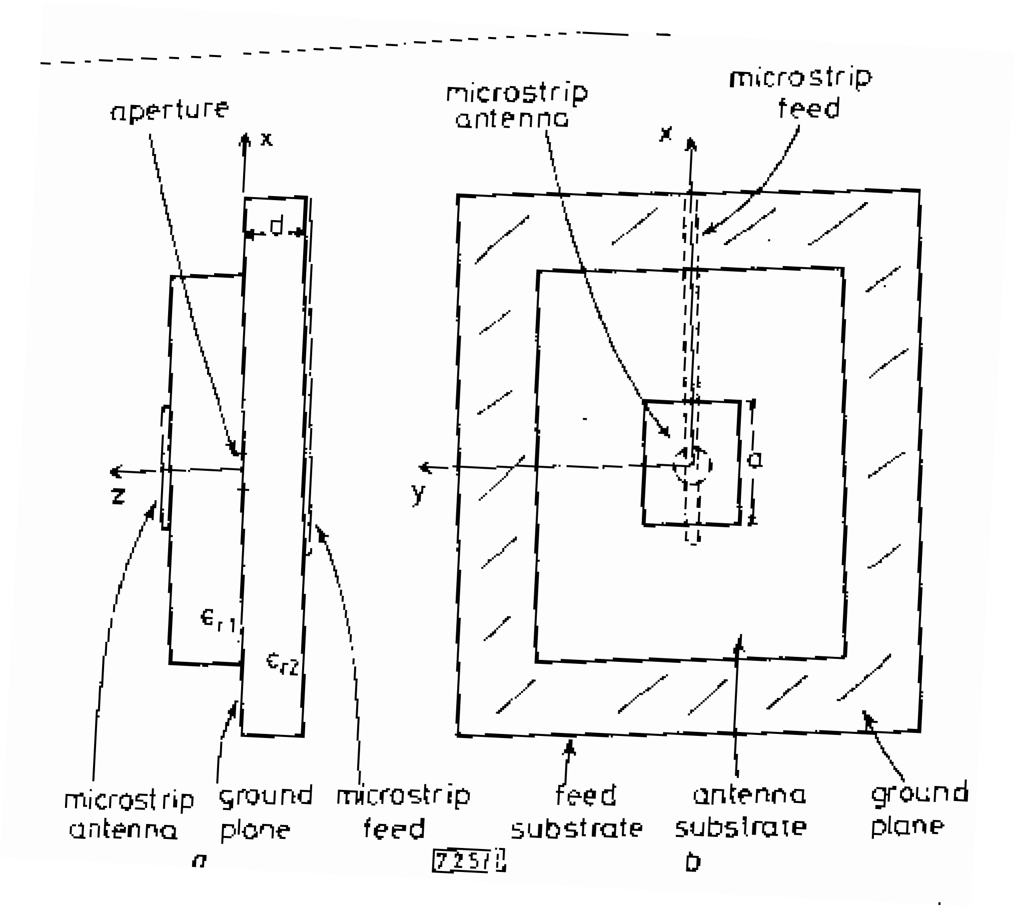


Fig. 2.12 Side view (a) and top view (b) of a rectangular microstrip antenna aperture coupled to a microstripline.

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 (ε_r = 12.8), while the radiating patch can be mounted on a low dielectric constant substrate in order to increase bandwidth and radiation efficiency.

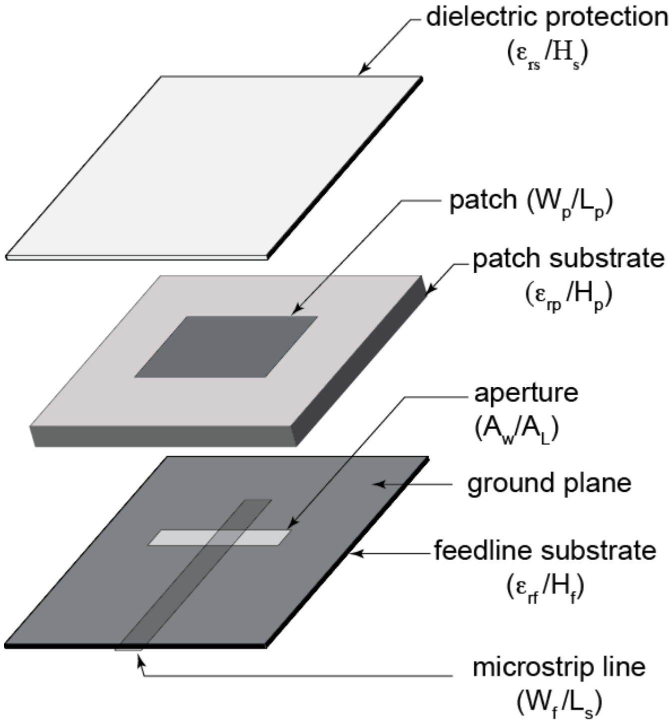
(c) The coupling slot can be resonant or non-resonant. The advantage of using a non-resonant slot is small backlobe radiation. The bandwidth obtained is typically 6-7% but can be as large as 10-13% by utilizing thick substrates, since the problem of probe impedance is not applicable here. By using a 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.



(a) Feed: ε_{rf} = 2.2; tg_{δ} = 0.001; H_f = 0.762mm; W_f = 2.32mm; L_s = 2.85mm

(b) Slot: A_w = 0.8mm; A_1 = 15.4mm

(c) Square patch: W_p = 17mm; H_p = 5.5mm; ε_{rp} = 1

(d) Radome: H_s = 1.6mm; ε_{rs}= 2.2; tg_{δ} = 0.001

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

- **D. M. Pozar, “Microstrip antenna aperture-coupled to a microstripline,” Electronics Letters, Vol. 21, pp. 49-50, 1985.**

- **P. L. Sullivan and D. H. Schaubert, “Analysis of an aperture coupled microstrip antenna,” IEEE Trans. on Antennas and Propagation, Vol. 34, No.8, pp. 977-984, 1986.**

- **F. Crog and A. Papernik, “Large bandwidth aperture-coupled microstrip antenna,” Electronics Letters, Vol. 26, pp. 1293-1294, 1990.**

- **S. D. Targonski, R. B. Waterhouse, and D. M. Pozar, “Design of wide-band aperture-stacked patch microstrip antennas,” IEEE Trans. On Antennas and Propagation, Vol. 46, No. 9, pp. 1245-1251, 1998.**

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.**

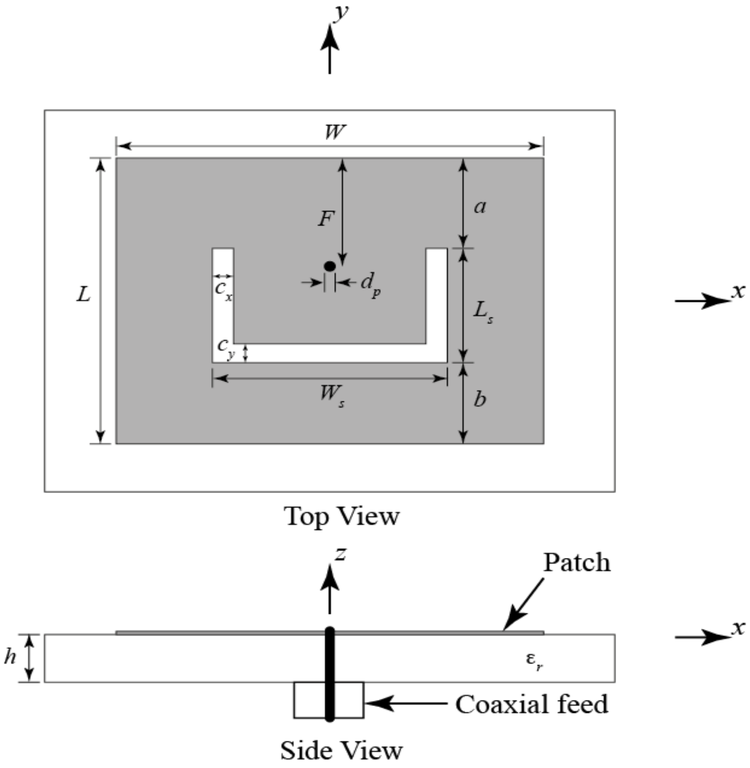
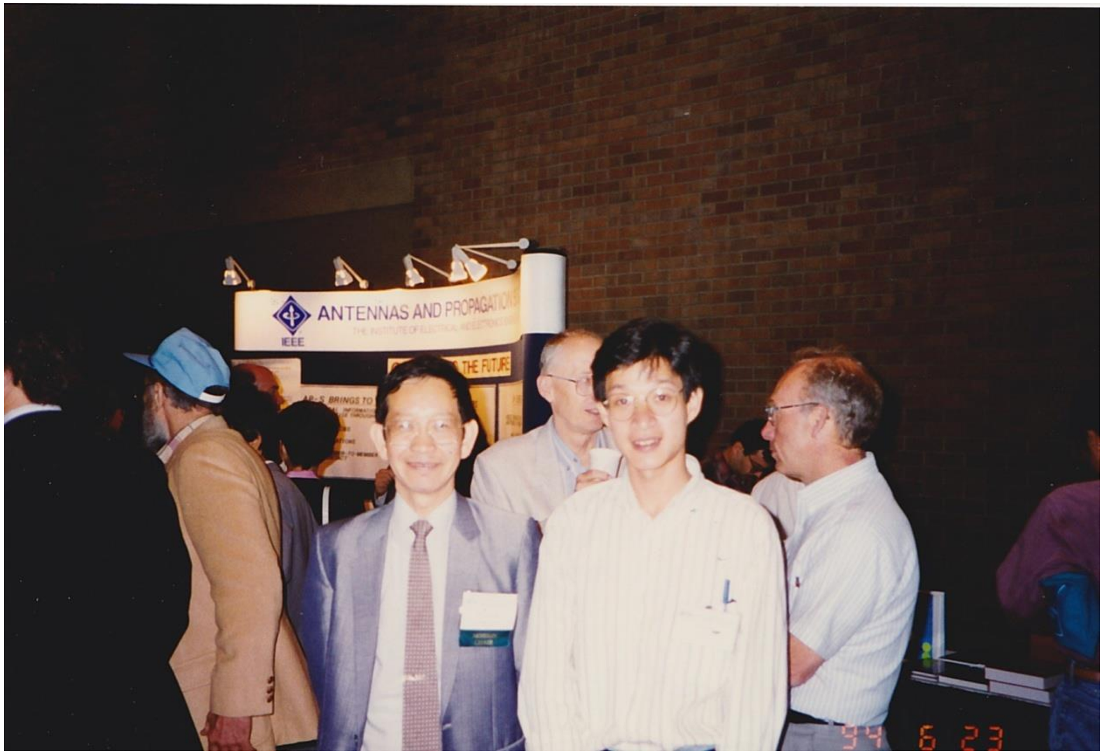


Fig. 2.14 Geometry of the U-Slot Patch Antenna



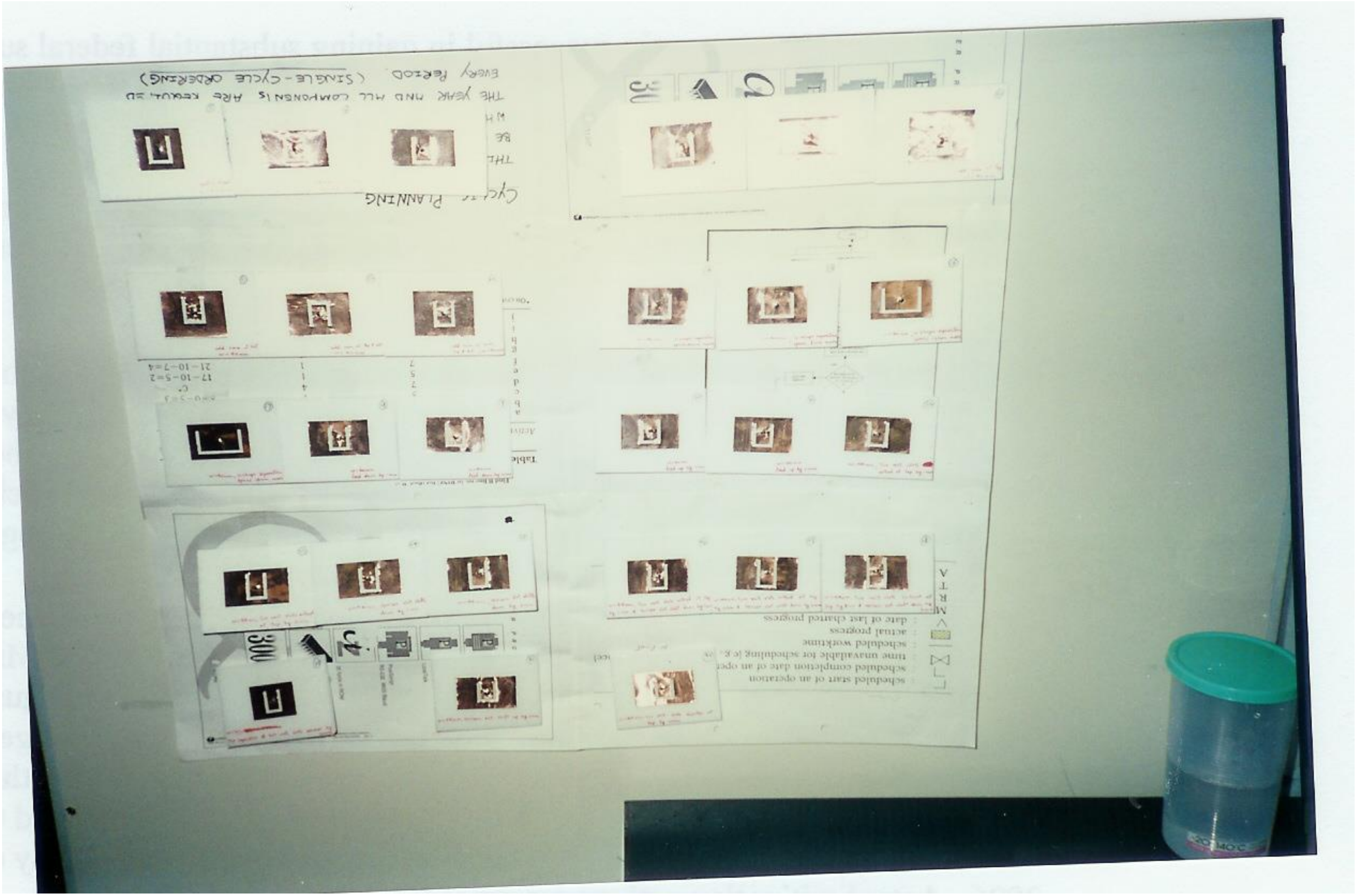
Tan Huynh and K. F. Lee, AP meeting, Seattle, WA 1994

- **The preliminary results were published in the Journal Electronics Letters in Oct. 1995: T. Huynh and K. F. Lee, “Single layer single-patch wideband microstrip antenna”, Vol. 31, No. 10, pp. 1310-1312, 1995. This paper has been cited about 560 times, according to Google Scholar.**
- **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 0.08λ_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 λ_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



K. F. Tong and K. F. Lee at University College London 3/2005

5.5.2 Air/foam Subsrate

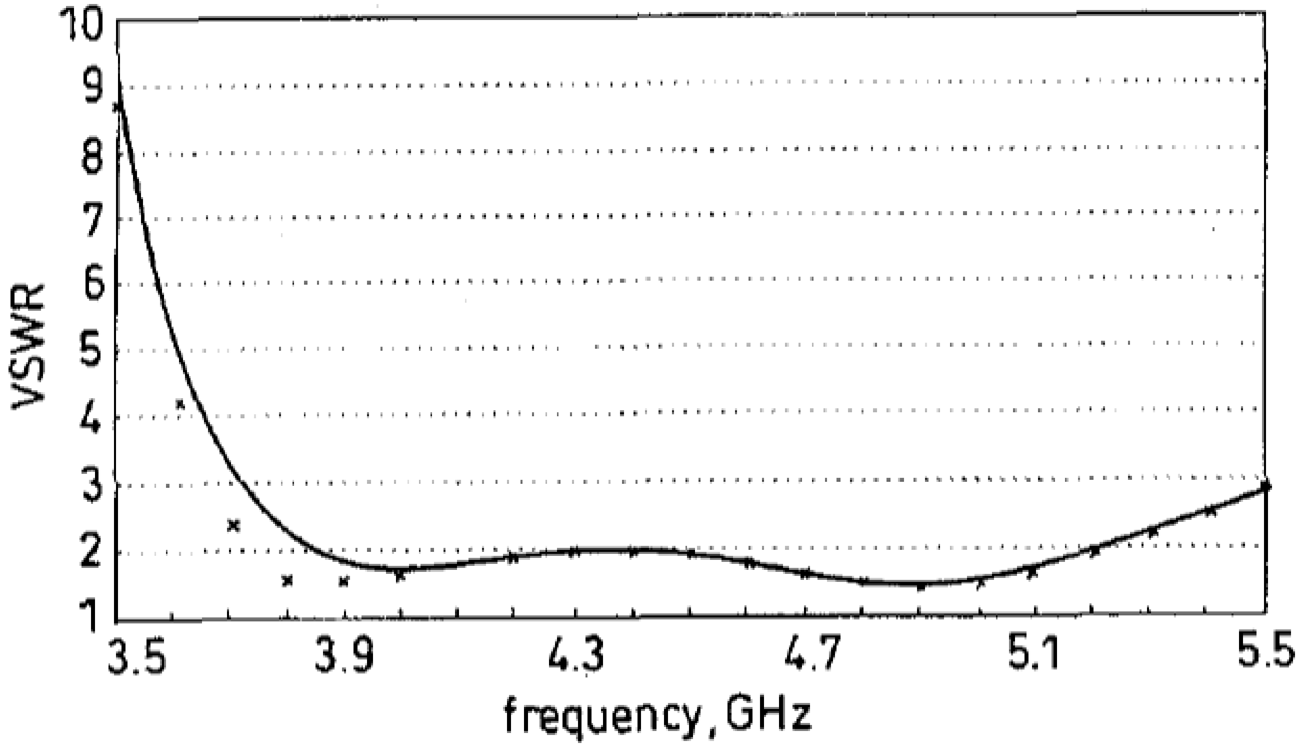


Fig. 2.15 VSWR of the U-slot patch antenna with dimensions: W=36 mm, L=26 mm, F=13 mm, W_s=12 mm, L_s=20 mm, a= 2mm, b=4 mm, c_x=c_y=2 mm, and h=5 mm. (x measured, — computed)

5.5.2 Air/foam substrate

- The impedance bandwidth was about 30%.
- The measured patters (not shown here) were stable across the band. The E and H plane beamwidths were about 70^{0} and 65^{0} 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 λ_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 thick, which has a 12% bandwidth.

5.5.3 Material Subsrate

- 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 ε_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

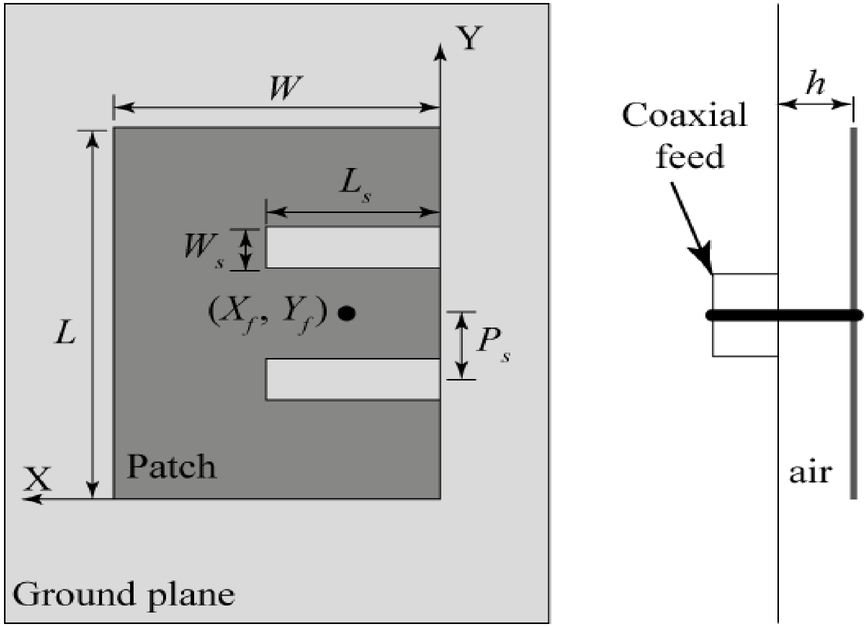
ε_r	W	L	W_s	L_s	b	F	c_x	c_y	h
2.33	36.0	26.0	14.0	18.0	4.0	13.0	2.0	2.0	6.4

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

	f_l(GHz)	f_o(GHz)	f_u(GHz)	BW (GHz)	BW (%)
Computed	2.87	3.28	3.69	0.82	25.0
Measured	2.76	3.16	3.56	0.80	25.3

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 a. 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 0.08λ_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.**



Top View

Side View

Fig. 2.16 Geometry of the E-patch

Prof. Fan Yang

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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.**

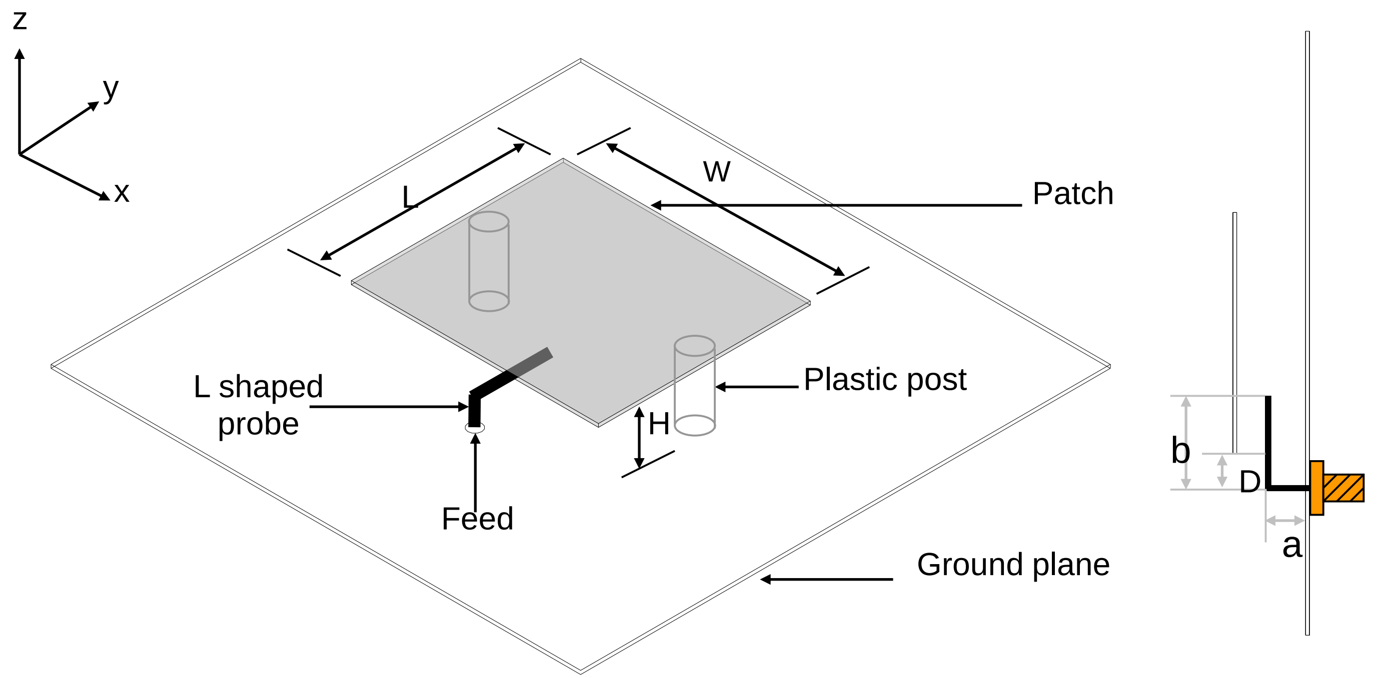
- **Similar to the U-slot patch, this design has only one patch and one layer. Using foam substrate between 0.08 to 0.1λ_0, it achieves 30% or more matching bandwidth.**

- **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)



(a) Perspective view

(b) Side view

Parameters	W	L	H	b	a	D
Value /mm	30mm	25mm	6.6mm	10.5mm	5.5mm	2mm
	$0.44\lambda_0$	$0.37\lambda_0$	$0.098\lambda_0$	$0.156\lambda_0$	$0.082\lambda_0$	$0.03\lambda_0$

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

5.6 The L-Probe Fed Patch

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

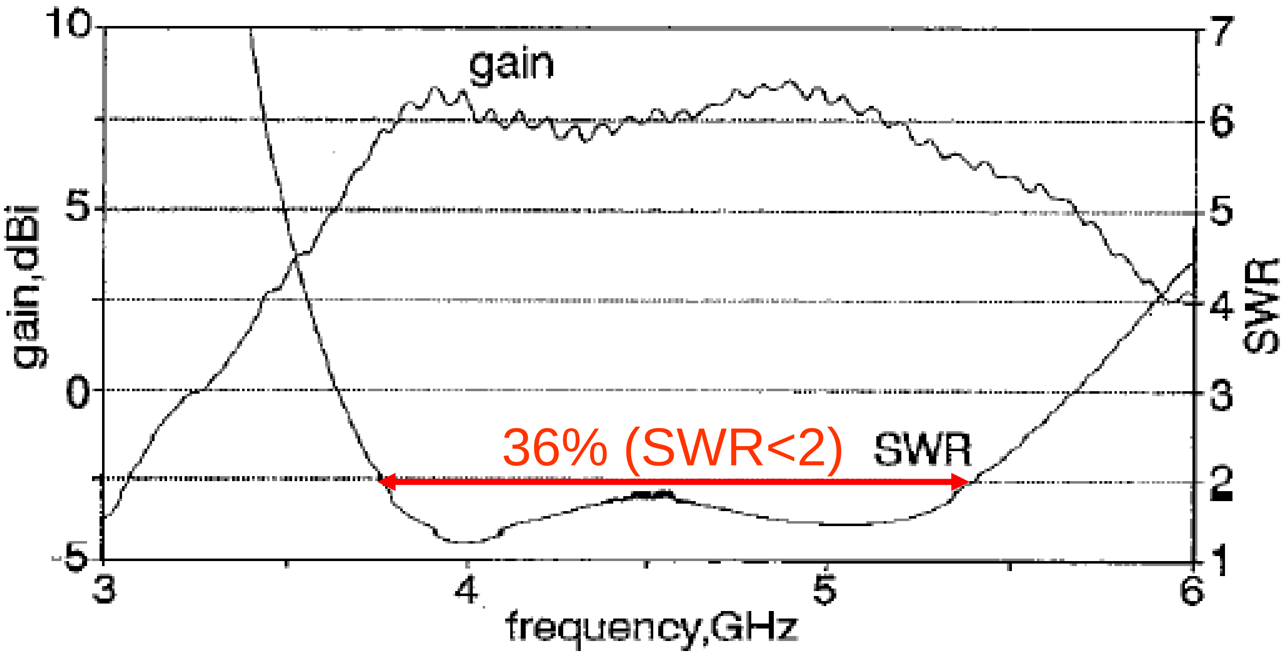


Fig. 2.18 Measured gain and SWR against frequency.

5.6 The L-Probe Fed Patch

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

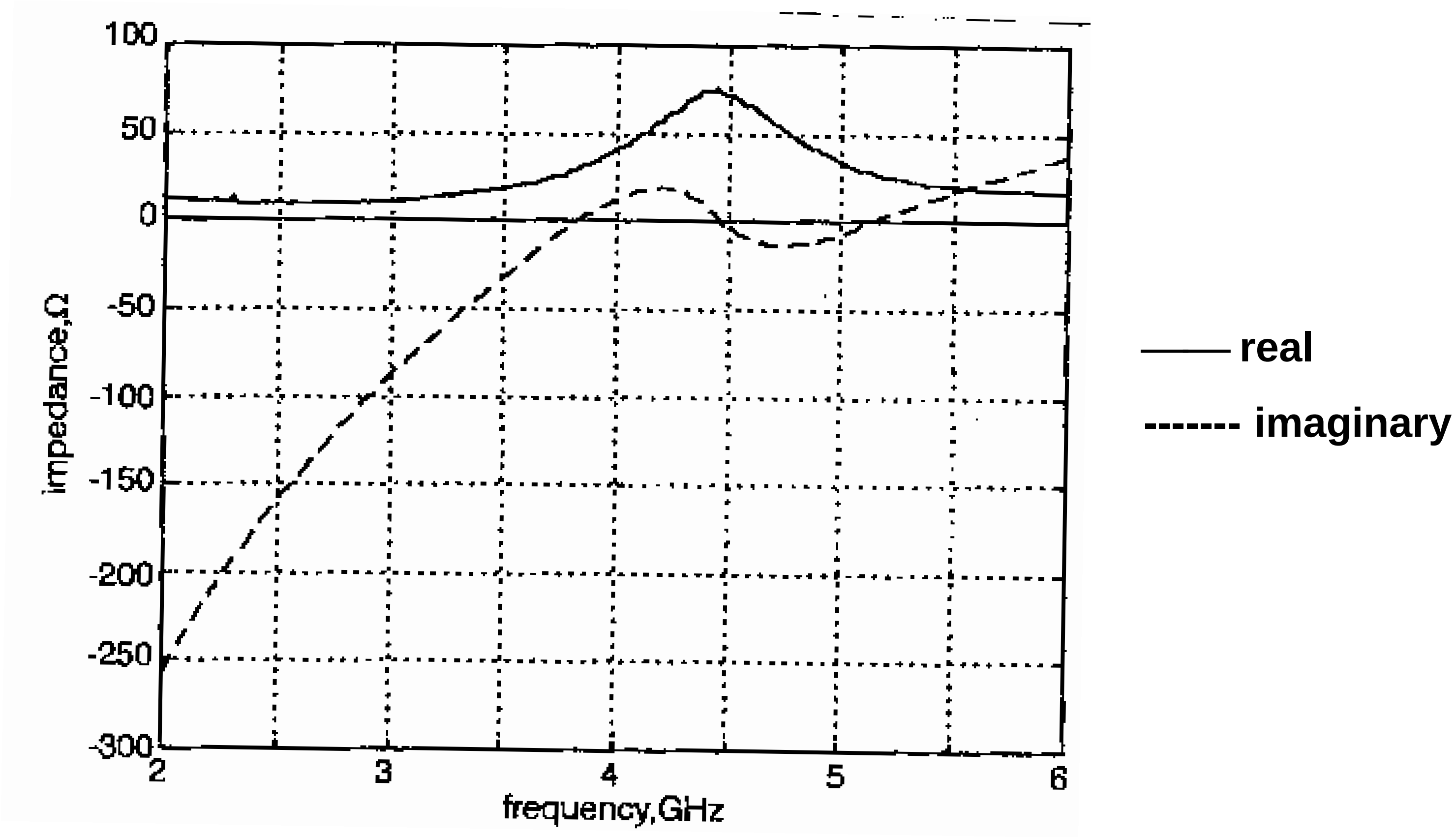


Fig. 2.19 Measured input impedance against frequency.

SWR and gain

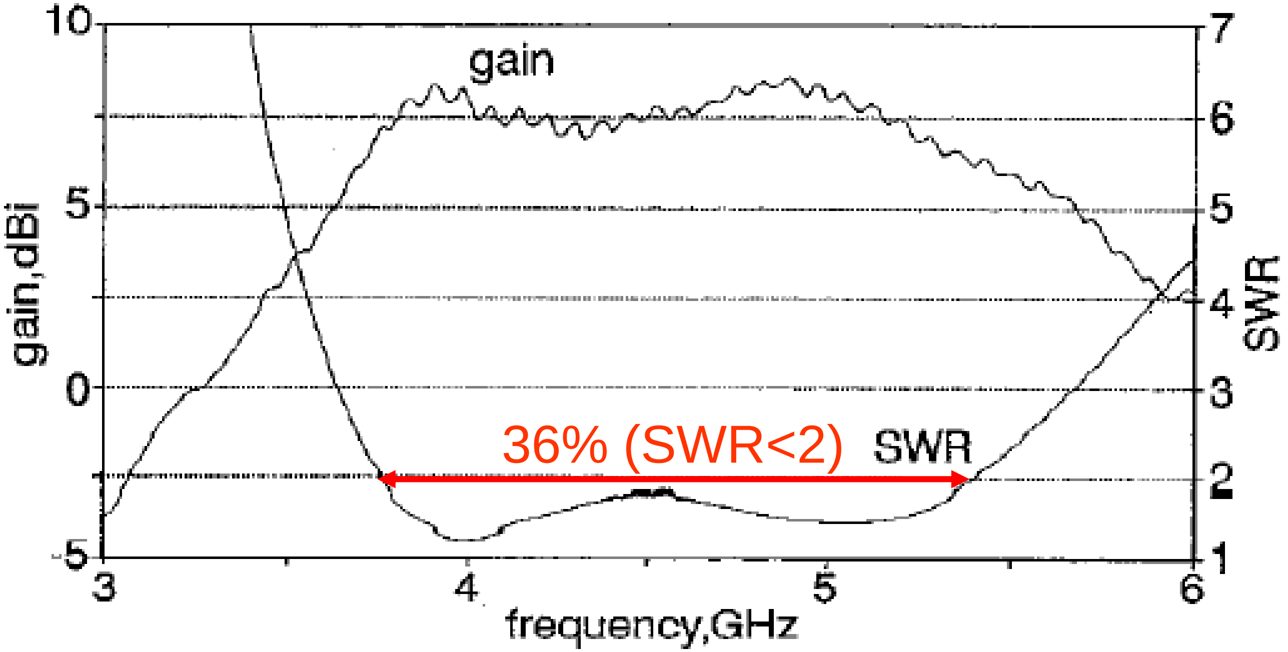


Figure 2.20 Measured gain and SWR against frequency

Radiation patterns

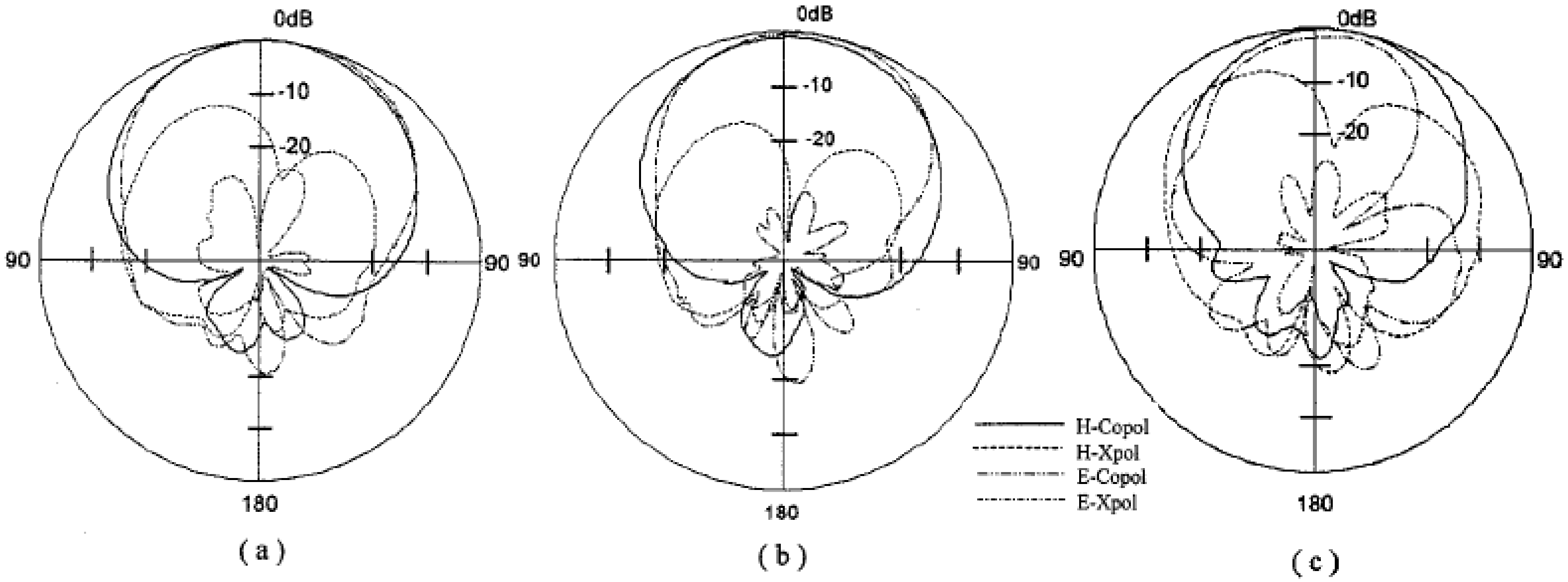


Figure 2.21 Measured radiation patterns at (a) 4GHz (b) 4.53GHz (c) 5.34GHz

C. L. Mak, K. M. Luk, K. F. Lee, and Y. L. Chow, “Experimental Study of a Microstrip Patch Antenna with an L-shaped Probe,” *IEEE Transactions on Antennas and Propagation*, vol. AP-48, No. 5, pp. 777-783, May 2000.

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%.**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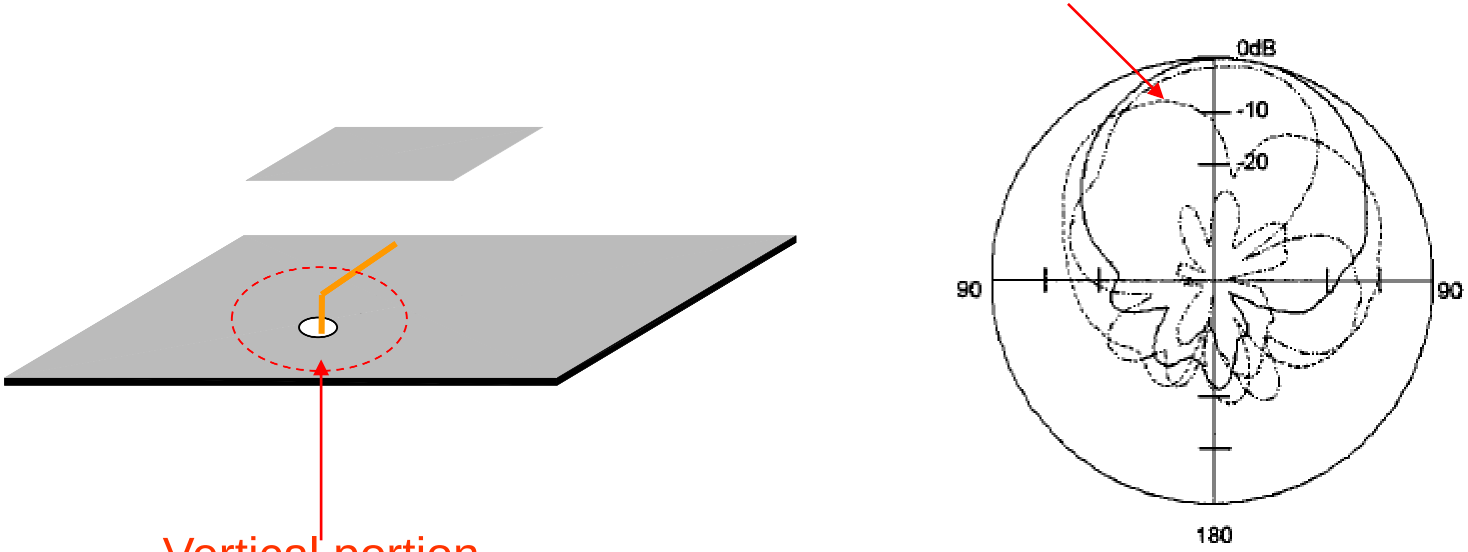
Disadvantage of L-shaped probe feeding mechanism

High cross polarization



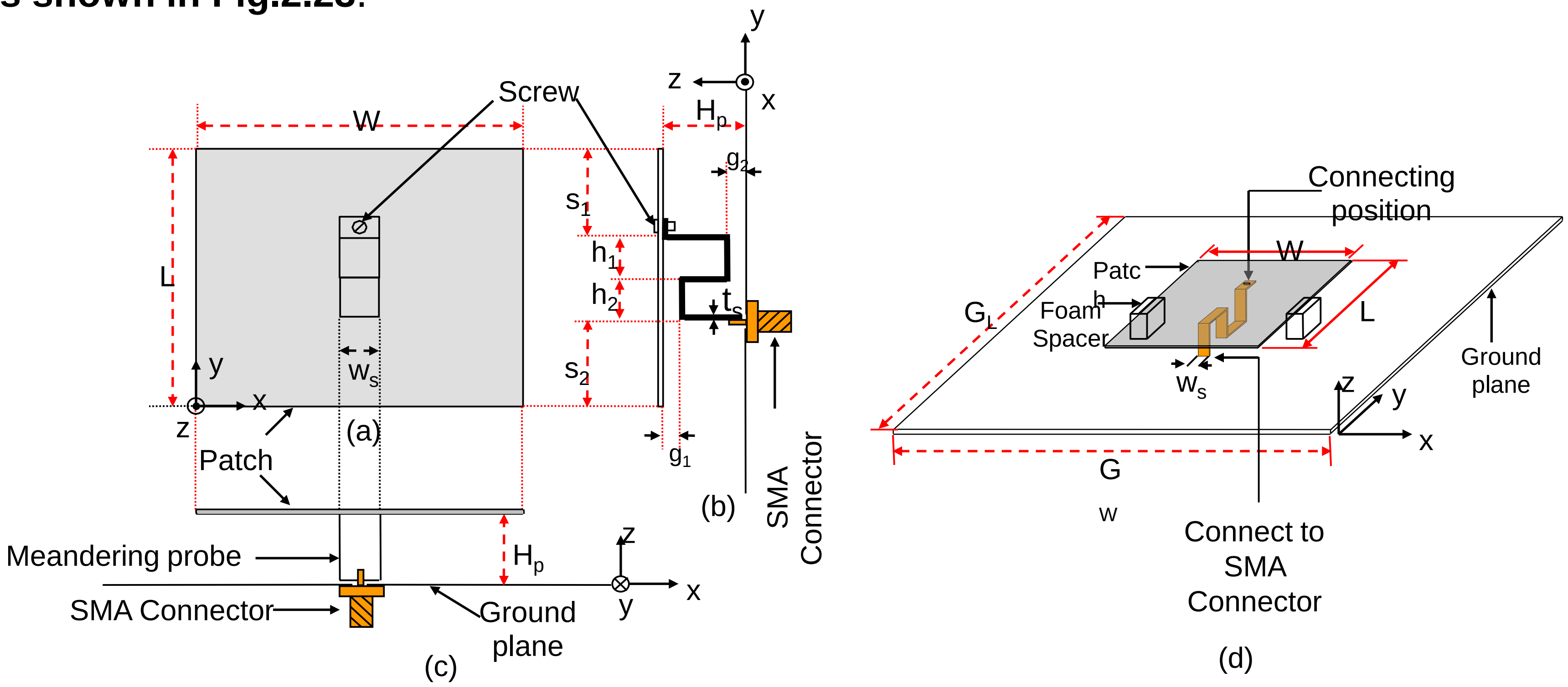
Vertical portion

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.



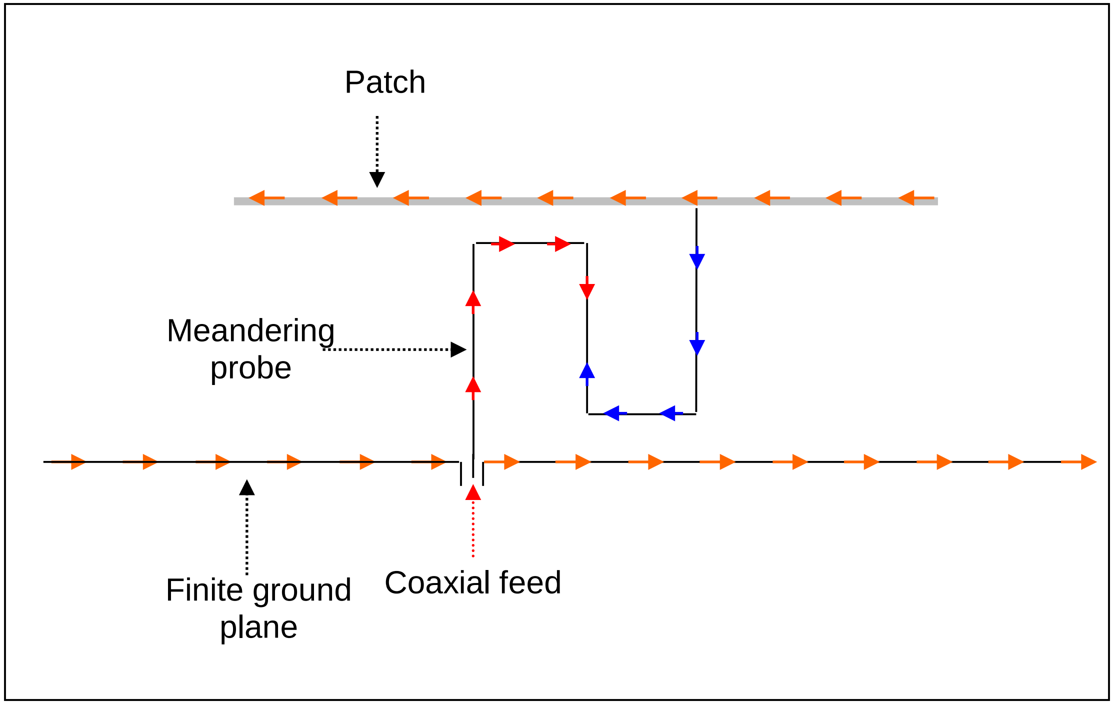
Parameters	L	W	H_p	G_L	G_W	$g_1=g_2$	$h_1=h_2$	$s_1=s_2$	t_s	w_s
Value/mm	60 $(0.364\lambda_0)$	70 $(0.425\lambda_0)$	17.5 $(0.106\lambda_0)$	300 $(1.82\lambda_0)$	200 $(1.21\lambda_0)$	1.5 $(0.01\lambda_0)$	9.5 $(0.06\lambda_0)$	20.5 $(0.123\lambda_0)$	0.2 $(0.0012\lambda_0)$	9.5 $(0.06\lambda_0)$

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

With Dr. H. W. Lau and Dr. H. Wong

Paris, October 2005

Current Distribution

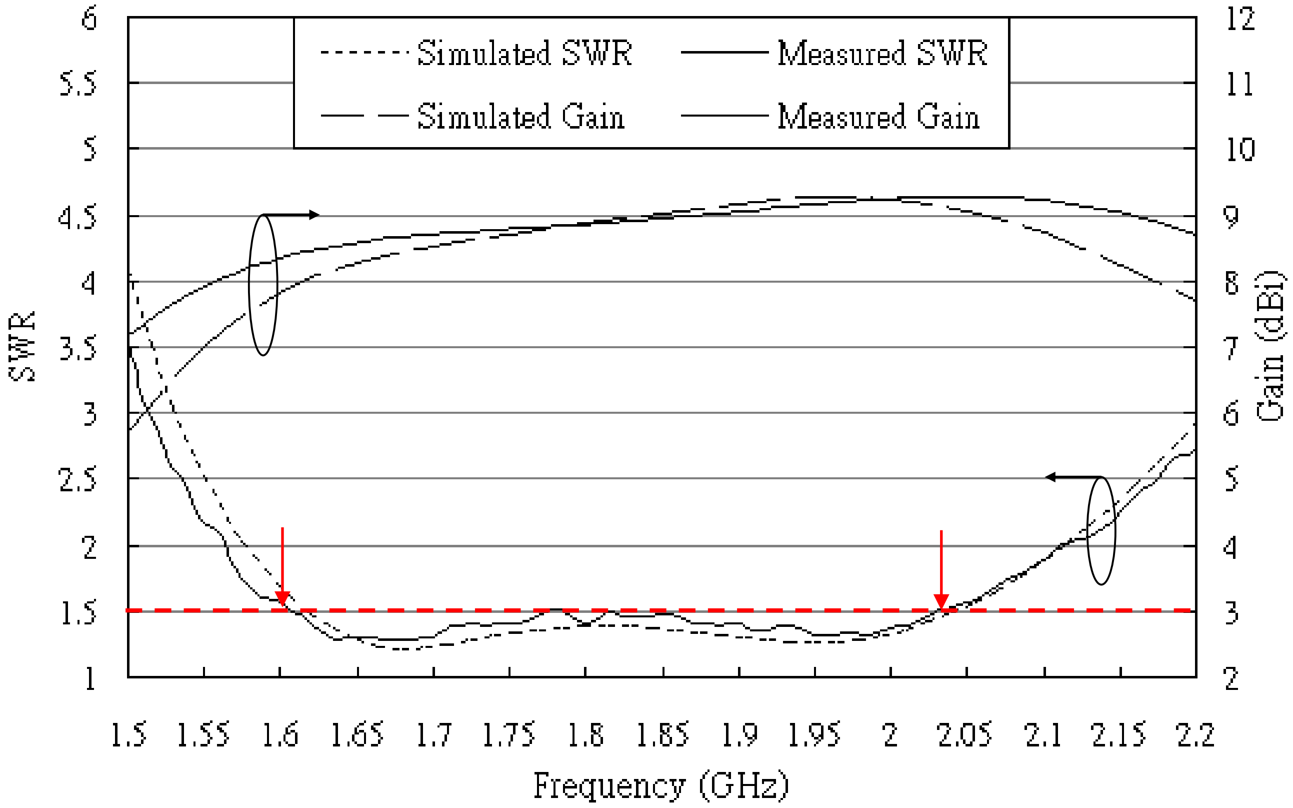


Low cross polarization level

➔ **180º 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

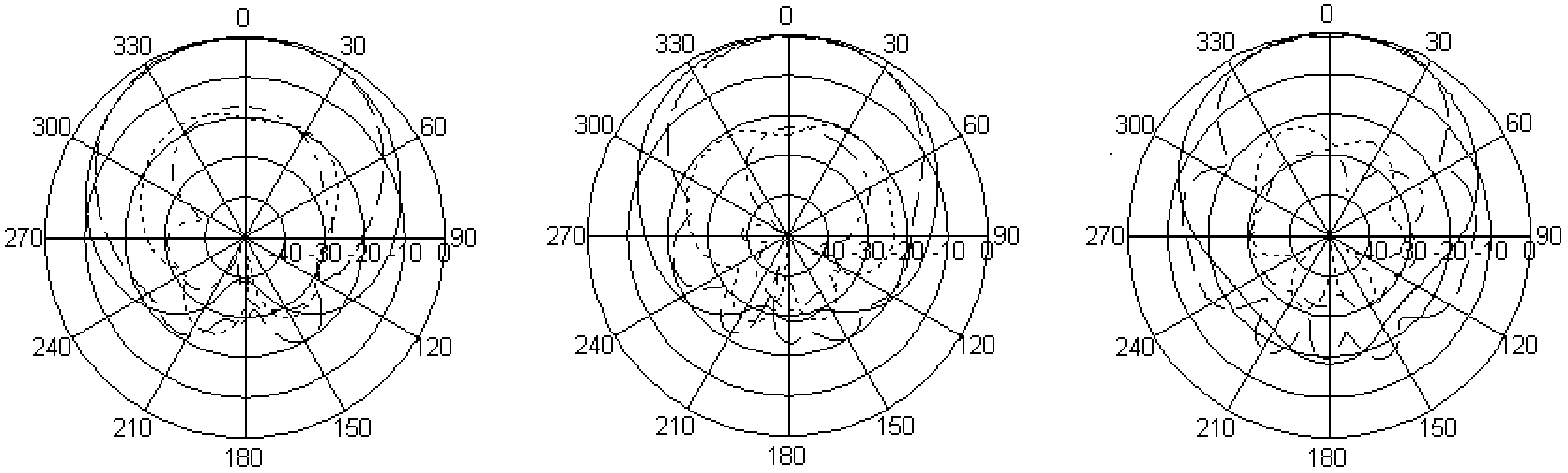


Impedance bandwidth (SWR<1.5) of 24%

Gain = 9dBi

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

5.6.3.1 The Meandering Probe Patch Antenna
(Lai and Luk, 2006)



(i) 1.56GHz

(ii) 1.82GHz

(iii) 2.12GHz

———	H plane co-polar
– – – – –	E plane co-polar
………………	H plane x-polar
– · – · – ·	E plane x-polar

X-pol level < -18dB

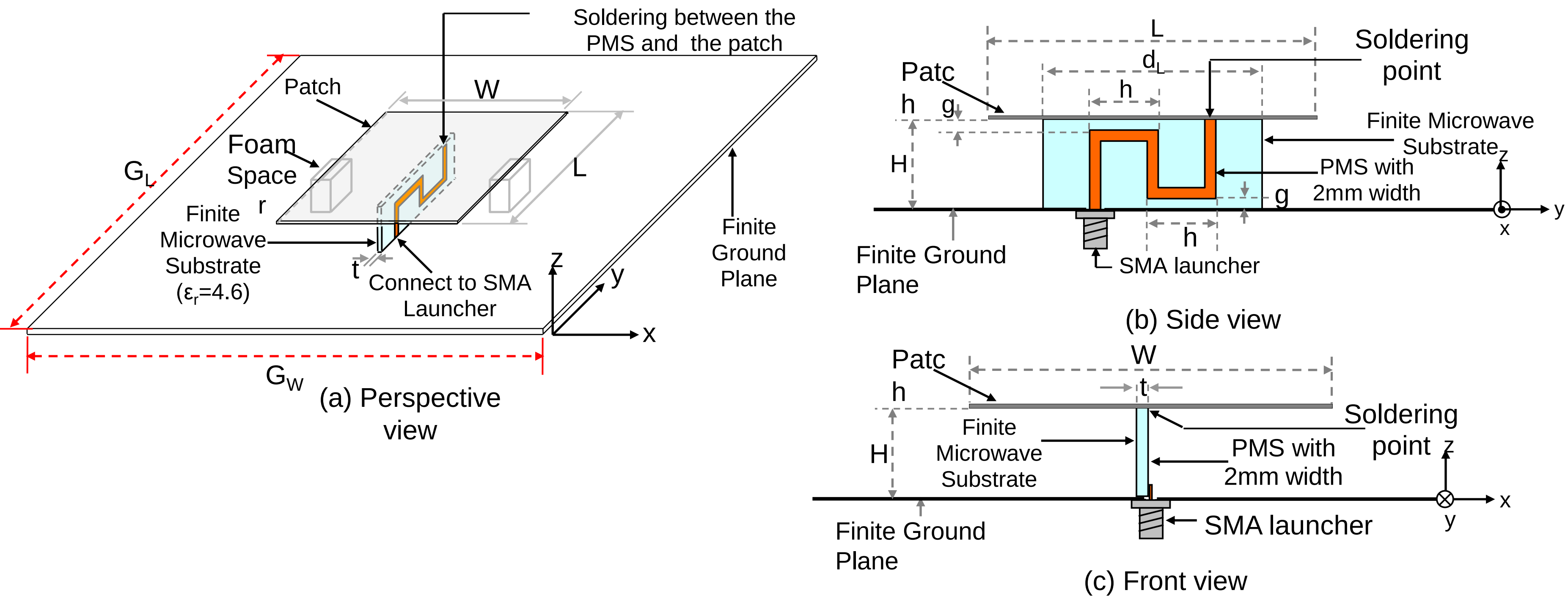
Front-to-back ➔ 18dB

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 printd circuit board, forming a printed meandering strip (PMS)



(a) Perspective view

(b) Side view

(c) Front view

Parameters	W	L	H_p	d_L	H	g	h	t
Values/mm	70 $(0.427\lambda_0)$	60 $(0.366\lambda_0)$	16.5 $(0.101\lambda_0)$	40 $(0.244\lambda_0)$	16.5 $(0.101\lambda_0)$	2 $(0.122\lambda_0)$	12.5 $(0.76\lambda_0)$	1.5 $(0.009\lambda_0)$

Fig. 2.27 Geometry of the printed meandering strip fed patch antenna.

5.6.3.2 The Meandering Strip Patch Antenna

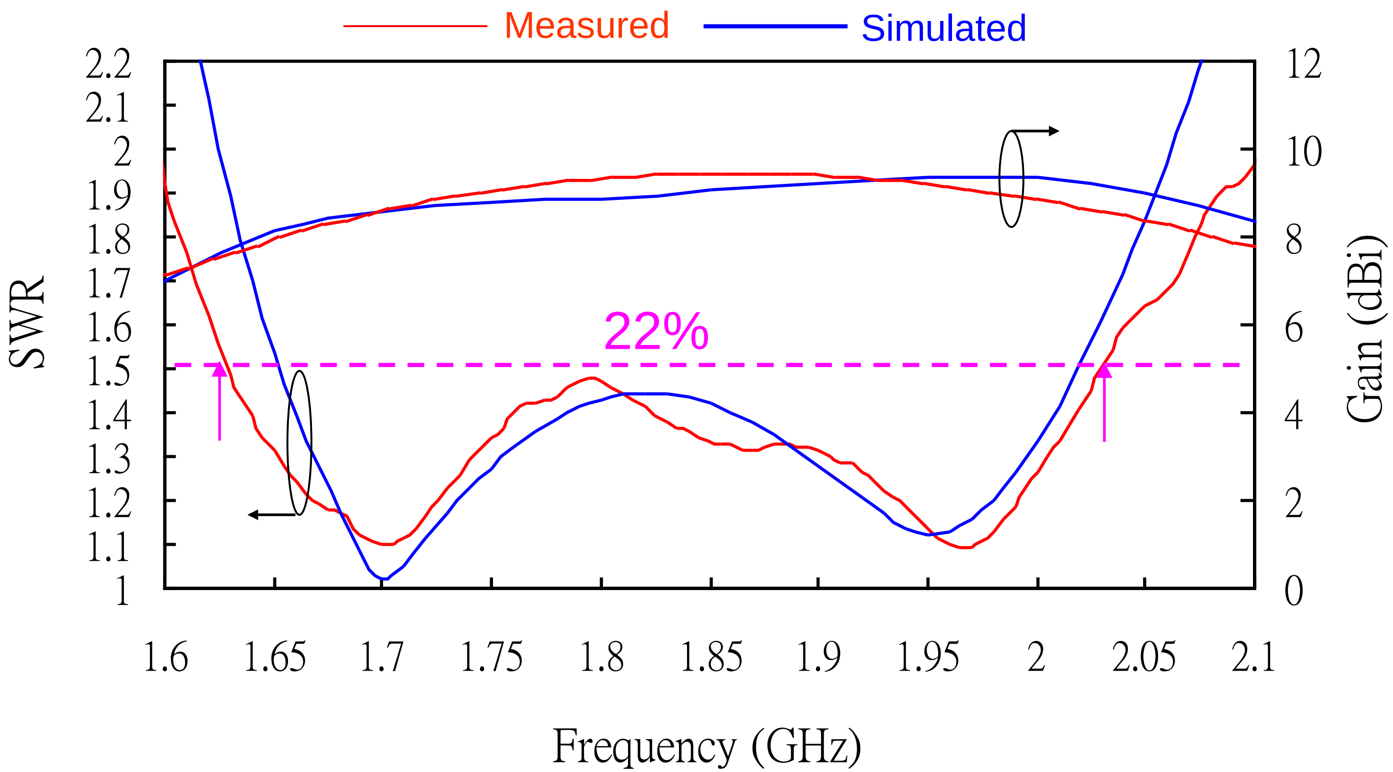
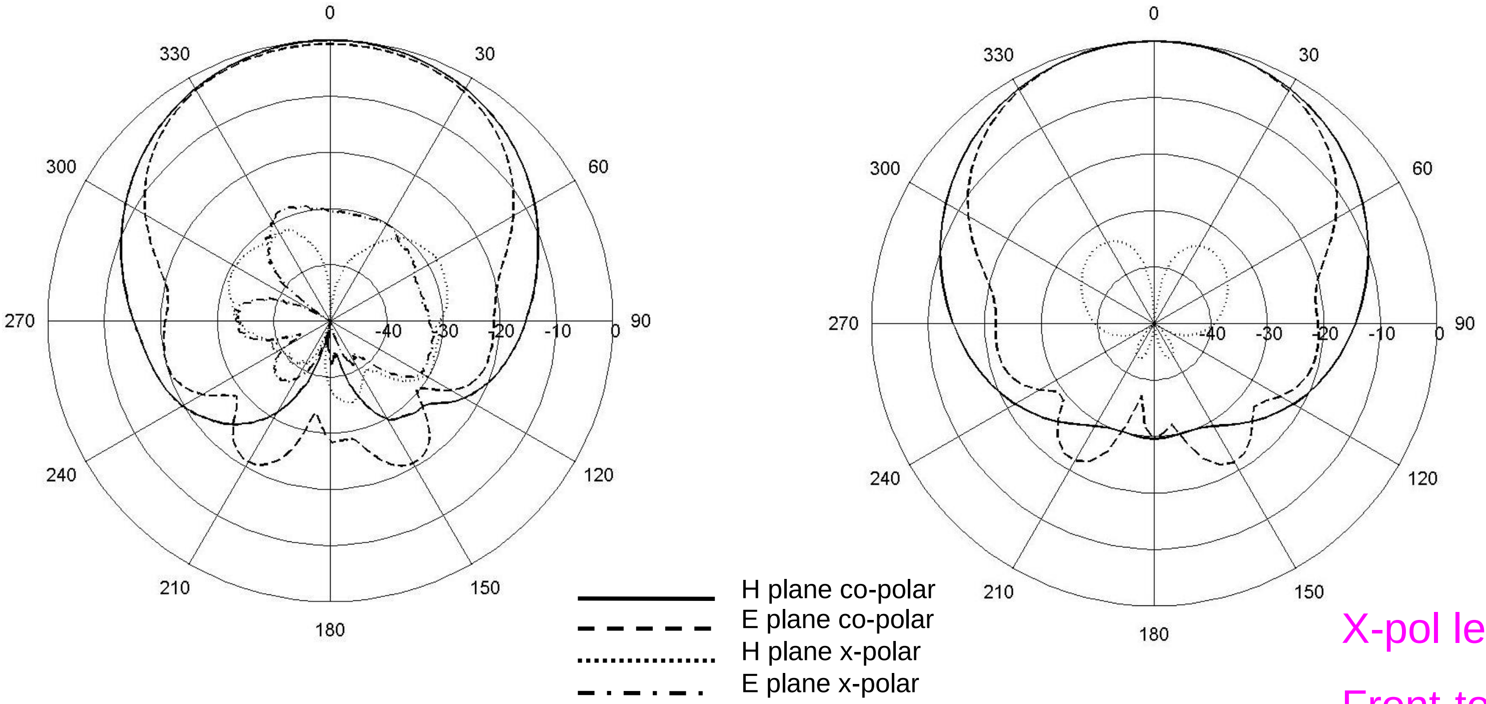


Fig. 2.28 Simulated and experimental results of SWR and gain against frequency of the printed meandering strip fed patch antenna of Fig. 53.

5.6.3.2 The Meandering Strip Patch Antenna



Measured

Simulated

X-pol level < -28dB

Front-to-back ➔ 20dB

Stable radiation pattern

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

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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

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Some of our papers using full wave analysis (continued)

- **W. Chen, K. F. Lee, R. Q. Lee, Spectral domain full-wave analysis of the input impedance of coaxially-fed rectangular microstrip antennas, Journal of Electromagnetic Waves and Applications, Vol. 8, No. 2, pp. 249-272, 1994.**

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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

Software name	***Theoretical model***	***Company***
Ensemble	Moment method	Ansoft
IE3D	Moment method	Mentor Graphic/Zeland
Momentum	Moment method	HP
EM	Moment method	Sonnet
PiCasso	Moment method / Genetic	EMAG
FEKO	Moment method	EMSS
PCAAD	Cavity model	Antenna Design Associates, Inc.
Micropatch	Segmentation	Microstrip Designs, Inc.
Microwave Studio (MAFIA)	FDTD	CST
Fidelity	FDTD	Zeland
HFSS	Finite element	Ansoft

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