# INDUSTRIAL TRAINING REPORT

# AT

# Centre for Wireless Communications

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1. Industrial Attachment Student's Log Sheet
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# SUMMARY

During my 6-month Industrial Attachment (IA) stint with the Centre for Wireless Communications (CWC), I have gained invaluable knowledge and experience in the field of antenna design, otherwise not possible in textbooks and lectures.

In my IA, I had focused on the novel design of planar monopole antennas with several geometrical shapes so as to achieve broad impedance bandwidths and stable radiation patterns. Methods such as cutting of slots and the use of electromagnetic coupling (EMC) were used to boost performance as well as to improve on the overall design of the antenna.

The results obtained with the optimized parameters were satisfactory and had thereafter paved the way for future developments in this area.

# ACKNOWLEDGEMENTS

I would like to thank Dr. Chen Zhi Ning, my supervisor at CWC for his guidance as well as in giving me the opportunity to learn more about the workings of an antenna. I have also gained invaluable experience in the designing, testing and analyzing the performance of broadband planar monopole antennas using the Network Analyzer.

In addition, I would also like to thank Dr Tan Eng Leong for spending his time in attending my presentations on the performance of the monopole antennas and sharing his views on the subject.

# I. INTRODUCTION

## A. CENTRE FOR WIRELESS COMMUNICATIONS (CWC)

The Centre for Wireless Communications (CWC) of the National University of Singapore is a national R&D centre funded by the Singapore National Science and Technology Board (NSTB). CWC's primary activities are centred on conducting strategic and industry-relevant R&D in telecommunications industry. The Centre currently employs about 216 full-time staffs, about 167 of whom are research staff. CWC occupies some 5300 sqm of space in the TeleTech Park building within Singapore's Science Park II.

R&D work within CWC include research, design and prototyping of systems in the technology areas of Advanced Modulation and Multiple Access, Signal Processing, RF, Antenna and Propagation, Network Protocols and Mobile Computing.

## B. OBJECTIVES

- To conduct world-class strategic research and industry-relevant R&D in telecommunications.
- To develop new and innovative telecommunication technologies and solutions for products, systems, services and applications.

- To develop the infrastructure necessary to promote and support R&D activities in the local telecommunications industry.
- To contribute actively towards the growth of a strong telecommunications industry cluster in Singapore through value-add activities, R&D manpower training and technology transfer.

## C. R&D Activities

4 Core Research Programmes are being held in CWC, covering the major areas in the field of Wireless Telecommunications. They are Internet Technologies, Pico and Broadband Access Networks, Wireless Identification and Location Systems, and Future Mobile Communication Systems.

This programme focuses on the development of next generation Internet technologies and mobile/wireless Internet access and applications. The main activities center around areas such as Quality of Service (QoS), mobility and wireless support.

The expected outcomes of the programme include contributions to international standardization efforts, and new technologies that will generate Internet-related start-ups and significant contributions to research on protocols, algorithms and mechanisms for Internet QoS support of future access technologies.

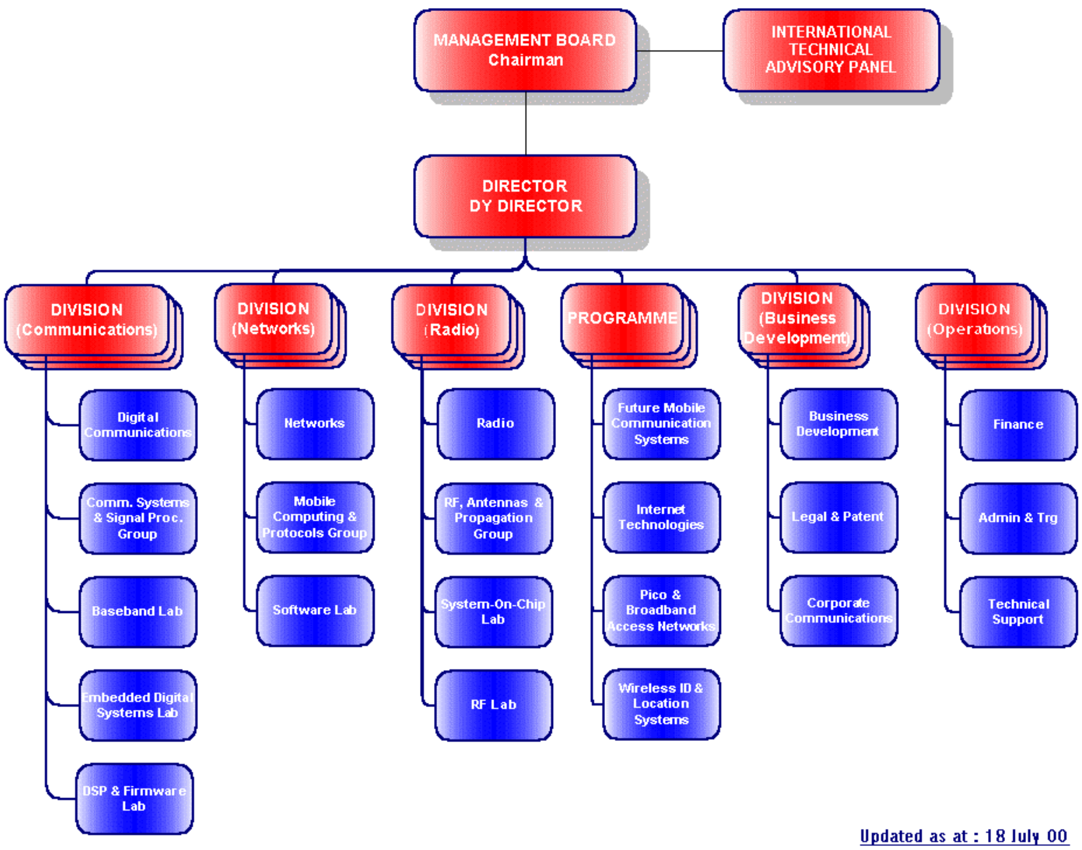
The programme will also result in the training of engineers skilled in design and implementation of Internet protocols to meet the needs of the local industry.

## D. VISION & MISSION

**Vision:** "CWC technology in all communications system!"

**Mission:** "To create leading communication technologies for a world-class industry in Singapore."

## E. THE ORGANIZATION




CWC is lead by its Director, Professor Lye Kin Mun to achieve its mission and goals.

# II. THE TRAINING PROGRAMME

The project title for this IA program is to design broadband monopole antennas in order to achieve optimum impedance bandwidths as well as to achieve stable radiation patterns. In order to achieve this, background preparation was necessary so that I could understand the basic concepts applied in antenna design as well as to keep myself updated of the current developments in this area. Hence, I was assigned to read up on the relevant literature, including journals and reference books.

A large portion of my IA was spent in the Radio Frequency (RF) Laboratory to perform testing on the bandwidth performance of the designed antennas. I was required to learn and handle the Network Analyzer, HP8510C as well as to calibrate the equipment before testing could be carried out. Data obtained was compiled and analyzed using Microsoft Excel. The results and observations were then documented in a technical report. Presentations on the findings were also conducted to interested supervisors.

Because of faulty equipment, the radiation characteristics of the antennas could not be obtained. As such, experiments on the radiation performance of the circular slotted planar monopole were conducted by Dr. M.J. Ammann from the Dublin Institute of Technology, Ireland.

## Summary of Training Program (8.1.2001 to 23.6.2001)

**Week 1-2**

After the briefings on the company's rules and regulations, I was orientated around CWC and brought to my supervisor, Dr. Chen Zhi Ning. I was assigned a project on the design of broadband monopole antennas. Read-ups on the fundamental theory of antennas as well as the broadband monopole antennas were carried out as instructed. I also constructed a ground plane (305 x 305mm$^2$) in order to mount my antenna for measurement and testing purposes.

**Week 3-4**

Read-ups on the broadband monopole antenna and the journal for the square slotted planar monopole were done. The design for the circular slotted planar monopole was completed. I also read up on the instruction guide for the Network Analyzer, HP8510C prior to the experiment.

**Week 5-6**

Measurements were carried out using HP8510C on the circular slotted planar monopole antenna in the laboratory. Thereafter, the results obtained were compiled and processed using MS Excel. A report was drafted for evaluation by my supervisor.

**Week 7-8**

The drafting of the report was completed and submitted. The design for the triangular slotted planar monopole was done as well. Measurements were carried out using HP8510C on the circular slotted planar monopole antenna in the laboratory.

**Week 9-10**

The results obtained from the laboratory session in Week 7-8 were compiled and processed using MS Excel. A report was drafted for evaluation by my supervisor. A presentation based on the findings was given for the triangular slotted planar monopole.

**Week 11-12**

The necessary amendments were made to the report on the circular slotted planar monopole. The report based on the experiment conducted in Week 7-8 was completed and submitted. I also assisted my supervisor to draft the paper on the circular slotted planar monopole for submission to the IEE.

**Week 13-14**

The design for the triangular planar monopole with electromagnetic coupling (EMC) was done. Measurements were then carried out using HP8510C on the designed antenna in the laboratory.

**Week 15-16**

The results obtained from the laboratory session in Week 13-14 were compiled and processed using MS Excel. A report was drafted for evaluation by my supervisor. The necessary amendments were made to the report on the triangular slotted planar monopole.

**Week 17-18**

The design for the pentagonal planar monopole was done. Measurements were then carried out using HP8510C on the designed antenna in the laboratory. The report based on the experiment conducted in Week 13-14 was completed and submitted.

**Week 19-20**

The results obtained from the laboratory session in Week 17-18 were compiled and processed using MS Excel. Thereafter, a report was drafted and submitted for evaluation by my supervisor. The design for the circular planar monopole with electromagnetic coupling (EMC) was carried out.

**Week 21-22**

Measurements were carried out using HP8510C on the circular planar monopole antenna with EMC in the laboratory. Thereafter, the results obtained were compiled and processed using MS Excel. A report was drafted and submitted for evaluation by my supervisor. A presentation based on the findings was given for the circular planar monopole with EMC.

**Week 23-24**

The IA report was drafted and submitted for evaluation by my supervisor. Further readings were done on journals released by the IEEE.

# III. TRAINING ASSIGNMENTS

## 1. Background

The antenna is one of the most critical components used in wireless communications. It is basically designed to radiate or to receive electromagnetic waves. Geometrical simplicity, modal purity and cost effectiveness are some of the factors which are considered in the design of an antenna. An antenna design which could give rise to a broad impedance bandwidth and stable radiation patterns, is desired. For this purpose, the wire element of a conventional monopole can be replaced by a planar element. Numerical methods, such as the method of moments with the use of a wire grid and triangular cell meshing have been used to analyze the impedance characteristics of the planar monopole.

Although the planar monopole is experimentally proven to be capable of producing broad bandwidth performance, it is not very feasible as the antenna is not able to resist the force of wind. Therefore, in this report, planar monopoles of different geometrical shapes with slot cuts made on them are presented. Another novel solution to improve the impedance bandwidth will be to make use of electromagnetic coupling (EMC) between two copper surfaces separated by a dielectric substrate.

During my 24-week Industrial Attachment (IA) stint with the Radio Division of the Centre for Wireless Communications (CWC), I have contributed to designing and testing the impedance performance for several planar monopole antennas. The results obtained and discussions are compiled in this report. In all, 5 types of antennas were designed and tested successfully, namely the circular slotted planar monopole, the triangular slotted planar monopole, the EMC triangular planar monopole, the EMC circular planar monopole as well as the pentagonal planar monopole.

## 2. Equipment

The HP 8510C Network Analyzer System can measure the magnitude and phase characteristics of networks and of components such as antennas, amplifiers, attenuators and filters. The minimum configuration of the HP 8510C consists of a source, a test set, and the network analyzer.

The source provides the RF signal. The test set separates the signal produced by the source into an incident signal, sent to the device-under-test (DUT), and a reference signal against which the transmitted and reflected signals are later compared. It also routes the transmitted and reflected signals from the DUT to the receiver. The network analyzer includes the HP 85101 Display/Processor and the 85102 IF/Detector (Receiver). The receiver together with the display/processor, processes the signals. Using its integral microprocessor, it performs accuracy enhancement and displays the results in a variety of formats.

## 3. Experimental Procedure

The line switch of each instrument in the network analyzer was turned on, with the network analyzer being turned on last. The instrument was then allowed to complete its initialization routine and a measurement trace appears on the system display when the system is ready. In our tests, the start frequency was set to 0.5GHz and the desired stop frequency was set to 8.5GHz.

The MENU button under STIMULUS was pressed and NUMBER OF POINTS selected. Since the frequency range of interest was 8GHz, the 801 points option was selected.

Next, a reflection frequency response calibration was performed to remove any systematic errors encountered during reflection measurements. This calibration is also known as the $S_{11}$ response calibration. A standard HP 85052, 3.5 mm calibration kit was used.

The channel was set to CHANNEL 1 and the parameter $S_{11}$ was selected in the PARAMETER function block. In the MENUS block, CAL was selected to display the calibration menu followed by CAL 1, CALIBRATE: $S_{11}$ 1-PORT.

At Port 1, a shielded open circuit was connected. When the trace was correct, ($S_{11}$): OPEN was pressed and open circuit data was measured. Next, a shielded short circuit was connected and ($S_{11}$): SHORT was pressed when the trace was correct to measure the short circuit data. Lastly, ($S_{11}$): LOADS was pressed to present the Loads menu. A broadband load was connected since the frequency sweep crosses 2GHz and when the trace was correct, BROADBAND was pressed and load data was measured. When it was completed, DONE LOADS was selected. To save the calibration, SAVE 1-PORT CAL was selected followed by a CAL SET 1. In order to ensure that the calibration had been carried out properly, the marker should be pointing to the center of the Smith Chart.

After the reflection frequency response calibration had been carried out, the 50Ω coaxial probe of a 0.6mm radius was fixed onto the finite-size ground plane ($305x305mm^2$) via an SMA connector.

As there was a gap between the source and the test port 1, there was a need to perform a receiver calibration so that all measurements will be taken with respect to the source interface instead. This was done to ensure that there would be minimal power losses in the path between the source and the test port.

To perform the receiver calibration, first CAL was selected. From the calibration menu displayed, MORE followed by PORT EXTENSIONS and PORT 1 were in turn selected. From the Smith Chart, the RPG knob was then rotated until the marker was positioned at the short circuit point. The calibration was then saved by pressing SAVE RCVR CAL and selecting a Cal Set number to store the calibration data.

The antenna was then soldered onto the SMA connector probe to investigate the impedance characteristics.

After connecting the ground plane to the coaxial cable, the SWR option under FORMAT, MENU was selected to view the waveform. For convenience, the SCALE was set to 10/div, REF POSN at 0 and the REF VALUE set at 1.

When all the 801 points had been swept through at least once and the waveform had become stable, the MARKER key was depressed and the RPG knob was adjusted until the cursor was positioned at the point where the waveform crossed the SWR = 2 line for the first time. The frequency (frequency of the lower edge of the pass-band or FLEPB) corresponding to that cursor position was then noted down.

The SWR data was saved to a floppy disk by pressing DISC, STORE, MORE, FORMATTED and selecting STORE FILE after assigning a filename to it using the RPG knob to choose the characters. Next, the SMITH CHART key was depressed and the data saved in a similar manner. A copy of the SMITH CHART and the SWR were, respectively, printed by pressing COPY followed by PLOT TO PRINTER.

The same set of equipment and experimental procedure will be used for all subsequent antenna measurements.

# IV. Experimental Studies on Impedance and Radiation Characteristics of Planar Monopole Antennas

## Chapter 1: Circular Slotted Planar Monopole Antennas

### 1.1 Introduction

In many communications antennas and microwave devices, coaxially fed monopoles have been an attractive choice for their cost effectiveness, geometrical simplicity and modal purity. A planar monopole of broad impedance bandwidth can be realized by replacing the wire element of a conventional monopole with a planar element such as a circle. Circular disc monopole antennas had been previously investigated using the numerical methods such as the method of moments by Hammoud et al. in 1993 to yield wider impedance bandwidth than the wire monopole antenna [1]. This had also been verified experimentally and it was shown that for VSWR ≤ 2 over a frequency range of 1-13GHz, the bandwidth ratio was 1:10.2 [2]. Square planar monopole antennas, though have a smaller bandwidth as compared to the circular disc monopole, had been shown to exhibit broadband characteristics [3]. In order to optimize the impedance bandwidth of the square planar monopole antenna, the sizes of slot cuts and the locations of feed points were adjusted. Results had shown that the introduction of slots enhanced the impedance bandwidth ratio, typically of >1:1 for VSWR = 2:1 [4].

With this knowledge, it will therefore be useful to proceed to investigate the effects of the presence of slots on the bandwidth. In this work, prototypes of circular monopole antennas having different slot radii were fabricated and VSWR measured over a frequency range of 0.5-8.5GHz. By having slot cuts, the surface area of the antenna will be reduced to minimize the effects caused by the wind. The distance of the antenna from the ground plane, known as the feed gap, was also varied for optimization. The impedance bandwidth for VSWR 2:1 and 3:1 was measured for each slot radius. The experiments demonstrated that the slot radius and feed gap have a significant effect on the impedance bandwidth, and optimization can be achieved at a slot radius up to 15mm and a feed gap of approximately 1.6mm. Furthermore, it has little or no effect on the radiation pattern at low frequencies and acceptable effects at higher frequencies.

In this Chapter, a description of the monopole is included in Section 1.2. Observations and discussions based on the bandwidth performance of the antenna with relation to its parameters are given in Section 1.3. In Section 1.4, relevant conclusions are drawn and useful references provided at the end of this chapter.

## 1.2 Description of Antenna

The circular slotted monopole antenna made of a thin copper sheet was placed vertically over a ground plane by soldering it onto the probe of the SMA as shown in Fig. 1.1. A 50Ω coaxial probe of a 0.6mm radius excites the bottom of the monopole through the ground plane via an SMA connector. The distance between the finite size ground plane

(305x305mm$^2$) and the bottom of the monopole is the feed gap, *g*. The radius of the slot cut concentrically on the monopole is given by *r* and the radius of the monopole denoted by *R*.

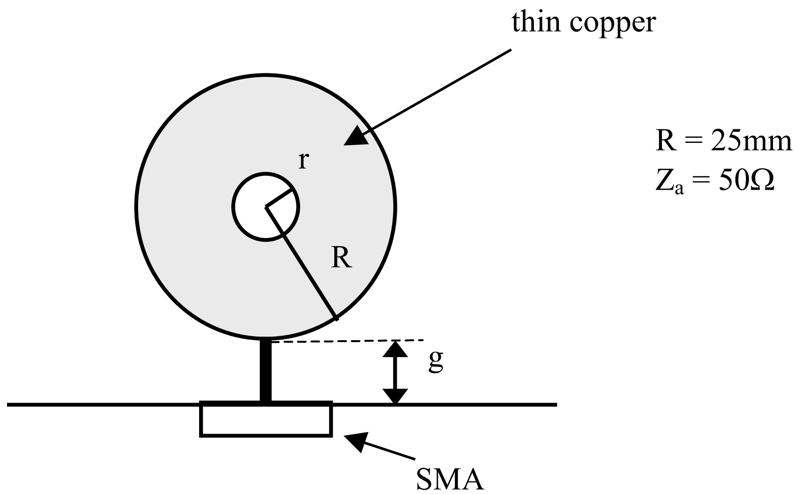



**Fig. 1.1**

R : Radius of monopole

r : Radius of slot

g : Feed gap

## 1.3 Results and Discussions

The measured impedance bandwidths (BWs) for the specific VSWR=2:1 and 3:1 are tabulated in Table 1.1, where the BW is calculated according to the following formula,

$$BW = \begin{cases} 2(f_u - f_l)/(f_u + f_l) \times 100\ \% & BW \le 100\% \\ f_u : f_l & BW > 100\% \end{cases}$$

where $f_u$ and $f_l$ denote the frequencies for the upper and lower edge of the pass-band, respectively.

**Table 1.1:** Measured impedance bandwidth (BW) and frequency corresponding to the lower edge of the pass-band (FLEPB)

| **Antenna** | ***g* (mm)** | **VSWR=2:1** | | **VSWR=3:1** | |
|---|---|---|---|---|---|
| | | **FLEPB (GHz)** | **BW** | **FLEPB (GHz)** | **BW** |
| **1** | 0.7 | 1.17 | >8.5:1 | 1.07 | >8.5:1 |
| *r*=0mm | 1.6 | 1.15 | >8.5:1 | 1.06 | >8.5:1 |
| | 2.3 | 1.14 | 6.72:1 | 1.00 | >8.5:1 |
| **2** | 0.7 | 1.18 | >8.5:1 | 1.09 | >8.5:1 |
| *r*=5mm | 1.6 | 1.17 | >8.5:1 | 1.06 | >8.5:1 |
| | 2.3 | 1.14 | 6.58:1 | 1.03 | >8.5:1 |
| **3** | 0.7 | 1.18 | >8.5:1 | 1.10 | >8.5:1 |
| *r*=10mm | 1.6 | 1.14 | >8.5:1 | 1.06 | >8.5:1 |
| | 2.3 | 1.14 | 6.64:1 | 1.00 | >8.5:1 |
| **4** | 0.7 | 1.17 | 72.8% | 1.08 | >8.5:1 |
| *r*=15mm | 1.6 | 1.14 | >8.5:1 | 1.05 | >8.5:1 |
| | 2.3 | 1.11 | 6.83:1 | 1.02 | >8.5:1 |
| **5** | 0.7 | 1.14 | 38.3% | 1.05 | 78.6% |
| *r*=20mm | 1.6 | 1.12 | 34.1% | 1.02 | >8.5:1 |
| | 2.3 | 1.08 | 30.6% | 0.97 | >8.5:1 |

It can be seen from Fig. 1.2 that for VSWR=2:1, the frequency corresponding to the lower edge of the pass-band (FLEPB) is in the range of 1.08-1.18GHz. For Antennas 1 to 3, remarkably broad bandwidth ratios, particularly of more than 100%, have been achieved for different *g*.

For Antenna 4, the optimal bandwidth can be achieved by having the feed gap at around 1.6mm whereas for Antenna 5, the achieved bandwidth is much narrower as compared to the other 4 antennas.

Moreover, as the feed gap *g* increases, the FLEPB gets lower and is minimal when the radius of the slot is the largest (*r* = 20mm).

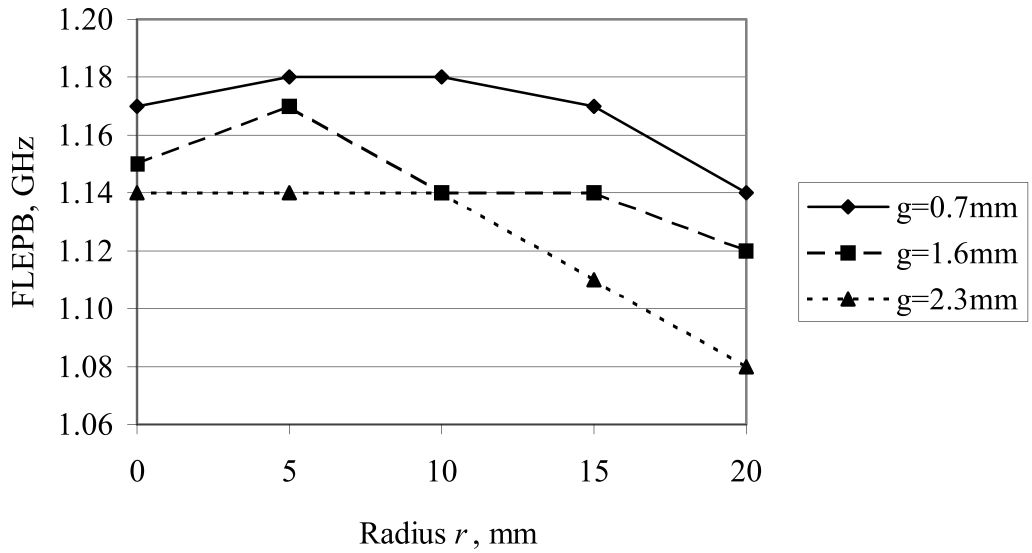



**Fig. 1.2**

The comparison of the measured VSWR of the five antennas with different feed gaps is made in Figs. 1.3-1.5.

For antennas with a feed gap of 0.7mm (refer to Fig. 1.3), the bandwidth performance is unsatisfactory for Antenna 5 as the VSWR is greater than 3. For Antenna 4, the performance is acceptable though the VSWR fluctuates rapidly along the frequency range. For Antennas 1 to 3, there is much better and stable bandwidth performance from 1.18GHz onwards. The monopoles exhibit the high-pass response feature although the matching conditions for larger radii (*r* =15 and 20mm) have become worse.

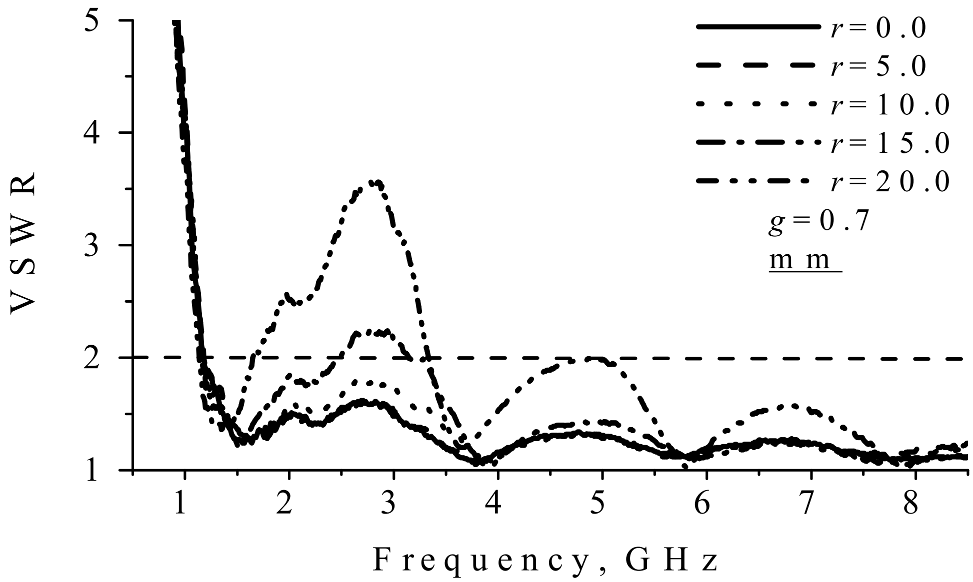



**Fig. 1.3**

It is seen from Fig. 1.4 that for the antennas with a feed gap of 1.6mm, they operate under very good matching conditions from 1.15GHz onwards. For Antenna 5, there is good matching (VSWR<2) from 3.25GHz onwards.

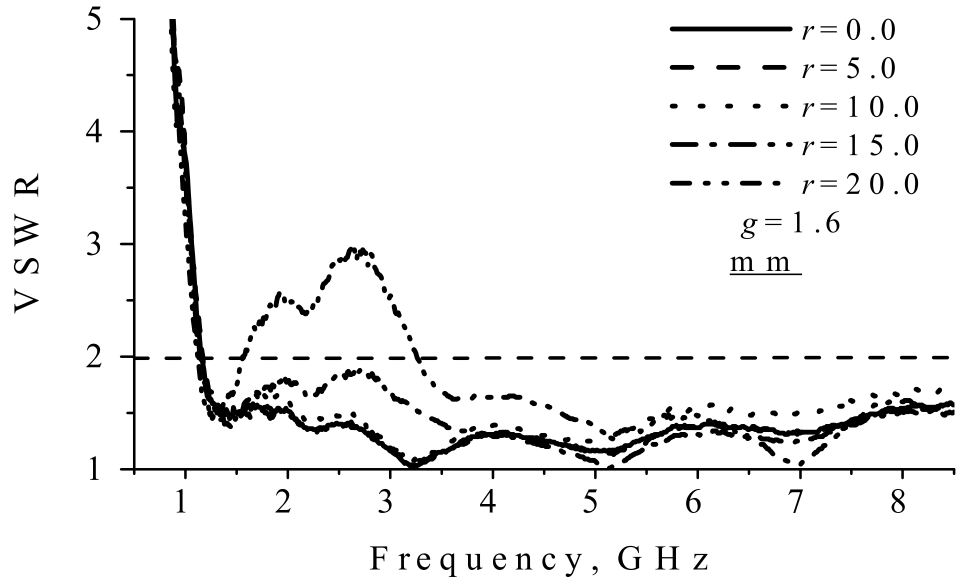



**Fig. 1.4**

For Antennas 1 to 4 with a feed gap of 2.3mm (refer to Fig. 1.5), there is good matching condition between 1.1GHz to 7.5GHz. As for Antenna 5, the bandwidth will be very narrow (1.1GHz to 1.5GHz) for VSWR=2:1. However, if VSWR=3:1 is considered instead, then the antenna will be having a much wider bandwidth performance (from 1.1GHz onwards). The high-pass response feature of all the monopoles disappears as the feed gap reaches 2.3mm.

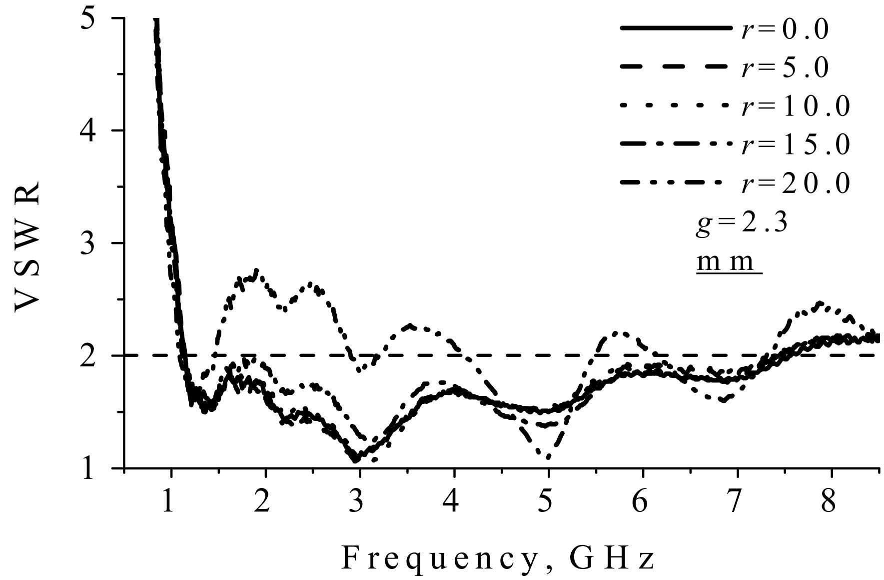



**Fig. 1.5**

The radiation patterns for the antennas with different slot radii are also examined and shown in Figs. 1.6-1.8. The slot radii of $r$ =0 and $r$ =15mm are selected for comparison. The tests are performed at 1.5GHz and 5GHz. A feed gap of 1.6mm is used for the measurements. It can be observed that introducing a slot of $r$ =15mm has negligible effects on the low frequency radiation patterns. At these frequencies, the antenna exhibits typical omni-directional monopolar patterns with a maximum gain of 4.8dBi, which is constant to within ± 0.5dB over polar angles from $\theta = 48°$ to $\theta = 63°$. The half-power beam-width is 48° in both $\phi = 0°$ and $\phi = 90°$ planes. The gain in the ground plane ($\theta = 90°$) is found to be 0.3dBi. The maximum gain at this frequency is unaffected by the introduction of the slot. With the increase in frequency, a slight increase in directivity is observed as the beam-width in the vertical planes becomes narrower. The gain in the ground plane ($\theta = 90°$) is also reduced. The effect of the slots on the radiation patterns becomes more pronounced and tends to offset the gain reduction in this plane.

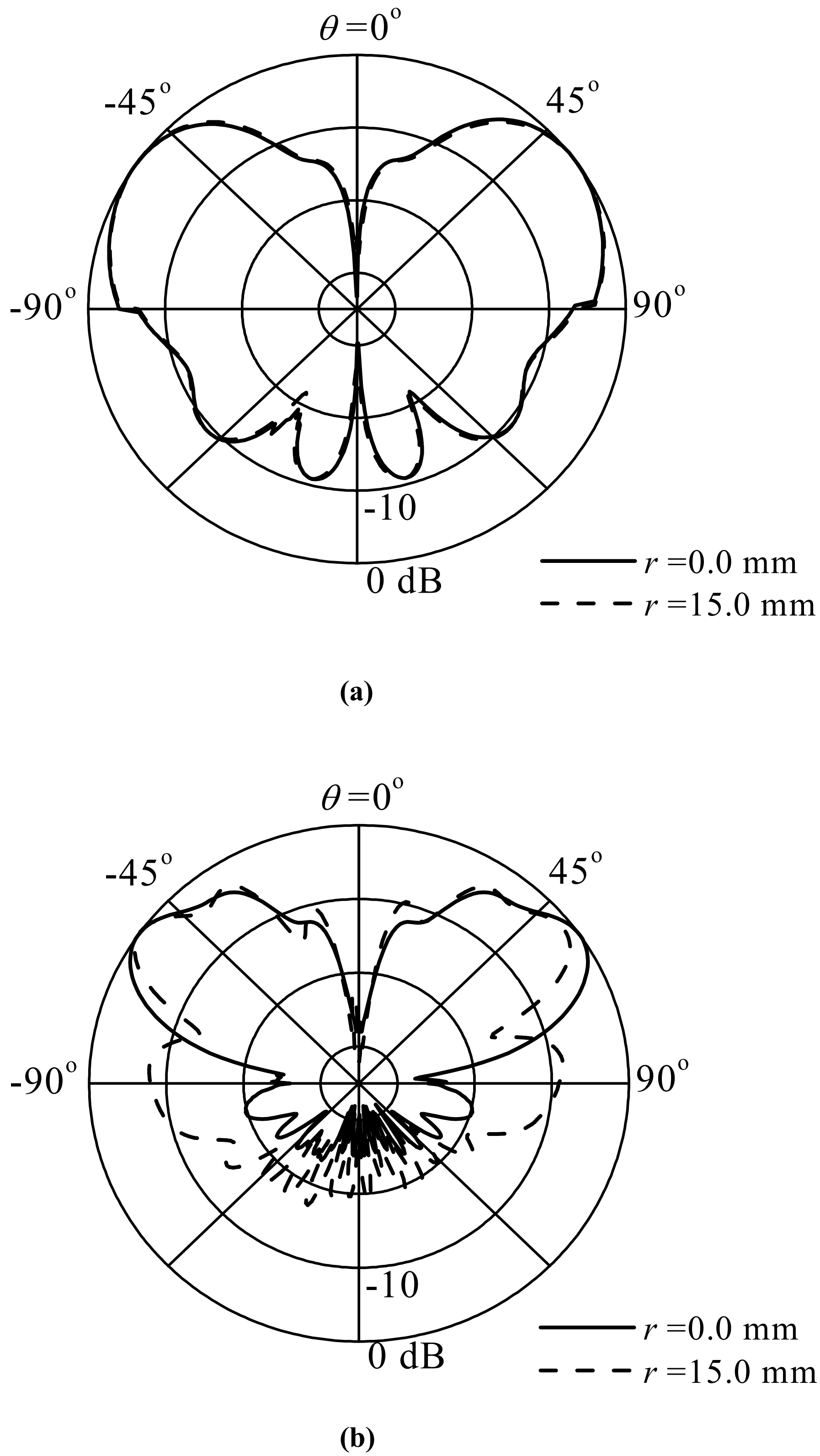
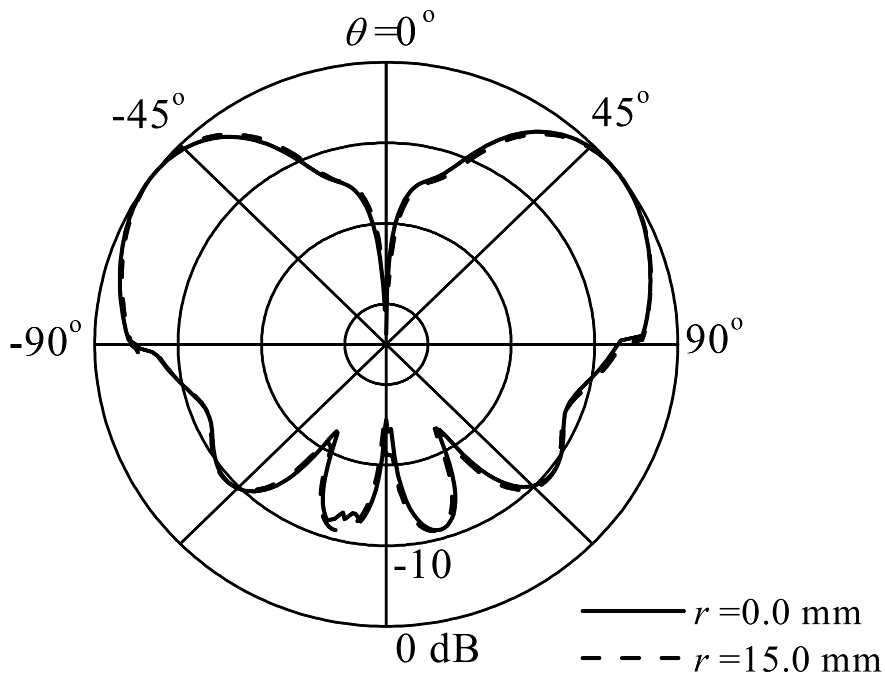
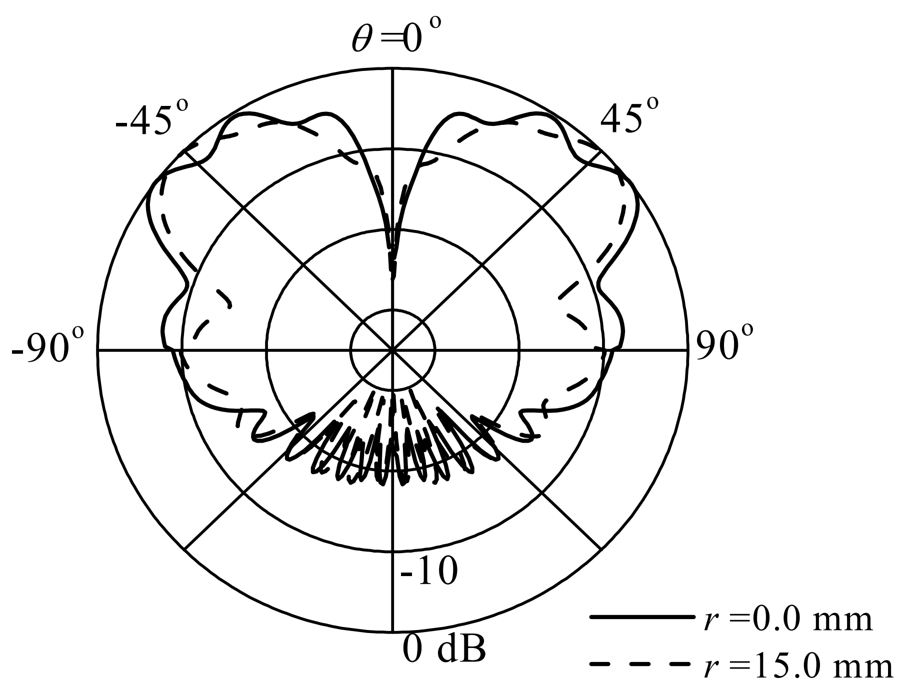



**Fig. 1.6:** Measured radiation patterns in $\phi = 0^{o}$ cut (a) at 1.5 GHz; (b) at 5.0 GHz

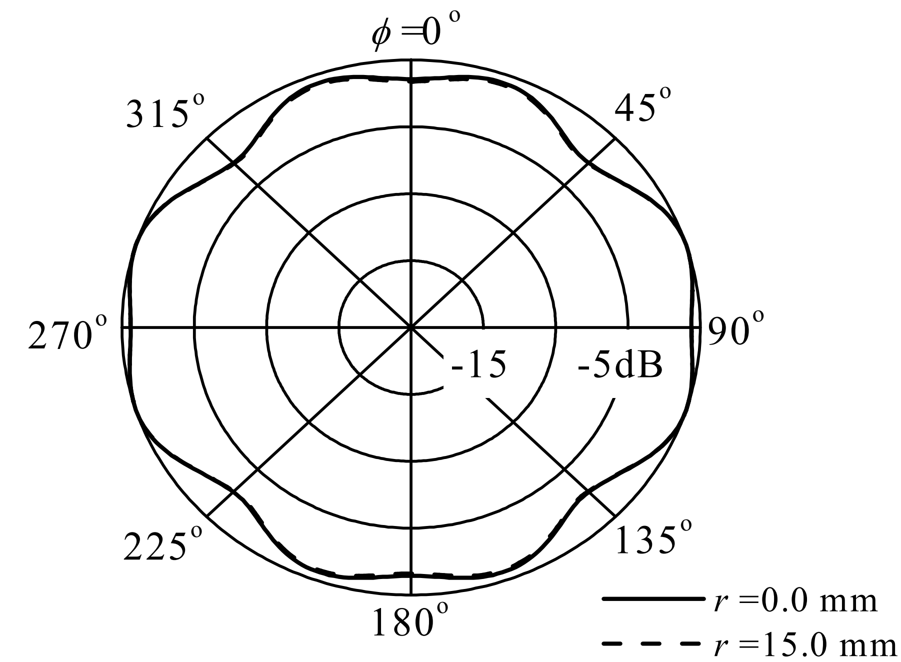



**(a)**

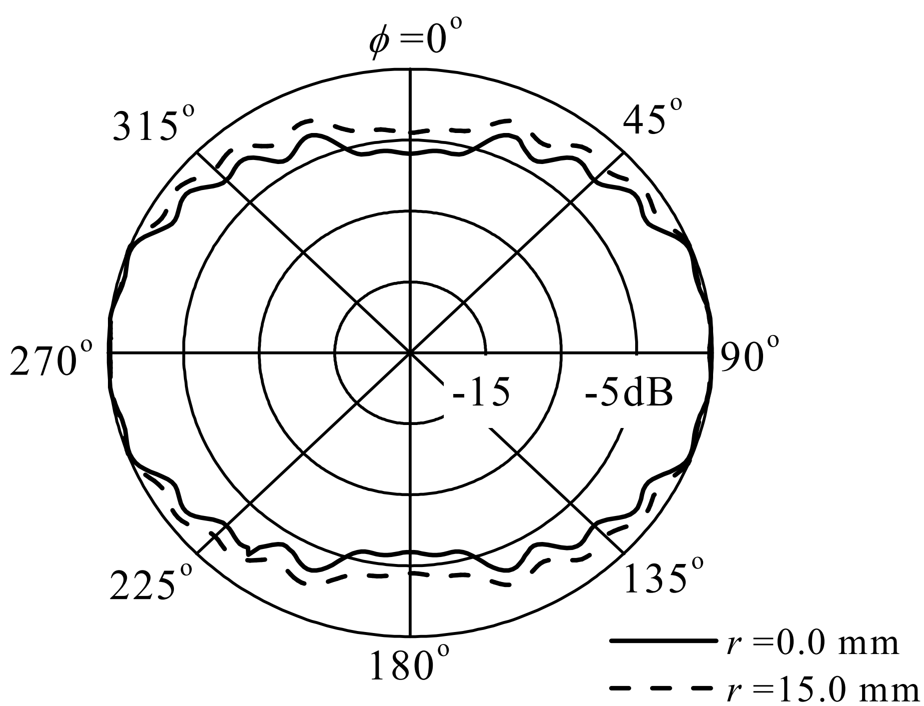



**(b)**

**Fig. 1.7:** Measured radiation patterns in $\phi = 90^o$ cut (a) at 1.5 GHz; (b) at 5.0 GHz




**(a)**




**(b)**

**Fig. 1.8:** Measured radiation patterns in $\theta = 90^{o}$ plane (a) at 1.5 GHz; (b) at 5.0 GHz

## 1.4 Conclusion

A broadband circular slotted monopole antenna has been investigated. It is found that for the antennas with up to 64% of the area being removed (*r*=15mm), a broad bandwidth performance could still be achieved as seen from the SWR waveform. As the slot radius increases beyond 15mm, the bandwidth has been found to be much narrower.

The feed gap has been seen to affect the bandwidth performance as well. The optimum feed gap will be around 1.6mm as the bandwidth achieved is the greatest. Beyond this, an increase in the feed gap will yield a correspondingly lower bandwidth. The FLEPB is also slightly lowered as the feed gap increased.

## 1.5 References

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# Chapter 2: Triangular Slotted Planar Monopole Antennas

## 2.1 Introduction

A planar element has been used to enhance the impedance bandwidth of a traditional wire element. Typically, a circular disc monopole has a 1:8 impedance bandwidth [1,2] and the square monopole has a typical bandwidth of 75% at S-band. Square planar monopoles with slot cuts produced a relatively wide bandwidth under optimized parametric conditions [3]. In the previous chapter, an experimental study was also made on the circular slotted monopole antenna and results showed that it could yield a bandwidth ratio, typically of >8.5:1. With these results, it will be feasible to embark on other antenna designs of different geometrical features such as the triangular planar monopole.

In this work, the prototypes of triangular monopole antennas with slot cuts were fabricated and soldered onto the ground plane to investigate the impedance bandwidth (BW) performance as well the frequency corresponding to the lower edge of the pass-band (FLEPB) by varying the size of the slot cut, *s*, the feed-gap, *g* and the location of the feed point, *D*. The VSWR were obtained over a frequency range of 0.5GHz to 8.5GHz. Firstly, the sizes of slot cut were varied with the location of the feed point kept constant at 25mm and the feed gap constant at 0.7, 1.6 and 2.3mm, respectively. Next, the experiment was repeated with the location of the feed point, *D* subsequently changed to 0, 6.25, 12.5 and 18.75mm.

In addition to this, the feed point of the triangular monopole antenna located at its vertex opposite to the base of the triangular antenna was also experimented upon and the performance compared against the case where the feed point is located along the bottom side of the monopole antenna.

## 2.2 Description of Antennas

The triangular slotted antenna was placed vertically above a ground plane by soldering it onto the probe of the SMA as illustrated in Fig. 2.1. The distance between the ground plane and the bottom of the antenna is the feed gap, *g*. The length of the two sides of the antenna is denoted by *S* (50mm) and the length of its base is given by *B* (56mm). The length of the two sides of the slot cut is represented by *s* and the length of the base of the slot is given by *b*. The location of the feed point is denoted by *D*.

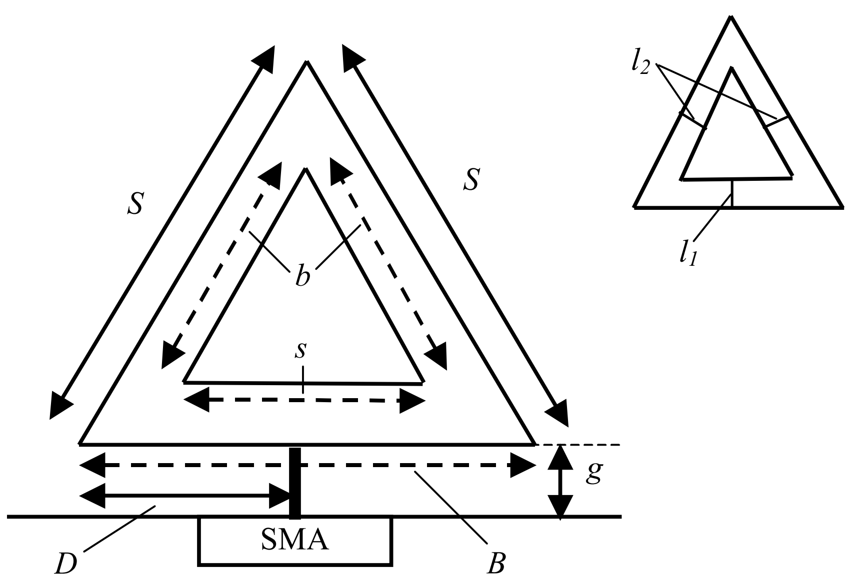


**Fig. 2.1**

Fig. 2.2 illustrates the scenario where the antenna is soldered at the vertex located directly opposite to the base of the antenna. The antenna was soldered to the probe of the SMA connector such that the feed gap is zero.

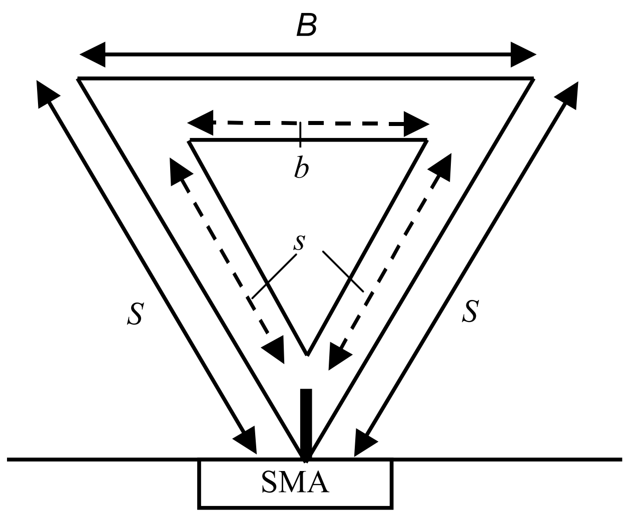


**Fig. 2.2**

In the experiments conducted, five triangular antennas of different slot sizes were tested. Their physical dimensions are shown in Table 2.1.

Table 2.1

| **Antenna** | ***s* (mm)** | ***b* (mm)** | **$l_1$ (mm)** | **$l_2$ (mm)** |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 7 | 8 | 13 | 12 |
| 3 | 20 | 19 | 10 | 9 |
| 4 | 32 | 28 | 7 | 6 |
| 5 | 42 | 39 | 3 | 3 |

### 2.3 Results and Discussions

The impedance bandwidth ratio is calculated according to the following formula:

$$BW = \begin{cases} 2(f_u - f_l)/(f_u + f_l) \times 100\ \% & BW \le 100\% \\ f_u : f_l & BW > 100\% \end{cases}$$

where $f_u$ and $f_l$ denote the frequencies for the upper and lower edge of the pass-band, respectively.

From Table 2.2, it can be observed that when the monopole was fed at the midpoint of the bottom side (*D*=25mm), the BWs for VSWR = 2:1 range from 20.2% to 62.2% as the feed gap, *g* varies from 0.7mm to 2.3mm.

As shown in Fig. 2.3, the achieved BWs increase when the feed gap *g* is increased for a monopole with a fixed slot size. Also, as the slot size is increased for a certain value of *g*, the BWs generally increase.

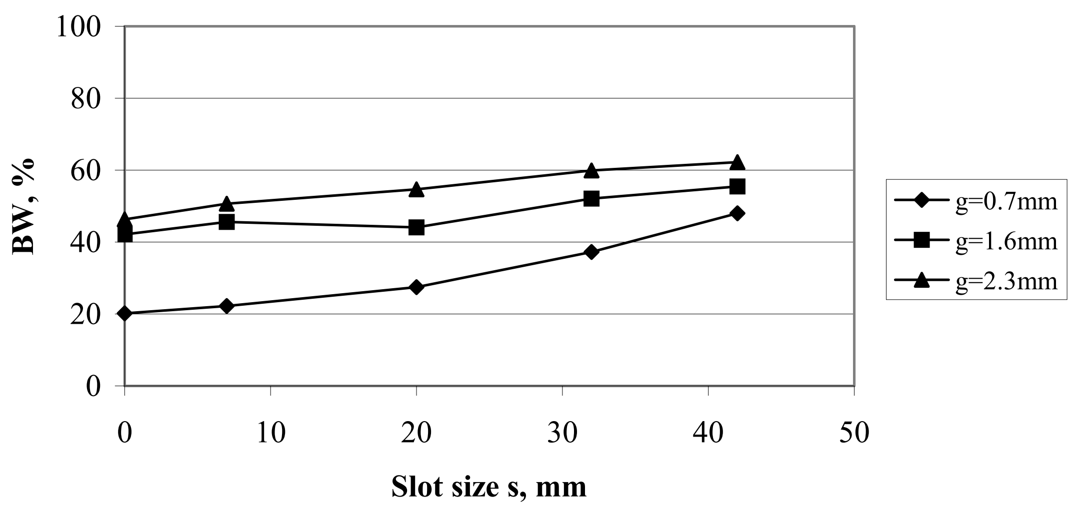


**Fig. 2.3**

**Table 2.2:** Measured impedance bandwidth (BW) and frequency corresponding to the lower edge of the pass-band (FLEPB)

| **Antenna** | ***g* (mm)** | **VSWR=2:1** | | **VSWR=3:1** | |
|---|---|---|---|---|---|
| | | **FLEPB (GHz)** | **BW (%)** | **FLEPB (GHz)** | **BW (%)** |
| **1** | 0.7 | 1.69 | 20.2 | 1.51 | 51.2 |
| (*s*=0mm, | 1.6 | 1.63 | 42.1 | 1.43 | 63.8 |
| *b*=0mm ) | 2.3 | 1.61 | 46.3 | 1.41 | 66.4 |
| **2** | 0.7 | 1.68 | 22.2 | 1.51 | 52.7 |
| (*s*=7mm, | 1.6 | 1.61 | 45.6 | 1.42 | 65.4 |
| *b*=8mm) | 2.3 | 1.59 | 50.7 | 1.34 | 72.7 |
| **3** | 0.7 | 1.66 | 27.5 | 1.49 | 54.3 |
| (*s*=20mm, | 1.6 | 1.61 | 44.1 | 1.43 | 63.8 |
| *b*=19mm) | 2.3 | 1.54 | 54.7 | 1.31 | 74.9 |
| **4** | 0.7 | 1.60 | 37.2 | 1.46 | 58.6 |
| (*s*=32mm, | 1.6 | 1.56 | 52.1 | 1.38 | 71.0 |
| *b*=28mm) | 2.3 | 1.52 | 59.9 | 1.28 | 81.2 |
| **5** | 0.7 | 1.44 | 48.0 | 1.27 | 71.4 |
| (*s*=42mm, | 1.6 | 1.42 | 55.5 | 1.25 | 76.2 |
| *b*=39mm) | 2.3 | 1.43 | 62.2 | 1.18 | 86.3 |

As the size of the slot cut gets larger with the constant feed gap, the FLEPB decreases as illustrated in Fig. 2.4. At a feed gap of 0.7mm, the FLEPB is 1.69GHz when the slot cut is 0mm whereas the FLEPB is 1.44GHz when the slot cut is 42mm. Also, for an antenna with a fixed slot size, as the feed gap is increased, the FLEPB is observed to decrease for Antennas 1-4. As the slot size gets to around 42mm (Antenna 5), the FLEPB is found to be relatively constant at around 1.42-1.44GHz.

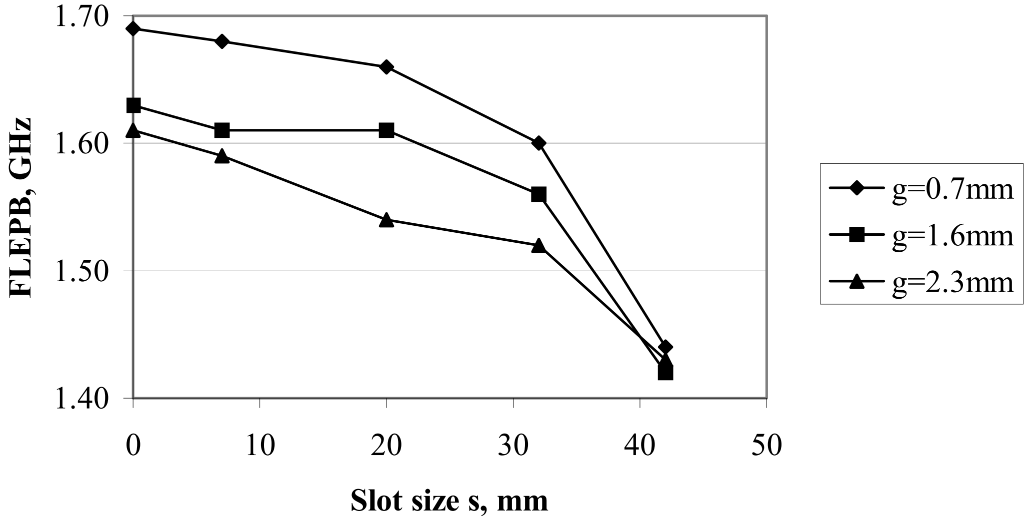


**Fig. 2.4**

From the results, it can be seen that when the feed point is located at the midpoint of the base of the monopole antenna, relatively broad bandwidth can be achieved either when the size of the slot cut or the feed gap is large.

Next, the experiments are repeated with the feed point varied along the base of the antenna and the feed gap constant at 1.6mm. The frequencies corresponding to the lower edge of the pass-band are recorded for VSWR=2:1 and 3:1 and tabulated in Table 2.4. The bandwidth is subsequently calculated based on the formula given at the beginning of this section.

**Table 2.4:** Measured impedance bandwidth (BW) and frequency corresponding to the lower edge of the pass-band (FLEPB)

| Antenna | D (mm) | VSWR=2:1 | | VSWR=3:1 | |
|---|---|---|---|---|---|
| | | FLEPB (GHz) | BW (%) | FLEPB (GHz) | BW (%) |
| **1** | 0 | 3.95 | 16.9 | 3.59 | 32.0 |
| | 6.25 | 4.18 | 65.8 | 1.56 | 33.2 |
| | 12.5 | 1.72 | 27.1 | 1.54 | 57.4 |
| | 18.75 | 1.64 | 62.8 | 1.47 | 77.5 |
| | 25 | 1.63 | 42.1 | 1.43 | 63.8 |
| **2** | 0 | 3.91 | 17.7 | 3.56 | 32.7 |
| | 6.25 | 4.57 | 22.2 | 1.57 | 34.3 |
| | 12.5 | 1.68 | 43.4 | 1.51 | 68.7 |
| | 18.75 | 1.67 | 64.8 | 1.50 | 81.4 |
| | 25 | 1.61 | 45.6 | 1.42 | 65.4 |
| **3** | 0 | 3.90 | 15.4 | 3.56 | 31.1 |
| | 6.25 | 4.18 | 67.5 | 1.56 | 33.6 |
| | 12.5 | 1.67 | 27.8 | 1.46 | 52.9 |
| | 18.75 | 1.65 | 63.1 | 1.45 | 81.4 |
| | 25 | 1.61 | 44.1 | 1.43 | 63.8 |
| **4** | 0 | 3.76 | 28.9 | 3.49 | 38.4 |
| | 6.25 | 3.89 | 20.1 | 1.62 | 24.4 |
| | 12.5 | 1.65 | 32.5 | 1.47 | 51.1 |
| | 18.75 | 1.61 | 59.4 | 1.44 | 76.1 |
| | 25 | 1.56 | 52.1 | 1.38 | 71.0 |
| **5** | 0 | 4.63 | 3.6 | 3.26 | 11.3 |
| | 6.25 | 1.61 | 26.4 | 1.33 | 49.3 |
| | 12.5 | 1.48 | 46.2 | 1.32 | 59.9 |
| | 18.75 | 1.49 | 49.5 | 1.31 | 68.7 |
| | 25 | 1.42 | 55.5 | 1.25 | 76.2 |

From Fig. 2.5, it can be observed that for VSWR = 2:1, Antennas 1 and 3 exhibited similar properties. The optimum performance occurred when *D* is 6.25 and 18.75mm (BW > 60%) and is higher as compared to the case when the antenna is fed at the midpoint of the base i.e. *D*=25mm. When *D* is 0 and 12.5mm, the BWs are found to be narrower. For Antenna 2, with *D* ≤ 18.75mm, the bandwidth increases to a peak value of 65%. However, as *D* gets larger to 25mm, the bandwidth decreases to approximately 45%. Antenna 4 has optimum bandwidth of 59.4% when *D* is 18.75mm. For Antenna 5, it is observed that the bandwidth increases with *D* to a maximum of 56%.

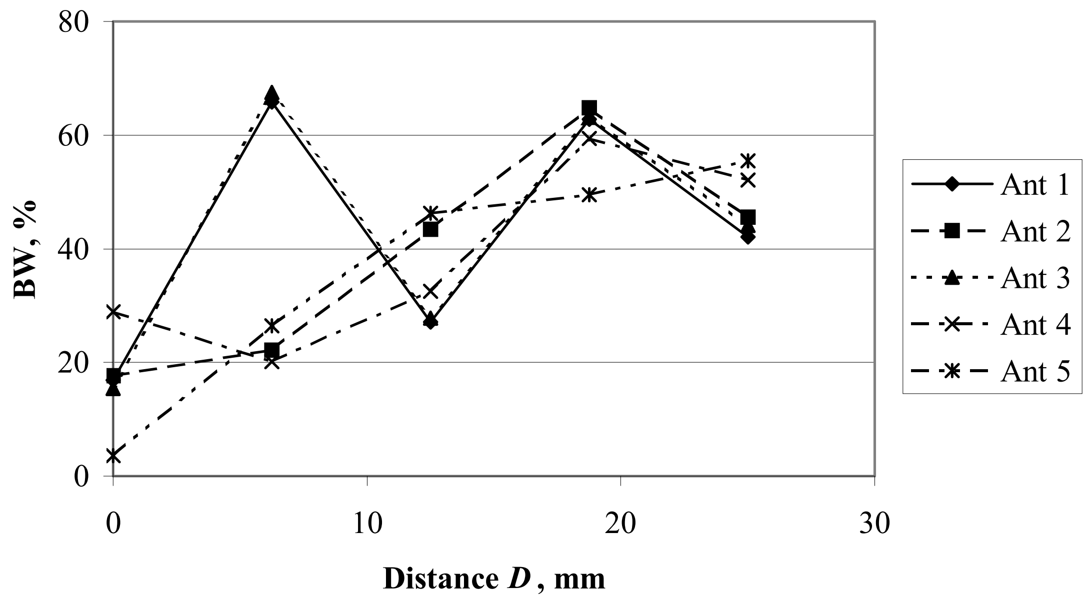


**Fig. 2.5**

From Fig. 2.6, Antennas 1, 2, 3 and 5 exhibited similar characteristics with the largest FLEPB (>4.5GHz) occurring when *D* is 6.25mm. For *D* between 12.5 and 25mm, the FLEPB is relatively stable at 1.6GHz. Antenna 4 has a relatively stable FLEPB at 1.6GHz when *D* ≥ 6.25mm.

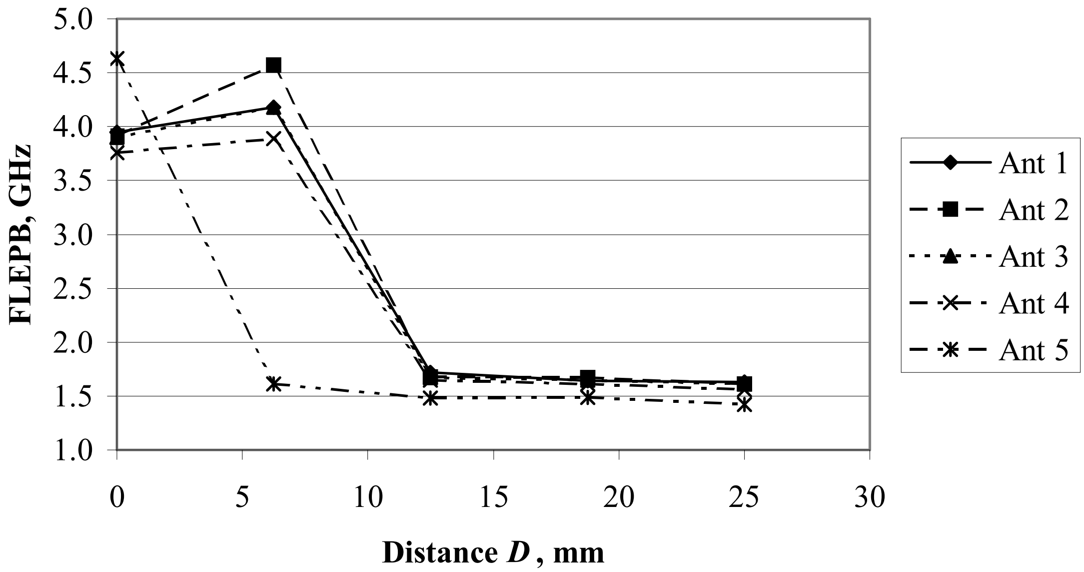


**Fig. 2.6**

If the VSWR=3:1, optimum bandwidth performance can be achieved when *D*=18.75mm. The FLEPB remains steady at around 1.5GHz for *D* ≥ 6.25mm and is always minimal when the slot size is the largest, i.e. Antenna 5.

When the triangular monopole antenna is soldered at its vertex as shown in Fig. 2.2 and tested, it can be seen that the performance is unsatisfactory as it gives a narrow 2:1 VSWR impedance bandwidth of approximately 14-18% for all the five antennas. The FLEPB lies in the range of 0.91-0.97GHz. (Refer to Table 2.3). In this case, the feed gap was taken to be zero since it will have minimal influence on the performance of the antenna.

**Table 2.3**

| Antenna | FLEPB (GHz) | BW (%) |
|---|---|---|
| 1 | 0.93 | 14.0 |
| 2 | 0.94 | 12.9 |
| 3 | 0.95 | 17.3 |
| 4 | 0.97 | 17.0 |
| 5 | 0.91 | 16.2 |

## 2.4 Conclusion

The experiments have demonstrated that the impedance bandwidth performance of the monopole is much better when the monopole is soldered along its base than when it is soldered at the vertex. In the former, when the monopole is fed at the midpoint of the base ($D$=25mm), the bandwidth performance is best when the feed gap is increased and also when the size of the slot cut is the largest. The introduction of the slot cut lowers the FLEPB as well.

When the monopole antenna is fed off the midpoint of the base, optimum bandwidth can be achieved when $D$=18.75mm. With the optimized location of the feed point and the size of the slot cut, a satisfactory bandwidth can be obtained.

## 2.5 References


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# Chapter 3: Triangular Planar Monopole Antennas with Electromagnetic Coupling (EMC)

## 3.1 Introduction

Monopole antennas have been widely used because of their simple structures and good performances. Wire elements have been recently replaced by planar elements and it is found that the impedance bandwidth performance has been significantly improved. For instance, the circular disk monopole has a noticeably broad bandwidth of typically 1:8 [1]. Subsequently, planar disks of different geometrical shapes such as the square, bow-tie-like and trapezoidal plates have been proposed to replace the wire elements.

In order to enhance the feasibility of the antenna, slot cuts are also made to the square monopole antenna and tested by varying the feed point, feed gap as well as the size of the slot cut. It was observed that optimization of the parameters yield a satisfactory bandwidth performance of more than 100% [2].

Another design for the square monopole antenna was implemented by electromagnetically coupling the square planar radiator with a probe-fed strip. The medium between the radiator and the strip is a thin dielectric slab. The antenna was demonstrated to have an impedance bandwidth of 70% for VSWR=2:1 and a stable radiation patterns across the pass-band [3].

This concept can be extended to monopoles of other geometrical shapes such as the triangular disk monopole. Slotted triangular monopoles have been tested to provide a relatively good bandwidth performance as illustrated in the previous chapter.

In this work, the triangular monopoles will be coupled to the probe-fed strip electromagnetically. By varying the position of the 4mm wide copper strip fed at its midpoint, the bandwidth performance will be investigated to provide useful design information.

### 3.2 Description of Antennas

Design 1:

The triangular monopole is placed vertically over a ground plane by soldering it to the probe of the SMA connector as shown in Fig. 3.1a. A 50Ω coaxial probe of a 0.6mm radius excites the centre of the copper strip through the ground plane via an SMA connector. The planar radiator and the strip are separated by a thin dielctric slab of thickness *t*=1.6mm. The distance between the finite size ground plane (305x305mm$^2$) and the bottom of the monopole is the feed gap, *g* where it is kept constant at 2mm in this experiment. The sides of the monopole are denoted by *S*, where *S*=46mm and the bottom of the monopole *B*=40mm. The feed point is located at *D*=20mm. The foil from one of the sides of the PCB is cut to a rectangular strip of width *w*=4mm. (Refer to Fig. 3.1b). The height of the strip, *l*, is varied by gradually removing the foil along its length. One of the PCB surfaces is fully covered by a very thin foil acting as a parasitic radiator.

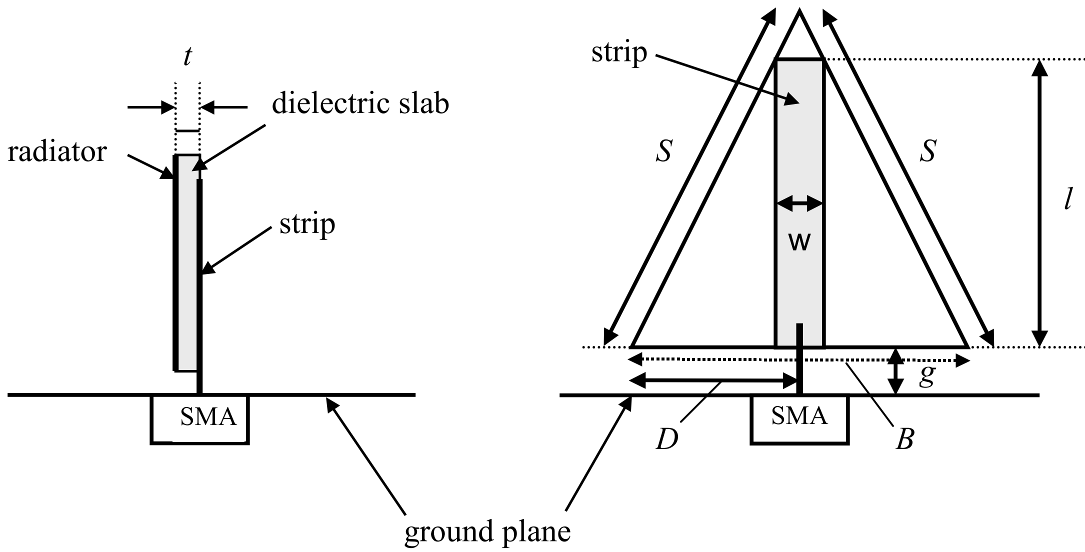


**Fig. 3.1a** **Fig. 3.1b**

Design 2:

In this design, the rectangular strip is cut off-centred from the bottom of the monopole, such that the feed point *D* is now 12.5mm. (Refer to Fig. 3.2).

Design 3

In this design, the monopole has its foil removed in a vertical manner from its edge. The probe excites the centre of the copper strip (grey area). The removal of the copper will result in the changes to *h* and *D*. The feed gap, *g* is maintained at 2mm. (Refer to Fig. 3.3).

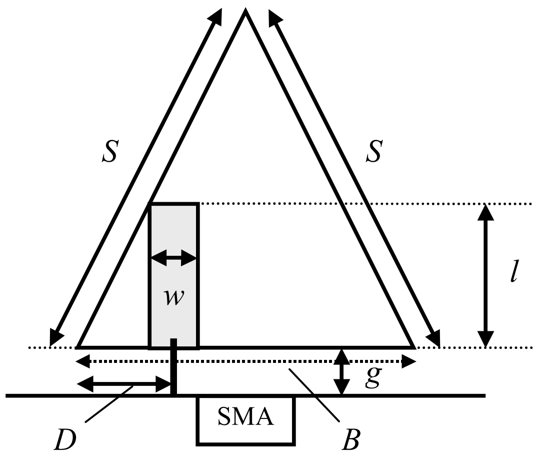


**Fig. 3.2**

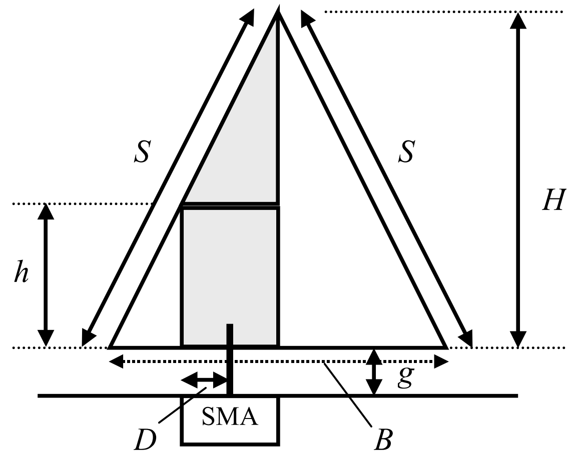


**Fig. 3.3**

<u>Design 4</u>

In this design, a rectangular strip (area in grey) is cut off such that the height, *h* is 20mm. The distance from the feed point to the end of the copper strip is denoted by *D*. (Refer to Fig. 3.4). The foil is gradually removed vertically along the width of the strip such that *D* changes. The probe excites the midpoint of the copper strip.

Design 5

In this design, the monopole has its copper being removed vertically from its centre such that *H* changes. The probe excites the midpoint of the copper strip (area in grey). (Refer to Fig. 3.5).

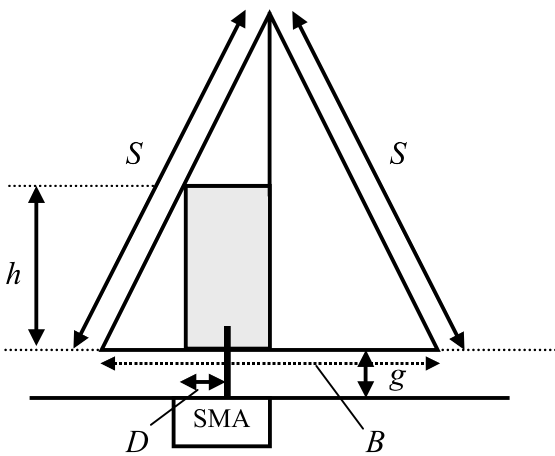


**Fig. 3.4**

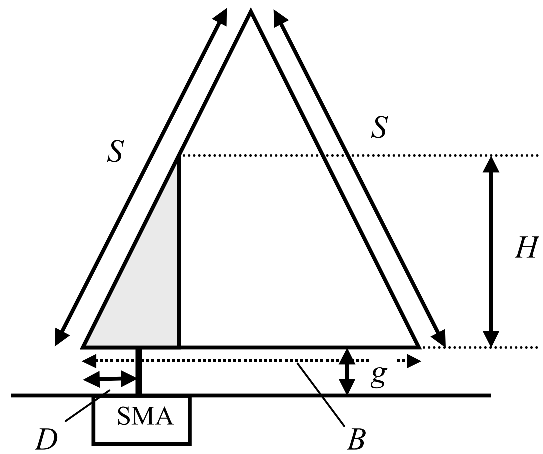


**Fig. 3.5**

### 3.3 Results and Discussions

The measured impedance bandwidths (BWs) for the specific VSWR=2:1 and 3:1 are tabulated in Table 3.1 and 3.2, where the BW is calculated according to the following formula,

$$\text{BW} = \begin{cases} 2(f_u - f_l)/(f_u + f_l) \times 100\ \% & \text{BW} \leq 100\% \\ f_u : f_l & \text{BW} > 100\% \end{cases}$$

where $f_u$ and $f_l$ denote the frequencies for the upper and lower edge of the pass-band, respectively.

**Table 3.1:** Measured impedance bandwidth (BW) and frequency corresponding to the lower edge of the pass-band (FLEPB)

| Design | *l* (mm) | VSWR=2:1 | | VSWR=3:1 | |
|---|---|---|---|---|---|
| | | FLEPB (GHz) | BW | FLEPB (GHz) | BW |
| **1** (*D*=20mm) | 34.0 | 4.79 | 4.3% | 2.79 | 25.1% |
| | 30.0 | - | - | 1.69 | 21.6% |
| | 25.0 | 1.90 | 14.6% | 1.67 | 41.7% |
| | 20.0 | 1.89 | 38.1% | 1.73 | 52.1% |
| | 17.5 | 1.90 | 50.9% | 1.76 | 55.4% |
| | 15.0 | 1.93 | 42.4% | 1.77 | 58.1% |
| | 12.5 | 1.96 | 39.3% | 1.81 | 58.9% |
| | 10.0 | 2.32 | 12.9% | 1.90 | 51.6% |
| **2** (*D*=12.5mm) | 20.0 | 1.86 | 31.3% | 1.67 | 51.9% |
| | 17.5 | 1.88 | 36.9% | 1.72 | 76.7% |
| | 15.0 | 1.90 | 42.7% | 1.74 | 81.0% |
| | 12.5 | 1.94 | 44.5% | 1.79 | 85.6% |
| | 10.0 | 2.16 | 44.0% | 1.88 | >2.5:1 |
| | 7.5 | 2.34 | 32.3% | 1.98 | >2.5:1 |
| | 5.0 | 2.73 | 16.2% | 2.38 | 36.7% |

For Design 1, the 2:1 VSWR BW performance is optimized at 51% when *l*=17.5mm. As *l*≤15mm, the BW gradually decreases. The FLEPB remains relatively stable at 1.9-1.96GHz for 12.5≤ *l* ≤25mm. There is considerably good matching in the region of 2-3GHz for 12.5≤ *l* ≤20mm. For VSWR=3:1, the BW performance is optimized at 59% when *l*=12.5mm. The FLEPB tends to increase as *l* gets smaller and varies between 1.69-1.9GHz for 10≤ *l* ≤30mm.

For Design 2, taking VSWR=2:1, the FLEPB is seen to increase as the length of the rectangular strip, *l*, gets smaller. The widest BW is 44.5% when *l*=12.5mm. For VSWR=3:1, the matching is much better as compared to Design 1. The optimized BW is

>2.5:1 at *l*=7.5 and 10mm. From the VSWR diagram shown in Fig. 3.6, it can be seen that as the length of the rectangular strip decreases to 7.5mm, the monopole exhibits high-pass response characteristics.

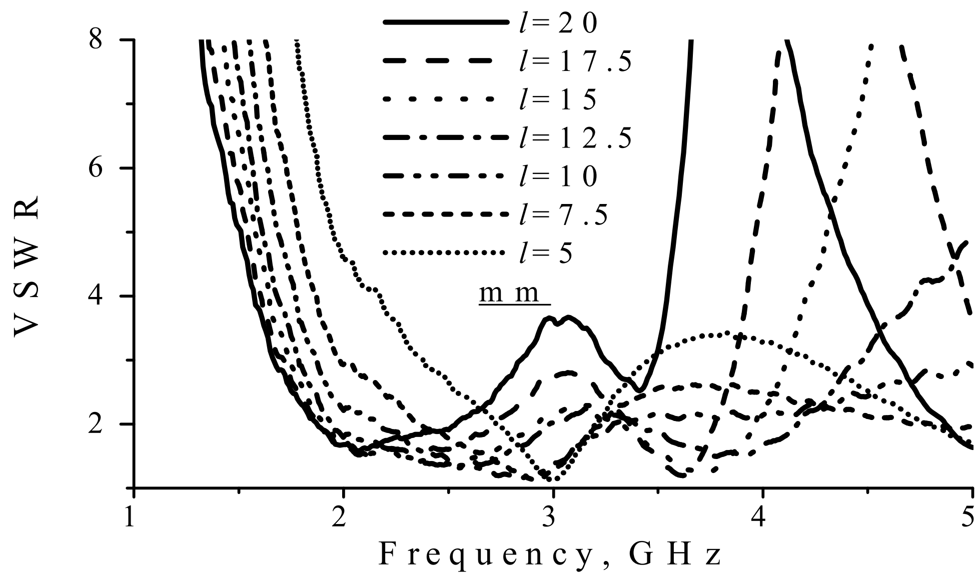


**Fig. 3.6**

The feed point for the first two designs has been maintained at *D*=20 and 12.5mm, respectively. For Designs 3-5, the *D* changes as the width of the strip is reduced. The FLEPBs and their corresponding impedance BWs are calculated and tabulated in Table 3.2.

**Table 3.2:** Measured impedance bandwidth (BW) and frequency corresponding to the lower edge of the pass-band (FLEPB)

| Design | *D* (mm) | VSWR=2:1 | | VSWR=3:1 | |
|---|---|---|---|---|---|
| | | FLEPB (GHz) | BW (%) | FLEPB (GHz) | BW (%) |
| 3 | 10 | 2.33 | 22.1 | 1.70 | 22.9 |
| | 7.5 | 2.39 | 53.1 | 1.66 | 27.5 |
| | 6.25 | 2.49 | 48.2 | 1.69 | 26.7 |
| | 5 | 2.64 | 39.5 | 1.67 | 26.0 |
| 4 | 5 | 1.90 | 41.3 | 1.69 | 59.5 |
| | 3.75 | 1.90 | 41.0 | 1.71 | 56.6 |
| | 2.5 | 1.91 | 37.8 | 1.74 | 52.5 |
| 5 | 8.75 | 1.99 | 7.7 | 1.73 | 30.8 |
| | 7.5 | 4.92 | - | 1.75 | 38.0 |
| | 6.25 | 1.96 | 12.9 | 1.74 | 45.0 |
| | 5 | 1.95 | 14.3 | 1.74 | 45.0 |
| | 3.75 | 1.93 | 28.4 | 1.78 | 47.2 |
| | 2.5 | 2.14 | 24.6 | 1.96 | 39.0 |

From Table 3.2, for VSWR=2:1, the FLEPB is stable at around 1.9GHz for Design 4. The FLEPB decreases as *D* increases and the BW is optimum when *D*=7.5mm for Design 3. For Design 5, the FLEPB for *D*≥5mm is not very responsive to the changes in *D*. For VSWR=3:1, Designs 3 and 5 show a sluggish response with respect to the changes in *D* while Design 4 has a FLEPB that decreases with increasing *D* and a BW which increases with *D*.

For Design 3, as *D* decreases, the first peak occurring at around 2.35GHz gets higher. There is good matching for *D*=10mm and it deteriorates for higher frequencies (>4GHz) as *D* decreases as seen from Fig. 3.7. However in the frequency range of 3-4GHz, the matching improves as *D* decreases.

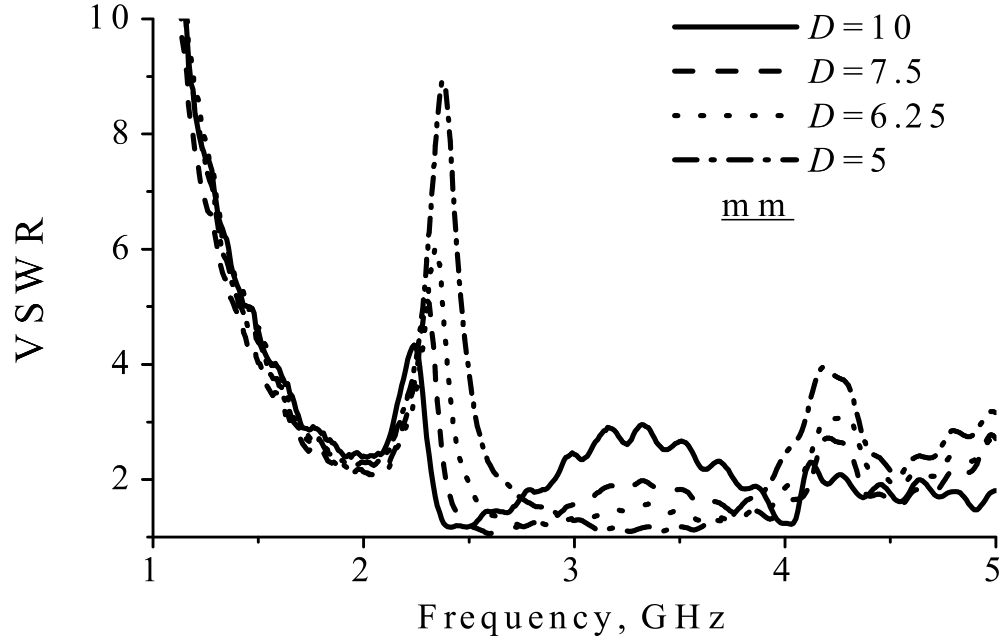


**Fig. 3.7**

For Design 4, the peak occurs at 3.7GHz and increases with decreasing *D*. There is good matching for VSWR<2:1 from 1.9-2.9GHz and remains the same for all values of *D* between 2.5 and 5mm. The BW performance is better than Designs 3 and 5 for VSWR=3:1.

For Design 5, the peaks occur at higher frequencies and become less pronounced as *D* decreases.

### 3.4 Conclusion

An experimental study on the effect of electromagnetic coupling on the triangular planar monopole antenna has been carried out. The measurements demonstrated that by etching a rectangular strip off-centred at *D*=12.5mm (Design 2), the BW performance can be optimized. Alternatively, implementing Design 4 with *D* between 2.5 and 5mm can attain lower FLEPB and wider BW.

### 3.5 References

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# Chapter 4: Circular Planar Monopole Antennas with Electromagnetic Coupling (EMC)

## 4.1 Introduction

With the rapid growth in wireless communications technology, antennas having good impedance and radiation performances are not the only factors in antenna design. Other considerations such as the ability to reduce cost, weight and ease of implementation are also equally important as well. Monopole planar antennas have shown that it had surpassed the wire elements in terms of impedance performance and stable radiation patterns [1-4]. Improvements in design included having slot cuts and the use of electromagnetic coupling for different geometrical shapes.

The square monopole antenna had been shown to exhibit broadband characteristics and by varying the feed point and by having slot cuts on the monopole, its performance can be enhanced further [5]. Another approach would be to couple the square planar radiator electromagnetically with a probe-fed strip. A bandwidth ratio of 70% for VSWR=2:1 and stable radiation patterns were achieved [6]. The triangular monopole with EMC has also been discussed in Chapter 3 and it is capable of producing lower FLEPBs and wider BWs under optimized conditions.

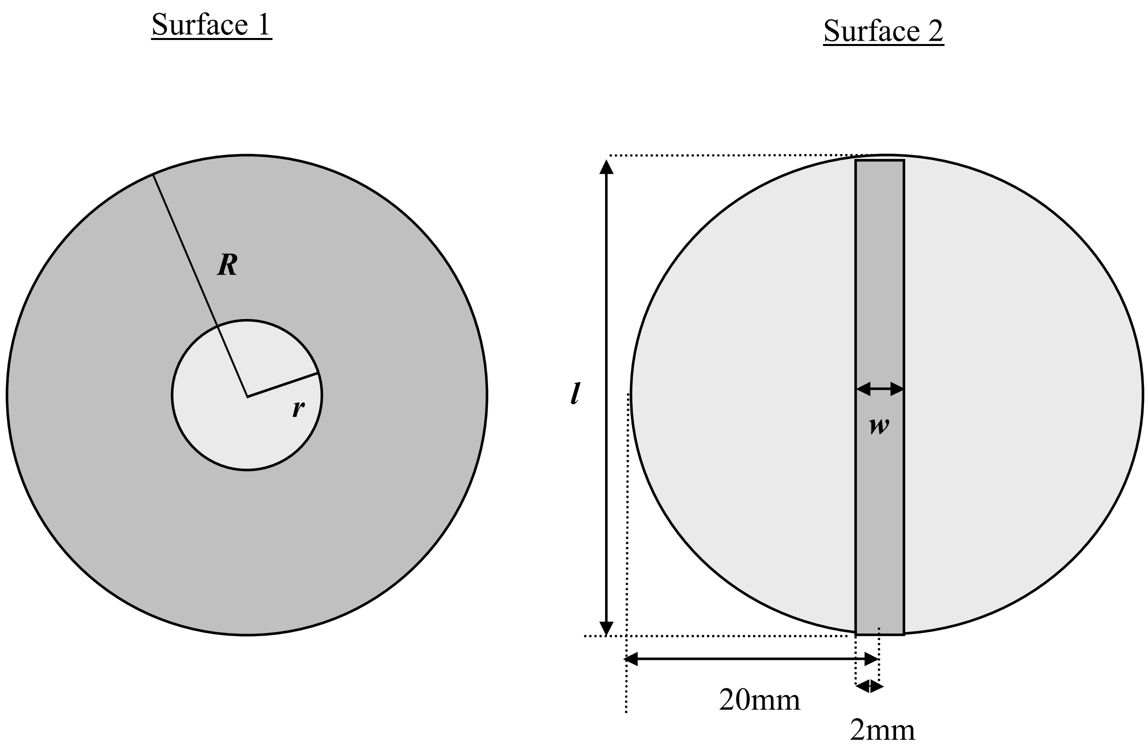
The circular disc monopole has shown to achieve a wide impedance bandwidth by numerical methods such as the method of moments with a wire grid and triangular cell meshing and had been verified experimentally to yield a wide bandwidth ratio [7-8]. Slot cuts were then made to the monopole [9] and results had shown that by optimizing the feed gap and the size of the slot, the slotted monopole was capable of producing a wider bandwidth than the slotted square monopole.

With this, it will be useful to investigate the effects of the electromagnetic coupling on the circular disc monopole. In this work, prototypes of circular monopoles with the foil concentrically removed from one of the sides were fabricated. The other side consists of a copper strip of 4mm width. A dielectric slab separates the two copper surfaces. The feed gap as well as the height of the copper strip were varied for optimization.

**4.2 Description of Antenna**

The circular planar monopole of radius *R*=40mm made of a PCB sheet (Roger 4003) having a dielectric constant of 3.38 and a thickness of 1.6mm was placed vertically over a ground plane by soldering it to the probe of an SMA connector. The monopole was mounted on a finite size ground plane (305x305mm$^2$) with a feed gap of *g*. The foil on one of the dielectric slab surfaces acted as a radiator while a strip measuring *w*=4mm wide was centrally etched on the other slab surface as shown in Fig. 4.1. A 50Ω coaxial probe of a 0.6mm radius excited the midpoint of the bottom of the copper strip through the ground plane via the SMA connector. A circular slot was cut concentrically on the planar radiator with a radius, *r*. The height of the strip, *l*, was varied by gradually removing the foil along its length. The measurements on the input impedance of the proposed planar monopoles were conducted.

**Fig. 4.1**




### 4.3 Results and Discussions

The measured impedance BWs for the specific VSWR=2:1 and 3:1 are tabulated in Table 4.1, where the BW is calculated according to the following formula,

$$\text{BW} = \begin{cases} 2(f_u - f_l)/(f_u + f_l) \times 100\ \% & \text{BW} \le 100\% \\ f_u : f_l & \text{BW} > 100\% \end{cases}$$

where $f_u$ and $f_l$ denote the frequencies for the upper and lower edge of the pass-band, respectively.

The input impedance for the prototype monopole having *r*=0mm is measured. For each strip length, feed gaps of *g*=0.7, 1.6 and 2.3mm are used.

**Table 4.1:** Measured impedance bandwidth (BW) and frequency corresponding to the lower edge of the pass-band (FLEPB)

| ***l*** **(mm)** | ***g*=0.7mm** | | | | ***g*=1.6mm** | | | | ***g*=2.3mm** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | VSWR=2:1 | | VSWR=3:1 | | VSWR=2:1 | | VSWR=3:1 | | VSWR=2:1 | | VSWR=3:1 | |
| | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW |
| 40.0 | 3.12 | 0% | 1.28 | 25.3% | 2.96 | 0% | 1.22 | 25.7% | 2.82 | 0% | 1.17 | 28.6% |
| 35.0 | 3.54 | 0% | 1.32 | 44.7% | 3.34 | 0% | 1.25 | 46.6% | 3.18 | 0% | 1.21 | 42.3% |
| 32.5 | 1.55 | 29.7% | 1.36 | 49.7% | 1.50 | 16.5% | 1.30 | 52.3% | 1.43 | 10.6% | 1.23 | 54.9% |
| 30.0 | 1.55 | 39.0% | 1.38 | 57.7% | 1.49 | 38.5% | 1.33 | 58.5% | 1.43 | 22.4% | 1.27 | 58.9% |
| 27.5 | 1.56 | 49.6% | 1.40 | 64.4% | 1.51 | 44.7% | 1.36 | 65.7% | 1.44 | 42.6% | 1.30 | 67.3% |
| 25.0 | 1.57 | 58.2% | 1.42 | 70.3% | 1.53 | 59.0% | 1.39 | 71.9% | 1.48 | 49.7% | 1.32 | 75.5% |
| 22.5 | 1.60 | 65.3% | 1.48 | 75.1% | 1.55 | 67.0% | 1.41 | 78.7% | 1.50 | 67.8% | 1.35 | 81.6% |
| 20.0 | 1.63 | 71.1% | 1.51 | 81.3% | 1.59 | 73.3% | 1.45 | 84.9% | 1.53 | 74.6% | 1.39 | 87.2% |
| 17.5 | 1.67 | 77.7% | 1.56 | 87.3% | 1.62 | 79.1% | 1.49 | 90.0% | 1.55 | 80.5% | 1.43 | 91.9% |
| 15.0 | 1.73 | 85.0% | 1.62 | 98.3% | 1.66 | 85.1% | 1.55 | 98.2% | 1.60 | 84.7% | 1.49 | 96.7% |
| 12.5 | 1.84 | 33.5% | 1.67 | 3.4:1 | 1.72 | 99.1% | 1.60 | 3.5:1 | 1.66 | 87.8% | 1.55 | 3.5:1 |
| 10.0 | 3.86 | 0% | 1.81 | 3.9:1 | 2.23 | 0% | 1.71 | 4:1 | 1.81 | 3.3:1 | 1.66 | 3.9:1 |
| 7.5 | 4.21 | 0% | 2.36 | 0% | 3.76 | 0% | 1.90 | >4.5:1 | 3.17 | 0% | 1.76 | 4.7:1 |
| 5.0 | 6.11 | 0% | 4.12 | 0% | 4.17 | 0% | 3.71 | 0% | 3.76 | 0% | 2.34 | 0% |

The FLEPB ranges between 1.50 to 1.84GHz for 12.5 ≤ *l* ≤ 32.5 mm. From the VSWR curves in Fig. 4.2, the frequency value corresponding to the first minimum that crosses the VSWR=2 line is taken to be the FLEPB. However, for *l*>32.5mm, the first minimum does not pass through the VSWR=2 line and hence the BW is considered to be zero. The frequency value corresponding to the second minimum was then taken to be the FLEPB. Likewise for *l*<12.5 (except when *g*=2.3mm), the second minimum is considered.

For the experiments, we only consider those strip length that gives rise to a VSWR curve that has its first minimum to cut the VSWR=2 line to be of interest.

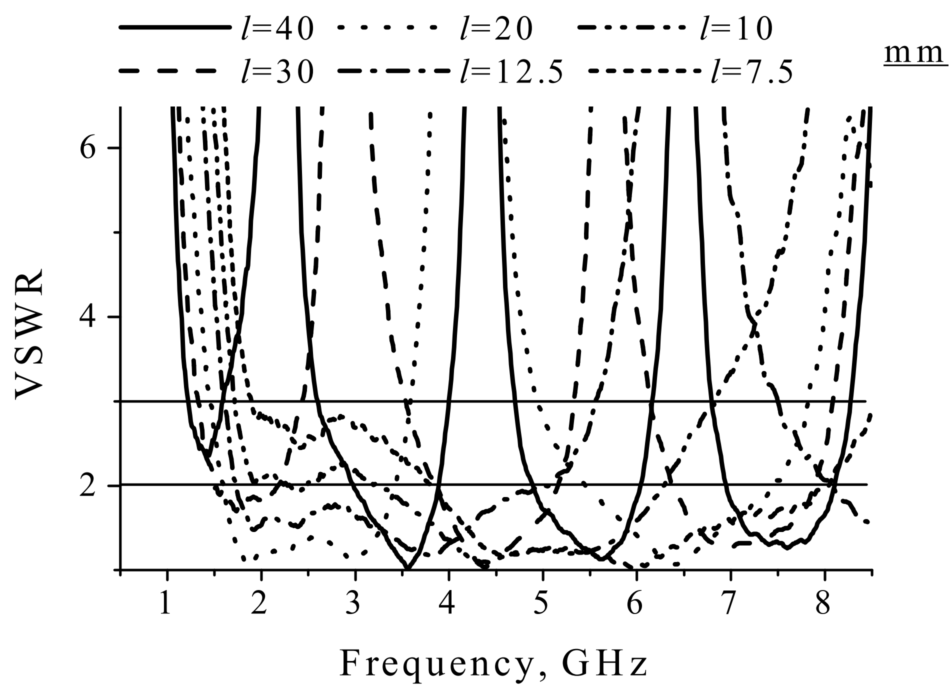



**Fig. 4.2**

It can be also be observed from Table 4.1 that for VSWR=2:1, that the BW for VSWR=2:1 generally increases as the strip length decreases for y ≤ *l* ≤ 32.5 mm, where y=15mm for *g*=0.7mm, 12.5mm for *g*=1.6mm and 10mm for *g*=2.3mm. For VSWR=3:1, the BW increases as the strip length decreases for any *g*.

A circular slot of *r*=5mm was concentrically cut from the radiator on the dielectric slab and the results tabulated in Table 4.2. With the introduction of the slot, there is no considerable increase in the FLEPB. For *g*=1.6 and 2.3mm, optimum BW performance occurs when *l*=12.5 and 10mm, which is similar to that when *r*=0. However for g=0.7mm, optimum BW occurs when *l*=12.5mm.

**Table 4.2:** Measured impedance bandwidth (BW) and frequency corresponding to the lower edge of the pass-band (FLEPB)

| ***l* (mm)** | ***g*=0.7mm** | | | | ***g*=1.6mm** | | | | ***g*=2.3mm** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | VSWR=2:1 | | VSWR=3:1 | | VSWR=2:1 | | VSWR=3:1 | | VSWR=2:1 | | VSWR=3:1 | |
| | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW |
| 40.0 | 2.85 | 0% | 1.24 | 12.1% | 2.33 | 0% | 1.20 | 15.4% | 2.27 | 0% | 1.18 | 17.1% |
| 30.0 | 1.54 | 33.5% | 1.39 | 46.8% | 1.52 | 29.2% | 1.33 | 50.1% | 1.45 | 22.1% | 1.29 | 51.7% |
| 25.0 | 1.60 | 60.0% | 1.47 | 69.6% | 1.56 | 61.9% | 1.42 | 72.6% | 1.49 | 64.5% | 1.37 | 75.2% |
| 22.5 | 1.62 | 69.9% | 1.49 | 79.6% | 1.58 | 72.3% | 1.44 | 82.4% | 1.51 | 73.4% | 1.39 | 84.4% |
| 20.0 | 1.64 | 75.3% | 1.51 | 86.0% | 1.60 | 76.9% | 1.47 | 87.4% | 1.54 | 77.3% | 1.41 | 89.0% |
| 17.5 | 1.65 | 79.1% | 1.53 | 89.5% | 1.61 | 80.1% | 1.47 | 91.9% | 1.56 | 79.8% | 1.43 | 91.5% |
| 15.0 | 1.67 | 83.0% | 1.56 | 95.5% | 1.62 | 84.7% | 1.50 | 95.3% | 1.59 | 83.3% | 1.46 | 96.8% |
| 12.5 | 1.75 | 99.9% | 1.63 | 3.4:1 | 1.71 | 94.7% | 1.59 | 3.5:1 | 1.65 | 87.9% | 1.54 | 3.5:1 |
| 10.0 | 3.81 | 0% | 1.77 | 4:1 | 1.88 | 30.2% | 1.69 | 3.9:1 | 1.81 | 3.2:1 | 1.65 | 3.9:1 |

For the prototype having *r*=10mm, the BW for VSWR=2:1 deteriorates for g=0.7mm to about 50%. (Refer to Table 4.3). However, for *g*=1.6 and 2.3mm, there is still satisfactory BW and the optimum results can be attained when *l*=15mm for *g*=1.6mm and *l*=12.5mm for *g*=2.3mm. A broad BW for VSWR=3:1 can still be observed as the strip length decreases. The FLEPB shows only a very slight increase with *r*=10mm.

**Table 4.3:** Measured impedance bandwidth (BW) and frequency corresponding to the lower edge of the pass-band (FLEPB)

| *l* (mm) | *g*=0.7mm | | | | *g*=1.6mm | | | | *g*=2.3mm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | VSWR=2:1 | | VSWR=3:1 | | VSWR=2:1 | | VSWR=3:1 | | VSWR=2:1 | | VSWR=3:1 | |
| | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW | FLEPB (GHz) | BW |
| 40.0 | 2.25 | 0% | 1.82 | 0% | 1.88 | 0% | 1.78 | 0% | 1.85 | 0% | 1.75 | 0% |
| 30.0 | 1.63 | 29.3% | 1.49 | 39.8% | 1.57 | 33.4% | 1.43 | 44.1% | 1.52 | 36.1% | 1.39 | 46.8% |
| 25.0 | 1.67 | 50.2% | 1.55 | 59.7% | 1.61 | 55.3% | 1.49 | 63.9% | 1.57 | 58.2% | 1.45 | 66.7% |
| 20.0 | 1.69 | 48.1% | 1.59 | 72.0% | 1.64 | 67.2% | 1.53 | 76.9% | 1.60 | 70.4% | 1.48 | 79.7% |
| 17.5 | 1.74 | 38.9% | 1.62 | 77.7% | 1.66 | 74.0% | 1.55 | 84.1% | 1.62 | 76.3% | 1.51 | 85.8% |
| 15.0 | 1.79 | 34.3% | 1.64 | 3.4:1 | 1.68 | 78.7% | 1.58 | 91.4% | 1.64 | 80.5% | 1.52 | 91.4% |
| 12.5 | 1.80 | 30.2% | 1.65 | 3.6:1 | 1.72 | 39.6% | 1.61 | 3.6:1 | 1.66 | 86.7% | 1.57 | 3.6:1 |
| 10.0 | 4.01 | 0% | 1.71 | 4:1 | 1.80 | 33.7% | 1.65 | 4:1 | 1.72 | 39.3% | 1.62 | 4:1 |

Finally, the prototype with *r*=15mm is tested similarly and the results in Table 4.4 show that the BW becomes worse considerably for all *g*.

**Table 4.4:** Measured impedance bandwidth (BW) and frequency corresponding to the lower edge of the pass-band (FLEPB)

| *l* (mm) | *g*=0.7mm | | | | *g*=1.6mm | | | | *g*=2.3mm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | VSWR=2:1 | | VSWR=3:1 | | VSWR=2:1 | | VSWR=3:1 | | VSWR=2:1 | | VSWR=3:1 | |
| | FLEPB (GHz) | BW(%) | FLEPB (GHz) | BW(%) | FLEPB (GHz) | BW(%) | FLEPB (GHz) | BW(%) | FLEPB (GHz) | BW(%) | FLEPB (GHz) | BW(%) |
| 40.0 | 4.34 | 0.0 | 1.76 | 0.0 | 3.66 | 0.0 | 1.72 | 0.0 | 1.83 | 0.0 | 1.71 | 0.0 |
| 30.0 | 1.71 | 13.6 | 1.60 | 23.7 | 1.64 | 21.3 | 1.51 | 30.8 | 1.59 | 24.8 | 1.46 | 34.6 |
| 25.0 | 1.81 | 7.5 | 1.63 | 30.2 | 1.69 | 24.4 | 1.59 | 37.3 | 1.65 | 32.5 | 1.53 | 42.3 |
| 20.0 | 5.82 | 0.0 | 1.69 | 25.8 | 1.73 | 16.9 | 1.62 | 42.0 | 1.68 | 32.4 | 1.58 | 47.0 |
| 15.0 | 4.08 | 0.0 | 1.72 | 23.1 | 6.24 | 0.0 | 1.66 | 36.9 | 1.74 | 13.9 | 1.62 | 44.2 |
| 10.0 | 3.99 | 0.0 | 1.81 | 10.0 | 3.96 | 0.0 | 1.71 | 31.9 | 1.88 | 2.6 | 1.68 | 35.7 |

Therefore, it can be observed from Fig. 4.3 that the minimum attainable FLEPB generally decreases as *g* increases. Also, the minimum FLEPB generally increases with the radius *r* for any particular *g*.

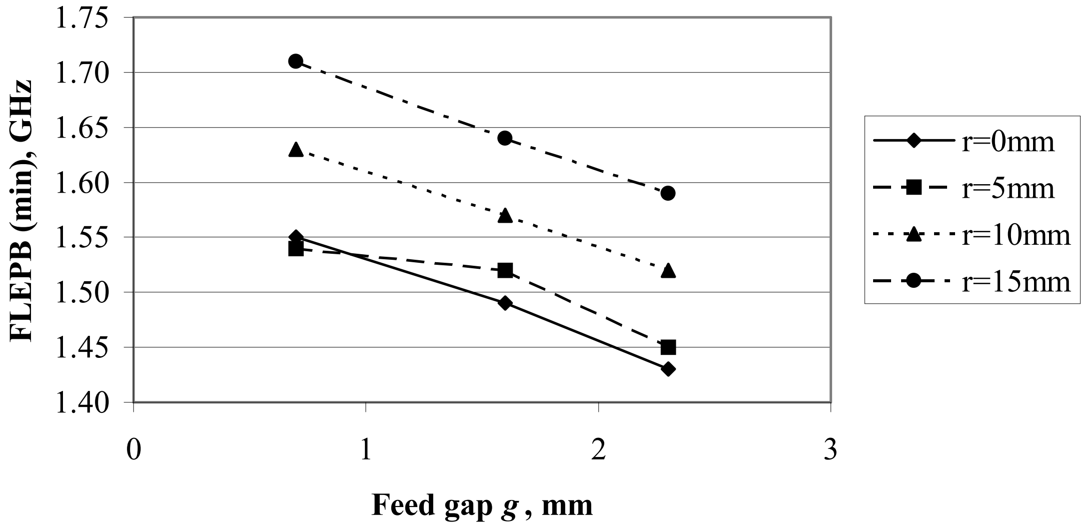



**Fig. 4.3**

In addition, with any fixed *g*, the minimum attainable FLEPB increases as the strip length *l* decreases as shown in Fig. 4.4. Also, an increase in the radius *r* at a fixed *l* also brings about a decrease in the minimum FLEPB.

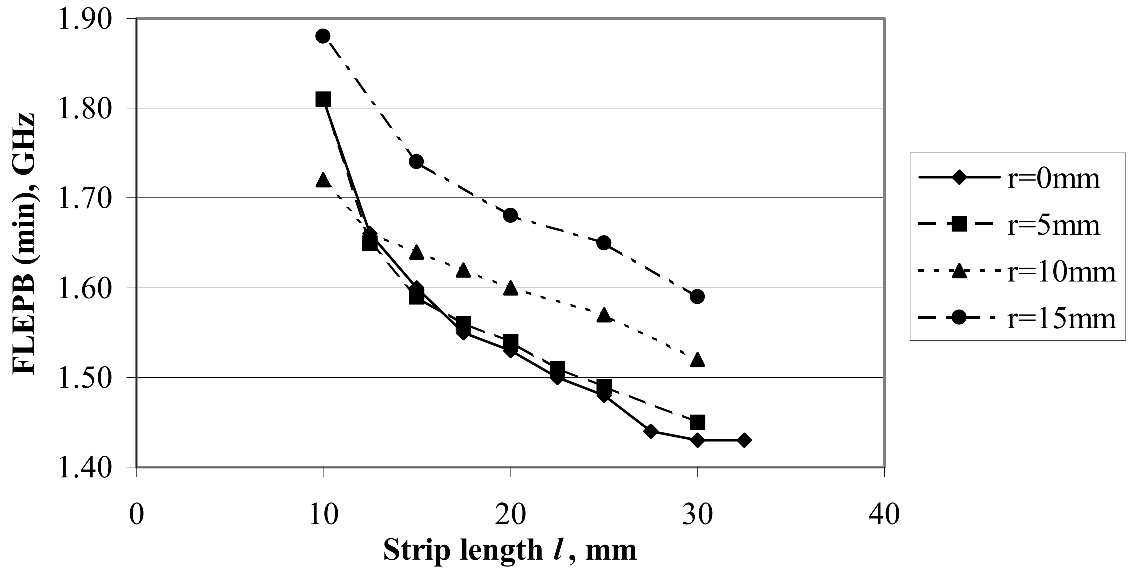



**Fig. 4.4**

The maximum achievable 2:1 VSWR BWs for any particular strip length are as shown in Fig. 4.5. It could be seen that as the radius *r* increases to beyond 10mm, the maximum BW dropped drastically, especially in the region where $10 \leq l \leq 25$mm. An increase in *r* from 0 to 10mm only results in a very slight decrease in the maximum attainable BW. For strip lengths where the BW=0%, the first minimum point from the VSWR curve does not pass through the VSWR=2 line and is therefore disregarded in our discussions.

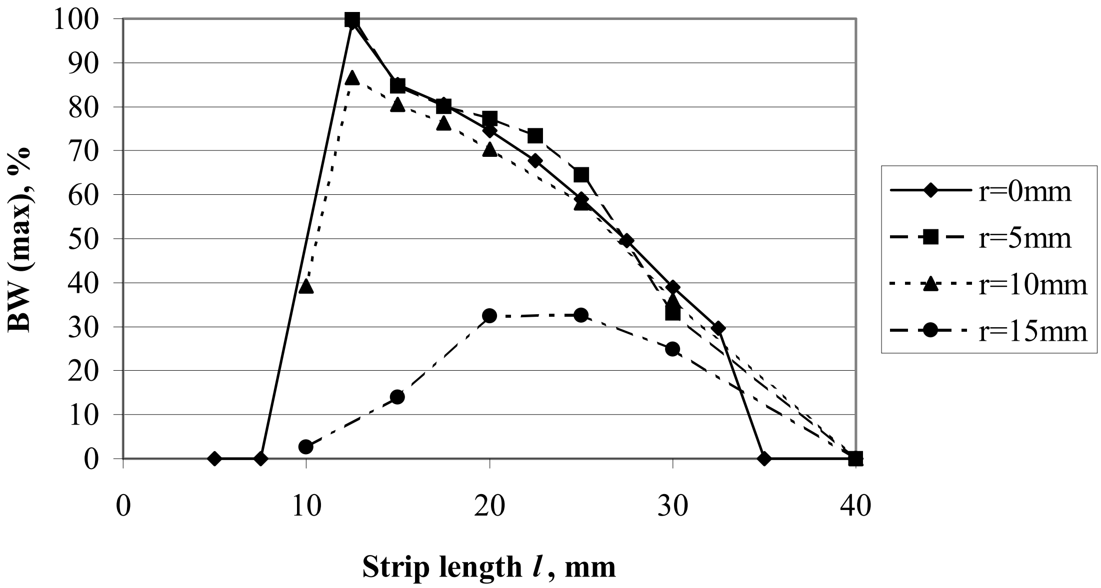



**Fig. 4.5**

Fig. 4.6 shows the maximum attainable 2:1 VSWR BW for any particular feed gap. The maximum BW for each case generally increases for larger *g*. Furthermore, it is observed that for *r*=0 and 5mm, the monopoles exhibits the same response. Both have the BW ratios of >3:1 at *g*=2.3mm. For *r*≥10mm, the maximum BWs decreases for all *g*.

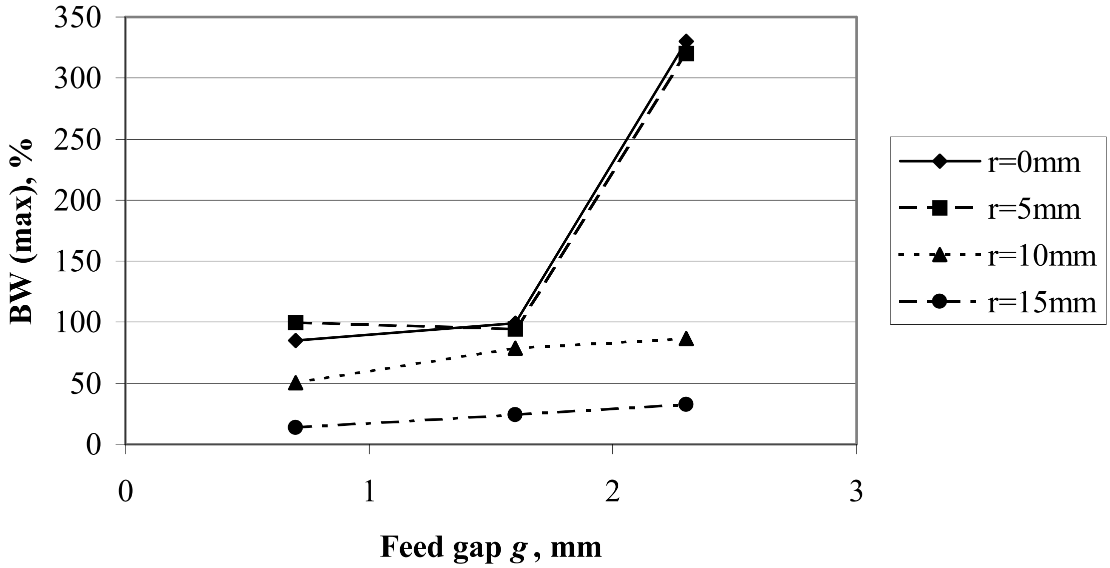



**Fig. 4.6**

## 4.4 Conclusion

The circular planar monopoles with the EMC had been tested. The experiments have shown that in order to lower the FLEPB, the strip length can be increased but at the expense of a narrower BW. Also, an increase in the feed gap leads to a corresponding increase in the BW and lowers the FLEPB as well. The BW is satisfactory for the radius up to 10mm, after which the BW starts to decline.

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# Chapter 5: Pentagonal Planar Monopole Antennas

## 5.1 Introduction

Planar monopole antennas with the square geometry have been analyzed and shown to provide wide impedance bandwidths while suffering little degradation of radiation patterns within the bandwidths. Attempts have been made to improve and control the impedance bandwidths of the monopoles including tilting the planar element with respect to the ground plane [1], cutting slots on the monopoles [2] and employing a trapezoidal geometry [3].

The input impedance of the square monopole has been found to be sensitive to the feed gap. The optimized impedance bandwidth ratio was found to be 2.4:1 for the simple square planar element and 4:1 for the shorted planar element [4].

In this chapter, a new planar monopole is proposed to cater for broadband applications. The monopole consists of a square piece of PCB with the foil entirely removed from one of the sides and the probe fed to the midpoint of the bottom side. By trimming the square foil symmetrically on the square edge near the ground plane, it forms a pentagonally shaped radiator. The performance of the antenna was taken into account over a frequency range of 0.5-8.5GHz.

## 5.2 Description of Antenna

The pentagonal planar monopole is placed vertically over a ground plane by soldering it directly onto the probe of the SMA as shown in Fig. 5.1. A 50Ω coaxial probe of a 0.6mm radius excites the bottom of the planar element through the ground plane ($305 \times 305 mm^2$) via the SMA connector. As the width of the bottom of the monopole parallel to the ground plane is only 3mm, it is directly soldered to the ground plane. By trimming the square on both sides of the feed probe, a symmetric pentagon is formed.

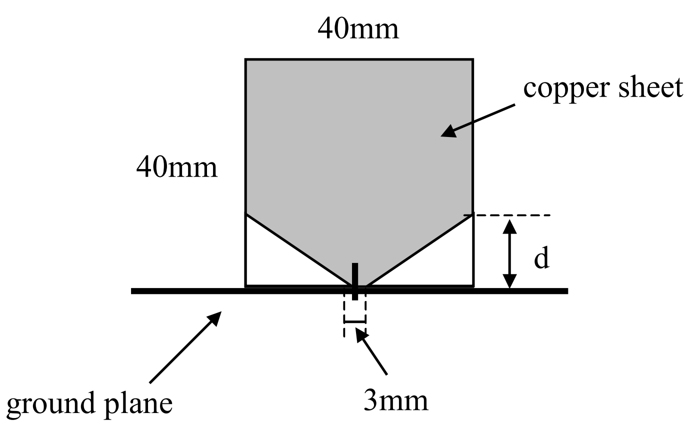


**Fig. 5.1**

## 5.3 Results and Discussions

The measured impedance BWs for the specific VSWR=2:1 and 3:1 are tabulated in Table 5.1, where the BW is calculated according to the following formula,

$$BW = \begin{cases} 2(f_u - f_l)/(f_u + f_l) \times 100\ \% & BW \le 100\% \\ f_u : f_l & BW > 100\% \end{cases}$$

where $f_u$ and $f_l$ denote the frequencies for the upper and lower edge of the pass-band, respectively.

**Table 5.1:** Measured impedance bandwidth (BW) and frequency corresponding to the lower edge of the pass-band (FLEPB)

| *d* (mm) | VSWR=2:1 | | VSWR=3:1 | |
|---|---|---|---|---|
| | FLEPB (GHz) | BW | FLEPB (GHz) | BW |
| 2.0 | 1.50 | 59.5% | 1.26 | 89.2% |
| 10.0 | 1.39 | 3.1:1 | 1.16 | >4.3:1 |
| 15.0 | 1.29 | 3.6:1 | 1.14 | >4.4:1 |
| 20.0 | 1.25 | 18.8% | 1.11 | >4.5:1 |
| 30.0 | 1.18 | 17.8% | 1.09 | 55.1% |
| 40.0 | 1.17 | 16.5% | 1.08 | 41.2% |

The upper and lower edge frequencies for the simple square planar monopole with sides 40mm have been experimentally shown to be 1.59GHz and 2.96GHz, respectively for VSWR=2:1, yielding an impedance BW of 60.2%. If the square element is trimmed symmetrically about the feeding probe such that *d* is now 10mm, the BW ratio improved significantly to 3.1:1. For *d* =15mm, the upper edge frequency increases to 4.68GHz.

The FLEPB decreases as *d* increases until the foil on the rectangular dielectric slab is reduced to a triangular geometry ($d$ = 40mm). However, for $d \geq$ 20mm, the BW is considerably narrower despite the lower FLEPB.

Experiments have also been conducted previously by using a copper plate instead of a PCB board. An interesting point to note is that for trim angles greater than 40°, the BW deteriorates [5]. In this experiment, as *d* gets above 20mm (trim angle is 45° in this case), the BW is reduced significantly.

## 5.4 Conclusion

The experimental study on the impedance characteristics has been conducted. Measurements have demonstrated that a monopole with an optimized pentagonal geometry has a bandwidth ratio of 3.6:1. The trimming distance, *d*, has an effect on the FLEPB and the bandwidth of the monopole.

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# V. CONCLUSION

The designs and experimental investigations on broadband planar monopole antennas have been successfully completed. The results have shown that the planar monopoles are capable of providing broader bandwidths than conventional wire elements. Cutting slots from the monopoles have improved the impedance bandwidths as well as lowered the FLEPB. With the parameters such as the feed gap, location of feed point and the sizes of slot being optimized, the designs are able to maximize their potential.

The circular slotted monopole has been shown to exhibit the broadband characteristics even when 64% of its area is being removed. The triangular slotted monopole offers the optimum bandwidths when the feed point was off-centred although its bandwidth is not as broad as the circular slotted monopole.

Other than by cutting slot from the planar monopoles, another method to seek to achieve broad impedance bandwidth is to make use of electromagnetic coupling (EMC). The circular and triangular planar monopoles are able to produce satisfactory performance under the optimized conditions.

By varying the shape of the monopole, the bandwidth can also be made broader. The pentagonal monopole has been demonstrated to provide broad impedance bandwidth, typically in the order of 3:1, with the optimized parameters.

The above designs done in my Industrial Attachment period have provided me with great insight on the workings and designs of a broadband antenna. Not only had I been able to learn to operate a Network Analyzer, valuable experience have also been gained in the area of antenna design and measurement.