CHAPTER 5
CONCLUSIONS

This chapter presents the conclusions drawn from the experimental and theoretical investigations carried out on L-strip fed microstrip antennas. Suggestions for further research work in the field are also given.
5.1 INFERENCES FROM EXPERIMENTAL INVESTIGATIONS

The radiation characteristics of different L-strip fed rectangular as well as circular microstrip antenna are studied experimentally and numerically. From the detailed experimental investigations, it is concluded that L-strip feed can successfully be used for bandwidth enhancement of the antenna. It is observed that the resonant frequency of the microstrip antenna shifts towards the lower frequency side when it is excited with L-strip feed. From the Table 3.1 and Figure 3.5 it is clear that with the feed segment length, bandwidth of the patch 3.6x2.6cm² is improved for each feed length. Maximum bandwidth of 17% has been obtained when the feed segment length is 0.4λ₀. From the Table 3.4 and Figure 3.17 it is found that a maximum bandwidth of 20% is obtained for the patch 4x2cm² when the feed segment length is 0.53λ₀. It is also noted that the resonant frequency varies only little with the feed segment length.

Table 3.10 shows the optimized feed parameters for different frequency bands. From these observations, it can be concluded that L-strip feed can effectively be used for bandwidth enhancement of antennas operating in L, S, C and X band frequencies. For all these cases, the antennas offered 11 to 20% bandwidth. This bandwidth enhancement is achieved without deteriorating the radiation characteristics.

Effect of permittivity of the substrates used for fabricating patch and feed on the bandwidth of the antenna is also studied. Figures 3.27 to 31 reveals that permittivity of the patch and feed is also has significant effect on the bandwidth of the L-strip fed antenna. It is found that when the patch and feed are on substrates with different permittivity, bandwidth enhancement is marginal. In this case, maximum bandwidth achieved is only 10-12%. Therefore it is confirmed that bandwidth is maximum if both the patch and feed are fabricated on the substrate having same permittivity.

Radiation patterns of the L-strip fed antennas of the optimum bandwidth configurations have been studied. From Figure 3.32 and Table 3.5, it is clear that the patterns are similar to those of rectangular patches. The patterns are broad with low cross polar level of the order of -40dB along the bore-sight direction.

Gain of the antenna is also studied in detail. Figure 3.33 gives the absolute gain of the L-strip fed antenna. From the figure, it is found that the gain of the antenna is not much affected as the feed position parameters varies. And maximum gain of the antenna is 8.2dBi. This enhanced gain is attributed as due to the in phase radiation from the L-strip feed.

L-strip feed is used to excite circular patches also. Experimental and simulated results are discussed in Section II. Circular patches resonating at 3.5GHz offered a maximum bandwidth of -17%. And patches resonating at 2.4 GHz and 1.8GHz offered a maximum bandwidth of 12%. Radiation patterns of the antenna are also studied. The patterns are similar to those of conventional circular patches. The cross polar level is found to be better than -25 dB. Gain of the antenna is also improved. L-strip fed circular antenna has a gain of 7.25dBi. From the experimental analysis, for the moderate bandwidth and optimum gain, L-strip feed is an ideal choice.

6.2 INFERENCES FROM THEORETICAL INVESTIGATIONS

Finite Difference –Time Domain (FDTD) method is used for the analysis of the L-strip fed rectangular patch antennas. The analysis could predict the resonant frequency, electric field variations over the patch surface, radiation patterns, input impedance etc., of the antenna with an error of less than ± 2%.

The resonance characteristics of the L-strip fed rectangular patches are given in Table 4.2 to Table 4.9. Both the experimental and theoretical results are in good agreement and the maximum error is 2%. Input impedance of the L-strip fed antenna is also computed using FDTD and exactly matching with the experimental results. The discrepancy may be due to the uncertainty in the permittivity of the substrate, non uniformity of the substrate layer and the trapped air between the substrates.
Field distribution over the patch is observed theoretically. From the Figure 4.9, it is clear that the antenna is excited in TM_{01} mode.

Radiation patterns of the antenna are computed theoretically from the calculated near field data. Theoretical and experimental radiation patterns are in good agreement. The slight discrepancies in the cross-polarization characteristics may be due to some reflections from the surroundings. This shows that the present theory can easily predict the radiation patterns of the antenna.

6.3 SCOPE OF FURTHER WORK

L-strip antenna may find applications where wide bandwidth is required. The bandwidth can further be increased by using stepped L-strip. Incorporating photonic band gap ground planes along with L-strip feed would be an interesting topic for future work for bandwidth enhancement along with surface wave reduction. This can improve the overall efficiency of the system.

The effect of air gap between the feed and the radiating patch can be an interesting problem to investigate further. This can considerably increase the bandwidth and gain of the antenna.

Another interesting area to be investigated further is loading the L-strip with Ferroelectric materials like BST. By applying suitable potential across BST, the effective dielectric constant can be varied and hence the system can operate at different frequencies.

APPENDIX A

T-STRIP FED WIDEBAND RECTANGULAR MICROSTRIP ANTENNAS

Experimental results of symmetric and asymmetric T-strip fed rectangular microstrip antenna are presented here. Symmetric T-strip fed antenna offered a maximum bandwidth of 23.23% while asymmetric T-strip fed antenna offered 35%. The gain of the antenna is improved with this feeding technique. The antennas are analysed using Finite - Difference Time - Domain method (FDTD). The resonant frequency, return loss, impedance bandwidth and radiation patterns are predicted and are in good agreement with the measured results.
AI INTRODUCTION

L-strip feed has successfully been used for bandwidth and gain enhancement of the rectangular as well as circular patch without affecting the radiation characteristics. Now T-strip feed has been used for exciting rectangular patches. T-strip feed has two versions, with symmetric arms and asymmetric arms. An electromagnetically coupled T-shaped microstrip feed is employed to excite a rectangular microstrip antenna fabricated on another substrate. An impedance bandwidth of ~23% is obtained for symmetric T-strip fed antenna and 35% for asymmetric T-strip fed antenna. The effect of the feed parameters on the radiation and reflection characteristics of the antenna is studied in both the cases. The antenna has a broad radiation pattern with a cross polarization level better than -35 dB. Effect of the feed parameters on the antenna characteristics like resonant frequency, impedance bandwidth, and radiation pattern are theoretically studied. Theoretical results are found to be in good agreement with the experimental ones.

AII SYMMETRIC T-STRIP FED ANTENNA

AII.1 Antenna Geometry

The geometry of the symmetric T-strip fed rectangular microstrip antenna is illustrated in Figure A.1. The feed is fabricated on a substrate with permittivity \( \varepsilon_r = 4.28 \) and height \( h = 0.16 \) cm. Patch is also fabricated on a similar substrate. The patch is electromagnetically coupled to the feed. The feed parameters that determine the characteristics of the antenna are the length of the two symmetric arms \( S_2 \) and \( S_3 \) and feed length \( S_1 \) of the T-feed.

Effect of feed parameters on the radiation and reflection characteristics of the antenna is studied.

AII.2 Experimental observations

Rectangular patches with dimensions \( L \times W = 4 \times 2 \) cm\(^2\) is excited with symmetric T-strip feed. The following antenna characteristics are studied.

(a) Resonant frequency
(b) Bandwidth
(c) Radiation pattern
(d) Gain

To study the reflection and radiation characteristics, \( S_1 \) is varied from \( 1 \lambda_d \) to \( 1.4 \lambda_d \) and \( S_2 \) and \( S_3 \) from \( 0.1 \lambda_d \) to \( 1.2 \lambda_d \). Resonant frequency and bandwidth variations of the antenna are studied. The measured results are given in the Table A.1. From the table it is clear that the bandwidth is decreasing as \( S_1 \) increases. Resonant frequency patch is shifting to the lower side when it is excited with T-strip feed. Feed parameters at the maximum bandwidth position are \( S_1 = 1.09 \lambda_d, S_2 = 0.651 \lambda_d, S_3 = 0.261 \lambda_d, d_1 = 0.217 \lambda_d \), and \( a = 0.195 \lambda_d \).

Gain of the antenna is measured by gain transfer method at the maximum bandwidth position. The antenna has a gain of 7.8dBi at the resonant frequency.
Table A.1 Resonant frequency and bandwidth variations of symmetric T-strip feed for different $S_2$ and $S_3$, $L=4\text{cm}$, $W=2\text{cm}$, $\varepsilon_r=\varepsilon_r' = 4.28$, $h_1 = h_2 = 0.16\text{cm}$

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AIL.3 Theoretical Investigations

The optimized antenna configuration is investigated using FDTD method. Space steps $\Delta x, \Delta y, \Delta z$ used for computation are 0.1cm, 0.1cm and 0.04cm and the total mesh dimensions are $110\times110\times20$ in $x$, $y$ and $z$ directions respectively. Time step $\Delta t$ is taken as 1.159ps and the Gaussian half-width $\tau$ as 15ps. The simulation is performed for 5000 time steps. To reduce the number of time steps required for convergence an external source resistance of 50$\Omega$ is used. Return loss characteristics, resonant frequency, bandwidth and radiation patterns of the antenna at the maximum bandwidth position are computed theoretically.

$S_{11}$ variation of the antenna at the maximum bandwidth position is shown in Figure A.3. Theoretical and experimental radiation patterns are shown in Figure A.4. The measured and computed cross polar levels are in good agreement.
III. ASYMMETRIC T-STRIP FED ANTENNA

III.1 Antenna Geometry

Asymmetric T-strip fed rectangular microstrip antenna geometry is illustrated in Figure A.5. The feed parameters that determine the characteristics of the antenna are the feed length $S_1$ and two asymmetric feed segment lengths $S_2$ and $S_3$. The feed is fabricated on a substrate with permittivity $\varepsilon_r = 4.28$ and height $h = 0.16$ cm. The patch is fabricated on a similar substrate. The patch is electromagnetically coupled to the feed.

![T-strip feed](image)

Figure A.5 Geometry of the asymmetric T-strip fed microstrip antenna

III.2 Experimental Observations

The performance of an asymmetric T-strip feed on rectangular microstrip patches is studied. The experimental studies are carried out by keeping feed length of the T-strip as $1.052\lambda_d$. The two feed segment lengths $S_2$ and $S_3$ are varied. One of the feed segment lengths, $S_3$ is fixed as $1.158\lambda_d$ and the other feed segment length $S_2$ is varied from $0.5\lambda_d$ to $1.5\lambda_d$. Experimental studies are conducted on patches of size $L \times W = 4 \times 2$ cm$^2$ which is fabricated on a substrate with height $0.16$ cm and permittivity $4.28$.

$S_1$, variations of the antenna for different asymmetric feed segment length $S_2$ are measured. The feed length $S_1$ and one of the asymmetric feed lengths $S_3$ are kept constant. The bandwidth of the antenna is found to be increasing. Maximum bandwidth of $\sim 35\%$ is obtained when $S_2$ and $S_3$ are $1.053\lambda_d$ and $1.158\lambda_d$ respectively. Gain of the optimized antenna configuration is measured and is found that the antenna has again of $7.87$ dBi at the resonant frequency.

III.3 Theoretical investigations

The optimized antenna configuration is analyzed using FDTD. Space steps $\Delta x, \Delta y, \Delta z$ used for computation are $0.1$ cm, $0.1$ cm and $0.04$ cm and the total mesh dimensions are $150 \times 120 \times 20$ in $x$, $y$ and $z$ directions respectively. Time steps and Gaussian half-width used are as in the above analysis.

Return loss variation of the asymmetric T-strip fed antenna at the maximum bandwidth position is obtained by numerically is shown in Figure A.6 along with experimental result. Theoretically the antenna resonates in the band $2.8569 \text{GHz} - 3.607 \text{GHz}$ ($f_r = 3.232 \text{GHz}$) with an impedance bandwidth of $23.3\%$ band, while experimental operating band is $2.665 \text{GHz} - 3.805 \text{GHz}$ ($f_r = 3.235 \text{GHz}$) with a bandwidth of $35.2\%$. This confirms that the present theory can accurately predict the resonant frequency of the antenna less than an error of $0.09\%$.

Radiation patterns are also computed at the maximum bandwidth position. Figure A.7 shows the theoretical and experimental radiation patterns of the antenna at the resonant frequency. The differences in the cross-polar levels may be due to the reflections from surroundings.
WIDEBAND RECTANGULAR MICROSTRIP ANTENNA

USING HOOK-STIP FEED

Experimental and theoretical results wideband rectangular microstrip antenna using hook strip feed is presented. Here a hook shaped microstrip line is used to excite the antenna by proximity method. This feeding technique enhances the bandwidth and gain of the antenna without affecting its size. The antenna is excited in TM_0 mode. This new feeding technique offered a maximum bandwidth of 22% without affecting other characteristics of the antenna.

APPENDIX B

Figure A.6 Experimental and theoretical return loss variations of the antenna at the maximum position

\[ \text{frequency (GHz)} \]

\[ S_{11} (\text{dB}) \]

Figure A.7 Theoretical and experimental radiation patterns of the antenna at the resonant frequency, \( L = 4 \text{ cm}, W = 2 \text{ cm}, S_1 = 1.0524, S_2 = 1.0524, d_1 = 0.4214 \text{ cm}, d_2 = 0.2954 \text{ cm}, \text{ and } a = 0.2114 \text{ cm} \).
B.I INTRODUCTION

L-strip and T-strip feed are successfully been applied for the bandwidth enhancement of rectangular microstrip antennas. L-strip feed is modified into hook shaped microstrip line and is used for exciting a rectangular microstrip patch. Experimental and theoretical observations of a hook strip fed rectangular microstrip antenna is discussed in the following sections.

An impedance bandwidth of – 22% is obtained without affecting the antenna characteristics. The effect of the feed parameters on the radiation characteristics of the rectangular patch antenna at resonant frequency is studied. The antenna has a broad radiation pattern with a cross polarization level better than -30 dB. Gain of the antenna is found to be 7.2 dBi at the resonant frequency. Experimental results are confirmed by computational results using FDTD.

B.II ANTENNA GEOMETRY

A rectangular patch antenna of dimension L x W is fabricated on a substrate having dielectric constant \( \varepsilon_r = 4.28 \) and thickness \( h_2 = 0.16 \text{ cm} \). The antenna is fed by electromagnetic coupling, using a hook shaped microstrip feed, fabricated on another substrate having the same dielectric constant and thickness. The antenna geometry is illustrated in Figure B.1. The feed parameters are feed length \( S_1 \), feed segment length \( S_2 \) and hook arm length \( S_3 \), which decides the antenna characteristics.

![Figure B.1 Geometry of hook strip fed microstrip antenna](image)

B.III RESULTS AND DISCUSSIONS

Hook strip feed is an extension of L-strip feed. The feed length of the hook shaped feed is also fixed as \( 1.3 \lambda_d \) since which gave optimum bandwidth for L-strip. Generally the feed segment length \( S_2 \) and hook arm length \( S_3 \) are varied from \( 0.1 \lambda_d \) to \( 0.9 \lambda_d \) keeping \( S_1 \) fixed.

Microstrip antenna with dimension \( 4 \times 2 \text{ cm}^2 \) is used for study. Reflection characteristics of the antenna were studied for different \( S_2 \). For each \( S_2 \), \( S_3 \) is varied from \( 0.1 \lambda_d \) to \( 0.9 \lambda_d \). Bandwidth of the antenna is found to be increasing as \( S_2 \) increases. The feed parameters are optimized for maximum bandwidth and the radiation characteristics of the optimized antenna are studied. Bandwidth and resonant frequency variations of the antenna for different \( S_2 \) and \( S_3 \) combinations are given in Table B.1. From the table it is observed that a maximum bandwidth of 21.99% is obtained when \( S_2 = 0.763 \lambda_d \) and \( S_3 = 0.654 \lambda_d \). The resonant frequency of the patch is shifting to the lower side as \( S_2 \) and \( S_3 \) varies.

The experimentally optimized antenna is analyzed using FDTD. Space steps \( \Delta x, \Delta y, \Delta z \) used for computation are 0.1 cm, 0.1 cm and 0.04 cm and the total mesh dimensions are \( 110 \times 110 \times 20 \text{ in } x, y \text{ and } z \) directions respectively. Time steps \( \Delta t \) is taken as 1.159 ps and the Gaussian half-width T as 15 ps. The simulation is performed for 5000 time steps. Resonant frequency, bandwidth variations with feed segment length and radiation patterns are computed theoretically. An external source impedance of 50 \( \Omega \) is used for fast convergence.

The return loss and the radiation patterns of the antenna at the optimum position are calculated numerically. Figure B.2 shows the theoretical and experimental \( S_{11} \) variations of the antenna at the maximum bandwidth position. Theoretical operating band of the antenna is from 3 GHz to 3.558 GHz while experimental operating band is 3 GHz to 3.7 GHz.

Figure B.3 shows the theoretical and experimental E-plane and H-plane patterns of the antenna at the resonant frequency. 3 dB beam width of the antenna at the resonant frequency is \( 92^\circ \) and \( 73^\circ \) in E-plane and H-plane respectively. The cross polarization level is found to be – 35 dB in the principal planes both in theory and experiment.
Table B.1 Resonant frequency and bandwidth variations of the hook-strip fed antenna with $L = 4\text{cm}$, $W = 2\text{cm}$, $e_{r1} = e_{r2} = 4.28$, $h_1 = h_2 = 0.16\text{cm}$ and $S_1 = 1.3\lambda_d$

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Table B.1 contd.. Resonant frequency and bandwidth variations of the hook -strip fed antenna with $L = 4\text{cm}$, $W = 2\text{cm}$, $e_{r1} = e_{r2} = 4.28$, $h_1 = h_2 = 0.16\text{cm}$ and $S_1 = 1.3\lambda_d$

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B.IV CONCLUSIONS

The effect of hook-strip feed on the characteristics of a rectangular microstrip antenna is studied. The antenna offered a maximum bandwidth of 22% with 7.2dBi gain. The antenna is analyzed using finite difference time domain technique and obtained an excellent agreement with experiment. This antenna may find applications in high speed personal communication systems where large bandwidth is required.
Figure B.2 Experimental and theoretical return loss variation with frequency of the antenna $L = 4\text{cm}$, $W = 2\text{cm}$, $S_1 = 1.3\lambda_d$, $S_2 = 0.763\lambda_d$, $S_3 = 0.654\lambda_d$, $d_1 = 0.109\lambda_d$, $d_2 = 0.371\lambda_d$

Figure B.3 Theoretical and experimental radiation patterns at the resonant frequency of the antenna, $L = 4\text{cm}$, $W = 2\text{cm}$, $S_1 = 1.3\lambda_d$, $S_2 = 0.763\lambda_d$, $S_3 = 0.654\lambda_d$, $d_1 = 0.109\lambda_d$, $d_2 = 0.371\lambda_d$

APPENDIX C

Appendix C deals with the experimental setup and the measurement techniques employed for the study of radiation characteristics of the developed antennas.
ANTENNA MEASUREMENTS

HP 8510C Vector Network Analyzer is used for the measurement of return loss, resonant frequency, gain and radiated power. Network analyzer can make automatic, rapid and accurate measurements.

C.1 Network Analyzer

A Network Analyzer is swept frequency measurement equipment to completely characterize the complex network parameters without any degradation in accuracy and precision in less time. Two types of network analyzers are available, scalar and vector network analyzers. Scalar network analyzer measures only the magnitude of reflection and transmission coefficients while the vector network analyzer measures both the magnitude and phase.

A vector Network Analyzer consists of the following system
1) Microwave Source
2) Test Set
3) Signal Processor
4) Display Unit

The synthesized source or the sweep oscillator provides the RF stimulus. It operates from 45MHz to 50 GHz. It can operate in ramp or in step mode. In the ramp mode the analyzer directs the source to sweep in a linear ramp over the frequency and in the step mode, which provides maximum precision. The schematic diagram of the network analyzer controlled by IBM PC is shown in Figure C.1.

C. II Measurement of return loss, resonant frequency and bandwidth

Network Analyzer is calibrated to one full port and the test antenna is connected to PORT 1 of the S-parameter test set. The measured $S_{11}$ LOGMAG data is acquired and stored in ASCII format in the computer interfaced with the NWA (Figure C.2), using the software MERL Soft. The resonant frequency is determined from the dip of the return loss curve. The impedance bandwidth is measured by taking the range of frequencies ($\Delta f$) over which the return loss is greater than or equal to 10dB. Percentage bandwidth can be calculated using the expression $(\Delta f/f_r) \times 100\%$, where $f_r$ is the center frequency of the operating band.

![Figure C.1 Schematic diagram of the HP 8510C network Analyzer](image)

C. III Measurement of radiation pattern

Antenna radiation pattern is the spatial distribution of the electromagnetic field radiated by the antenna. Generally patterns in two-principle planes, E and H plane are taken. The principal plane patterns (co and cross polar) of the test antenna are measured by keeping the antenna in receiving mode inside an anechoic chamber. The experimental setup for the measurement of radiation pattern is shown in Figure C.2.
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HP 8510C Network Analyzer, interfaced to an IBM PC, is used for the pattern measurement. The PC is attached to a STIC 310C position controller. The test antenna is mounted on the antenna positioner kept inside the anechoic chamber. A wideband horn antenna is used as the transmitter. The test antenna and the transmitting antenna are connected to Port 2 and Port 1 respectively of the network analyzer. The test antenna is mounted on the Positioner and the transmitting wide band horn antenna is mounted on a stand at the aperture of the Anechoic Chamber. After selecting the start, stop frequencies and number of points in Network Analyzer stimuli menu, the antenna is bore-sighted. The test antenna at the Bore-sight position a thru calibration is done in the Network Analyser. The test antenna is rotated by 90°.

Radiation patterns of the antenna at multiple frequency points can be measured in a single rotation of the test antenna by using antenna position controller and MERL software. The postioner will stop at each step angle and take S₂₁ measurement at different frequency points in the operating band. The process will repeat till it reaches the stop angle. The entire measured data is stored in ASCII format and can be used for further processing. The different radiation pattern characteristics like half power beam width, cross-polar level, etc. are obtained after the analysis of the stored data.

Figure C.2 Experimental setup for the measurement of return loss and resonant frequency.

Figure C.3 Experimental setup for the measurement of radiation pattern.
C.IV Measurement of Gain

The antenna set up for measuring the radiation pattern can be used for the measurement of gain. Here the gain transfer method is used to calculate the absolute gain of the test antenna.

The test antenna is positioned to the bore-sight direction. Select the start and stop frequencies and number of points in the Network Analyser. The response is switched to S22. A THRU response calibration is performed in the NWA and stored in the CAL SET. Now replace the test antenna with the standard gain antenna. Measure the S21 data and store it in the computer. Then the computer will look at the lookup table of the standard gain data and compute the absolute gain in the following manner.

Gain of the test antenna = Standard gain data from the lookup table – the standard gain S21 data.

If the gain of the test antenna is less than the standard gain antenna, the S21 data of the standard antenna may be positive and the computer will calculate the difference. If the gain of the test antenna is greater than the standard antenna, S21 data stored in the computer is negative and it will add this data with the standard antenna gain.

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