obtained results for the antenna parameters, S_{11}, Z_{11}, VSWR and Smith chart, are compared with those required for the design specifications. In the first run, the simulation results for the antenna parameters do not match well with the antenna parameters required, to satisfy the design specifications. Therefore, the antenna model is improved by changing any one of antenna model parameters, the patch dimensions or ground dimensions or the feed location and the resulting model is simulated and obtained results are compared again with the antenna parameters required. The process of changing antenna model, simulating it and comparing results with the antenna parameters, required to satisfy design specifications, is repeated until a good match between simulation results and required antenna parameters is obtained.

The final microstrip patch antenna model dimensions and feed location, obtained using the technique of iteratively improving antenna model, described previously, is shown in the Table 2.

Table 2: Final Design Parameters

Parameter	Value in mm	RT5880™	
L	47.132799	h	3.175 mm
W	60.813032	ε_r	2.2
L_g	79.863032	$\tan(\delta)$	0.0009
W_g	79.863032		
x_f	11.864407		
y_f	0		
d	1.30		

The antenna characteristics for S_{11} and Z_{11} are presented in Fig 2 and Fig 3, respectively. The VSWR and Smith chart for the antenna design, are presented in Fig 4 and Fig 5 respectively.

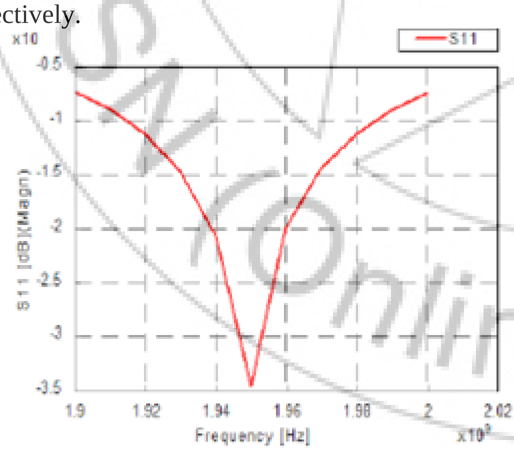

Figure 2: S_{11} Characteristics

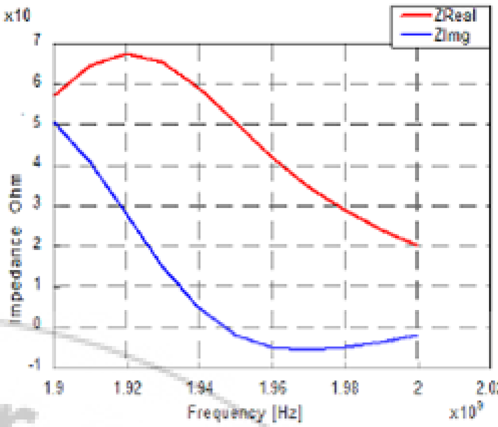

Figure 3: Z_{11} Characteristics

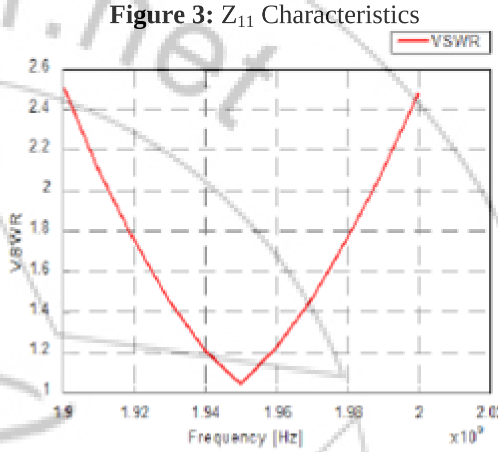

Figure 4: VSWR

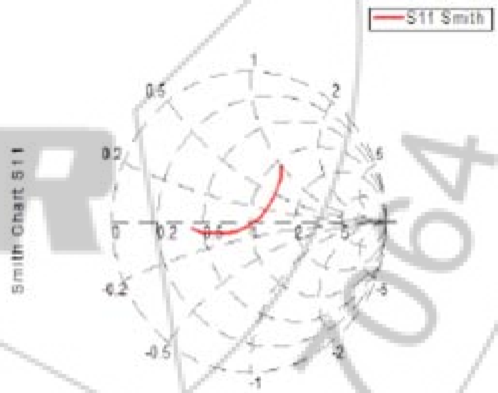

Figure 5: Smith Chart

The results for some important antenna parameters are given in the Table 3

Table 3: Rectangular Microstrip Patch Antenna

Antenna Parameter	Value	Unit
f_o	1950	MHz
S_{11} Minimum	-34.5935	dB
VSWR Bandwidth	60	MHz
S_{11} Bandwidth	60	MHz
Z_{11} at resonance	50.4816-j1.80978	Ohm

3. Quarter Wave Gap Coupled Rectangular Microstrip Patch Antenna Design

The gap or capacitively coupled rectangular microstrip patch antenna designs offer broader bandwidths than the conventional ones. The gap coupled design consists of a driven half wavelength patch gap coupled to parasitic patches. The parasitic patches have resonant frequencies close to the resonant frequency of the driven patch. The parasitic patches may be gap coupled to either the radiating edges and or to the non radiating edges, of the driven patch.

The broader bandwidth half wavelength gap coupled rectangular microstrip patch antenna design is accompanied by the disadvantage of larger total patch size than the conventional design. The quarter wavelength gap coupled rectangular microstrip patch antenna design , on the other hand, provides broader bandwidth and 50% size reduction over conventional rectangular microstrip patch antenna.

This type of design, consists of, non radiating edge gap coupled, quarter wavelength driven and parasitic patches. These patches are obtained by halving the half wavelength patch of half wavelength rectangular microstrip patch antenna design along its length and width. They are shorted to ground along their one radiating edge. The quarter wavelength gap coupled rectangular microstrip patch antenna design is illustrated in Fig 6.

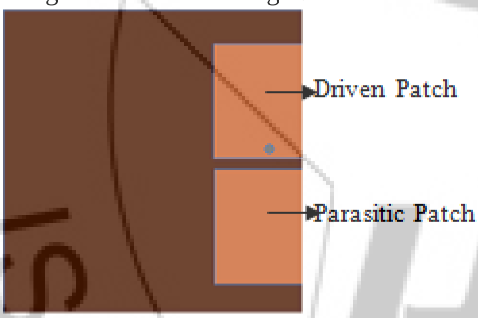

Figure 6: Quarter Wavelength Gap Coupled Rectangular Microstrip Patch Antenna

3.1 Initial Design

The initial estimates for the dimensions of quarter wavelength driven and parasitic patches are obtained by halving the patch dimensions shown in Table 2 for the final design of conventional rectangular microstrip patch antenna. The initial estimates of the design parameters for quarter wavelength gap coupled rectangular microstrip patch antenna are shown in the Table 4. The new design parameters are, length of the driven patch $L_{d,}$, length of the parasitic patch $L_{p,}$ the width of driven patch W_{d},, the width of parasitic patch W_p and the gap between the driven and the parasitic patch g.

Table 4: Initial Design Parameters

Parameter	*Value in mm*	*RT5880™*	
L_d, L_p	23.5663995	h	3.175 mm
W_d, W_p	30.406516	ε_r	2.2
L_g	79.863032	$\tan(\delta)$	0.0009
W_g	79.863032		
x_f	35.4308065		
y_f	0		
g	1.5		
d	1.30		

3.2 Simulation and Final Design

The design specifications for the quarter wavelength gap coupled rectangular microstrip patch antenna are, the resonant frequency of driven patch f_d =1950 MHz and the resonant frequency of parasitic patch fp =1980 MHz. The bandwidth of driven as well as parasitic patch should be 50 MHz. The total bandwidth should be 100 MHz. The initial antenna model created using the design parameters shown in the Table 3 is improved using iterative process of simulation, comparison of simulation results with the design specifications and changing design parameters.

The final design parameters obtained for the quarter wavelength gap coupled rectangular microstrip patch antenna, are shown in the Table 5.

Table 5: Final Design Parameters

Parameter	Value in mm	Parameter	Value in mm
L_d	23.758518	x_f	32.790992
L_p	23.482393	y_f	5.5
W_d	30.406516	g	1.5
W_p	30.406516	d	1.30
L_g	79.863032		
W_g	79.863032		

The simulation results for S_{11}, Z_{11}, VSWR and Smith chart are presented in Figs 7 to 10.

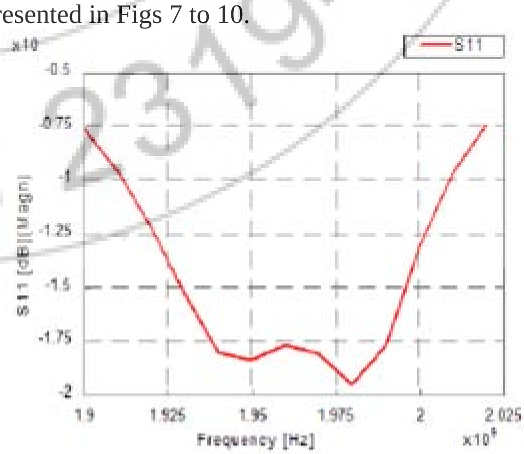

Figure 7: S_{11} Characteristics

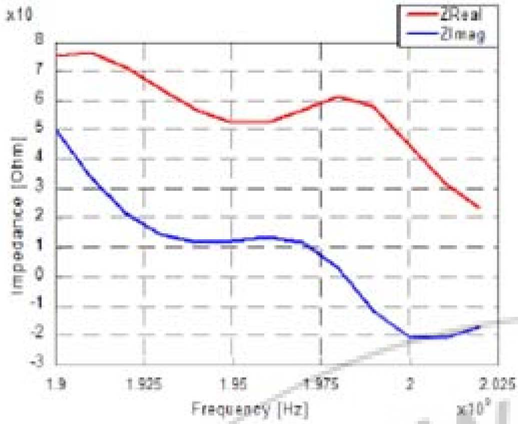

Figure 8: Z_{11} Characteristics

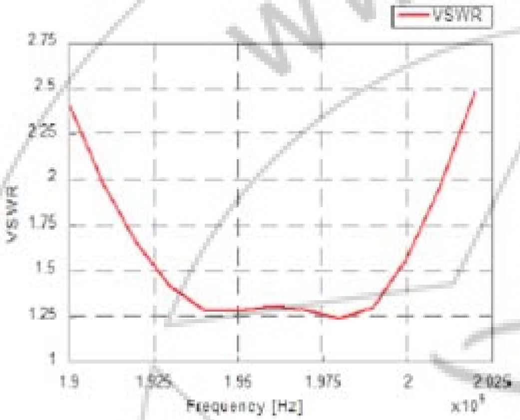

Figure 9: VSWR

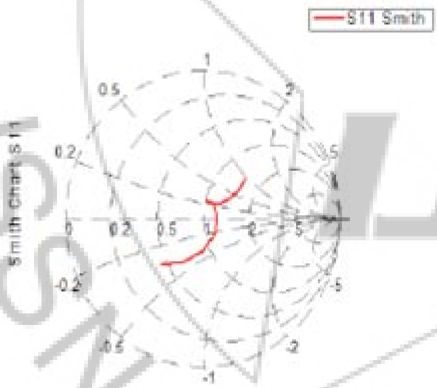

Figure 10: Smith Chart

The simulation results show the presence of two resonant frequencies, corresponding to the driven and the parasitic patches. The presence of these frequencies is confirmed by the Smith chart. The bandwidth of 98 MHz is obtained for this design.

4. Conclusions and Discussions

The half wavelength rectangular microstrip patch antenna design is resonant at frequency f_o = 1950 MHz. The -10dB bandwidth is 60 MHz. The lower and upper cutoff frequencies are f_L = 1920 MHz and f_U = 1980 MHz. The impedance characteristic shows that the antenna is slightly capacitive at resonance. The patch size is about 2866.2884 mm^2. The ground plane size is 6378.1039 mm^2.

The quarter wavelength gap coupled rectangular microstrip patch antenna design shows excitation of two TM10 resonant modes of frequencies, f_d = 1950 MHz and f_p = 1980 MHz, corresponding to the driven quarter wavelength patch and parasitically coupled quarter wavelength patch. The presence of these resonant modes is confirmed by Smith chart. The –10dB bandwidth is 98 MHz. The lower and upper cutoff frequencies are f_L = 1911 MHz and f_U = 2009 MHz. The

antenna design is not perfectly matched to the transmission line at the resonant mode frequencies, the input impedance is inductive at f_d = 1950 MHz and f_p = 1980 MHz. The overall patch size is about 1444.8275 mm^2 while the ground plane size remains 6378.1039 mm^2.

The quarter wavelength gap coupled rectangular microstrip patch antenna design, enhances bandwidth from 60 MHz of conventional design to 98 MHz. The proposed design has patch size which is 50% smaller than the conventional design. However, more simulation study is needed to reduce the inductive reactance of this design. The comparison of conventional microstrip patch antenna design and the proposed quarter wavelength gap coupled rectangular microstrip patch antenna design is presented in the Table 6.

Table 6: Comparison of Designs

Conventional Design		Proposed Design	
Parameter	Value	Parameter	Value
f_o	1950 MHz	f_d	1950 MHz
		f_p	1980 MHz
Bandwidth	60 MHz		98 MHz
Z_{11}	50.4816-j1.80978 Ohm	f_d	52.6065+ j12.1723 Ohm
		f_p	61.437+ j2.82774 Ohm
Patch Area	2866.2884 mm^2		1444.8275 mm^2
Ground Plane	6378.1039 mm^2		6378.1039 mm^2

5. Acknowledgements

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References

[1] R. Garg, P. Bhartia, I. J. Bhal, and A. Ittipiboon, Microstrip Antenna Design Handbook. Artech House, 2001.
[2] G. Kumar and K. P. Ray, Broadband Microstrip Antennas. Artech House, 2003.

[3] A. K. Bhattacharyya and R. Garg, "Effect of Substrate on the Efficiency of an Arbitrarily Shaped Microstrip patch Antenna," IEEE Transactions on Antennas and Propagation, vol. 34, no. 10, pp. 1181–1188, 1986.

[4] E. Chang, S. Long, and W. Richards, "An Experimental Investigation of Electrically Thick Rectangular Microstrip Antennas," IEEE Transactions on Antennas and Propagation,, vol. 34, no. 6, pp. 767–772, 1986.

[5] P. S. Hall, "Probe Compensation in Thick Microstrip Patches," Electronics Letters, vol. 23, no. 11, pp. 606–607, 1987.

[6] G. Kumar and K. C. Gupta, "Broad-Band Microstrip Antennas Using Additional Resonators Gap-Coupled to the Radiating Edges," IEEE Transactions on Antennas and Propagation, vol. 32, no. 12, pp. 1375–1379, 1984.

[7] G. Kumar and K. C. Gupta, "Nonradiating Edges and Four Edges Gap-Coupled Multiple Resonator Broad-Band Microstrip Antennas," IEEE Transactions on Antennas and Propagation, vol. 33, no. 2, pp. 173–178, 1985.

[8] EMCoS Antenna VLab [Online]. Available: http://www.emcos.com

[9] R. F. Harrington, Field Computation by Moment Methods. Wiley, 1993.

[10] H. Pues and A. Van de Capelle, "Accurate transmission-line model for the rectangular microstrip antenna," in IEE Proceedings H (Microwaves, Optics and Antennas), vol. 131, pp. 334–340, 1984.

[11] Y. T. Lo, D. Solomon, and W. Richards, "Theory and Experiment on Microstrip Antennas," IEEE Transactions on Antennas and Propagation, vol. 27, no. 2, pp. 137–145, 1979.

[12] "RT duroid 5870 5880 High Frequency Laminates, Rogers Corporation, USA," Tech. Rep.