Journal of Basic and Applied Engineering Research
p-ISSN: 2350-0077; e-ISSN: 2350-0255; Volume 5, Issue 7; October-December, 2018, pp. 596-602

http://www.krishisanskriti.org/Publication.html

Pin Loaded Microstrip Antenna for 2.45 GHz

Rajesh Kumar Raj[1] and Himanshu Khandelwal[2]

[1]Assistant Professor, Government Engineering College Ajmer, Rajasthan
[2]M.Tech. Scholar, Government Engineering College Ajmer, Rajasthan
E-mail: [1]rajeshraj@ecajmer.ac.in, [2]maiet.himanshu@gmail.com

Abstract—*In order to design microstrip patch antenna for 2.45 GHz with 3 and 4 shorted pins this paper is prepared. The antenna contains patch, shorting pins, substrate and ground plane. Overall size of antenna is 30 x 35 x 1.670 mm^3. It is shown that shorted pins increases impedance matching of antenna and its radiation pattern. Resonant frequency of antenna is 2.45 GHz. As per calculations, it depicts that antenna's Resonant frequency is directly related to its width. The proposed aerial has various applications on Resonant frequency and it has Band Width around 500 MHz.*

1. INTRODUCTION

The increasing demand of multifunctional small wireless communication systems with higher mobility is generated during past few years.

Compact, small, microstrip patch antenna at Frequency of 2.45 GHz has various applications in the wireless(Analog/Digital) communication system. During the past decade, use/applications of compact, reduced size, integrated microstrip antennas is increased.

Microstrip antenna is being designed and studied since 1953[1]. Recently, various new methodology have been emerged for designing integrable microstrip patch aerials with smaller device. Latest emerging and encouraging methods is to use the loading of shorting pin. Pin loading technique with diode was introduced in [2]. On the basis cavity model[3], theoretical and experimental analysis is done using the Green's function approach. In order to govern the input impedance[4] and double band [5], this technique shall be applied for improved matching [6] and polarization agile [7] of patch antennas. To suppress surface wave propagation, demonstration is suggested in [8] for shorting post in contiguity to the feed point. Recently, Pin-loaded circularly-polarised patch antenna demonstrated with sharpened gain roll-off rate and 3-dB widened axial ratio beamwidth [9], higher & improved gain and increased bandwidth in [10]–[14] patch antennas. Different position of loading pins are tried for modification in the current distribution and consequently manipulate impedance of aerial (to attune the resonance frequency & broaden the

bandwidth of aerial), decreasing the radiation beamwidth and improves polarization characteristics.

But, it is observed that such kind of structures don't depict electrically small size aerials. Studies of these works show that a shorting pin will result in the resonant frequencies above the fundamental mode of the unloaded patch antenna. Other side to these designs, focus is on miniaturizing the patch antenna by the use of pin loading technique; but, as per the studies[15]–[18], the results are having disadvantages due to their low gain .

This paper has main goal to present a small, low cost, miniaturized, planar, thin aerial with a medium gain and good impedance matching. Physical perspective shows that the proposed aerial structure could be integrated with various types of movable devices, where the antenna has to be thin and easy to integrate. In such kind of applications, the antennas like dipole might be preferred because of existence of ground plane that is normally implemented to support Radio Frequency(RF) and digital circuits and their radiation pattern(omnidirectional), the antenna like wire is not applicable. To determine the possibility of reducing the patch width, the pin-loaded aerial is studied and simultaneously increasing the resonant frequency of antenna. It is depicted that the physical limitations(low gain and low efficiency) of conventional microstrip patch antennas could be overcome by shorting pin. Second, an approach by utilizing additional shorting pins is proposed to mitigate the drawbacks of low-efficiency. By utilizing the proposed method, the matching as well as radiation of a shorted pin single-patch antenna are enhanced.

To cover the desired frequency band, the dominant mode's resonant frequency can be tuned due to shunt inductive effect of shorting pins. The width of patch is directly related with number of resonant frequencies.

In addition to this, a greatly enhanced matching observed when it compared with an equivalent simple patch antenna loaded with pins with the same resonant frequency.

2. THE PROPOSED AERIAL STRUCTURE IS DESIGNED USING THE CST AND DIFFERENT CASES HAVE BEEN DESIGNED AND STUDIED, THE RESULTS OF THE SIMULATION ARE SHOWN AT FIG.3 TO 11.SUBJECT DEFINITION

Shorting pins can be loaded in a miniaturized, slim patch antenna. Loading of pin results in the electrical length enhancement of the patch and miniaturization made in the antenna, significantly, it decreases the radiating edge, due to which, aerial gain drops. Proposed design in this paper has main target to study, design and bring a solution to understand the effective tuning as well as matching of patch antenna by pin loading technique.

To excite the patch antenna, Microstrip feed is used from the edge of substrate at a distance of L_f (which is distance between substrate edge and patch edge). To examine the behaviour of antenna, an effective and latest version simulator is used.

Further, we are to utilize the same patch antenna as above, with a single shorting pin at centre/offset/ at the diagonal (beside the edge of patch) to demonstrate the miniaturization. After the use of shorting pin having radius of 0.5 mm, the distribution of field is definite to be changed because of effect of introduced shorting pin. Fig. 1 to 3 depicts the design and results after simulation of patch antenna with/without pin loading effect on S-Parameter. Simulation shows that the patch antenna without pin loading in the dominant mode has resonant frequency is about to 5.*4* GHz.

The aerial(loaded without/with three pins) radiation pattern is also shown in the figure.4(a&b).It distinctly shows the pattern of a conventional patch antenna in fig. 4(a) and changes in a shorted-pin microstrip patch antenna in fig. 4(b).

Reducing the width and length of a patch a changes the resonant frequency, due to which, radiating edge also reduces. Accordingly, radiation efficiency and aerial gain decreases. Although the electrical length of the patch increases by the use of a shorting pin, which helps in miniaturization of antenna, significantly the radiating edge also decreases, due to which, the aerial gain to drops. Two additional pins are used for keeping the electrical length small and increasing the aerial gain and efficiency. The other 2 pins help in prevention of the opposite current cancelation and attune the surface current directions.

3. IMPROVED DESIGN, SIMULATION & RESULTS

To validate the proposed concept, a simple microstrip patch antenna has been picked, shown in fig.1, whose parameters are mentioned in table-1. The schematic of a pin-loaded patch antenna is shown in fig. 2 [further, extended in fig.8{case-V(a)}] and its parameters in table-2.

The aerial is designed on a single-layer FR-4 substrate having dimensions/area 30 × 35 mm^2, whose dielectric constant is 4.4 and a height of substrate is 1.6 mm and the size of patch is 10×25.5 mm^2. The side pin is loaded along the antenna diagonal and beside the edge to show the miniaturization.

Shorting pins are implemented between the patch and a ground plane. A microstrip line used to feed the antenna. To examine the proposed design, CST simulator is utilized. The parameters of aerial are mentioned in fig.1 & 2 and table-1 & 2. The aerial is designed so that it can easily integrate and work in the portable/ movable/handheld applications.

Fig.3 to fig.11 depicts the S-Parameter(S_{11}) results after simulation of the various designs and the effects of pins and its position on it. when operating in each of its resonant modes, a patch antenna can be comparable to a lossy shunt resonator. For a better understanding, the results are shown from fig. 3 to 11. We can analyse from these figures that position of loading of pin beside the edge of patch has a impressive effect on the resonant frequency of antenna. Low resonant frequency increases up to 2 GHz by aiding of a centered pin, which is analysed later, which has a important role to improve the gain & efficiency. This also helps in changing the surface current direction and preventing the opposite current cancelation. The offset pin is used for tuning the low frequency band to the required application, although, it does not change the upper band much considerably.

According to numerical calculations and fig.2, the proposed structure provides more than 75% patch area reduction as per the numerical simulations. The overall dimension of patch is 0.08λr × 0.21λr × 0.01366λr, and the overall dimension of aerial is 0.245λr × 0.286λr × 0.01366λr [fr = 2.45 GHz and λr is the wavelength(free-space) analogous to the resonant frequency]. It must be noted that the shorted-pin patch antenna is totally not matches at all in the required band by reflection at the port, the low gain and efficiency are mainly observed, the proposed aerial resolves the issues of matching, simultaneously, it provides high gain and efficiency.

The latest structure is proposed in [25], suffers from the large electrical size. A miniaturized, single feed, single-layer aerial results in dual band behaviour.

Furthermore, increasing the shorting pins doesn't help, but, properly positioned shorting pins helps to change and improve the resonant frequency (fig. 5 to 11).

The behaviour of a patch antenna as a function of pin loading and positioning of pins is also analysed and the results are demonstrated here. Moreover, the pins location variation in the perpendicular direction has a dramatic effect on the dominant resonant frequency of aerial. It has a drastic effect on the aerial gain.

As per the numerical simulation analysis, the various cases shows that increasing the pins results in decreasing resonant frequency, but, could not be matched to requirement, due to which, overall performance of aerial decreases.

In this paper, a simple patch antenna designed and simulated and further, study of shorting pins on the same dimension of patch antenna have been done and various cases have been designed, studied and illustrated for one pin, two pins, three pins, four pins, five pins and six pins loading, which can be seen from fig.1 to 11. The analysis of case is also studied and demonstrated, as under:

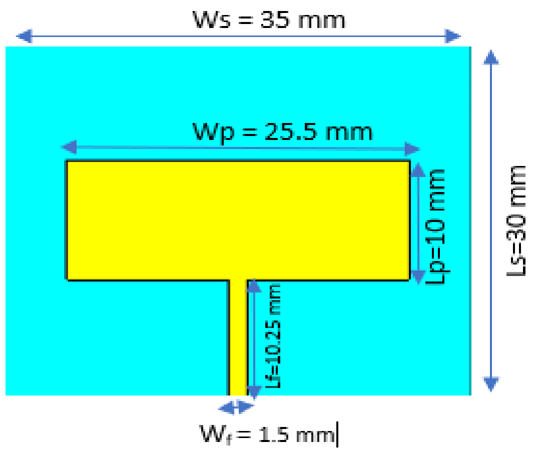

Fig. 1: Patch Antenna

Parameters of patch antenna shown in fig.1 is as under in table-1:

Table 1: Parameters of Patch Antenna (shown in fig.1)

S.N.	Particulars/Parameters	Details
1.	Substrate material	FR-4
2.	Loss Tangent (tan □)	0.025
3.	Substrate height(Hs)	1.6 mm
4.	Substrate width((Ws)	35 mm
5.	Substrate length(Ls)	30 mm
6.	Ground width(Wg)	35 mm
7.	Ground length(Lg)	30 mm
8.	Ground height (Hg)	0.035 mm
9.	Patch width(Wp)	25.5 mm
10.	Patch length(Lp)	10 mm
11.	Patch height(Hp)	0.035 mm
12.	Feed length(Wf)	10.25 mm
13.	Feed width	1.5 mm

A simple Patch Antenna is designed on CST having above parameters, which is shown in fig.1 and simulated & results obtained. Further, the same aerial was loaded with three(3) pins, and the new design is again simulated in CST, the new results obtained for resonant frequency of 2.45 GHz. Accordingly Bandwidth(BW) is also calculated, i.e. aprox 500 MHz. The pin loaded Antenna resonated at 2.45 GHz and S_{11} parameter obtained, i.e. -25.26 DB, the same antenna resonated at 2.445 GHz with S_{11} = -32.59.

S_{11} Graph of both the antenna shown in fig-1 & fig-2 is compared and shown at Fig. -3.

In the patch antenna design, three (3) shorting pins loaded, shown in fig.2, additional parameters are as under in table-2.

Radiation pattern is shown at fig.4(a & b).Loading of three pins in patch antenna, resulted in impedance matching and improved gain along with shifting of resonant frequency.

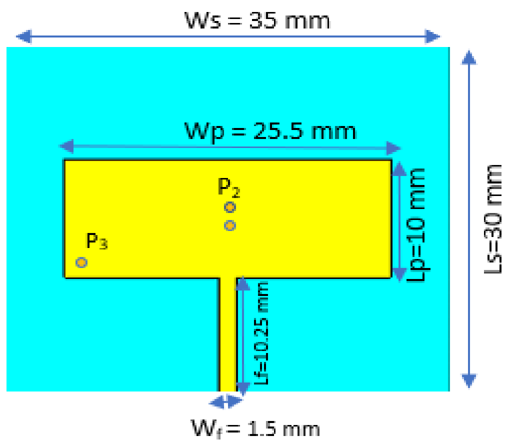

Fig. 2: Patch Antenna loaded with three(3) pins

Table 2: Parameters of Patch Antenna (shown in fig.2)

S.N.	Particulars/Parameters	Details
1.	Radius of Centre loaded pin(P_1)	0.5 mm
2.	Radius of Offset loaded pin (P_2)	0.5 mm
3.	Radius of Side loaded pin (P_3)	0.5 mm
4.	Distance of centre point of upper base of P_3 from both nearest edges of patch	2 mm
5.	Distance between the centre point of upper base of P1 and P2	1.6 mm

Simulation results for patch antenna shown in fig.1 & fig.2 using CST showns in fig.3 that the effect of pin loading is resulting in shifting the resonant frequency to lower side(i.e 2.445 GHz) with improved negative peak in S_{11}, but, the patch antenna having same dimensions of patch antenna without any pin loading resulting in resonant frequency 5.410 GHz.

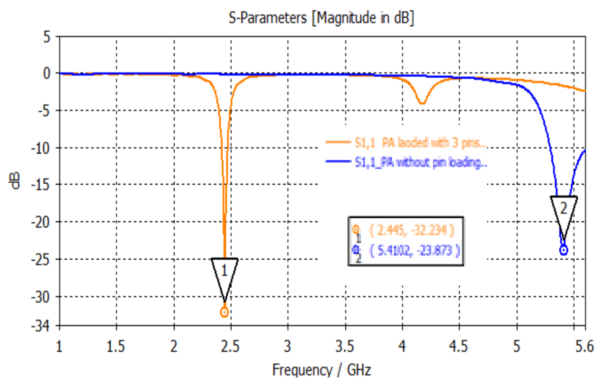

Fig. 3: Comparison of S-Parameter of patch antenna loaded with three pins and without loading of pins (as shown in Fig. 1 and Fig.2)

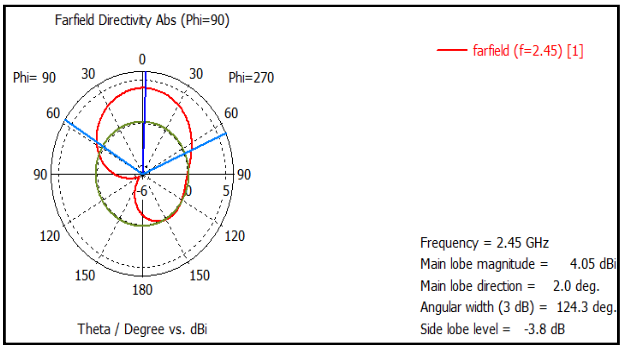

Fig. 4 (a) Radiation Pattern of patch antenna without pin loading

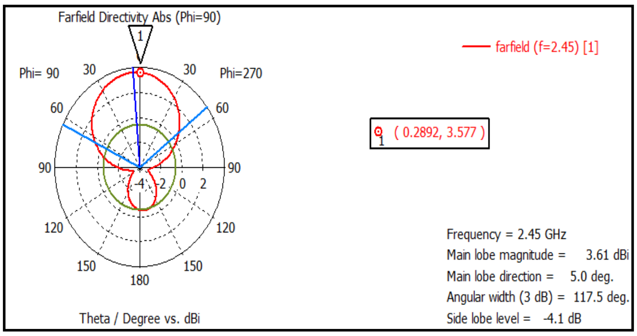

Fig. 4 (b) Radiation Pattern of patch antenna loaded with three pins

Effects on S-Parameter by loading of single/multiple pin on patch antenna have been studied in details by various designs and simulation using CST. During the designing of patch antenna using pin loading technique, various desgins have been simulated and studied with obtained results of S-paramenter. Some of the results/ designs are as under:

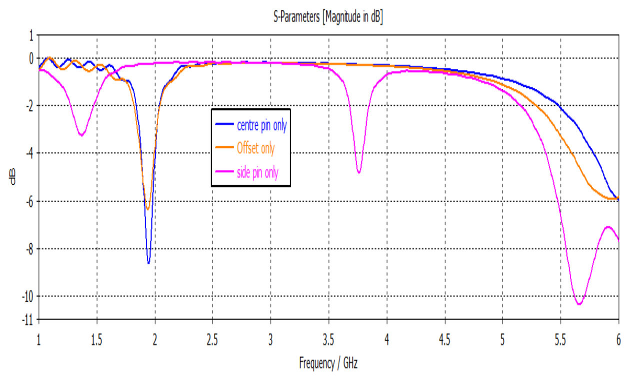

Fig. 5: Single Pin Loading effects on patch antenna (3 cases: Center, Offset & Side)

3.1 One Pin loading

The patch antenna having the same parameter, as shown in fig.1 & table-1 is used for checking the one pin loading effect, here radius of pin is 0.5 mm. Three cases were checked, as under:

3.1.1 Case I- center pin

One pin loaded in the centre of substrate, whose axis is at the vartical distance of 15 mm from both the edge (upper/lower) of substrate and horizointal distance of 17.5 mm from both the side edges of substrate.

3.1.2 Case II – offset pin

One pin loaded, whose axis is at the vertical distance(opposite to feed) of 1.6 mm from the centre of substrate, which is at the vartical distance of 16.6 mm from the lower edge(feed side) of substrate and horizointal distance of 17.5 mm from both the side edges of substrate.

3.1.3 Case III – side pin

One pin loaded, whose axis is at the vertical distance of 12.25 mm from the lower edge(feed side) of substrate and horizointal distance of 6.75 mm from nearest(left side) edge of substrate.

The result of S-Parmeter of above three cases compared and shown in fig.5, but, the obtained results shows that this antenna is not resonating with one pin loading(shorting) at any frequency between 1 to 6 GHz, therefore, 1 pin loading did not worked for designing of 2.45 GHz antenna.

3.2 Two Pin loading

Further, the same antenna(depitced in fig.1) has been designed with two pin loading technique, here radius of pin is 0.5 mm. Three cases were checked, as under:

3.2.1 Case I- center & offset pin

Center pin and offset pin dimensions and distance from edges of substrate are same, which were studied in one pin loading technique, as above. (fig.6)

3.2.2 Case II – center & side pin

Center pin and side pin dimensions and distance from edges of substrate are same, which were studied in one pin loading technique, as above. (fig.6)

3.2.3 Case III – offset & side pin

offset pin and side pin dimensions and distance from edges of substrate are same, which were studied in one pin loading technique, as above. (fig.6)

The result of S-Parmeter of above three cases compared and shown in fig.6, but, the obtained results shows that this antenna is resonating in second case with one two loading(shorting) at frequency of 2.28 GHz (between range of 1 to 6 GHz), therefore, two pin loading did not worked for designing of 2.45 GHz antenna, but given indication that it resonant frequency may be effectively and sifted with some more designs, further, one more pin may be added with case II(center & side pin).

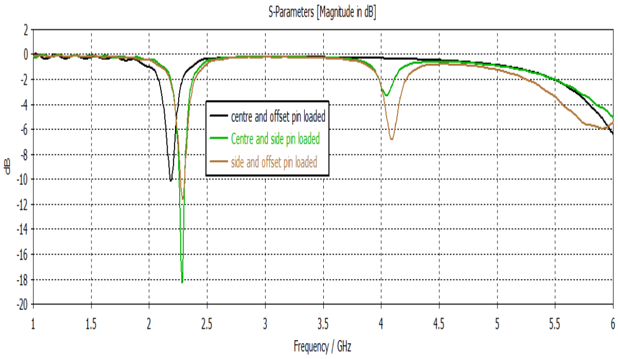

Fig. 6: Two Pin Loading effects on patch antenna(3 cases: Center & Offset, Center & Side and Side & Offset)

3.3 Three Pin loading

Further, the same antenna(depitced in fig.1) has been designed with three pin loading technique, here radius of pin is 0.5 mm. Various cases were checked, as under:

3.3.1 Case I- center, offset & side pin

Position of center, offset & side pin and distance from edges of substrate are same, which were studied in one pin loading technique, as above. (fig. 2 & 3)

3.3.2 Case II – offset, side & center(relocated, aligned with side pin) pin

Position of offset & side pin and distance from edges of substrate are same, which were studied in one pin loading technique, but, centre pin relocated from centre position to left, at horozointal distance of 6.75 mm(not aligned vertically with side pin) from left edge of substrate, vertical position kept same. (fig.7)

3.3.3 Case III – offset, side & center(relocated, at opposite to side pin) pin

Position of offset & side pin and distance from edges of substrate are same, which were studied in one pin loading technique, but, centre pin relocated from centre position to right, at horizointal distance of 25.75 mm(at opposite to side pin) from left edge of substrate and at vertical distance of 12.25 mm from lower edge(feed side)s of substrate. (fig.7)

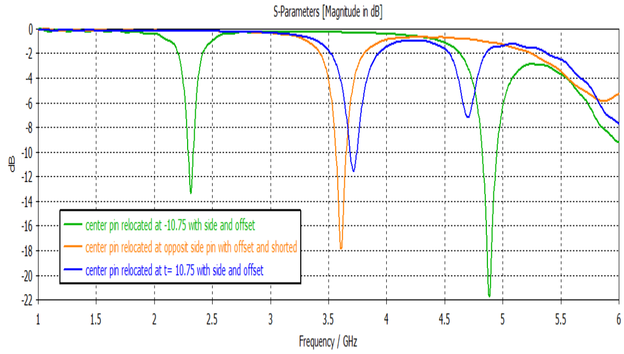

Fig. 7: Three pins Loading effects with relocation of centre pin on patch antenna(Case I- Center pin relocated at -10.75 mm from center point of substrate; Case II- Center pin relocated opposite side of shorted pin, which is 2 mm distant from nearest edges; Case III- Center pin relocated at 10.75 mm from center point of substrate)

3.3.4 Case IV – offset, side & center(relocated, not alligned with side pin) pin

Position of offset & side pin and distance from edges of substrate are same, which were studied in one pin loading technique, but, centre pin relocated from centre position to right, at horizointal distance of 25.75 mm(not aligned vertically with side pin) from left edge of substrate, vertical poistion kept same. (fig.7)

3.3.5 CaseV– offset, center & side(relocated vertically at 15/15.25 mm from feed side edge of substrate, horizointal position kept same)pin

Position of center & offset pin and distance from edges of substrate are same, which were studied in one pin loading technique, but, side pin relocated at vertical distance of 15(Case-a)/15.25(Case-b) mm from feed side edge of substrate, horizointal poistion kept same, i.e. 6.75 mm from left edge of substrate.(fig.8)

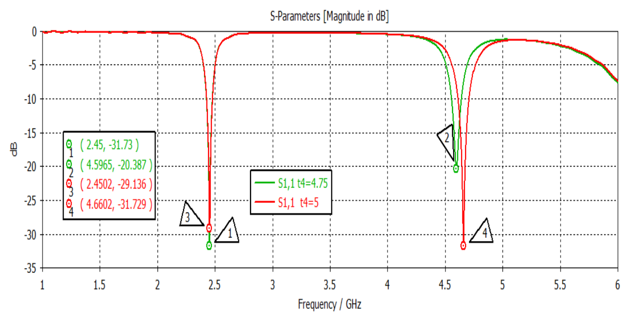

Fig. 8: Three pins Loading effects with relocation of side pin(at vertically center, which is 15 (Case : V-a)/15.25 (Case:V-b) mm distant from feed side edge of substrate, horizointal position kept same, i.e. 6.75 mm from left edge)

The result of S-Parmeter of above five cases compared and shown in fig.3, 7 & 8, the obtained results shows that this antenna is best resonating in case I & V with three pins loading(shorting) at frequency of 2.45 GHz (between range of 1 to 6 GHz), therefore, three pins loading worked for designing of 2.45 GHz antenna, and given indication that resonant frequency may be more effective with some more designs, further, one more(fourth) pin may be added & studied.

3.4 Four Pin loading

Further, the same antenna(depitced in fig.1) has been designed with four pin loading technique, here radius of pin is 0.5 mm. Various cases were checked, as under:

3.4.1 Case I- center, offset & two side pins

Position of axis of center, offset & first side pin is same, which were designed in one pin loading technique(as above) and second side pin is positioned with two different cases [Case-a: at horizointal distance of 6.75 mm from right side edge(opposite side of first side pin) of substrate and aligned with centre pin means vertical distance is 15 mm from feed side edge of substrate; Case-b: at horizointal distance of 6.75 mm from left side edge of substrate and aligned with centre pin means vertical distance is 15 mm from feed side edge of substrate] [fig. 9 (a &b)]

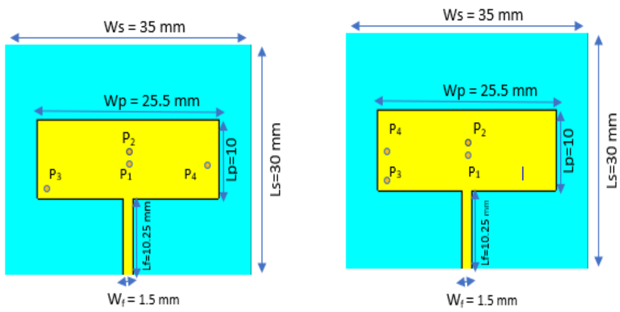

Fig. 9(a). Patch antenna loaded with Four pins

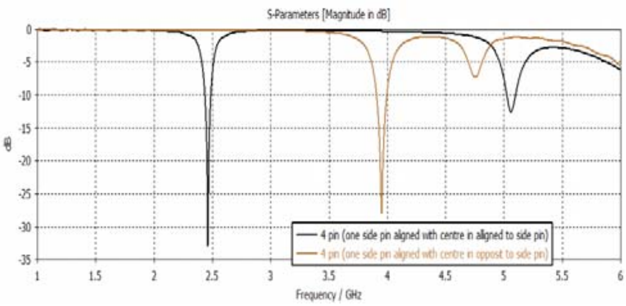

Fig. 9(b). Patch antenna loaded with Four pins[In addition of 3 pins(side, centre, offset), one more pin loaded [at 2 mm distant from nearest edge of patch, Case-a: aligned to side pin as well as center pin and Case-b: aligned to center pin but at opposite side of first side pin, as shown above]

3.4.2 Case II- center, offset & two side pins

Position of axis of center, offset & first side pin is same, which were designed in one pin loading technique and second side pin is positioned with two different cases [Case-a: at horizointal distance of 6.75 mm from left side edge of substrate (aligned vertically with first side pin) and vertical distance is 13.85 mm from feed side edge of substrate; Case-b: at horizointal distance of 6.75 mm from left side edge of substrate(vertically alligned with first side pin) and vertical distance is 14.25 mm from

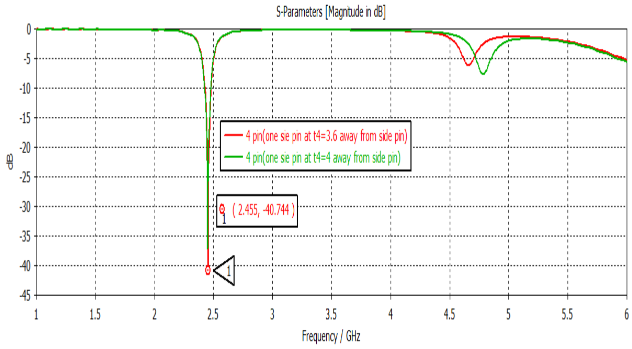

Fig. 10: Patch antenna loaded with Four pins[In addition of 3 pins(side, centre, offset), one more pin loaded

feed side edge of substrate]. In case-a, S_{11} parameter obtained, i.e. S_{11} = -40.744 DB at 2.455 GHz. (fig. 10)

3.4.3 Case III- center, offset(shifted 1.6 mm opposite to feed) & two side pins

Position of axis of center pin is same, which were designed in one pin loading technique and offset pin is shifted 1.6 mm opposite to feed side edge of substrate,i.e. at 18.2 mm from feed side edge of substrate and one side pin is at the same position, which were desined in one pin loading technique and axis of other side pin is 1.6 mm distant from the side pin, i.e. 13.85 mm from feed side edges of substrate. [fig. 11-Case(a)]

3.4.4 Case IV- center(shifted 1.6 mm opposite to feed), offset(shifted 1.6 mm opposite to feed) & two side pins

Position of axis of center pin and offset pin is shifted 1.6 mm opposite to feed side edge of substrate,i.e. at 16.6 mm & 18.2 mm from feed side edge of substrate and one side pin is at the same position, which were desined in one pin loading technique and axis of other side pin is 1.6 mm distant from the side pin, i.e. 13.85 mm from feed side edges of substrate. [fig. 11-Case(b)]

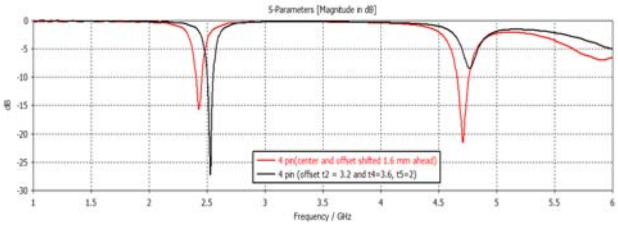

Fig. 11: Patch antenna loaded with Four pins[In addition of 3 pins(side, centre offset), one more pin loaded at 1.6 above of side pin](Case-a: offset pin shifted 3.2 mm above from centre point of substrate ; Case-b: centre & offset pin shifted 1.6 mm & 3.2 mm above from centre point of substrate)

4. CONCRETE RESULT

We proposed a new aerial, whose Resonant Frequency is 2.45 GHz, simple microstrip line is used for feeding. Use of centered, offset with side pins helps in impedance matching and results in miniaturization of a patch aerial at the lower frequency. Simultaneously, it also matches impedance and improves radiation. The shorting pin technique reduces the patch width. A compact, thin/slim, and single/dual band patch antenna is presented.

After simulation, S-Parameter obtained but these aerial are not resonating at desired frequency with incorrect positioning of pins as shown in figures 5,6,7 & 11, which shows that single/multiple pin with center and offset pin does not work but proper positioning of side pin affects the results, which leads to correct matching and desired resonant frequency.

The overall dimensions of aerial is $0.3\lambda \times 0.18\lambda \times 0.01\ \lambda$ and may be fabricated as per case results shown in fig.2 or 8 or 10 above. The aerial shows a proper resonant frequency of 2.45 GHz and the decent bandwidth of around 500 MHz.

REFERENCES

[1] G. A. Deschamps, “Msicrostrip microwave antennas,” presented at *the 3rd USAF Symp. on Antennas*, 1953.

[2] C. S. Malagisi, “Electronically scanned microstrip antenna array,” *U.S. Patent 4053895*, Oct. 11, 1977.

[3] W. F. Richards and Y. T. Lo, “Theoretical and experimental investigation of a microstrip radiator with multiple lumped linear loads,” *Electromagnetics, vol. 3*, pp. 371–385, 1983.

[4] A. Ali-Khan, W. F. Richards, and S. A. Long, “Impedance control of microstrip antennas using reactive loading,” *IEEE Trans. Antennas Propag.,* vol. 37, no. 2, pp. 247–251, Feb. 1989.

[5] W. Richards, S. Davidson, and S. Long, “Dual-band reactively loaded microstrip antenna,” *IEEE Trans. Antennas Propag.*, vol. AP-33, no. 5, pp. 556–561, May 1985.

[6] Xu Hong, Yulong Xia, Badar Muneer, Zhu Qi, “Design of Polarization-agile Antenna by Using Integrated Structure of Phase Shifter and Power Divider,” *4th Asia-Pacific Conference on Antennas and Propagation, IEEE*, pp. 523–524, July 2015.

[7] J. S. Row, “A simple impedance-matching technique for patch antennas fed by coplanar microstrip line*,” IEEE Trans. Antennas Propag.,* vol. 53, no. 10, pp. 3389–3391, Oct. 2005.

[8] A. K. Bhattacharyya, D. R. Jackson, J. T. Williams, R. Smith, “Microstrip patch designs which do not excite surface waves,” *Antennas and Propagation Society Symposium 1991 Digest., IEEE*, pp. 68–71, June 1991.

[9] X. Zhang, L. Zhu, N. Liu, D.P. Xie “Pin-loaded circularly-polarised patch antenna with sharpened gain roll-off rate and widened 3-dB axial ratio beamwidth,” *IET Microwaves, Antennas & Propagation,* Vol. 12 Iss. 8, pp. 1247-1254, June 2018.

[10] X. Zhang and L. Zhu, “Gain-enhanced patch antennas with loading of shorting pins,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 8, pp. 3310–3318, May 2016.

[11] N.-W. Liu, L. Zhu, W.-W. Choi, and X. Zhang, “Wideband shorted patch antenna under radiation of dual-resonant modes,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 6, pp. 2789–2796, Jun. 2017.

[12] N.-W. Liu, L. Zhu, and W.-W. Choi, “A differential-fed microstrip patch antenna with bandwidth enhancement under operation of TM10 and TM30 modes,” *IEEE Trans. Antennas Propag.,* vol. 65, no. 4, pp. 1607–1614, Apr. 2017.

[13] N.-W. Liu, L. Zhu, W.-W. Choi, and X. Zhang, “A low-profile aperturecoupled microstrip antenna with enhanced bandwidth under dual resonance,” *IEEE Trans. Antennas Propag.,* vol. 65, no. 3, pp. 1055–1062, Mar. 2017.

[14] R. Waterhouse, “Small microstrip patch antenna,” *Electron. Lett.*, vol. 31, no. 8, pp. 604–605, Apr. 1995.

[15] R. B. Waterhouse, S. D. Targonski, and D. M. Kokotoff, “Design and performance of small printed antennas,” *IEEE Trans. Antennas Propag.,* vol. 46, no. 11, pp. 1629–1633, Nov. 1998.

[16] R. Porath, “Theory of miniaturized shorting-post microstrip antennas,” *IEEE Trans. Antennas Propag*., vol. 48, no. 1, pp. 41–47, Jan. 2000.

[17] K. Hirasawa and M. Haneishi, Analysis, Design and Measurement of Small and Low-Profile Antennas. *Norwood, MA, USA: Artech House*, 1992.

[18] D. F. Sievenpiper et al., “Experimental validation of performance limits and design guidelines for small antennas,” *IEEE Trans. Antennas Propag*., vol. 60, no. 1, pp. 8–19, Jan. 2012.

[19] N. Amani and A. Jafargholi, “Internal uni-planar antenna for LTE/WWAN/GPS/GLONASS applications in tablet/laptop computers,” *IEEE Antennas Wireless Propag. Lett.,* vol. 14, pp. 1654–1657, 2015.

[20] A. Jafargholi and A. Jafargholi, “Miniaturisation of printed slot antennas using artificial magnetic conductors,” *IET Microw. Antenna Propag.*, vol. 12, no. 7, pp. 1054–1059, 2018.

[21] M. Aboualalaa, A. B. Abdel-Rahman, A. Allam, H. Elsadek, and R. K. Pokharel, “Design of a dual-band microstrip antenna with enhanced gain for energy harvesting applications*,” IEEE Antennas Wireless Propag. Lett.,* vol. 16, pp. 1622–1626, 2017.

[22] M. C. Kang, H. Choo, and G. Byun, “Design of a dual-band microstrip loop antenna with frequency-insensitive reactance variations for an extremely small array*,” IEEE Trans. Antennas Propag.*, vol. 65, no. 6, pp. 2865–2873, Jun. 2017.

[24]S. H. S. Esfahlani, A. Tavakoli, and P. Dehkhoda, “A compact single-layer dual-band microstrip antenna for satellite applications,” *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 931–934, 2011.

[25] Amir Jafargholi, Ali Jafargholi and and Behbod Ghalamkari, Dual-Band Slim Microstrip Patch Antennas,” *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 6818–6825, Dec, 2018.