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A Novel of Suspended Plate Compact Antenna Design for 2.4 GHz Applications

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Abstract

In wireless communication system, one of the unique challenges is the requirement for smaller and cheaper antenna design that becomes an important aspect in the deployment of wireless enabled products. To meet this challenge, we developed a simple, small, compact, low cost, and practical antenna targeted for 2.4 GHz (ISM Band) application. A detailed investigation on miniaturized microstrip planar new antenna design using a combination of proposed shorted patch and meandering method are presented. All design and simulations were done using Agilent's Advanced Design System (ADS) Momentum. To ensure the precision, verification has been done, designs were fabricated, and measurements on return loss and impedance bandwidth were performed by using FieldFox RF Analyzer. In realizing the design, a study on the surface current is conducted by simulation in order to maintain the target resonance frequency, 2.45 GHz. The designs have resulted in 86.5% and 95.5% size reduction, in comparison with a conventional rectangular patch antenna which is used as benchmark in this work. The performance of the proposed antenna is proven to be better than other existing miniaturization techniques such as the meandered line antenna (MLA) at the same size. Further improvement on radiation characteristic is also achieved by implementing Suspended Plate Antenna (SPA) approach. From the significant size reduction obtained, the concept used in this work would be suitable for cost centric products requiring small sized wireless module.

Keywords: wireless, ISM band, shorted patch and meandering

1. Introduction

Wireless feature implementations have rapidly evolved over the past decades. Driven by this rapid progress, requirement for smaller and cheaper antenna design becomes an integral factor in the deployment of wireless enabled products. It is evident that the wireless feature has become an important aspect in an introduction of any new products nowadays, regardless it being mobile or not. Manufacturers nowadays are pushing for a cheaper, smaller, simpler and more integrated way to implement wireless features (Dhande, A.P. 2012; Chen, W., 2001). One key element in wireless feature is the antenna design. Choosing the appropriate antenna design is crucial in order to optimize the wireless coverage and robustness of the transmission. The selection will also reflect to the material cost, implementation simplicity and manufacturability of the product. The size of the antenna is an important factor. Small sized is typically desirable since it is generally cheaper and flexible to be used in small products. Nevertheless the limitation of antenna size is still bounded to its relation the wavelength of the transmission (Wong, K.L., 1997; WiFi Alliance, 2013; Choi, S., 2010). Thus reductions of antenna generally will have a negative impact to the performance. In most cases, trade-off needs to be done in order to get good balance between all of these factors (Kapoor, J., 2012; Sarkar, M., 2005). Understanding in the standard requirements and a good knowledge on the variation of antenna design will greatly aid this trading off process. It is well known that the microstrip antennas have been widely used in the past decade for wireless enabled devices. This is mainly due to its attractive characteristics such as small size, low profile, low cost and good repeatability, among others. Although microstrip antennas is by conventions are physically small, the requirement to further shrinkage in size is still highly desired (Skrivervik, A. K., 2001; Vandenbosch, Y. S. 2007).

In this article, we implementing a combination of the proposed patch shorting and meandering technique for antenna size reduction. Target resonance frequency is set to 2.4 GHz. The shorted patch method realized by the theory that when an antenna is operating in the lowest mode, a virtual short circuit forms through a plane centered between the two radiating edges (Wong, K. L., 2002; Vasylchenko, A., 2008). This is achieved by implementing either a shorting wall, shorting plate or shorting pin. The proposed method in this implementation is the Planar Inverted F-Antenna (PIFA). As for meandering technique, resonant frequency is lowered by lengthening surface current paths. This is achieved by introducing disruption on the resonant-length path causing the surface current to wonder according to a longer path. The proposed method in this implementation is the Meandered Line Antenna (MLA) and the Bowtie Antenna (Wong, K. L., 1997; Guha, D., 2011).

In ensuring this work is relevant to a practical implementation of a wireless module commonly used in the industry, a few limitations are set. The following describes these limitations and its reasoning:

- Low Cost PCB material: Due to economy of scale, FR4 PCB material is significantly cheaper than others. 2 layer FR4 PCB is chosen in this work.
- Full ground plane backed: To minimize internal interference from the product itself to the wireless transmission, a full grounded antenna structure is maintained.
- 2-D structure: To simplify manufacturability and repeatability of the antenna a 2D antenna structure is proposed.

The antenna design and analysis in this work utilizes Agilent's Advanced Design System (ADS) Momentum simulator (Hansen, R., 2005), and the results were verified with actual fabricated antenna.

2. Rectangular Patch Antenna Design and Simulation

A microstrip rectangular patch antenna is one the most basic antenna configuration used for practical application. A rectangular patch antenna can be represented as an array of two radiating narrow apertures, each of width, *W* and heights, *h*, separated by a distance, *L* (Balanis, C. A., 2005), typically half wavelength of the intended resonance frequency as illustrated in Figure 1. Because the dimensions of the patch are finite along the length and width, the fields at the edges of the patch undergo fringing. Radiation will occur from this fringing field which extends the effective open circuit beyond the edge.

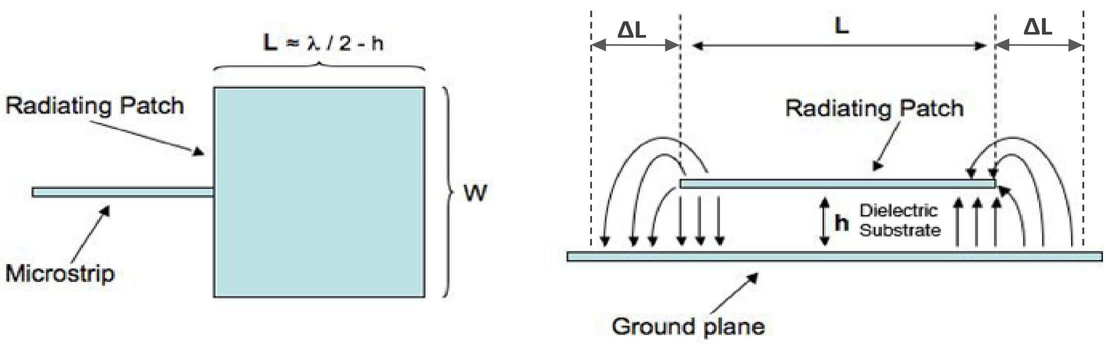


Figure 1. Rectangular patch antenna and fringing fields

Due to the fringing field, the patch is electrically slightly larger than its actual physical length. This difference between electrical and physical length is dependent on the height and dielectric constant of the PCB. This deviation is given by formula below.

$$\Delta L = \frac{0.412(h)\left(\varepsilon_{eff}(W)+0.3\right)\left(\frac{W}{h}+0.264\right)}{\left(\varepsilon_{eff}(W)-0.258\right)\left(\frac{W}{h}+0.8\right)} \tag{1}$$

Where an approximation of effective dielectric constant, ε_{eff} is given by:

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \tag{2}$$

ε_r is the substrate dielectric constant. Since the length of the patch has been extended by ΔL on each side the effective length, L_{eff} of the patch is now ($L=\lambda/2$ for dominant T<010 mode with no fringing)

$$L_{eff} = L + 2\Delta L \tag{3}$$

For the dominant TM010 mode, the resonant frequency, f_{res} is dependent on the length of the antenna itself, which usually given as,

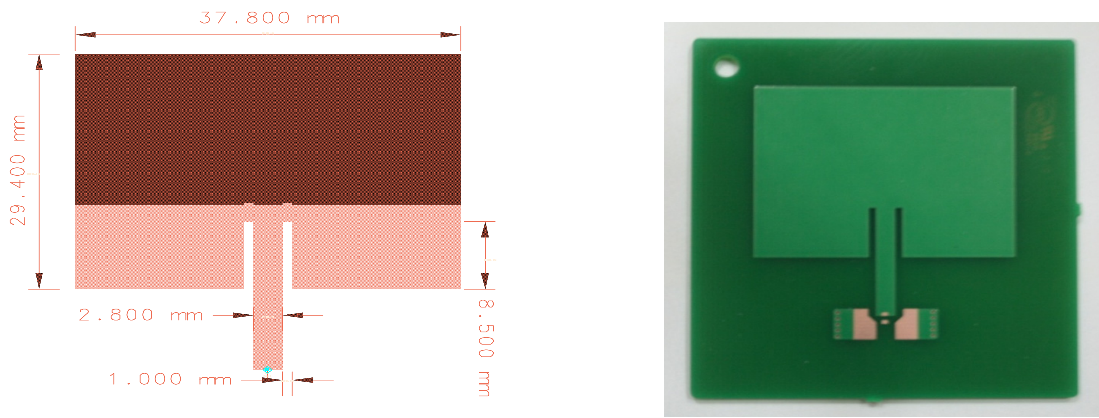
$$f_{res} = \frac{1}{2L_{eff}\sqrt{\varepsilon_{eff}}\sqrt{\mu_0\varepsilon_0}} = \frac{c}{2L\sqrt{\varepsilon_{eff}}} \tag{4}$$

Where $\mu_{o,}$ $\varepsilon_{o,}$ and c are the free space permeability, permittivity and speed of light, respectively. Then it gives the equation of patch physical length in relation of resonant frequency. For a design of an efficient radiator, the following equation solves an optimized width, W that provides good radiation efficiency, (Balanis, C. A., 2005; Milligan, T., A. 2005).

$$W = \frac{c}{2f_{res}}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{5}$$

3. Setting Benchmark and Measurement

In this work, a conventional rectangular patch antenna with inset feed is designed by using transmission-line model and simulation. This is aimed to be a benchmark for antenna miniaturization study in terms of size and radiation properties. Consistency of PCB parameters in simulation and material in fabrication is maintained for accurate comparison. The dimensions are realized in the theory (Balanis, C. A., 2005; Milligan, T., A. 2005; Fang, D., 2010) and (Wong, K. L., 2002). By solving the equation discussed is section 2, a conventional rectangular patch was designed as performance benchmark in this study. The target resonance frequency, f_{res} is 2.45GHz with center frequency of 2.4GHz ISM band. Figure 2(a) illustrates the dimension of the conventional antenna. To confirm the actual performance of the designed and simulated antenna, the design is fabricated by using actual mass producer of PCB as in Figure 2(b).



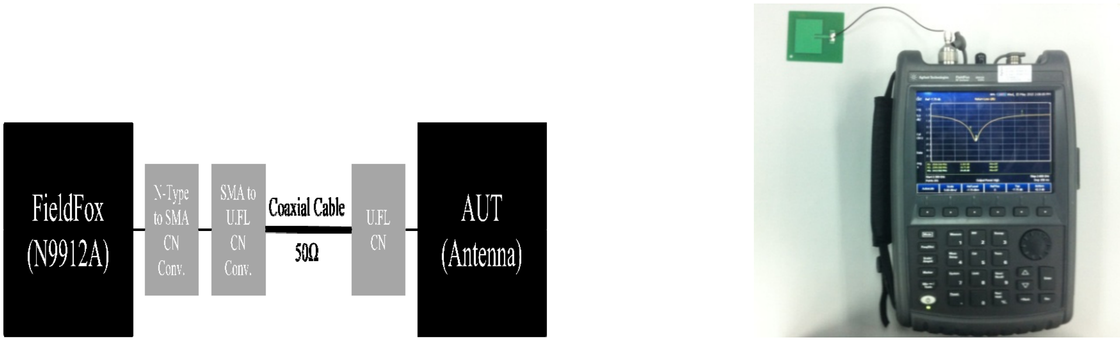
(a) Dimension (b) Fabricated

Figure 2. Conventional rectangular patch antenna

Table 1. Simulated parameters for rectangular patch antenna

Parameter	Simulated Data
Physical Size	1111.32 mm^2 (Actual)
Resonance Frequency	2.45GHz
10dB Bandwidth	2.12%
Return Loss	-34.6dB
Gain	2.42dBi
Directivity	6.45dBi

The measurement for return loss and bandwidth is done by using Agilent RF Analyzer (N9912A) as seen in Table 1 which indicates the physical and radiation characteristics of the antenna. It is a handheld RF analyzer which is reasonably agrees with a conventional bench top analyzer. For the antenna itself, a U.FL connector is soldered to the feed and it is connected to the equipment via a 50Ω coaxial cable. Figure 3 show the measurement system block diagram and hook- up.

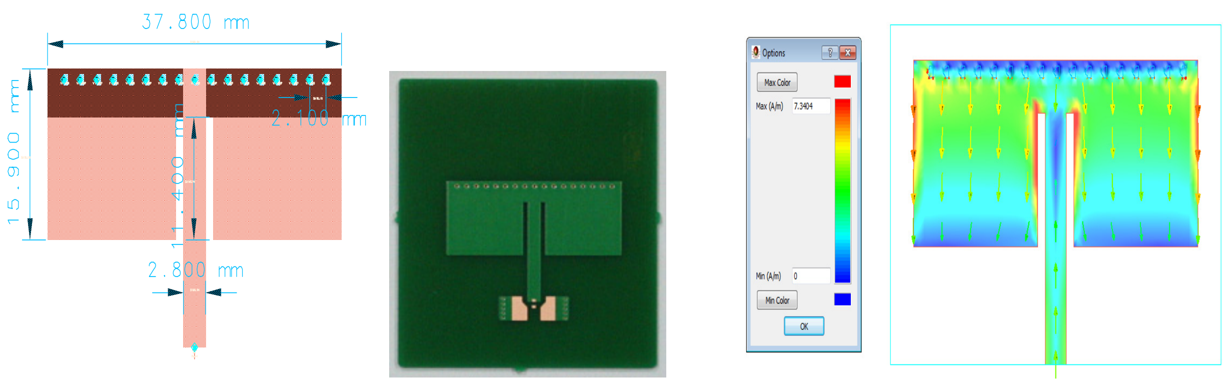


(a) Block Diagram (b) Hook-Up

Figure 3. Measurement system

4. Antenna Design and Results

A few miniaturized antenna designs were attempted in this work to observe the working principle of proposed shorted patch and meandering. The first design is based on shorting wall concept where a series of vias are added in the middle of the patch where current is set maximum and voltage is zero. The quantity and positioning were tuned to optimize the size and reduce inductive effects. The size of antenna is half of conventional patch where $L \approx \lambda/4$ as (Milligan, T., A. 2005). Figure 4(a) illustrates the actual structure of the antenna design together with the result of behavior of surface current in Figure 4(b).



(a) Structure (b) Result of surface current

Figure 4. Miniaturized antenna by shorting wall

As shown in Figure 5, in this design we obtained return loss of -29.4dB and an accurate desired resonance frequency at 2.45 GHz is achieved. This is true as long as impedance of the pin shorting remains low. With high impedance shorting path the antenna will detune and causes the resonance frequency to be shifted as (Milligan, T., A. 2005). It is also observed that the impedance bandwidth of the antenna at10dB is 1.8% which is a little reduced compared to a full patch. This reduction also causes the radiation pattern to behave differently compared to a full patch antenna. As seen in Figure 6, the radiation spreads equally above the ground plane. This result a lowers the directivity compared to a full patch antenna. The simulated directivity of this antenna is 3.61 dB. The efficiency remains the same at 40%.

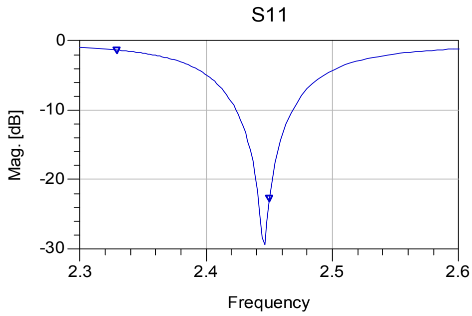


Figure 5. Return loss of miniaturized antenna by shorting wall

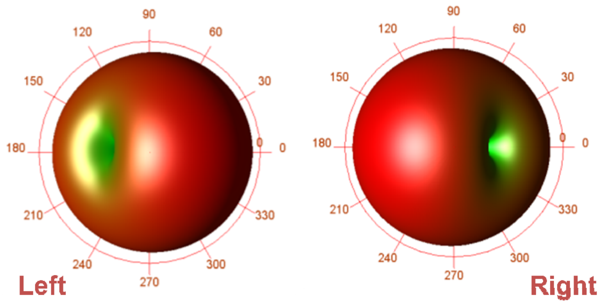


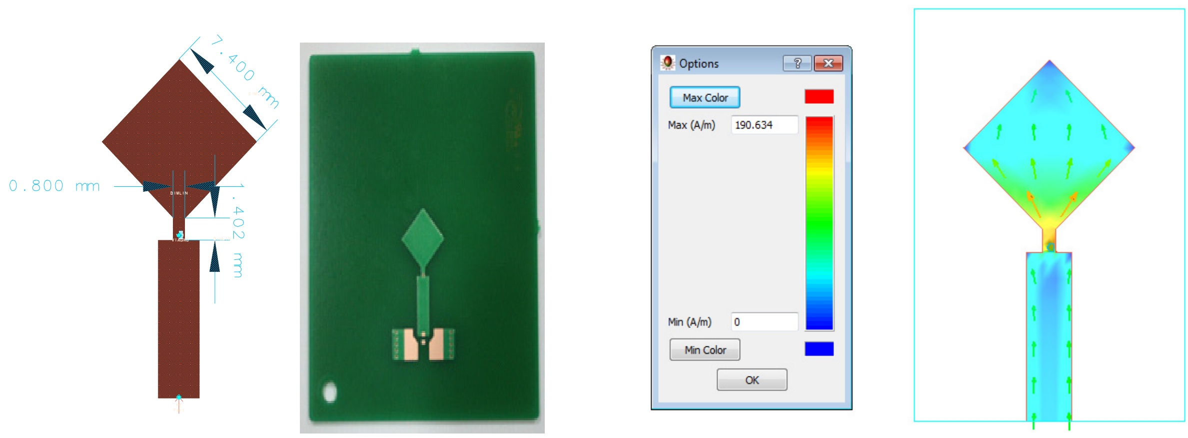
Figure 6. Simulated radiation pattern of miniaturized antenna by shorting wall

The analysis of the surface current as seen in Figure 4(b) shows that the flow of the current will maintain in direction of the feed excitation. No major changes observed in the distribution of voltage and current in comparison with the conventional patch antenna. Nevertheless, since the middle of full patch is shorted, current path will be folded to the ground. This eliminates the fringing field on the top of the antenna which in turn degrades the radiation characteristics in terms of bandwidth and gain as proved in (Milligan, T. A., 2005) and as summarized in Table 2.

Table 2. Simulated parameters for miniaturized antenna by shorting wall

Parameter	Simulated Data
Physical Size	601.02 mm^2 (Actual)
Resonance Frequency	2.45GHz
10dB Bandwidth	1.8%
Return Loss	-29.4 dB
Gain	-0.39 dB
Directivity	3.61 dB

To further miniaturize the antenna, a pin shorting concept is proposed instead of a shorting wall. A shorting pin is added at the feed of a 'diamond' shaped antenna. The shape is chosen to maximize the distance from feed to radiating edge giving size reduction of 95.1% from the benchmarked antenna. The wavelength of the antenna is now a function of length and width as proved in (Milligan, T., A. 2005). Transmission line is then truncated for impedance matching. Figure 7 illustrates the physical dimension of the antenna and simulated result of surface current.



(a) Physical dimension (b) Result of surface current

Figure 7. Miniaturized antenna by shorting pin

From the analysis of the surface current, we can see that the direction of the current now will flow along both the length and width of the patch. The distance travelled is almost equal to λ/4 as in previous design. Radiating edge remained on top of antenna where current is minimal. The detail of significant volume reduction in this design is summarized in Table 3. However the fundamental frequency is kept at 2.45 GHz in simulation. A slight deviation (~3%) compared to measurement result of fabricated board. It is a typical accuracy level as suggested in various literatures (Dhande, A.P., 2012). Figure 8 shows the return loss of the antenna followed by Table 3 which summarized the characteristics of the antenna. Figure 9 illustrates the radiation pattern for shorting pin antenna, it shows almost same characteristics as the previous half patch antenna. Radiation to the top seems almost omni-directional while the two dip on the bottom of the antenna remains. However it is observed that the gain dip is narrower compared to shorting wall designed.

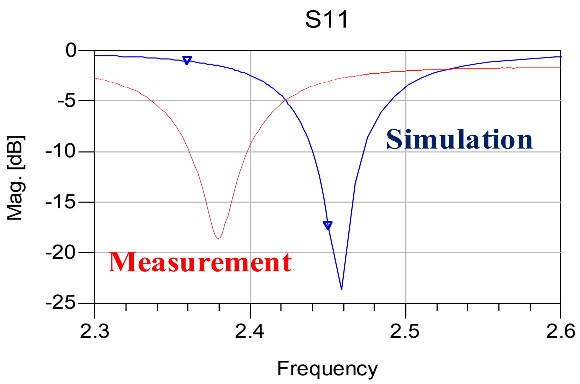


Figure 8. Simulated and measured return loss of miniaturized antenna by shorting pin

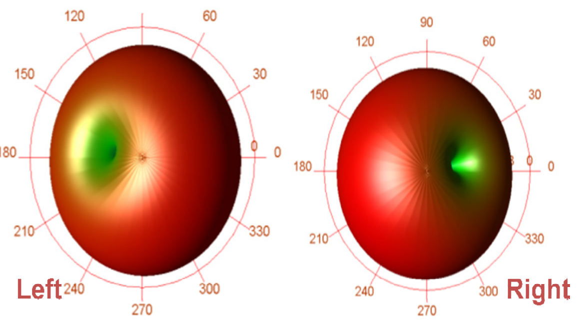


Figure 9. Radiation pattern of miniaturized antenna by shorting pin

Table 3. Simulated parameters for miniaturized antenna by shorting pin.

Parameter	Simulated Data
Physical Size	54.76 mm^2 (Actual)
Resonance Frequency	2.45GHz
10 dB Bandwidth	1.29%
Return Loss	-23.71dB
Gain	-3.99 dB
Directivity	5.48 dB

In the 3rd design, which is on miniaturized antenna by shorting wall and meandering, the behavior of meandering to a quarter-wave patch antenna is shorted by shorting wall, which antenna designed in previous antenna section is cut into half as in Figure 10. This is to simplify impedance matching and analysis. The characteristics of the surface current and resonance frequency should not be affected by this reduction. The following is an image of the antenna and the return loss data before meandering was attempted.

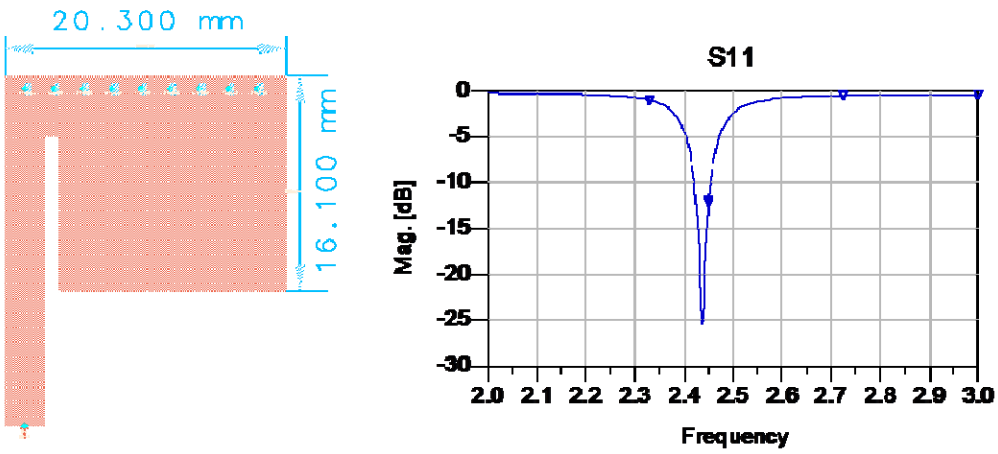


Figure 10. Antenna Structure and Characteristic before Meandering

Meandering miniaturization with slits method is implemented in this design. Based on the 2nd designed antenna, it would be assumed that the antenna wound retain 2.45GHz resonance frequency if the distance from radiation edge from the feed is kept at around 1/8 λ_0 or around 14.1mm. However, simulation results show that this is not true. Hence a study is made in order to understand the relation between the slit lengths, slit position, slit width and slit quantity to the resonance frequency and the return loss performance. The first step is to cut a single slit with length at a 2.5mm increment as in Figure 11. The vertical reference position fixed at inset y-axis position with a slit width of 0.3mm. The following data as in Table 4 was obtained from this simulation.

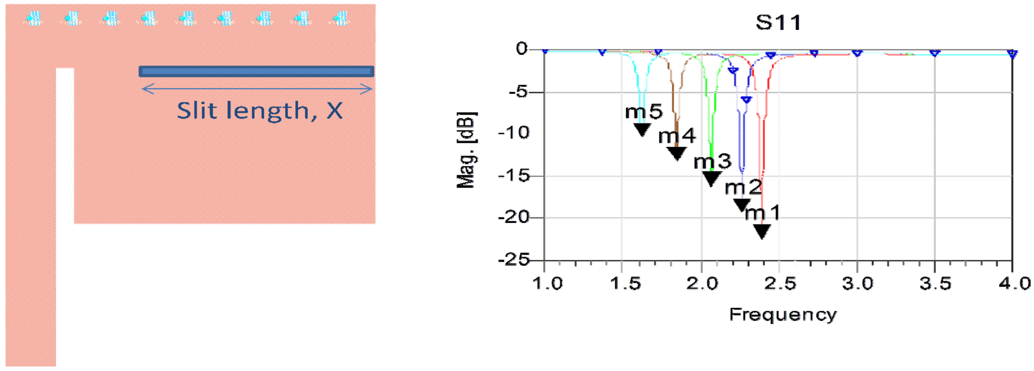


Figure 11. Resonance Frequency by Varying Slit Length

Table 4. Resonance Frequency by Varying Slit Length

Reference	Slit Length, X (mm)	Resonance Frequency (GHz)	Return Loss (dB)
	0	2.45	-25.00
m1	2.5	2.39	-22.48
m2	5	2.26	-29.40
m3	7.5	2.07	-16.30
m4	10	1.84	-13.27
m5	12.5	1.62	-10.45

It is observed that resonance frequency can be significantly reduced by increasing the slit length. The S11 simulated value also reduced gradually, however this can be improved by impedance matching. By using the final slit length, 12.5mm, the position of the meandering slit is then studied. Distance is varied in respect of the radiating edge and the S11 measurement is simulated as in Figure 12.

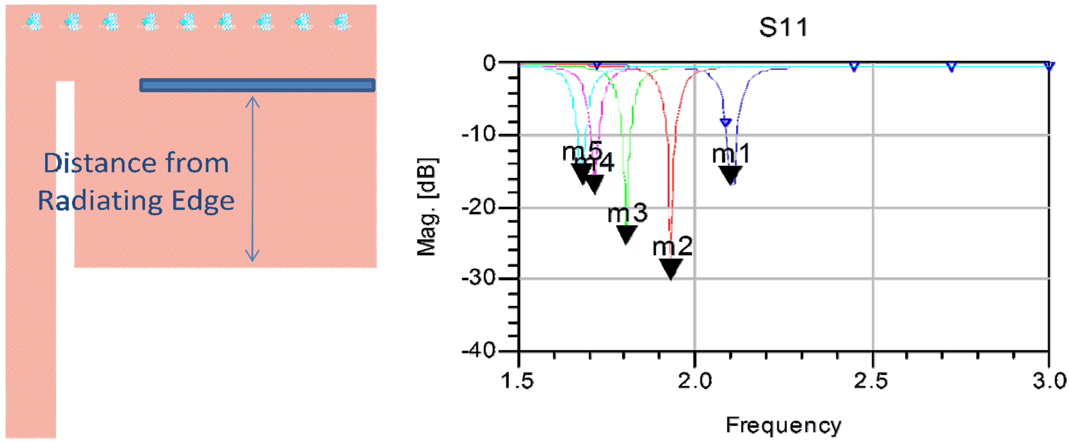


Figure 12. Resonance Frequency by Varying Slit Distance

Table 5. Resonance Frequency by Varying Slit Length

Reference	Distance from Radiating Edge (mm)	Resonance Frequency (GHz)	Return Loss (dB)
m1	3	2.10	-17.16
m2	5	1.93	-30.19
m3	7	1.81	-25.48
m4	9	1.71	-18.41
m5	11	1.68	-16.94

It is observed that resonance frequency can be significantly reduced by increasing distance of the meandered slit to the radiating edge. The S11 simulated value also reduced gradually, however this can be improved by impedance matching. By using the final slit length, 12.5mm, and distance from the radiating edge, multiple meandering slits is added to confirm the behavior. Distance is varied in respect of the radiating edge and the S11 measurement is simulated as in Figure 12. The S11 measurement is simulated as below. It is also observed that increasing the slit quantity will bring some reduction on the resonance frequency, however the impact is not significant. Varying the slit size also does not bring significant reduction on the resonance frequency. Thus, only a single slit with 0.3mm width is used. Figure 13 and Table 6 presents these observations.

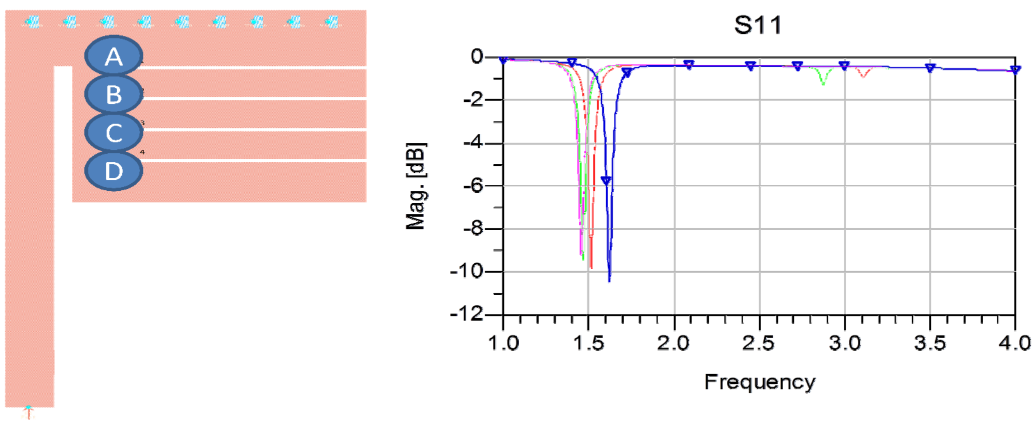
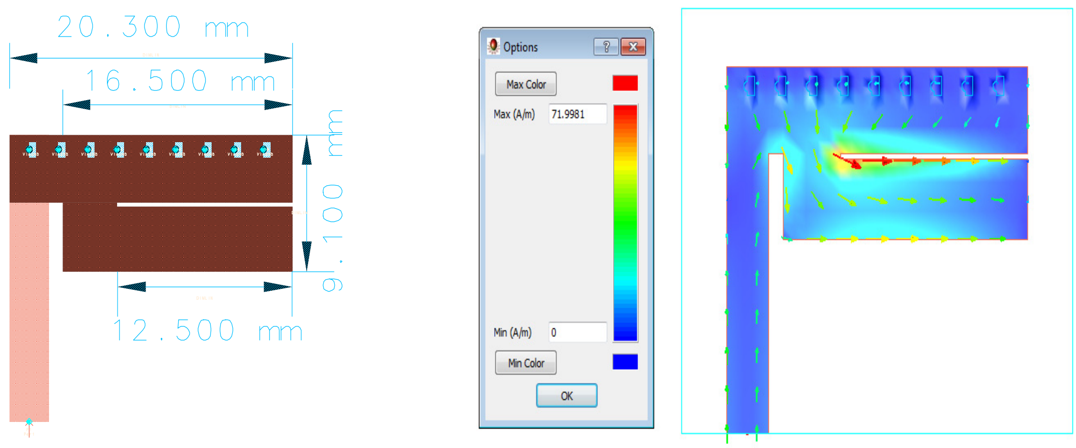


Figure 13. Resonance Frequency by Varying Slit Quantity

Table 6. Resonance Frequency by Varying Slit Quantity

Meandered Slit Quantity (mm)	Resonance Frequency (GHz)	Return Loss (dB)
1 (A)	1.62	-10.45
2 (A +B)	1.52	-9.815
3 (A+B+C)	1.47	-9.429
4(A+B+C+D)	1.46	-9.251



(a) Structure (b) Surface current

Figure 14. Miniaturized Antenna by Shorting Wall and Meandering

From the study of all meandering parameters above, the final antenna design is as Figure 14. The antenna dimension shows a size reduction of 86.5% compared to a conventional rectangular patch. The inset length is modified to match with feed impedance. Input impedance obtained under this design is 52.7 –j8.25 Ω. It is observed that surface current for this antenna greatly differs from the previous half patch or full patch design. Instead of flowing according to the direction of the feed, the current flows horizontally to the sides of antenna. Thus the fringing field or radiating edge is now on the sides of the antenna instead of bottom. Figure 15 below shows the return loss of this antenna. Resonance frequency is kept at 2.45GHz with return loss of -21.47 dB. The 10 dB bandwidth of this antenna is 1.27%, quite similar with the previous diamond shaped antenna.

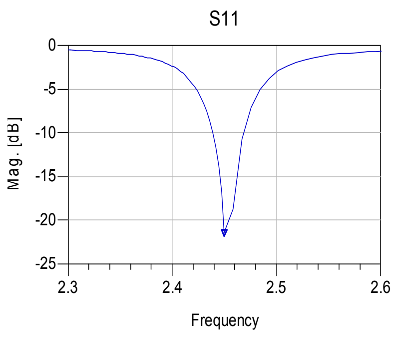


Figure 15. Return Loss of Miniaturized Antenna by Shorting Wall and Meandering

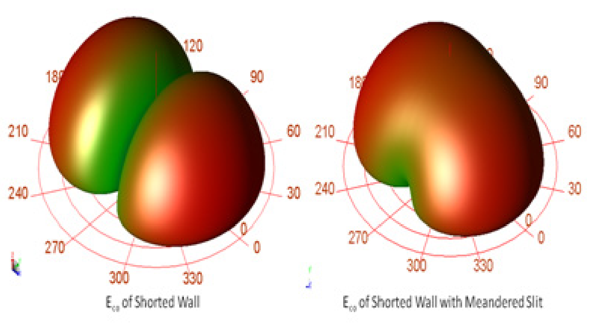


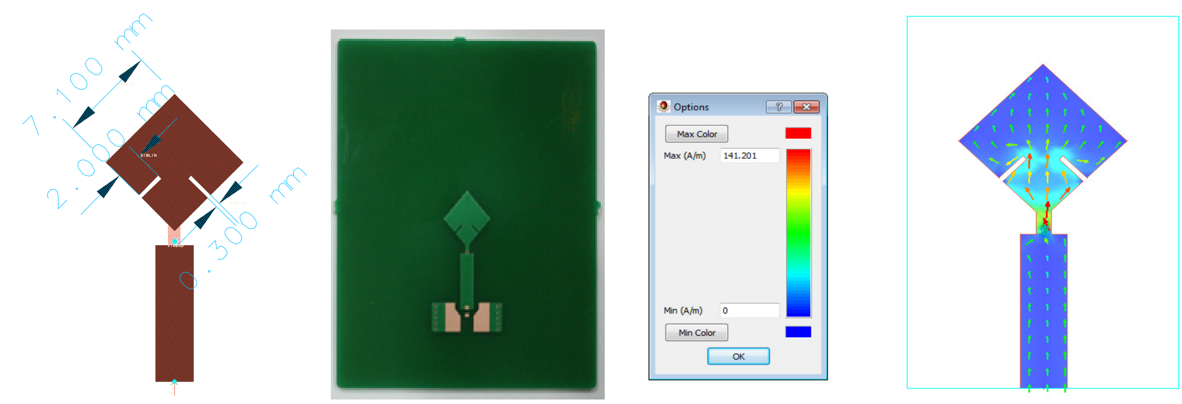
Figure 16. Co-Polarization by Adding Meandered Slit

In general the radiation property of this antenna is a little degraded than the pin shorting method implemented previously. Although the fringing field is somewhat expended compared to 2nd design, the efficiency is not improved perhaps due to the size of this antenna is bigger, and the flow of the current is not uniformed which can contribute to higher surface wave losses. The simulated directivity value is 5 dB with efficiency of 10.78%. This results a maximum gain of -4.68 dB. Nevertheless, the gain can be further improved by modifying the geometry so that the current flow is more uniformed and fringing area is maximized. As for the radiation pattern of this antenna, from the E field plot, no significant differences is observed compared to a half patch antenna. But due to the changes on the current excitation direction and radiating edge location, the polarization of the radiation is changed. This can be seen in the Figure 16 which compares the E-field Co-Polarization of the shorted wall antenna with this novel design (by adding meandered slit). The following Table 7 summarized the overall characteristics of this antenna.

Table 7. Simulated Parameters of Miniaturized Antenna by Shorting Wall and Meandering

Parameter	**Simulated Data**
Physical Size	150.15 mm^2 (Actual)
Resonance Frequency	2.45GHz
10 dB Bandwidth	1.27%
Return Loss	-21.47 dB
Gain	-4.68 dB
Directivity	5.00 dB
Efficiency	10.78 %

In the final design, meandering slits are added to the 'Miniaturized Antenna by Shorting Pin'. An analysis was conducted beforehand to obtained the optimal meandering parameters such slit length, slit distance to radiating edge and amount of slits. From the study, it can be concluded that the resonance frequency is inversely proportional to slit length, resonance frequency is inversely proportional to distance of slit length to radiating edge and slit amount do not have significant impact to resonance frequency. From the results above, optimized and practical meandering slits are added. Further size reduction of 8% from 2nd design is acquired by adding the meandering slits. Figure 17 illustrates the physical dimension of the antenna and the simulated result of surface current.



(a) Physical dimension (b) Result of surface current

Figure 17. Miniaturized antenna by shorting pin and meandering

The simulated surface current shows that the flow of the current maintains almost same characteristics as in previous design. However, the meandering slit now disturbs the surface current flow. This causes the propagation path to be lengthened and thus result in lower resonance frequency. Figure 18 shows the return loss of this antenna. Resonance frequency is kept at 2.45GHz with good return loss at -18.2 dB. The 10 dB bandwidth of this antenna is 1.27%, quite similar to the previously designed antennas. A slight reduction is also observed in radiation properties as summarized in Table 8. Figure 19 shows a radiation pattern of this antenna. From the E field plot, no significant difference is observed compared to a half patch antenna. But due to the changes on the current excitation direction and radiating edge location, the polarization of the radiation is changed, which compares the E-field co-polarization of the shorted wall antenna with this novel design, which is by adding meandered slit.

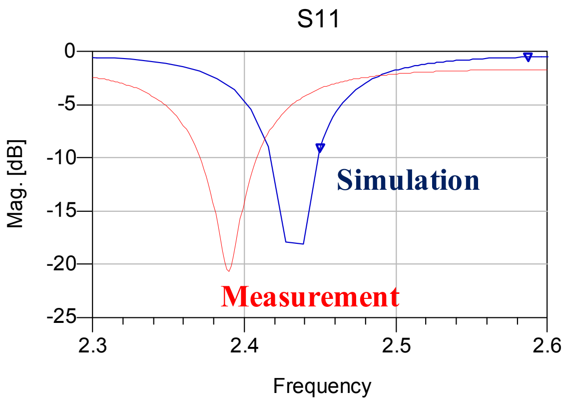


Figure 18. Simulated and measured return loss of miniaturized antenna by shorting pin and meandering

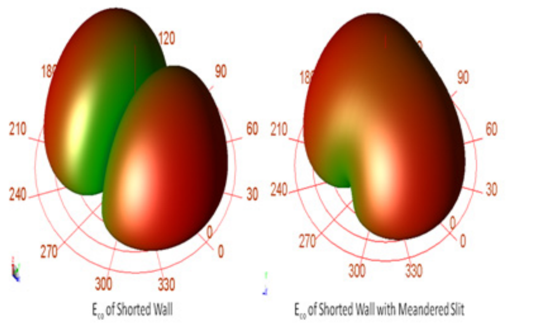


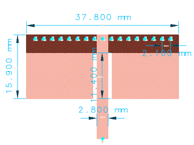
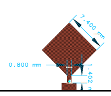
Figure 19. Comparison of co-polarization by adding meandered slit

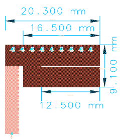
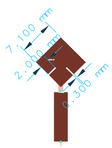
Table 8. Simulated parameters for miniaturized antenna by shorting pin and meandering.

Parameter	Simulated Data
Physical Size	50.41 mm^2 (Actual)
Resonance Frequency	2.45GHz
10 dB Bandwidth	1.27%
Return Loss	-18.2 dB
Gain	-4.37 dB
Directivity	5.5 dB

In general, all comparison shows that the actual measurement frequency data is lower than the simulated results. This is consistent with the correlation made from the reference antenna as discussed before. From the comparison it seems that the usage of vias has some impact on the simulation accuracy as summarized in 1st design and 2nd design in Table 9. From the analysis if the fabrication report, the actual measured via hole diameter is 0.6mm instead of 0.5mm used in simulation. As for the simulation software, an accurate model for via is quite difficult to make. In Momentum it uses a 3D distributed model that simulates vertical and horizontal currents. However, the 268odeling itself has its limitation in terms of substrates thickness. These entire factors can cause the degradation on the simulation accuracy. Another observation that can be made is for all the designed antennas, the impedance bandwidth is bigger than the simulated results. This suggests that perhaps the actual thickness of the substrate is larger than the simulation settings. Besides, as mentioned before, the actual dielectric constant is also slightly lower than the simulation parameter. Both of these factors could contribute to larger impedance bandwidth as realized in (Balanis, C. A., 2005; Milligan, T., A. 2005). Table 9 summarizes performance for all the designed antennas.

Table 9. Performance comparison for all designed antennas.

	Measurement Item	**Simulation Data**	**Measurement Data**	**Simulation Accuracy**
1st Design	f_{min} (GHz)	2.424	2.337	96.28%
	f_{max} (GHz)	2.467	2.393	96.91%
	f_c (GHz)	2.446	2.366	96.62%
	BW (MHz)	43	56	Δ 13
	Return Loss (dB)	-29.398	-48.593	-
	f_{min} (GHz)	2.440	2.361	96.65%
	f_{max} (GHz)	2.472	2.399	96.96%

	f_c (GHz)	2.459	2.380	96.69%
	BW (MHz)	32	38	Δ 6
	Return Loss (dB)	-23.710	-18.623	-
3rd Design	f_{min} (GHz)	2.439	2.420	99.20%
	f_{max} (GHz)	2.468	2.456	99.51%
	f_c (GHz)	2.450	2.438	99.51%
	BW (MHz)	29	36	Δ 7
	Return Loss (dB)	-21.465	-40.775	-
4th Design	f_{min} (GHz)	2.433	2.370	97.41%
	f_{max} (GHz)	2.465	2.408	97.69%
	f_c (GHz)	2.450	2.390	97.55%
	BW (MHz)	32	38	Δ 6
	Return Loss (dB)	-27.730	-20.706	-

In general, the analysis in this work has shown a good miniaturization results in respect of the benchmarked antenna size. However, the improvements on bandwidth and gain is still practically desirable for an actually usage. To do these improvements, the characteristics degradation factors needs to be attended. As discussed before, these degradation comes from the elimination of one radiating slots, and the overall reduction of the total volume of the antenna. These reductions will degrade the radiation quality factor of the antenna and thus reduces the gain and bandwidth.

In order to address the degradation imposed by the miniaturization process, a simulation on the Suspended Plate Antenna (SPA) concept is attempted. In this implementation, the radiator pattern is etched to a substrate is placed at an elevated position from the reference plane or ground. In result the thickness of the antenna will increase and air is used as part of the substrate. Since air have very low losses (Ɛr=1, tan δ=0), the overall efficiency of the antenna will improve. Surface wave will also be suppressed by using this method giving almost zero losses from surface current.

To demonstrate the implementation of SPA, the design in Figure 20 which is based on 4th designed antenna, is simulated.

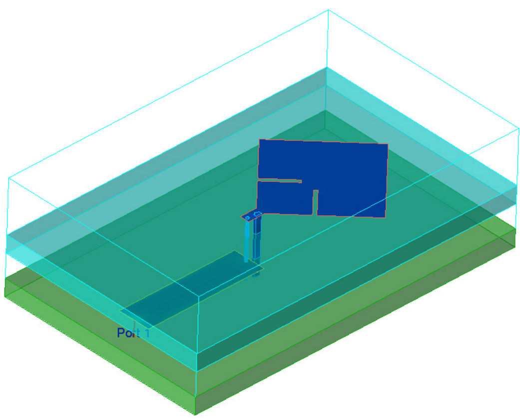


Figure 20. Proposed SPA Antenna Design

In this design, the radiator is etched on a separate board from the wireless module. This board is elevated 2 mm from the main module PCB creating an air gap. A probe feeding method needs to be implemented by using a metal pin. Since probe feeding is used, the input impedance can be controlled by modifying the distance between feed pin and shorting pin. The shape of the antenna is maintained, however minor size adjustment is needed in order to maintain the resonance frequency of 2.45GHz. Based on simulation, the bandwidth of the antenna improved to 1.8% (from 1.27% in its coplanar form). As for the efficiency and gain, it improved to 95% and 4.98 dB (from -4.37dB in its coplanar form) respectively.

5. Conclusion

A new, compact and low cost suspended plate antenna miniaturization design for 2.4GHz application has been presented. It is observed that significant size reduction from a conventional rectangular patch antenna can be achieved by implementing these proposed techniques. For this, the radiation properties such as impedance bandwidth, return loss, gain, directivity, efficiency, radiation pattern and surface current was discussed and analyzed. Improvements were also made based on best efforts to minimize the degradation. Two novel antenna designs by using pin/wall shorting and meandering technique for the purpose of antenna miniaturization in compliance of the limitations set in the earlier stage. Antenna designed were resulted in 95.1% and 95.5% size reduction respectively compared to benchmarked design while maintaining desired resonance frequency of 2.45GHz. For a typical 2L FR4 material PCB, the antenna designed will result in around USD 0.10 BOM cost reduction of the antenna or module. In mass production this can generate significant additional revenue. Smaller and extraordinary antenna designs are also useful for other smaller devices or products that can accommodate these proposed antennas thus supporting wireless features seamlessly in the world.

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