Progress In Electromagnetics Research Letters, Vol. 39, 181–198, 2013

TRUNCATED RHOMBUS-LIKE SLOTTED ANTENNAS WITH APERTURE COUPLING TECHNIQUE

Suzilawati Muhamud-Kayat[1, *], Mohd Tarmizi Ali[1], Mohd Khairul Mohd Salleh[1], Mohd Hazri Mohd Rusli[2], Nurulazlina Ramli[1], and Hafiza Alias[1]

[1]Antenna Research Group (ARG), Microwave Technology Center (MTC), Faculty of Electrical Engineering, Universiti Teknologi MARA (UiTM), Shah Alam, Selangor 40000, Malaysia

[2]Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM), Shah Alam, Selangor 40000, Malaysia

Abstract—This paper presents two novel designs of truncated rhombus-like slotted antenna (TRLSA) based on aperture-coupled feeding technique. In conventional antennas, different patch dimensions are required to accommodate different frequencies which normally result in bigger antenna structures. Therefore, this paper proposes a unique structure of 'zig-zag' slot embedded on two different antennas to achieve two different resonant frequencies but of the same patch dimensions. An analysis on design transformation which includes comparative simulation results of two reference antennas and TRLSAs has also been presented to provide better understanding on the design concept. CST Microwave Studio software has been used for design simulations and optimizations. The simulation and measurement results of TRLSAs are also presented. The results confirm that the antennas can operate at two different frequencies, 5.3 GHz and 5.8 GHz with the same patch dimensions by integrating the 'zig-zag' slot at two different orientations in x- and y-axis respectively. Hence, size reduction is achieved for lower frequency patch which gives a great advantage for future development of a frequency reconfigurable antenna in an array configuration.

Received 17 February 2013, Accepted 22 April 2013, Scheduled 28 April 2013
* Corresponding author: Suzilawati Muhamud-Kayat (suzilawati.mkayat@yahoo.com).

1. INTRODUCTION

The rapid development in modern wireless communication systems in recent years has resulted in the requirement of multi-functional devices in compact size including antennas. Microstrip patch antennas are preferred for many applications because of the compact structure, lightweight and ease of manufacturability. However, the main disadvantage is their radiation performance including narrow bandwidth [1].

Various techniques have been applied to overcome this problem including the use of aperture coupler technique [2] or by modifying the patch shape [3]. Both offer more degrees of freedom in antenna designing. The aperture coupled microstrip antenna has the flexibility in design parameters due to various shapes of aperture slot and patch which gives more freedom in antenna design. There are also various types of suitable substrate material that can be chosen with different dielectric constant and dielectric loss tangent values to improve antenna performance [4, 5]. The bandwidth can be improved by increasing the electrical thickness of the substrate [6]. However, the main drawback is that a multi-layer substrate structure with the coupling slot on the ground plane can result in coupled surface-wave modes which can lead to radiation-pattern distortion and radiation efficiency reduction [7].

Modification on patch shape can be done by integrating the microstrip patch with one slot or more of various shapes and sizes. Depending on the shapes and sizes of the slot, it would totally change the initial design of a rectangular patch into a different shape such as E-shape, and H-shape [8–10]. Truncating the corners of radiating patch is one of the popular techniques for bandwidth enhancement, besides it reduces the patch size and makes it compact [10]. A slot can be embedded on the radiating patch to achieve dual or triple band operation. However, depending on the slot shape, the band operation can be converted from triple band to dual band or single band. Two resonant frequencies were obtained in [11] using V-slotted patch. Half U-slot patch resulted in dual and triple band [12, 13].

Theoretically, the size of an antenna is inversely proportional to the operating frequency [14]. A small antenna patch accommodates high frequency and vice versa. Similar work was done by [15], a study on a reconfigurable array patch antenna using switchable feed network. However, the patch size is different in accordance to the operating frequency. Therefore, there is a waste in term of spacing between the antenna elements. As a result, the overall size of the array antenna can be considered big and bulky.

In this paper, we focus on the shape of the radiating patch so that the proposed antennas are able to operate at two different frequencies using the same patch dimensions. A new design of rhombus-like shaped microstrip patch antenna with four truncated edges is introduced. A unique 'zig-zag' slot is embedded on the radiating patch of each antenna to achieve two different frequencies. This paper includes a comparative analysis on the effects of several antenna parameters from the base antenna of rhombus-shape. Both simulation and measurement results are also reported. The proposed antenna is suitable for the applications in microwave communication systems operating at IEEE 802.11a (5.15–5.35 GHz), HIPERLAN/2 (5.725–5.825 GHz).

2. ANTENNA STRUCTURES

2.1. Design Procedures

The geometrical structures of the proposed truncated rhombus-like slotted antenna (TRLSA) are based on basic design formulas of a conventional rectangular microstrip antenna [16, 17]. Two different patch sizes are needed to achieve two different operating frequencies, 5.3 GHz during F_1 mode and 5.8 GHz during F_2 mode. The design parameters are calculated using the equations as follows:

The width of the patch:

$$W_p = \frac{c[1/\sqrt{(\varepsilon_r + 1)/2}\,]}{2f_o} \tag{1}$$

The length of the patch:

$$L_p = \frac{c}{2f_o\sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{2}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12h/W_p}} \tag{3}$$

$$\Delta L = 0.412h\frac{(\varepsilon_{reff} + 0.300)\left(\frac{W_p}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W_p}{h} + 0.800\right)} \tag{4}$$

The width of the substrate, W_g;

$$W_g = 6h + W_p \tag{5}$$

The length of the substrate, L_g;

$$L_g = 6h + L \tag{6}$$

The width of transmission line, W_f

$$W_f = \exp\left(\frac{Zc(\varepsilon_r + 1.41)}{87}\right)\frac{0.8}{5.98h} \tag{7}$$

where

f_o = Operating frequency (GHz); c = Speed of light (m/s)
h = Substrate thickness (mm);
Z_c = Impedance of transmission line (Ω)
ε_r = Relative dielectric constant; ε_{reff} = Effective dielectric constant

Next, we designed a rhombus patch antenna as depicted in Figure 1(a) based on the calculation values obtained from Equations (1)–(7). The first step of the design was to optimize the patch length, L_p and width, W_p so that it becomes a basic square patch. Then the square patch is transformed into a rhombus by rotating the square patch to 45°. As illustrated in Figure 1(b) from the rhombus shaped antenna design, the radiating patch is truncated at its four edges ($L_t * W_t$). It is expected that by truncating the edges the antenna becomes compact in its size as compared to that of a conventional shape [10]. These two antenna designs will act as reference. Note that, the patch dimensions of each design vary according to its operating frequencies. Each design requires two different patch sizes in order to operate at two different frequencies. Finally, to design a TRLSA the truncated-edge antenna is loaded with a unique 'zig-zag' slot. As shown in Figure 2, this final design structures will be further explained in next section.

Each of the antennas employs aperture coupler as its feeding technique. The radiating patch is fed by a 50 ohm transmission line

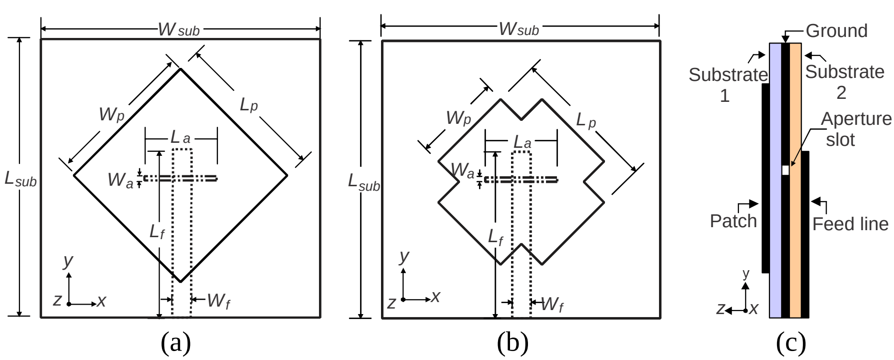


Figure 1. Initial designs. (a) Rhombus shape (top view). (b) Rhombus shape with truncated edges (top view). (c) Side view of the design structure.

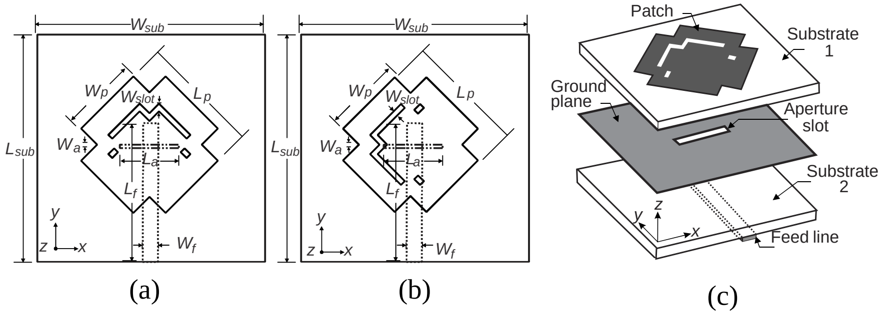


Figure 2. The geometry of TRLSAs. (a) $TRLSA_1$ at F_1 mode. (b) $TRLSA_2$ at F_2 mode. (c) 3D view of TRLSA.

$(L_f * W_f)$ via a small aperture slot embedded on the ground plane (Figures 1(a)–(b)). As depicted in Figure 1(c), the ground plane $(L_g * W_g)$ is located in between two substrates $(L_{sub} * W_{sub})$. The two substrates and the ground plane are of the same dimensions $(L_{sub} = W_{sub} = L_g = W_g)$. The width, W_a and length, L_a of the aperture slot and its position have been optimized to obtain the desired bandwidth and to control the radiation pattern. It is suggested that aperture slot should be placed at the centre of the radiating patch to increase coupling level [18]. The same parameters of aperture slot, ground plane and substrates have been used throughout the design of reference antennas and TRLSAs

2.2. Design Structures of Truncated Rhombus-like Slotted Antenna

Figure 2 shows the design structures of truncated rhombus-like slotted antenna (TRLSA). The proposed antennas have a unique rhombus-like shaped patch with four truncated edges and a 'zig-zag' slot embedded on the radiating patch. The resonant frequencies of the antennas can be affected by different orientations of the patch slot [19]. Thus, the unique 'zig-zag' slot is embedded at two different orientations in x- and y-axis so that the proposed antennas can operate at two different frequencies by using the same patch size. The main reason of having this configuration is that the designs can be implemented for future development of a frequency reconfigurable antenna in an array configuration whereby the size of the radiating patch is maintained regardless of its frequency [21]. The size of the patch at lower frequency can be reduced which normally requires bigger patch size. Hence, the overall structure of the array antenna can be reduced which makes the antenna more compact. In this study, the proposed antennas are expected to operate at two different frequencies, 5.3 GHz and 5.8 GHz during F_1 mode and F_2 mode respectively. As shown in Figures 2(a)–(b), the 'zig-zag' slot with a width, W_{slot} of 0.5 mm is located at x-axis for F_1 mode and y-axis for F_2 mode.

Two different materials have been used for the substrates (Figure 2(c)). RT/Duroid 5880 with a lower permittivity ($\varepsilon_r = 2.2$) and thickness, h_1 of 0.787 mm is chosen for upper substrate (substrate 1) to produce loosely bound fringing fields, yielding better radiation. On the other hand, the lower substrate (substrate 2) is made of FR-4 board with higher permittivity ($\varepsilon_r = 4.7$) and thickness, h_2 of 0.8 mm for tightly coupled fields that produce less spurious radiation. FR-4 is a low cost material with good reproducibility [6] but high loss which may results in low gain. Etching slots in the ground plane can help improve the low gain (efficiency) [20]. Therefore, the proposed antenna employs aperture coupler as its feeding technique whereby a small aperture slot is etched on the ground plane which is located in between of the two substrates. The ground plane serves as a very effective shield between the radiating patch and the feed. Thus, unwanted effects such as spurious feed radiation can be reduced. The design parameters of the proposed antenna are tabulated in Table 1.

Table 1. Parameters and dimensions of the proposed antennas.

Parameters	Substrate (L_{sub}, W_{sub})	Patch (L_p, W_p)	Truncated Corner (L_t, W_t)	Aperture Slot (L_{slot}, W_{slot})	Feed line (L_f, W_f)
Length (mm)	30	15.5	3.0	7.75	18.0
Width (mm)	30	9.6	3.0	0.48	2.0

3. ANALYSIS OF DESIGN TRANSFORMATION

In this section, an analysis on design transformation of a conventional rhombus shape to a unique shape of TRLSA is presented. Theoretically, to design a microstrip patch antenna a smaller patch is required for higher frequency and vice versa [14]. Therefore, two different patch sizes are needed in order the antennas to operate at two different frequencies during F_1 mode and F_2 mode respectively. However, by integrating a unique 'zig-zag' slot on the patch at two different orientations in x- and y-axis, two different frequencies can be achieved by using the same patch size. In other words, if the slot is integrated at x-axis, the antenna will operate at F_1 mode. On the other hand, the antenna of the same patch size will operate at F_2 mode when the slot is at y-axis. The effects of several parameters has been analysed to show how the proposed design are transformed from a conventional rhombus shape. Next, the performance of each antenna will be compared and analysed.

3.1. Parametric Analysis

3.1.1. Case 1: Effects of Patch Width, W_p and Patch Length, L_p

In this case we investigated the effect of having the same patch width, W_p and patch length, L_p on return loss and resonant frequency. The antenna design is referred as rhombus-shaped antenna illustrated in Figure 1(a). As depicted in Figure 3, it is clearly shown that the patch size has significant effect on return loss and resonant frequency. Smaller patch yields higher frequency and vice versa. The size of the antenna is $L_p = W_p = 16.5$ mm when operating at 5.24 GHz (F_1 mode) and $L_p = W_p = 14.5$ mm when operating at 5.81 GHz (F_2 mode). The difference in excitation of each resonant frequency is approximately 3 GHz.

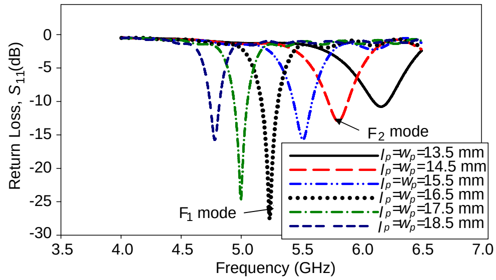


Figure 3. The effects on return loss and resonant frequency due to the change of L_p and W_p [$L_p = W_p$].

3.1.2. Case 2: Effects of Truncated Edges

The effects of the truncated edges have been analyzed when designing Figure 1(b). The area of the truncated edge ($L_t * W_t$) can also be considered using the patch length, L_p and width, W_p with one of the parameters being maintained. From the result in case 1, $W_p = 16.5$ mm is chosen so that the antenna is expected to operate at F_2 mode

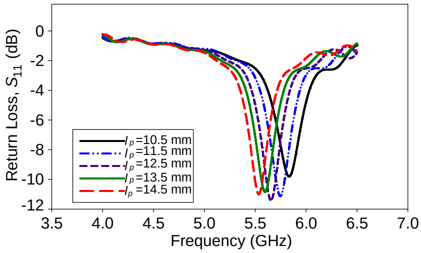


Figure 4. The effect on return loss due to the change of L_p [$W_p = 16.5\,\text{mm}$].

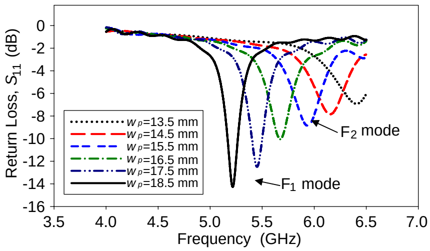


Figure 5. The effect on return loss due to the change of W_p [$L_p = 10.5\,\text{mm}$].

of higher frequency. As shown in Figure 4, only a small frequency shift can be seen when L_p is increased from 10.5 mm to 14.5 mm at $W_p = 16.5\,\text{mm}$. The best result for the antena to operate at F_2 mode is when $L_p = 10.5\,\text{mm}$. Next, the effect on the return loss has been analyzed by changing the value of W_p from 13.5 mm to 18.5 mm and the value of L_p is maintained at 10.5 mm. As shown in Figure 5, there is a moderate increment in frequency shift when the value of W_p decreases, but the value of return loss drops significantly. The antenna operates at two different frequencies, F_1 mode and F_2 mode when $W_p = 18.5\,\text{mm}$ and $W_p = 16.5\,\text{mm}$ while L_p is maintained at 10.5 mm. In this case 2, the width or length of the patch is relative to the area of the truncated edges. Bigger W_p or L_p results in bigger area of radiating patch elements but smaller area of the truncated edges.

3.1.3. Case 3: Effects of 'Zig-zag' Slot

In this case 3, the effects of the 'zig-zag' slot which is embedded on the radiating patch have been analysed. Different orientations in x- and y-axis resulted in two different frequency modes, F_1 and F_2 respectively. As depicted in Figure 6(a), when the slot is located at x-axis, significant changes in return loss and frequency can be seen when the width of the 'zig-zag' slot, W_{slot} is varied from 0.5 mm to 2.0 mm. However, only a slight shift can be seen during F_2 mode when the slot is located at y-axis (Figure 6(b)). To further improve the magnitude of return loss during F_2 mode, the length of the feed line, $L_f = d$ is varied accordingly so as to maintain the same patch size. The best result for F_1 mode is when $L_f = 18\,\text{mm}$ which is the same with the initial length. For F_2 mode, the length of the feed line needs to be shorten, $L_f = 16.8\,\text{mm}$ to obtain the best result. Both results are shown in Figures 7(a) and (b) respectively with the same slot width, $W_{slot} = 1.0\,\text{mm}$.

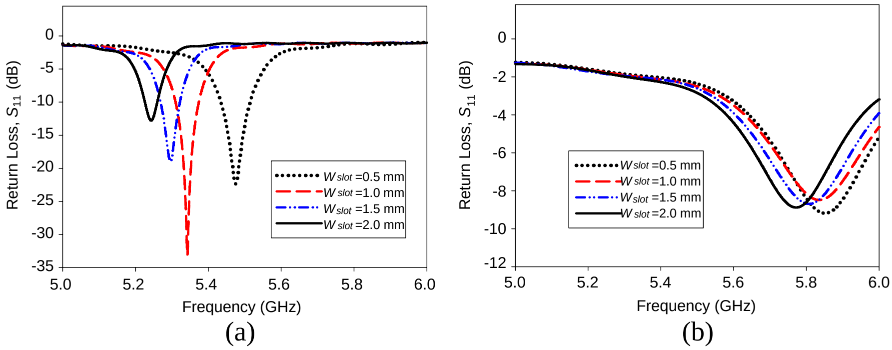


Figure 6. The effect on return loss due to the change of W_{slot}. (a) During F_1 mode. (b) During F_2 mode.

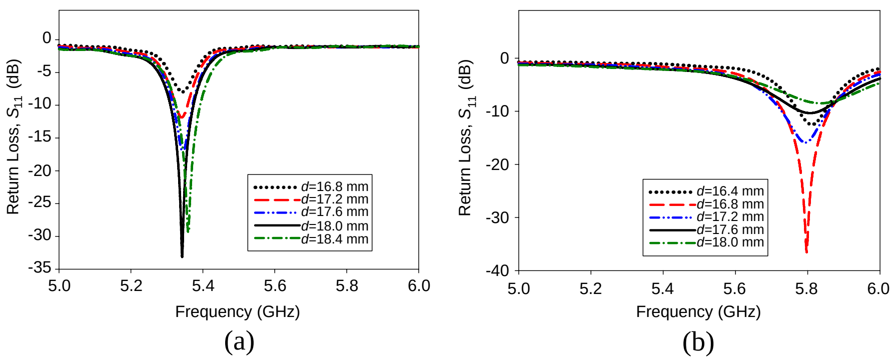


Figure 7. The effect on return loss due to the change of L_f $[L_f = d]$. (a) During F_1 mode. (b) During F_2 mode.

Surface current distributions of the proposed TRLSA at each layer during F_1 mode and F_2 mode are shown in Figure 8 and Figure 9 respectively. The arrow shows current flow along radiating patch, ground plane and feed line of each frequency mode. During F_1 mode when the 'zig-zag' slot is oriented at x-axis, the magnitude of surface current at each layer is higher than during F_2 mode. However, as shown in Figure 9(a) the current seems to be uniformly distributed along the 'zig-zag' slot at the radiating patch during F_2 mode when the 'zig-zag' slot is oriented at y-axis. By introducing a 'zig-zag' slot at different orientations, the path of surface current can be controlled. Hence, the distributions of surface current for the resonance at two different frequency modes, F_1 and F_2 are altered based on the orientations of the 'zig-zag' slot in x- and y-axis accordingly.

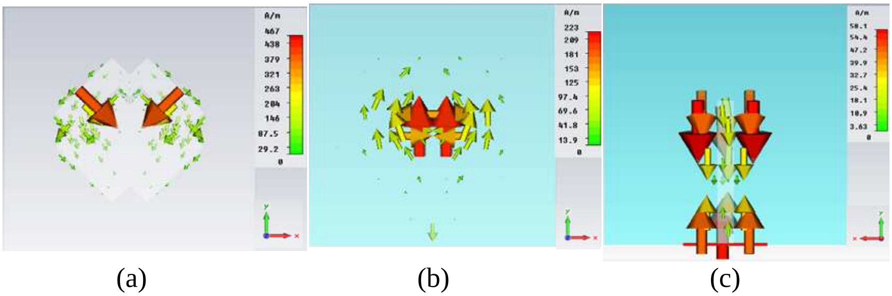


Figure 8. Surface current distributions at each layer during F_1 mode. (a) Radiating patch. (b) Aperture slot at the ground plane. (c) Feed line.

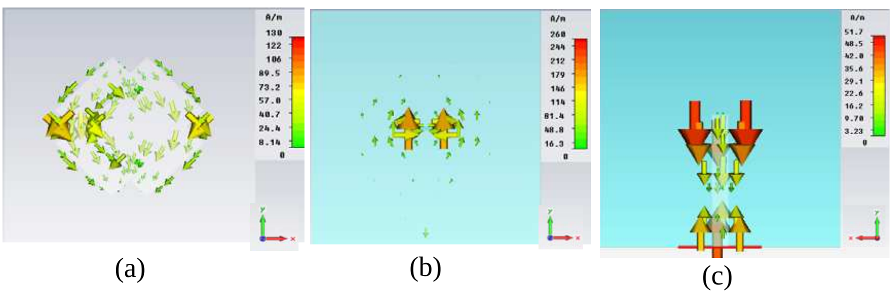
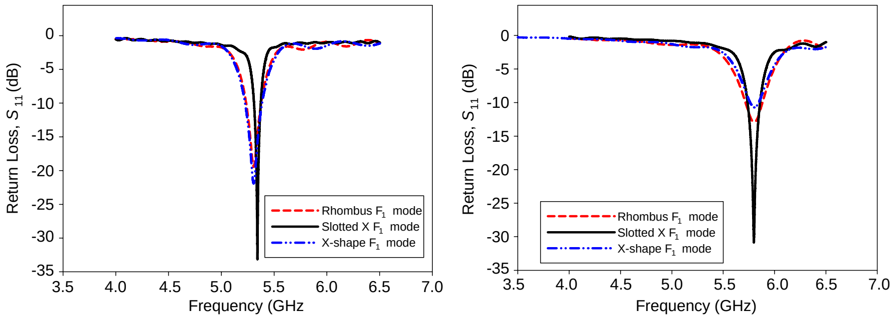


Figure 9. Surface current distributions at each layer during F_2 mode. (a) Radiating patch. (b) Aperture slot at the ground plane. (c) Feed line.

3.2. Comparative Analysis

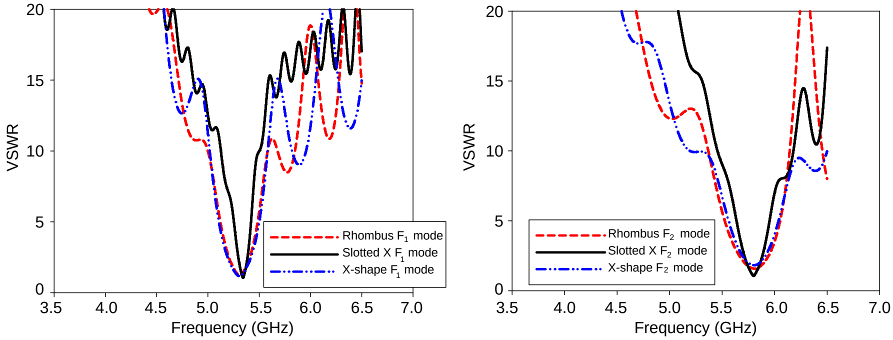
A comparative analysis has been carried out in order to analyze and compare the performance of the reference antennas with the proposed TRLSA at two different frequency modes (F_1 mode and F_2 mode). The reference antennas are denoted as 'Rhombus' and 'X-shape', while the proposed TRLSA is referred as 'Slotted X'.

Figure 10 shows the comparison of simulated return losses and bandwidth for both reference antennas and the proposed TRLSA at two different frequencies, 5.3 GHz and 5.8 GHz during F_1 mode and F_2 mode respectively. The proposed TRLSA has better return loss as compared to the reference antennas for both frequency modes. A significant difference can be seen at the bandwidth of TRLSA during F_1 mode whereby it is approximately half less than of the reference antennas.



(a) (b)

Figure 10. Comparison of simulated return losses during (a) F_1 mode, (b) F_2 mode.



(a) (b)

Figure 11. Comparison of simulated VSWR values during (a) F_1 mode, (b) F_2 mode.

As depicted in Figure 11, the reference antennas and TRLSA have similar voltage standing wave ratio (VSWR) values during F_1 mode. However, during F_2 mode, the VSWR value of TRLSA is the lowest as compared with of the reference antennas. The VSWR values are below 2 at both frequency modes. The value of VSWR indicates how well an antenna is matched to the cable impedance where the reflection, $|\Gamma| = 0$. This means that all power is transmitted to the antenna and there is no reflection. Although the optimal value of VSWR is 1, it must be lower than 2 so that the antenna yields a return loss of less than -10 dB [15]. Figure 12 shows the comparison of simulated gains during F_1 and F_2 modes. The gain value is referred as phi gain, at phi $= 0$. The results indicate that the proposed TRLSAs have the highest

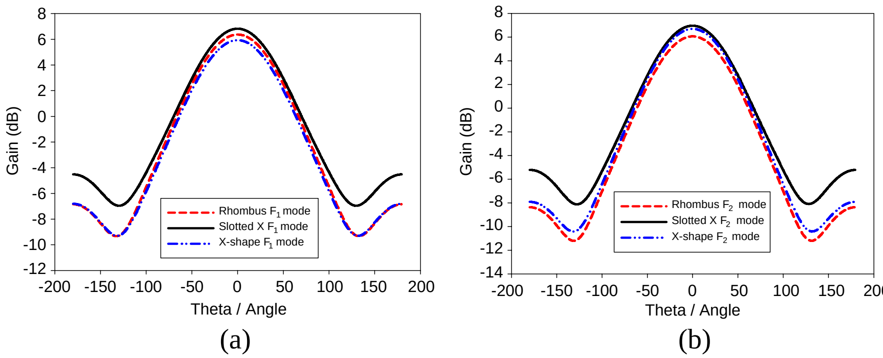


Figure 12. Comparison of simulated gains (phi = 0) during (a) F_1 mode, (b) F_2 mode.

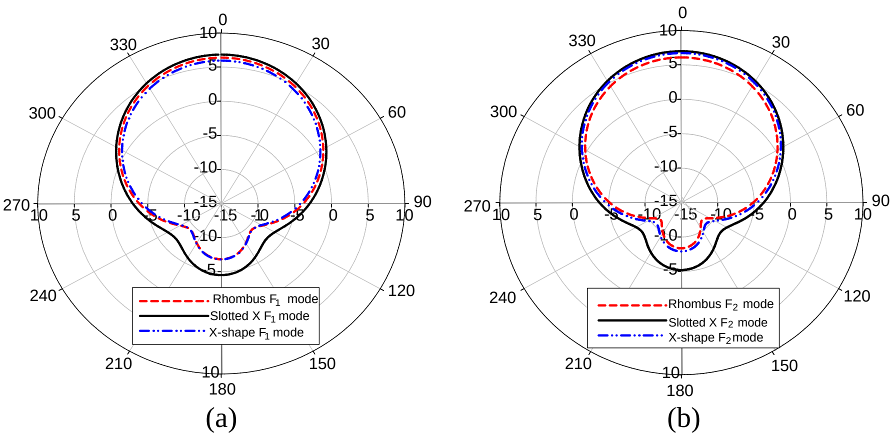


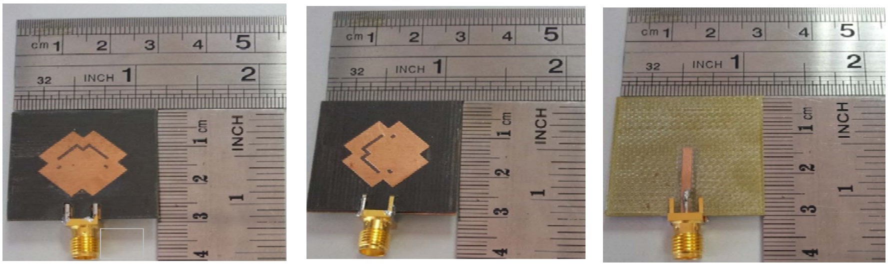
Figure 13. Comparison of radiation patterns in polar-plot (phi = 0) during (a) F_1 mode, (b) F_2 mode.

gains at both frequency modes as compared to the reference antennas.

Radiation patterns of the reference antennas and TRLSAs have been compared for both frequency modes, F_1 mode and F_2 mode. As clearly shown in Figure 13, they are similar in shape with one main lobe and one back lobe. The results indicate the back lobes of all antennas can be considered very small. The small area (0.48 mm × 7.75 mm) of aperture slot results in low back radiation level which leading to less spurious radiation in the back region [18]. However, the back lobes of TRLSA at both F_1 mode and F_2 mode are slightly bigger than of the reference antennas. This may due to the 'zig-zag' slot embedded on the radiating patch.

4. RESULTS AND DISCUSSIONS

The proposed antennas have been successfully fabricated and measured. As depicted in Figures 14(a)–(b), there are two types of prototypes to indicate that each of them is operating at two different frequencies, 5.3 GHz (F_1 mode) and 5.8 GHz (F_2 mode) respectively. The comparison between simulation and measurement results of return loss at both frequency modes is shown in Figure 15. The measured result at F_1 mode seems to have a slight frequency shift and lower value of return loss than of the simulated. The return loss is measured at 5.25 GHz with −13.435 dB and −33.146 dB at 5.34 GHz during simulation. Meanwhile, at F_2 mode, there is a good agreement in term of return loss magnitude for both simulated and measured results but the frequency is shifted significantly. During simulation, the magnitude of return loss is −30.787 dB at 5.8 GHz. However, during measurement the frequency has been shifted to 5.92 GHz with return loss of −29.367 dB.



(a) (b) (c)

Figure 14. Final prototypes of the proposed TRLSA. (a) $TRLSA_1$ at F_1 mode = 5.3 GHz. (b) $TRLSA_2$ at F_2 mode = 5.8 GHz. (c) Bottom view.

The discrepancies in the results may due to the challenging double-layer structure of the antenna. These may occur during fabrication process and improper handling when gluing both layers. There might be a slight shift between layer 1 and layer 2. If both layers are not glued properly at the right position, the excitation of radiation fields would give significant impact to the radiation characteristics. Hence, the excitation of resonant frequencies can also be affected.

Figures 16 and 17 show the simulated radiation patterns of the proposed antenna based on two different polarizations: co-polarization and cross-polarization at two different frequency modes, F_1 mode at 5.3 GHz and F_2 mode at 5.8 GHz respectively. The radiation patterns were cut based on two major planes, H-plane (x-z direction) at phi

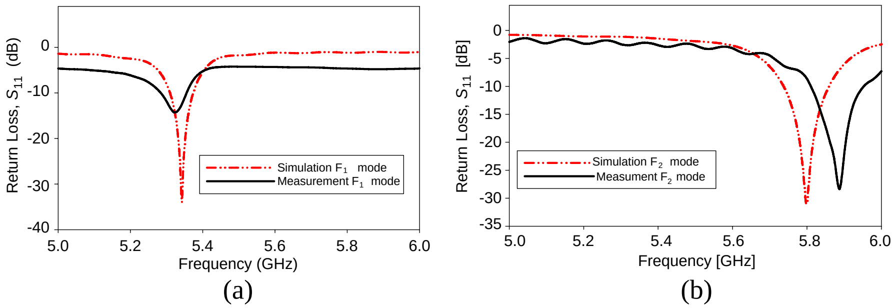


Figure 15. Simulated and measured return losses of the proposed antenna during (a) F_1 mode, (b) F_2 mode.

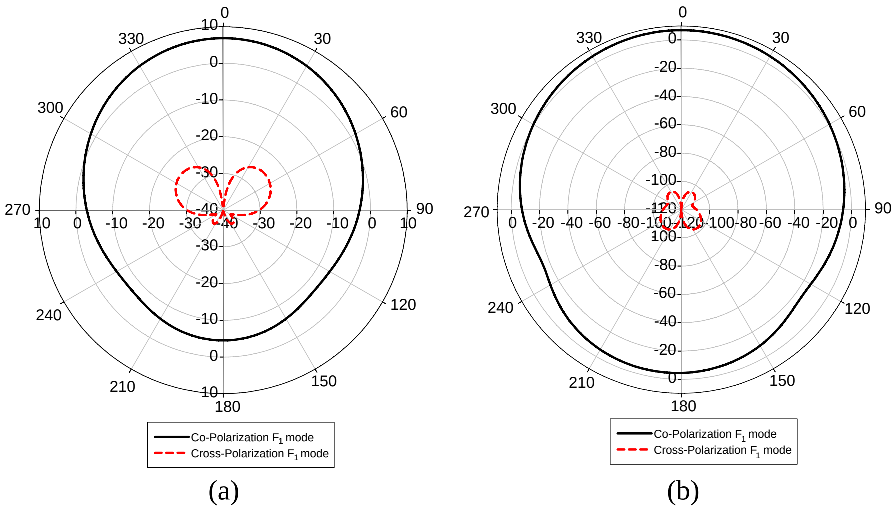


Figure 16. Simulated radiation patterns of the proposed antenna during F_1 mode = 5.3 GHz. (a) H-plane (Phi = 0°). (b) E-plane (Phi = 90°).

= 0° and E-plane (y-z direction) at phi = 90°. Note that, each figure has different scale which represents the lowest range possible for each pattern of cross-polarization. It clearly shows that a significant difference can be seen on the pattern shape during co- and cross-polarization. Meanwhile, as depicted in Figure 18, a good agreement between measured and simulated results can be seen at the main lobe at both frequency modes. However, there are some discrepancies at the back lobe which may be due to improper measurement environment since it was not done in an anechoic chamber.

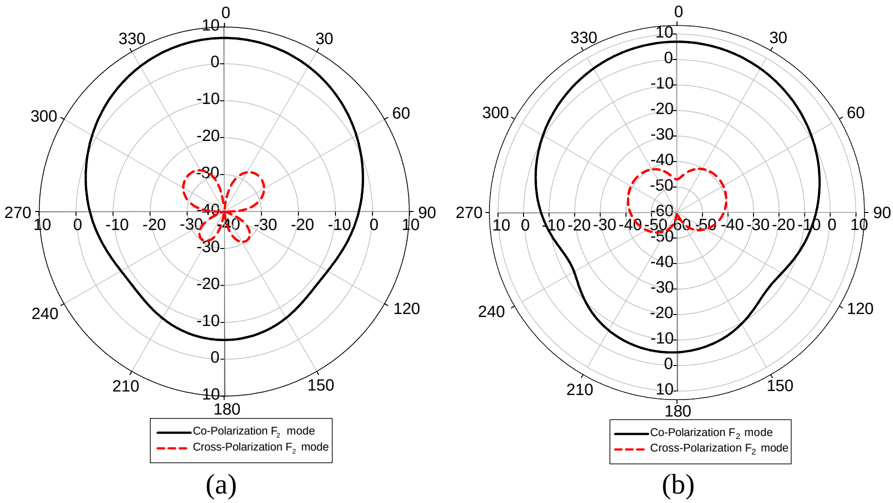


Figure 17. Simulated radiation patterns of the proposed antenna during F_2 mode = 5.8 GHz. (a) *H*-plane (Phi = 0°). (b) *E*-plane (Phi = 90°).

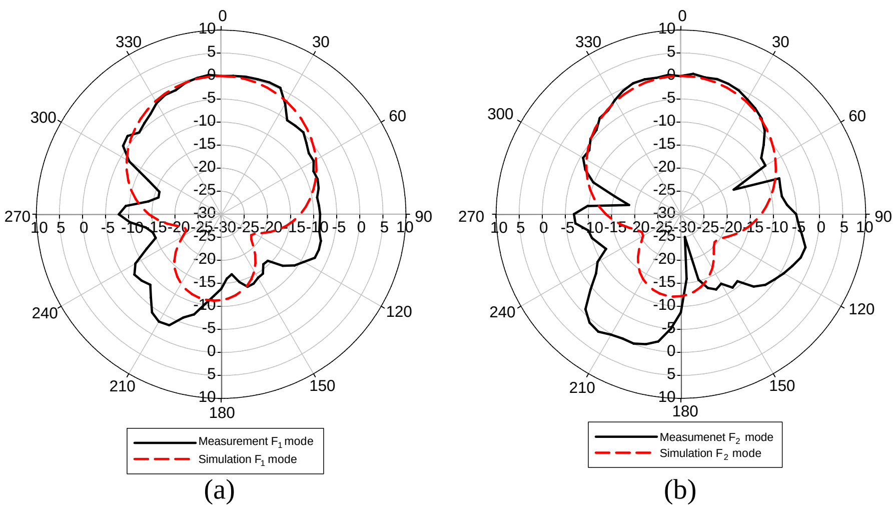


Figure 18. Simulated and measured radiation patterns (normalized) of the proposed antenna in polar-plot during (a) F_1 mode, (b) F_2 mode.

5. CONCLUSION

In this paper, the proposed antenna design has a unique rhombus-like shape with truncated edges and slotted patch elements fed by an aperture coupler. The different orientations in x- and y-axis of the 'zig-zag' slot embedded on the radiating patch resulted in the excitation of different frequencies, F_1 mode = 5.3 GHz and F_2 mode = 5.8 GHz respectively without changing the patch dimensions. The design transformation has been presented to further explain the design concept of the proposed TRLSAs. A good agreement has been achieved between simulation and measurement results. The major benefit of the design is that the patch size can be reduced for lower frequency which normally requires bigger patch size. Hence, the overall size of an array antenna can be reduced lowering the manufacturing cost. For future work, a frequency reconfigurable antenna can be built in an array configuration based on the proposed TRLSA design concept with the integration of switching components.

ACKNOWLEDGMENT

The authors would like to thank the Faculty of Electrical Engineering, Universiti Teknologi MARA (UiTM) for the financial support and facilities rendered.

REFERENCES

1. Lee, K. F. and W. Chen, *Advances in Microstrip and Printed Antennas*, New York, John Wiley & Sons, 1997.
2. Rao, Q. and T. A. Denidni, "A new aperture coupled microstrip slot antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 9, 2818–2826, 2005.
3. Srifi, M. N., M. Meloui, and M. Essaaidi, "Rectangular slotted patch antenna for 5–6 GHz applications," *International Journal of Microwave and Optical Technology*, Vol. 5, No. 2, 52–57, Mar. 2010.
4. Schaubert, D. H., "A review of some microstrip antenna characteristics," *Microstrip Antennas — The Anlaysis and Design of Microstrip Antennas and Arrays,* D. M. Pozar and D. H. Schaubert (Eds.), John Wiley & Sons, Inc., 1995, ISBN 0-7803-1078-0.
5. Madhav, B. T. P. and V. G. K. M. Pisipati, "Comparative study of microstrip rectangular patch array antenna on liquid crystal

polimer and RT Duroid substrates," *International Journal of Electronics and Communication Engineering*, Vol. 4, No. 2, 161–167, 2011.

6. Ke, S.-Y., "Single-feed microstrip antenna with two layer substrate for circular polarization," *IEEE Antennas and Propagation Society International Symposium (APSURSI)*, 1–4, 2010.
7. Rahim, M. K. A., A. Asrokin, M. H. Jamaluddin, M. R. Ahmad, T. Masri, and M. Z. A. Abdul Aziz, "Microstrip patch antenna array at 5.8 GHz for point to point communication," *International RF and Microwave Conference Proceedings*, 216–219, Sep. 12–14, 2006.
8. Ang, B.-K. and B.-K. Chung, "A wideband E-shaped microstrip patch antenna for 5–6 GHz wireless communications," *Progress In Electromagnetics Research*, Vol. 75, 397–407, 2007.
9. Yang, F., X.-X. Zhang, X. Ye, and Y. Rahmat-Samii, "Wide-band E-shaped patch antennas for wireless communications," *IEEE Transactions on Antennas and Propagation*, Vol. 49, No. 7, 1094–1100, Jul. 2001.
10. Singh, K. and S. N. Mulgi, "Complementary-symmetric corner truncated compact square microstrip antenna for wide band operation," *International Journal of Electronics and Communication Engineering*, Vol. 1, No. 1, 99–106, 2010.
11. Al-Maznee, T. and H. E. Abd-El-Raouf, "Design of reconfigurable patch antenna with a switchable V-slot," *Progress In Electromagnetics Research C*, Vol. 6, 145–158, 2009.
12. Hadian, A. M. and H. R. Hassani, "Wideband rectangular microstrip patch antenna with U-slot," *The Second European Conference on Antennas and Propagation*, 1–5, Nov. 11–16, 2007.
13. Vedaprabhu, B. and K. J. Vinoy, "A double U-slot patch antenna with dual wideband characteristics," *2010 National Conference Communications (NCC)*, 1–4, Jan. 29–31, 2010.
14. Balanis, C. A., *Antenna Theory Analysis and Design,* 3rd Edition, John Wiley & Sons, New Jersey, 2005.
15. Lee, H. M., "Pattern reconfigurable micro-strip patch array antenna using switchable feed-network," *Asia-Pacific Microwave Conference Proceedings (APMC)*, 2017–2020, 2010.
16. Kayat, S. M., M. T. Ali, and M. K. M. Salleh, "A reconfigurable microstrip antenna with a slotted patch at dual frequency," *IEEE 8th International Symposium on Wireless Communication Systems (ISWCS)*, 695–699, 2011.

17. Ali, M. T., T. A. Rahman, M. R. Kamarudin, and M. N. Md Tan, "A planar antenna array with separated feed line for higher gain and side lobe reduction," *Progress In Electromagnetics Research C*, Vol. 8, 69–82, 2009.
18. Aijaz, Z. and S. C. Shrivastava, "Effect of the different shapes: Aperture coupled microstrip slot antenna," *International Journal of Electronics Engineering*, Vol. 2, No. 1, 103–105, 2010.
19. Muhamud Kayat, S., M. T. Ali, and M. K. M. Salleh, "An aperture coupled microstrip antenna (ACMSA) with orientations of patch slot," *IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC)*, 913–916, 2012.
20. Kuo, J. S. and G. B. Hseih, "Gain enhancement of a circularly polarized equilateral-triangular microstrip antenna with slotted ground plane," *IEEE Transactions on Antennas and Propagation*, Vol. 51, 1652–1656, 2003.
21. Kayat, S. M., M. T. Ali, and M. K. M. Salleh, N. Ramli, and H. Alias, "Truncated rhombic microstrip patch array antenna with frequency reconfigurability," *IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE)*, 313–317, 2012.