*Progress In Electromagnetics Research C, Vol. 50, 11–19, 2014*

# Study of Cross-Slotted Circular Microstrip for Reflectarray Design

**Wai-Hau Ng[1], Eng-Hock Lim[1, *], Fook-Loong Lo[1], and Kia-Hock Tan[2]**

**Abstract**—In this paper, a circular microstrip patch centrally etched with a cross slot is studied. The slot dimensions are varied for controlling the reflection loss and the phase range of a reflectarray. It is found that the dominant TM mode of the slotted circular patch can be easily excited, and the slot length can be varied to function as a phase-changing parameter. Cross slots with equal and unequal arms are investigated. Study shows that the slope of the $S$ curve can be made slow-changing by increasing the slot widths simultaneously. A maximum reflection phase range of 328.68° is achievable in the $S$ curve. Rectangular waveguide method has been deployed for simulating and verifying the design idea. Reasonable agreement is found between the measurement and simulation.

## 1. INTRODUCTION

Reflectarray antenna was first proposed by Berry et al. in 1963 [1] with the intention of providing a better solution than the parabolic reflector and phased array. Although containing both features, its implementation using truncated waveguides made it extremely bulky. This problem was later solved with the introduction of microstrip reflectarray [2, 3] in 1991, which provided advantages such as low profile, flat surface, and low manufacturing costs. A microstrip reflectarray consists of an array of microstrip resonators, also known as unit elements, printed on a grounded substrate. A good unit element should possess low reflection loss, slow reflection phase change, and large reflection phase range. Additional reflection phase can also be easily introduced by changing of resonator size [4] or by loading a microstrip patch with an additional phase-delay stub [5] for linear polarization.

Microstrip patch is the earliest planar resonator explored for designing various reflectarrays due to its simplicity. Loading patch with slots was found to be able to provide phase shifts that are required for designing a reflectarray [6, 7]. This method is very easy in the sense that the separation distance between any two of the elements is a constant. In [6], it was shown that a phase range about 270° can be achieved by introducing a square hole in the middle of a rectangular patch. However, the phase range obtained is still less than the optimal phase range of 360° and is insufficient to build a large-size reflectarray. A triple-patch structure loaded with double slots was proven to be able to provide a phase range greater than 360° [7], but it has many parameters to be optimized. Multilayer microstrip patch unit element structure is another option that is able to introduce reflection phase shift for designing reflectarray [8, 9]. In [8], a multilayer unit element with variable slot lengths etched on its ground plane is proven to be able to provide phase range of 330°; however, the gradient of the $S$ curve changes too rapidly, making it difficult to be used as a reflectarray element. An annular slot and a C patch can be combined to design a broad-range reflectarray [9]. Unfortunately, fine tuning such a multilayer structure may not be easy. Other broad-range configurations such as circular patch, ring [10], and fractal-shaped [11] unit elements have also been demonstrated. Adding planar amplifier arrays to a passive microstrip unit element was another possible way for designing reflectarray [12]. However, the use of active elements in the design can introduce a higher loss which in turn compromises the radiation efficiency of a reflectarray.

*Received 21 March 2014, Accepted 27 April 2014, Scheduled 30 April 2014*

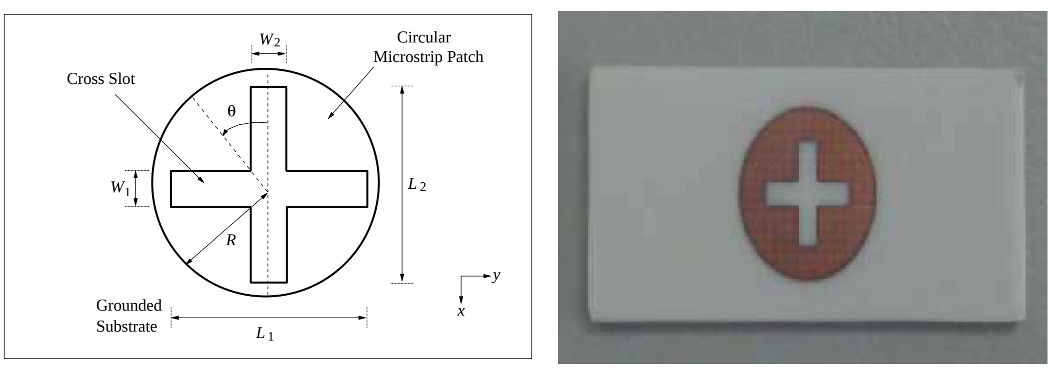
* Corresponding author: Eng Hock Lim (limeh@utar.edu.my).

[1] Department of Electrical and Electronic Engineering, Universiti Tunku Abdul Rahman, Kuala Lumpur, Malaysia. [2] Department of Industrial Engineering, Universiti Tunku Abdul Rahman, Kuala Lumpur, Malaysia.

In this paper, a unit element made of a cross-slotted circular microstrip patch is explored for reflectarray design. The reflection properties are studied for different slot dimensions. It is found that the dimensions of the cross slot can be used to tune the reflection loss and phase range of the patch element. Slots with equal and unequal arms are studied. Simulations were conducted using the CST Microwave Studio software, and experimental verification was done using the R&S®ZVB8 Vector Network Analyzer (VNA). The resonance is analyzed, along with a comprehensive parametric analysis.

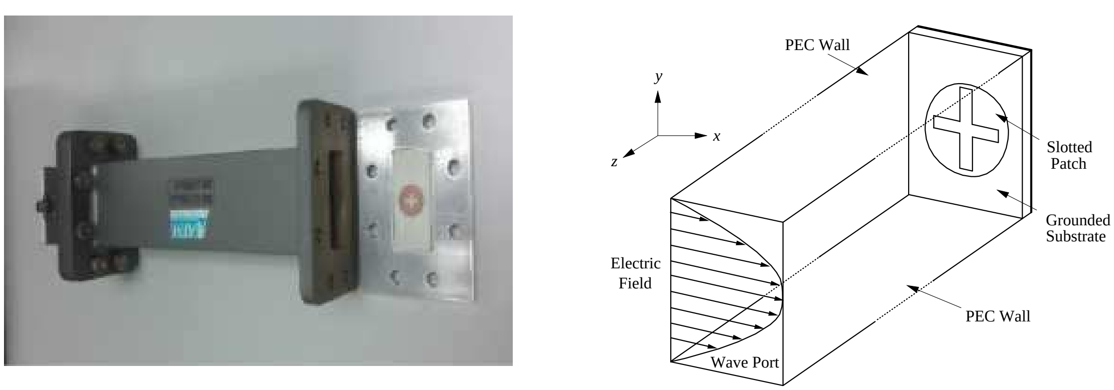
## 2. UNIT CELL STRUCTURE

Figure 1 shows the schematic of the proposed unit element made of a circular microstrip patch, working at the resonant frequency of 6.5 GHz, with a cross slot etched at its center. It is made on a Duroid RO4003C substrate with a thickness of 1.524 mm and a dielectric constant of $\varepsilon_r = 3.38$, with its ground laminated on the reverse surface. The circular patch has a radius of $R = 5.5$ mm. With reference to Figure 1(a), the cross slot is built by intersecting a horizontal ($y$-directed) slot and a vertical ($x$-directed) rectangular slot with their widths given by $W_1 = W_2 = 1.4$ mm. Here, the slot lengths ($L_1$, $L_2$) are used as the phase-shifting elements. Figure 1(b) shows the fabricated sample. Waveguide method is adopted to characterize the proposed design. A section of C-band waveguide ($a = 34.85$ mm $\times$ $b = 15.8$ mm, covering 5.8 GHz–8.2 GHz) with length of 154 mm, is used for measurement. Figure 2(a) shows the measurement setup with its corresponding simulation model depicted in Figure 2(b). It can be seen that the sample is placed inside a rectangular trench carved




(a) (b)

**Figure 1.** (a) Schematic of the proposed circular microstrip patch with a cross slot at the center. (b) Photograph of the fabricated sample.




(a) (b)

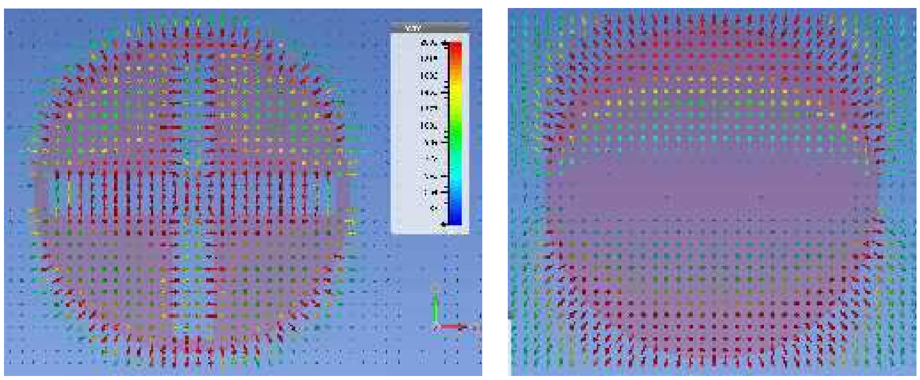
**Figure 2.** (a) Photograph of the measurement setup. (b) Simulation model for the proposed cross-slotted circular patch unit cell.

on a metallic shorting plate, with the patch aligned flush to the metal surface. Electromagnetic wave is guided from the coaxial-to-waveguide adaptor, travelling along the length of the waveguide section to reach the slotted patch, which is placed on the other end. In measurement, the reference plane is de-embedded down to the waveguide flange of the adaptor. An $x$-polarized wave is launched from the wave port, as can be seen from the simulation model in Figure 2(b), with the patch and substrate located on the other end of the waveguide section. All lateral walls are defined to be perfect conductors (PEC) in simulation.

## 3. RESULTS AND DISCUSSION

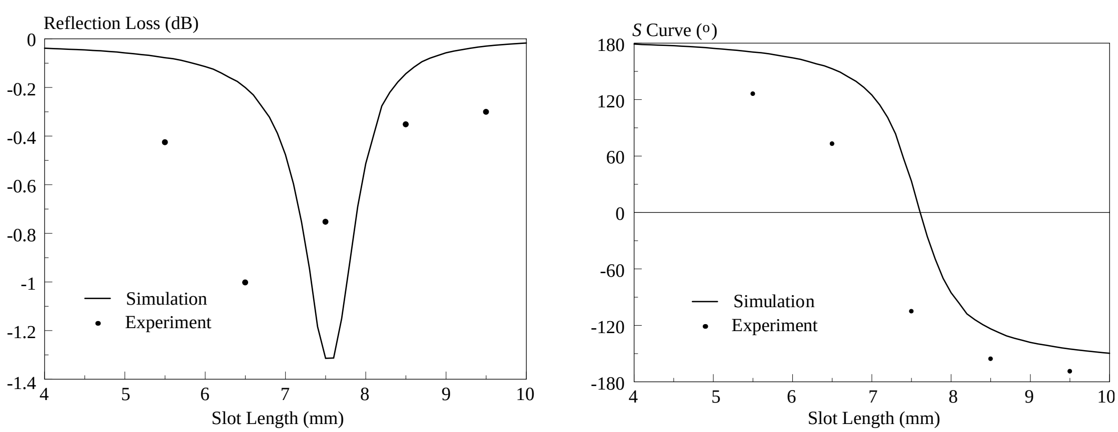
The electric field distributions are now studied. Figure 3(a) shows the electric field distributions formed in between the cross-slotted circular microstrip patch resonator and its ground when it is excited by an incident wave of 6.5 GHz. For comparison purpose, the electric field for a solid circular patch is also given in Figure 3(b). It can be observed from the field distributions in Figures 3(a) and (b) that they are the $TM^z_{110}$ mode of the circular microstrip patch [13].

Figure 4 depicts the simulated and measured reflection losses and reflection phases ($S$ curves) of the proposed unit element when both of the slot lengths ($L_1$, $L_2$) are varied simultaneously. Generally, the measurement result agrees reasonably well with simulation. Referring to Figure 4(a), the measured



(a) (b)

**Figure 3.** Electric field distributions on the circular patches, (a) with cross slot ($R = 5.5$ mm, $L_1 = L_2 = 10$ mm, and $W_1 = W_2 = 1.4$ mm), (b) without cross slot ($R = 5.5$ mm).




(a) (b)

**Figure 4.** Measured and simulated (a) reflection losses, (b) $S$ curves of the proposed cross-slotted circular patch unit cell.

reflection loss peaks at −1 dB at the slot length of 6.5 mm while the simulated reflection loss peaks at −1.3 dB at the slot length of 7.5 mm. Low reflection loss implies that the unit element dissipates very little power for all dimensions of the cross slot. Figure 4(b) shows the simulated and measured $S$ curves. A gradual decreasing slope of 267.9°/mm with a total reflection phase range of 328.68° is successfully achieved. This phase range is sufficient for designing small-size reflectarrays. Figure 5 depicts the simulated and measured frequency responses for the case of $L_1 = L_2 = 9.5$ mm in the range 6.3 GHz–6.7 GHz. Reasonable agreement is found between the simulated and measured results. With reference to Figure 5(a), the measured reflection has the same trend as its simulation, both are increasing with frequency. Higher loss (∼0.3 dB) is observed in the measurement due to minor impedance mismatch which is unavoidable. With reference to Figure 5(b), minor discrepancy (∼1%) is found between the measured and simulated reflection phases, which is acceptable.

Parametric analysis has been performed to visualize the effects of slot and patch dimensions on the reflection loss and the reflection phase. The effects of the slot widths ($W_1$, $W_2$) are studied first. With reference to the $x$-axis of Figure 6, the lengths of the horizontal ($L_1$) and vertical ($L_2$) slots are varied simultaneously from 4 mm to 10 mm. As can be seen from Figure 6(a), the maximum reflection losses of three cases of slot widths ($W_1 = W_2 = 0.6$ mm, 1.4 mm, and 3.5 mm) are in the range of −1.3–1.5 dB. The reflection phase is then studied in Figure 6(b) and it is observed that the phase ranges for the

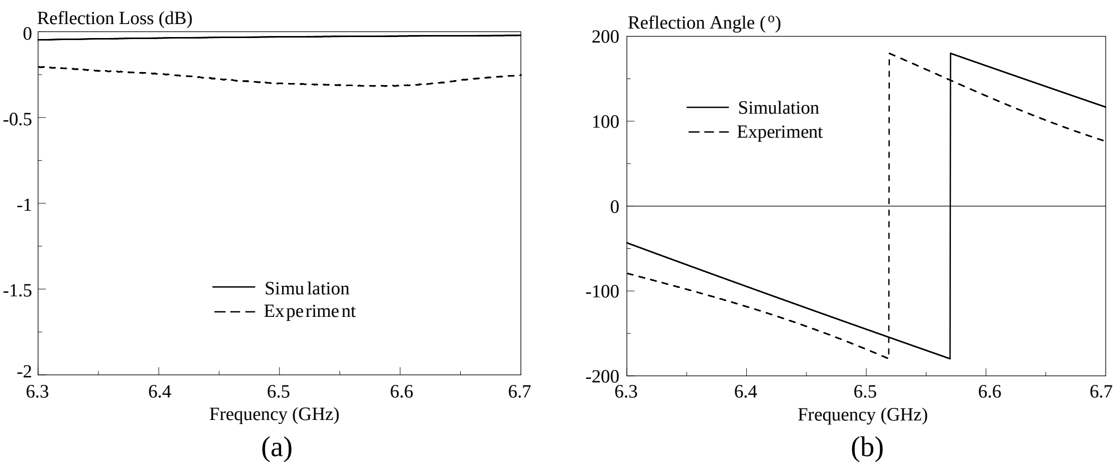



**Figure 5.** Measured and simulated (a) reflection losses, (b) reflection angles against frequency for $L_1 = L_2 = 9.5$ mm for the proposed cross-slotted circular patch unit cell.

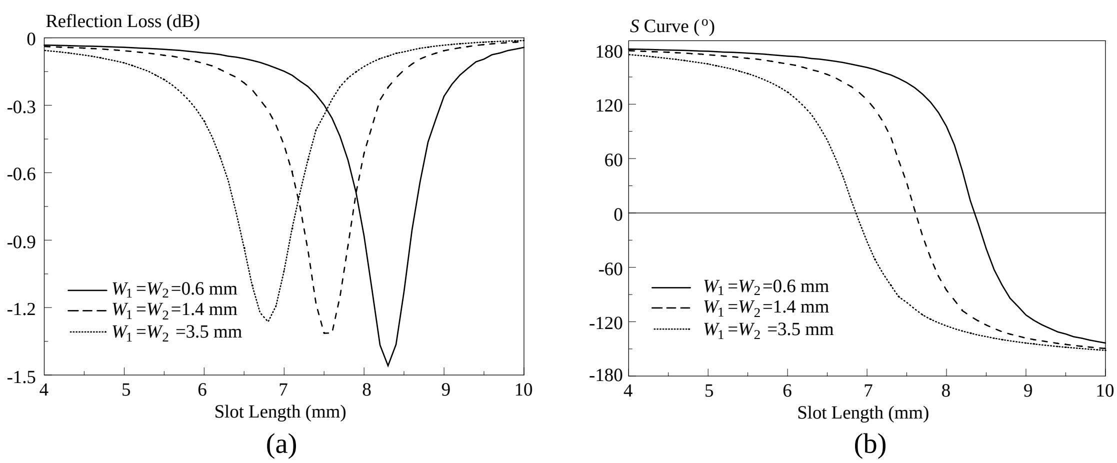
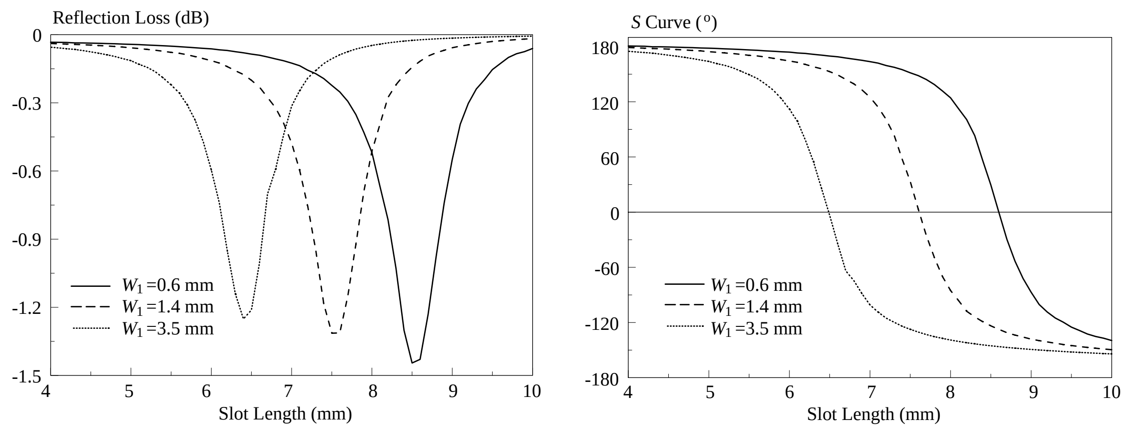



**Figure 6.** Effects of the slot widths ($W_1 = W_2$) on the (a) reflection loss, (b) $S$ curve of the proposed cross-slotted circular patch unit cell.

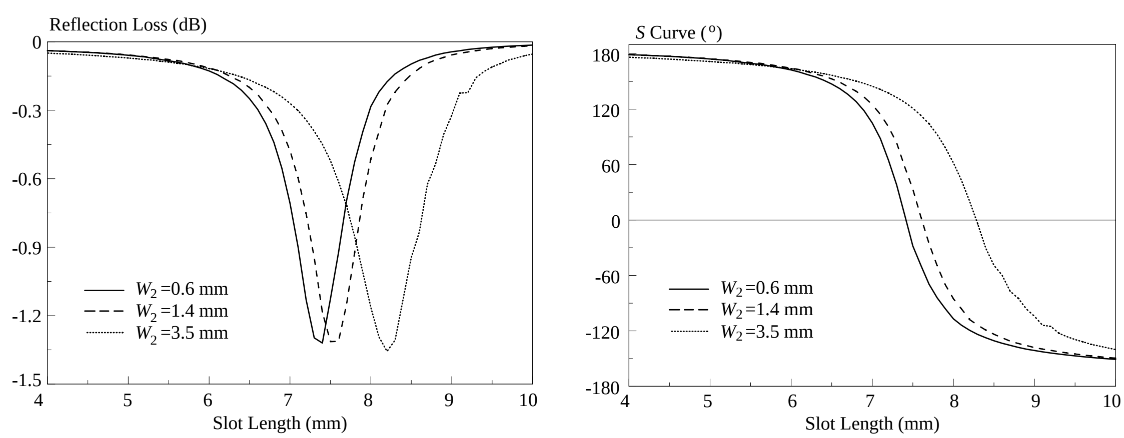
three cases are 324.36° (0.6 mm), 328.68° (1.4 mm), and 326.38° (3.5 mm). Although the phase ranges remain almost unchanged for all of the three cases, the curve gradient reduces from 292.1°/mm to 224.92°/mm, with increasing slot width ($W_1$ and $W_2$) from 0.6 mm to 3.5 mm, which is much desired to make the elements more distinguishable in dimension. It was also found from simulations that changing slot length $L_1$ or $L_2$ alone does not affect the reflection characteristics of the slotted patch much. The reflection loss and $S$ curve of the slotted circular microstrip patch will only vary when both of the slot lengths ($L_1$ and $L_2$) are changed at the same time.

Next, the reflection properties are characterized by varying only one of the slot widths. Again, $L_1$ and $L_2$ are changed simultaneously (shown in the $x$-axis). Figure 7 shows the reflection loss and $S$ curve for different horizontal slot widths ($W_1 = 0.6$, 1.4, and 3.5 mm), where the width of the vertical slot is made constant at ($W_2 = 1.4$ mm). Again, it is observed that the reflection loss can be kept well below $-1.5$ dB at all slot lengths. With reference to Figure 7(b), the reflection phase range is slightly improved from 320.28° to 329.1° when the horizontal slot width ($W_1$) is increased from 0.6 mm to 3.5 mm. Although a phase range of 329.1° is achievable for the case of $W_1 = 3.5$ mm, it has a faster changing rate (295.65°/mm) of $S$ curve when compared to the cases of $W_1 = 0.6$ mm (273.2°/mm) and $W_1 = 1.4$ mm (267.9°/mm). By keeping the horizontal slot width ($W_1 = 1.4$ mm) unchanged, with reference to Figure 8, the effects of vertical slot width are studied for $W_2 = 0.6$, 1.4, and 3.5 mm. It is




(a) (b)

**Figure 7.** Effects of the horizontal slot width $W_1$ on the (a) reflection loss, (b) $S$ curve of the proposed cross-slotted circular patch reflectarray unit cell.




(a) (b)

**Figure 8.** Effects of the vertical slot width $W_2$ on the (a) reflection loss, (b) $S$ curve of the proposed cross-slotted circular patch reflectarray unit cell.

observed from simulation that the phase range reduces from 329.78° to 316.6° and the curve gradient decreases from 284.93°/mm and 202.42°/mm, with increasing of vertical slot width ($W_2$). By keeping the slot widths at $W_1 = W_2 = 1.4$ mm and varying the slot lengths ($L_1 = L_2$) from 2 to 11.5 mm, Figure 9 shows the changes in reflection loss and $S$ curve when the patch radius $R$ is varied. With reference to Figure 9(b), the reflection phase range and the gradient of the $S$ curve decrease from 339.13° to 314.18° and 469.15°/mm to 121.27°/mm, respectively, when the patch radius $R$ is varied from 5 to 6 mm. It is obvious that making the patch radius smaller is helpful to expand the reflection phase range of the unit element, but at the cost of having a higher reflection loss and a steeper reflection phase slope. Therefore, tradeoff is needed here as designing a reflectarray requires an $S$ curve with broad reflection phase range but slow gradient.

To further study the effects of patch geometry on the reflection characteristics, a square patch (5.5 mm × 5.5 mm), which is etched with a cross slot ($L_1 = L_2 = 10$ mm and $W_1 = W_2 = 1.4$ mm), is simulated. The square patch is made to have close footprint as its circular counterpart. In this case, the cross slot is placed at the patch center (shown in the inset of Figure 10(a)). The reflection loss and $S$ curve of the cross-slotted rectangular patch are presented in Figure 10, along with the results of the circular one (already shown in Figure 4) for ease of comparison. With reference to Figure 10(a),

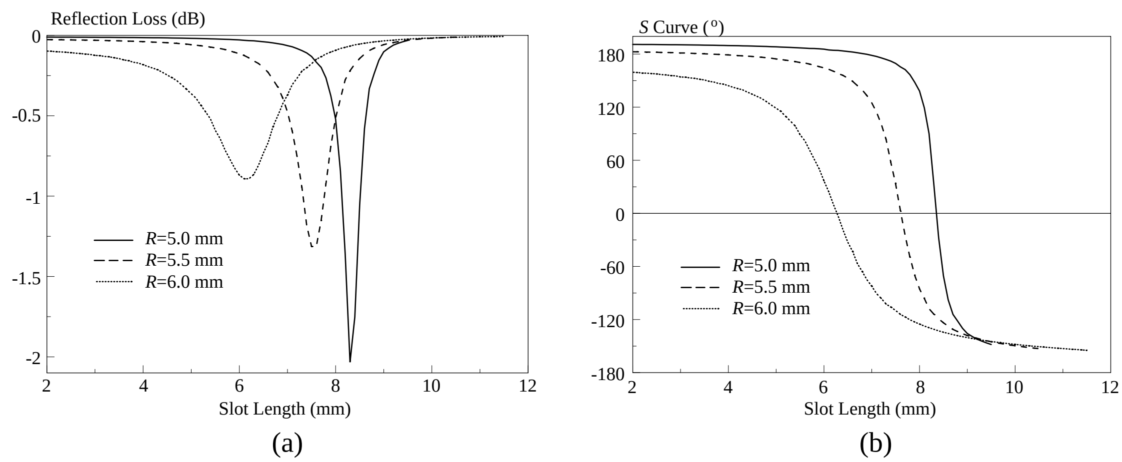



**Figure 9.** Effects of the patch radius $R$ on the (a) reflection loss, (b) $S$ curve of the proposed cross-slotted circular patch reflectarray unit cell.

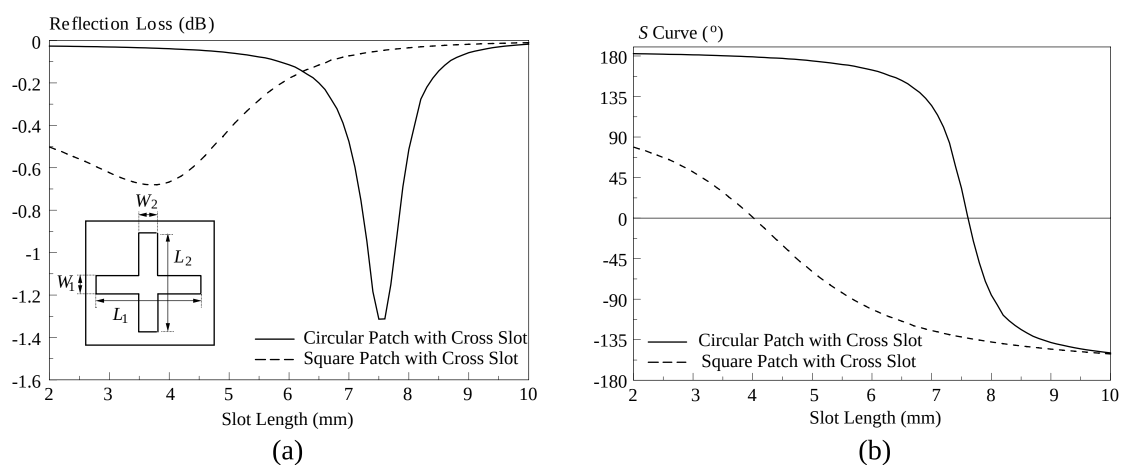



**Figure 10.** Comparison of the (a) reflection losses, (b) $S$ curves of the cross-slotted circular patch ($R = 5.5$ mm) and the cross-slotted square patch (5.5 mm×5.5 mm) with the same slot dimension ($L_1 = L_2 = 10$ mm and $W_1 = W_2 = 1.4$ mm).

the reflection losses of the patches maximize at different slot lengths, mainly due to their difference in resonance frequencies. Interestingly, it is noted that the reflection phase range of the cross-slotted square patch (∼230°) is much smaller than its circular counterpart (328.68°) in this case. However, the gradient of the cross-slotted square patch is much better than its circular counterpart where a sensitivity of 58.83°/mm is obtainable.

To visualize the effects of the neighboring elements on the reflection characteristics of a unit element when it is placed in an array, the Floquet model is deployed [14] for simulating the reflection coefficient, shown in Figure 11. This simulation model duplicates the unit element infinitely in the $x$- and $y$-directions by taking account of their mutual coupling. In the Floquet simulation model, the unit cell is made to be square ($l \times l$), implying that every two of the circular patches have a center-to-center separation distance of $l$. With the use of this model, the reflection coefficients for the cases of $l = 0.3\lambda$, $0.6\lambda$, and $0.8\lambda$ are simulated for the slotted circular patch with the dimension of $R = 5.5$ mm and $W_1 = W_2 = 1.4$ mm, as depicted in Figure 12. Again, the horizontal ($L_1$) and vertical ($L_2$) slot lengths are varied simultaneously from 4 to 10 mm. It can be observed in Figure 12(a) that larger separation distance induces higher reflection loss. A maximum reflection loss of ∼−8.4 dB is obtained for the case of $0.8\lambda$. With reference to Figure 12(b), a larger separation distance between the neighboring elements contributes to a broader phase range, but at the cost of having steeper $S$ curve. The phase

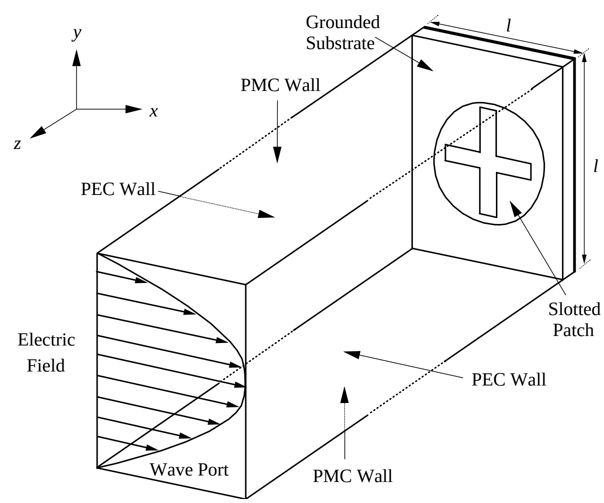



**Figure 11.** Floquet simulation model for the cross-slotted circular patch unit cell.

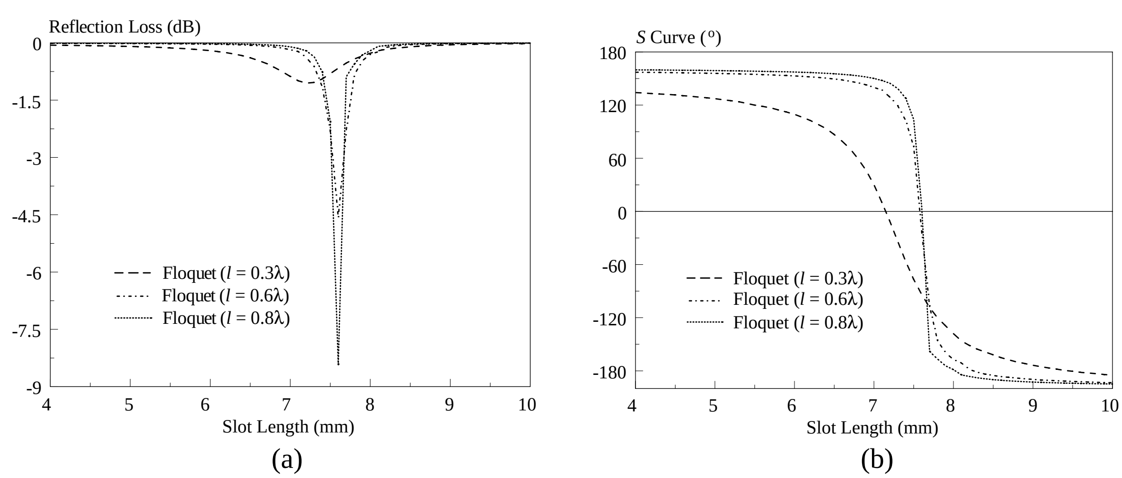



**Figure 12.** Effects of the separation distance between any two neighboring elements on the (a) reflection loss, (b) $S$ curve of the proposed cross-slotted circular patch reflectarray unit cell.

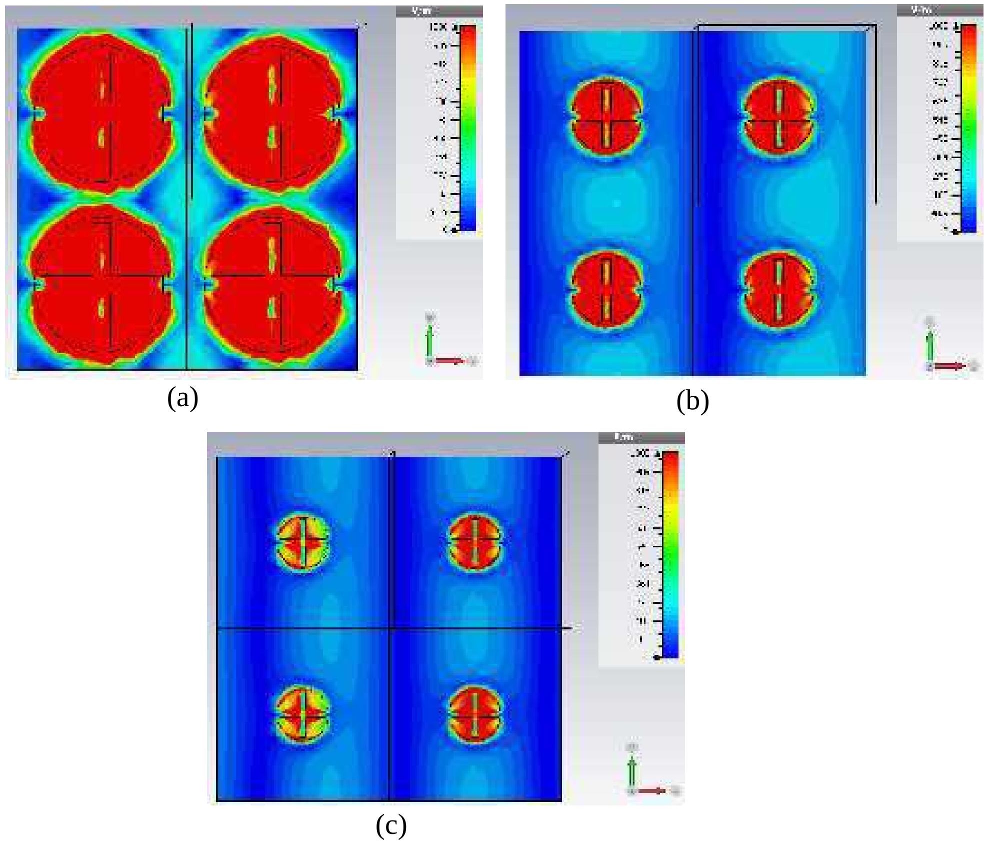



**Figure 13.** Electric field coupling between the neighboring elements for the separation distance of (a) $0.3\lambda$, (b) $0.6\lambda$, (c) $0.8\lambda$.

range and gradient of the $S$ curve increase from 319.1° to 354.66° and from 207.36°/mm to 1310°/mm, respectively, when the separation distance is varied from $0.3\lambda$ to $0.8\lambda$. The electric field coupling between the neighboring elements is now studied in Figure 13. It is obvious that the coupling field between the adjacent elements becomes more intense when the elements are placed closer. Although the Floquet model does not pose any constraints on the unit cell size and it can be used to simulate reflection coefficient with respect to the phase-changing parameter for an incoming wave with any frequency and incident angle, the simulated results are not able to be experimentally verified at the cell level.

## 4. CONCLUSIONS

A cross-slotted circular microstrip patch is explored for reflectarray design. The cross slot is etched centrally and symmetrically at the center of a circular microstrip patch, the effects of the slot dimensions are investigated. A reflection phase range of 328.68° is achievable. It has been found that the changing rate of the reflection phase can be easily tuned by varying the slot width. It has been shown that with the same footprint, the cross-slotted circular patch can be made to have a broader phase range than its square counterpart. Also, it has been found that smaller separation distance between the adjacent elements is good for lowering the changing rate of the $S$ curve, but at the cost of reducing phase range. Good agreement has been found between the simulated and experimental data.

## ACKNOWLEDGMENT

The work described in this paper was supported by a Science Fund (Project No. 06-02-11-SF0154) funded by the Ministry of Science, Technology and Innovation, Malaysia. Part of the project is also sponsored by an UTAR Research Fund 2013 (Project No. 6200/LA5).

## REFERENCES

1. Berry, D., R. Malech, and W. Kennedy, "The reflectarray antenna," *IEEE Trans. Antennas Propag.*, Vol. 11, No. 6, 645–651, Nov. 1963.
2. Pozar, D. M., S. D. Targonski, and H. D. Syrigos, "Design of millimeter wave microstrip reflectarrays," *IEEE Trans. Antennas Propag.*, Vol. 45, No. 2, 287–296, Feb. 1997.
3. Huang, J. and J. A. Encinar, *Reflectarray Antennas,* John Wiley & Sons, Inc., Hoboken, 2007.
4. Encinar, J. A., "Design of two-layer printed reflectarrays using patches of variable size," *IEEE Trans. Antennas Propag.*, Vol. 49, No. 10, 1403–1410, Oct. 2001.
5. Huang, J., "Analysis of a microstrip reflectarray antenna for microspacecraft application," TDA Progress Report 42-120, 153–173, Feb. 1995.
6. Trampuz, C., M. Hajian, and L. P. Ligthart, "Design, analysis and measurements of reflected phased array microstrip antennas at Ka-band, using hollow phasing," *3rd European Radar Conference*, 57–60, Sep. 2006.
7. Cadoret, D., A. Laisné, R. Gillard, and H. Leday, "A new reflectarray cell using microstrip patches loaded with slots," *Microw. Opt. Technol. Lett.*, Vol. 44, No. 3, 270–272, 2005.
8. Chaharmir, M. R., J. Shaker, M. Cuhaci, and A. Sebak, "Reflectarray with variable slots on ground plane," *IEE Proceedings — Microwaves, Antennas and Propagation*, Vol. 150, No. 6, 439–439, Dec. 2003.
9. Pham, K. T., B. D. Nguyen, V. Tran, L. P. Bui, and L. Mai, "Reflectarray element based on variable line length for millimeter-wave radar applications," *International Conference on Advanced Technologies for Communication*, 218–221, Oct. 2012.
10. Zhou, D., Z. Niu, and R. Li, "Investigation on a single-layer microstrip circular-patch/ring-combination reflectarray element," *Cross Strait Quad-Regional Radio Science and Wireless Technology Conference*, Vol. 1, 664–667, Jul. 2011.
11. Zubir, F. and M. K. A. Rahim, "Simulated fractals shape for unit cell reflectarray," *Asia Pacific Microwave Conference*, 583–586, Dec. 2009.
12. Robinson, A. W. and M. E. Bialkowski, "An $X$-band active microstrip reflectarray," *Asia-Pacific Microwave Conference Proceedings*, Vol. 3, 925–928, Dec. 1997.
13. Eriksson, A., P. Linner, and S. Gevorgian, "Mode chart of electrically thin parallel-plate circular resonators," *IEE Proceedings — Microwaves, Antennas and Propagation*, Vol. 148, No. 1, 51–55, Feb. 2001.
14. Dzulkipli, I., M. H. Jamaluddin, R. Gillard, R. Sauleau, R. Ngah, M. R. Kamarudin, N. Seman, and M. K. Abd Rahim, "Mutual coupling analysis using FDTD for dielectric resonator antenna reflectarray radiation prediction," *Progress In Electromagnetics Research B*, Vol. 41, 121–136, 2012.