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PERFORMANCE IMPROVEMENT OF REFLECTARRAYS BASED ON EMBEDDED SLOTS CONFIGURATIONS

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Abstract—An infinite reflectarray antenna in the X-band frequency range has been designed, and various slot configurations have been proposed to optimize the design of reconfigurable reflectarray antennas in the X-band frequency range. It has been demonstrated that the introduction of slots in the patch element causes a decrease in the maximum surface current density (**J**) and electric field intensity (**E**) and hence causes a variation in the resonant frequency of the reflectarray. Waveguide simulator technique has been used to represent infinite reflectarrays with a two patch unit cell element and scattering parameter measurements have been carried out using vector network analyzer. A change in resonant frequency from 10 GHz to 8.3 GHz has been shown for a slot width of $0.5W$ (W is the width of patch element) as compared to patch element without slot. Furthermore, a maximum attainable dynamic phase range of 314° has been achieved by using slots in the patch element constructed on a 0.508 mm thick substrate with a maximum surface current density (**J**) of 113 A/m and electric field intensity (**E**) of 14 kV/m for $0.5W$ slot in the patch element.

1. INTRODUCTION

Reflectarray is a high gain antenna proposed as an alternative to the bulky parabolic and expensive phased array antennas in 1963 [1]. However, it acquired the attention of the world after the concept of microstrip reflectarrays introduced in 1991 [2]. A microstrip reflectarray consists of an array of microstrip patch elements printed on a dielectric substrate. The individual elements of the reflectarray are designed to scatter the incident field with proper phase required

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to form a planar phase surface in front of the periodic array of the aperture [3]. The design techniques commonly used such as identical patches of variable-length stubs [4], square patches of variable sizes [5], and identical planar elements of variable rotation [6] offer a very high efficiency for a very large aperture to be tilted in a large angle. All the above mentioned techniques are used to introduce a small change in the resonant frequency of the individual patch element and hence cause a progressive phase distribution of the reflectarray antenna ranging up to 360° [7]. In this work different slot configurations in the patches of the reflectarray designed at 10 GHz are introduced to achieve a progressive phase distribution using fixed patch size with variable slot dimensions. It has been demonstrated that the introduction of slots in the patch element can alter the resonant frequency of the reflectarray and hence can be used for frequency tuning of reflectarray antennas. Different types of slot configurations have been employed for operation in the X-band frequency range and the slot dimensions have been varied. This affects the electrical dimensions and the surface current distributions on the patch elements and hence produces a change in the resonant frequency and reflection phase of a reflectarray. It has been demonstrated in [8] that the limited phase range of microstrip antenna elements reduces the operational bandwidth of reflectarray. In this work the static linear phase range [9] obtained for slot configurations is compared with some of the previous works. It has been observed that the design of slot configurations proposed in this work gives an additional advantage of improved bandwidth performance with an increased phase range and a reduction in the phase errors when compared with other design techniques.

2. BASIC DESIGN

Commercially available computer model of CST Microwave Studio has been used to design a unit cell patch element with proper boundary conditions in order to analyze the scattering parameters of an infinite reflectarray. Initially a reflectarray with rectangular patch element is designed to resonate at 10 GHz using Rogers RT/Duroid 5880 ($\varepsilon_r = 2.2$ and $\tan\delta = 0.0010$) as a substrate with thickness of 0.508 mm. Then different types of slot configurations are introduced in the patch element and the effect on the performance of the reflectarray was observed. The direction of port excitation and surface currents on a patch without slot is shown in Figure 1. It can be observed from Figure 1 that the maximum current on the surface of the patch occurs in the centre of the length of patch when the electric field is excited in the Y-direction.

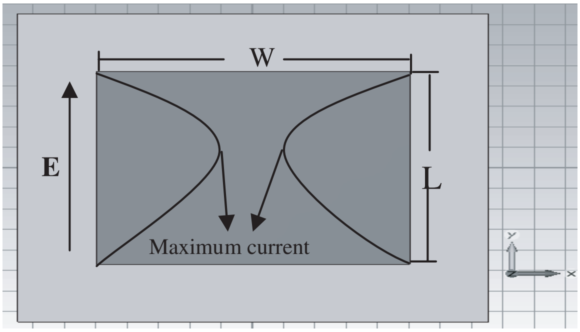


Figure 1. A reflectarray unit cell surface currents.

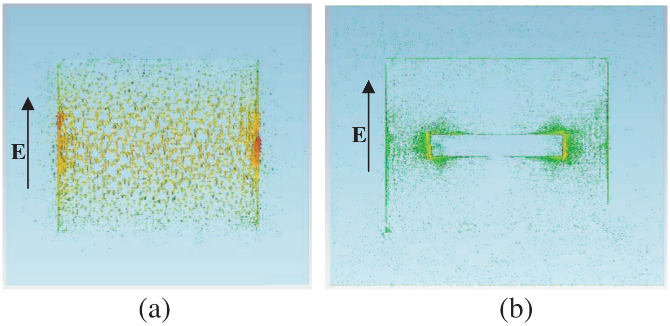


Figure 2. Surface current distribution on a patch element. (a) Without slot. (b) With a rectangular slot.

3. SLOTS IN THE PATCH ELEMENT

3.1. Theoretical Analysis

The phenomenon of the occurrence of maximum current in the centre of the patch element is shown in Figure 2(a) by simulating the reflectarray in commercially available computer model of CST Microwave Studio. In Figure 2(b), it has been clearly shown that the current on the surface of the patch element is significantly modified by the introduction of rectangular slot in the patch element. This variation in the surface current density varies the electric field intensity on the patch element and hence produces a change in the resonant frequency of the individual element. A similar effect has been observed when a circular slot has been introduced in the centre of the patch element.

The modification of the surface current distribution on the patch element, shown in Figure 2, is due to the fact that the effective area of the conducting material (copper) is reduced because of the extraction of slot from the patch element. This decreases the surface current density (**J**) which furthermore reduces the amount of current (**I**) according to Maxwell's equations [10]. The reduction of surface current density on the conducting material causes a decrease in the electric field intensity as well. This results in an increase in the electrical dimensions of the patch element and hence causes a decrease in resonant frequency.

3.2. Simulations

In order to observe the effect of introduction of slot configurations in the patch element on the surface current density (**J**) and electric field intensity (**E**), infinite reflectarrays designed in the X-band frequency range have been simulated and the width of the slot W_0 is varied from $0.1W$ to $0.6W$ while the length of the slot is kept constant at $0.125L$. Figure 3 shows the rectangular slots with variable width configuration in the patch element.

The effect of variable width slots in the patch element on the maximum surface current density (**J**) and maximum electric field intensity (**E**) analyzed by Finite Integral Method (FIM) is shown in Figure 4. As depicted in Figure 4, both surface current density and electric field intensity decrease from 255 A/m to 113 A/m and 121 kV/m to 14 kV/m respectively by an increase in the width of the slot configuration from $0.1W$ to $0.5W$. The decrease in the electrical field intensity has the effect of increasing the dielectric constant. Consequently the resonant frequency of the patch element decreases and reflection loss increases. In order to validate the results obtained by CST MWS simulations, various slot configurations have been introduced in the fabricated patch samples. The detailed analysis

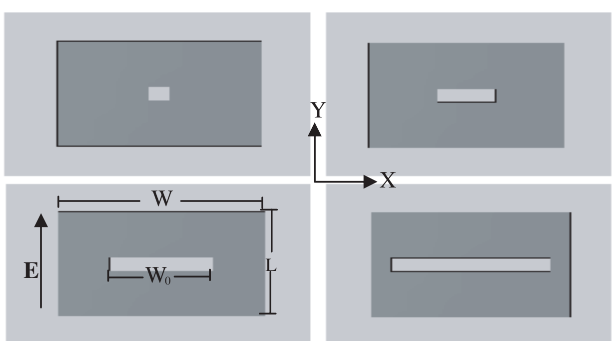


Figure 3. Rectangular slots with different widths in patch elements.

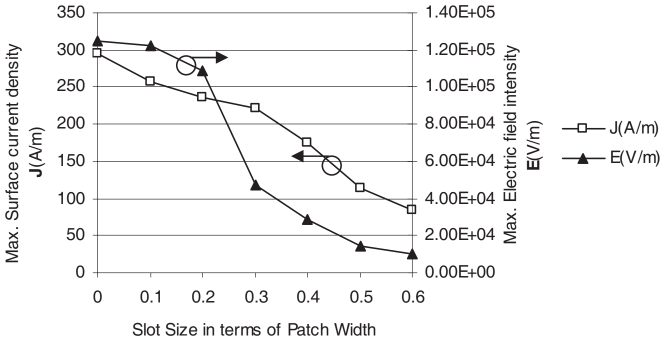


Figure 4. Maximum surface current and electric field intensity for different patch widths at resonant frequency.

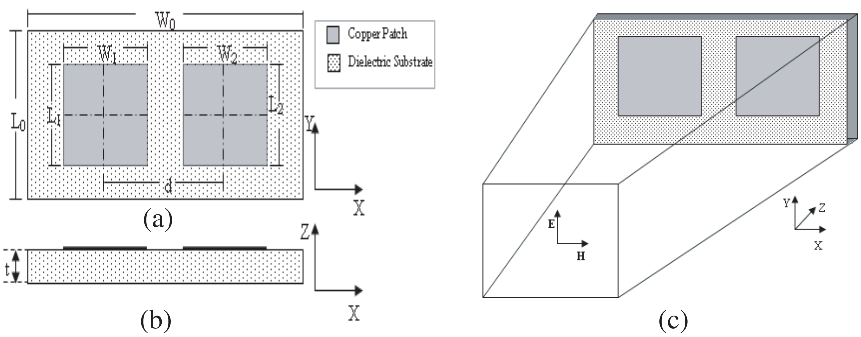


Figure 5. Geometry of two patch element reflectarray (a) top view and (b) side view (c) waveguide simulator for simulating an infinite array.

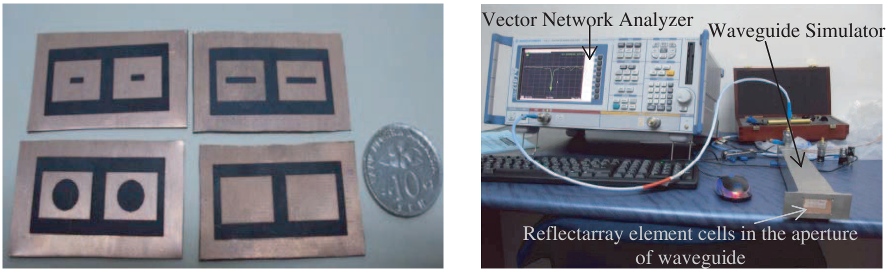
carried out using waveguide measurements with variable width slots in the patch element and a circular slot configuration in the centre of patch element is explained in the following section.

4. MEASUREMENTS AND COMPARISONS FOR DIFFERENT SLOT CONFIGURATIONS IN THE PATCH ELEMENT

Waveguide simulators can be used to represent infinite reflectarrays using a unit cell patch element [11]. In this work, two patch element unit cell reflectarray as shown in Figure 5(a) and Figure 5(b) has been designed to represent infinite reflectarrays using the waveguide simulator technique. The two patch elements of identical size have been used in order to consider the effects of mutual coupling where the interelement spacing d is kept at half wavelength to minimize the grating lobes [12]. Figure 5(c) shows the structure of a waveguide simulator where, electric fields are excited in the Y-direction which creates E-walls on the upper and lower walls in the cavity of waveguide simulator. Consequently H-walls are created on the left and right walls of the inner cavity of waveguide simulator.

Dielectric substrate of Rogers 5880 ($\varepsilon_r = 2.2$ and $\tan\delta = 0.001$) has been used to design two patch element unit cell reflectarrays, resonating in the X-band frequency range, with substrate thickness of 0.508 mm and different slot configurations embedded in the patch elements as shown in Figure 6(a). In order to carry out the scattering parameter measurements, two patch element unit cell has been inserted into the aperture of the wave guide which is connected to the vector network analyzer using a waveguide to coax adapter as shown in Figure 6(b).

The fabricated samples include the patch elements with a circular slot in the centre of patch with a radius of 3 mm and rectangular slots in which the width varies from $0.3W$ to $0.6W$ while the length is kept constant at $0.125W$. In the case of $0.6W \times 0.125L$ slot, the resonant frequency is observed to exceed the X-band frequency range and therefore the waveguide designed for X-band frequency range can not be used for the scattering parameter measurements of $0.6W$ sample. For that reason fabricated samples with width varying from $0.3W$ to $0.5W$ are used for measurements. The purpose of performing the scattering parameters measurements of a circular slot was to practically validate the change in the resonant frequency by the introduction of



(a) (b)

Figure 6. (a) Fabricated samples of reflectarrays with different slot configurations. (b) Measurement setup for scattering parameters measurements.

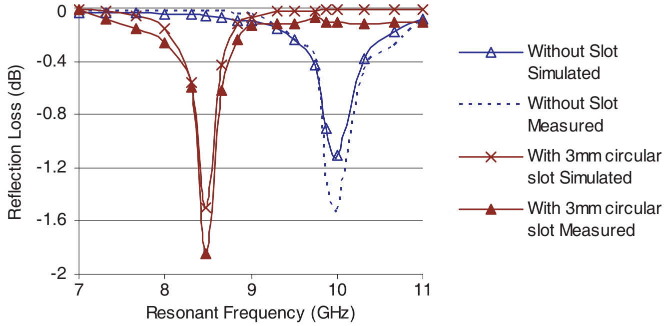


Figure 7. Simulated and measured reflection loss for 3 mm Circular slot.

the circular slot in the centre of the patch element. Figure 7 shows the measured and simulated reflection loss for 3 mm circular slots in the centre of patch and reflection loss for a patch without slot. A clear change in the resonant frequency can be observed from the comparison of the two configurations. Furthermore it is also shown that the measured reflection loss is higher than the simulated reflection loss. The discrepancy in the measured and simulated reflection loss can be attributed to the losses introduced by the interconnections of cables, connectors and waveguide.

Measured and simulated reflection phase plots for 3 mm circular slot and a patch without slot are shown in Figure 8. It can be observed from Figure 8 that the slopes of the simulated reflection phases are almost same but the difference in the measured reflection phases of both the curves is easily noticeable. This occurred because of the difference in the measured reflection losses as depicted in Figure 7. The detailed analysis for different widths of rectangular is also carried out as demonstrated below.

Figure 9 shows the measured and simulated reflection loss curves for different values of rectangular slots embedded into the patch. The width of the slot is varied from $0.3W$ to $0.5W$ and the change in resonant frequency was observed to vary from 9.64 GHz to 8.3 GHz while the reflectarray with patch without slot is shown to resonate at 10 GHz. Moreover, despite of the differences in the reflection losses due to the interconnections, the trend of the loss performance of both measured and simulated reflectarrays is identical. The reason that can justify the change in the resonant frequency and loss performance of different materials is that by the introduction of slots with different widths, the electrical length and the current distribution on the surface of the patch can be varied as explained in Section 3.1.

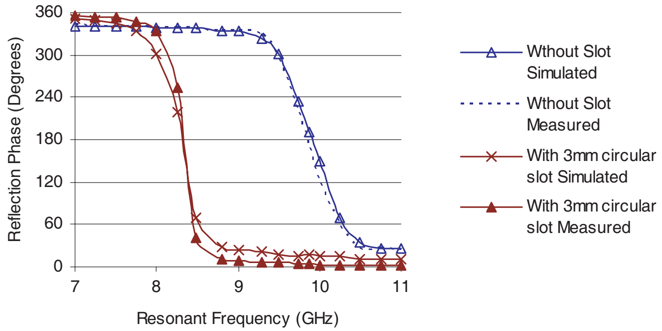


Figure 8. Simulated and measured reflection phase for 3 mm Circular slot.

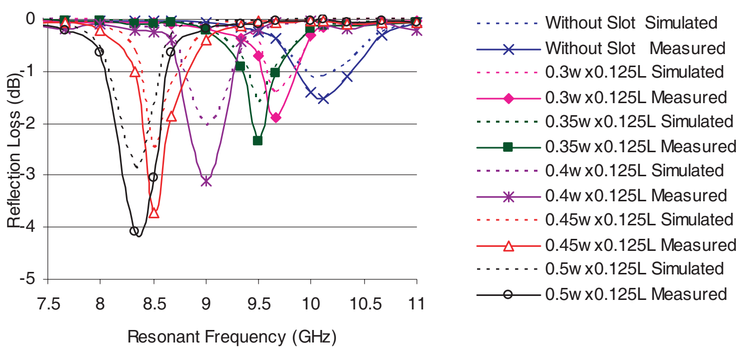


Figure 9. Simulated and measured reflection loss for different widths of rectangular slots.

The variation in the reflection phase of the reflectarrays with different width of slots in the patch element is shown in Figure 10. It can be observed from Figure 10 that both the measured and simulated reflection phase curves are in good agreement with each other. The slight difference that can be observed in the measured and simulated reflection phases is due to the differences in the loss performance of measured and simulated reflectarrays. Moreover it can be observed from Figure 10 that the slope of the reflection phase curve defined as a figure of merit (FOM) for bandwidth in [13] increases from 0.334°/MHz to 0.588°/MHz as the width of the slot is increased from $0.3W$ to $0.5W$ showing a degradation in the bandwidth performance. This effect can be attributed to the increased reflection loss from 1.5 dB to 4.2 dB with increasing slot width as depicted in Figure 9. As a figure of merit, dynamic phase range (DPR) has been defined as the difference

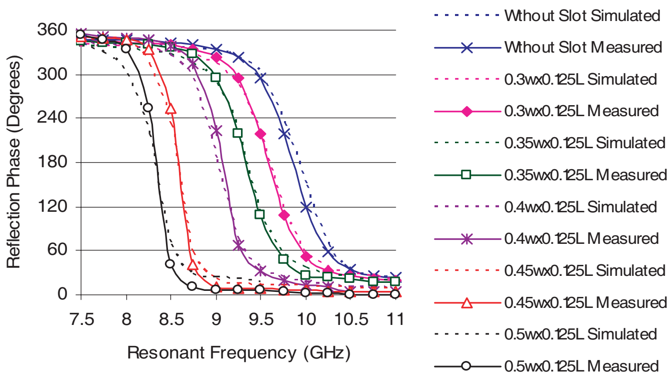


Figure 10. Simulated and measured reflection phase for different widths of rectangular slots.

Table 1. Dynamic phase range (DPR) and % volume reduction for different width of slot configurations in patch element.

		$0.3W \times 0.125L$	$0.35W \times 0.125L$	$0.4W \times 0.125L$	$0.45W \times 0.125L$	$0.5W \times 0.125L$
DPR	Measured	120°	210°	235°	295°	314°
	Simulated	122°	207°	233°	291°	319°
Volume Reduction		5.85%	8.08%	14.89%	19.6%	24.36%

in the reflection phase variation curves ($\Delta\O_d$) without slot and with a particular slot at the mean frequency of two curves as shown in Figure 11.

The summary of the measured and simulated dynamic phase ranges for different lengths of slot configurations is shown in Table 1. It can be observed from Table 1 that a measured dynamic phase range of 120° to 314° is achievable with a variation of slot width from $0.3W$ to $0.5W$ which shows the feasibility of using slot configurations to achieve a dynamic phase tuning control of a reflectarray antenna. Furthermore the possibility of reducing the volume of a unit cell patch element in a reflectarray designed at 10 GHz has also been demonstrated in Table 1 where, a maximum reduction of 24.36% in the volume of the patch is shown for slot of $0.5W \times 0.125L$. Therefore, a larger number of patch elements can be used to design a reflectarray without varying its overall aperture dimensions.

In order to compare the results of the reflection phase plots produced in this work, static linear phase range ($\Delta\O_s$) as shown in

Figure 12 has been used. It was observed that the previous studies [14, 15] which proposed the slots in the ground plane demonstrated a simulated static linear phase range of 180° and 210° respectively for single layer structures. A measured static linear phase range of 190° has also been reported for a structure of reflectarray having slots in the patch element [16]. The results depicted in Figure 12 demonstrate that an increased measured static linear phase range of 230° is achieved using slots of variable width in the patch element. Therefore due to the increased attainable static linear phase range, the contribution of phase errors in the reduction of bandwidth of a reflectarray can be minimized by using the proposed slot configurations.

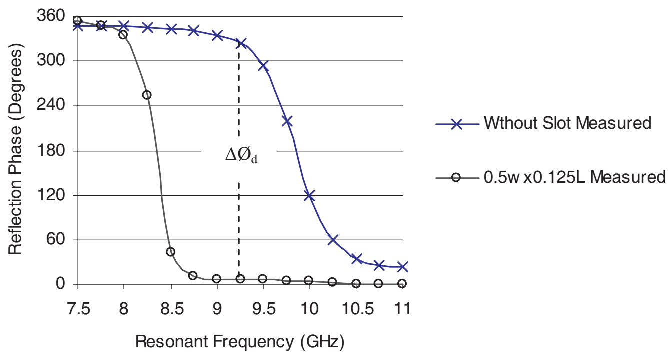


Figure 11. Dynamic phase range for $0.5W \times 0.125L$ rectangular slot.

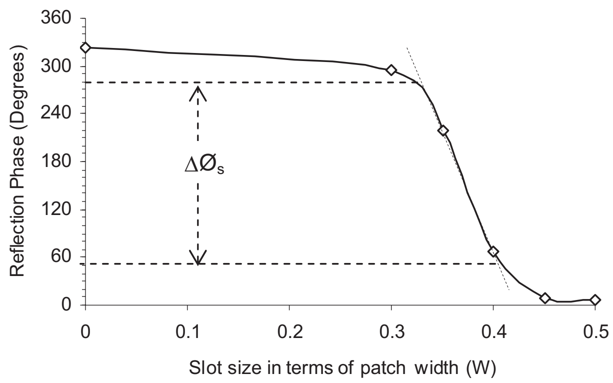


Figure 12. Measured phase shift versus slot size curve.

5. CONCLUSION

Various slot configurations have been introduced in the patch element for the performance improvement of reflectarray antennas designed in the X-band frequency range, and the scattering parameter measurements of slot configurations have been carried out. A change in resonant frequency from 10 GHz to 8.3 GHz has been demonstrated for a slot width of $0.5W$ as compared to patch element without slot and the possibility of achieving a dynamic phase range up to 314° is also demonstrated by waveguide measurements of infinite reflectarrays. From the measurements of the slot configurations in the patch element, it can be concluded that different type of slot configurations can be employed for the miniaturization of the reflectarrays as a wide range of resonant frequencies can be achieved without varying the size of the patch element. An increased static linear phase range of 230° is achieved when the slot is introduced in the patch element. Moreover the reduction in the phase errors produced by the limited phase range and the possibility of designing a reflectarray with a 24.36% reduced volume of patch is also shown when a slot width of $0.5W \times 0.125L$ is introduced in the patch element. In future the dynamic phase, demonstrated in this work can be utilized do design electronically controllable reflectarrays with progressive phase distribution.

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REFERENCES

1. Berry, G. D. G., R. G. Malech, and W. A. Kennedy, "The reflect array antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 11, 645–651, 1963.
2. Huang, J., "Microstrip reflectarray," *IEEE AP-S/URSI Symposium Digest, London, Ontario, Canada*, 612–615, 1991.
3. Pozar, D. M., S. D. Targonski, and H. D. Syrigos, "Design of millimeter wave microstrip reflectarrays," *IEEE Transactions on Antennas and Propagation*, Vol. 45, No. 2, 287–296, 1997.
4. Targonski, S. D. and D. M. Pozar, "Analysis and design of a

microstrip reflectarrayusing patches of variable size," *IEEE AP-S/URSI Symposium, Seattle, Washington*, 1820–1823, 1994.
5. Javor, R. D., X. D. Wu, and K. Chang, "Design and performane of microstrip reflectarray antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 43, No. 9, 932–938, 1995.
6. Huang, J. and R. J. Pogorzelski, "Microstrip reflectarray with elements having variable rotation angle," *IEEE AP-S Symposium Digest*, 1280–1283, 1993.
7. Ismail, M. Y., M. Inam, and A. M. A. Zaidi, "Reflectivity of reflectarrays based on dielectric substrates," *American J. of Engineering and Applied Sciences*, Vol. 3, No. 1, 180–185, 2010.
8. Bialkowski, M. E. and K. H. Sayidmarie, "Bandwidth considerations for a microstrip reflectarray," *Progress In Electromagnetics Research B*, Vol. 3, 173–187, 2008.
9. Ismail, M. Y., M. F. M. Shukri, Z. Zakaria, A. F. M. Zain, M. F. L. Abdullah, and M. A. Ubin, "Investigation of static phasing distribution characteristics of passive reflectarray antenna elements," *PIERS Proceedings*, 1218–1222, Moscow, Russia, 2009.
10. Pozar, D. M., *Microwave Engineering*, John Wiley and Sons, Inc., USA, 1998.
11. Hannan, P. W. and M. A. Balafour, "Simulation of phased array antenna in waveguide," *IEEE Transactions on Antennas and Propagation*, Vol. 13, No. 3, 342–353, 1965.
12. Huang, J. and J. A. Encinar, *Reflectarray Antennas*, IEEE Press, Johan Wiley and Sons, Inc., USA, 2007.
13. Ismail, M. Y. and M. Inam, "Analysis of design optimization of bandwidth and loss performance of reflectarray antennas based on material properties," *Modern Applied Sci. J. CCSE*, Vol. 4, No. 1, 28–35, 2010.
14. Rajagopalan, H., Y. R. Samii, and W. A. Imbriale, "RF MEMES actuated reconfigurable reflectarray patch-slot element," *IEEE Transactions on Antennas and Propagation*, Vol. 56, No. 12, 3689–3699, 2008.
15. Chahmir, M. R., J. Shaker, M. Cuhai, and A. Sebak, "Reflectarray with variable slots on ground plane," *IEE Proc.-Microwaves, Antennas and Propagation*, Vol. 150, No. 6, 436–439, 2003.
16. Cadoret, D., A. Laisne, R. Gillard, and H. Legay, "A new reflectarray cell using microstrip patches loaded with slots," *Microwave and Optical Technology Letters*, Vol. 44, No. 3, 270–272, 2005.