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A NOVEL BANDWIDTH ENHANCEMENT TECHNIQUE FOR X-BAND RF MEMS ACTUATED RECONFIGURABLE REFLECTARRAY

Y. Raedi, S. Nikmehr, and A. Poorziad

Faculty of Electrical Engineering
University of Tabriz, Tabriz, Iran

Abstract—In this paper, a wideband microstrip antenna for X-band (8.2 GHz–12.4 GHz) applications is introduced. First, simple patch antennas are studied, and a narrowband reflectarray antenna is designed. The resultant design demonstrates better performance than the previously published narrowband microstrip reflectarray antennas. The important features of the employed elements are simple structure, linear operation, and use of Radio Frequency Micro Electro Mechanical Systems (RF MEMS) switches for programmable pattern control. Next, employing our novel method, the designed narrowband structure is converted to broadband reflectarray antenna that can cover the whole X band. This novel idea is based on introducing several ground plane slots and controlling their electrical lengths by RF MEMS switches. By means of this method, 952 and 587 degree phase swing are achieved for continuous and discrete slot length variations, respectively. Application of this method along with smaller switches results in phase swing improvement of up to 1616 degree. In all structures a RT duroid (5880) substrate is selected to lower the back radiation. The achieved return loss in all cases is less than 0.32 dB. In comparison with the previous publications, our novel bandwidth enhancement technique has more generalization capability and results in single layered broadband reconfigurable microstrip reflectarray antennas with linear phase swing, lower cost, and ease of RF MEMS implementation.

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Corresponding author: Younes Raedi (raedi.communication@gmail.com).

1. INTRODUCTION

Reflector antennas have always been a common choice for radar and satellite applications. Some of the blemishes of these antennas are as follows: they have large and curved structures; the pattern sweeping is done by means of mechanical rotation of the antennas; they have beam forming difficulties; and their radiation parameters are highly dependent on environmental conditions. Reflectarray Antennas (RAs) can improve these deficiencies and, therefore, are good candidates for replacing reflector antennas. There are many antenna elements in RAs, and each acts as a reflecting aperture. The radiated wave from a horn antenna, which is placed in front of the array, is transformed to scattered plane wave from RA apertures. This wave transformation is accomplished by means of phase shiftings from array elements, as shown in Figure 1. Reflectarray was first introduced by Berry et al. [1]. In their work, the array elements were waveguides of variable length. This antenna with its bulky and large structure enticed limited attention in practical applications. By introduction and development of microstrip technology, an appealing option was their use in the RAs. The concept of a microstrip reflectarray antenna (MRA) was conceived in 1978 by Malagisi [2] and was patented in 1987 by Munson et al. [3].

The elements of MRAs were printed dipoles or patches over the grounded substrates, and sometimes with slotted ground planes. MRAs combined some of the good features of the printed phased

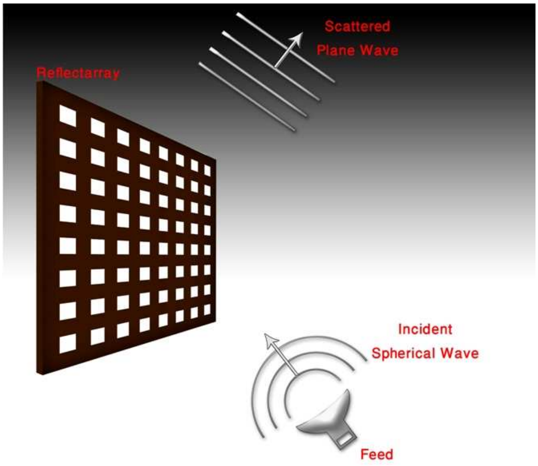


Figure 1. Reflectarray structure.

arrays and parabolic reflectors. One of the problems in microstrip phased arrays is the amount of loss and complexity in their feed network, especially in higher frequencies. This problem is eliminated in MRAs, due to their indirect feeding mechanism with horn antenna. The other features of the MRAs are their ease of fabrication, the ability to conform to any surface, low profile structure, low mechanical complexity, high scanning and tracking capability, and reduction of interference effects. These features of MRAs have made a good candidate of them for use in satellite, radar, and remote sensing applications.

The previous works on RAs can be grouped in two classes: Fixed Beam Reflectarray Antennas (FBRAs), and Reconfigurable Reflectarray Antennas (RRAs). In the case of FBRAs, the phase shifting of each element is constant. Moreover, the radiation parameters of FBRAs such as gain, shape of radiation pattern and beam width of these RRAs, which are determined in the design process, are fixed. Various methods have been introduced for synthesis of FBRAs microstrip elements, such as: With elements of the same shape and size which are loaded with stubs of different size [4], with elements of the same shape but different lengths [5], with elements of the same shape having slots of different size on the patch [6], with elements of the same shape and slots of different size on the ground plane [7], with loaded elements that their rotation angle is changed with stubs of circular polarization [8], with slot ring resonator elements [9], with ring resonator elements [10], with folded reflectarray elements [11], ... FBRAs are mostly used in the applications that demand high gain with low interference effects. The main drawback of these antennas is their narrow bandwidth and incapability for fast beam scanning.

In many applications such as radar systems, in order to improve the performance of antennas, controllable radiation parameters are desired. While in FBRAs the radiation pattern is fixed and could only be changed by mechanical rotation of the antennas, RRAs fulfills this demand. RRAs employ electronically varied characteristics of array elements to achieve the desired radiation patterns. The reconfigurability property requires that the contributed phase swing from each element to be controllable. In recent years a variety of design methods have been introduced for RRAs. In what it follows, some of these methods are mentioned. One class of these methods are based on using materials with tunable electromagnetic parameters by bias voltage, such as liquid crystal [12–17], Barium Strontium Titanate (BST) [18] and ferroelectric materials [18–20]. The other class is based on using the electronical elements such as PIN diodes [21, 22], GaAs FETs [23], Varactor diodes [24–27] and photonically controlled semiconductors [28]. The third class is mechanical method in which the phase shifting from each element is changed using small electrical motors [29]. Finally, there is a newly developed electromechanical method employing RF MEMS (Micro Electro Mechanical Systems) switches to control the contributed phase swing from each element [30–37]. In [38], using MEMS switches on the ground plane slot of the MRA element, a new RRA was introduced. In comparison with other tunable elements, RF MEMS switches have low insertion loss, high linearity, high isolation, low power consumption (nearly zero), good performance up to high frequencies and capability of integration with the antennas.

MRAs inherently have narrow bandwidth which is essentially caused by two parameters: the inherent narrow bandwidth of the microstrip array elements, and the frequency dependency of the phase delay of the radiated field from the horn antenna upon the array elements [39, 40]. In recent years, variety of methods has been used for bandwidth enhancement of MRAs. One of the common methods is using MRA with stacked microstrip patch elements [41–43]. The main drawback of this method lies in its high fabrication cost. There are other methods that use single layer structures. In [44] double crossed loops, in [45] cross shaped array elements, and in [46, 47] ring elements of variable size have been used on a single layer microstrip structure. The bandwidth enhancement of the MRAs is the most important problem of these antennas and is ongoing research concern.

It should be mentioned that in all of our reviewed publications, the effort had been either toward addition of reconfigurability feature to the fixed beam reflectarrays (FBRAs) or their bandwidth enhancement. To the best of our knowledge, so far, there has not been any publication for bandwidth enhancement of reconfigurable reflectarray antennas (RRAs) in literature.

In this paper, a novel bandwidth enhancement technique for microstrip reconfigurable reflectarray antennas using RF MEMS switches is introduced and studied. In Section 2, a circular patch, from amount of phase shifting and its slop, reflection amplitude and bandwidth point of view is studied. It is shown that this structure has good characteristics for reflectarray performance, in comparison to the previous works. In Section 3, a novel idea of bandwidth broadening for RRA of Section 2 is proposed. It is shown that the submitted method can be generalized to attain phase shifting of much larger than previous works. In Section 4, the RF MEMS switches are implemented in the introduced RA structure. Rajagopalan et al. in [38] have used a patch over substrate with slotted ground plane as a base element for S-band and proved its practical competency by measurement. Acknowledging their work in establishing the credibility of this element, we have developed a similar element in X-band to demonstrate our novel bandwidth enhancement method for reconfigurable reflectarray antennas. In our proposed technique, several other slots have been cut through the ground plane.

2. ARRAY STRUCTURE

2.1. Array Modeling

We have used Ansoft High Frequency Structure Simulator(HFSS) software for array modeling and simulation, and waveguide method ([38, 47, 48, 50–52]) for reduction of simulation time. The waveguide method is a powerful method which most researchers have used for many years in reflectarray antenna simulations, even, some publications have benefited from its power and competency in measuring the overall array performance. Namely, instead of constructing the whole array, measurements are done on equivalent structure which is composed of an element situated inside a waveguide [38]. The theory of this technique is thoroughly investigated by Tsai and Bialkowski [48]. Based on the proficiency of this method, in recent works on reflectarrays [47], the measuremental validation of the structures has been replaced by simulation results of waveguide method.

The standard X-band waveguide of dimensions 22.86 mm × 10.16 mm, with inserted single array element has been used. The element comprises of a patch over the substrate backed by slotted ground plane, as represented in Figures 2(a) and 2(b). The slot width is selected to be 1.8 mm, based on the Radant MEMS SPST-RMSW100 RF MEMS switch dimensions of 1.45 mm × 1.45 mm × 0.25 mm. However, the array performance deploying smaller switches are also studied. The TEM mode is used as an incident wave on the element. In order to create such a mode in rectangular waveguide, two of side walls are assumed to be electrical conductor and the other two as magnetic conductors [48], as represented in Figure 2(c).

In order to investigate the effect of the substrate height, we have examined the return loss and phase shift of a typical array of circular patch of 4.25 mm radius. It should be noted that in the reflectarray a large return loss and linear phase shifting is desirable. Figure 3 depicts the effect of the substrate height in return loss and linear region of phase shifting. It is obvious that the return loss is not affected by height increments, while the slop of phase shifting is decreased. Notice that the cost of this linearization of phase shifting diagram was decrement of overall phase shift. Based on these results and also the size of RF MEMS switches, a substrate with standard height of 62 mil (1.574 mm) was chosen.

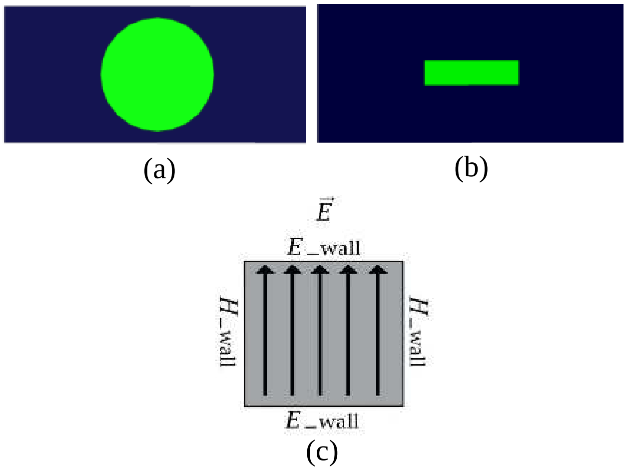


Figure 2. Array element: (a) Top view, (b) bottom view and (c) equivalent unit cell waveguide model.

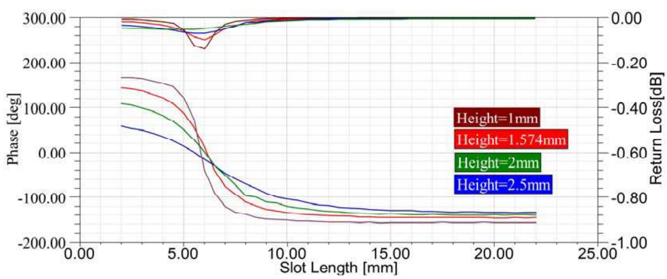


Figure 3. Reflection amplitude and phase for various substrate heights.

A brief yet important investigation of the effects of the substrate parameters on the structure performance is represented in Figure 4. Two substrates, Foam and RT duroid (5880) with static dielectric constants of 1.005 and 2.2, respectively, are considered. It can be seen from this figure that for substrate with bigger dielectric constant, the linear phase shifting region occurs at smaller length of ground plane slot. Thus, using RT duroid (5880) substrate guarantees the slot length of much less than half wavelength and, hence, minimization of back radiation of the structure. Employing substrates with higher dielectric constants, despite of lowering the slot length for linear phase shifting region, would result in degradation of radiation characteristics of the structure.

2.2. Circular Patch

Here, we consider a circular patch over a substrate which is backed by slotted ground plane. The rectangular slot is cut through the ground plane and is located symmetrically beneath the patch. The phase shift and return loss for several values of patch radius is illustrated in Figure 5. As it is obvious from this figure, in most cases the phase shift is about 310° with a low slop. The return loss is very small and less than 0.32 dB. The achieved phase swing occurs between slot lengths of 2.5 mm–12.5 mm. This ground slot length variation over 10 mm region is consistent with the size of RF MEMS switches.

It can also be seen from Figure 5 that increments of patch radii results in phase shifting decrements. However, linear phase shifting region occurs in smaller slot lengths and as it was mentioned earlier, this guaranties the largest slot length to be much smaller than half wavelength. The patch and slot radiations for a patch of 2 mm and 4.25 mm radii are shown in Figure 6. It can be observed that for a patch of 2 mm radius, the slot radiation is intense, and thus, the

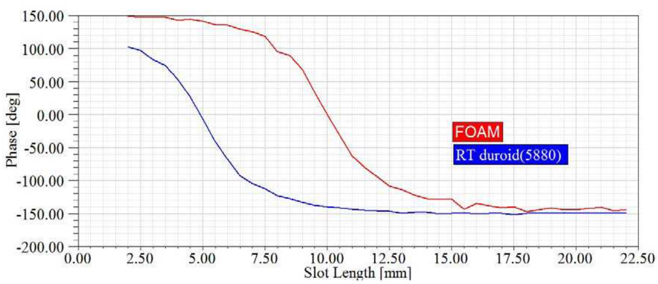


Figure 4. Reflection phase for various substrate permittivity.

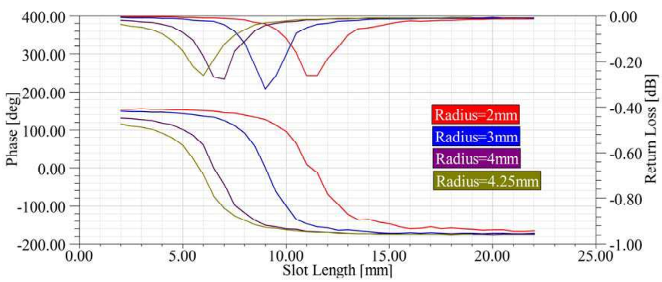


Figure 5. Reflection amplitude and phase for various circular patch radii.

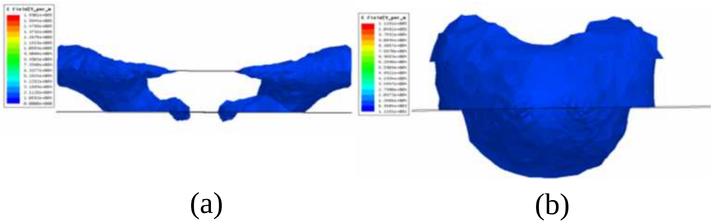


Figure 6. Field distribution for: (a) Radius=4.25 mm, (b) radius=2 mm.

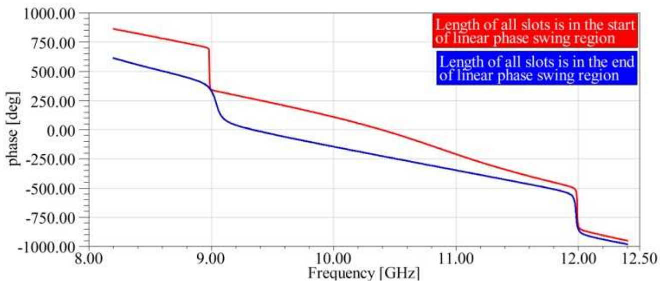


Figure 7. Bandwidth of reflectarray using circular patch elements.

structure would have high back radiation.

Based on the results of Figures 5 and 6, a circular patch of 4.25 mm radius is selected and its bandwidth performance is studied. Radii of larger than this value were not chosen, since that would cause phase shifting degradation. As we know the reflectarray bandwidth is the frequency range for which the array phase shift is approximately constant. Figure 7 represents the phase shift for two values of slot length over the X-band.

In this analysis, the slot lengths of 2 mm and 10 mm are used, which are the beginning and ending points of the linear region of the phase swing diagram. Although, the slot lengths beyond these values could also be used, resulting in larger but impractical bandwidth, since, in practice, it is desirable to obtain larger phase swing with smaller number of switches. In other words, the linear region of the phase diagram should be used.

3. BANDWIDTH ENHANCEMENT

Here, a new method of bandwidth enhancement is introduced. First, the idea is implemented to the RRAs with circular patch elements, and then it is generalized. As discussed earlier, the ground plane slot has significant role in the phase swing of the reflected wave. It was shown that the slot length in the range of about 2.5 mm to 10 mm creates linear phase shift. Here we explain this idea for array of circular patch elements.

Frequency dependency of path delay is the source of degradation in reflectarray performance which causes lower bandwidth. In order to overcome this problem, we propose adding more ground plane slots surrounding the central slot. In this case, the wave has to travel different distances at different frequencies to reach different slots. Therefore, better RRA performance would be possible at larger bandwidth.

In our proposed method several parallel slots are cut in the ground plane. Based on the operation frequency and the size of available RF MEMS switches, the width of slots are chosen to be 1.8 mm. Having practical considerations in mind, the distances between slots are chosen to be 0.2 mm. Here, as an example, we have used three slots on the ground plane. However, as it will be explained later, the idea can be generalized to employ more slots to attain higher phase shifting. In order to attain the overall phase shift diagram, initially, all slot lengths are fixed at 4 mm which is the starting point of the linear phase swing region of single slot. Then, the slot lengths are varied continuously, one at a time toward the end of linear phase swing region, to obtain the maximum overall phase shift.

In the first stage of design process, we increase the length of the middle slot until the point that the slot length increments have negligible effect on the phase shift. This point marks the end of first stage at the slot length of 12 mm. In the second stage, while the length of the middle slot is at the marked value of the first stage, the length of one of its adjacent slots is increased. The second stage ends when the slot length reaches to 12 mm, the point that the phase shift becomes constant. This process is pursued for other slot as shown in Figure 8.

It should be obvious that in practical applications, the ground plane slots are cut with the final designed values. Then, RF MEMs switches are implemented to decrease their lengths, discretely. This idea can be implemented for all structures that are comprised of a patch on the substrate and slot on the ground plane.

The bandwidth of our proposed RRA with circular patch elements is represented in Figure 9. It is obvious that the introduced reflectarray covers the entire X band and removes the significant MRAs disadvantages.

Now, we are going to show the generalization capabilities of the introduced method. We insert 2 more slots (overall 5 slots) on the

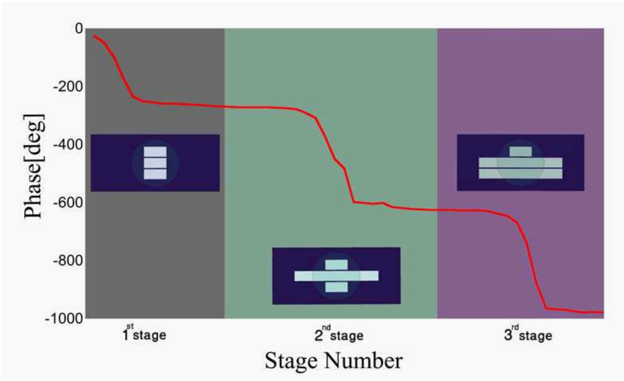


Figure 8. Overall enhanced phase shifting for RRA using circular patches elements.

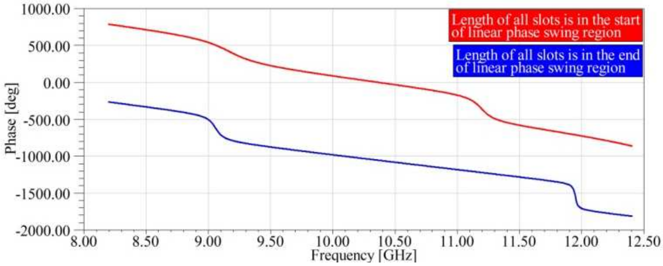


Figure 9. Bandwidth of proposed reflectarray using circular patch.

ground plane. The phase swing and bandwidth of this new structure is presented in Figure 10. For comparison purposes, the bandwidth results for FBRA of [40] are also included in this figure. The phase bandwidth (dotted blue double arrow) in [40] is obtained as the phase difference between two cases of largest (solid line) and smallest (dashed line) possible patch radius of array elements. The illustrated bandwidth of our method in this figure is obtained as the phase difference (dotted red double arrow) between two cases where either the lengths of all slots are at the initial point of the linear phase swing region (solid line) or at the final point (dashed line). Our achieved larger phase bandwidth in comparison with [40] is obvious from this figure. Although, the advantage of our novel method not only lies in its better bandwidth enhancement but also in its applicability to reconfigurable reflect array antennas, while bandwidth enhancement method of [40] is only applicable for fixed beam reflect array antennas.

It is also obvious form comparing the results of our method in

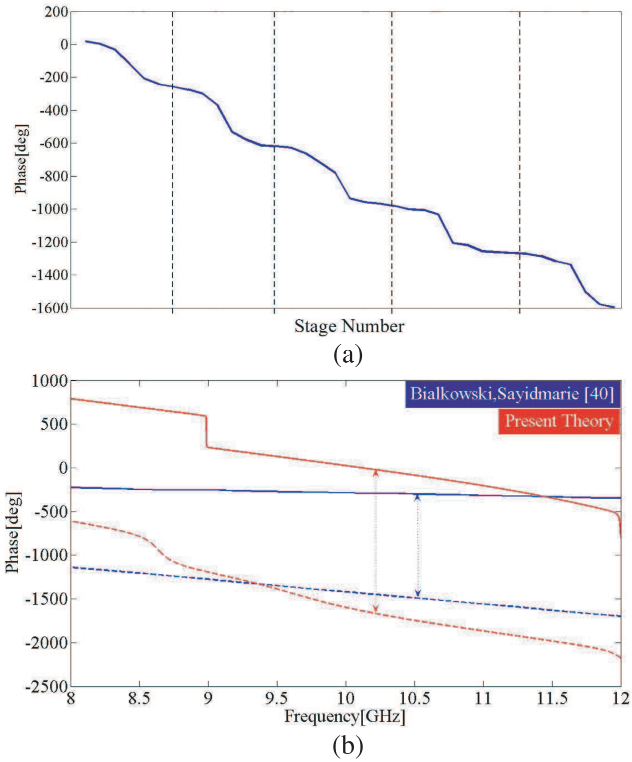


Figure 10. (a) Phase shift and (b) the comparison of the bandwidth results of our method with [40].

Figures 9 and 10 that increasing the number of slots has resulted in more phase shifting and bandwidth improvements. However, due to space limitation, the number of slots could only be increased if the RF MEMS switches of smaller sizes are used, as to be discussed later.

4. RF MEMS SWITCHES MODELING ALONG WITH REFLECTARRAY

Up to this stage, one could assume that the slot lengths were varied by a conducting connection that covered the slot width. However, in practical applications, slot length variations are accomplished by RF MEMS switches. Now, for accurate analysis of the array, we model the switches in the reflectarray. For modeling of the switches, we have used the model that has been introduced in [38]. As Figure 11(a) represents, four RF MEMS switches are used for each slot. The operations of the modeled switches in on and off states are shown in Figure 11(b). The Son (switch is on) shorts out the current, and thus the electrical length of slot is decreased. High current density over this switch shows its proper operation. On the other hand, the small value of current density over the switch in off status represents its insignificant effect on the slot performance.

The phase shift diagram for discrete variations of slot length by RF MEMS switches is given in Figure 12. To obtain this diagram, unlike the case of continuous variation, the length of slots are initially at the end value of their linear phase swing region, with all switches being in off position. Then, as the switches go to the on state, the electrical lengths of the slots are decreased, and the required value of the phase shift would be obtained. Although there is a practical limitation on the number of RF MEMS switches that could be used, with limited number of switches, the whole coverage of the slot length is not possible. Therefore, the attained phase swing would be lower than that we acquired in the case of continuous slot length variation. Figure 12 and Table 1 show the phase swing for discrete variation of

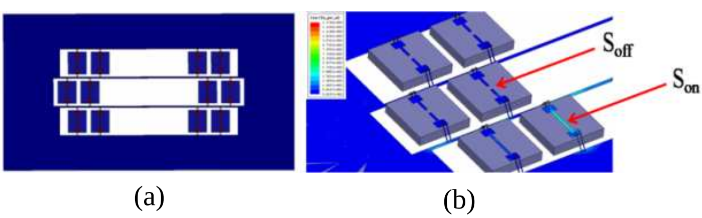


Figure 11. (a) Simulation model for the RF MEMS switches (bottom view) and (b) operations of the modeled switches in on and off states.

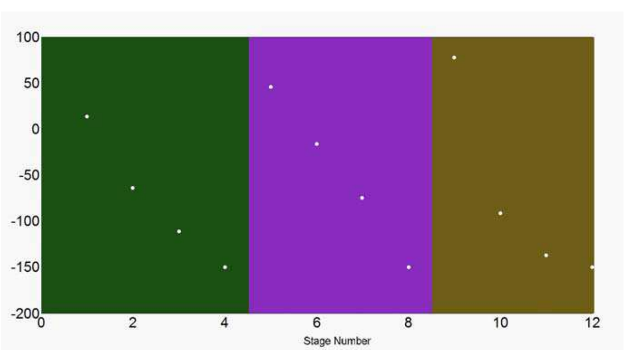
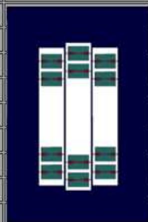
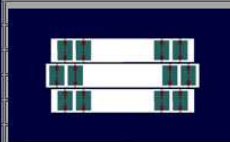


Figure 12. Reflection phases for different switch states.

Table 1. Simulation results of reflection amplitude for 19 various states.





Stage Number	Slots State	Switches State	Normalized Phase
1	0-0-x	0-0-0-1	-150
2		1-0-0-1	-136.95
3		0-1-1-0	-91.54
4		1-1-1-1	78.33
5	x-0-15	0-0-0-1	-150
6		0-1-1-0	-74.58
7		1-0-0-1	-15.71
8		1-1-1-1	46.03
9	15-x-15	0-0-0-1	-150
10		1-0-0-1	-110.95
11		0-1-1-0	-63.93
12		1-1-1-1	13.3

lengths of slots. For the achievement of this diagram, the symmetric states of the RF MEMS switches and their closer phase swing states are neglected.

5. CONCLUSIONS

The phase swing and bandwidth performance of circular patch as elements of reflectarrays were investigated. The reconfigurable feature was added to these reflectarrays, by means of RF MEMS switches. These elements have slots on the ground plane that made the implementation of the switches easy. A novel ideal for bandwidth enhancement of the investigated reflectarrays were introduced and implemented. With four RF MEMS switches on each slot of the structure, a broadband reconfigurable reflectarray was attained. Results showed that the proposed reconfigurable reflectarrays cover the entire X band. The generality performance the proposed idea was also established. In this work, the main concern was presenting the novel bandwidth enhancement method for reconfigurable microstrip reflectarray antennas. Therefore, we did not present any discussion about biasing of RF MEMS switches. Bias circuits can readily be implemented using high resistivity lines with minimal effects on array performance. Interested readers about biasing methods of RF MEMS can refer to [38, 49, 53].

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