Slotted Tunable Reflectarray Antenna

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***Abstract* — This paper presents a detailed investigation on the phase agility of reflectarray antennas designed in the X-band frequency range. A novel technique for the analysis of the required reflection phase from individual reflectarray elements to form a planar wavefront of the periodic aperture is presented. Various slot configurations embedded in the patch elements of reflectarrays are also proposed for the performance improvement of reflectarray antennas. The feasibility of using these slot configurations for frequency tunable reflectarrays and designing periodic structure of slotted patch elements are also demonstrated. The designed reflectarray antenna with attainable frequency tunability of 1700MHz, demonstrated that a maximum dynamic phase range of 320° and a volume reduction of up to 24.36% are achieved at 10 GHz.**

***Index Terms* — Reflectarray; phase agile; frequency tunable; dynamic phase range.**

I. INTRODUCTION

A microstrip reflectarray is a planar reflector which was proposed as a future candidate high-gain antenna [1]. It consists of an array of microstrip patches on the grounded dielectric substrate illuminated by a primary feed horn which is placed at a particular distance from the array. The individual elements of the array are designed to scatter the incident field with proper phase distribution required to form a planar phase surface in front of the aperture [2]. Different techniques have been proposed for this purpose such as identical microstrip patches with variable length phase delay lines to compensate for the phase delays over the different paths from illuminating feed [2]-[3] variable size patches, dipoles or rings [4]-[6] to vary the scattering impedance of elements and eliminate the effect of different path lengths and variable rotation angle of elements [7] for circular polarization. Because of its flat structure and low profile characteristics, a reflectarray antenna is considered to be a suitable alternative for the bulky parabolic and expensive phased array antennas.

However narrow bandwidth performance and high losses are some of the factors that limit its use in many applications [8]. The dependence of reflectarray performance on the substrate thickness and material properties is discussed in [9] while this paper provides novel configurations of patch elements to enhance reconfigurable reflectarray antenna performance. Moreover the technique that is used to determine the required reflection phase from the individual element is also described in this work.

II. ALGORITHM FOR REFLECTION PHASE

In the absence of a microstrip patch element, the resulting electric field will be the sum of incident and the field reflected from the grounded dielectric slab [9].

$$\bar{E}_{tot} = \bar{E}_{inc} + \bar{E}_{ref} \qquad (1)$$

Where, $\bar{E}_{tot}$ is the total electric field vector, $\bar{E}_{inc}$ is the incident electric field and $\bar{E}_{ref}$ is the electric field vector for ground plane reflection. But in the presence of the patch element, the resulting field induces currents on the surface of the perfectly conducting patch element and the surface current density J_s causes radiation in the presence of grounded dielectric slab to produce scattered electric fields in the dielectric substrate and the air region. Hence the total electric field is given by:

$$\bar{E}_{tot} = \bar{E}_{inc} + \bar{E}_{ref} + \bar{E}_{scat} \qquad (2)$$

Where, $\bar{E}_{scat}$ is the vector for the electric field scattered by the patch elements. As the surface current Js on the conducting patch is varied by applying one of the phasing techniques mentioned above, the scattered electric field varies and produces a change in the reflection phase of a reflectarray. Waveguide simulators are usually used to perform the scattering parameter measurements of a reflectarray. Therefore the individual elements are needed to be analyzed in the presence of the waveguide simulator. General relation for the calculation of total electric field in the plane of a microstrip radiator for a waveguide simulator technique shown in Fig. 1 can be derived from equation (1) and equation (2) which is given by the following relation [10].

$$\tilde{\bar{E}}_{tot} = \tilde{\bar{G}}.\tilde{\bar{J}} + \tilde{\bar{E}}_{inc}\left(1+\tilde{\bar{\Gamma}}\right) \qquad (3)$$

Where, $\tilde{\tilde{E}}_{tot}$ is the vector of tangential electric field, $\tilde{\tilde{G}}$ is Green's function, $\tilde{\tilde{J}}$ is the current density, $\tilde{\tilde{E}}_{inc}$ is the vector of incident electric field and $\tilde{\tilde{\Gamma}}$ is the reflection coefficient. As the electric field is excited in the Y-direction, the total electric field then can be given by:

$$\tilde{\tilde{E}}_{ytot} = \tilde{\tilde{G}}_{yy}.\tilde{\tilde{J}}_{y} + \tilde{\tilde{E}}_{y,inc}\left(l + \tilde{\tilde{G}}_{yy}\right) \qquad (4)$$

Where, l is the length of the unit cell patch element and J_y can be given by:

$$J_y = \sum_n A_n \varphi_n(x, y) \qquad (5)$$

Where A_n is the unknown vector coefficient and can be obtained using Glarekin's procedure. Once the current density J_y is known, the current on the surface of the patch element can be determined by taking the surface integral of current density as:

$$I = \int Jds \qquad (6)$$

In order to calculate the required phase which enables the conversion of the spherical wave radiated by the feed horn into a planar wave, the basic geometry of reflectarray shown in Figure 1 can be considered.

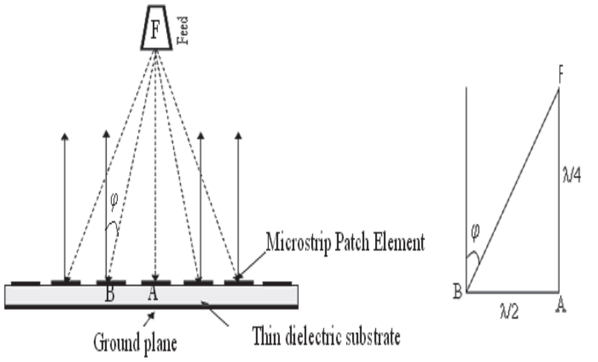


Fig. 1. Basic geometry of a reflectarray showing the inter element spacing of λ/2 and distance between feed and patch A to be λ/4

As depicted in Fig. 1, it can be observed that φ, which is the reflection phase from the individual patch of an array is changing in order to form a planar phase wave in front of aperture. By using the trigonometric ratio, we can find the required reflected phase from individual patches by:

$$\phi = \begin{cases} k_l - \tan^{-1}\left(\dfrac{d_p}{nd_{ie}}\right); \ldots\ldots n < 0 \\ k_r + \tan^{-1}\left(\dfrac{d_p}{nd_{ie}}\right); \ldots\ldots n > 0 \end{cases} \qquad (7)$$

Where, d_p is the port distance and d_{ie} is the distance between two consecutive elements while k_r and k_l are angle in degrees for the patch elements on right and left of the central patch which offers the phase range of the curve associated with the material properties of substrate used for reflectarray design.

III. EFFECTS OF SLOTTED PATCH ELEMENTS

The current on the surface of the patch element can be significantly modified by the introduction of rectangular slot in the patch element. The 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. The modification of the surface current distribution on the patch element 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 (Js) which furthermore reduces the amount of current (I) according to Maxwell's equations [11]. 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.

The dependence of reflectarray performance on the surface current density and electric field intensity has been demonstrated in [12] with the help of lumped components.

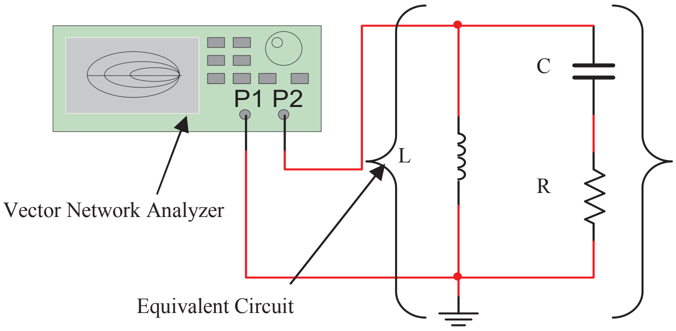


Fig.2. Equivalent circuit model of a typical reflectarray connected to a Vector Network Analyzer

Fig. 2 shows an RLC resonant tank as the equivalent circuit model of a reflectarray. The equivalent circuit is connected to the vector network analyzer in order to perform scattering parameter measurements. It has been demonstrated that different material properties and configurations of elements produces different resistance, inductance and capacitance in the equivalent circuit and hence varies the reflectarray output characteristics.

In order to validate the theory presented above, various configurations of slots embedded in the patch elements have been fabricated on Rogers 5880 dielectric substrate and the scattering parameter measurements have been carried out using vector network analyzer.

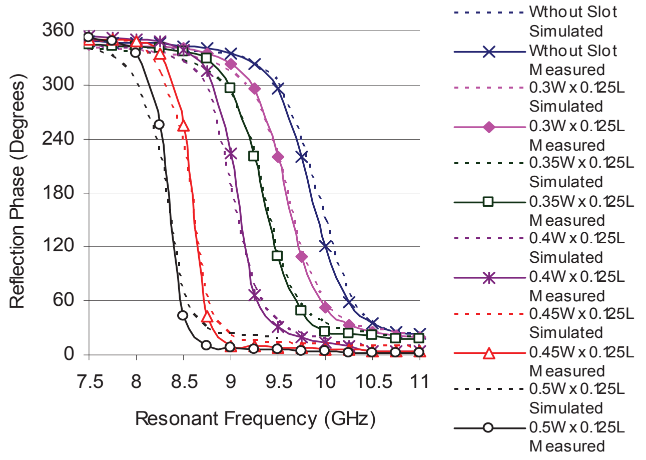


Fig. 3. Reflection phase curves for variable width rectangular slots

Fig. 3 shows the reflection phase curves for the variable width slots embedded in the centre of the unit cell patch elements. Frequency tunability from 10 GHz to 8.3 GHz can be observed from the reflection phase curves. Moreover a reduction in the volume of reflectarray up to 24.36% can also be achieved if slots with the width of 0.5W are used for design at 10GHz.

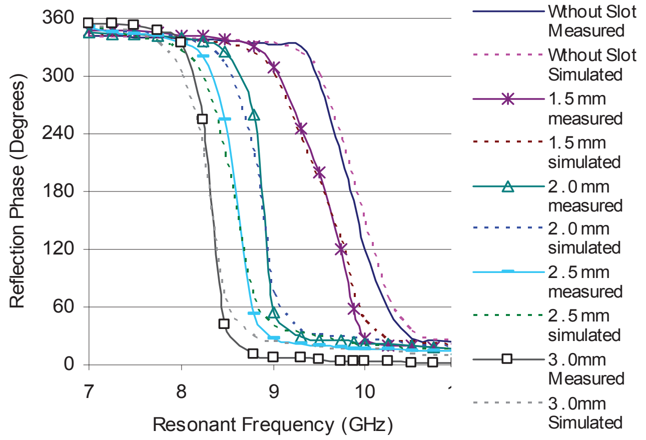


Fig. 4. Reflection phase curves for variable circular slots

Fig. 4 shows the comparison of measured and simulated results for circular slots in the centre of the patch element. As in the case of rectangular slots, patch elements with circular slots also showed the feasibility of designing frequency tunable reflectarrays.

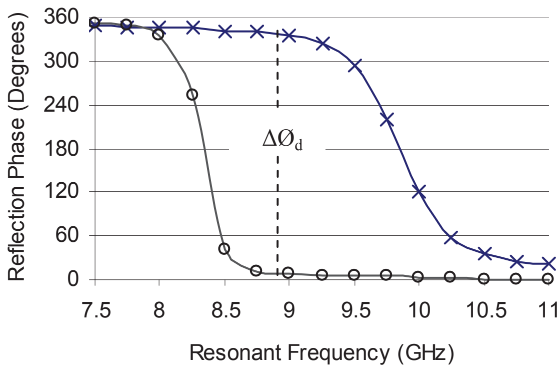


Fig. 5. Dynamic phase range for a slotted patch element

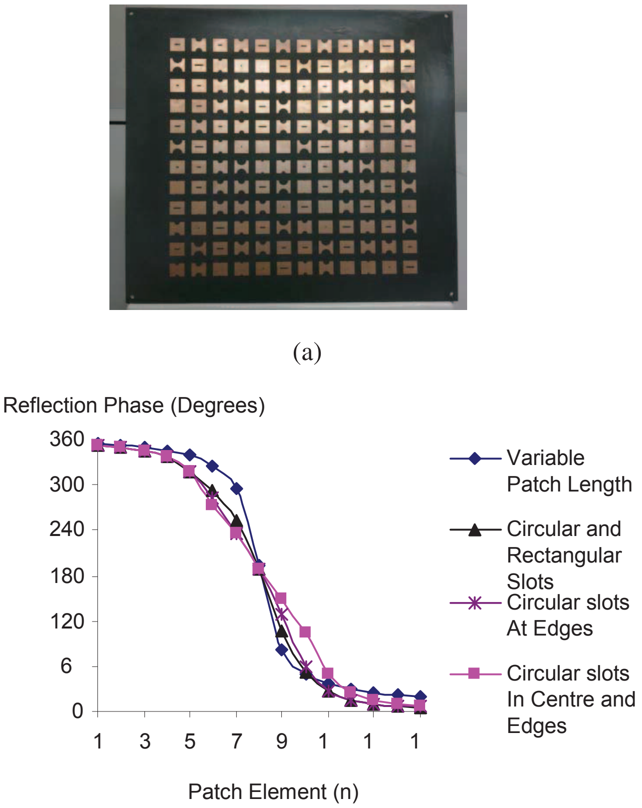
Fig. 5 shows the dynamic phase range (Ød) achieved by the introduction of a slot in the patch element of reflectarray. A maximum measured dynamic phase range of 320° is demonstrated in the case of 0.5W rectangular slot.

IV. Periodic Array Using Different Combinations of Slotted Patch Element

In section III, the use of slotted patch elements for the design of a tunable reflectarray is explained while in this section, different combinations of the slotted patches have been utilized to design a periodic array of reflectarray elements. Various slot configurations have been demonstrated in [13] to design a complete periodic reflectarray that covers X-band frequency range. The primary advantage of employing slotted patches is that the equal dimensions of all slotted patch element reflectarray design. Hence the variation in the scattering from patch and reflection from ground plane can be avoided. This effect therefore provides the opportunity to limit the mutual coupling effects.

Another significant advantage is the reduction of phase errors. In the design of reflectarray with variable size patches, the phase errors occur due to the fact that the for smaller patches the reflection takes place from the ground plane while the larger patches occupy most of the area of unit cell where the reflection is mainly caused by the patch surface. This causes a difference in the path length resulting in phase errors of the periodic structure of reflectarray antenna.

On the other hand the reflectarray design with slots in the patch elements have a constant patch size which limits the phase errors caused by the difference in patch size of the elements away from resonance. It is also shown that the reduction in the phase errors also causes an enhanced bandwidth performance of the reflectarray with variable slots in patch element.



(a)

(b)

Fig. 6. (a) Fabricated 12 x 12 reflectarray using slots
(b) Results showing better bandwidth performance as compared to variable patch reflectarray

Fig. 6 (a) and (b) shows a fabricated 12 x 12 element reflectarray with slot embedded in the patch element and the comparison of different configuration used for reflectarray design. It can be observed from Fig. 6 (b) that the reflection phase curve for "variable patch length" gives the maximum slope as compared to other three combinations. While the combination of "circular slots in the centre and edges" shows minimum slope of the reflection phase curve around the resonance. Additionally the phase errors which can be seen from attainable linear phase range defined in equation (2) are also reduced in the case of slots in the patch element as compared to variable length slots.

V. CONCLUSION

An algorithm for obtaining the required reflection phase from the individual elements of a reflectarray antenna is presented that can be used for designing a reflectarray producing a planar wave in front of aperture. Different slot configurations have been discussed to realize a tunable reflectarray antenna design with a wide dynamic phase range. The slots embedded in the patch elements with different combinations have also been discussed for designing a periodic array. The results of the proposed design are compared with conventional design and a significant improvement in the reflection phase and bandwidth performance has been demonstrated.

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