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Design of Capacitive Integrated Reflectarray Radiating Elements for Beam Scanning Reconfigurability

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Abstract: The design of reconfigurable reflectarray with a single varactor to provide capacitance effect embedded inter-patch are presented. The essence of this concept lies in the behavior of the capacitance variation contributes to phase changes of element. Simulated radiation patterns with single element phase characteristics as a reference are reported to demonstrate reconfigurability of elements for beam scanning at Ku-band. The consistency in pattern and value of single and 2×2 sub-array will provide guideline and indicator on how to get promising beam scanning result for full reflectarray fabrication and measurement. The radiation pattern of linear array by three different elements with 35° scanning angle at Ku-band is analyzed and has confirmed the important of single and sub-array characteristics in array realization.

Key words: Reflectar ray antenna, reconfigurable, capacitance, tunable, Ku-band

INTRODUCTION

Reconfigurable reflectarrays have recently attracted tremendous interest as they combine the favorable features of phased-array antennas and mechanically-scanned reflectors with low-mass and low-profile features (Huang, 1991; Pozar and Metzler, 1993). It is not just can be conformal to the mounting surface but their main beam can be designed to point at a large fixed angle (up to 600) from broadside direction without bulky and complex feeding network (Boccia September, 2001). Each reconfigurable reflectarray element is designed to collimate the main beam to desired direction (Abd-Elhady, 2012a, b). Beam scanning and pattern recon gurability have found a great demand in the fields of wireless communications, satellite communications and radar with ease of manufacturing and handling. This active antennas can be used in many applications such as space probe communication, weather research, radio-frequency identification, broadcasting, low-profile and low cost in-motion satellite TV reception system, earth science missions, earth based sensors for remote sensing and application to satellite TV (Hajian *et al*., 2006).

Array is a configuration of elements arranged in certain grid as an advantage to be placed onto any surface by controlling the phase of the reflected wave as shown in Fig. 1. The required phase distribution at each element of the array $\phi_R\,(x_{ce}, y_{ce})$ to collimate a beam in the (θ_0, ϕ_0) direction is determined as: Eq. 1 and 2 by considering the array on the x-y plane illuminated by a feed horn (Abd-Elhady *et al*., 2010):

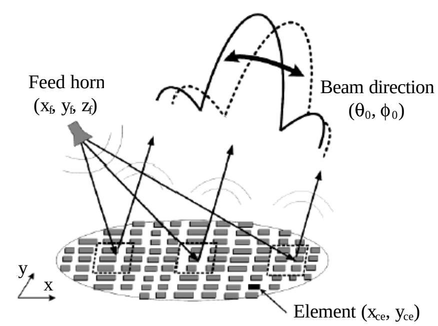

Fig. 1: Beam scanning configuration of reflectarray antenna

$$\varphi_R\,(x_{ce}, y_{ce}) = k_0\,[d_i - x_{ce}\sin(\theta_o)\cos(\phi_o) - y_{ce}\sin(\theta_o)\sin(\phi_o)] \tag{1}$$

$$d_i = \sqrt{(x_{ce} - x_f)^2 + (y_{ce} - y_f)^2 + z_f^2} \tag{2}$$

where, k_0 is wave number in free space, (x_{ce}, y_{ce}) is coordinates of reflectarray unit cell, (x_f, y_f, z_f) is coordinates of feed phase centre and (θ_0, ϕ_0) is the desired direction of the main beam.

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The general design procedure in reflectarray antenna is to determine the phase diagram that provides the data needed for designing the individual elements in planar form array. The phase diagramphase diagram as a function of variable parameters such as length, width and rotation angle behaviour simulated by single element will be used as a reference to design the reflectarray antennas whereas the other parameters are kept the same. For reconfigurable reflectarray, the variable parameter is such as capacitance of varactor diode and ON OFF state of PIN diode. In reflectarray element, the validity of the concept is applicable for passive design where the variation of single element and array is not a major problem but for element with active component, it is not considered to be the same. Most of a reconfigurable antenna is identical in geometry and shape but the assumption of single element characteristics could not be true without considering the effect of active component location embedded on the patch.

Commonly, the phase diagram as a function of capacitance behaviour simulated by single element will be used as a reference to get the required phase to design the array antenna. In this study, a design procedure and more accurate simulation result can be achieved comprehensively by analysis approach of a single element and sub-array of 2×2 with small set of identical elements. Three different elements namely Concentric Circle Square Ring (CCSR), Circle Ring Patch (CRP) and Circle Ring Gap (CRG) are presented to discuss about the effect of single element and sub-array of 2×2 to achieve the promising radiation pattern hence the possibility of array configuration could be realized.

MATERIALS AND METHODS

Single and sub-array reflectarray element: The geometry of the Ku-band single element is presented in Fig. 2. The three designs of reflectarray elements proposed namely Concentric Circle Square Ring (CCSR), Circle Ring Patch (CRP) and Circle Ring Gap (CRG) are designed using the commercial software CST and specifications are mentioned in Table 1. The cell dimension, d is 0.42-0.47 λ_0 with close element spacing that less than or equal to half wavelength ($\lambda_0/2$) in preventing the grating lobes (Abd-Elhady, 2012a, b) and requirement for a large scan angle (Venneri *et al*., 2013). A single varactor diode is integrated inter-patch on each element on grounded substrate. A plane wave is linear horizontal polarization along the positive y-direction and with normal incidence on the patch. Dimension of a single element is selected to resonate at the desired frequency band. This shift in resonance leads to the change of the reflected phase. The phase diagram for designing reflectarray antenna is based on variation of capacitance. The results are optimized using the full wave EM field simulator CST. The dielectric constant and thickness of the Rogers 5880 substrate are ε_r = 2.2, h = 0.787 mm, respectively with a loss tangent, tan δ = 0.00 09 (Table 1).

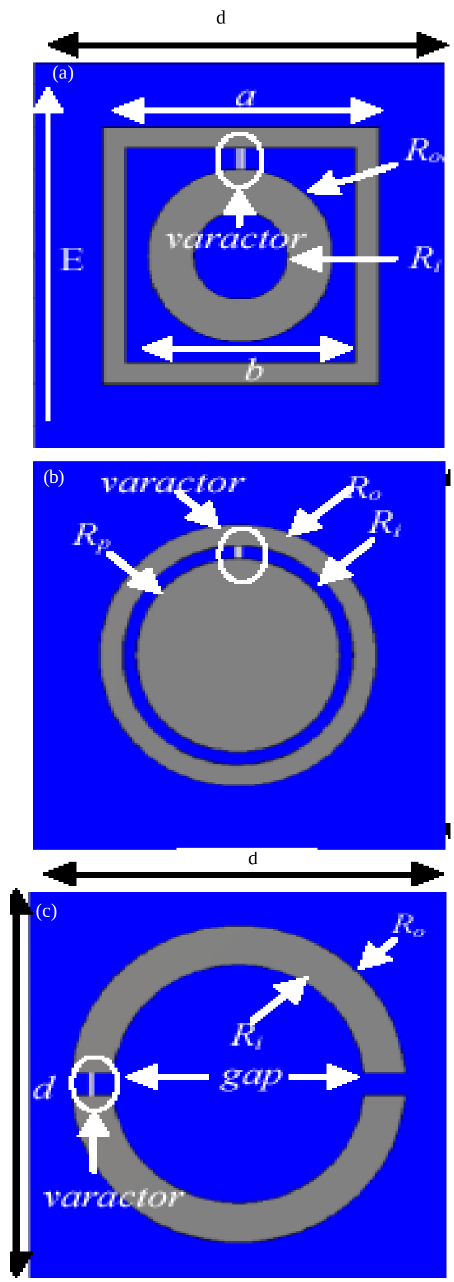

Fig. 2: Geometry of reflectarray element: a) CCSR; b) CRP and c) CRG

Table 1: Specification of designs

Specification	Design 1 (CCSR)	Design 2 (CRP)	Design 3 (CRG)
Copper (mm)		0.035	
Cell dimension, d (mm)	0.42 λ_o	0.42 λ_o	0.47 λ_o
Parameter (mm)	a = 6	R_p = 2.2	gap = 1
	b = 5		
	R_o = 2	R_o = 3.0	R_o = 4
	R_i = 1	R_o = 2.5	R_i = 3

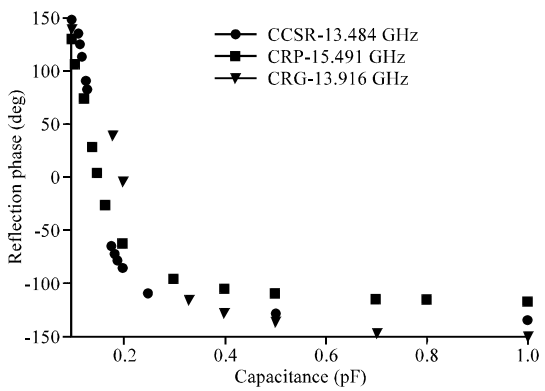

Fig. 3: Reflection phase versus capacitance of three reflectarray elements at Ku-band

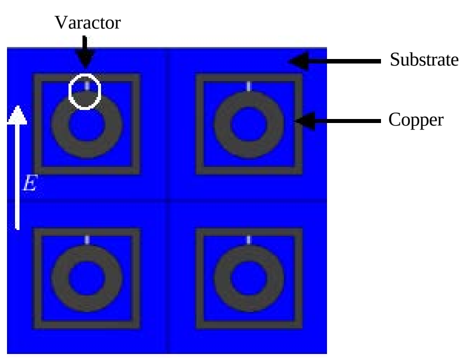

Fig. 4: Geometry of 2×2 sub-array CCSR reflectarray element

The voltage supply to varactor was varied to observe the phase shift around the resonance frequency. The variation of phase with respect to capacitance from range 0.1-1.0 pF is shown in Fig. 3 for three different designs and demonstrate a reflection phase versus frequency characteristic behaviour. By examining the figure, a variation of approximately 300° is observed at Ku operational frequencies. This figure represents the data needed for the array design and it is required to stay within the slope of the curve for design purposes (Hajian *et al*., 2006).

The behaviour of single element and array of 2×2 elements were investigated before designing the array antenna. Figure 4 shows a 2×2 CCSR elemen ts with 0.42, λ_0 centre to centre spacing in x and y direction as an example of array arrangement. This inter-patch spacing is acceptable for less pronounced of mutual coupling and the change in resonance frequency (Karnati *et al*., 2012). The reflected phase of both configurations will be compared to demonstrate that the reflected phase diagram of a single element can be used appropriately in array antenna design. The optimization process of element has been carried out for linear polarization and normal incidence.

RESULTS AND DISCUSSION

Figure 5 shows the direction of port excitation and surface current on the elements with the presence of capacitance. It can be observed from Fig. 5a that the distribution of maximum current on the surface of the CRG in the left and right side of the ring patch occurred when the electric field is excited in the y-direction. High concentration of surface current is seen in x-direction between proximity element of CRG compared to CCSR and CRP in Fig. 5b and c. Therefore, the elements are being less coupled for both designs than CRG (Islam and Alam, 2013). The strong couple of CRG element results in degradation of the radiation characteristic versus scan angle (Kwak *et al*., 2013).

The three elements having a quasi pattern and value for both single and 2×2 array result. For CCSR and CRP element as shown in Fig. 6a and b, the phase matches very well. A very good agreement in phase curve between single and sub-array of 2×2 is shown but for CRG the phase is shifting extremely greater in array arrangement. It is observed that the simulated reflection phase for CRG exhibits 20-130° variations for the both single and 2×2 array from capacitance range of 0.1-1.0 pF at 13.916 GHz.

Tunable reflectarray design: The reflectarray consists of an array of equally separated antenna elements. A linear reflectarray of varactor loaded microstrip antenna has been designed to scan the beam in one plane only. As shown in Fig. 7, the array is made of 9×3 elements with uniform spaced based on each design. The elements have a similar physical structure and differ by active elements state. Antenna elements are designed to provide a constant phase gradient F along the interface. It modifies the wavefront of incident wave by altering its phase in a desired manner (Zou *et al*., 2014) as shown in Fig. 8. The gradient of phase shift generates an effective wavevector along the interface which is able to deflect light from specular reflection. The required progressive phase shift, Φ between elements is determined to get desired scan angles (Hajian *et al*., 2006; Javor *et al*., 1995). Where, d is the element spacing, λ_0 the free space wavelength and θ_0

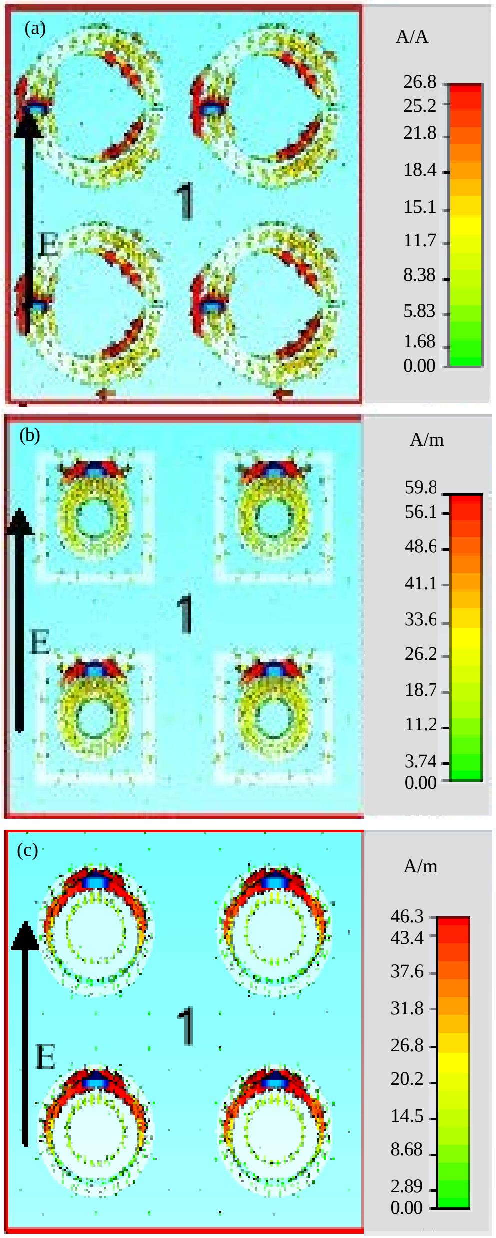

Fig. 5: Surface current of sub-array of three elements: a) CRG; b) CCSR and c) CRP

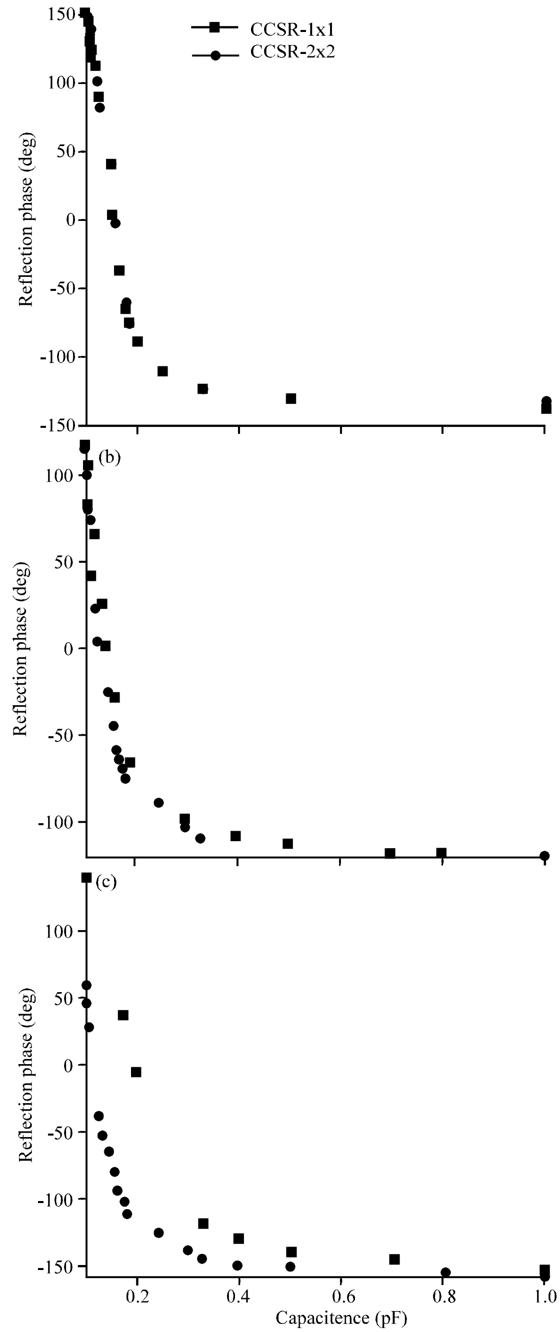

Fig. 6: Comparison reflection phase vs capacitance of single and 2×2 sub-array: a) CCSR; b) CRP and c) CRG

the scan angle. The elements are geometrically identical but the diodes are switched in different positions in x-direction to control the beam scanning far-field characteristics.

$$\Phi = -\frac{2\pi}{\lambda_0} d\sin(\theta_0) \qquad (3)$$

The simulated radiation patterns for three designs are shown in Fig. 9. A 35° scanning angle has been demonstrated from broadside direction in polar plot. From the simulation results, it is shows clearly that CCSR and CRP perform desired scanning angle as calculated previously, hence affirm that the matches pattern and value of reflection phase over capacitance value in simulation of single and array of 2×2 will lead to get promising radiation pattern. For CRG design, the main

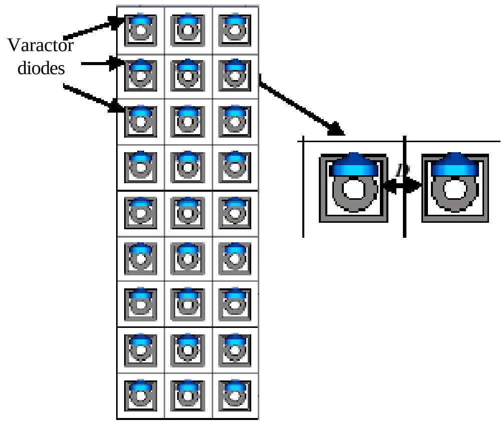

Fig. 7: CCSR linear reflectarray design

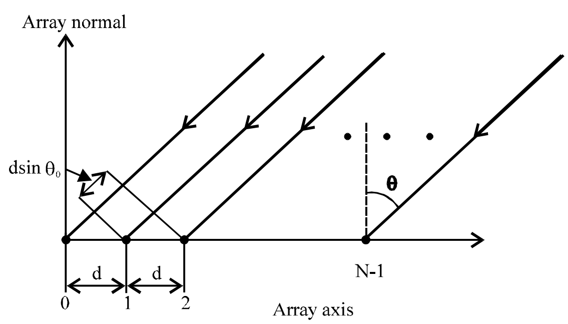

Fig. 8: Operation principle of the reflectarray

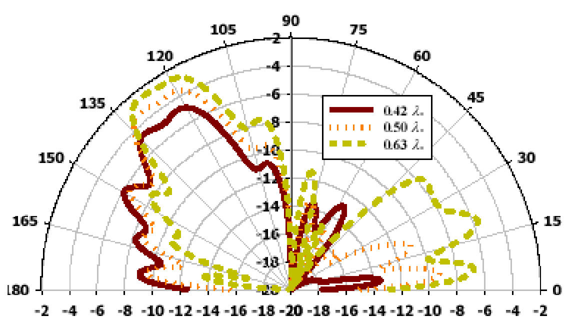

Fig. 9: Electric far field simulation results for 35° scan angle for CCSR, CRP and CRG

lobe and side lobe are almost in same value and pattern. The radiation pattern is not indicate scan angle required and agree very well that dissimilar value of reflection phase as mentioned above is affect overall radiation pattern required.

The important parameter in reflectarray design is element spacing and the number of elements. The antenna elements spacing are typically 0.5 λ_0 and increase up to 0.9 λ_0 particularly for fixed beam which are consist of

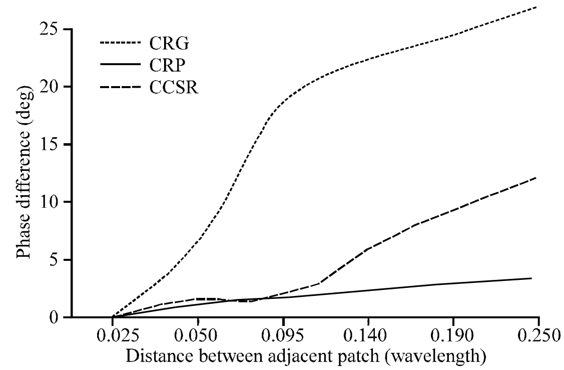

Fig. 10: Simulated phase difference of three reflectarray elements at Ku-band

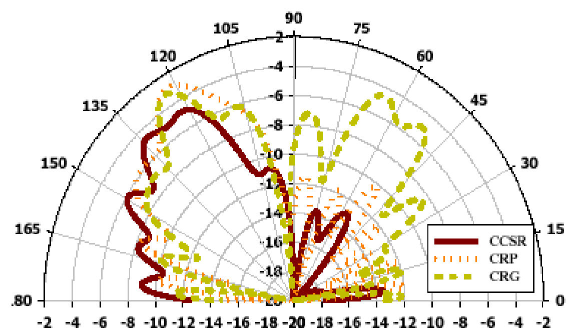

Fig. 11: Electric far field simulation results for 35° scan angle for CRG with different spacing

non-identical elements. It will increase the directivity but also a trade off with the side lobe levels. The variation of elements spacing will create the closer or larger distance, D between edge of the patch itself as shown in Fig. 7.

A wide range of spacing in x-direction is done by simulation of each design with different spacing from 0.025-0.25 λ_0 mm. Simulated values of phase versus edge spacing are presented in Fig. 10. It can be seen that there is a great variation in phase difference for CRG design compared to the other two. It will conclude that for edge separation of 0.025 λ_0 to one quarter wavelength of CRP and CCSR designs, the phase difference is insensitive to the spacing but the phase difference is more pronounced for CRG with phase variation up to 27°. The effects from inter-element spacing in array arrangement will cause the element to resonate at different frequencies and consequently resulting in a complete different radiation pattern, particularly at relatively small inter-element spacing (Karnati *et al*., 2012). Additionally, the effective electrical length of the patch looks longer than its physical length due to the capacitive effect. It can be observed in Fig. 11, the effect of different spacing in 0.42, 0.6 and 0.8 λ_0 to the radiation pattern. The larger distance will produce main beam with higher directivity but with the high side lobe level.

CONCLUSION

An analysis in single and sub-array for microstrip reflectarray elements provides guideline and indicator to get promising beam scanning result for full reflectarray fabrication and measurement. The radiation pattern of tunable array by three different elements with 35° scanning angle at Ku-band has confirmed the important of single and sub-array characteristics in array realization. The results given in this study are the initial study to design, build and measure the active capacitive loading reflectarray antenna for future research.

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