British Journal of Applied Science & Technology
4(34): 4807-4815, 2014
ISSN: 2231-0843

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Design and Analysis of Compact H-Like Element Microstrip Reflectarray Antenna for X-Band Applications

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Authors' contributions

This work was carried out in collaboration between all authors. Author MHW designed the study, performed the statistical analysis, and wrote the first draft of the manuscript and managed literature searches. Authors ASA and RSA managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/BJAST/2014/13300
Editor(s):
(1) Mark Vimalan, Department of Physics, Syed Ammal Arts and Science College, India.
Reviewers:
(1) Anonymous, Tunis El Manar University, Tunisia.
(2) Anonymous, AVIC LEIHUA Electronic Technology Research Institute, China.
Complete Peer review History: http://www.sciencedomain.org/review-history.php?iid=671&id=5&aid=6236

Original Research Article

Received 12th August 2014
Accepted 11th September 2014
Published 27th September 2014

ABSTRACT

This paper introduces a design and analysis method of a microstrip reflectarray antenna (MRA) with a proposed H-like shape radiating element at a frequency of 10.5 GHz. The proposed structure has been analyzed and compared with the traditional square shape one. It is found that the H-like element shape presents a good phase range to compensate for the frequency fluctuation of the differential spatial phase delay even when the single layer printed patches are applied. It is also found that this reflectarray has maximum realized gain of 29.3dB with radiation efficiency of 92.3%, half-power beamwidth (HPBW) of 5.6º, and very low side-lobe level (SLL) of about -32.4dB. This reflectarray is found to possess a volume reduction of about 43.24% compared with the traditional square shape one.

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Keywords: Microstrip antenna; reflectarray; H-like patch; X-band.

1. INTRODUCTION

The reflectarray antenna is constructed of many resonant patch elements laying on a flat surface, which is illuminated by a source feed [1]. Reflectarrays combine most advantages of parabolic reflectors and phased array elements to form a radiation beam as required in high gain antennas [2]. For satellite applications at higher microwave frequency bands, it is found difficult to manufacture parabolic reflector because of its curved shape [3]. Besides, phased arrays may support the losses and complexity of the antenna due to the power division of the transmission lines and any other electronic devices that attached to the antenna [4]. In space communication applications, reflectarray is preferred because their surface can be folded as a part of spaceship cargo before being deployed, hence, both volume and mass required in space application can be reduced greatly [5-6]. Phase compensation is vital in designing reflectarray, and it is so important for reflectarrays to behave exactly like ordinary parabolic reflector which will collect and re-radiate the particular rays to the marked position or receiver antenna. Otherwise, reflectarray will have the same behavior as a normal metal plate or ground plane where it will scatter the rays away from the receiver. Therefore, all elements on the reflectarray plane are required to be specifically designed with the appropriate phase because the incident wave will propagate and presents a different phase from one element to another. There are some methods involving phase compensation available for the reflectarray, such as using patch with variable size [6], stubs with open circuit ended [7], microstrip patch with a slot loaded ground plane [8], microstrip patch with a slot loaded [9], and the use of electronic components [10]. Stubs produce some dispersal losses and a spurious radiation as well. In addition, more space must be kept for the open circuit ended stub on the reflectarray design. The method as suggested in [8] may produce a backward radiation, which is the reason why [9] had been proposed to reduce and overcome those backward radiations. However, method in [9] has limited phase variation because of its patch size. The integration of electronic components in one patch as proposed in [10] may contribute many losses and complexity so bad that it is very hard to analyze especially when applied to arrays at millimeter-wave frequency [11].

All the phase compensation methods that have been mentioned above were using square or rectangular patch as their array elements which are assumed as not good enough to be employed in the reflectarray design. The reflection losses and side-lobe level (SLL), realized gain, and phase difference are the major concerns in the design process [12,13]. The use of traditional shape radiating element is vital to develop a novel configuration of the passive reflectarray unit cell, that uses a modified shape as a radiating element in the MRA design [14].

In this paper, a new structure is proposed comprises of a square patch with two half-circular slots, namely H-like element, which may give a better reflection phase range compared to the conventional square element.

2. ANTENNA STRUCTURE AND DESIGN

The pivot element for a single layer of reflectarray is proposed to be of H-like shape as shown in Fig. 1.

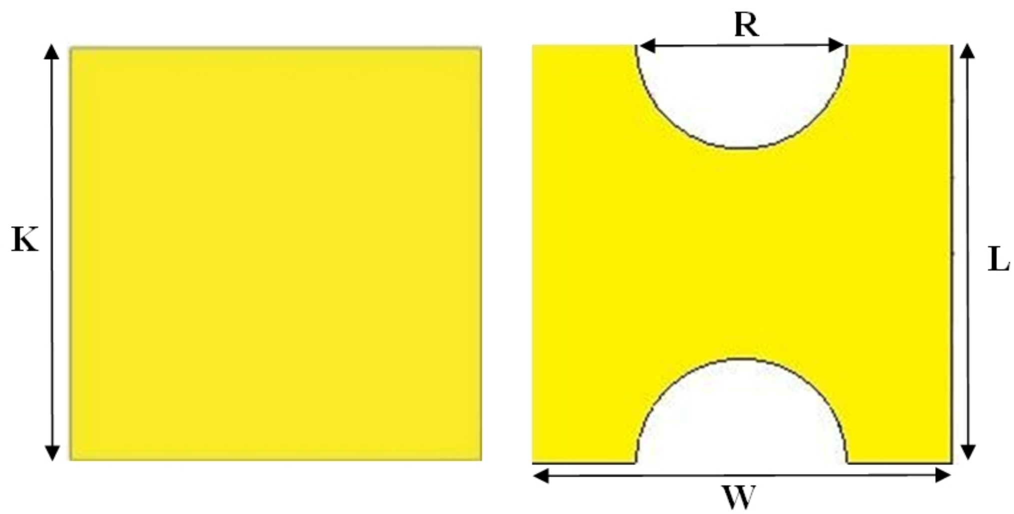


Fig. 1. The dimensions of element geometry (a) Square (b) H-Like

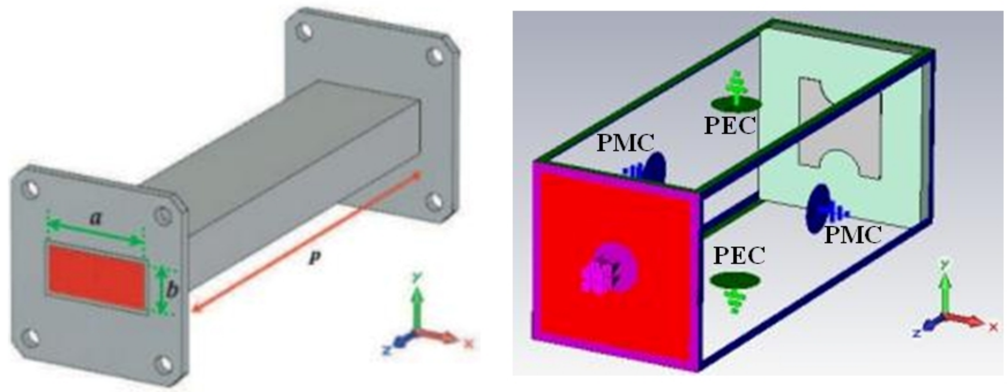
The proposed and traditional square element geometries are tested as resonant elements at 11 GHz for a periodic reflectarray structure separately. The traditional square and proposed elements at the targeted resonant frequency of 11 GHz are printed on an FR-4 substrate material with thickness t=1.524mm, tangential loss tanδ=0.025, and relative permittivity ε_r=4.3. The width dimensions of the proposed and traditional elements are L=5.46 mm and K=6.06 mm respectively. The value of R dimension is taken smaller than L/3 by adopting an iteration factor of m=0.75 in the following equation [15]:

$$R = m \times (L/3)\,, \qquad 0 < m < 1 \tag{1}$$

The rate of the unit cell reflectarray is based on a standard waveguide dimension due to the simplicity of measuring the reflection coefficient [16]. Fig. 2 shows the geometry of rectangular waveguide (X-band) that has been used as a model in terms of its dimension to design a unit cell for reflectarray, and a boundary condition in the simulation setup for infinite array approach. Since the waveguide standard dimensions are a=22.86mm, b=10.16mm and p= 120mm, a suitable periodicity of the unit cell reflectarray is chosen as L_1=10mm and W_1=10mm, with a copper thickness of 0.035mm. In the simulation, there is only one unit cell being excited using TEM-mode, and actually illuminated by a linearly polarized plane wave with a normal incidence angle. The resonant behavior of periodic arrays of squares is determined by the element size, periodicity, and the electrical properties of the substrate materials [17]. In the absence of mutual coupling, the squares resonate giving 180º reflection phase with respect to the incident wave when *λeff=nK*, where λeff is the effective wavelength, *n* is a constant > 1 (*n* = 2, 3, 4, 5 and so on), and *K* is the square element dimension [18].

2.1 Proposed Element Design and Behavior

To investigate the new element behavior, the initial dimension of the square element is taken as L=6mm (which constitutes λ/5). By using the utilizing parameter sweep software, which takes L range variation as ±20% of the chosen value, the resonant value is found 6.5mm at 10.5GHz. The circular slot radius R is initially taken as R=3mm (which constitutes λ/10), and is tested by using parameter sweep software to yield R range (1 to 4).



(a) (b)

Fig. 2a. Illustration of the standard X-band waveguide. (b) Microstrip reflectarray unit cell in the TEM-mode waveguide

The resonant frequency of the proposed element is found to be varying with the value of the circular slot radius R as shown in Fig. 3. The maximum directivity of the proposed element at R=3mm is found to occur at 10.5GHz as shown in Fig. 4. From the above, it's clear that, choosing the 10.5GHz as the resonant frequency instead of 10GHz is more reasonable. Fig. 5 depicts the simulated reflection phase responses for different patch sizes. The proposed patch has an improved reflection coefficient (-0.345dB or 92.3% reflection) compared with that of the square patch (-0.17dB or 96% reflection) as appeared in [12]. The results shows that the proposed element has a higher reflection losses compared to the traditional square element, but still have more than 90% reflection at resonant frequency (10.5GHz), which satisfies the reflector design consideration [19].

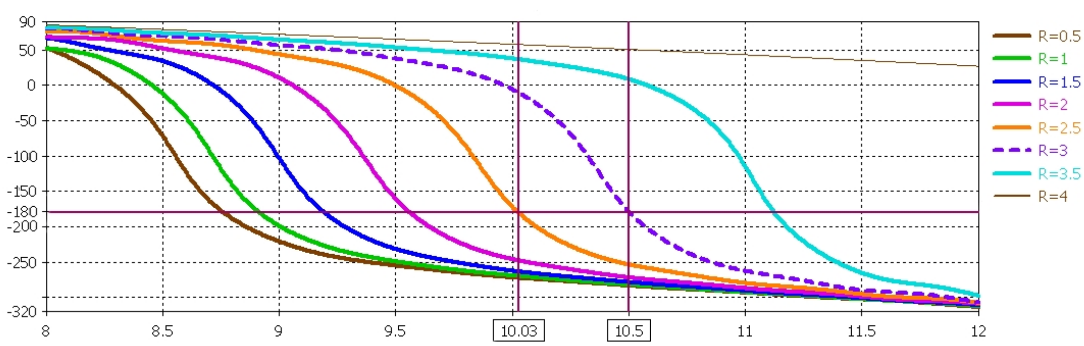


Fig. 3. The simulation phase result for the proposed element with various circular slot radius R

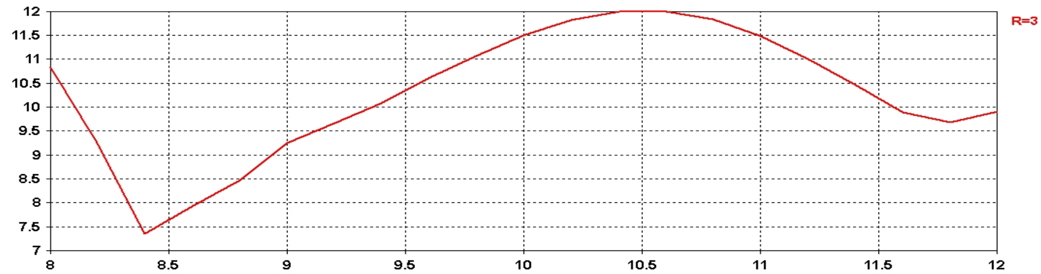


Fig. 4. The simulation directivity result for the proposed element at R=3 mm

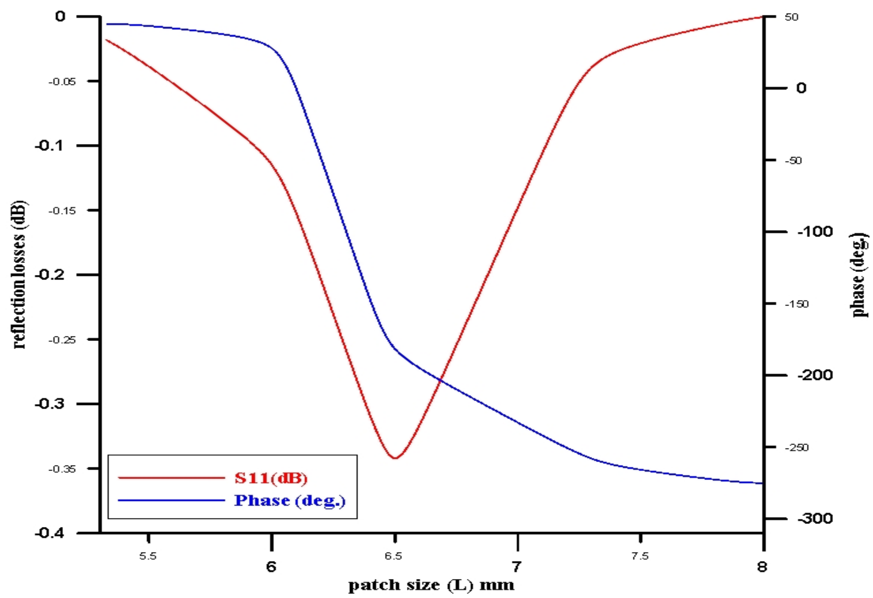


Fig. 5. Reflection coefficient and phase responses at f = 10.5 GHz

2.2 Progressive Phase Distribution

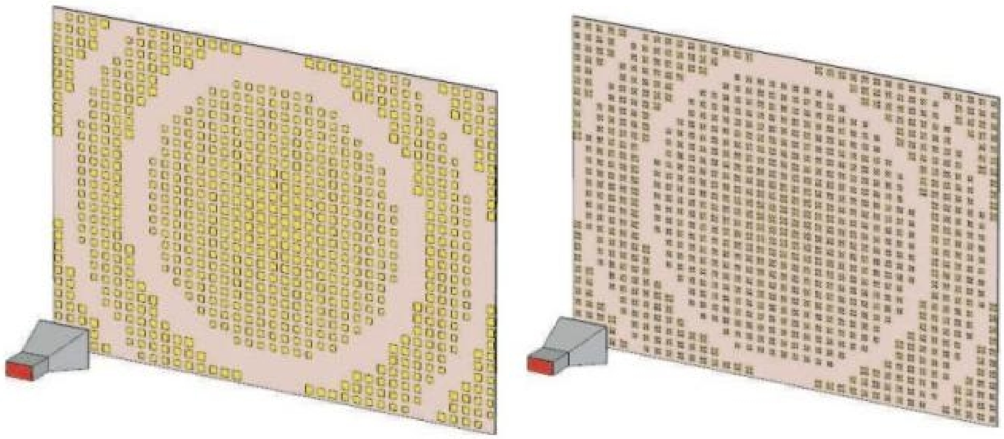
The whole geometry of the antenna is as shown in Fig. 6. The technique used in this paper to determine the progressive phase distribution on the microstrip reflectarray surface with a centered focal point that will produce a narrow beam normal to the surface is shown in Fig. 7. The required phase of each element can be deduced as [20].

$$\phi(x,\lambda) = -\beta\{\Delta R_{max} - \Delta R(x)\}$$
$$= -\frac{2\pi F}{\lambda}\{\sqrt{1+(D/F)^2/4} - \sqrt{1+(x/F)^2} \qquad (2)$$

where,

φ - Is the required phase-shift,

x - Is the radial distance of the element location inside the reflectarray aperture,
λ - Is the operating wavelength,
D and *F* - are the diameter and the focal length of the feed to the reflecarray center, respectively



(a) (b)

Fig. 6. Simulated MRA structures. (a) MRA with square elements. (b) MRA with H-like elements

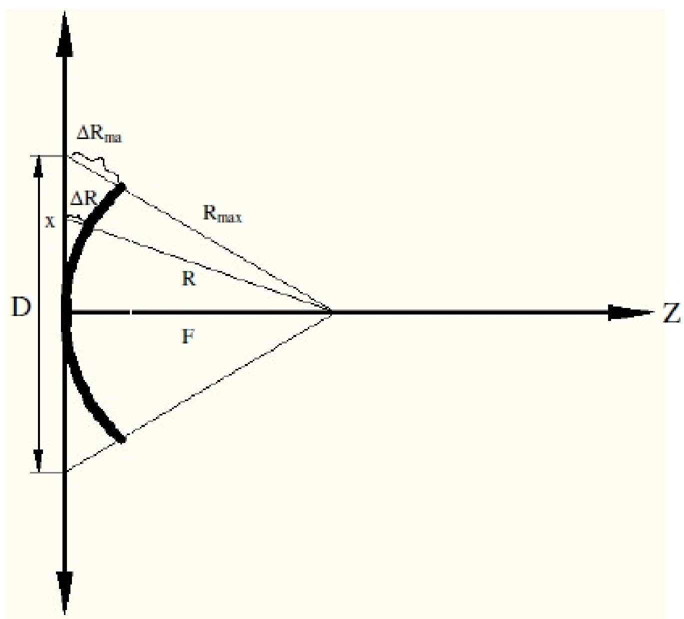


Fig. 7. The coordinate system used in determining the phase-shift of each reflectarray unit cell

The negative sign in the above equation expresses a delay. After obtaining the required phase-shift at the respective unit cells, a phase distribution on a rectangular reflectarray of

(29x21) elements of (290x210) mm^2 with F/D=1 at 10.5GHz is used for deploying the element at the surface of the array.

3. RESULTS AND DISCUSSION

A typical X-band rectangular pyramidal horn antenna (R100/WR90) with a gain around 15dB has been used with the proposed microstrip reflectarray. Fig. 8 shows the plot of the E-plane radiation pattern of H-like radiating element at 10.5GHz. The realized gain of the H-like radiating element is found as 29.3dB with radiation efficiency of -0.345dB (or 92.3%). It is clear that the SLL of the H-like element equals to -32.4dB, and the HPBW approximately equals to 5.6º. Table 1 compares the results of this work with that stated in [6].

Table 1. Summary of the simulation results compared with [12]

Antenna parameters	MRA with H-Like radiating elements	MRA with square radiating elements [12]
Operating frequency	10.5GHz	11GHz
Array volume (mm^3)	974.4	1716.8
Realized gain	29.3dB	27.4dB
Side-lobe level (SLL)	-32.4dB	-19dB
HPBW	5.6º	3.6º
Radiation efficiency	92.3%	95.6%
Reflection phase range	320º	250º

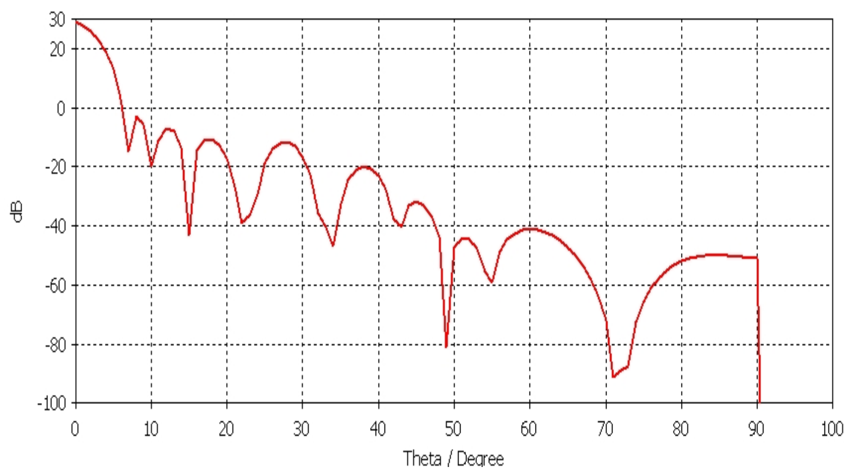


Fig. 8. The E-plane radiation pattern of H-like radiating element at 10.5 GHz

4. CONCLUSION

A design and analysis procedure for microstrip reflectarray antenna with proposed H-like shape radiating elements are presented in this paper. It is found that modifying the current distribution of the physical geometry of the basic square element leads to a better phase compensation, and also gives a wider phase rang for a good practical region. The MRA with H-like shape of radiating elements is found to provide higher realized gain, good radiation efficiency, and very low SLL due to its wider reflection phase range (320º) compared to the MRA with square elements (250º). The results also reveals that there is a volume reduction of about 43.24% gained by using the H-Like element.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
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http://www.sciencedomain.org/review-history.php?iid=671&id=5&aid=6236