

# Analysis of Concentric Split Ring Square Element for Broadband Reflectarray Antenna

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## Abstract

An investigation of phase variation and phase range of concentric split ring square element for broadband reflectarray antenna is presented in this paper. This is realized by exploiting the physical geometry of three element shapes namely square element, concentric ring square element and concentric split ring square element. Modifying the current distribution of basic concentric ring square element, leads to a less steep phase variation and also the bandwidth performance. An analysis of frequency response is described and analysed. The physical interpretation of the elements is also discussed. The proposed antenna element effectively covers two frequency operations (13.44 GHz and 18.36 GHz) in Ku-band range. Bandwidth broadening is achieved by introducing the ring square combination of element and the practical phase range is achieved through the use of RF 35 (thickness = 1.524 mm) as the substrate. The new concept of split initiates to a wider bandwidth (up to 67.6 %) for the antenna and can applied to any two frequency operations of Ku-band applications.

Keywords: broader bandwidth, dual frequency, Ku-band, reflectarray antenna.

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## 1. INTRODUCTION

Microstrip reflectarrays present an alternative to the conventional parabolic reflectors [8], [9]. As its name implies, a reflectarray antenna combines some of the best features of reflector and array antennas. In its basic form, a microstrip reflectarray consists of a flat array of microstrip patches or dipoles printed on a thin dielectric substrate. A feed antenna illuminates the array whose individual elements are designed to scatter the incident field with the proper phase required to form a planar phase surface in front of the aperture, as shown in Fig. 1. A large reflectarray antenna is made of thousands antenna elements printed on the flat surface and illuminated by a feed horn [1], [3].

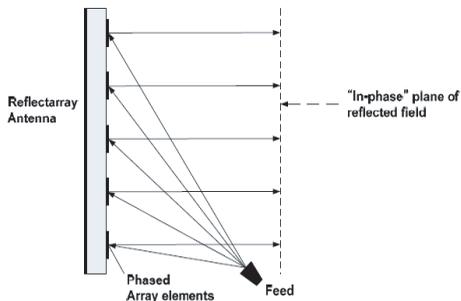


Fig. 1 Geometrical view of a reflectarray antenna.

A plane wavefront can be obtained by controlling the scattering properties of each element. The basic design procedure entails the use of phase-design curves. Various approaches have been proposed in the past which include the use of variable size patches and identical patches with variable size stubs for obtaining the required phase shift [3], [10].

The key feature of a reflectarray antenna design is the adjustment of the reflected

phase of each of its elements [1], [9]. Microstrip patches of variable size have been used to control the reflection phase [10]. This method can be viewed as introducing a small shift in the resonant frequency of an element which in turn changes the phase of the reflected field. When a plane wave from a transmitter reaches the flat reflectarray aperture, the operation of a reflectarray antenna can be explained as collimating the incident plane wave into the feed horn by suitable phase variations across the surface of the reflectarray [1].

The microstrip reflectarray has several applications due to its low-profile and small mass characteristic. One of the applications is that the flat reflectarray can be surface-mounted on a building side wall as a Ku-band Direct Broadcast Satellite (DBS) antenna. It also can be mounted on the rooftop of a large vehicle for satellite reception [3].

However, there is one distinct disadvantage associated with the reflectarray antenna which is its inherent characteristic of narrow bandwidth, which generally cannot exceed much beyond 10% depending on its element design, aperture size, focal length, etc [3]. For a printed microstrip reflectarray, its bandwidth is primarily limited by two factors which are the microstrip patch elements on the reflectarray surface and the differential spatial phase delay. The first factor can be solved by using thicker substrate or stacking multiple patches. More than 15 % bandwidth has been reported [3] by using these techniques. The second

factor can be solved by reducing the frequency excursion error by reducing the  $N$  integer in  $\Delta S = (N + d) \lambda$  formula where  $N$  is the integer and  $d$  is a fractional number of freespace wavelength  $\lambda$ . One of the methods is to design the reflectarray with a larger focal-length-to-diameter ( $f/D$ ) ratio [3].

## 1. ANTENNA STRUCTURE AND DESIGN

This paper discusses two types of single element namely ring element and square element and two types of concentric element which is the combination of ring and square elements and the combination of split ring and split square ring elements.

Substrate RF-35 is used for all designs with the dielectric constant of 3.54 and the loss tangent of 0.0018 at 1.9 GHz. The unit cell size is 10 mm x 10 mm. CST Microstripes software is used as the tool to analyze the phase variation graph.

### 2.1. Single ring element behaviour

The conductive ring is a simple symmetrical element, which can be nested and optimised for dual frequency and/or broadband operation [5]. The resonant behaviour of periodic arrays of rings is determined by the element size, periodicity and the electrical properties of the substrate materials [7]. In the absence of mutual coupling, when  $\lambda_{\text{eff}} = \pi d$  (where  $\lambda_{\text{eff}}$  is the efficient wavelength and  $d$  is the ring element diameter), the rings resonate giving  $180^\circ$  reflection phase [7]. The

phase can therefore easily be controlled by varying the ring element diameter, and it is this method which is used to provide the required phase correction across the reflectarray antenna aperture [7].

### 2.2. Single square element design and behaviour

The new proposed element in this paper is a single square element which can give a better reflection phase range and phase variation compared to the single ring element.

The 3-D geometrical views of the single square element is shown in Fig. 2, where  $a$  is the square length and  $R$  is the ring radius from the end edge of the conductor. For investigation of square element structure performance and behaviour, the ratio of the square length and ring radius ( $a/R$ ) was selected to be 0.7, 0.86, 1 (square length and ring radius is the same), 1.2 and 1.4.

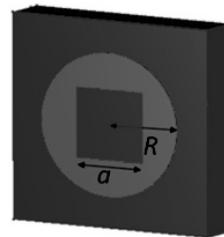


Fig. 2 The 3-D geometrical view of a single square reflectarray element.

Fig. 3 shows the frequency response for variable-ratio of  $a/R$  at the nominal size of ring radius,  $R = 3.46$  mm, the periodicity = 10 mm, the dielectric constant for the substrate,  $\epsilon_r = 3.54$  and the thickness of the substrate,  $t = 1.524$  mm.

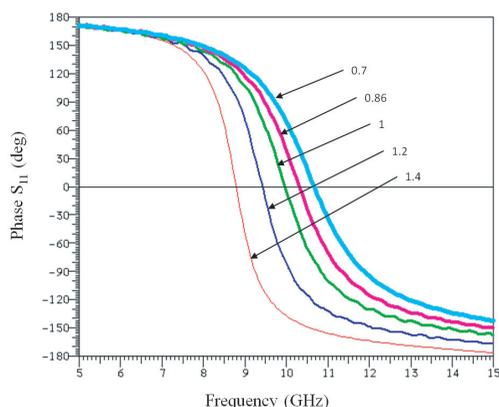


Fig. 3 Frequency response of a single square reflectarray element with different  $a/R$  ratio.

The resonant behaviour of a periodic square element is determined by the element size, periodicity and the electrical properties of the substrate materials. The phase is controlled by varying the square length,  $a$  and the ring radius,  $R$ . From Fig. 3, it is clearly shown that the phase slope is reduced for the smaller ratio of the square length and the ring radius ( $a/R$ ). In other words, when  $R$  is fixed to one value, the bandwidth performance is improved for smaller value of square element size,  $a$ . However, the linear phase range is also decreased, and therefore, a trade off must be made between these two parameters. In MicroStripes model,  $0^\circ$  phase reflection is used to define the resonance, whereas for a perfect conductor this is  $180^\circ$  relative to the incident wave.

Fig. 4 shows that a high current density is observed at area  $x$ , at the resonant frequency, 9.97 GHz. For a smaller area of copper size  $x$  and  $y$ , the gradient is improved while the practical phase range is decreased. The element ratio of  $a/R = 1$  therefore is used for further investigation due to the optimum value of the linear phase range and the phase gradient given.

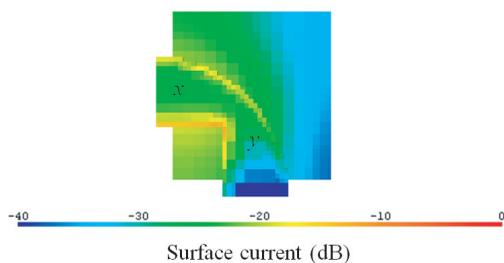


Fig. 4 Surface current distribution at 9.97 GHz for a grounded square reflectarray element with  $a/R$  ratio = 1. ( $a = 3.46$  mm,  $R = 3.46$  mm, periodicity = 10 mm,  $\epsilon_r = 3.54$  and  $t = 1.524$  mm)

## 2.1. Concentric ring square element design and behaviour

It is shown that the bandwidth of a reflectarray antenna can be increased by exploiting the scattering properties of a dual resonant periodic array consisting of nested rings printed on the surface of a grounded dielectric substrate [6]. In common with other types of dual frequency elements, the Q factor and the linearity of the reflection phase response can be controlled by varying the inner to outer size ratio. Fig. 5 shows the configuration of concentric ring with square reflectarray element.

In Fig. 5,  $I$  is the square ring element radius and  $O$  is the outer ring radius from the first edge of the conductor to the centre. For concentric ring square element structure, the ratio of the square ring radius and outer ring radius ( $I/O$ ) was selected to be 0.7, 0.86 and 0.91. Fig. 6 shows the response for the varies ratio of  $I/O$  (changing the outer ring radius) at the nominal size of square ring element radius,  $I = 3.06$  mm. The ratio of  $a/R$  is kept constant to the value of 1. The periodicity is 10 mm, the dielectric constant for the substrate,  $\epsilon_r$  is 3.54 and the thickness of the substrate,  $t$  is 1.524 mm.

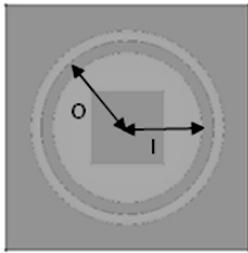


Fig. 5 The top-view of concentric ring square reflectarray element.

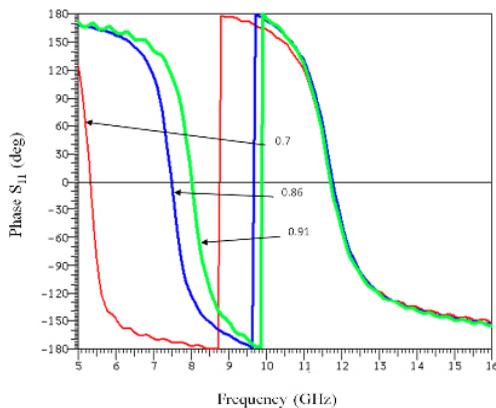


Fig. 6 Frequency response of concentric ring square reflectarray element with different  $I/O$  ratio.

The reflection phase for concentric ring square element is controlled by varying the outer ring radius,  $O$  and the square ring radius,  $I$ . From Fig. 6, it is shown that the first resonant occur depending on the  $O$  dimension whereas the second resonant is similar for all ratios. The phase slope at first resonance varies for all ratios of the square ring radius and the outer ring radius ( $I/O$ ). However, the linear phase range is increased for higher  $I/O$  and the plateau region [6] factor is abolished because the first resonant frequency and the second resonant frequency are closer. For smaller gap between outer ring and square ring element, performance of phase range is improved.

Fig. 7 shows the frequency response for varies ratio of  $a/R$  (changing the square element dimension) with the resonant frequencies at the nominal size of outer ring radius,  $O = 3.56$  mm with  $I/O = 0.86$ , periodicity = 10 mm, the dielectric constant for the substrate,  $\epsilon_r = 3.54$  and the thickness of the substrate,  $t = 1.524$  mm. The ratio of square length and ring radius,  $a/R$  was selected to be 0.7, 0.86, 1, 1.2 and 1.4.

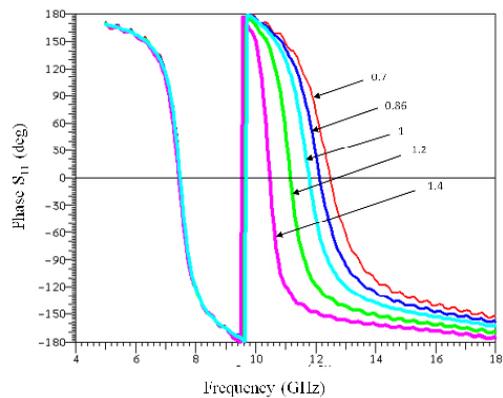


Fig. 7 Frequency response of concentric ring square reflectarray element with different  $a/R$  ratio.

From Fig. 7, it is shown that the phase slope and phase range for second resonance is varied for all ratios of  $a/R$ . The phase slope is decreased for smaller ratio of  $a/R$ , however the linear phase range is decreased and the plateau region is abolished. For smaller size of square element  $a$ , the gradient performance for concentric ring square is improved.

It is evident that the outer ring radius determines the first resonant frequency because the first resonance in Fig. 6 is varied when the outer ring radius is changed while the square element determines the second frequency because the second resonance in Fig. 7 give various frequency resonance when the square element parameter is changed.

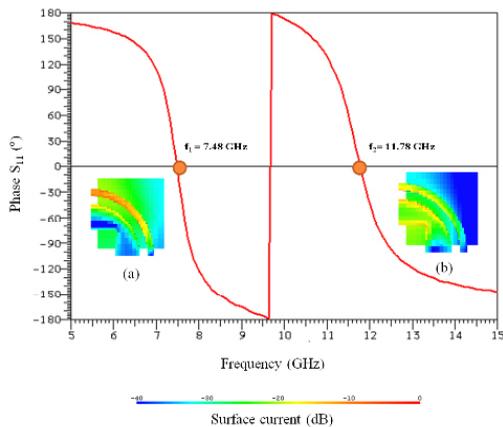


Fig. 8 Surface current distribution (a) at 7.48 GHz and (b) at 11.78 GHz for a grounded concentric ring square reflectarray element with  $a/R = 1$  and  $I/O = 0.86$ . ( $O = 3.56$  mm,  $a = 3.06$  mm,  $R = 3.06$  mm, periodicity = 10 mm,  $\epsilon_r = 3.54$  and  $t = 1.524$  mm)

Fig. 8 shows the current distribution predicted by Microstripes. It is clear from the fig. that, at the first resonance (7.48 GHz), the current density in the outer ring is very high, while at the frequency of the second resonance (11.78 GHz), the square element is strongly excited.

## 2.2. Concentric split ring square element design and behaviour

In Fig. 9,  $I$  and  $O$  gives the same meaning as with the design in Fig. 5, while  $g$  is the gap size for the split of the elements. The nominal inner radius of the outer split ring element is 3.56 mm and the radius of the split square ring is 3.06 mm which give the ratio of  $I/O$  value = 0.86. In this work, the gap size is limited to 0.28 mm due to fabrication tolerances, but ideally it should be smaller [6], [11] so that the

resonant frequency is not increased. The unit cell size is 10 mm x 10 mm. RF-35 with a dielectric constant of 3.54 and a loss tangent of 0.0018 at 1.9 GHz was used. Copper metal was used to simulate the designed element and the ground plane.

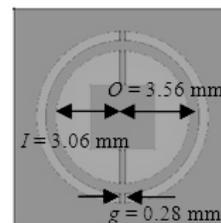


Fig. 9 The top-view of concentric split ring square reflectarray element.

Based on studies in [6] and [11], the introduction of gap on a structure can affect the frequency response performance. In this work, gap is also introduced to improve the performance of both phase range and gradient for periodic reflectarray elements. In this work, we also compare the performance and behavior of three concentric square element and systematically introduced gap in the structure. Fig. 10 shows the frequency response for the three designed element which are concentric solid ring square element (without any gap), concentric ring square element with gap on the ring element, and concentric split ring square element (gaps are on both ring and square structure).

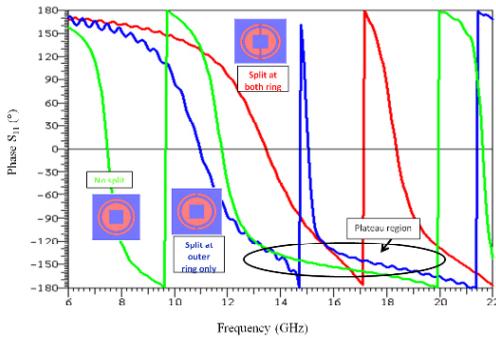


Fig. 10 Frequency response for three element designed.

It is clearly shown in Fig. 10 that, for the first resonance, the gradient of the curve is largely decreased when gap is introduced in the design. The bandwidth performance is improved from 26.9% to 67.6%. While for the second resonance, the phase slope is slightly improved from 19.8% to 20.3% only, however the plateau region is largely improved for the element with gaps.

Fig. 11 shows the current distribution for concentric split ring square reflectarray element. It is evident that the outer ring determines the first resonance, while the inner square ring determines the second resonance. For the first resonance, it is observed that the outer ring element is strongly excited, and for the second resonance, the inner square ring element is strongly excited.

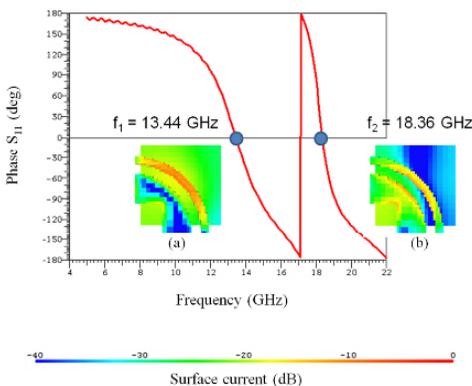


Fig. 11 Surface current distribution (a) at 13.44 GHz and (b) at 18.36 GHz for a grounded concentric split ring square reflectarray element with  $a/R = 1$  and  $I/O = 0.86$ . ( $O = 3.56$  mm,  $a = 3.06$  mm,  $R = 3.06$  mm, periodicity = 10 mm,  $\epsilon_r = 3.54$  and  $t = 1.524$  mm)

### 3. RESULTS AND DISCUSSION

With the designed structure dimension given in Section 2, the simulated reflection phase versus ring radius of the proposed antenna is plotted and shown in Fig. 12, 13 and 14.

As stated before,  $a/R = 1$  is used for further investigation on square element resonant behavior. The reflection phase versus square ring radius is plotted at the resonant frequency of 23.70 GHz. The linear phase range is  $403^\circ$  which is sufficient enough for practical design [6] while the gradient is  $0.34^\circ/\mu\text{m}$ . Bandwidth performance for this element is 40.8%. Fig. 12 also shows that the maximum radius,  $R$  for the square ring is 4.46 mm. This is because the phase given at the higher  $R$  is not an acceptable resonance because the edge of the ring almost touched the next periodic array and caused short-circuit.

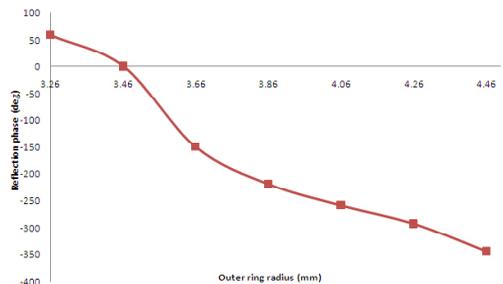


Fig. 12 Reflection phase versus outer ring radius for single square element with  $a/R = 1$  at 23.70 GHz. (periodicity = 10 mm,  $\epsilon_r = 3.54$  and  $t = 1.524$  mm)

For concentric ring square element,  $I/O = 0.86$  and  $a/R = 1$  is used in reflection phase versus outer ring radius graph (Fig. 13) at the resonant frequencies of 7.48 GHz and 11.78 GHz. The linear phase range achieved at the first resonance is  $249^\circ$  with the gradient  $0.54^\circ/\mu\text{m}$  and the phase range at the second resonance is  $230^\circ$  with the gradient  $0.50^\circ/\mu\text{m}$ . Bandwidth performance for first resonance is 26.9% and 19.8% for the second resonance.

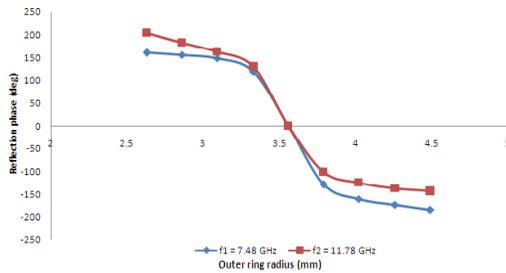


Fig. 13 Reflection phase versus outer ring radius for concentric ring square element with  $I/O = 0.86$  and  $a/R = 1$  at 7.48 GHz and 11.78 GHz. (periodicity = 10 mm,  $\epsilon_r = 3.54$  and  $t = 1.524$  mm)AA

While for the concentric split ring square element performance as in Fig. 14,  $I/O$  and  $a/R$  ratio used is similar to the design (without gaps) at the resonant frequencies of 13.44 GHz and 18.36 GHz. The linear phase range achieved for the first resonance is  $320^\circ$ , which is acceptable for practical design [6] with the gradient  $0.15^\circ/\mu\text{m}$  and  $464^\circ$  (phase range) with gradient  $0.33^\circ/\mu\text{m}$  at the second resonance. The bandwidth performance is 67.6 % and 20.3 % for the first and second resonance respectively.

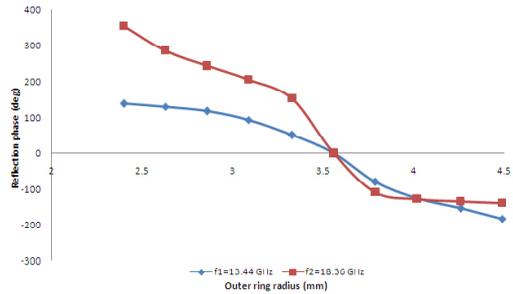


Fig. 14 Reflection phase versus outer ring radius for concentric split ring square element with  $I/O = 0.86$  and  $a/R = 1$  at 13.44 GHz and 18.36 GHz. (periodicity = 10 mm,  $\epsilon_r = 3.54$  and  $t = 1.524$  mm)

The performance for concentric split ring square element in Fig. 14 is improved from the design in Fig. 13 (without split). As shown in Fig. 14, the curve at the first resonance is largely improved where the plateau region is almost abolished and the curve is more linear. The frequency is shifted from 7.48 GHz to 13.44 GHz which then give the bandwidth improvement of about 40.7%.

For the second resonance, the plateau region is again improved but with a slight change. This results the bandwidth improvement of about 0.5% only. However, the new concept of split is still giving the better performance compared to the previous design with no split introduced. The second resonant frequency shifted from 11.78 GHz to 18.36 GHz.

The concentric element concept in the other hand is used to achieve a dual frequency operation compare to the single element performance which gives only one resonant frequency, as shown in Fig. 3. The phase range performance in a single element is bigger compared to the first resonance of the concentric split ring square element. However, the phase

gradient which leads to the bandwidth performance is improved from  $0.34^\circ/\mu\text{m}$  to  $0.15^\circ/\mu\text{m}$ .

In concentric element design, the critical feature of mutual coupling should be taken care of because the design consist two elements which use the copper metal material. In this work, the gap between the first and second element for concentric design is fixed at 0.5 mm, except for studies in *I/O* ratio as shown in Fig. 6.

#### 4. CONCLUSION

A new design of reflectarray element for broadband dual frequency Ku-band application is proposed in this work which is the concentric split ring square element. By modifying the current distribution of the physical geometry of the basic concentric ring square element leads to a better phase variation and bandwidth.

This new design gives the good performance in bandwidth which is up to 67.6 % and 20.3 % in dual frequency operations. The phase range for the element is also in a good practical region which gives the value of  $320^\circ$  and  $464^\circ$  at both frequencies respectively.

This antenna is easy to fabricate and low cost. These features are very useful for worldwide portability of communication applications.

#### ACKNOWLEDGMENT

The authors would like to thank the MOSTI Secretariat, Ministry of Science, Technology and Innovation of Malaysia, Science fund: 01-01-02-SF0376, for sponsoring this work.

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