Design and analysis of dual U slot reflectarray antenna for X-band applications

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Abstract. A novel design of a dual frequency single layer reflectarray antenna is presented for X-band frequency applications. Dual U slots embedded on conventional rectangular microstrip reflectarray have been designed to attain a dual frequency operation. A detailed analysis of the effect on surface current distributions with the introduction of dual U slots is presented. Moreover a parametric study on the variation of significant dimensions of the design have been carried out and analysed thoroughly using a commercially available CST computer model. Proposed design configurations were fabricated above a 0.508 mm thick substrate of Rogers Duroid 5880. The dual U slot configuration offers a significant dual frequency behavior at 8.54 and 11.56 GHz with 10% bandwidth improvement of 47 and 56 MHz with a reflection loss of -4.54 and 4.11 dB respectively.

1. Introduction
Parabolic dish reflectors have been widely used particularly for high gain and efficient bandwidth applications. They have demonstrated efficient performance for their long range communication effectiveness and radar applications, but the bulkiness of size and the rotary mechanism needed for the paraboloid, increases the complexity and cost. A reflectarray antenna on the other hand has a light weight flat surface with strategic arrangement of distributed elements. The flat surface reflects the incident electromagnetic energy of a feed antenna in such a way that a planar wavefront is formed at a far field region from the antenna [1].

Reflectarray antennas were introduced to replace the widely used parabolic dish reflectors [2]. The planar surface of the reflectarray is spatially fed by a feed antenna usually a horn antenna. The spherical beam front of horn antenna is converted into a planar beam front by strategic phase distribution of the elements over the array [3]. The first presented design of reflectarray was a bulky arrangement of open ended wave guides [2]. The idea though was not advanced further at that time, due to sheer size of the waveguide array. In the past few years, reflectarrays have significantly evolved with the advent of printed circuit board technology (PCB) in which printed reflectarrays emerged as compact and easily fabricated antennas compared to parabolic dish reflectors. However due to intrinsic low bandwidth, microstrip reflectarray antennas face a critical challenge of a narrow bandwidth and high Q factors [1].

Microstrip reflectarrays pose a narrow bandwidth generally less than 5%. In order to improve the bandwidth performance of microstrip reflectarray, different techniques have been presented in the literature. In the past, different techniques have been reported to realize dual frequency reflectarrays such as the use of split ring slots, variable dual band gaps embedded in conventional rectangular patches, split ring square elements and by adding phase delay lines to microstrip reflectarray elements [4-7]. Multilayer structures have also been reported for bandwidth improvement of reflectarrays. It
has been demonstrated that two and three layer structures can also be used for bandwidth improvement and for realizing a dual frequency of operation [8-10]. However the addition of phase delay lines to microstrip patches leads to undesired spurious radiation losses which adds up to increased cross polarization levels in arrays. Additionally, the use of multilayer structures for dual band of operation also increases the complexity of the design. The two or three layer structure needs precise alignment of layers to achieve fruitful results. Moreover the increase in the substrate height also may result in generation of unwanted surface waves that increase the loss of array. The individual reflectarray element reflection phase is required to cover entire range of 360°, however due to fabrication tolerances this requirement is not fulfilled and leads to phase errors in an array. To avoid this problem dual resonance elements have also been reported in order to achieve a phase shift greater than 360°, thus avoiding phase errors [11].

This paper presents a novel dual U slot configuration for dual resonance operation in X-band. Dual U slots embedded in a conventional rectangular patch element were designed. Significant parameters of the design were also swept over suitable frequency ranges to analyse the effect over the two resonances. Fabricated samples were tested for scattering parameters using a waveguide simulator in order to cater the effects of an infinite array [12-13]. The results demonstrate a good agreement between the simulated and fabricated element designs.

2. Design Considerations
Simulation designs of the proposed dual frequency reflectarray element were done using CST MWS. The proposed dual U slot element design is shown in figure 1(a). By using controlled boundary conditions for a dual U slot unit reflectarray element, perfect electric and magnetic walls have been realized to obtain an infinite periodic reflectarray.

![Figure. 1. Simulated designs of dual U slot element configuration (a) Simulated design and (b) Boundary conditions of a dual U slot unit cell](image)

**Table 1. Dual U slot element dimensions on Rogers Duroid 5880**

| Parameter | Dimension (mm) |
|-----------|----------------|
| $W_a$     | 12             |
| $L_a$     | 8.8            |
| $l_1$     | 3              |
| $W_1$     | 4              |
| $W_2$     | 6              |
| $l_2$     | 1              |
The boundary conditions for the unit element are shown in figure 1(b). The orientation of the incident electric field is shown by the E-field vector while the dotted line shows the electric and magnetic walls. The dimension of the U slot elements were selected in such a way that dual frequencies can be realized in the X-band frequency range The U slot elements were printed above a Rogers Duroid substrate of 0.508 mm thickness, a dielectric permittivity of 2.2 and a loss tangent of 0.0009. The simulated dimensions for the patch element are tabulated in Table 1.

3. Parametric Analysis

In order to fully understand the behavior of the proposed design, different parameters of the elements were studied. The variation of the selected parameters were studied for X-band frequency range to monitor the effect on the reflection phase and the reflection loss of element. The selection of the dimensions was done such that the resonances remain in the X-band of operation. The variation of selected dimensions is tabulated in Table II, Where L_a is the length of the antenna and l_1 is the length of the arms of bigger U slot.

| Parameter | Range (mm) |
|-----------|------------|
| L_a       | 8.8 – 10   |
| l_1       | 2.5 – 3    |

Reflection loss of the element over this range was simulated and compared with the surface current distribution of the element to analyse the results. The length of the antenna L_a was varied from 8.8 to 10 mm. Sweeping the element length (L_a), results in decrease of frequency for both the upper and lower resonances of the element. Figure 3 shows the effect of patch length on the reflection loss of both resonant frequencies. As shown in figure 2, by increasing the patch length L_a from 8.8 to 10 mm, the lower and upper resonant frequencies are observed to be shifted by 470 and 600 MHz respectively. Moreover the loss is shown to offer an alternate effect for both resonances. The loss for lower resonance decreases from -3.58 to -2.54 dB while for higher resonance the loss increases from -2.67 to -3.35 dB. Since the surface currents for both the resonances lie in between the top and bottom edges of patch, so increasing length of the patch will increase the current paths for both the resonances, thus reducing the resonant frequencies.

As shown in figure 3, the variation of the U slot arms significantly affects both upper and lower resonant frequencies. The increase of arm length results in decrease in both resonant frequencies. As the length is increased from 2.5 to 3.2 mm, the lower frequency is observed to decrease from 8.4 to 8.0 GHz.
8.06 GHz, whereas upper resonant frequency tends to decrease from 11.49 to 10.74 GHz respectively. This effect is due to the decrease in the path length of the charge carriers that exists between the lower edges of the path element around the arm lengths (l1) and the upper edge of element. Additionally it is observed that, the loss for this parametric sweep follows alternate trends for both the resonances. For the lower resonance the loss increases from -2.63 to -3.2 dB, whereas the loss of the upper resonance decreases from -3.67 to -2.57 dB respectively. This behavior shows that both the length of the patch element and the length of the arms of U slot should be monitored in order to control the resonance behavior of the patch element.

4. Measurements
In order to validate the reliability of simulated results, dual U slot configurations were fabricated above Rogers Duroid 5880 substrate of 0.508 mm thickness. The proposed designs were fabricated using photolithic etching technique. The ground plane of the elements were extended to fit in the aperture of the waveguide. Before development of full array individual elements of the array needs to be characterized for their reflection phase and loss. Waveguide simulator technique provides realization of an infinite reflectarray with perfect magnetic and electric boundaries [12]. Fabricated elements were placed inside the aperture of the waveguide simulator to record the scattering parameters. Figure 4 shows the fabricated sample, waveguide simulator and the measurement set up for the measurement of reflection loss.

Figure 4(a) shows the fabricated dual U slot elements over Rogers Duroid 5880. As shown in figure 4(b) an X-band adapter connected to a tapered waveguide to form a waveguide simulator. Multiple samples of single design were fabricated and measured to ensure the repeatability of the results. Dimensional errors were introduced after the fabrication of the samples due to limitation of the fabrication process. In order to cater those dimensional errors, dimensions of the samples and the inserted U slots were measured again using a microscope. The simulated results were then updated with the fabricated dimensions for correction.

Figure 4(c) shows the measurement set up for scattering parameter measurements. The measurement set up consists of a waveguide simulator over the X-band frequency operation. A vector network analyzer (VNA) was used to measure the scattering parameters of the elements under test. Waveguide and the vector network analyzer are connected together by a coaxial cable. The vector network analyzer was calibrated for the X-band and was tested for short, open and matched loads to remove any discrepancies of the set up. The fabricated elements were then placed one by one in the aperture of the waveguide to record the reflection loss and the reflection phase of the elements. Scattering parameters for the proposed design are presented in Figure 5.

![Figure 4. Measurement setup for scattering parameters (a). Fabricated sample for dual U slot configuration. (b) An X-band adapter connected to a tapered waveguide (c) Measurement set up with a waveguide simulator attached to VNA for scattering parameter measurements](image-url)
The results shown in figure 5 demonstrate that a good agreement of a dual frequency operation is realized at 8.52 and 11.51 GHz respectively as shown in figure 5(a). Moreover a reflection loss of -4.5 dB and -4.11 dB have been achieved. The simulated results are shown by red line while the measured results for dual U slot element is shown by dotted black line. The ripple present in the measured results may be due to deviation of the waveguide simulator from its ideal behavior. The results show that the bandwidth performance of 47 and 56 MHz have been achieved for upper and lower resonances, with a reflection loss of -4.5 and -4.11 dB respectively.

Figure 5(b) shows the reflection phase of the fabricated element. Due to the dual resonance behavior of the proposed element, reflection phase should cover a phase range of 720 deg ideally. The reflection phase of simulated design covers a phase range of 670 degrees. However fabricated sample covers a phase range of 690 degrees. The increase in the phase coverage comes at cost of increased loss of the element. In order to compare the linear static region of the phase curves, a Figure of Merit (FOM) is defined as a ratio of reflection phase covered to the change in frequency and can be mathematically expressed as.

$$FOM = \frac{\Delta \phi}{\Delta f}$$

where $\Delta \phi$ the phase range is covered by the reflection phase curve and $\Delta f$ is the change in resonant frequencies in MHz. The FOM is measured as deg/MHz. FOM is calculated for both the resonances. A summary of the scattering parameter results is tabulated in Table 3.

| Resonant Frequency (GHz) | Reflection Loss (dB) | Phase Range (Deg) | Bandwidth (MHz) | Figure of Merit (Deg/MHz) |
|--------------------------|----------------------|------------------|----------------|--------------------------|
| Simulated                | -3.01 | -2.94 | 670 | 65 | 80 | 1.03 | 0.91 |
| Measured                 | -4.55 | -4.56 | 690 | 47 | 56 | 1.33 | 1.45 |

Table 3 shows the summarized results of the simulated and measured designs for dual resonance behavior. The results depicted in Table 3 show that, there is an increase in the measured loss when compared to simulated design, which is due to the loss of measurement set up and fabrication limitations. The phase range covered by the fabricated samples is slightly more than the simulated. This may be due to the increased loss of the fabricated samples. A good bandwidth performance is
shown by both the samples, however the reduction of bandwidth compared to simulated is due to increased loss. Figure of merit shows that increase in loss increases the slope of the phase curve thus FOM for fabricated samples is more than that of simulated designs.

5. Conclusion
A novel dual U slot microstrip reflectarray configuration has been presented for dual frequency operation. By embedding two U slots of variable sizes in a conventional rectangular patch, a phase range greater than 360° can be achieved which provides an improved bandwidth performance. A detailed parametric study for significant dimensions of the design shows that both the resonances can be adjusted conveniently with in X-band operation. A 13 % bandwidth improvement has been achieved by dual U slot configuration compared to conventional rectangular patch element. Moreover a Figure of Merit (FOM) defined shows that a phase range greater than 360 deg can be attained at a gradient of 1.33 and 1.45 for the higher and lower resonance of 8.58 and 11.52 GHz respectively.

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