# A Single-Layer Multi-Band Reflectarray Antenna in X/Ku/K-Bands

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***Abstract*** **─** A new center-fed tri-band reflectarray antenna is presented in this paper. Elements of the reflectarray antenna are circular rings and patches loaded with slots. The proposed antenna operates in three bands (X, Ku and K). The introduced element, has been optimized to achieve large linear phase range at the three bands. Phase compensation is achieved by varying the size of elements. Height of the horn antenna has been optimized to get maximum gain and bandwidth at the three bands.

***Index Terms*** **─** Microstrip, multi-band, reflectarray antenna, single layer.

## I. INTRODUCTION

Reflectarray antennas combine the best features of reflector antennas and phased array antennas [1], so they have a lot of advantages such as: low profile, small mass and volume and low cost [2]. They are easy to manufacture and have potential for beam control and shaping. A reflectarray consists of many printed radiating elements, illuminated by a horn antenna. The elements provide required phase shift to produce a contoured beam [3].

A disadvantage of microstrip reflectarray antennas is their limited bandwidth because of the narrow bandwidth of microstrip patch elements and differential spatial phase delay as a result of different distance of the feed antenna to each element [4]. Phase compensation is achieved using patches with attached variable length stubs [5], or varying sized patches, dipoles and rings [6], or identical patches with different angular rotation [7]. Several techniques have been presented to overcome the limited bandwidth of the reflectarray antennas, such as using stacked two or more arrays [8], aperture-coupled patches [9], the elements with a large linear phase range [10], or multiresonant elements [11].

Multi-band operation of the reflectarray antenna can be achieved using two or more layers [12], or FSS-backed structures [13], with the drawback of more cost and complexity, while single-layer multi-band reflectarray antenna is easily manufactured and has a much less cost. In [14-16] single-layer, dual-band reflectarray antennas have been presented.

In this paper, a single- layer tri-band reflectarray antenna with linear polarization is introduced. By varying the size of the element, 600 degrees linear phase range within X-band (10.8 GHz~12.8 GHz), 680 degrees linear phase range within Ku-band (15.3 GHz~17.3 GHz) and 900 degrees linear phase range within K-band (24 GHz~26 GHz) have been achieved.

Variable sized patch elements have advantages of producing less dissipative loss and cross polarization, compared to the patches with attached variable length stubs [17].

## II. DESIGN AND ANALYSIS OF THE PROPOSED REFLECTARRAY

A single-layer microstrip element, consisting of a circular ring and patch with slots on it, is introduced as the elements of tri-band reflectarray antenna in X-, Ku- and K-bands. The designed element structure is shown in Fig. 1. The unit cell is 10 mm. It operates in center frequencies of 11.8 GHz, 16.3 GHz and 25 GHz.

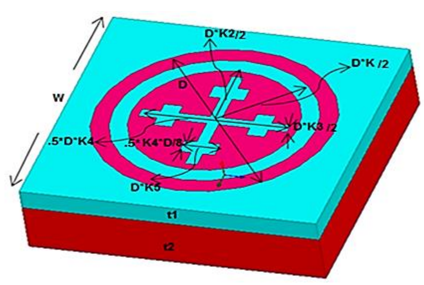


Fig. 1. Element structure.

Rogers 4003 with relative permittivity of 3.55 and the thickness (t1) of 0.813 mm is used as substrate. t2 is

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an air distance between the ground plane and the substrate for obtaining a more linear phase range.

For analyzing the reflection phase characteristics of the element, an infinite periodic array model was performed, using the HFSS simulation [18]. The boundary conditions on the side walls are master-slave and the excitation is a floquet port as shown in Fig. 2 [2].

According to Fig. 1, there are six undefined parameters (k, k2, k3, k4, k5 and t2) whose values, should be optimized to obtain a large linear phase range at the three bands. Primary values of these parameters are chosen in a way that the element has three resonant frequencies.

Figures 3 to 8, show the phase responses of the element for different values of parameters at center frequencies in each band when one parameter changed and the other parameters keep unchanged, in order to study the influence of each parameter on the phase curves. It can be seen that k2 and k4 have the most effect on the phase response. Also we find that K3, K4 and K5 does not much effect on the phase curves at the first band and it shows that the slots are responsible for exciting two other bands. The curves indicate that the best values for these parameters are k=0.85, k2 = 0.7, k3 = 0.1, k4 = 1.25, k5 = 0.15, t2 = 2 mm, because with these values of parameters, the curves are more linear than other values.

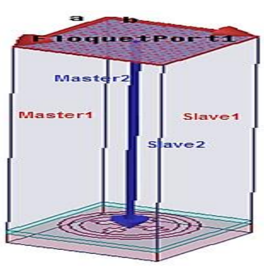


Fig. 2. HFSS model for obtaining the phase response.

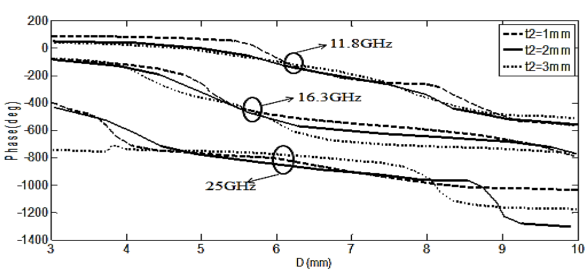


Fig. 3. The phase response of the element for different values of t2: (k=0.85, k2 = 0.7, k3 = 0.1, k4 = 1.25, k5 = 0.15).

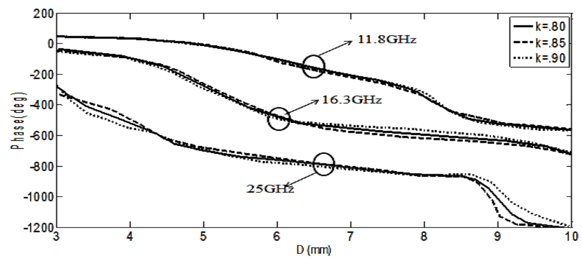


Fig. 4. Phase response of the element for different values of k: (t2=2 mm, k2 = 0.7, k3 = 0.1, k4 = 1.25, k5 = 0.15).

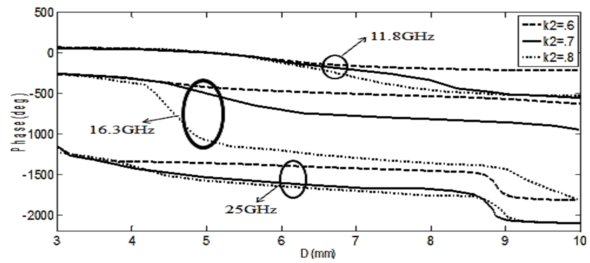


Fig. 5. The phase response of the element for different values of k2: (k=0.85, k3 = 0.1, k4 = 1.25, k5 = 0.15, t2=2 mm).

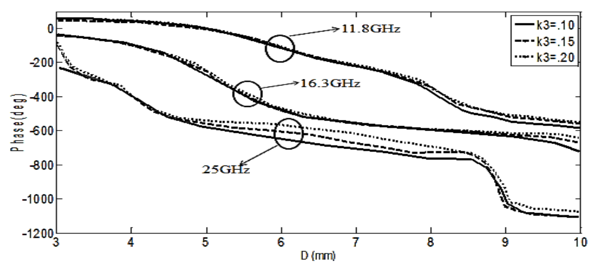


Fig. 6. The phase response of the element for different values of k3: (k=0.85, k2 = 0.7, k4 = 1.25, k5 = 0.15, t2=2 mm).

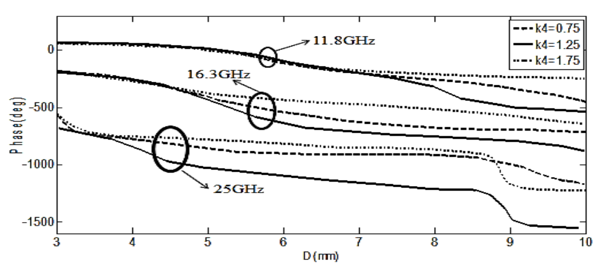


Fig. 7. The phase response of the element for different values of k4: (k=0.85, k2 = 0.7, k3 = 0.1, k5 = 0.15, t2=2 mm).

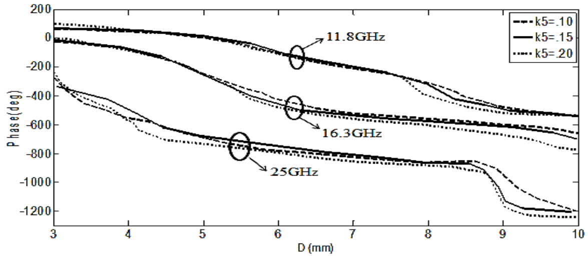


Fig. 8. The phase response of the element for different values of k5: (k=0.85, k2 = 0.7, k3 = 0.1, k4 = 1.25, t2=2 mm).

With these optimized parameters and by varying the ring size, 600 degrees linear phase range at 11.8 GHz and 680 degrees linear phase range at 16.3 GHz and 900 degrees linear phase range at 25 GHz have been achieved, as shown in Figs. 9 to 11. They also show that the phase curves, in all three bands are parallel in adjacent frequencies, resulting in a good bandwidth of the reflectarray antenna, designed with this element. Figure 12 shows the amplitude of the reflection coefficient for the proposed element. It can be seen that by increasing the frequency, dielectric loss increases.

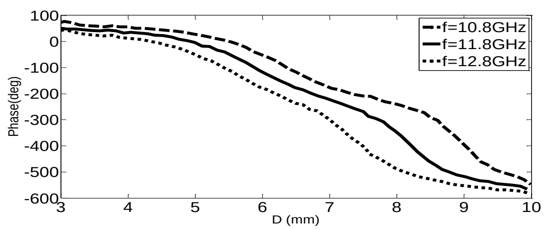


Fig. 9. Phase response to different frequencies at X-band.

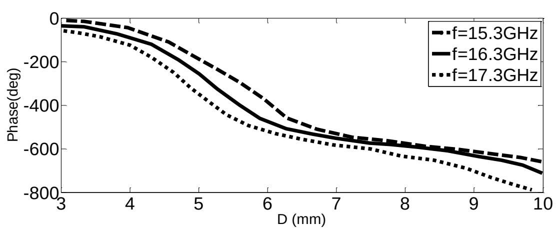


Fig. 10. Phase response to different frequencies at Ku-band.

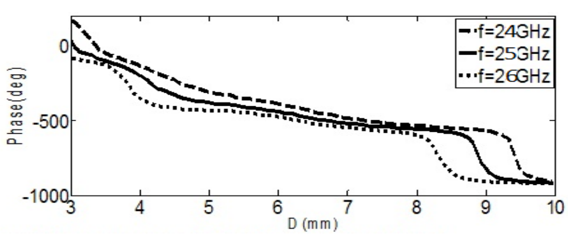


Fig. 11. Phase response to different frequencies at K-band.

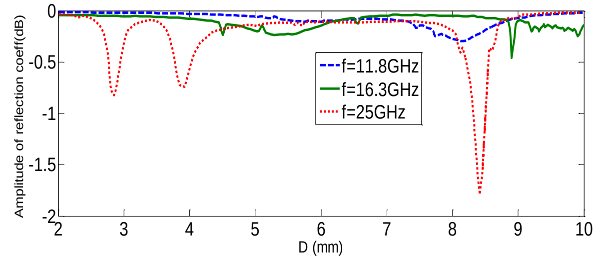


Fig. 12. Amplitude of the reflection coefficient for the element.

Figures 13 to 15 show the phase responses for different angles of incidence in the three bands. It is concluded that at 11.8 GHz the phase curves for theta=20 and 40 are the same as the phase curve for the normal incidence, but for oblique incidence more than 60 degrees, we cannot assume that it is the same as the normal incidence, because they are not similar enough according to Fig. 13. At 16.3 GHz and 25 GHz the phase curves for theta=20 and 30 are almost the same as normal incidence but for oblique incidence more than 40, it is not true. According to Equation (1) (where θ is angle of wave incidence, D is the biggest dimension of the reflectarray aperture and F is focal point of the reflectarray antenna), and maximum angles of incidence whose curves can be considered similar as the normal incidence (60 degrees for 11.8 GHz and 40 degrees for 16.3 GHz and 24 GHz), the ratio of F/D should be more than 0.29 at 11.8 GHz and 0.6 at 16.3 GHz and 25 GHz;

$$\theta = \tan^{-1} (D/2F). \tag{1}$$

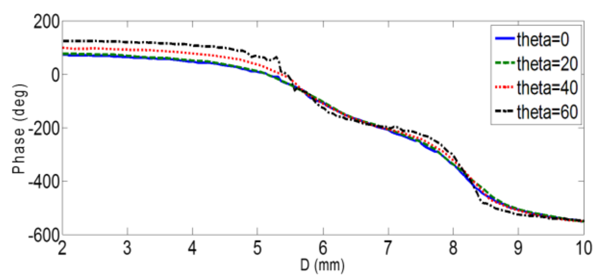


Fig. 13. Phase responses of the element at 11.8 GHz.

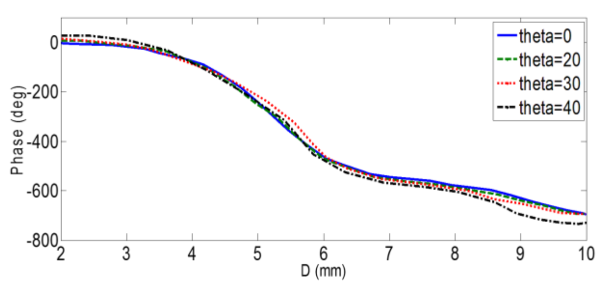


Fig. 14. Phase responses of the element at 16.3 GHz.

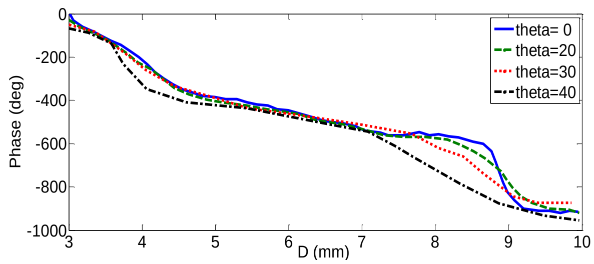


Fig. 15. Phase responses of the element at 25 GHz.

For feeding the reflectarray antenna, two horn antennas are used. The first horn is a pyramidal one with 4.8×3.3 $cm^2$ aperture size used for X- and Ku-bands and the second horn is a pyramidal one too, with 3.5×2.7 $cm^2$ aperture size used for feeding the reflectarray in K-band. Figure 16 shows the radiation patterns of the feeds at the center frequencies.

Next, the feed position is determined. It should be optimized, so that the required phase delay, calculated from the formula 1 [17] (where k0 is the propagation constant in a vacuum, di is the distance from the phase center of the feed to the element i, (xi, yi) is the coordinates of the element i, (xf, yf, zf) is the coordinates of the phase center of the feed and (θb, Ψb) is the direction of the main beam) is achieved at the three bands simultaneously, with the minimum phase error for each element.

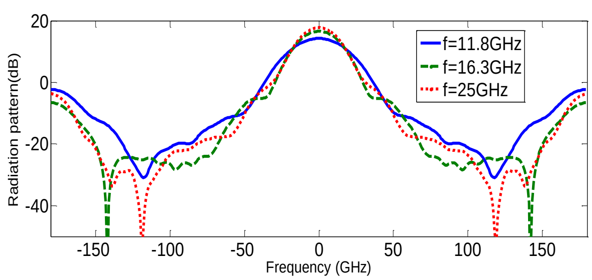


Fig. 16. Radiation patterns of the feeds in center frequencies at the three bands.

In other words, the feed position, should be considered in a way that, the size of each element, determined from the phase curves, is almost the same for the three bands, so that the single-layer reflectarray will operate properly at the three bands. The required phase shift was calculated with Matlab program[19] for each element at each band for several different feed positions and finally the optimum value for the distance, between the horn and the reflectarray antenna was chosen so that the phase curves in each three bands, could satisfy the Equation (2). If the height of the horn antenna is considered to be 22 cm for the first two bands and 28 cm for the third band, maximum required phase shift at 11.8 GHz will be 500 degrees, at 16.3 GHz will be 590 degrees and at 25 GHz will be 700 degrees. They are not the whole phase ranges which have been achieved of the element. By varying D from 3 mm to 8.5 mm required phase shift, can be satisfied at the three bands:

$$\Phi(R) = k_0(d_i - (x_i \cos(\Psi_b) + y_i \sin(\Psi_b)) \sin(\theta_b)), \quad (2)$$

$$d_i = ((x_i - x_f)^2 + (y_i - y_f)^2 + z_f^2)^{1/2}. \quad (3)$$

After finding the optimum feed position and calculating the size of each element, the elements are set in the reflectarray aperture in the proper positions, the horn antenna is put in the optimized location, and the boundary conditions are determined in CST Microwave Studio environment [20]. In order not to waste the simulation time and the computer memory, the symmetry planes are used.

## III. RESULTS

A 21 cm×18.9 cm single-layer center-fed tri-band reflectarray antenna using 387 variable sized patch elements has been designed and fabricated on the 2 mm air and 0.813 mm Rogers 4003 substrate, as shown in Fig. 17. The feed position has been optimized to obtain minimum phase error and more efficiency at the three bands.

Figure 18 shows the measurement equipments and fabricated antenna with the 22 cm optimized distance of the horn antenna and reflectarray.

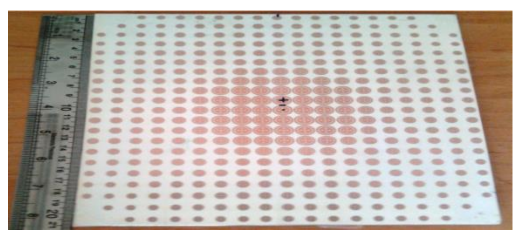

Fig. 17. Fabricated multi-band reflectarray antenna.

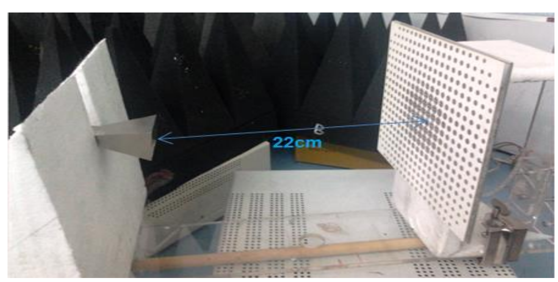


Fig. 18. Measurement equipment.

The simulated and measured radiation patterns for the E-plane and H-plane at the center frequencies of 11.8 GHz and 16.3 GHz are shown in Figs. 19 to 22. The side lobe level of this antenna is not good because the array is small and the feed aperture is big and it causes feed blockage. To overcome this problem, we should design bigger array and offset feed.

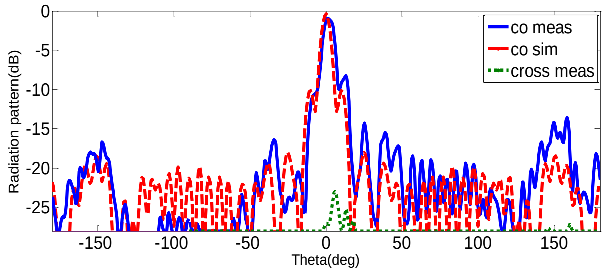


Fig. 19. Measured and simulated radiation pattern at 11.8 GHz for the E-plane.

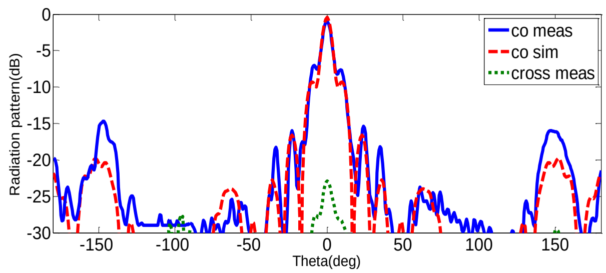


Fig. 20. Measured and simulated radiation pattern at 11.8 GHz for the H-plane.

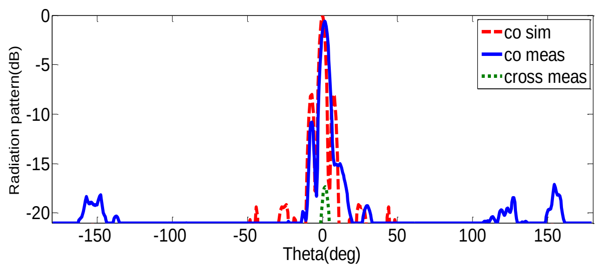


Fig. 21. Measured and simulated radiation pattern at 16.3 GHz for the E-plane.

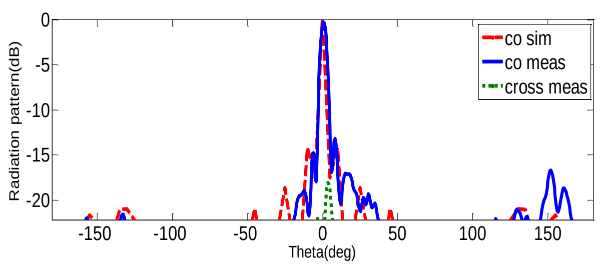


Fig. 22. Measured and simulated radiation pattern at 16.3 GHz for H-plane.

Because the measurement equipments don't have the potential to operate at very high frequencies, measurement of the antenna parameters in the third band, with the center frequency of 25 GHz was not possible for us, so the simulation has been done with two different methods of Transient Solver Parameters and Frequency Domain Solver Parameters. Figures 23 and 24 show radiation patterns at 25 GHz in the E-plane and H-plane, comparing these two methods.

Figure 25 shows the maximum gain of 22.9 dB at 11.8 GHz with 2980 MHz, 3 dB bandwidth; Fig. 26 shows the maximum gain of 27.5 dB with 2990 MHz, 3 dB bandwidth; Fig. 27 shows the maximum gain of 27.5 dB with 2500 MHz, 3 dB bandwidth.

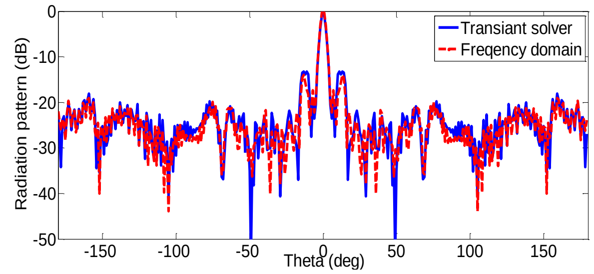


Fig. 23. Simulated radiation pattern at 25 GHz for E-plane with 2 different methods.

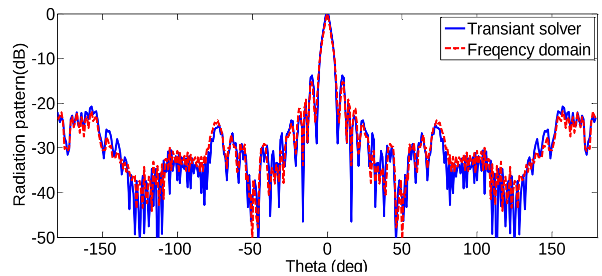


Fig. 24. Simulated radiation pattern at 25 GHz for H-plane with 2 different methods.

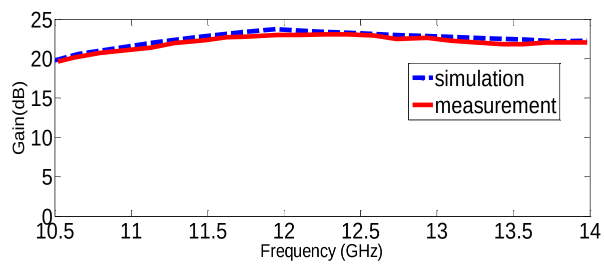


Fig. 25. Gain of the reflectarray antenna in X-band.

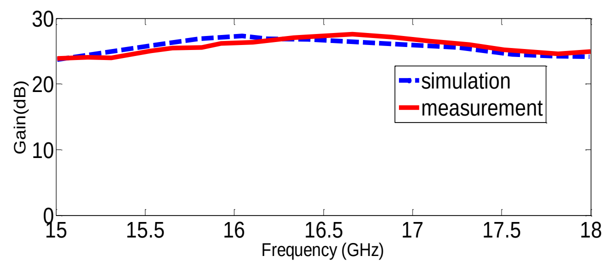


Fig. 26. Gain of the reflectarray antenna in Ku-band.

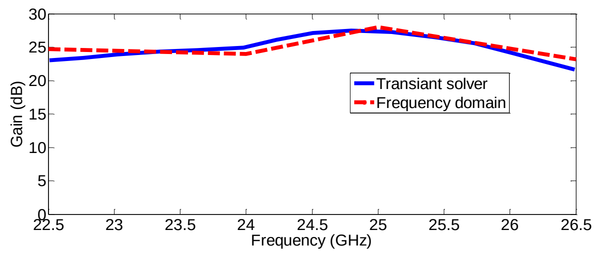


Fig. 27. Simulated gain of the reflectarray antenna in K-band.

The reflectarray antenna efficiency is 35.6% at 11.8 GHz, 33% at 16.3 GHz and 20% at 25 GHz. The most important reason that the efficiency is low, is the feed blockage due to the center-fed design. Feed-blockage shows its effect more at higher frequency because of reduction of the wavelength. Another reason is dielectric loss tangent. According to Fig. 12, this loss is much higher at 25 GHz. That's why the efficiency at 25 GHz is lower than the first two bands. By designing, offset-fed reflectarray and using substrate with lower dielectric loss tangent, much higher efficiency can be achieved.

## IV. CONCLUSION

A tri-band single-layer patch and ring element was introduced to design a tri-band microstrip reflectarray antenna. Phase compensation was achieved by varying the size of the elements. By optimizing the element, 600 degrees linear phase range at 11.8 GHz, 680 degrees at 16.3 GHz and 900 degrees at 25 GHz was achieved. Feed position was optimized to get a minimum phase error and obtain better efficiency. The designed reflectarray antenna was simulated with CST Microwave Studio, fabricated and measured. Measurement results show good agreement with simulation results. The reflectarray antenna operates properly at the three bands with wide bandwidth.

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