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A Study Of Dual-Layer Dual-Band Reflectarray Antenna Design Based On Dipole And Polygon Unit Cells For High Gain Applications

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ABSTRACT

This work discusses the design of a dual-band reflectarray antenna which involves the design of a high frequency transmit band unit cell for operation in the (12.75 – 14.5) GHz band and a low frequency receive band unit cell for operation in the (10.7-11.7) GHz band for high gain applications. The unit cells are designed to achieve linear polarization viz. vertical polarization in the receive band and horizontal polarization in the transmit band. A circular FSS is designed to act as the ground plane for the transmit band and to provide isolation between the two bands. Full wave analysis of the designed dual layer is performed in CST MWS. The simulation results exhibit a farfield gain of 22.6 dBi for the receive band center frequency of 11.2 GHz and 15 dBi for the transmit band center frequency of 13.6 GHz.

Keywords: *Dual-band, FSS, isolation, linear polarization, reflectarray*

1. INTRODUCTION

Reflectarray antennas are a category of antennas that are utilized for high gain applications such as satellite communications, remote sensing, and so on. They are designed for several frequency bands such as Ku, Ka, X, and W. Their low profile nature coupled with low fabrication cost turn out to be the major advantages. This low profile nature enables easier transportability unlike the traditional bulky parabolic dishes. Hence, they prove handy for establishing communications during emergency situations.

Reflectarray antennas are designed on a single layer as well as multi-layers. The starting step in the design of any reflectarray antenna is the design of a unit cell. Two important requirements of the unit cell need to be satisfied: the first one is about achieving 360 degrees of reflected phase range and the second one is having a linear phase response curve with smooth transitions. A reflected phase range of at least 360 degrees is required to mitigate phase errors in the design. Phase ranges that are multiple cycles of 360 degrees have been achieved in literature.

After finalizing the unit cell, the array is constructed using multiple numbers of the unit cells that are phase compensated. A horn is used as a feed for illuminating the unit cells of the array. In this work, a dual-layer reflectarray antenna is designed for two bands namely the transmit band (12.75– 14.5) GHz and the receive band (10.7 GHz – 11.7) GHz. The dimensions of the ground plane and the radiating unit cell are usually expressed in the integral multiples of λ or λ_g /2 where λ is the free space wavelength and λ_g is the guided wavelength. Both of them are expressed in mm. The choice of the unit cell usually depends on the requirements of the application. Several geometries are available for the unit cell. Some of the most commonly used geometries for the unit cell include circle, rectangle, square, square loops, dipoles, crossed dipoles, polygons, and so on. In each case, the required reflected phase range of 360 degrees is achieved by varying one or more parameters pertinent to the unit cell. As an example, the length of a rectangle can be varied from a starting value to a stop value to achieve the desired phase range.

In the case of dual layer, the reflectarray antenna is designed with the phase compensated unit cells on two layers of a same or different substrate. The top substrate layer will be having the unit cells designed for one band while the bottom substrate layer will be having unit cells designed for the other band. Thus, we can reduce the mutual coupling existing between the two bands by providing isolation in the form of a frequency selective structure (FSS).

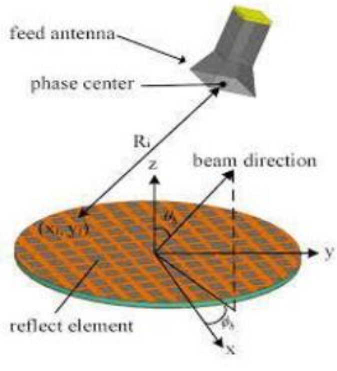

Fig. 1 Basic Reflectarray

A reflectarray antenna system consists of an array of reflectarray unit cells that are illuminated by an incident electromagnetic (EM) wave of a desired (band of) frequency. Upon incidence, the unit cells reflect the EM wave which then collimates towards a target. In this work, a dual-layer reflectarray antenna is designed. The basic principle of the dual-layer reflectarray antenna remains the same.

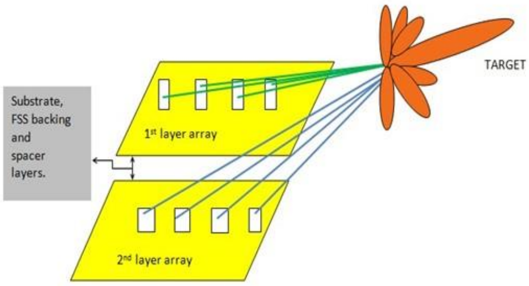

Fig. 2 Dual-layer reflectarray antenna

Fig. 2 illustrates the basic operation of a dual-layer reflectarray antenna. EM waves, upon reflection from the unit cells, constructively interfere and collimate in the direction of the target. [1] Presented the design of a reflectarray antenna in two layers wherein the Ku-band unit cells were placed on top of X-band unit cells. An FSS was used to create isolation between the two bands. The FSS acts as a ground plane for the Ku-band unit cells. The high reflection coefficient of the FSS layer enabled maximum reflection for the Ku-band and maximum transmission for the X-band. A delay line was used in the unit cell to achieve linearity in the phase response. [2] Proposed the design of a reflectarray antenna for the Ka and X bands. The higher band elements (Ka-band elements) were placed on top of the X-band unit cells. The work highlighted the significance of reflectarray antennas in the military Ka-band (MKa band) for military satellite applications. The unit cells of both the bands were etched on the same substrate and an air gap of 5 mm was maintained between the FSS layer present below the substrate of Ka-band elements and the X-band elements. In [3], a two-layer reflectarray antenna was designed using rectangular patches. Two separator layers were used in the design: one present in between the two arrays and the other between the bottom array and the ground plane. It was reported that a smooth phase response curve and consequently broad bandwidth was achieved by increasing the thickness of the dielectric however; the obtained phase range was less than 360 degrees. Moreover, to handle the non-linearities in the phase response curve, it was asserted to have two or more arrays stacked. Likewise, [4] reported the design of a dual-band reflectarray antenna that discusses independent operation in Ku and Ka bands. The unit cell was based on dipoles. Five parallel dipoles were chosen as the unit cell geometry for the Ku band while a three parallel dipole was chosen as the unit cell for the Ka-band. In this work, the symmetry of the dipoles was maintained in the design to achieve low levels of cross-polar radiation. [5] Discussed the design of a transmit-receive reflectarray antenna for DBS applications. Three layers of varying sized rectangular copper patches were utilized. The layers of the substrate were the same and instead of copper ground, aluminum was used. Dual-band FSS backed reflectarray could minimize the coupling between the unit cells of two bands of interest [6].

2. DESIGN OF REFLECTARRAY UNIT CELL

A single vertical dipole and a hexagonal polygon were chosen as unit cells for operations in the transmit and receive bands respectively. The ground plane, substrate, and air gap have dimensions of 22 mm x 22 mm as their length and width. The transmit band unit cell was etched on a standard Rogers RT 6002 substrate with dielectric constant 2.94 and thickness 3.048 mm while the dielectric constant and thickness of the receive band unit cell substrate were 3.02 and 0.76 mm respectively. In the case of the transmit band unit cell, the length of the dipole was varied from 1 mm to 21 mm. For the receive band unit cell, the side parameter ‘l1’ was varied from 1.75 mm to 9.75 mm.

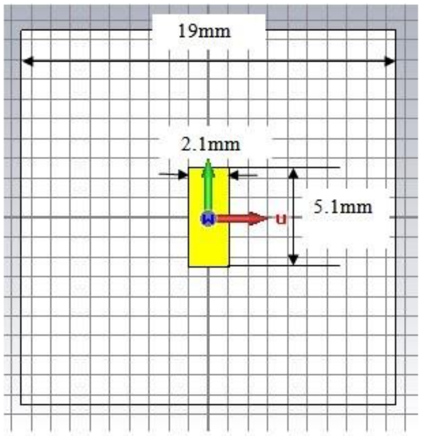

Fig. 3 Transmit band unit cell

Fig. 3 and Fig. 4 illustrate the transmit and receive band unit cells respectively along with their dimensions. The transmit band unit cell is a simple dipole whose length is varied during the parametric study to obtain the required phase range. In the case of receive band unit cell, which is constructed as a polygon in CST MWS, the side parameter ‘l1’ is varied to achieve the phase range. The coordinates used for designing the receive band unit cell are as follows in the correct order: (-l1,0); (-l2,lu); (l2,lu); (l1, -0); (l2,-lu); (-l2,-lu) and (-l1,0). Initially, l1 is set to 7.25 mm while lu = l1 and l2 = (2/3)*l1.

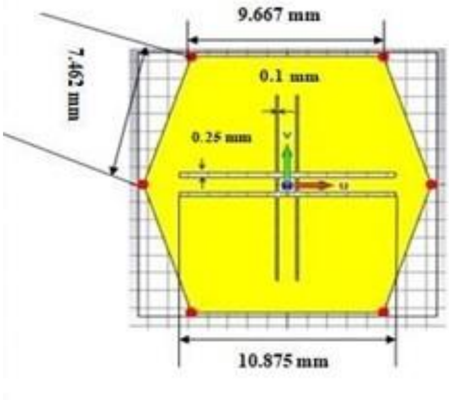

Fig. 4 Receive band unit cel

The receive band unit cell is loaded with four slots-two parallel slots along the Y-axis and the other two parallel slots along the X-axis. The width of these slots remains constant during the parametric study and the lengths of the slots vary during the study. The slot lengths are expressed as ll = 1.5*l1.

The reflected phase responses obtained with the designed unit cells were studied in terms of the phase range and the slope of the response curve. The thickness and dielectric constant of the substrate affect the achievable phase ranges. For the same substrate, various thicknesses are available in the datasheet and the phase response can be studied for various values of thicknesses.

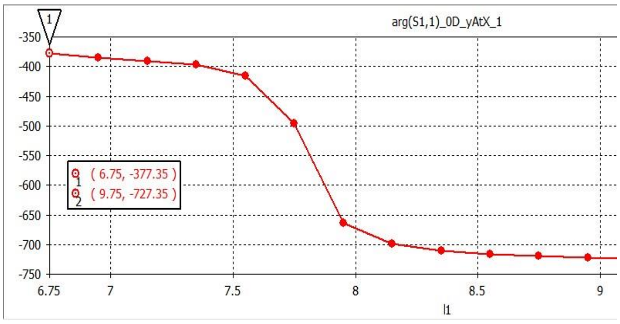

Fig. 5 Reflected Phase Range for 11.2 GHz

A phase range of 350 degrees is obtained with this unit cell designed for receive band. The parameter ‘l1’ was originally swept from 1.75 mm to 9.75 mm however, the phase response for the values from 6.75 mm to 9.00 mm alone was studied and the curve for the rest of the values was ignored. The figure above shows a truncated version of the actual phase response obtained. The response was very steep for the values ignored.

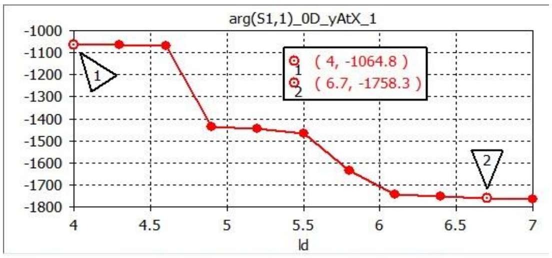

Fig. 6 Reflected Phase Range for 13.6 GHz

A phase range of 694 degrees was achieved with the designed transmit band unit cell. The phase response for the other four frequencies namely 10.7 GHz, 11.7 GHz, 12.75 GHz, and 14.5 GHz were studied. Fig. 7 and Fig. 8 show the comparison plots of the phase versus length response for all the three frequencies of the receive band and transmit band respectively.

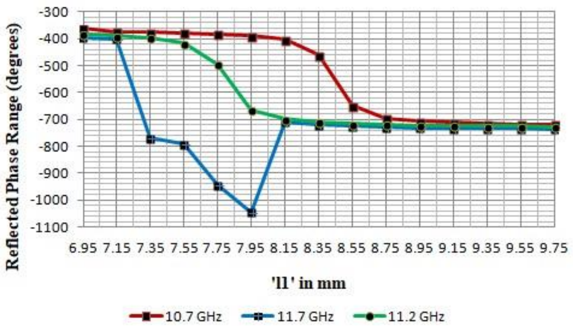

Fig. 7 Reflected Phase Ranges for the receive band

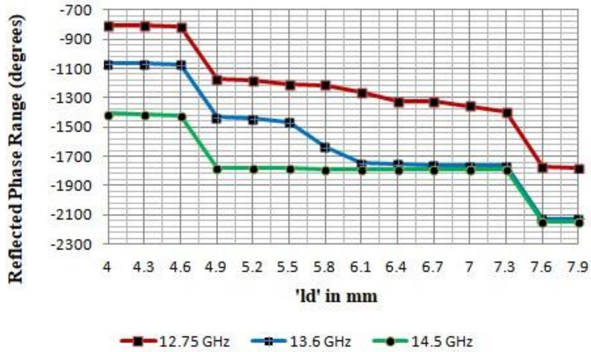

Fig. 8 Reflected Phase Ranges for transmit band

3. FSS DESIGN

A circular FSS was designed and placed at the back of the transmit band substrate. The FSS provides maximum reflection to the transmit band array and maximum transmission to the receive band array.

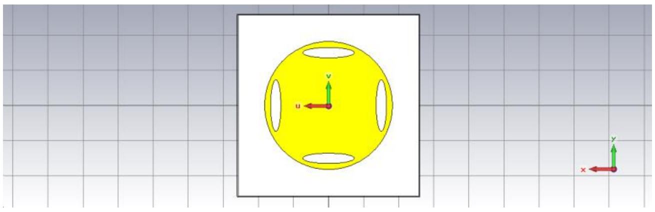
Fig. 9 Circular FSS

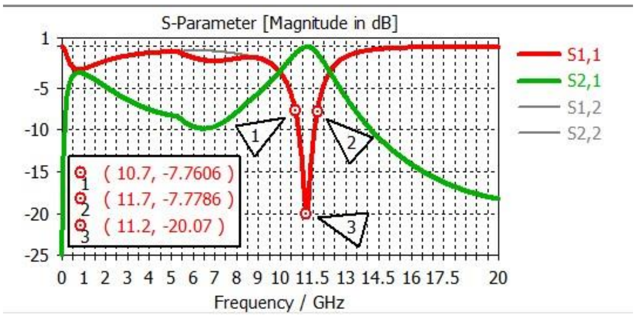

Fig. 10 FSS: S_{11} and S_{21} results

A circle of radius 1.82 mm loaded with four elliptical slots that are equally displaced from each other with respect to the center of the circle is designed as FSS. All the ellipses are the same with major axis 0.735 mm and minor axis 0.147 mm. The FSS should yield return losses less than -10 dB (as shown in simulation environments) for the entire receive band that spans from 10.7 GHz to 11.7 GHz. This is a necessary condition that will ensure that the FSS will provide maximum reflection to the transmit band array. Failure to achieve this will introduce mutual coupling between the two bands. Fig. 10 shows the return loss and transmission coefficient of the designed FSS.

FREQUENCY (GHz)	RETURN LOSS (dB)
10.7	-7.7606
11.2	-20.07
11.7	-7.7786

Table 1. Return loss results for FSS

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4. ARRAY DESIGN

An array of the designed unit cells is constructed in CST MWS. A 15x15 array is designed with overall length and width as 0.33 m respectively. For this design, an f/D ratio of 0.8 is maintained. The distance between the horn and the centermost unit cell (which is the unit cell with the coordinates (0,0,0)) of the array divided by the overall width (length) of the array is termed the f/D ratio. It is quite common in the literature to fix this ratio as 0.8 which, again, can be varied and the effect of which can be studied.

A full wave analysis was being performed for all six frequencies, three in each band. For receive band, a wideband horn centered around 11.2 GHz was used as the feed. In the case of transmitter, a similar wideband horn centered around 13.6 GHz was used for illuminating the unit cell elements of the array. Fig. 11 and Fig. 12 show the 2D radiation pattern of the simulated array.

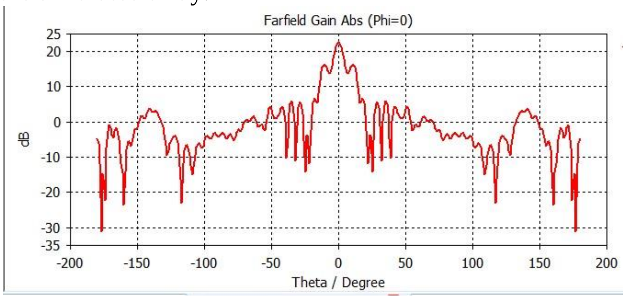

Fig. 11 2D Radiation Pattern for 11.2 GHz

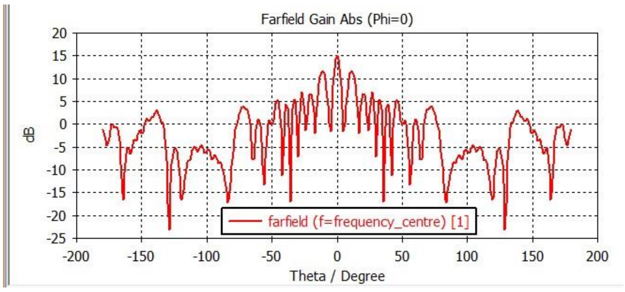

Fig. 12 2D Radiation Pattern for 13.6 GHz

BAND	f (GHz)	MAIN LOBE (dBi)	SIDE LOBE (dB)	ANGULAR WIDTH (º)
RECEIVE	10.7	22.3	-9.2	6.4
	11.2	22.6	-6.4	6.3
	11.7	21.4	-2.9	6.6
TRANSMIT	12.75	18.5	-4.7	13.4
	13.6	15.0	-3.4	4.1
	14.5	16.6	-6.9	10.2

Table 2. Array performance

We can observe a sharp difference in the farfield gains for 11.2 GHz and 13.6 GHz. The 2D farfield gain vsersus frequency plot is nearly a straight line for the receive band which isn't the case for transmit band. A dip is observed at the center frequency of the transmit band. In general, the gain versus frequency plot is expected to be nearly a straight line.

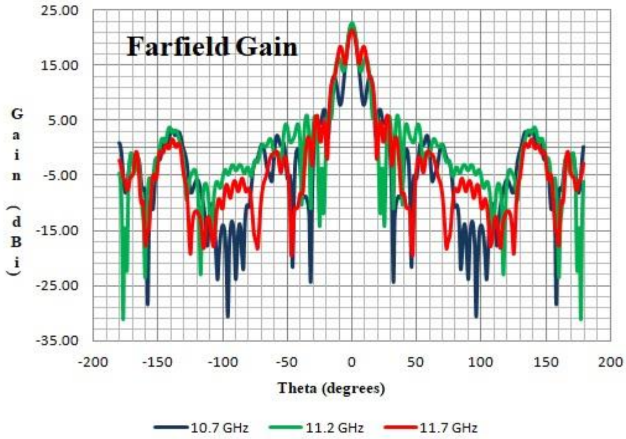

Fig. 13 Receive band comparison plot

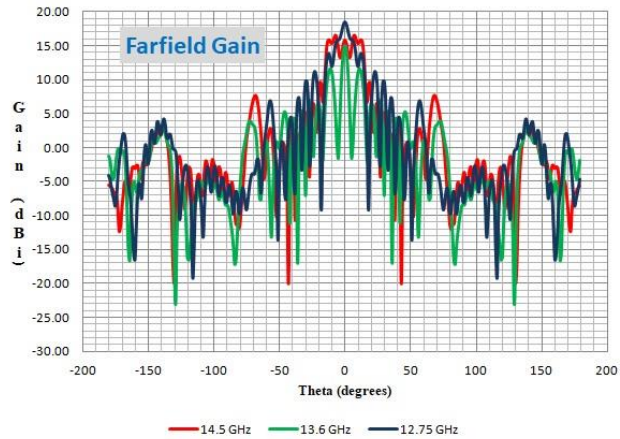

Fig. 14 Transmit band comparison plot

The farfield gain for the center frequency of the receive band namely 11.2 GHz is 22.6 dBi while that of the transmit band is 15 dBi. Fig. 13 and Fig. 14 illustrate the farfield gains of the three frequencies of receive band and transmit band respectively as comparison plots.

5. DISCUSSION OF RESULTS

From the results obtained upon simulation, we can find that the farfield gains for the frequencies of the receive band are nearly the same and high when compared to the transmit band frequencies. From Fig. 5, it can be observed that the response curve does not have a smooth transition throughout the curve. From 4.9 mm to 6.7 mm along the X-axis, the curve follows a smoother transition when compared to the values from 4 mm to 4.9 mm. For 'ld' taken from 4.9 mm to 6.7 mm, the phase range is 323 degrees, which is short of the required 360 degrees. It can thus be noted that for a unit cell to be qualified as 'good', it should have a gradual slope instead of a steep one along with good linearity.

From Fig. 10, it can be observed that the designed FSS doesn't yield the required return loss throughout the receive band. For the start and stop frequencies of 10.7 GHz and 11.7 GHz respectively, the return losses are greater than -10 dB (nearly -7.7 dB) which, despite being closer to the -10 dB level, are still insufficient.

6. SINGLE LAYER VS. DUAL LAYER REFLECTARRAY ANTENNA

Apart from the difference in the geometry or architecture between the two, certain factors have to be considered before selecting a single layer or dual layer for the unit cell and array design. Mutual coupling is the first factor. The effects of mutual coupling can be reduced to a good extent in case of dual-layer design by providing proper isolation and/or physical separation between the two bands in the form of an FSS. However, this isn't the case in a single layer. With proper placement of the unit cells of the two bands and appropriate spacing between the unit cells, the mutual coupling can be reduced in single layer reflectarray design.

Compactness is the second factor. If stacking layers prove to be space consuming, it is then wise to select the single layer as the final design with proper placement of unit cells on the substrate and suitable spacing between them.

7. CONCLUSION

Thus, it can be concluded that the FSS hasn't provided maximum reflection to the transmit band array, and consequently there isn't sufficient isolation between the two bands. Therefore, mutual coupling between the two bands has occurred. This has not affected the radiation performance of the receive band array. The relatively poor results of the transmit band array are due to the inefficiencies in the designed unit cell and FSS. We can, therefore, understand the importance of a good unit cell design and a proper FSS design particularly for multilayer reflectarray systems.

If the transmit band unit cell and FSS are improved performance-wise, we can obtain improvements in the performance of the transmit band array which will then make it suitable for high gain applications.

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