Design of Ka-Band Reflectarray for Space

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***Abstract*—This paper presents a design of a Ka-band reflectarray consisting of 2601 (51×51) square ring-patch elements, operating at 28 GHz. The elements are printed on a 60mil Rogers 4003C substrate, backed by a ground plane. The element grid size is 4.4 mm (~0.411λ_0). The square ring-patch element can achieve more than 360° of reflection phase. The proposed reflectarray, fed by an off-set pyramidal horn, achieves a peak realized gain of 33.94 dB corresponding to 57% aperture efficiency, and a 1-dB gain bandwidth of 6%.**

***Index Terms*—reflectarray; aperture efficiency analysis; microstrip antenna; reflector antenna; square ring patch resonator**

I. Introduction

THE very first reflectarray antenna dates back to 1963, where it used waveguides as the element for the reflector [1]. Its major drawback is its bulkiness and heavy weight. Reflectarray antenna only garnered attention after the breakthrough in printed microstrip antenna, making this idea more practical and affordable. The modern reflectarray can be thought as an amalgamation of a parabolic reflector antenna and a phased array antenna. The parabolic reflector antenna is expensive due to precision manufacturing and it is also incapable of wide-angle electronic beam scanning due to its bulky nature. Even though a phased array antenna can provide electronic beam scanning, the phase shifters required to perform this function are expensive. Moreover, the phased array antenna also suffers losses in the complex feeding network. The reflectarray combines the advantages of both the parabolic reflector antenna and the phased array antennas to attain a low cost, high gain and wide-angle beam scanning antenna [2].

Despite its desirable traits, there are several shortcomings in a reflectarray antenna. First, the limited bandwidth due to the fact that each element is designed for a specific frequency range, which is especially so when the reflectarray gets larger in size [3]. Second, the bandwidth is limited by the differential spatial phase delay [4]. Nevertheless, there are several methods to increase the bandwidth such as multi-layer design and use of true time delay [2].

In a reflectarray antenna, the elements are the important building blocks. The element should achieve a full cycle 360° phase range. There are several techniques to phase tuning such as varying element size, adding a stub line or by rotating* the element [2] (*for a circularly polarization). However, usually a single resonator element is unable to reach a full cycle. Hence techniques such as multilayer variable size design [5] and single layer - multiple resonator [6] have been introduced. Aperture coupled designs [7] are also explored to eliminate the space conjestion to accommodate the stub line & spurious radiation from it.

In this paper, a multi-resonant element in the form of a variable size square ring-patch combination is proposed for a 51×51-element reflectarry iilluminated by an offset pyramidal horn feed (LB-28-15). The designed reflectarray has a high gain with low-sidelobes.

II. Element Design

Fig. 1 depicts the configuration of the element design. The square ring-patch element is printed on 60 mils Rogers 4003C substrate backed by a conducting ground plane. The grid size is 4.4mm or ~0.411λ_0 to avoid grating lobes [2]. The square ring-patch element offers a greater phase range of more than 360° compared to the single square patch element.

There are three dimensionality freedom for the square ring-patch, namely, the relative size of the outer ring to the center patch, the thickness of the ring and the gap between the patch and ring. The size of the inner patch is R2 = K1×R1 and that of the ring width is $\boldsymbol{w}$ = K2×R1. By varying K1 and K2, the optimal parameter combination is derived, to produce a slowly varying and full cycle phase variation. CST Microwave Studio Suite 2018 was used for this derivation [8].

Fig. 2 shows the influence of K1 and K2 factors on the phase variation of the reflected wave versus the length of the outer ring R1. Looking into the K1 factor curve, K1 = 0.4 & 0.5 is definitely out due to its insufficient phase shift range, whereas K1 = 0.7 has a steep gradient at between 1.6 to 1.7mm making it undesirable. Hence through elimination, K1 is selected to be 0.6. K2 does not have a lot of influence on the phase variation as all three curves look vastly similar, choosing any will not affect the outcome too significantly. However, bear in mind that the smallest width to be manufactured is 0.1mm, hence K2 = 0.75 might be too thin. K2 = 0.125 is fine, but K2 = 0.1 displays a more linearity. Therefore, K2 is selected to be 0.1.

Based on the derivation, the parameters are K1=0.6 and K2=0.1, varying R1 from 1 to 4mm and substrate thickness of 60mil. Ultimately the phase curve shows in Fig. 3a. From the figure, the element provides a very broad phase shift variation of about 400° at theta = 0°, with good linearity and a very gentle dimension to phase change gradient. With the properties above, this makes the element a suitable candidate for the reflectarray design.

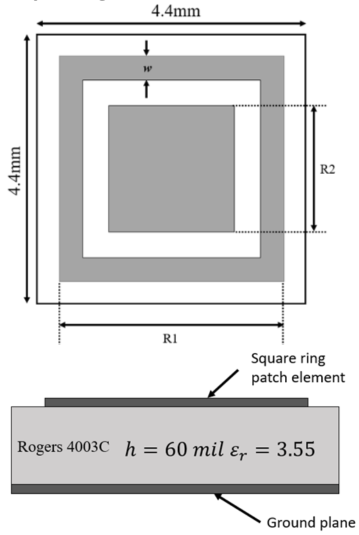
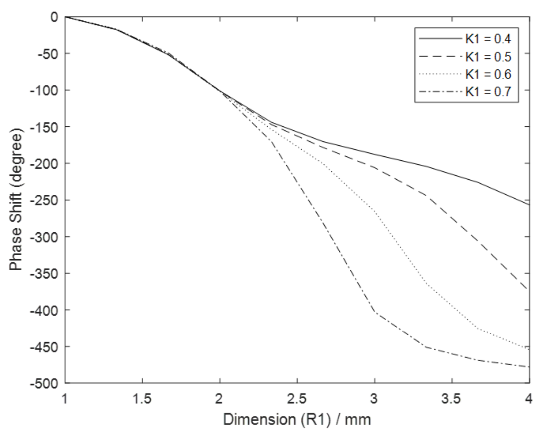
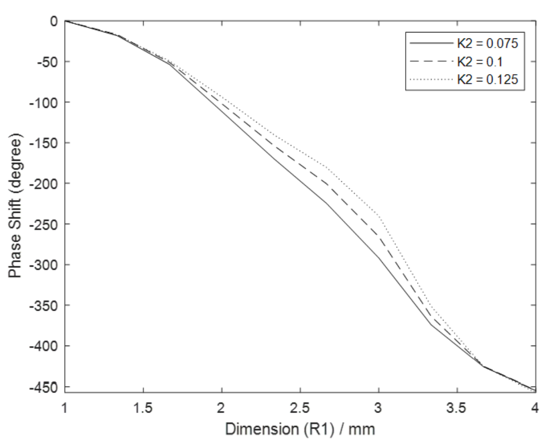


Fig. 1. Geometry of square ring patch element.

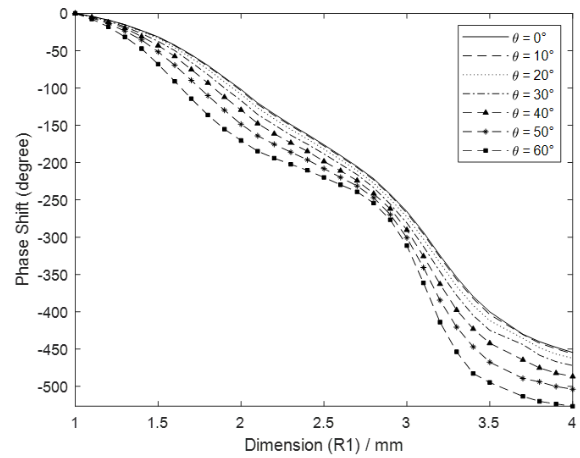


(a)

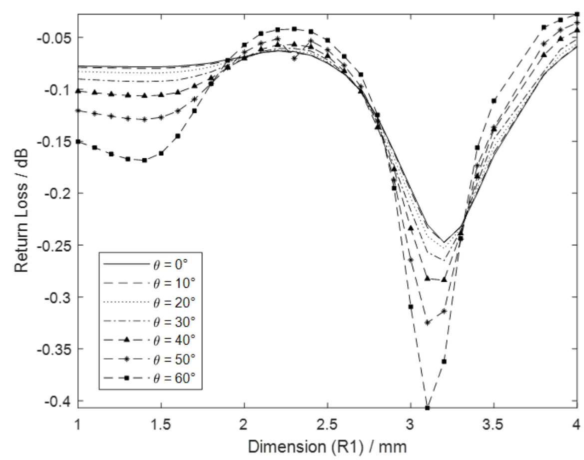


(b)

Fig. 2. Phase curve of unit cell for different (a) K1 factor (for K2 = 0.1); (b) K2 factor (for K1=0.6) at 28GHz center frequency.



(a)



(b)

Fig. 3. (a) Reflective phase curve ; (b) Return loss curve for K1=0.6 & K2=0.1

III. System Design

A. Optimal Focal to Diameter (F/D) ratio

The F/D ratio determines the position of the feed. In order to have good aperture efficiency, both the spillover efficiency and illumination efficiency must be balanced out. A common practice is to use -10dB taper as in [9]. However, a more formal and analytical approach introduced in [10] is used in this paper. Fig. 4 show the various efficiencies versus F/D for $q = 6.4$ and $D = 224.4$ mm.

From Fig. 4, an F/D of 0.9 will provide the peak aperture efficiency of the reflectarray for a prime-focus reflectarray. Although this analysis is for a prime-focus configuration, it provides a good starting point for our off-fed design.

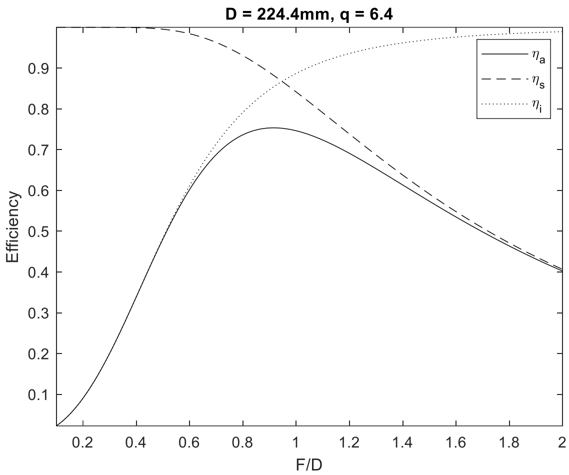


Fig. 4. F/D curve for the proposed design where $\boldsymbol{\eta_a}$: aperture efficiency, $\boldsymbol{\eta_s}$: spillover efficiency, $\boldsymbol{\eta_i}$: illumination efficiency.

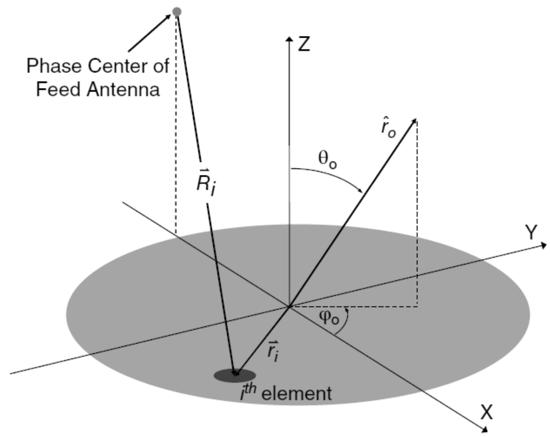


Fig. 5. Geometry of reflectarray [2].

B. *Phase Distribution on a reflectarray aperture*

The element phase on a reflectarray is given by [3]:

$$\phi_{RA} = k_0\left(R_i - \sin\theta_o\left(x_i\cos\varphi_o + y_i\sin\varphi_o\right)\right) + \phi_0 \quad (1)$$

where (x_i, y_i) is the coordinates of the element *i*, R_i is the displacement from the feed to the element *i*, k_0 is the wavenumber and $\theta_0,\varphi_0)$ is the desired beam direction. The spatial parameters of the reflectarray are shown in Fig. 5.

For this paper, an offset feed configuration is being considered to further reduce aperture blockage by the feed and support structure. The blockage is usually more significant in small reflectarray where the feed has a similar proportion to the aperture. Aperture blockage will lead to increase in sidelobe level and reduced gain.

The aperture blockage is a function of D_0/D where D_0 refers to the blockage area and *D* refers to the aperture area. If the blockage ratio is lesser than 0.2, the blockage will not affect the radiation significantly. In most cases, an offset configuration does not result in an increased gain but possibly a reduced gain because the projected aperture becomes smaller.

The feed in our reflectarray is positioned at [60, 0, 192.84] mm with respect to the center element at position [0, 0, 0] in the Cartesian coordinate system. The feed is rotated so that its boresight points at the origin as illustrated in Fig. 6. The desired beam direction is fixed at (0°, 0°). The resultant phase distribution using (1) for a circular reflectarray consisting of 51×51 square ring-patch elements is shown in Fig. 7.

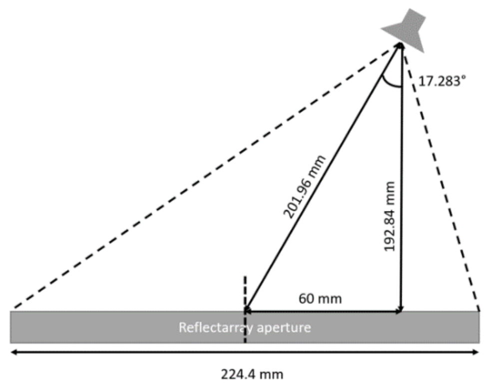


Fig. 6. Geometry of the off-set configuration.

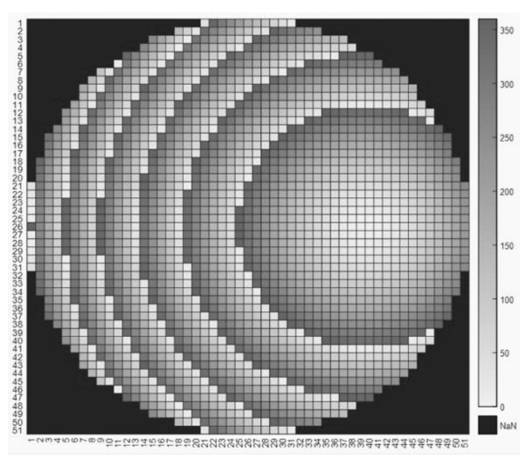


Fig. 7. Phase distribution plot of the proposed design.

IV. Full-Wave Simulation and Implementation of the Reflectarray

The full-wave EM simulation of the reflectarray is performed using CST Microwave Studio TLM time domain solver. The simulated 3D radiation pattern of the reflectarray at 28 GHz is shown in Fig. 8.

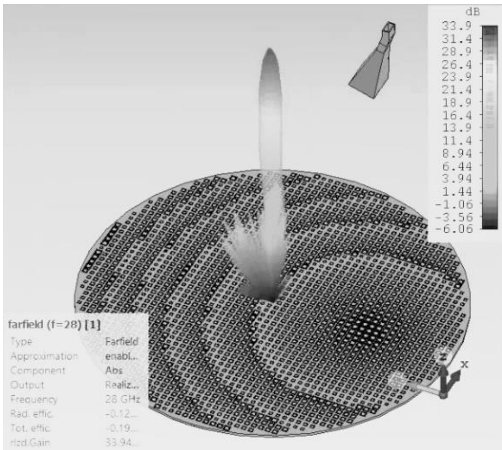


Fig. 8. Simulated 3D radiation pattern of the reflectarray at 28 GHz.

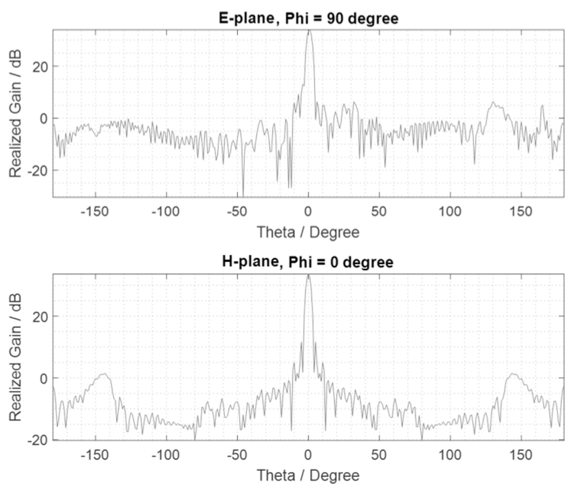


Fig. 9. 2D radiation pattern of the reflectarray at 28 GHz.

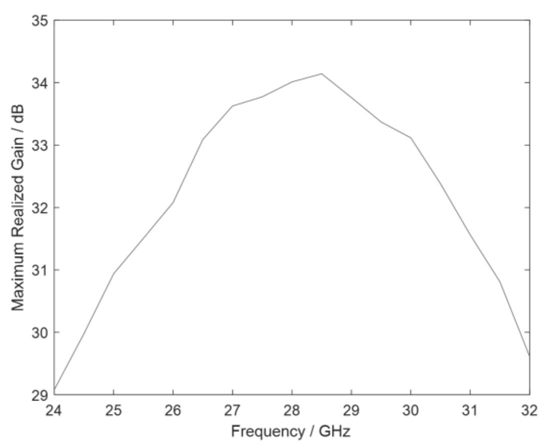


Fig. 10. Frequency vs Gain for the proposed reflectarray.

The proposed design has low sidelobes of -22 dB in the E-plane ($\varphi = 0°$) and -20.9 dB in the H-plane ($\varphi = 90°$) as shown in Fig. 9. The aperture efficiency is 57.1% for a realized gain of 33.94 dB at 28 GHz. The reflectarray also has a decent 1-dB bandwidth of 6% as shown in Fig. 10.

V. Implementation and Experimental Result

The proposed design was sent for fabrication and was measured using the compact range facility in the National University of Singapore. The measurement used 0.1° step angle and 0.1 GHz step frequency from 26 to 31 GHz, measuring along the E-plane. The far-field measurement setup of the reflectarray is demonstrated in Fig. 11.

The measured radiation pattern is shown in Fig. 12. The measured result agrees with the simulated result quite closely, albeit with slightly higher sidelobe on both sides. Note that the simulation does not consider the holding structure of the reflectarray. The maximum gain is also slightly lower (by ~ 1dB) than the simulated result.

The measured gain-bandwidth performance is compared to the simulation result in Fig. 13. Although the gain is lower than the simulation, its 1-dB bandwidth (from 26.4 to 30.7 GHz) of 7.53% is greater than the simulated result of 5.93% (from 26.55 to 29.9 GHz). Overall, the fabricated reflectarray antenna achieved the desired result and goal of this project.

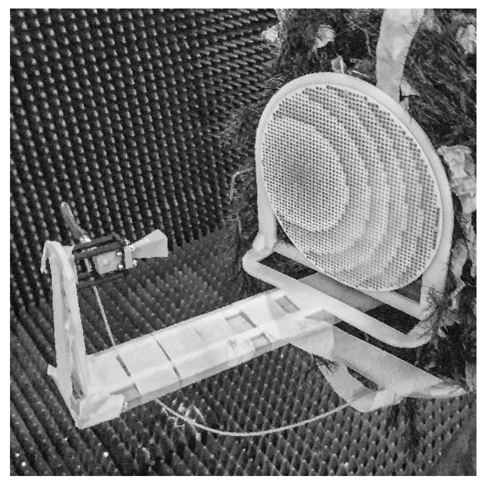


Fig. 11. Far-field measurement setup of the proposed reflectarray in compact range facility.

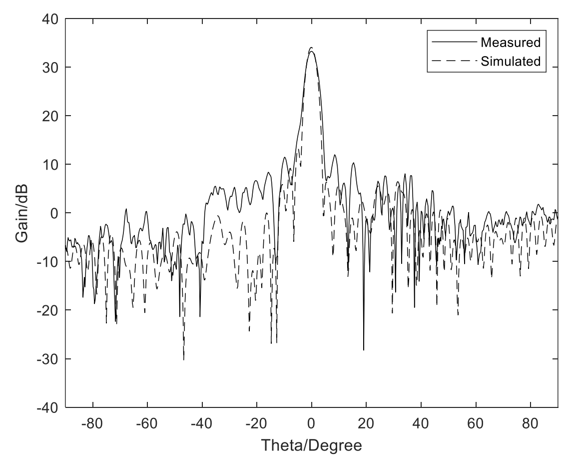


Fig. 12. Measured vs Simulated result at 28GHz.

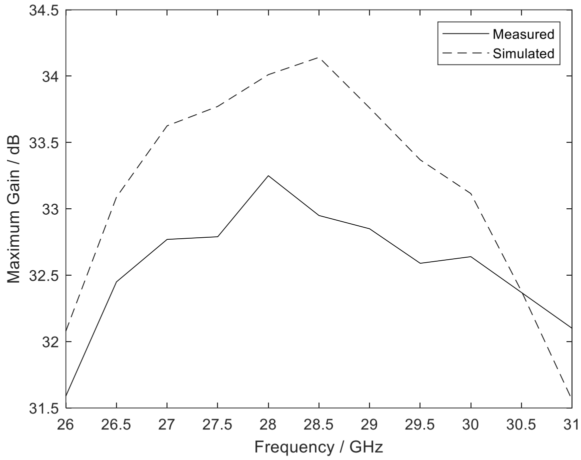


Fig. 13. Measured maximum gain over frequencies.

VI. Conclusion

The proposed reflectarray antenna exhibits high gain and good aperture efficiency with decent 6% bandwidth. The sidelobes levels are well-controlled with under -20dB on both planes. The fabricated antenna also agrees with the theoretical simulated result. Overall, the project has achieved its objective and purpose.

Acknowledgment

The author would like to give his most heartfelt appreciation to Prof. Chen Zhi Ning, Dr. Chia Tse Tong and Dr. Li Teng for the support in this project.

VII. References

[1] D. G. Berry, R. G. Malech and W. A. Kennedy, "The reflectarray antenna," *IEEE Trans.Antennas Propagat,* Vols. AP-11, pp. 645-651, 1963.

[2] P. Nayeri, F. Yang and A. Z. Elsherbeni, Reflectarray Antennas Theory, Designs, and Applications, Wiley IEEE Press, 2018.

[3] J. Huang and J.A. Encinar, Reflectarray Antennas, John Wiley & Sons, 2008.

[4] J.Huang, "Bandwidth study of microstrip reflectarray and a novel phased reflectarray concept," *IEEE AP-S/URSI Symp*, pp. 1134-1137, 1998.

[5] J. Encinar and J. Zornoza, "Broadband design of three-layer printed reflectarrays," *IEEE Trans. Antennas Propagat,* vol. 51, no. 7, pp. 1662-1664, 2003.

[6] W.y.Li, Y.C.Jiao and G.Zhao, "S novel microstrip rectangular-patch/ring combination reflectarray element and its application,," *IEEE Antennas Wireless Propag.Lett.,*, vol. 8, pp. 1119-1122, 2009.

[7] E. Carrasco, M. Barba and J. A. Encinar, "Reflectarray Element Based on Aperture-Coupled Patches With Slots and Lines of Variable Length," *IEEE Trans. Antennas Propagat,* vol. 55, no. 3, pp. 820-825, 2007.

[8] CST Microwave Studio, "CST Studio Suite," Computer Simulation Technology AG, [Online]. Available: https://www.cst.com/products/cstmws. [Accessed 2019].

[9] L. Guo, P.-K. Tan and T.-H. Chio, "Design of An X-Band Reflectarray Using Double Circular Ring Element," in *7th European Conference on Antennas and Propagation (EuCAP)*, 2013.

[10] F. Y. A. Yu, A. Z. Elsherbeni, J. Huang and Y. Rahmat-Samii, "Aperture Efficiency Analysis of Reflectarray," *Microw. Opt. Techn. Lett.*, vol. 52, no. 2, pp. 364-372, 2010.