

Design of a Bifocal Single Reflectarray Antenna with Improving Beam Scanning Performance

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Abstract: A novel scheme is introduced to design the high gain beam scanning reflectarray antennas for limited scan range application. At first, various existing schemes for beam scanning reflectarray antennas design are reviewed and it is concluded that as a convenient design scheme, the feed displacement technique is preferred for limited scan range applications. In order to improve the scan range, a bifocal single reflector aperture phase is introduced for reflectarray aperture phase design, and in order to further improve the performance, a circular path for feed displacement is introduced to take the place of the conventional lateral path. Based on the introduced scheme, a Ku band bifocal single reflectarray antenna is designed for limited scan range application. The scan performances of the designed reflectarray are analyzed numerically and compared with conventional parabolic design. Numerical results show that the bifocal design shows significant improved scan performance with less 0.8 dB gain loss and lower than -13 dB side lobe level over entire scan range -30° to +30°, which illustrates that the bifocal design for limited field of view beam scanning reflectarray is a promising attempt.

Keywords: Beam scanning, Bifocal, Circular arc path, Feed displacement, Limited scan range, Reflectarray antenna.

1. INTRODUCTION

High gain antennas play an essential role in the long distance wireless communication link systems, and it is well known that the reflectors, lens and phased arrays are the conventional candidates for the antennas in these systems [1]. As one important capability, the beam scanning ability of antennas can enable the multi-function performance of these systems and improve the efficiency of these systems. The markets for high gain beam scanning antennas are primarily dominated by military radar and tracking platform, however, there are some other demands in commercial applications such as low earth orbit satellite communications and collision warning systems [2, 3].

In general, for high gain beam scanning applications, a reflector or a phase arrays is chosen in terms of the factors relating to scan speed, scan range and cost [4]. In order to scan the beam of these aperture antennas, the phase distribution on the aperture must be adjusted according to the direction of the scan beam. Although the methodology for both designs is similar with each other, the schemes for realizing beam scanning are distinguished for reflectors and phased arrays.

Since the 1980's, microstrip reflectarray antennas, which combine the favorable features of both microstrip phased arrays and reflector antennas, have emerged as a new generation of high gain antennas with low-profile, low-mass and

low-cost features [1, 5]. In addition, because of the hybrid nature of the reflectarray antennas, they offer more flexibility in aperture phase control and the beam of a reflectarray antenna can be scanned by means of the reflectors nature or the phased arrays nature. The phase distribution for each element on the reflectarray aperture consists of two components [1].

$$\phi_a(x_i, y_i) = -k_0 R_i + \phi_e(x_i, y_i) \quad (1)$$

In this equation, the first term $-k_0 R_i$ corresponds to the spatial delay, which is the electrical distance between the phase center of the feed and the element position on the aperture. The second term $\phi_e(x_i, y_i)$ is the reflection phase of the element on the aperture. Since these two terms can be controlled almost independently in a reflectarray antenna, two different methods are available for the design of the beam scanning reflectarray antennas.

In the first method, the aperture phase distribution of reflectarray antennas can be adjusted by changing the spatial delay. This beam scanning scheme is similar to the technique used to scan the beam of the reflector antennas [6], which is categorized as the feed displacement method. As the placement of reflectarray aperture is generally fixed, the adjustment in the spatial delay can be realized by displacing the feed phase center. Depending on the scan speed requirement, the availability of feed antenna and the overall system cost, beam scanning performance can be realized mechanically by using a single movable feed, or electronically by using a feed array. The second method is adjusting the reflection phase of the element to achieve the adjustment of the aperture phase distribution of reflectarray antennas [7]. This methodology is basically similar to a phased array design, which is

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categorized as the element phase tuning method. It is worthwhile to point out that reflectarray antennas with individual phase control for each element can achieve a dynamic pattern without the need of an RF feed network. This can potentially improve the gain and allow for greater flexibility in array configurations, since beam scanning performance can be achieved by implanting low loss phase shifters into each reflectarray element without the need for T/R modules [3, 4].

In recent years, various investigators have done investigations on the design of the beam scanning reflectarray antennas. However, almost all of the investigations have concentrated on the element phase tuning method, such as beam scanning reflectarray antennas with phase controlled elements using micro-machines [8], MEMS switches [9], diodes [10], and exotic materials [11]. Although some of these designs can achieve a good beam scanning performance, the major disadvantage of these designs is the high loss of the element phase control mechanism, particularly at high frequencies [12]. In addition, these designs also have need of a control board to offer control voltages or rotation angles to each element, which makes the designed system more complicated. In the meantime, the beam scanning performance of reflectarray antennas realized by lateral displacement of feed is investigated in [13]. From a comparative study on the performance of these two methods [14], it is concluded that for the limited field of view system in beam scanning applications, feed displacement method is the suitable choice since the loss and complexity of this type of design is much lower. On the other hand, element phase tuning reflectarray antennas are preferable for wide angle beam scanning, despite their high loss and low efficiency.

It is well known that a bifocal dielectric lens shows wider scan coverage than a single focus dielectric lens, because it can focus quite well from near and between the two focal points [15]. Moreover, it is also shown that a bifocal dual reflector antenna has a better scan performance than a classical Cassegrain reflector [16]. A bifocal folded dual reflectarray antenna using a feed array with seven elements has been demonstrated in [17], which exhibits the scan capability with scan range of about 27° ($\pm 13.5^\circ$). The scan range is further improved to 49° ($\pm 24.5^\circ$) by designing a system with restricted apertures for each beam. In addition, a dual reflectarray with dual-offset feeds is also presented in [18]. It should be noted that in all designs, the ideal bifocal reflectors or lens require two surfaces for phase correction. Although these designs have achieved some significant improvements of beam scanning performance over the conventional single reflector parabolic phase compensations, the primary drawback focuses on the design complexity and fabrication difficulty of dual reflector system.

The aim of this paper is to design a high gain Ku band reflectarray antenna with 60° ($\pm 30^\circ$) scan range utilizing the feed displacement method based on concept of bifocal single reflector. Instead of the traditional parabolic type phase distribution, a novel aperture phase distribution based on the concept of a bifocal single reflector is introduced for the reflectarray antenna. Moreover, in order to further improve the scan performance, a novel path along a circular arc is introduced to take place of the conventional lateral displacement path for the feed displacement. The beam scanning perfor-

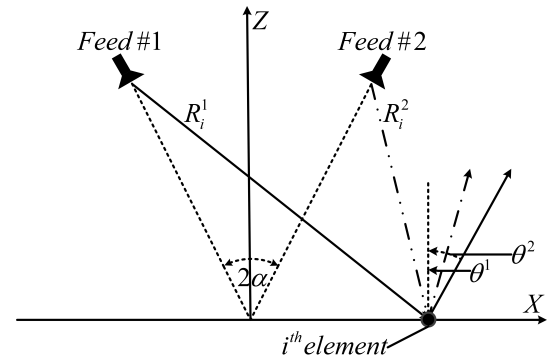


Fig. (1). Coordinate system for the bifocal single reflectarray.

mances of the designed bifocal single reflectarray antennas are analyzed numerically and then compared with those of the conventional parabolic type reflectarray antennas. Numerical results demonstrate that for the limited scan range, a bifocal design shows a significant improvement over the conventional parabolic design, which illustrates that the bifocal single reflector scheme is a promising attempt for the design of limited field of view beam scanning reflectarray.

2. CHARACTERIZATION OF A BIFOCAL SINGLE REFLECTARRAY

It has been discussed that for the feed displacement method to realize beam scanning performance, the reflectarray aperture is passive and the phase of the elements on the aperture are fixed with the assumption that the reflection phase of elements are not very sensitive to excitation angle. However, for beam scanning applications, the conventional designs whose elements phase are adjusted based on the phase compensation of a parabolic reflector antenna with a same subtended angle, have shown a poor performance with the scan range of just limited few beam widths [1, 13]. In order to improve the scan performance, a new design scheme for the aperture phase distribution of the reflectarray based on the bifocal single reflector systems has been introduced.

2.1. Principle of a Bifocal Single Reflectarray

In order to model the question of designing a bifocal single reflectarray system, the system parameters which should be considered, are illustrated in Fig. (1), where the reflectarray aperture is located on xoy plane and two offset feed antennas, each with an offset angle of α° , are placed in xoz plane.

For the two feed reflectarray system, the required aperture phase distribution corresponding to each feed and beam direction can be expressed as follows:

$$\phi_i^f = k_0(R_i^f - \sin \theta^f (x_i \cos \varphi^f + y_i \sin \varphi^f)) \quad (2)$$

In this equation, the superscript f denotes the corresponding feed, and θ and φ represent the direction of the scanning beam. The difference between a single feed and a two feed reflectarray system is that the aperture phase distribution must compensate for two different feed positions and beam directions. In order to simplify the question at hand, a sym-

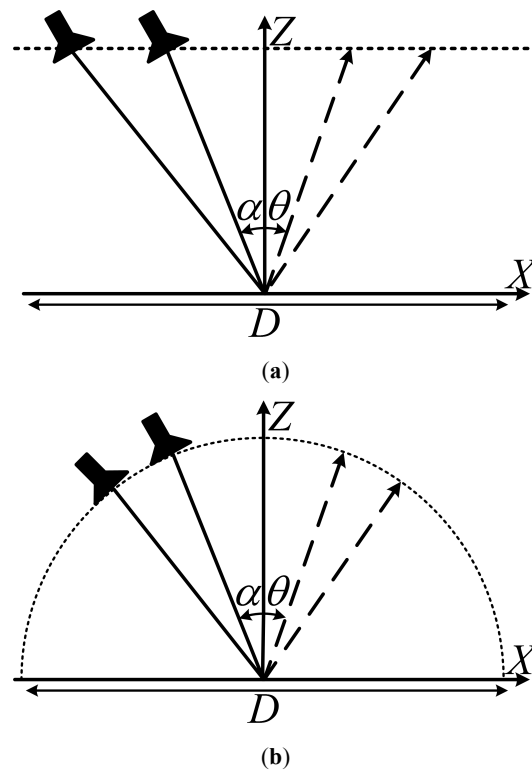


Fig. (2). Two different paths for feed displacement: (a) lateral movement (H/D is fixed), (b) circular arc movement (F/D is fixed).

metric system is considered. When the feed is at position 1, the scanning beam is set in the direction of $(\theta=\theta^1, \varphi=0^\circ)$. Similarly, when the feed is at position 2, the scanning beam will be set in the direction of $(\theta=\theta^2, \varphi=180^\circ)$. It should be noticed that for a symmetric system it has $\theta = \theta^1 = \theta^2$. For this system, the phase requirements can be expressed as:

$$\begin{aligned}\phi_i^1 &= k_0(R_i^1 - x_i \sin\theta) \\ \phi_i^2 &= k_0(R_i^2 + x_i \sin\theta)\end{aligned}\quad (3)$$

It is obvious that for passive reflectarray design, the i^{th} element cannot realize two different phase requirements. Therefore, an average phase is set for the i^{th} element to minimize phase errors,

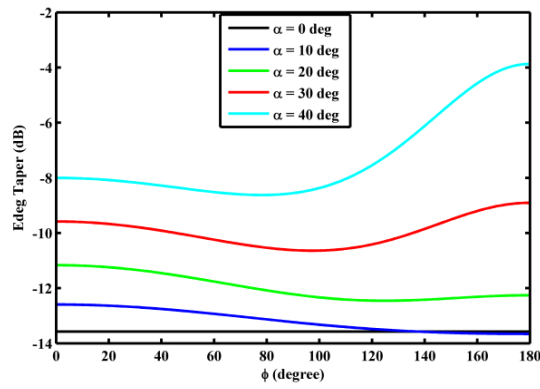
$$\phi_i = \frac{\phi_i^1 + \phi_i^2}{2}\quad (4)$$

It is implied that since the far field beam direction θ is cancelled out in equation (4) because of the symmetry of the system, the direction of the main beam of the reflectarray will only depend on the feed offset angle α . Dealing with the question of scanned beams, there is an important parameter defined as the beam deviation factor $BDF = \theta/\alpha$, which is expected to be less than 1 [13]. Nonetheless, it is possible to achieve the required scanned beams by compensating for this factor experimentally.

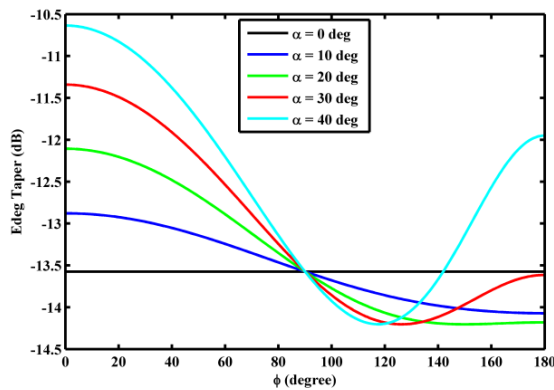
2.2. Feed Displacement Path

In the previous investigation, it has been shown that moving the feed antenna along the lateral path can be used to

scan the beam of reflectarray antennas [13]. In practice, however, different paths can be used for the feed movement. Since the feed is always set to point to the geometrical center of the reflectarray aperture surface, a practical path would be a circular arc with a radius of F . Fig. (2) illustrates two different paths for feed displacement, one is lateral movement with fixed H/D , and the other is circular arc movement with fixed F/D . A notable advantage of later paths is that the change in the edge taper (ET) as a function of the feed angle α can be improved. For a 10λ aperture reflectarray ($F/D=0.75$) with $q_f=6.5$, the ET of the two paths for various feed angles α is plotted in Fig. (3). It can be observed that for lateral displacement path, as the feed angle α increases, the change in ET shows significant increase where the maximum ET increases to about -4 dB in the extreme case. However, for circular arc displacement path, the change in ET shows not too much increase where the maximum ET increases to about -10.5 dB which is still enough small to minimize the effect of the edge diffraction. In addition, it is worthwhile to point out that the spillover efficiency is also significantly affected by the choice of feed displacement path. The spillover efficiencies for different feed displacement paths as function of various feed angles α are exhibited in Fig. (4). It can be seen that as the feed angle α increases, the decrease of spillover efficiency for the circular arc displacement path is much smaller than that for the lateral displacement path. Based on these parameter studies, it can be concluded that the feed movement along a circular arc shows a much better performance, and as results, this displacement path is used for the feed movement to scan beam of the reflectarray antenna.



(a)



(b)

Fig. (3). Edge taper for various feed angles: (a) lateral movement (H/D is fixed), (b) circular arc movement (F/D is fixed).

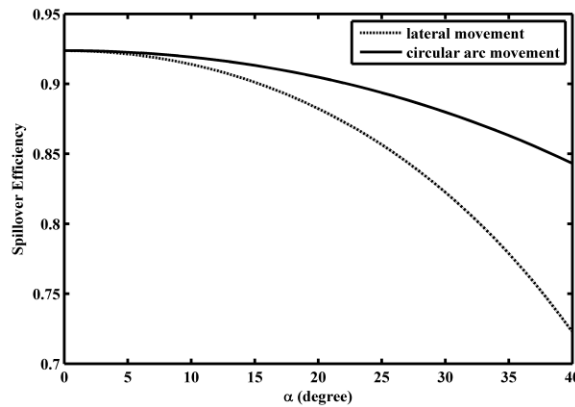


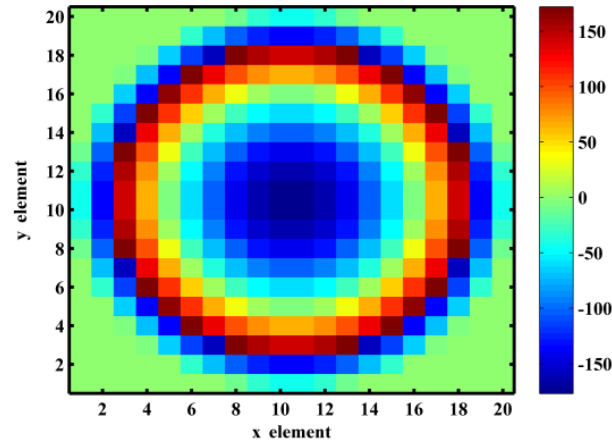
Fig. (4). Spillover efficiencies for different feed displacement paths as function of various feed angles.

3. BEAM SCANNING PERFORMANCE ANALYSIS

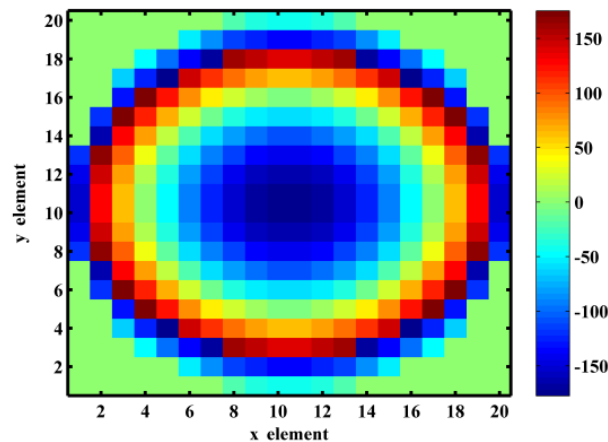
In order to investigate the beam scanning performance of the bifocal single reflectarray, a Ku band reflectarray with main beam direction pointing to 30° off broadside has been designed. By using the feed displacement technique, this reflectarray antenna can achieve a 60° scan range (-30° to +30°). The reflectarray aperture is a circular aperture with 10 wavelengths diameter at the design frequency of 12 GHz, and the element space is set at the half wavelength to minimize the effect of grating lobe. The feed displacement path is

set along circular arc with a radius of F. To further improve the beam scanning performance of the reflector, the maximum attainable F/D has been selected for this design [19]. The maximum F/D of 0.75 is determined based on the feed horn antennas which have the power $q = 6.5$ of the feed horn $(\cos \theta)^q$ radiation pattern model, to ensure that the edge taper is below -10 dB when the feed is tilted at α degrees.

To compare the scan performance of this design, a reflectarray antenna with a broadside beam has been designed as reference using the conventional parabolic equation. It is



(a)



(b)

Fig. (5). Element phase distribution: (a) parabolic design, (b) bifocal design.

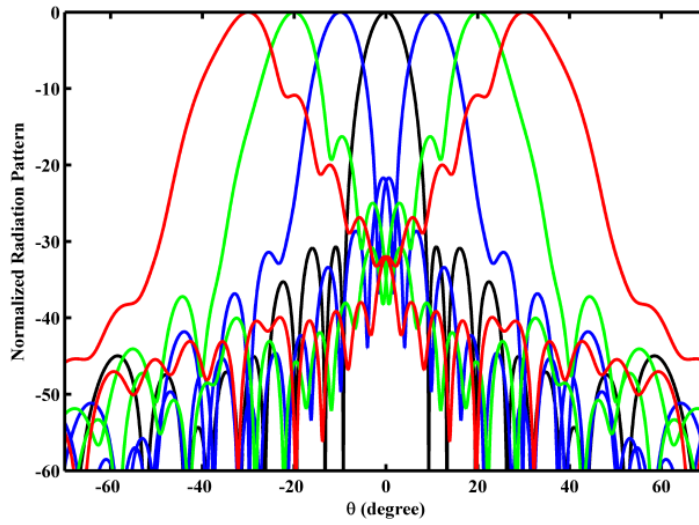
worthwhile to point out that for both investigated cases, the radiation of the reflectarray is computed using the array theory method as discussed in [20]. The reflectarray required element phase distribution for both designs are given in Fig. (5). It can be seen that the element phase distribution changes from circular ring shapes for parabolic design into elliptical ring shapes for bifocal design.

It should be noticed that for both design cases, the required offset feed angle is different and has to be obtained experimentally to compensate for the BDF as discussed in [13, 14]. For a 30° scan, the BDF for parabolic and bifocal designs is 0.9036 and 0.8955, respectively. The scanning normalized radiation patterns of both the parabolic and bifocal designs are plotted in Fig. (6), and the comparison of the both designs at the maximum scan angle is plotted in Fig. (7). From Fig. (6), it can be seen that for the parabolic design, as the beam is scanned toward the maximum scan angle, the side lobe level increases and the main beam width broadens, which results in significant pattern deterioration at the maximum scan angle. However, for the bifocal design, the side

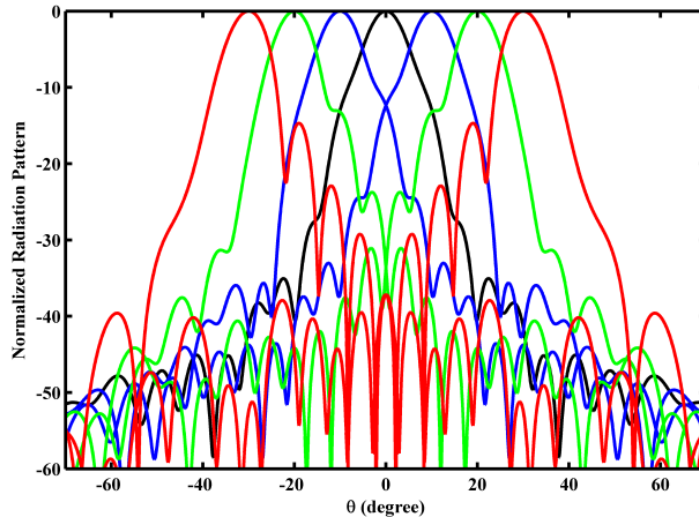
lobe level increases slowly as the beam is scanned toward the broadside direction, and eventually merges with the main beam resulting in a relatively wide main beam. From Fig. (7) it can be observed that compared with the scanning pattern of the parabolic design at the maximum scan angle, the scanning pattern of the bifocal design shows much narrower main beam and reduced side lobe level which is below -13 dB and 6 dB lower than that of parabolic design.

The directivity, spillover efficiency and gain of the scan pattern for both designs are calculated according to the method discussed in [20], and summarized in Table 1. It is worthwhile to point out that the antenna directivity listed in the second column also takes into account the taper efficiency. From Table 1, it can be concluded that a gain variation is less than 0.8 dB across the entire scan range for the bifocal design. However, in comparison, the gain loss for the parabolic design is more than 2.5 dB across the entire scan range.

Moreover, some other numerical studies which have been done by the author, but are not listed here for brevity, show



(a)



(b)

Fig. (6). Scanning normalized radiation patterns of reflectarray antennas: (a) parabolic design, (b) bifocal design.

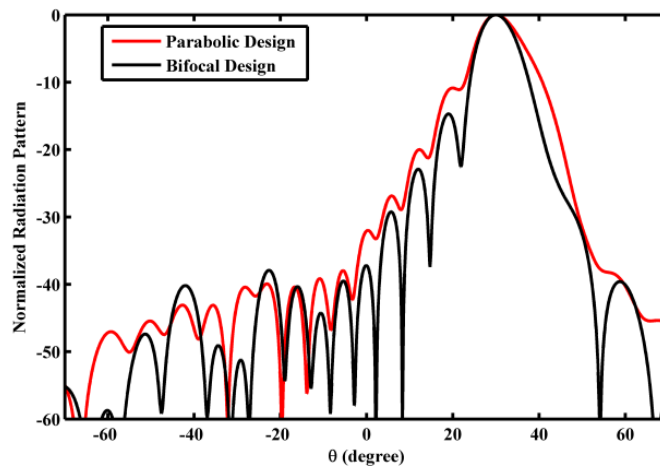


Fig. (7). Comparison of the two type designs at the maximum scan angle.

Table 1. Directivity, spillover efficiency and gain versus scan angle.

Parabolic Design			
Scan Angle (Degree)	Directivity (dB)	Spillover Efficiency (%)	Gain (dB)
±30	27.0002	86.94	26.3923
±20	28.3159	89.98	27.8574
±10	28.9387	91.79	28.5667
0	29.1728	92.38	28.8286
Bifocal Design			
Scan Angle (Degree)	Directivity (dB)	Spillover Efficiency (%)	Gain (dB)
±30	27.9294	86.84	27.1366
±20	28.2464	89.99	27.7884
±10	28.2026	91.80	27.8310
0	28.1997	92.38	27.8554

that although the bifocal designs can achieve a good performance with the main beam not scanning far from broadside, as the scan range increases, the SLL performance of the bifocal system degrades significantly. This is mainly because of the fact that for a larger scan angle, the distinction in spatial delay associated with the two feed reflectarray increases, thus averaging these values results in a higher error in element phase distribution. Similarly, this scheme will be less effective as aperture size increases. Nonetheless, for limited scan range system, a bifocal single reflectarray design scheme shows a significant scan performance improvement over the conventional parabolic design.

The numerical results presented here show that the scan limitation of conventional reflectarray using the feed displacement technique is primarily attributed to the parabolic phase distribution on the aperture. With a single reflector bifocal or multifocal aperture, the scan performance can be improved beyond those of the parabolic phase distribution.

CONCLUSION

In this paper, different methods for designing beam scanning reflectarray antennas are first reviewed and it is concluded that as a convenient design scheme, the feed displacement technique is preferred for limited scan range applications. In the next stage, a novel bifocal aperture phase distribution has been introduced for a single reflectarray antenna to improve the scan range. Moreover, a novel feed displacement path moving along circular arc with radius of F has been introduced to improve the illumination performance of feed. Finally, a Ku band bifocal single reflectarray antenna has been designed based on the introduced design scheme, and the scan performances of the designed reflectarray have been analyzed numerically and compared with conventional parabolic design. From numerical results, it can be concluded that the bifocal design shows significantly improved scan performance beyond the parabolic design, which illustrates

that the bifocal single reflectarray design scheme for limited scan range beam scanning reflectarray is a promising attempt.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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REFERENCES

- [1] J. Huang, and J. A. Encinar, *Reflectarray Antenna*. New York: John Wiley & Sons, 2007.
- [2] R. C. Hanson, *Phased Array Antenna*, 2nd ed. New York: John Wiley & Sons, 2009.
- [3] R. J. Mailloux, *Phased Array Antenna Handbook*, 2nd ed. Boston: Artech House, 2005.
- [4] M. I. Skolnik, *Radar Handbook*, 3rd ed. New York: McGraw-Hill, 2008.
- [5] D. M. Pozar, S. D. Targonski, and H. D. Syrigos, "Design of millimeter wave microstrip reflectarray", *IEEE Trans. Antennas Propag.*, vol. 45, no. 2, pp. 287-286, 1997.
- [6] W. L. Stutzman, and G. A. Thiele, *Antenna Theory and Design*, 2nd ed. New York: John Wiley & Sons, 1998.
- [7] E. Carrasco, M. Barba, M. Arrebola, and J. A. Encinar, "Recent developments of reflectarray antennas for reconfigurable beams using surface-mounted RF-MEMS", *Int. J. Antennas Propag.*, vol. 2012, pp. 1-13, 2012.
- [8] V. F. Fusco, "Mechanical beam scanning reflectarray", *IEEE Trans. Antennas Propag.* vol. 53, no. 11, pp. 3842-3844, 2005.
- [9] J. P. Carrier, and A. K. Skrivervik, "Monolithic MEMS-based reflectarray cell digitally reconfigurable over a 360 phase range", *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 138-141, 2008.
- [10] S. V. Hum, M. Okoniewski, and R. J. Davies, "Modeling and design of electronically tunable reflectarrays", *IEEE Trans. Antennas Propag.*, vol. 55, no. 8, pp. 2200-2210, 2008.

- [11] W. Hu, R. Cahill, and J. A. Encinar, "Design and measurement of reconfigurable millimeter wave reflectarray cells with nematic liquid crystal", *IEEE Trans. Antennas Propag.* vol. 56, no. 10, pp. 3112-3117, 2008.
- [12] K. Kisher, and S. V. Hum, "An amplifying reconfigurable reflectarray antenna", *IEEE Trans. Antennas Propag.* vol. 60, no. 1, pp. 197-205, 2012.
- [13] S. R. Rengarajan, "Scanning and defocusing characteristics of microstrip reflectarray", *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 163-166, 2010.
- [14] P. Nayeri, "Advance Design Methodologies and Novel Applications of Reflectarray Antennas", PhD dissertation, University of Mississippi, 2012.
- [15] D. McGrath, "Planar three-dimensional constrained lenses", *IEEE Trans. Antennas Propag.*, vol. 34, no. 1, pp. 46-50, 1986.
- [16] B. L. J. Rao, "Bifocal dual reflector antenna", *IEEE Trans. Antennas Propag.*, vol. 22, no. 5, pp. 711-714, 1974.
- [17] W. Menzel, M. Al-Tikriti, and R. Leberer, "A 76 GHz multiple beam planar reflector antenna," In: *Proceedings of the 32nd European Microwave Conference*, Sep 23-26; Milano, Italy, 2002.
- [18] J. Rodriguez-Alvarez, M. Arrebola, C. Tienda, J. A. Encinar, and F. Las-Heras, "Bifocal antenna based on dual-reflectarray dual-offset configuration," In: *Proceedings of the 6th European Conference on Antennas and Propagation*, Mar 26-30; Prague, Czech Republic, 2012.
- [19] P. Nayeri, F. Yang, and A. Z. Elsherbeni, "High-gain beam-scanning reflectarray antennas using an active-feed scheme," In: *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, July 8-14; Illinois, US, 2012
- [20] Y. Qu, C. J. Guo, H. Guo, and J. Ding, "Fast analysis for aperture efficiency and radiation patterns of reflectarray antennas," *Int. J. Signal Process. Image Process. Pattern Recognit.*, vol. 7, no. 4, pp. 243-254, 2014.

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