Progress In Electromagnetics Research C, Vol. 18, 19–29, 2011

BANDWIDTH IMPROVEMENT OF REFLECTARRAY ANTENNAS USING CLOSELY SPACED ELEMENTS

P. Nayeri, F. Yang, and A. Z. Elsherbeni

Electrical Engineering Department
The University of Mississippi, MS 38677, USA

Abstract—A bandwidth improvement method in reflectarray antennas by using closely space elements, i.e., unit-cell sizes smaller than $\lambda/2$, has been investigated both numerically and experimentally in this paper. A new definition of phase error has been introduced to analyze the broadband mechanism of closely spaced phasing elements. Through full wave EM simulations, it is revealed that closely spaced elements achieve a smaller phase error over the band. Based on these theoretical studies two Ka-band reflectarrays were fabricated and their performance was measured across the frequency range of 30 to 34 GHz. It is demonstrated that the reflectarray designed with closely spaced elements achieves a notable improvement in gain bandwidth performance.

1. INTRODUCTION

The reflectarray antenna [1] has received considerable attention in the recent years due to its revolutionary capabilities. It combines the numerous advantages of both printed arrays and high gain parabolic reflectors to create the new generation of high gain reflector antennas. The reflectarray antenna is finding applications in satellite communications, contoured beam space antennas, cloud/precipitation radars and commercial usages [2]. Compared to the parabolic reflectors, the reflectarray is low profile, low mass, easy to fabricate and transport, and most notably its printing process results in a low fabrication cost. However despite these advantages, this antenna suffers from the major drawback of printed antenna structures which have an inherently narrow bandwidth. A main factor that controls the bandwidth of a reflectarray antenna is the bandwidth of the phasing

Received 15 September 2010, Accepted 10 November 2010, Scheduled 18 November 2010
Corresponding author: Atef Z. Elsherbeni (atef@olemiss.edu).

elements [3–5]. Reflectarray elements have a narrow bandwidth because the nonlinear S-shaped phase curve is very sensitive to frequency variations near resonance; therefore in order to improve the bandwidth of the antenna, broadband phasing elements need to be designed. Different approaches have been implemented to improve the bandwidth of the reflectarray antenna, such as multi-layer structures [6], single-layer multi-resonant designs [7, 8], aperture coupled lines [9–11] and true-time delay lines [12].

Traditionally the reflectarray phasing elements are designed with unit-cell sizes around $\lambda/2$. Recent advances on metamaterials [13] reveal that similar reflection phase response can also be realized using closely spaced elements. The work in [10, 11] presents theoretical and experimental results for bandwidth improvement of reflectarray antennas using sub-wavelength aperture-coupled reflectarray elements. In a theoretical study [14] it is shown that a reflectarray using closely spaced patch elements can also improve the bandwidth of the antenna, and a practical design is presented in [15]. In this paper we investigate the feasibility of designing a broadband reflectarray antenna using closely spaced patch elements. A new definition of phase error is introduced to analyze the phase behavior of reflectarray elements. Numerical studies are then performed to understand the broadband mechanism of closely spaced elements. Based on these studies two Ka-band reflectarrays are designed using variable size square patches. One is designed using the conventional $\lambda/2$ elements, and the other one with $\lambda/3$ elements. While both antennas demonstrated good performance, the reflectarray designed with closely spaced elements showed a 36% increase in the gain bandwidth.

2. ANALYSIS OF PHASING ELEMENTS

2.1. Phase Requirement in Reflectarray Design

The reflection phase of a reflectarray element is designed to compensate the spatial phase delay from the feed horn to that element; thus a certain phase distribution can be achieved on the reflectarray aperture so that the radiation beam will point at a specific direction. The reflection phase ψ_i of the ith element is calculated as

$$\psi_i(f_0) = k_0 \left(R_i - \bar{r}_i \cdot \hat{r}_o\right) + \psi_0, \tag{1}$$

where R_i is the distance from the feed horn to the ith element, $\bar{r}_i$ is the position vector of the ith element, and $\hat{r}_o$ represents the main beam direction. A constant phase ψ_0 is added here, indicating that it is the relative reflection phase rather than the absolute reflection phase required in the reflectarray design. Without loss of generality, let's

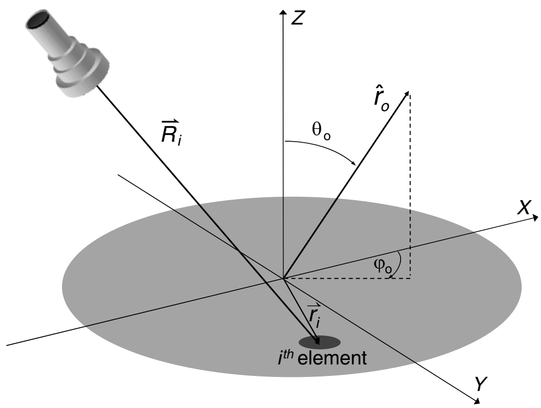


Figure 1. Geometry of the reflectarray antenna.

consider a reflectarray with a main beam at the broadside direction ($\bar{r}_i \cdot \hat{r}_o = 0$). A center element (element 1) is selected as a phase reference and an element 2 is arbitrarily selected on the reflectarray surface to explain the required phase relation.

The phase difference between these two elements at the center frequency (f_0) satisfies the following relation:

$$\psi_2(f_0) - \psi_1(f_0) = k_0 \cdot (R_2 - R_1). \tag{2}$$

According to the above reflection phase requirement and the specific element design method, the parameters of elements 1 and 2 can be determined using the infinite array theory. When the frequency changes, the phase difference will also change. An ideal phase relation is:

$$\psi_2(f) - \psi_1(f) = k \cdot (R_2 - R_1). \tag{3}$$

Combining (2) with (3), one can obtain:

$$\frac{\psi_2(f) - \psi_1(f)}{f} = \frac{\psi_2(f_0) - \psi_1(f_0)}{f_0} = \frac{2\pi}{c} \times (R_2 - R_1). \tag{4}$$

It should be noted that $\psi(f)$ here is the elements phase which is obtained by full-wave simulations, while $\psi(f_0)$ is the ideal elements phase at the center frequency. It is clear from above equations that the phase difference ($\Delta\psi(f) = \psi_2(f) - \psi_1(f)$) should be a function of frequency. When the frequency increases, the phase difference should also increase. Again, it's worthwhile to point out that frequency behavior of the phase difference is important here rather than the reflection phase of an individual element.

In practice, this ideal frequency behavior of the phase difference cannot be satisfied. Depending on the element designing methods, phase errors will occur with frequency, which reduces the reflectarray gain and narrows the reflectarray bandwidth. To study this effect quantitatively, a phase error (PE) term is defined as follows:

$$PE(f) = \{\psi_2(f) - \psi_1(f)\} - k \cdot (R_2 - R_1). \tag{5}$$

At the center designed frequency (f_0), the phase error is zero. As the frequency changes, different element design methods will give different error curves vs. frequency. Thus, Equation (5) provides a good indicator to evaluate element design methods: the smaller the phase error, the wider the reflectarray bandwidth.

2.2. Comparisons of Half-wavelength and Closely Spaced Elements

Based on above discussion, let's compare the reflectarray element designs using half-wavelength and closely spaced elements. Variable size approach is used in these element designs, and the main difference is the selection of element periodicity. In particular, $\lambda/2$, $\lambda/3$, and $\lambda/4$ are selected as the periodicities in the following study. Although smaller periodicities such as $\lambda/10$ can be selected in the analysis and design, it will bring difficulties to the fabrication tolerance and increase the fabrication cost.

A 20 mil Rogers 5880 substrate ($\varepsilon_r = 2.2$) is used here for this study. For the unit-cell analysis here we used the commercial electromagnetic software packages Anosft Designer and Anosft HFSS. Figs. 2(a) and 2(b) show the reflection coefficients versus patch size at the design frequency (32 GHz) for normal incidence. It can be seen that the results obtained from both software packages are in close agreement with each other. Also it is important to point out that the results in Fig. 2(b) show that in all cases the maximum reflection loss is below 0.98 (Ohmics losses less than 0.2 dB) which contributes to a good efficiency. From the results in Fig. 2(a), for example when a zero degree reflection phase is required, the patch size will be 2.69, 2.41, and 2.04 mm for $\lambda/2$, $\lambda/3$, and $\lambda/4$ designs. When a 90 degrees reflection phase is required, the patch size should be 2.41, 2.1, and 1.81 mm. It is important to point out that in general the reflection characteristics are angle dependent and oblique incidence needs to be considered, however it has been shown that normal incidence can present good approximations for incidence angles up to 30° [16]. This was also confirmed by our simulations of several oblique incidence excitation angles with different unit-cell sizes. It should be noted that in the unit-cell analysis here periodic boundary condition is being used to account for the coupling between the unit-cell elements. The coupling between the elements is a function of the patch size and the gap between the patches. For a fixed unit-cell size, the coupling between the patch elements increases by reducing the spacing between them. However if the size of the unit-cell is reduced, a closer spacing between the patch elements is required to achieve the same level of coupling for larger unit-cell sizes. Consequently this would mean that smaller unit-cell sizes with the same gap size would have a weaker coupling between the elements which would reduce the phase range versus patch size for these elements.

Figure 2(c) shows how the reflection phases of these 0° and 90° elements vary with frequency. It is observed that $\lambda/2$, $\lambda/3$, and $\lambda/4$

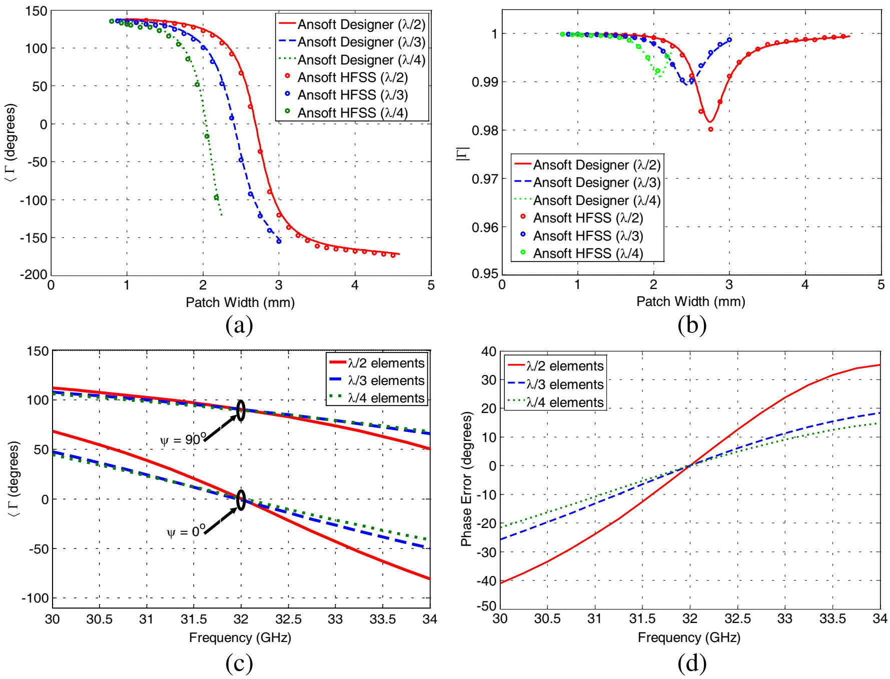


Figure 2. (a) Reflection phases versus patch size at the center frequency 32 GHz for $\lambda/2$, $\lambda/3$, and $\lambda/4$ unit-cells. (b) Reflection magnitude versus patch size at the center frequency 32 GHz for $\lambda/2$, $\lambda/3$, and $\lambda/4$ unit-cells. (c) Reflection phases versus frequency for 0° and 90° elements for $\lambda/2$, $\lambda/3$, and $\lambda/4$ unit-cells. (d) Phase errors for a 90° relative phase difference versus frequency for $\lambda/2$, $\lambda/3$, and $\lambda/4$ unit-cells.

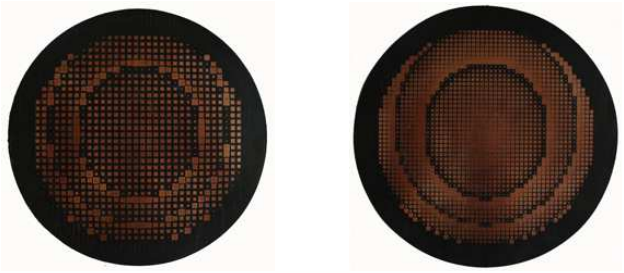
designs have different frequency behaviors for the element reflection phase. When the frequency changes, the closely spaced elements show a smaller phase variation with frequency. As discussed previously, it is the frequency behavior of the phase difference that determines the reflectarray bandwidth. Thus, the phase error curves of the $\lambda/2$, $\lambda/3$, and $\lambda/4$ designs, as defined in Equation (5), are obtained and plotted in Fig. 2(d). It is clear from this figure that the closely spaced elements have a smaller phase error over the frequency than the half-wavelength elements. Similar studies have been performed on the reflectarray elements with different relative phase requirements, and the same observation is obtained. Therefore, it is clear that the reflectarray bandwidth can be increased by using closely spaced elements.

3. EXPERIMENTAL RESULTS

3.1. Fabrication

The minimum gap size between the patch elements is a critical factor in controlling the maximum achievable phasing range. In our designs a minimum gap size of 0.1 mm is dictated by the size of the smallest drill bit in our LPKF ProtoMat S62 milling machine. By enforcing this fabrication limit in the unit-cell simulations the phasing range of the elements is reduced to 310°, 290° and 247° for $\lambda/2$, $\lambda/3$ and $\lambda/4$ elements, respectively. Typically a phasing range around 300° is required for a reflectarray design. This achievable phasing range of elements which is directly related to fabrication tolerance of the gap sizes should be viewed as the lower limit in selecting closely spaced elements for the reflectarray with variable size patches. As the phase range of the elements is decreased, the antenna gain decreases and the sidelobe level increases; however the antenna bandwidth is mainly determined by the frequency behavior of the phasing elements. Considering the phase range of elements studied here, our analysis showed that going from $\lambda/2$ to $\lambda/3$ elements did not result in any gain reduction or increase in sidelobes. For a $\lambda/4$ design however, the reduction of phase range resulted in almost 0.5 dB loss in antenna gain and 6 dB increase in sidelobe level relative to the $\lambda/2$ design. This 0.5 dB loss is acceptable relative to the high gain reflectarray, since this $\lambda/4$ design is adding an additional advantage of a wider reflectarray bandwidth; however we believed that this design was not suitable for demonstration purposes. In summary there is a tradeoff between the reflectarray gain and bandwidth if one would use sub-wavelength elements.

Based on the above considerations, two Ka-band microstrip reflectarrays are designed and fabricated for the operating frequency



(a) (b)

Figure 3. Photographs of the fabricated arrays. (a) $\lambda/2$ array with 848 square patches, (b) $\lambda/3$ array with 1941 square patches.

of 32 GHz. One is designed using the conventional $\lambda/2$ elements and the other one is designed using $\lambda/3$ elements. Both antennas have a circular aperture with a diameter of 17λ at the design frequency and are fabricated on a 20 mil Rogers 5880 substrate. The total number of square patch elements is 848 and 1941 for $\lambda/2$ and $\lambda/3$ arrays, respectively and the elements phase is adjusted to scan the main beam 25° off broadside to minimize feed blockage. Photographs of the fabricated reflectarrays are shown in Fig. 3.

The offset feed horn ($\theta_i = 25°$) is a circularly polarized corrugated horn and is positioned at $X_{feed} = 0$ mm, $Y_{feed} = -45.9$ mm, $Z_{feed} = 98.4$ mm based on the array coordinate system in Fig. 1. The measured gain of the feed horn is 14.2 dB at 32 GHz and the variation across the 30 to 34 GHz band is less than 0.5 dB. The power q of the feed horn $\cos^q(\theta)$ radiation pattern model increases almost linearly from 5 to 8.3.

3.2. Measurements

The antennas performances were measured over the frequency range from 30.0 to 34.0 GHz which were set by the limits of the feed horn and the Ka-band measurement probe of our NSI near-field system. The vertical plane radiation patterns at 32 GHz for both antennas are shown in Fig. 4. Note that the main beam is correctly scanned to 25° and the sidelobe levels are below −22 dB for both antennas. The simulated results here were obtained using the approach described in [17]. It can be seen that the measured and simulated results show a good agreement in the main lobe; however some discrepancies exist in the side lobe region. These are due to the phase errors in simulations where the normal incidence data are used for the design. The fabrication errors also cause some discrepancies in the comparisons. Similar results were also observed in the horizontal plane. At 32 GHz the measured -3 dB beamwidth for the $\lambda/2$ array is 4.5° and 4.6° for vertical and horizontal planes, respectively and the measured gain is 30.99 dB, which corresponds to an overall aperture efficiency of 44.0%. For the $\lambda/3$ array the measured -3 dB beamwidth at 32 GHz is 4.4° and 4.6° for vertical and horizontal planes, respectively and the measured gain is 30.95 dB, which corresponds to an overall aperture efficiency of 43.6%.

The measured antenna gains across the entire band are given in Fig. 5. The 1 dB gain bandwidth of the $\lambda/2$ array is 8.0% and this antenna achieves its max gain of 31.34 dB at 31.8 GHz. The

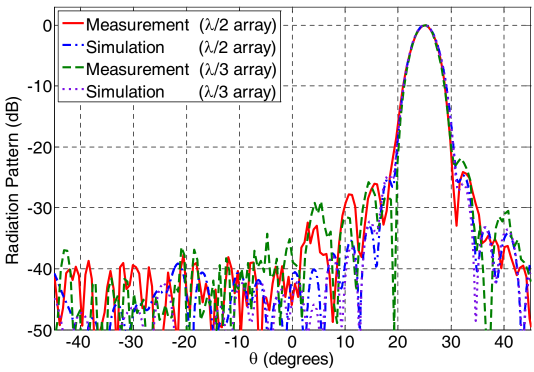


Figure 4. Measured and calculated radiation patterns of the antennas at 32 GHz.

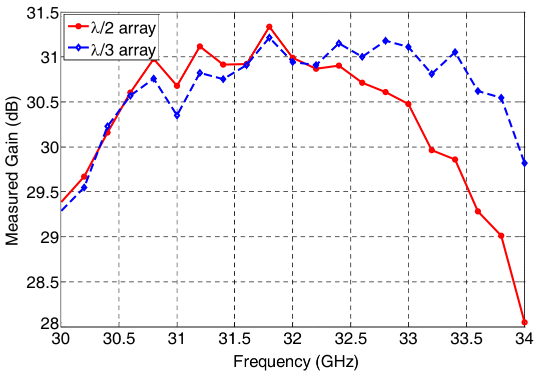


Figure 5. Measured gain of the fabricated reflectarrays. The 1 dB gain bandwidth is 8.0% for the $\lambda/2$ reflectarray and 10.9% for the $\lambda/3$ reflectarray.

measured results also show that the $\lambda/3$ array achieves a considerable bandwidth improvement, where the 1 dB gain bandwidth has been increased to 10.9%. Similarly this antenna achieves its max gain of 31.22 dB at 31.8 GHz. The measured radiation patterns show a similar performance across the entire band except for a slight increase in sidelobe level at the extreme frequencies.

4. DISCUSSION

In general the bandwidth of a reflectarray antenna is limited by two different factors, the bandwidth of the element and the bandwidth limitation by spatial phase delay. The sub-wavelength broadband technique studied here improves the reflectarray element bandwidth. Consequently this broadband technique is applicable to small size reflectarray antennas. As the size of the aperture increases the broadband effect of the sub-wavelength elements would be less effective due to the effect of the spatial phase delay which will become dominant. Our numerical results showed that for this Ka-band reflectarray going from $\lambda/2$ elements to $\lambda/3$ elements, the percentage of bandwidth improvement will be significantly reduced as the aperture diameter is increased. These numerical results are summarized in the table below.

Aperture diameter	10λ	20λ	30λ	40λ
Relative bandwidth improvement	61.63%	36.28%	22.25%	15.47%

5. CONCLUSION

The concept of using closely spaced elements with variable size in reflectarray antenna designs has been investigated both numerically and experimentally. A new definition of phase error is introduced to analyze the phase performance of reflectarray elements. Numerical analysis are then performed to understand the broadband mechanism of closely spaced elements. It is shown that closely spaced phasing elements have a smaller phase variation and reduced phase error over frequency. Based on these theoretical results two Ka-band reflectarrays were designed, fabricated and tested. One reflectarray uses the conventional $\lambda/2$ elements and the other one is designed using $\lambda/3$ elements. The measured gain at the design frequency of 32 GHz is 30.99 dB and 30.95 dB for $\lambda/2$ and $\lambda/3$ arrays, respectively. The 1 dB gain bandwidth of the $\lambda/2$ array is 8.0% where for the $\lambda/3$ array it has increased to 10.9%, indicating a 36% increase in the gain bandwidth.

This study reveals that closely spaced reflectarray antennas can provide a notable bandwidth improvement with the advantages of being low-profile, having simple phasing elements and a low fabrication cost. Therefore closely spaced reflectarray elements could be a good solution for bandwidth improvements in reflectarray antennas.

ACKNOWLEDGMENT

The authors acknowledge the assistance of C. H. Loo, M. Hickman, and A. Yu from The University of Mississippi in fabrication and measurement of the antennas.

REFERENCES

1. Pozar, D. M., S. D. Targonski, and H. D. Syrigos, "Design of millimeter wave microstrip reflectarrays," *IEEE Trans. Antennas Propag.*, Vol. 45, No. 2, 287–296, Feb. 1997.
2. Huang, J. and J. A. Encinar, *Reflectarray Antennas*, Institute of Electrical and Electronics Engineers, John Wiley & Sons, 2008.
3. Huang, J., "Bandwidth study of microstrip reflectarray and a novel phased reflectarray concept," *IEEE Antennas and Propagation Society International Symposium*, California, USA, Jun. 1995.
4. Pozar, D. M., "Bandwidth of reflectarrays," *Electronics Letters*, Vol. 39, No. 21, Oct. 2003.
5. Bialkowski, M. E. and K. H. Sayidmarie, "Bandwidth consideration for microstrip reflectarrays," *Progress In Electromagnetic Research B*, Vol. 3, 173–187, 2008.
6. Encinar, J. A., "Design of two-layer printed reflectarrays using patches of variable size," *IEEE Trans. Antennas Propag.*, Vol. 49, No. 10, 1403–1410, Oct. 2001.
7. Chaharmir, M. R., J. Shaker, M. Cuhaci, and A. Ittipiboon, "A broadband reflectarray antenna with double square rings," *Microwave and Optical Technology Letters*, Vol. 48, No. 7, 1317–1320, Jul. 2006.
8. Li, H., B. Z. Wang, and W. Shao, "Novel broadband reflectarray antenna with compound-cross-loop elements for millimeter-wave application," *Journal of Electromagnetic Waves and Applications*, Vol. 21, No. 10, 1333–1340, 2007.

9. Carrasco, E., M. Barba, and J. A. Encinar, "Reflectarray element based on aperture-coupled patches with slots and lines of variable length," *IEEE Trans. Antennas Propag.*, Vol. 55, No. 3, 820–825, Mar. 2007.
10. Costanzo, S., F. Venneri, and G. Di Massa, "Bandwidth enhancement of aperture-coupled reflectarrays," *Electronics Letters*, Vol. 42, No. 23, Nov. 2006.
11. Venneri, F., S. Costanzo, G. Di Massa, and G. Amendola, "Aperture-coupled reflectarrays with enhanced bandwidth features," *Journal of Electromagnetic Waves and Applications*, Vol. 22, 1527–1537, 2008.
12. Carrasco, E., J. A. Encinar, and M. Barba, "Bandwidth improvement in large reflectarrays by using true-time delay," *IEEE Trans. Antennas Propag.*, Vol. 56, No. 8, 2496–2503, Aug. 2008.
13. Yang, F. and Y. Rahmat-Samii, *Electromagnetic Band Gap Structures in Antenna Engineering*, The Cambridge RF and Microwave Engineering Series, Cambridge University Press, 2008.
14. Pozar, D. M., "Wideband reflectarrays using artificial impedance surfaces," *Electronics Letters*, Vol. 43, No. 3, Feb. 2007.
15. Hu, W., M. Arrebola, R. Cahill, J. A. Encinar, V. Fusco, H. S. Gamble, Y. Álvarez, and F. Las-Heras, "94 GHz dual reflector antenna with reflectarray subreflector," *IEEE Trans. Antennas Propag.*, Vol. 57, No. 10, 3043–3050, Oct. 2009.
16. Nayeri, P., M. E. Bialkowski, and K. H. Sayidmarie, "Design of double-ring unit cells for single-layer microstrip reflectarrays," *Asia Pacific Microwave Conf.*, Hong Kong, China, Dec. 2008.
17. Huang, J. and R. J. Pogorzelski, "A Ka-band microstrip reflectarray with elements having variable rotation angles," *IEEE Trans. Antennas Propag.*, Vol. 46, No. 5, 650–656, May 1998.