An Efficient Progressive Phase Distribution Consideration of Reflectarray Antennas

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Abstract— This paper provides a novel and efficient procedure for the X-band reflectarray antenna design emphasizing on the progressive phase distribution which is required to achieve the planar wave in front of antenna aperture. Detailed theoretical procedure has been provided with mathematical modeling of the required reflection phase from each of the individual reflectarray elements. The importance of material properties in reflectarray antenna design has been highlighted and different novel design configurations has been proposed for the unit cell reflectarray elements. Scattering parameter measurements and simulated results provide a very close agreement for different slot embedded designs proposed in this work. Two different configurations of mixed rectangular and circular slots embedded patch elements have been investigated. The variation in width of slot in the case of three rectangular slot patch configuration, the measured reflection loss varied from 2.89 dB to 5.60 dB while in the case of mixed rectangular and circular slot configurations, measured reflection loss is varied from 7.90 dB to 5.60 dB by varying the radius of circular slot. Moreover a maximum frequency variation of 2.58 GHz and a dynamic phase range of 345° with the variation in slot dimensions have also been demonstrated.

1. INTRODUCTION

Reflectarray is a high gain antenna which combines the unique features of a flat reflector and an array of microstrip patch elements printed on a thin dielectric substrate. It is illuminated using a primary feed horn placed at a particular distance from the array. The reflectarray exhibits a number of significant advantages over conventional parabolic reflector and phased array antennas such as easy deployability, lower manufacturing cost, scannable beam, and surface mountability with lower mass and volume [1]. Due to these growing numbers of advantages, reflectarray has been considered as a potential alternative to the parabolic reflector and phased array antennas.

The most important aspect of reflectarray antenna design is the design of printed microstrip elements which can be used for the performance appraisal of the antenna. The individual elements of the periodic array have to be designed with progressive phase distribution so that the spherical beam from the horn antenna can be converted into a planar wavefront. The required reflection phase values from individual elements of an array also depend on the location of the feed horn. For proper phase requirements, different techniques such as, identical patches of variable-length stubs [2], square patches of variable sizes [3], identical planar elements of variable rotation [4] and identical rectangular patches with different types of slot configurations have been used [5, 6]. All these phasing techniques increase the possibility of reflectarrays to become an alternative option to the parabolic reflectors. However one of the main concerns of a reflectarray antenna is its limited bandwidth performance as compared to the parabolic reflector antennas [7–9]. Different configurations have been proposed by researchers in the past few years for the bandwidth improvement of reflectarray antennas [10, 11] but considerable efforts are still required to improve the bandwidth performance of reflectarrays.

This paper provides a detailed mathematical analysis for obtaining the required reflection phase of the array element which is used to produce a progressive phase distribution for any dielectric material using either centre or off-set feed configuration.Novel proposed individual reflectarray elements have been simulated using CST Microwave Studio and verified experimentally using waveguide scattering parameter measurements. Although the paper concentrates on the explanation of X-band reflectarray design, the same procedure can be used to design reflectarray in any frequency range.

2. REFLECTARRAY REFLECTION PHASE

2.1. Progressive Phase Distribution

In a reflectarray antenna, the incident field ($\bar{E}_i$) being illuminated by the feed horn is reflectedand scattered from the ground plane and resonating patches respectively. The reflected field ($\bar{E}_r$)

depends on the properties of the dielectric material used for the reflectarray design and scattered field ($\bar{E}_s$) depends on the resonating element design configuration. Therefore the total electric field ($\bar{E}_t$) in a reflectarray can be represented by:

$$\bar{E}_t = \bar{E}_i + \bar{E}_r + \bar{E}_s \tag{1}$$

This work concentrates on the analysis of reflection phase (φ_n) from the individual patch elements of a reflectarray. Fig. 1 shows the geometry of the centre feed and off-set feed reflectarrays for different planar reflector designs. The feeds F_1 and F_2 are placed at the off-set distance of $\Delta X_f = X_0 - X_1$ and $\Delta X_f = X_0 - X_2$ respectively. Different feed locations (F_0, F_1, F_2) as shown in Fig. 1 have been used to obtain the reflection phase of resonant elements which take into account the effect of material properties.

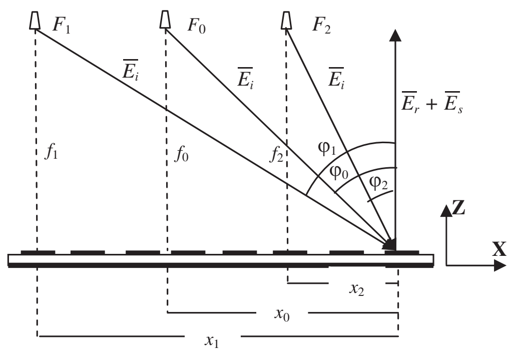

Figure 1: Reflection phase from different feed points in a reflectarray antenna.

Based on the required phase shift of reflectarray elements shown in provided in [12–14], it has been observed that the required phase shift remains constant for elements lying on circles of radius (r) in a periodic array. Hence if φ_n is calculated for the elements lying on the X-axis with radius $r = x_i$, the required phase shift of all the elements of the periodic array can be effectively approximated. In order to calculate the phase shift for the elements on X-axis, a basic formula can be derived as:

$$\varphi = -\frac{2\pi}{3}\cot^{-1}\frac{f}{x_i} \tag{2}$$

where, f is the vertical distance of feed from surface of the array and x_i is the distance between the center of ith element and the point perpendicular to the feed and φ is in degrees. Once φ, is calculated for different values of $x = x_i$, $y = 0$, the phase shift for all the array elements can be obtained. This method simplifies the calculation of the required phase shift from each of the array elements and reduces the complexity and time required for the periodic reflectarray design.

The above technique can also be used for the progressive phase distribution of off-set feed reflectarrays. In the case of off-set feed reflectarrays ΔX_f has to be introduced as the distance between the feed and the line perpendicular to the array centre. The required reflection phase can then be calculated by:

$$\varphi = -\frac{2\pi}{3}\cot^{-1}\frac{f}{x_i \pm \Delta X_f} \tag{3}$$

Figure 2 shows the progressive phase distribution obtained for the design of planar reflectors with center and off-set feed positions. X (mm) shows location of the element placed in an array with total dimensions of 120 mm × 120 mm. In the case of off-set feed, the feeds were placed at a distance of one wavelength (λ) away from the centre of the array on both sides. It can be observed from Fig. 2 that the required reflection phase curve provides a phase range of 180° to −180° while the position of the feed clearly varies the reflection phase required from the individual element in order to produce progressive phase distribution.

2.2. Effect of Material Properties

The above analysis provides a general formulation for the design of reflectarray with progressive phase distribution for any dielectric material and either centre or off-set feed configuration. In order to obtain the progressive phase distribution of planar reflector designed with different dielectric substrates, the material properties should be incorporated in (2).

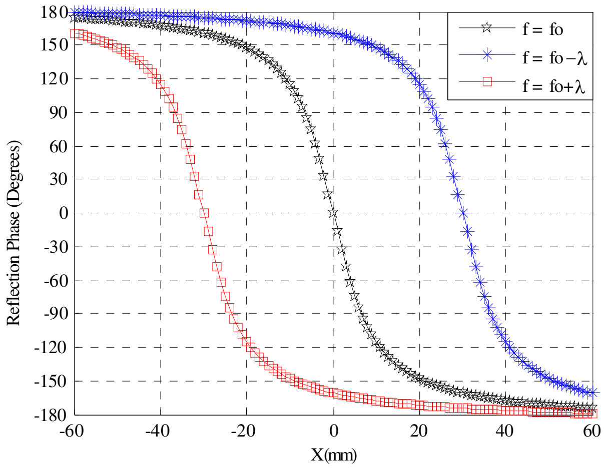

Figure 2: Reflection phase curves for progressive phase distribution of planar reflectors with different feed positions.

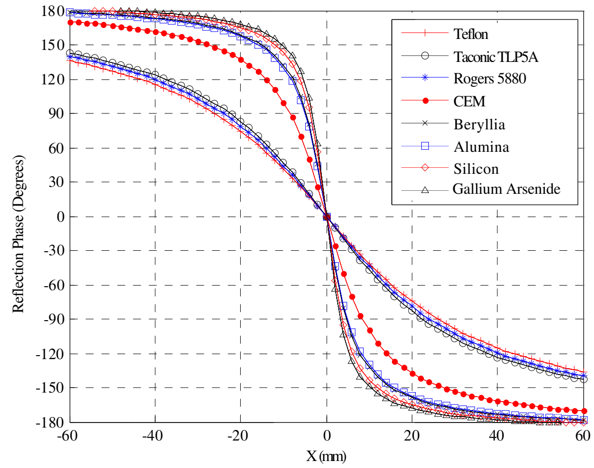

Figure 3: Reflection phase curves for planar reflectors modeled with different substrates at 10 GHz

The material properties affect the reflection coefficient (Γ) which effects the reflection phase of the reflectarray. In this case, Γ depends on the attenuation due to dielectric and conductor loss which are given by:

$$\alpha_d = \frac{\omega}{2}\sqrt{(\mu_0\epsilon_0\epsilon_r)}\tan\delta \tag{4}$$

$$\alpha_c = \frac{8.68}{WZ_m}\sqrt{\left(\frac{\omega\mu_0}{2\sigma_c}\right)} \tag{5}$$

where, α_d and α_c are attenuation due to dielectric and copper loss respectively. After incorporation of effects of dielectric and copper attenuation on Γ and reflection phase of planar reflector, (2) can be written as:

$$\varphi = -\frac{2\pi}{3}\cot^{-1}\frac{f}{K(x_i \pm \Delta X_f)} \tag{6}$$

In (6), K is a variable which relates φ with Γ and depends on resonant frequency and material properties which affects the radiated and scattered fields. The value of K will be higher for the materials with higher values of dielectric permittivity and loss tangent. Therefore K is directly proportional to attenuation due to dielectric and conductor given by (4) and (5) respectively or K can be given by:

$$K \propto \alpha_d + \alpha_c \tag{7}$$

$$K = C \cdot (\alpha_d + \alpha_c) \tag{8}$$

where, C is a compensation variable and varies with different design requirements and materials used. In (8), C is dependent on the dielectric permittivity and loss tangent values of the substrate in a way that (6) can be written as:

$$\varphi = -\frac{2\pi}{3}\cot^{-1}\frac{f}{x\left(\frac{\varepsilon_r}{\tan\delta}\right)(\alpha_d+\alpha_c)(x_i \pm \Delta X_f)} \tag{9}$$

where, x is a constant that has to be derived for different materials while ε_r and $\tan\delta$ are the dielectric permittivity and loss tangent values of the substrate respectively. Mean values of x for different permittivity values have been calculated for operation at 10 GHz as:

$$x_{avg} = \begin{cases} 0.00080, & 2.08 \le \varepsilon_r \le 6.5 \\ 0.00040, & 6.50 < \varepsilon_r \le 13 \end{cases} \tag{10}$$

The dependence of K on α_d and α_c depicts that as the value of K is increased, the slope of the reflection loss curve gets steeper which shows a lower bandwidth value in planar reflector design. Moreover for lower values of K, the reflection phase range decreases much lower than 360° which indicates the rise of phase errors. This trade-off between bandwidth and phase errors for the periodic array follows the same trend as given in [15, 16] for the unit cell reflectarray elements designed in an infinite array environment. In order to characterize the bandwidth performance with respect to different material properties, a Figure of Merit (FoM) is defined here as the slope of reflection phase curve with respect to the dimensions of the planar reflector and is given by:

$$FoM = \frac{\Delta\emptyset}{\Delta X}\,^{\circ}/\mathrm{mm} \tag{11}$$

Table 1 provides the evaluated values of K and FoM for different dielectric materials. It can be observed form Table 1 that the value of K is higher for the materials with higher dielectric permittivity and loss tangent values. This shows that Gallium Arsenide will provide lowest bandwidth if used for reflectarray design. Fig. 3 shows the reflection phase curves for planar reflectors designed with different dielectric materials in X-band frequency range.

Table 1: Material properties and calculated values of x for a planar reflector design at 10 GHz.

Material	ε_r	**tan**δ	K	FoM (°/mm)
Teflon	2.08	0.0004	0.25	3.90
Taconic TLP5A	2.17	0.0004	0.29	4.40
Rogers RT/d 5880	2.20	0.0009	0.27	5.20
CEM	4.50	0.0250	0.77	10.8
Beryllia	6.50	0.0004	1.39	20.0
Alumina	9.75	0.0003	1.33	20.3
Silicon	11.9	0.0040	1.78	22.6
Gallium Arsenide	13.0	0.0060	2.05	24.0

It can be observed from Fig. 3 that for X-band planar reflector design, a minimum FoM of 3.90°/mm for Teflon as compared to a highest FoM of 24°/mm for Gallium arsenide has been depicted. It can be validated from Fig. 3 and Table 1 that materials with lower permittivity and low loss tangent values provide a smoother phase curve showing a higher bandwidth and lower phase range. On the other hand materials with high dielectric permittivity and loss tangent values offer a steeper phase. Hence phase range is increased but the bandwidth of the planar reflector is decreased by using higher dielectric permittivity and loss tangent materials which shows the trade-off between phase range and bandwidth performance.

3. UNIT CELL DESIGN AND MEASUREMENTS

In order to further investigate and provide elements for the reflectarray design with progressive phase distribution, mixed slot configurations embedded on the patch elements has been proposed in this work. Unit cell patch elements have been designed and fabricated in X-band frequency range using Rogers RT/d 5880 dielectric substrate. The substrate dimensions were kept same for all the design at $\lambda/2 \times \lambda/2$ and were fabricated on 0.381 mm thick sheet. It has been demonstrated earlier that the variation in the dimensions of embedded slot causes a modification in the surface current distribution and electric field intensity of the resonant element. Therefore different resonant frequencies can be obtained by varying the dimensions of one of the embedded slot configurations. This basic principle has been used in this work and a number of unit cells have been designed for each of the proposed configuration. Scattering parameter measurement has been carried out for the two patch element unit cells using vector network analyzer. The measurement procedure was followed as explained in [16]. Two different configurations proposed for this work are explained in this section.

3.1. Rectangular Slot in Centre and Along Length of Patch Elements

Two constant size vertical rectangular slots are introduced along length of patch element while one variable width horizontal rectangular slot is embedded in the centre of the patch element. In order to keep the resonant frequency within X-band, the dimensions of the rectangular patch have been adjusted to $L \times W = 7.9\,\mathrm{mm} \times 10.0\,\mathrm{mm}$. The dimensions of slots along length are $Ls_0 = 3\,\mathrm{mm}$ and

$Ws_0 = 1$ mm. The length of slots in the centre of patch element is kept at $0.15L$ while the width is varied from $0.5W$ (L and W are the length and width of rectangular patch element respectively). The detailed design configuration is shown in Fig. 4.

Figure 5 shows the reflection loss and reflection phase curves for the proposed design obtained by simulations and measurements. Both the reflection loss and reflection phase curves provided a very close agreement in all the cases. It can be observed from Fig. 5 that a change in resonance frequency from 10.62 to 9.04 can be obtained by varying the slot width from $0.1W$ to $0.5W$. Moreover by this variation in width of slot, the measured reflection loss varies from 2.89 dB to 5.60 dB. The trend of increasing reflection loss with increasing width in simulated and measured results can also be observed by the slope of the reflection phase curves. The reflection phase curve provides a dynamic phase range of 323° calculated at 9.83 GHz.

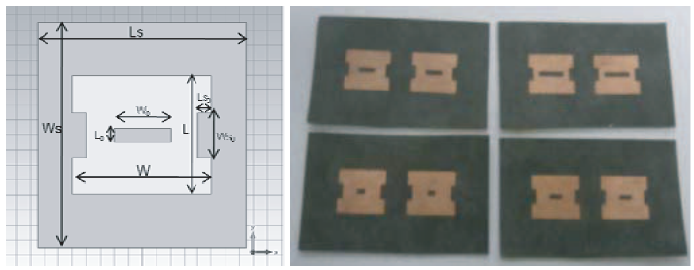

Figure 4: Proposed design and fabricated samples of rectangular slots in centre and along length of patch elements.

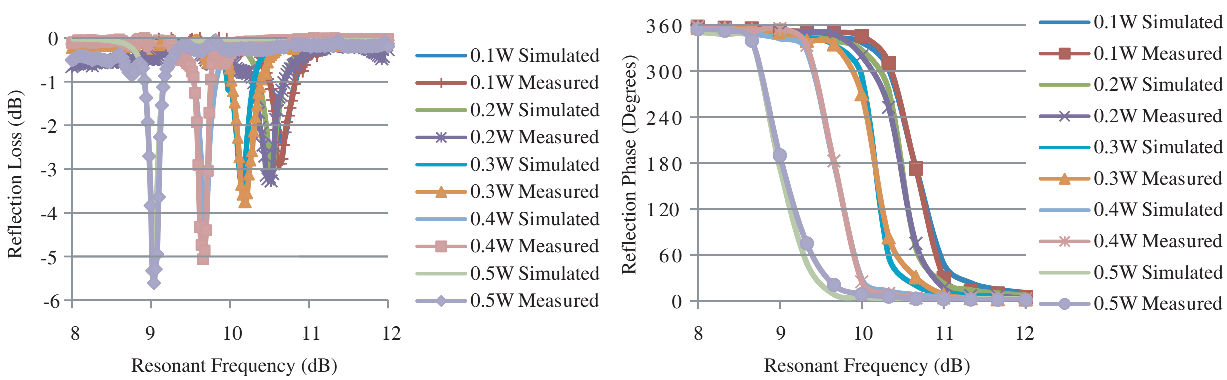

Figure 5: Reflection loss and reflection phase curves for rectangular slot in centre and along length of patch elements.

3.2. Rectangular Slot in Centre and Circular Slots Along Width of Patch Elements

Another mixed slot configurations has also been analyzed in this work where a rectangular slot with constant dimension is embedded in the centre of patch and two variable radius circular slots along the width of the patch element are introduced as shown in Fig. 6. This design can also be used for active reflectarray design where a lumped component can be integrated in the central rectangular slot while the slots along width can provide the progressive phase distribution. In the proposed X-band design, the dimensions of the rectangular patch are $L \times W = 8.7\,\text{mm} \times 10.0\,\text{mm}$. The dimensions of rectangular slot in the centre are kept constant at $L_0 \times W_0 = 1.0\,\text{mm} \times 6.0\,\text{mm}$ while the radius of the circular slots are varied from 0.5 mm to 3.5 mm.

Varying the radius of circular slots from 0.5 mm to 3.5 mm causes a change in resonant frequency from 8.74 GHz to 11.32 GHz depicted in Fig. 7. It can also be observed from Fig. 7 that measured and simulated results provide a very close agreement. The measured reflection loss is decreased from 7.90 dB to 5.60 dB as the radius of the slot is increased from 0.5 mm to 3.5 mm. Similarly a close agreement between the simulated and measured results can also be observed from the reflection phase curves shown in Fig. 7. In the case of rectangular slot in centre and circular slots along width of patch elements configuration, a dynamic phase range of 345° has been demonstrated at 10.03 GHz.

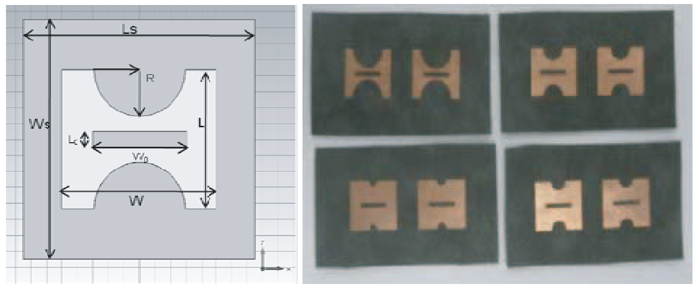

Figure 6: Proposed design and fabricated samples of rectangular slot in centre and circular slots along width of patch elements.

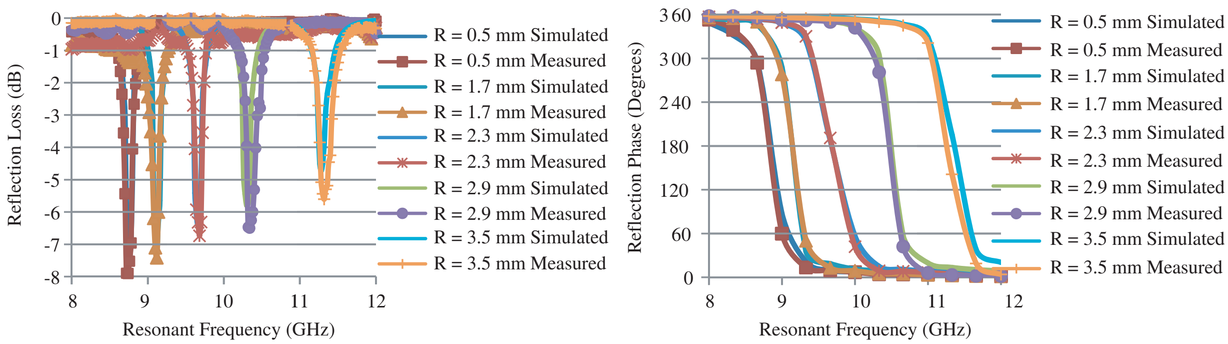

Figure 7: Reflection loss and reflection phase curves for rectangular slot in centre and circular slots along width of patch elements.

4. CONCLUSION

Mathematical modeling provided for the design of reflectarrays with progressive phase distribution can be used for different single layer configurations of unit cell patch elements. Material properties, which play an important role in the performance analysis of reflectarrays, must be included in the reflection phase analysis while designing a reflectarray antenna. Different designs, proposed in this work with validation of scattering parameter measurements, can be used for the reflectarray design with progressive phase distribution and a wide dynamic phase range.

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REFERENCES

1. Huang, J., "Analysis of microstrip reflectarray antenna for microspacecraft applications," *Spacecraft Telecommunications Equipment Section*, 42–120, TDA Progress Report, Feb. 15, 1995.
2. javor, R. D., X. D. Wu, and K. Chang, "Design and performane of microstrip reflectarray antenna," *IEEE Trans. Antennas and Propagation*, Vol. 43, No. 9, 932–938, Sep. 1995.
3. Targonski, S. D. and D. M. Pozar, "Analysis and design of a microstrip reflectarrayusing patches of variable size," *IEEE AP-S/URSI Symposium*, 1820–1823, Seattle, Washington, Jun. 1994.
4. Huang, J. and R. J. Pogorzelski, "Microstrip reflectarray with elements having variable rotation angle," *IEEE AP-S Symposium Digest*, 1280–1283, Apr. 1993.
5. Ismail, M. Y. and M. Inam, "Performance improvement of reflectarrays based on embedded slots configurations," *Progress In Electromagnetics Research C*, Vol. 14, 67–78, 2010.
6. Chahmir, M. R., J. Shaker, M. Cuhai, and A. Sebak, "Reflectarray with variable slots on ground plane," *IEE Proc. — Microwaves, Antennas and Propagation*, Vol. 150, No. 6, 436–439, 2003.

7. Ismail, M. Y. and M. Inam, "Analysis of design optimization of bandwidth and loss performance of reflectarray antennas based on material properties," *Modern Applied Sci. J. CCSE*, Vol. 4, No. 1, 28–35, 2010.
8. Biallowski, M. E. and J. Encinar, "Reflectarray: Potential and challenges," *International Conference on Electromagnetics in Advanced Applications*, 1050–1053, ICEAA, 2007.
9. Pozar, D. M. and S. D. Targonski, "A shaped-beam microstrip patch reflectarray," *IEEE Transactions on Antennas Propogation*, Vol. 47, No. 7, 1167–1173, 1999.
10. Huang, J. and J. Encinar, *Reflectarray Antennas*, Wiley, Interscience, 2007.
11. Sze, K. Y. and L. Shafal, "Analysis of phase variation due to varying patch length in a microstrip reflectarray," *IEEE Trans. Antennas and Propagation*, Vol. 46, No. 7, 1134–1137, 1998.
12. Rajagoapalan, H., S. Xu, and Y. R. Samii, "Reflectarray reflection phase diagnostics," *2011 IEEE International Symposium on Antennas and Propagation (APS/URSI)*, 1636–1638, Washington, USA, 2011.
13. Tienda, C., J. A. Encinar, E. Carrasco, and M. Arrebola, "Design of dual-reflectarray antenna for beam scanning," *Journal of Wireless Networking and Communication*, Vol. 2, No. 1, 9–14, 2012.
14. Carrasco, E., J. A. Encinar, and M. Barba, "Bandwidth improvement in large reflectarrays by using true time delay," *IEEE Transactions on Antennas and Propagation*, Vol. 56, No. 8, 2498–2503, 2008.
15. Rajagopalan, H. and Y. R. Samii, "On the reflection characteristics of a reflectarray element with low-loss and high-loss substrates," *IEEE Antennas and Propagation Magazine*, Vol. 52, No. 4, 73–89, 2010.
16. Inam, M. and M. Y. Ismail, "Reflection loss and bandwidth performance of X-band infinite reflectarrays: Simulations and measurements," *Microwave and Optical Technology Letters*, Vol. 53, No. 1, 77–80, 2011.