Full-Wave Analysis of Planar Reflectarrays with Spherical Phase Distribution for 2-D Beam-Scanning using FEKO Electromagnetic Software

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Abstract: This paper presents a novel reflectarray antenna design for two-dimensional beam-scanning based on the concept of a planar array with spherical phase distribution. The restricted aperture approach is used to minimize the effects of spherical aberration on the reflectarray aperture and a Ka-band beam-scanning reflectarray antenna with 20 dB gain and 30 degrees elevation coverage is designed and analyzed using the commercial electromagnetic software FEKO. The simulation results show that a good 2D beam-scanning performance is obtained with this passive reflectarray antenna designed with spherical phase distribution.

Keywords: Beam-scanning, High-gain, Reflectarray, Spherical Reflector

1. Introduction

Microstrip reflectarrays combine many favorable features of both reflectors and printed arrays, and offer a low profile, low mass, and low cost solution for high-gain antennas in deep space communication systems [1, 2]. In addition to these mechanical advantages, they are also quite suitable for applications requiring high-gain beam-scanning [3]. The beam of a reflectarray antenna can be scanned by means of the reflector nature or the array nature of the antenna; thus owing to their hybrid nature, the reflectarray antenna provides advantages over these two types of antennas. While an aperture phase tuned beam-scanning reflectarray antenna has its own advantages, in many applications a passive design is preferable. The challenge however is that the conventional passive reflectarray antenna cannot achieve a good beam-scanning performance [4].

In this paper, we propose a new design for the reflectarray antenna based on the concept of a planar array with spherical phase distribution, and beam-scanning is achieved by mechanical movement of the feed. To minimize the effects of spherical aberrations, the restricted aperture approach is used for the design [5]. The effectiveness of this approach is first demonstrated for spherical reflector antennas [6], and then applied to the design of a planar array. Here, a Ka-band 2-D beam-scanning reflectarray antenna based on spherical phase distribution with 30 degrees elevation coverage and 20 dB gain is designed and simulated using the commercial electromagnetic software FEKO [7]. In addition the full-wave radiation patterns are compared with theoretical results, which shows a good agreement. This study shows that a passive planar reflectarray antenna with spherical phase distribution can be a suitable choice for high-gain beam-scanning applications.
2. Planar Reflectarray Antennas with Spherical Phase Distribution for 2-D Beam-Scanning Applications

High-gain beam-scanning antennas are an essential part of a radar system and tracking platform. The conventional choices for the antennas in these systems are reflectors, or phased arrays [8]. Owing to their many advantageous features, beam-scanning reflectarray antennas have received a notable attention in the recent years [1, 3]. A reflectarray antenna can scan the beam by means of a mechanical or electronic displacement of the feed, essentially utilizing the reflector nature of the reflectarray antenna. Another design approach is to equip the elements on the reflectarray aperture with a phase tuning mechanism. This is basically similar to a phased array antenna design [9]; with the added advantage of replacing the feed network, which is a major challenge in phased array design, by a space feed system. While both design approaches are suitable for beam-scanning applications, the drawback of the latter approach is the complicated design of phase shifter reflectarray elements [3], and in many cases a passive array with a movable feed system will be more advantageous. The challenge however is that with the feed displacement technique the scan performance is quite poor [4].

Conventionally, the aperture phase distribution of a reflectarray antenna is designed based on the phase compensation of a parabolic reflector antenna with the same subtended angle [2]. However, similar to parabolic reflectors, the scan range of these parabolic-phase planar reflectarrays is limited to a few beam-widths. On the other hand, in a reflectarray antenna one has direct control over the phase shift of each element, and any phase distribution can be realized on the aperture. As such, since we are not bound to a parabolic phase distribution, we may design the phase shift on the aperture in a manner to improve the beam-scanning performance.

![Parabolic Reflector and Spherical Reflector](image)

**Fig. 1.** Comparison of the radiation performance of parabolic and spherical reflectors using the physical optics solver in FEKO: (a) magnitude of the surface electric currents, (b) gain patterns in xz-plane.

The spherical reflector antenna, based on the concept of concave spherical mirrors in optics, has been recognized for years as a suitable design for wide-angle high-gain beam-scanning applications [5]. Because of its perfectly symmetric geometrical configuration, the spherical reflector can make an ideal wide-angle scanner, i.e. without radiation performance degradation. However, it is plagued by poor inherent collimating properties due to spherical aberrations. Nevertheless, different approaches have been introduced over the years to minimize these effects [5]. One of the simplest techniques is to use a restricted aperture and a reflector with a sufficiently large radius. In the restricted aperture design approach, one would only illuminate a small portion of the aperture, i.e. $D_{\text{ill}}$, which has the minimum phase error. The total aperture size ($D$) will then depend on the required scan range. However, if no scan is required for the design, $D_{\text{ill}} = D$, and one only needs to select the optimum sphere radius according to the feed position [5]. To demonstrate the effectiveness of this approach, we compare the radiation
performance of a spherical reflector designed using the restricted aperture approach, with a parabolic reflector that is an ideal collimating design. Here, we only study the radiation performance of a broadside beam, thus for both designs the aperture size is $15\lambda$, and the feed is placed with an $F/D = 0.75$. For the spherical reflector this would correspond to a sphere radius of $23.125\lambda$. The reflectors are excited with a point source radiation pattern modeled with $a \cos^{\theta}(\theta)$ function with $q = 4.6873$. The current distribution on the aperture and the radiation pattern of both designs are shown in Fig. 1. It can be seen that although the parabola has a slightly better performance, a very similar radiation pattern can be obtained with the spherical reflector, illustrating the effectiveness of the restricted aperture approach.

To design a reflectarray antenna with spherical phase distribution, the elements on the reflectarray aperture have to compensate for the phase of the sphere ($\Delta \phi$). A geometrical model of the reflectarray antenna system is given in Fig. 2. Here $R_S$ and $D_S$ are the radius of the sphere and diameter of the spherical reflector, respectively. $R_{SRA}$ is the vector from the center of the sphere to any point on the aperture of the reflectarray, and $D_{SRA}$ is the diameter of the spherical-phase reflectarray.

Fig. 2. The cross-sectional geometry of a spherical-phase reflectarray antenna.

To achieve a similar performance as the spherical reflector, the reflectarray is designed with the same subtended angle; however the position of the aperture plane ($z = H_{SRA}$), may be determined depending on the design. Note that depending on the position of the aperture plane, the size of the reflectarray aperture would be different; as such it could be advantageous to have the aperture plane closer to the sphere center, such as the reflector edge, to reduce the aperture size. However, in spherical reflectors, the focal point is close to the paraxial focus (half the radius of the sphere), thus selecting the edge of the reflector as the aperture plane may result in the feed being placed too close to the aperture, if not impossible. Nonetheless, once the system is specified, computing the aperture phase shift is straightforward. Mathematically the required element phase shift can be given as $\psi = 2k_0(R_{SRA} - R_S)$. With the phase distribution on the aperture specified, the next task is to determine the position of the feed. The theoretical formula to determine the focal optima for spherical reflectors is based on a uniform taper on the illuminated aperture. In practice when a feed antenna is used the focal optima will be slightly different which can be determined by experiment. The procedure used to determine the focal point will be discussed in the next section.

3. Designing a Ka-band Spherical-Phase Reflectarray Antenna

To demonstrate the feasibility of this novel reflectarray design, here we study a Ka-band planar reflectarray antenna with spherical phase distribution for $30^\circ$ two-dimensional scan coverage. To achieve a gain about 20 dB, we select the size of the illuminated aperture ($D_{ill}$) to be $5\lambda$, at the center design frequency of 32 GHz. For an $F/D = 0.73$, the size of the sphere was then determined to be $7.52\lambda$. With $30^\circ$ scan coverage, the diameter of such a spherical reflector should be $11.42\lambda$, thus we select a circular
aperture with a diameter (D) of $12\lambda$ for the reflectarray antenna. With this reflectarray aperture size, $H_{SRA} = 2.38\lambda$, and thus the reflectarray aperture is placed quite close to the edge of the comparable spherical reflector. To mimic the spherical phase distribution on the reflectarray aperture, 408 elements with a unit-cell size of $4.7\times4.7$ mm$^2$ are required. For the phasing elements we use variable size square patch elements on a 10 mil Rogers 5880 substrate. The patch size varies from 1 to 4.2 mm with a 0.05 mm step. With normal incidence excitation, these elements provide $330^\circ$ of phase range which is sufficient for the design. The dimensions of the patch elements were then determined based on the phase requirement and a parasolid geometry file was created using Matlab© and imported into FEKO. The mask of the reflectarray antenna and the geometrical model of the spherical-phase reflectarray in FEKO are given in Fig. 3 (a, b).

In the next stage, the position of the feed (focal optima) for the broadside beam was determined by moving the feed along the Z-axis (see Fig. 2), to determine the position where maximum gain is obtained. It should be noted that in the analysis here the antenna gain was computed using the array theory formulation as described in [10]. A similar procedure is used to obtain the focal optima for scanned beams, however for this case the feed moves along the direction of the sphere radius. The value of $q$ for the feed pattern was set to achieve a -10dB taper on the edges of the area of illuminated aperture for the broadside beam. For this system, the selected value of $q$ is 2.56 which corresponds to a gain of 10.9 dB for the feed. While it is possible to design a feed with such requirements as demonstrated in [11], here we use the point source radiation pattern model for simplicity. The radiation pattern of the feed is shown in Fig. 3 (c).

![Fig. 3. (a) Mask of the spherical-phase reflectarray antenna. (b) Geometry of the reflectarray in FEKO. (c) 3D radiation pattern of the point source used to excite the array.](image)

Full-wave simulation of a reflectarray antenna is a tedious and computationally expensive task. For this design 418,374 unknown basis functions need to be calculated by the FEKO method of moments (MoM) solver. Considering this large number of unknowns, the multilevel fast multi-pole method (MLFMM) solver was selected for this simulation. In total, the full-wave simulation here required 21.88 GB of memory with a CPU time of 19.87 hours on an 8 core 2.66 GHz Intel(R) Xeon(R) E5430 computer. The electric currents on the reflectarray aperture for a broadside beam, and 30° scanned beams are given in Fig. 4. Moreover to demonstrate the 2-D beam-scanning capability of this design, for the 30° scanned beam we study two cases, i.e. $\phi = 0^\circ$, and $\phi = 45^\circ$. Note that unlike a spherical reflector, the taper on the aperture is slightly different here for the three cases due to the planar geometry of the reflectarray. In addition for the scanned beams different azimuth beam direction will result in a different taper on the array. Nonetheless, an almost similar scan performance is obtained for the broadside and scanned beams as shown in the 3-D gain patterns given in Fig. 5. Fig. 6 (a) also shows the 2-D gain patterns along the scan directions. As discussed earlier, in this design beam-scanning is achieved by mechanical movement of the feed. For the broadside beam, the feed is placed at $X_{feed} = 0$, $Y_{feed} = 0$, $Z_{feed} = 23.21$ mm based on the coordinate system in Fig. 2. For the 30° scanned beams, the feed is placed at $X_{feed} = -14.80$ mm, $Y_{feed} = 0$, $Z_{feed} = 22.48$ mm for $\phi = 0^\circ$, and at $X_{feed} = -10.46$ mm, $Y_{feed} = -10.46$ mm, $Z_{feed} = 22.48$ mm for $\phi = 45^\circ$. It
should be noted that in practice for a continuous beam-scanning, a rotating mechanism has to be developed to move the feed along this spiral path.

Fig. 4. Normalized magnitude of electric currents on the reflectarray aperture: (a) for broadside beam, (b) for 30° scanned beam ($\varphi = 0^\circ$), (c) 30° scanned beam ($\varphi = 45^\circ$).

Fig. 5. 3D radiation pattern of the reflectarray antenna simulated in FEKO: (a) broadside beam, (b) 30° scanned beam ($\varphi = 0^\circ$), (c) 30° scanned beam ($\varphi = 45^\circ$).

The peak gain at broadside and at $\theta = 32.5^\circ$ is 20.83 dB and 20.12 dB, respectively, indicating a maximum scan loss about 0.7 dB. The gain in the diagonal scan direction ($\varphi = 45^\circ$) is 20.61 dB. In comparison the scan loss of a parabolic phase reflectarray is more that 3 dB for such coverage [3, 4]. It should be noted that the slight deviation in the scanned beam direction is due to the fact that the optimum feed position was selected based on maximum gain. In other words a slightly larger aperture was illuminated which increases the gain, but results in a higher phase error on the aperture, which deteriorates the radiation pattern. For this spherical-phase reflectarray design the side-lobe level is -18.08 dB at broadside. The side-lobe increases as the beam is scanned however at maximum scan direction the side-lobes are -14.88 dB and -13.16 dB for $\varphi = 0^\circ$ and $\varphi = 45^\circ$, respectively, which is quite acceptable.

The normalized scanned patterns in the $xz$-plane are also given in Fig. 6 (b) and compared with theoretical results which are obtained using the array theory approach. It can be seen that a good agreement in the radiation pattern shape is observed between the analytical and full-wave approach. In particular, the main beam direction and beam-width show a close agreement. The discrepancies however, which are mainly observed outside the main beam areas, are due to the approximations in the array theory approach, as discussed in [11].
Fig. 6. Beam-scanning performance of the spherical-phase reflectarray antenna: (a) gain patterns obtained using FEKO, (b) normalized patterns compared with theoretical results.

4. Conclusions

A novel design of a passive beam-scanning reflectarray antenna is proposed, which is based on the concept of a planar array with spherical phase distribution and mechanical movement of the feed. The restricted aperture approach is used to minimize the effects of spherical aberration for the spherical phase reflectarray, and a 408 element Ka-band antenna with 20 dB gain and 30 degrees elevation coverage is designed and analyzed using the commercial electromagnetic software FEKO. The results presented in this work show that a planar reflectarray antenna with spherical phase distribution can be a good choice for a high-gain beam-scanning antenna.

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References