Compact Folded MM-Wave Reflectarray Antennas

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Abstract
Printed reflectarrays are an interesting solution for high gain antennas, especially in the mm-wave range. They show low loss, and they are potentially low cost. This concept has been extended to folded reflectarrays, exploring the dual polarization properties of reflectarrays, resulting in a small depth of such antennas, too. Principles and results for such antennas in the millimeter-wave range are shown. Furthermore, recent developments including modified radiation characteristics like sector antennas, omnidirectional antennas, or multi-beam antennas for point-to-multipoint applications are demonstrated.

Keywords: Millimeter-wave antennas, reflectarrays, omnidirectional antennas, sector antennas, multibeam antennas

1. INTRODUCTION

Printed antennas are of great interest for all types of microwave applications. With increasing frequency and increasing antenna size, however, these antennas often exhibit unacceptable losses mainly caused by the feed network. Based on printed structures, planar reflector antennas (reflectarrays) have been developed [1 - 6]. With these antennas, feeding of the printed radiating elements is done quasi-optically; the necessary reflection phase angle is adjusted either by attaching some transmission line section to a microstrip patch antenna acting as reflection phase shifter, or by adjusting the reflection phase angle by a specific geometry of the reflecting elements. These antennas typically show low loss, but require a feed element at the focal point in front of the reflectarray. Exploiting the dual polarization properties of reflectarrays, a folded version of such reflectarrays has been proposed and realized [7 - 9].
In section 2, the general principle for calculating element properties for such antennas is given. Section 3 presents folded reflectarray antennas. Antennas with omnidirectional pattern in azimuth are demonstrated in section 4, and the paper finishes with a description and results of multibeam antennas in section 5.

2. BASIC PRINCIPLE OF A REFLECTARRAY

The basis for the design procedure of reflectarray antennas as described in this paper is a periodic array of dipoles printed on a single dielectric substrate with backside metallization. Typically, the distance between the printed elements is chosen to about half a free space wavelength. In this way, grating lobes can be avoided for all antenna arrangements. The reflection behavior of such dipole arrays is calculated using a standard spectral domain method [10] and Floquet's theorem. The basic equation describing the fields excited by a plane wave incident on a periodic structure is given by

$$\tilde{\tilde{\boldsymbol{E}}}_{total} = \tilde{\tilde{\boldsymbol{Z}}} \cdot \tilde{\tilde{\boldsymbol{J}}} + \tilde{\tilde{\boldsymbol{E}}}_{in} + \tilde{\tilde{\boldsymbol{E}}}_{refl} \qquad (1)$$

All quantities are Fourier transforms, indicated by the tilde. The electric fields are taken in the metallization plane. $\tilde{\tilde{\boldsymbol{Z}}}$ is the dyadic Green's function, in this case of a dielectric layer with backside metallization and free space above:

$$\tilde{\tilde{\boldsymbol{Z}}} = \begin{pmatrix} \tilde{Z}_{xx} & \tilde{Z}_{xz} \\ \tilde{Z}_{xz} & \tilde{Z}_{zz} \end{pmatrix} \qquad (2)$$

with
$$\tilde{Z}_{xx} = -\frac{\alpha^2 Z_e + \beta^2 Z_h}{\alpha^2 + \beta^2}, \quad \tilde{Z}_{zz} = -\frac{\beta^2 Z_e + \text{á}^2 Z_h}{\alpha^2 + \beta^2}, \quad \tilde{Z}_{xz} = -\frac{\alpha\beta(Z_e - Z_h)}{\alpha^2 + \beta^2}, \qquad (3)$$

$$Z_e = \frac{1}{\frac{j\omega\varepsilon_0\varepsilon_r}{\gamma_2} coth(\gamma_2 h) + \frac{j\omega\varepsilon_0}{\gamma_1}}, \quad Z_h = \frac{1}{\frac{\gamma_2}{j\omega\mu_0} coth(\gamma_2 h) + \frac{\gamma_1}{j\omega\mu_0}}, \quad \gamma_i = \sqrt{\alpha^2 + \beta^2 - k_0^2 \cdot \varepsilon_{ri}}. \qquad (4)$$

α and β are the Fourier variables for *x* and *z*. $\tilde{\tilde{\boldsymbol{J}}}$ represents the current density on the strip, $\tilde{\tilde{\boldsymbol{E}}}_{in}$ is the incident plane wave, and $\tilde{\tilde{\boldsymbol{E}}}_{refl}$ is the electric field reflected by the dielectric layer ***without*** the printed patches. The indices 1 and 2

in the preceding equations refer to the free space and the dielectric layer, respectively. The current densities on the metal elements – in this paper, only rectangular elements are considered – are expanded with entire domain functions including edge terms [10]. Galerkin's method is used to transform equ. (1) into an inhomogeneous system of equations. Due to the periodic nature of this arrangement, only discrete Fourier variables have to be taken into account for the numerical procedure. The system of equation can be solved for the amplitudes of the current density functions and the reflection coefficient of the wave. The wave incident on the substrate is completely reflected, the phase angle, however, depends on dipole length and, to a minor degree only, on patch width (Fig. 1).
Using such patches as phase shifters, planar reflector antennas can be designed. For a single layer substrate, a range of phase angles of about 320° is covered.
For the orthogonal polarization, it is possible to adjust phase angles independently. In this way, antennas with two different radiation diagrams, two different feed positions, or even two different frequencies of operation can be realized [8]. Another feature of dual polarization use of such reflectarrays is the generation of circular polarization or a 90° twist of the polarization, as will be demonstrated in the following sections.
For the design of an antenna, the necessary phase shift, adjusted by the respective patch dimension, is determined using a simple ray tracing procedure. Although the original assumptions of a structure with equal element size and a broadside incidence of the waves are no longer true, and although not the complete range of angles is covered, this method has proven to give reasonably good antenna results.

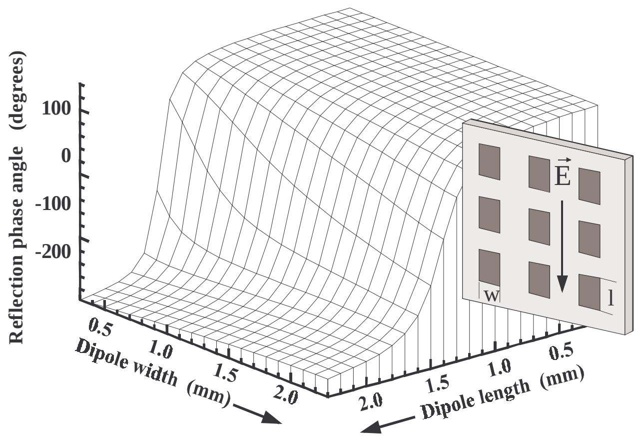


Fig. 1: Reflection phase angle of a plane wave reflected from a periodic array of printed dipoles. (Frequency 58 GHz, substrate thickness 0.254 mm, dielectric constant 2.22, dipole grid spacing 2.4 mm, normal incidence of the wave).

3. PLANAR FOLDED REFLECTOR ANTENNA

Although "standard" reflectarrays already provide some advantages due to their printed reflectors, they still exhibit a reasonable high depth. This disadvantage is overcome by folding such an antenna, as it is known from parabolic reflectors or lens antennas, e.g. [11]. The basic cross section of a planar folded reflector antenna [7 - 9] is sketched in Fig. 2, left side. The radiation from the feed is reflected by a printed grid or slot array at the front of the antenna. Then the wave is incident on the reflectarray with printed patches. For the folded reflector antenna as described here, the patch axes of the array are tilted by 45° with respect to the incident electric field (Fig. 2, right side). The dimensions of the patches are selected in such a way that a phase difference of 180° occurs between the reflection phase angles of the two field components parallel to the axes, leading to a twisting of the polarization by 90°. This 180° phase angle difference can be achieved for a large number of combinations of length and width of the patches differing by their *absolute* reflection phase angle. This degree of freedom now is used to adjust the required phase angles and to transform the incident spherical wave into an outgoing plane wave which now can pass the polarizing structure in front of the antenna.

3.1 Pencil beam folded reflector antennas

Based on the principle explained above, a number of antennas have been designed and tested. Fig. 3 shows a photograph of the reflectarray substrate and the radiation diagram of a folded reflectarray antenna at 61 GHz with a diameter of 100 mm and a depth of 25 mm. Beamwidths are 3.2° and 3.4° in E- and H-plane, respectively, and sidelobe level is better than –24 dB. Gain is about 34 dB at 61 GHz and better than 31 dB in a 7.2 GHz bandwidth (Fig. 4). An antenna of this kind even can be integrated into a 900 MHz patch antenna resulting in a dual frequency antenna [12]. At 77 GHz, some scanning has been demonstrated tilting the reflectarray, and an antenna with three beams for automotive applications has been designed, too [9].

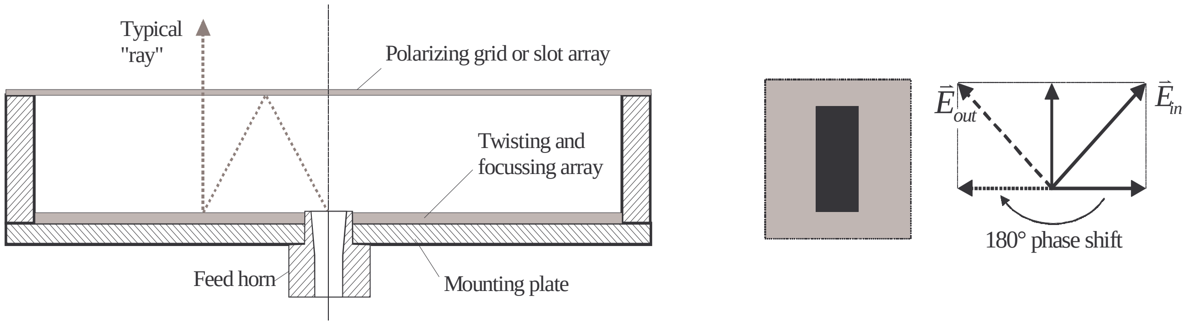


Fig. 2: Basic principle of the folded reflector antenna (left) and single patch with vector decomposition of incident and reflected electric field for 180° of reflection phase angle difference (right).

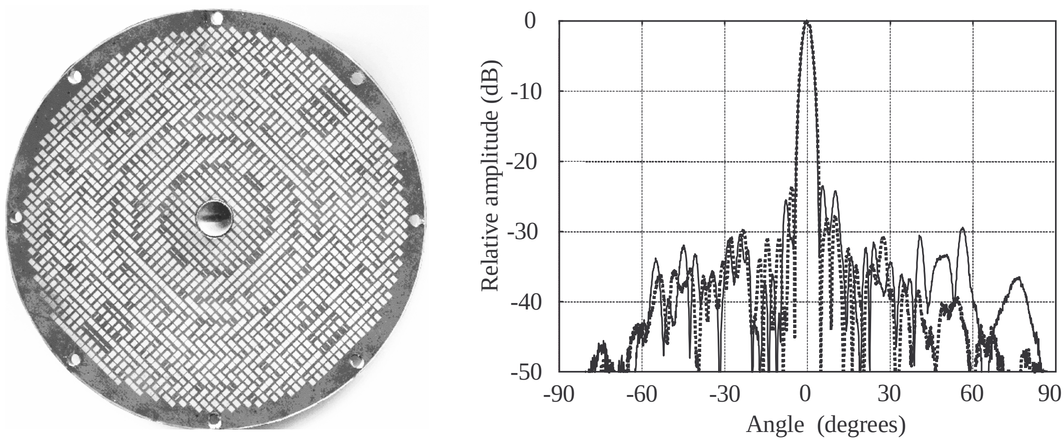


Fig. 3: Photograph of the reflector substrate and E- and H-plane radiation diagrams of a folded reflector antenna at 61 GHz.(solid line: E-plane, dotted line: H-Plane*)*.

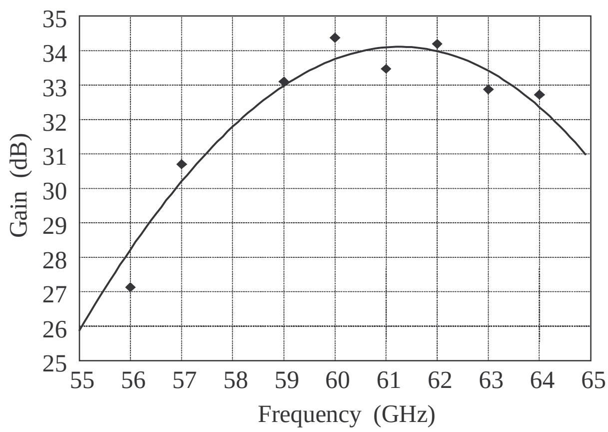


Fig. 4: Gain of the 61 GHz antenna versus frequency (dots: measured values, solid line: polynomial approximation of the measured values).

3.2 Sector antennas

For point-to-multipoint communication links, antennas with sector or omnidirectional characteristics in azimuth are required. For a sector antenna, a folded reflector antenna was redesigned such that a suitable non-planar phase distribution in azimuth results [13]. As a first test, an antenna with a sector width of 90° was built and tested. Fig. 5 shows layout as well as desired and achieved azimuth (H-plane) radiation diagram. Requirements for low phase angle errors are quite high in this application; nevertheless, the results look quite good. In elevation, a beamwidth of about 3° is achieved; sidelobe level, however, rises up to –8 dB; here some re-optimization is necessary.

4. OMNIDIRECTIONAL ANTENNAS

A possible solution to realize antennas with a constant azimuth diagram is the combination of a focusing reflector with a cone reflector (Fig. 6, left side). If the feeding waveguide, for simplicity, is excited with the TE_{11} mode, antenna polarization is depending on the radiation direction. One way out of this problem is the use of circular

polarization. Two of the necessary functions – focusing and generation of circular polarization – now are combined in a planar reflector. The basic function of the reflector is the same as for the folded reflectarray (Fig. 2, right side), except that in this case, the two field components incident on the reflector undergo a differential phase shift of 90° only. Another way to solve the polarization problem was discovered only recently, using tilted patches (Fig. 6, right side). This polarization adjustment works like that for the 90° polarization twisting, except that the electric field is not necessarily incident at 45° with respect to the patch axes, but at an arbitrary angle. The electric field then is twisted by twice the angle between incident field and patch axes. In this way, an arbitrary polarization of the reflected wave can be adjusted locally, e.g. to achieve vertical or horizontal polarization of the overall antenna.
If the polarization of the feed is changed, the sense of the circular polarization is reversed, or vertical polarization is changed to horizontal polarization and vice versa. Elevation and azimuth radiation diagrams of an antenna with circular polarization at 60 GHz are plotted in Fig. 7. A fairly constant radiation could be achieved in azimuth, combined with a narrow beamwidth (6.2°) in elevation. Due to the specific amplitude distribution in that plane (maximum amplitude at the upper edge), a sidelobe level of only -12 dB is achieved. Very similar results have been achieved for an antenna with linear polarization.

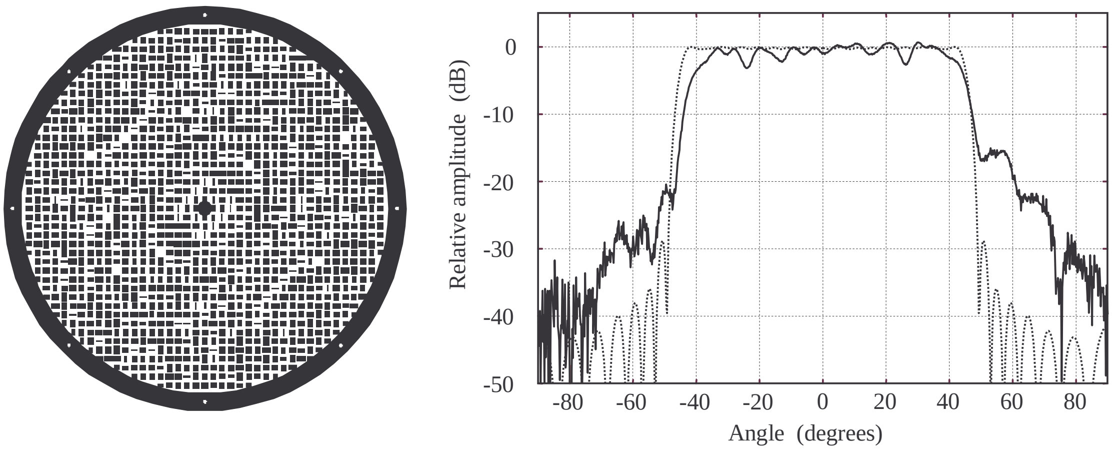


Fig. 5: Layout and azimuth (H-plane) radiation diagram of a folded reflectarray sector antenna (dotted line: designed diagram; solid line: experiment. In the antenna, the orientation of the layout is twisted by 45°).

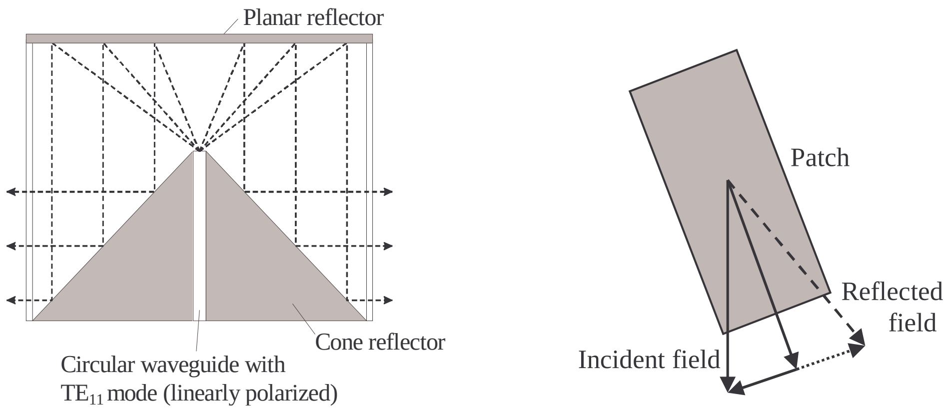


Fig. 6: Left side: Basic principle of an omnidirectional antenna with planar reflector. Right side: Principle of adjustment of an arbitrary polarization twisting angle (180° phase shift between the two reflected field components).

5. MULTIBEAM ANTENNAS

As the folded reflector antennas basically are reflector antennas with a short focal length, only a small offset of the feed is possible to allow beam scanning or multi-beam operation [9]. A way out of this problem is the extension to a bifocal type of reflector antenna which exhibits a focal ring instead of a focal point [14], thus allowing a much wider scanning range. To achieve this, another phase adjusting structure is added to the top substrate of a folded reflector antenna (Fig. 8, [15]). This composite structure consists of a polarizing grid on one side and narrow dipoles parallel to the grid on the other side of one substrate; a second substrate serves for stabilization and as a radom. For an electric field parallel to the grid, the dipoles act as phase adjusting elements, for the orthogonal field direction, the dipoles and the grid are nearly transparent. The design of both reflectors is done using a ray-tracing procedure ([14, 15], Fig. 8, right side).

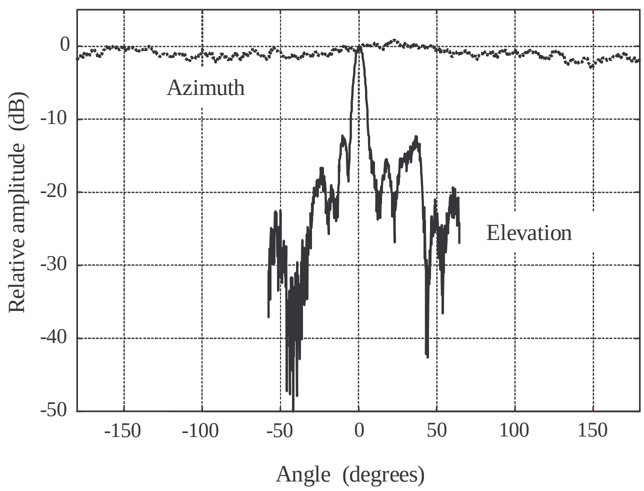


Fig. 7: Radiation diagram of an omnidirectional antenna with circular polarization.

For the ray tracing procedure, feed position and beam angle as well as axial symmetry of both reflectarrays are prescribed. The upper substrate is a composite structure as mentioned earlier and shown in Fig. 8 (top left), the lower substrate a reflectarray including the twisting performance as described in section 3. A ray (1) is incident on the lower reflector at the axis of the antenna. The incident beam angle is as desired; polarization of the wave is such that it can pass the top substrate. Due to symmetry, it is reflected at the bottom substrate at the same angle while the polarization is twisted by 90°. Back on the top structure, it has to be reflected such that it ends at the feed point. From the known angles of incidence and reflection, the reflector properties can be calculated at the reflection point. Exploiting symmetry, these properties must be the same on the opposite side of the antenna. Consequently, the reflection of a ray (2) starting at the feed point can be traced up and down to the lower reflector. Knowing the angle of incidence and the angle of the outgoing ray, the properties of the lower reflector can be determined at this point, and consequently, at the point symmetric to this one. The whole procedure is continued until the edge of one of the reflectors is reached. A second set of data can be derived in the same way starting with a ray from the feed point to the center of the upper reflector. These two sets of data are merged and approximated by two polynomials for both upper and lower reflector. From these, the reflection phase angles of the two reflectors and the respective patch dimensions can be determined.

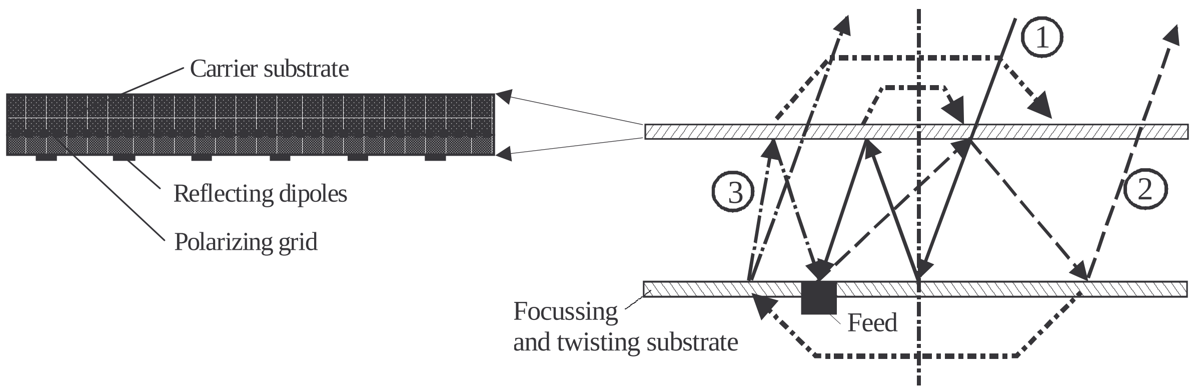
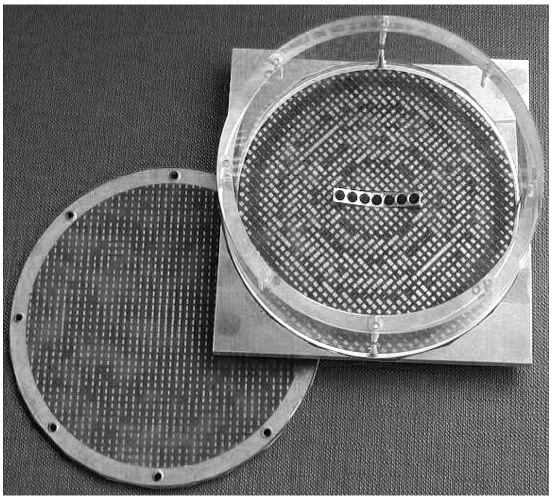


Fig. 8: Setup and ray tracing procedure for a bifocal antenna based on two reflectarrays.

Fig. 9, left side, shows the photograph of a folded bifocal reflector antenna with the front substrate removed. Antenna diameter is 90 mm, the distance between the two reflectors is 26 mm. Both reflector substrates are 0.254 mm thick. The carrier substrate for the front reflector is 1.02 mm thick. The dielectric constant of all layers is 2.2. Seven feeds with an inner diameter of 3 mm and distances of 4 mm are used. The antenna was designed in such a way that the center feed opening is in the reflector plane, the other ones protrude out of this plane for best performance. On the right side of Fig. 9, the E-plane beams for the seven feeds are plotted. All beams are normalized to their respective maximum amplitude value. Beamwidths are between 3° and 3.3°, scan range is ±13.5°, and sidelobe level – except for the outer beams – is better than –18 dB. Very similar performance is found over a bandwidth of at least 76.5 ± 1 GHz. With another design of such an antenna with 130 mm diameter, a scanning range of ±24° has been demonstrated, too [15].



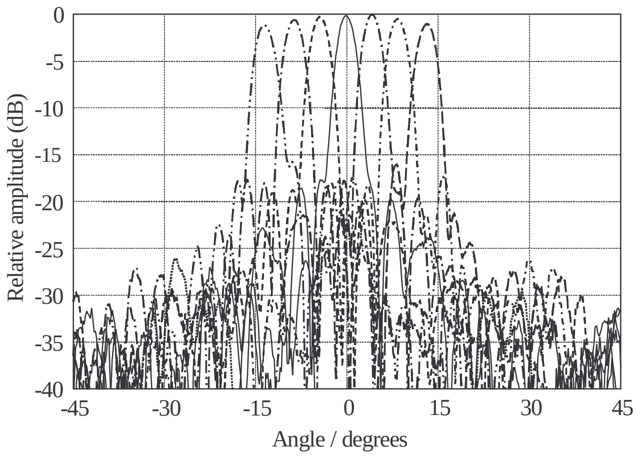


Fig. 9: E-plane diagrams for the seven feeds of an antenna with 90 mm diameter and ±13.5° scanning range .

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