Folded Millimeter-Wave Shaped-Beam Reflectarrays

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***ABSTRACT* — The concept of printed reflectarrays is extended to folded arrangements, exploiting the dual polarization properties of reflectarrays. In addition to standard pencil beam antennas, e.g. for an automotive radar, this principle has been applied to a number of different antenna characteristics, e.g. sector antennas with narrow beam in elevation and 90° and 60° in azimuth, multi-beam antennas using the principle of bifocal antennas, or omnidirectional antennas using a planar reflectarray and a metal cone, fed by a simple circular waveguide with the TE_{11} mode.**

I. Introduction

Printed antennas are of great interest for all types of microwave applications. With increasing frequency and increasing antenna size, however, typical microstrip antennas often exhibit unacceptable losses mainly caused by the feed network. Based on printed structures, planar reflector antennas (reflectarrays) have been developed, e.g. [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 acting as reflection phase shifter, or by adjusting the 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 this way, a low profile of such antennas is achieved, and the feed element now is placed at the backside of the antenna. Another antenna configuration for omni-directional coverage in azimuth is the combination of a parabolic reflector and a cone [10]. Here again, a reflectarray can replace the parabolic reflector.

Chapter II will shortly review the basic principle of a folded reflectarray antenna. In the next chapter, shaped beam antennas based on this principle are described. Chapter IV reports an extension of such antennas for multi-beam applications, and finally two examples for omnidirectional antennas are given.

II. Basic principle of a folded reflector antenna

For the reflectarrays described in this contribution, the reflection phase angle for a plane wave incident on a periodic structure of printed patches or dipoles on a dielectric substrate with backside metallization is adjusted by the geometry of the patches. The phase angle mainly depends on patch length (Fig. 1). For a single layer substrate, a range of phase angles of only about 320° is covered (instead of 360° necessary in principle), but this has proven to give reasonably good antenna results. The basic cross section of a planar folded reflector antenna [7 - 9] is sketched in Fig. 2, top. 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 the 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, bottom). 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 to transform the incident spherical wave into an outgoing plane wave (for a pencil beam antenna) which now can pass the polarizing structure in front of the antenna.

If a phase difference of 90° is adjusted between the two components of the electric field, circular polarization results which can be used in other antenna arrangements as will be described later on in this paper.

The calculation of the reflection phase angles is done based on a spectral domain method, and the antenna design is done assuming the normal incidence of a plane wave on a periodic structure. Although these assumptions are not really true and lead to some phase errors, the antenna results mostly are quite acceptable. A number of pencil beam antennas have been realized in the frequency range from 28 GHz to 77 GHz, and this type of antenna has already found a commercial application in automotive radar.

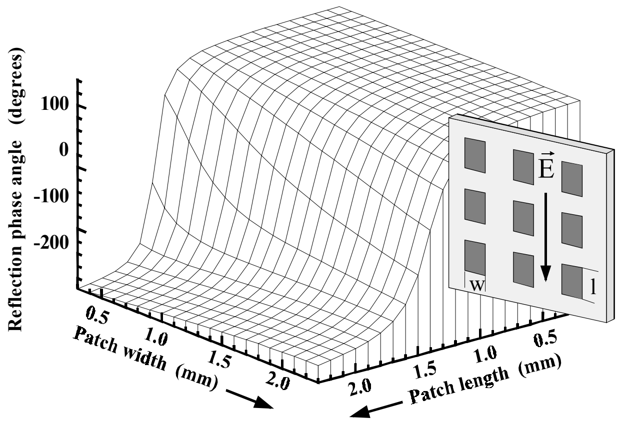

Fig. 1: Reflection phase angle of a plane wave reflected from a periodic array of printed patches. (Frequency 58 GHz, substrate thickness 0.254 mm, dielectric constant 2.22, patch spacing 2.4 mm, normal incidence of the wave).

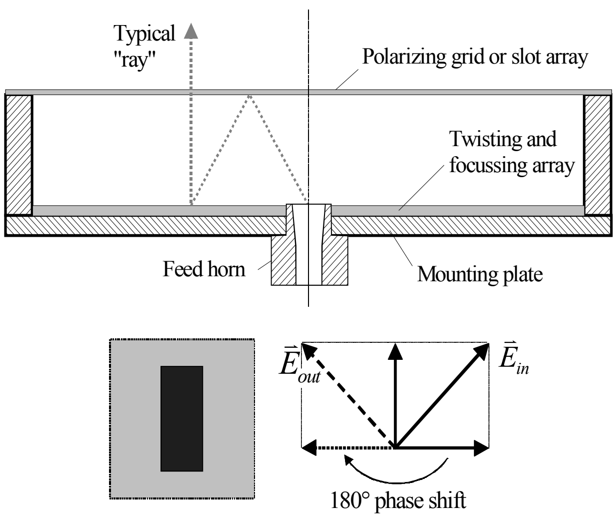

Fig. 2: Basic principle of the folded reflector antenna (top) and single patch with vector decomposition of incident and reflected electric field for 180° of reflection phase angle difference (bottom).

III. SHAPED-BEAM ANTENNAS

For point-to-multipoint communication links, antennas with sector or omnidirectional characteristics in azimuth are required. As a first test for a shaped-beam characteristic, a folded reflector antenna with a dual beam was designed and tested. Diameter of this antenna is 100 mm, frequency 60 GHz. For this antenna characteristic, the required antenna aperture illumination (for constant amplitude) simply is the superposition of two distributions with linear phase progression of different sign; the result is a cosine amplitude distribution including a change of sign (180° phase steps). With the planar reflector, however, only the phase steps are adjusted, i.e. the steps are added to the original phase angle distribution for a pencil beam antenna. The resulting radiation diagram is shown in Fig. 3. In this plane, beamwidth is 4.5° for each beam, sidelobe level amounts to nearly 20 dB.

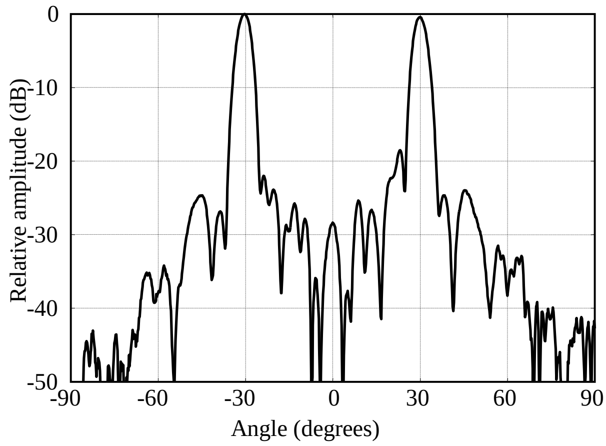

Fig. 3: Azimuth radiation diagram for the dual-beam folded reflector antenna.

In a next step, the phase angle distribution of the reflectarray is optimized for sector antenna characteristics in azimuth [11], maintaining a narrow beam in elevation. Tests have been made in the 60 GHz range for sector angles of 30°, 60° and 90°. Figs. 4 shows the layout of the reflectarray, Fig. 5 demonstrates the radiation characteristics both in azimuth and elevation for a 90° sector antenna, together with the theoretical azimuth diagram. Requirements for low phase errors are quite high in this application, and some problem was found in predicting correctly the amplitude distribution. Nevertheless, the results look quite good. In elevation, a beamwidth of about 3° is achieved; sidelobe level, however, rises up to –10 dB. Later on, even some error in the design procedure was found, and some re-optimization is necessary.

Improvements of the design procedure were applied to the 60° antenna; for example, the illumination of the reflectarray by the feed was measured and included into the design. In this way, an improved side lobe level could be achieved as demonstrated in Fig. 6.

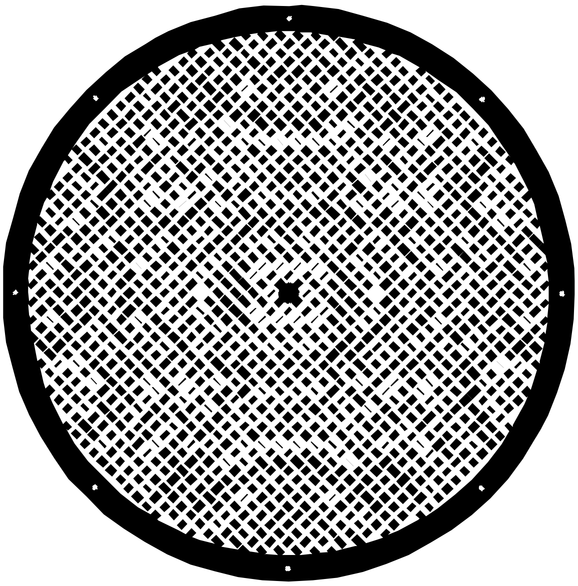

Fig. 4: Layout of the reflectarray for the 90° sector antenna. The patches are tilted by 45° to achieve the twisting of the polarization by 90°.

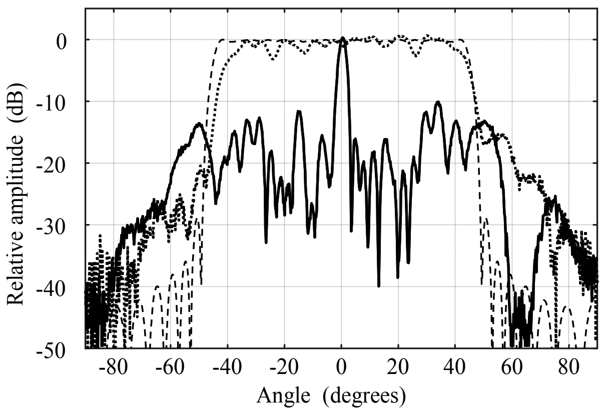

Fig. 5: Azimuth (H-plane) and elevation (E-plane) radiation diagrams of a 90° folded reflectarray sector antenna. Dashed line: theoretical azimuth diagram; dotted line: experimental azimuth diagram, solid line: experimental elevation diagram.

IV. Multi-Beam Antennas

An alternative to sector antennas are antennas with narrow switchable beams. In principle, this can be achieved using a number of feeds separated some distance from each other. For compact antennas, i.e. antennas with a short focal length, this, however, works only for a very limited range of angles; for wider scan angles, the antenna beam quality deteriorates considerably. A better solution can be achieved using bifocal antennas, either based on a special lens or dual reflector antenna [12]. A second reflector can be included into the folded antenna configuration replacing the front grid by another reflectarray with a grid as ground plane – in such a way another phase angle adjustment can be made in one polarization, while the structure is transparent for the other polarization. A second substrate serves for stabilization and as a radom (Fig. 7). A detailed description of the design procedure based on ray tracing is given in [13].

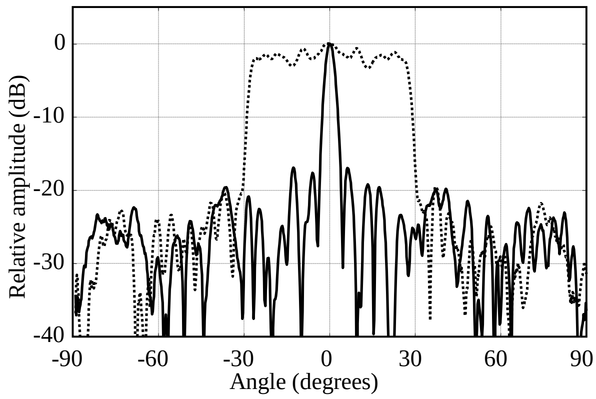

Fig. 6: Azimuth (H-plane) and elevation (E-plane) radiation diagrams of a 60° folded reflectarray sector antenna. Dotted line: experimental azimuth diagram, solid line: experimental elevation diagram.

As an example, Fig. 8 shows the photograph of an antenna with nine different feeds. Diameter is 130 mm, distance between the two reflectarray substrates 30 mm. Frequency is 76.5 GHz, but the antenna equally can be scaled to other frequencies. The E-plane radiation diagrams for the nine different feeds are plotted in Fig. 8. With the available feed structure, a range of ±24° is covered; according to simulations, ±30° or even ±40° should be possible. Beamwidths are 4° ... 4.5°; this is wider than the antenna diameter would imply, but only part of the aperture can be used due to the wide beam scanning. Sidelobe level is between –15 dB ... –13 dB.

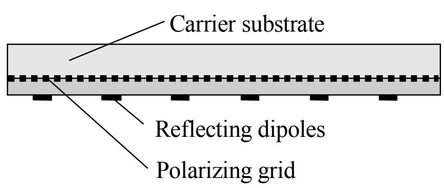

Fig. 7: Double-layer substrate acting as reflectarray in one polarization. For the orthogonal polarization, it is transparent

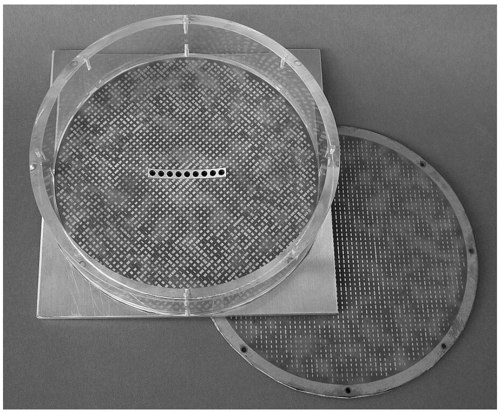

Fig. 8: Photograph of a multi-beam folded reflector antenna. In the final set-up, the reflectarray at the bottom right is fixed face down on top of antenna the arrangement. Diameter: 130 mm, distance between the two reflectarray: 30 mm.

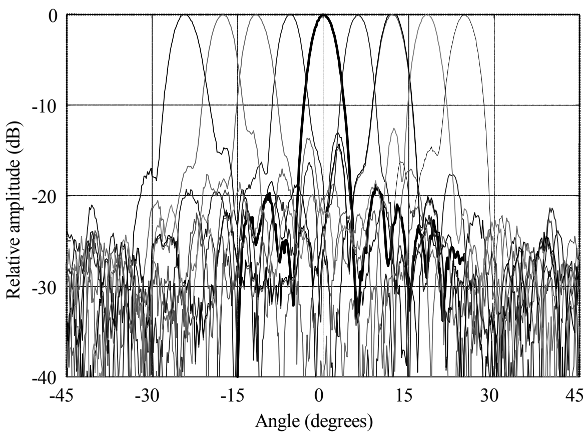

Fig. 9: Azimuth (E-plane) radiation diagrams of a multi-beam folded reflector antenna for the nine different feeds.

V. Omnidirectional Antennas

A possible solution to realize antennas with a constant azimuth diagram is the combination of a focusing reflector with a cone reflector [10]. 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 (Fig. 10). The basic function of the reflector is the same as for the folded reflectarray, except that in this case, the two field components incident on the reflector (Fig. 2, bottom) undergo a differential phase shift of ±90° only, resulting in circular polarization. The sense of the circular polarization depends on the sign of the phase shift.

For a vertical or horizontal *linear* polarization of the antenna, the electric field of the incident wave must be rotated by an angle depending on the position on the reflector. The principle of this rotation is indicated in Fig. 11. Here, the patches are oriented with respect to the incident electric field at an arbitrary angle, mostly different to 45°. The electric field vector once again can be decomposed into the two components along the patch axes. If the patch dimensions are chosen such that a phase differences of 180° occurs between the reflection phase angles of the two components, the electric field vector is rotated as shown in Fig. 11. To perform a rotation of the electric field vector for a required angle 2φ, the patch must be tilted by the angle φ. Once again, different combinations of such dimensions can be found, leaving the freedom for adjusting the overall phase angle necessary for focusing the feed radiation.

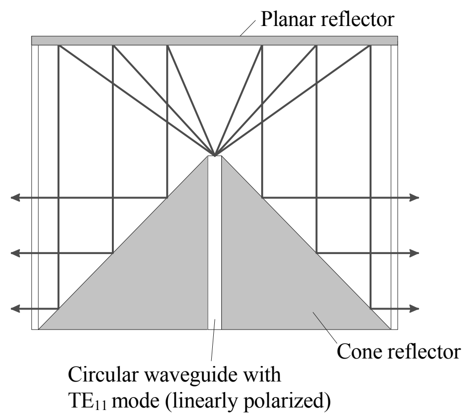

Fig. 10: Basic principle of an omnidirectional antenna.

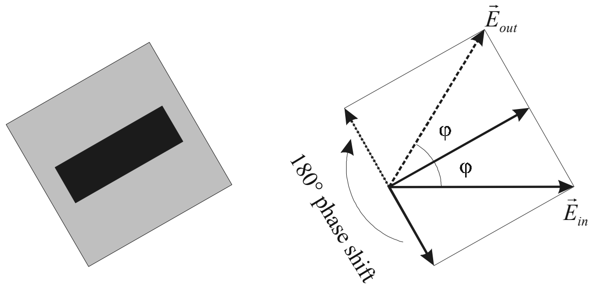

Fig. 11: Principle of rotation of the electric field vector by an arbitrary angle.

Fig. 12 shows a center cut-out of the reflectarray for circular (left) and linear (right) polarization of the omnidirectional antenna. If the polarization of the field in the feed is changed, the polarization is change to the orthogonal one in both cases; i.e. a change between the sense of circular polarization or a change between vertical and horizontal polarization can be achieved easily just by changing the polarization of the feed.

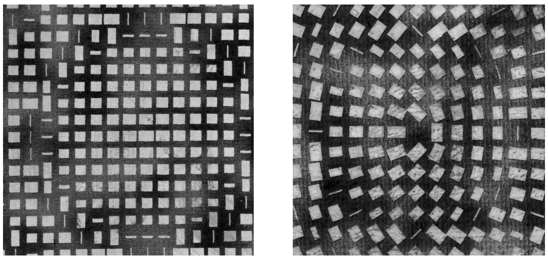

Fig. 12: Cutout of the planar reflectors for circular polarization (left) and linear polarization with polarization rotation (right).

Elevation and azimuth radiation diagrams of two antennas realized at 60 GHz are plotted in Fig. 13 and 14 for circular and linear polarization, respectively. A fairly constant omnidirectional radiation is achieved in azimuth, combined with a narrow beamwidth (6.2°) in elevation. It should be noted that the effective vertical antenna aperture of these antennas is half the diameter of the reflectarray. Due to the asymmetric amplitude distribution in that plane (maximum amplitude at the upper edge of the cone), sidelobe levels of only -12 dB … -14 dB have been achieved.

ACKNOWLEDGEMENT

Part of this work was funded by the German Research Association (DFG; contract no. ME 1016/7).

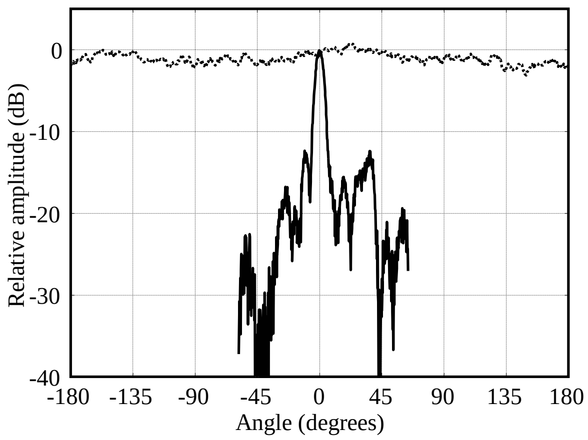

Fig. 13: Azimuth (dotted line) and elevation (solid line) radiation diagram of an omnidirectional antenna with planar reflector and circular polarization.

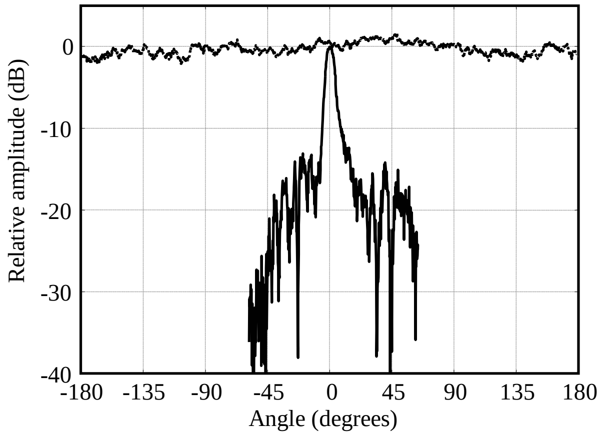

Fig. 14: Azimuth (dotted line) and elevation (solid line) radiation diagram of an omnidirectional antenna with planar reflector and linear polarization.

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