Loss Mechanisms of Folded Reflectarray Antennas

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***Abstract*— Folded reflectarray antennas can provide a good solution for millimeter-wave systems requiring compact, low-cost antennas, e.g. in automotive applications. This contribution investigates different approaches of such antennas with rectangular and composite reflecting elements. Special emphasis is put on gain and antenna loss mechanisms, including increased beamwidth and sidelobe level as well as metallization losses.**

I. Introduction

Printed planar reflectarrays [1 - 6] have gained increasing interest due to their low weight, design flexibility, or ease of fabrication. A more compact version of such antennas is provided by folded reflectarray antennas [4 - 6] which have already been implemented into an automotive radar.

The cross section and the photograph of part of a typical folded reflectarray antenna are shown in Fig. 1. This antenna consists of a circular waveguide feed horn, a polarizing grid printed on a dielectric substrate, and the specific reflectarray substrate with printed metal elements, for example rectangular patch elements, which, simply by their geometry, both adjust the overall phase angle and twist the polarization of the incoming wave by 90° providing a 180° phase shift between the two polarizations of the reflected wave (Fig. 2). This dual function requires that the reflection phase angle can be adjusted independently for both polarizations.

The array amplitude distribution generally is determined by the feed illumination, and for pencil beam antennas, the phase angle distribution is adjusted to realize an outgoing plane wave. The relation between reflection element phase angle and geometry typically is calculated based on

- an infinite periodic structure of elements (or unit cell approach)
- a plane wave incident from normal (or from a single direction)
- the assumption that the incident power is completely reflected with no amplitude variation over phase angle
- the assumption that all phase angle values can be adjusted
- zero metallization thickness.

For a typical reflectarray design, none of these assumptions holds, leading to a degradation of the antenna performance. Metallization thickness is the less critical item, as it affects only the performance of very narrow elements or large elements coming close together (narrow air gap), but such dimensions can be largely avoided, as the phase angle curve is very flat for these dimensions (see Fig. 3). In principle, metallization thickness can even be included in the unit cell calculation with some additional effort. Consequently, this investigation will deal with the remaining items.

Looking at the photograph in Fig. 1, it becomes immediately clear that the assumption of periodicity is not valid at all. Varying phase angles and, above all, the large change of element geometry in case of phase angle steps of 360° leads to phase errors.

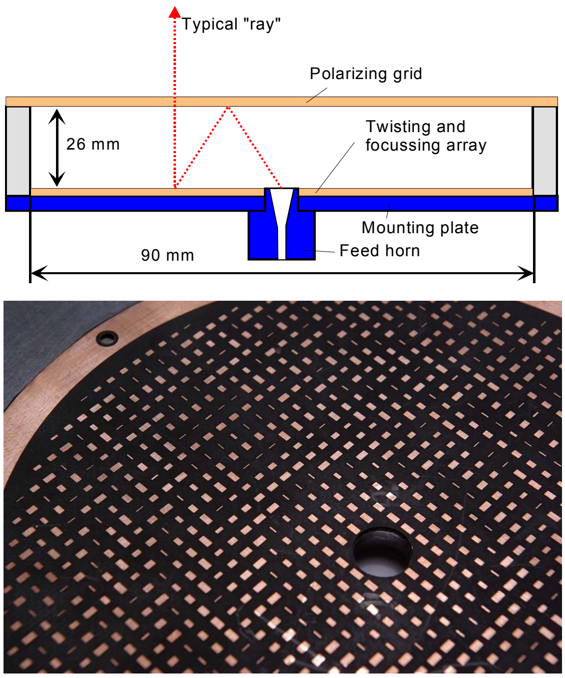

Fig. 1 Cross section of folded reflectarray antenna and photograph of a section of a reflectarray with rectangular elements.

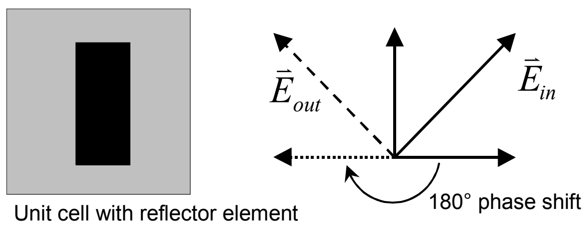

Fig. 2 Principle of polarization twisting.

Fig. 3 shows reflection phase angle and amplitude of rectangular reflector elements as a function of length (parallel to the direction of the electric field) for two different substrate thicknesses. Both metal conductivity as well as loss tangent of the dielectric have been included in the simulation [7]. From this diagram it can be seen that the phase adjustment depends on a resonance of the involved elements. With such single elements, not all phase angle values can be covered. Furthermore, losses mostly occur at the resonance frequency, i.e. at specific phase angles for the reflectarray. With thinner substrates, a wider phase angle range can be achieved, but at the expense of higher losses and a higher sensitivity with respect to fabrication tolerances (steep slope of the curve).

A further effect is the dependence of phase angle on the angle of incidence, even differing with respect to TE or TM incidence of a wave (see Fig. 6), leading to phase angle errors. In addition to the absolute error, also the difference between TE and TM incidence is extremely critical for folded reflectarray antennas, because of the required 180° phase angle difference between the two polarizations for polarization twisting.

In summary, there are both phase and amplitude errors which are not equally distributed but appear in certain phase angle ranges and towards the outer area of the antenna. As a consequence, the overall radiated power is reduced and errors appear in the radiation characteristics in the following form:

- Broadening of the main beam
- Higher first order sidelobe levels
- Higher far-off sidelobe level
- In special cases, even grating-lobe-like sidelobes due to a quasi periodic appearance of phase and amplitude errors.

In the following section, some of these effects will be investigated in more detail, and a number of modified antennas will be compared to a simple reference antenna.

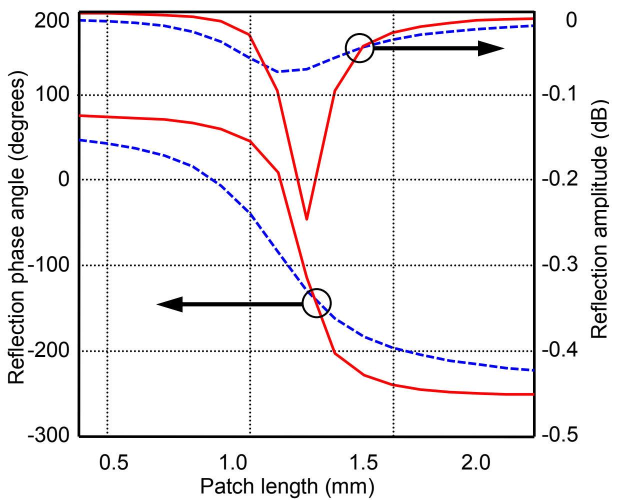

Fig. 3 Phase angle and reflection amplitude for rectangular patch elements on substrates with different thickness h. Solid line h = 0.254 mm, dashed line h = 0.508 mm, cell size 2.2 mm × 2.2 mm).

II. Reference Antenna

As a reference for the following investigations, a folded reflectarray antenna with the overall dimensions as given in Fig. 1 was designed. The polarizer consists of a grid printed on a substrate with a thickness of 1.143 mm and a dielectric constant of 2.2; metallization thickness, conductor width, and periodicity of the strips are 0.017 mm, 0.2 mm, and 0.4 mm, respectively. The reflectarray itself is realized on a 0.254 mm thick substrate with a dielectric constant of 2.2; unit cell size is 2.2 mm × 2.2 mm (see solid lines in Fig. 3). The radiation diagram of this antenna at 76.5 GHz is plotted in Fig. 4. Beamwidths are 3° and 3.2° in the two planes, maximum gain at this frequency is 33.7 dB (see Fig. 8), the 3 dB gain bandwidth is 10 GHz, and aperture efficiency 46%.

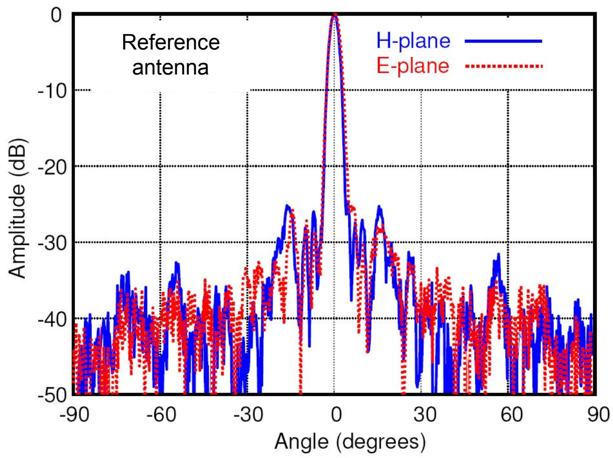

Fig. 4 E-plane and H-plane radiation diagrams of the reference antenna at 76.5 GHz.

III. Improved Phase Angle Range

A disadvantage of simple rectangular patches for single-layer reflectarrays is a reduced phase angle range of only 300°… 320° (see Fig. 3). This problem may be overcome by dual or triple layer reflectarrays, e.g. [6]. The underlying principle is based on coupled resonances thus doubling or tripling the range of phase angles. For some applications however, like in automotive radars, such multilayer substrates with their increased fabrication effort and cost are not acceptable.

A solution to this problem could be the realization of coupled resonators on a single layer. In addition, in this case, a thicker substrate can be used resulting in a flatter phase angle curve. Recently, some modified structures have been proposed for an increased phase angle range for single polarization, e.g. [8 - 14], based on multiple elements, partly combined with slots. Losses now occur at both resonances, although losses may be lower. In general, the two resonances should be close together to achieve a flat phase angle curve. For *folded* reflectarrays, phase adjustment is necessary *independently for both polarizations* requiring some degree of double symmetry. Double-ring or -cross structures, for example, could be a solution, but for closely spaced resonances, these result in very narrow conductors and consequently high losses. As a way out of this, composite structures as shown in Fig. 5 were investigated resulting in a phase angle range of over 500° and a flat slope. General cell size for the four triple-finger resonators is 5.2 mm, the cells, however, are arranged in an interleaved configuration as can be seen in the inset photograph of Fig. 5. An antenna (*"Antenna 1"*) was designed and realized with these structures [15], resulting in a similar radiation diagram as in Fig. 4, but with wider beamwidths (3.3° × 3.8°) and a maximum gain of 31.6 dB only (but with slightly higher bandwidth). Major reasons for this are higher ohmic losses due to the narrow side elements and increased phase angle and polarization errors for increasing angle of incidence towards the antenna edges, see Fig. 6, which is largely related to the big cell size.

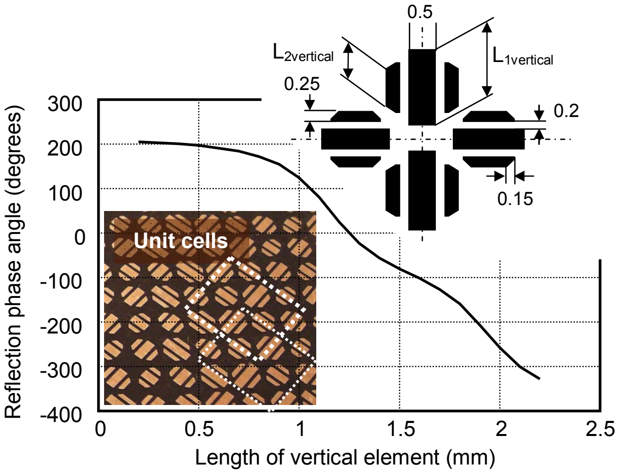

Fig. 5 Layout and phase angle curve (vertical polarization) as a function of vertical length for a modified reflector element. According to the symmetry, the phase angle for horizontal polarization can be adjusted independently by the horizontal length. The inset photograph shows a section of a reflectarray with such elements.

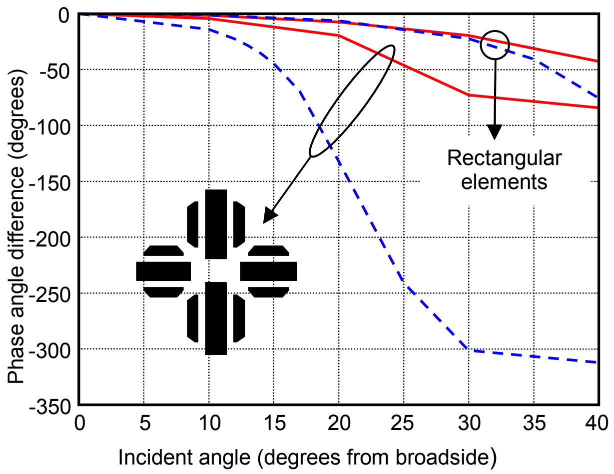

Fig. 6 Phase angle curves as a function of incident angle for simple rectangular elements (Fig. 1, bottom) and crossed three finger elements. Solid line: TE incidence, dashed line: TM incidence. (Substrate thickness 0.508 mm, $\varepsilon_r = 2.2$)

To reduce the cell size, similar reflector structures were investigated on a dielectric substrate with higher permittivity ($\varepsilon_r = 3$). In this way, the involved resonators get smaller. In addition, also the edges of the main resonators were mitered so that neighboring resonator structures could be placed closer together, resulting in a reduction of unit cell size to 4.6 mm. An antenna based on such elements (*"Antenna 2"*) results in beamwidths of 3.7° and 3.3° and a maximum gain of 31.1 dB with a considerable decay towards higher frequencies (Fig. 8). One reason for the lower gain is the larger loss tangent of this material.

Finally, a further modification was introduced. With many PTFE substrates, the interface between substrate and metallization is roughened to ensure a good bonding strength of the metal, leading to increased losses from surface currents at the rough interface. In the new approach as indicated in Fig. 7, the metallization has been etched on a thin substrate ($h = 0.127$ mm, $\varepsilon_r = 2.2$), this was then bonded face down on a 0.508 mm thick substrate ($\varepsilon_r = 3$). In this way, the main surface current is flowing on the much smoother top side of the metallization, reducing current losses [16]. Furthermore, as the reflector elements are embedded in the dielectric, cell size could be further reduced (4.4 mm), and the smaller side resonators are slightly wider as well. This antenna (*"Antenna 3"*) exhibits beamwidths of 3.6° and 3.2° and a maximum gain of 32.2 dB, being closer to the reference antenna, although the loss tangent of the base substrate is again higher than that of the reference antenna.

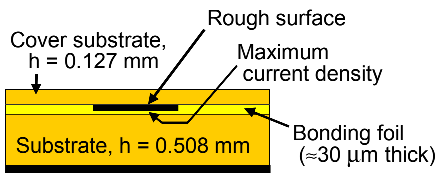

Fig. 7 Substrate configuration of covered reflector element.

IV. Comparison of the Antennas and Evaluation of Loss Contributions

In the following, these four antennas are compared in more detail, and different loss mechanisms are evaluated. At first, Fig. 8 displays the gain of all antennas as a function of frequency. Gain was measured at intervals of about 20 MHz and averaged over 10 frequency samples. It also should be mentioned that the reference antenna and the antenna 1 were realized on a substrate with a loss tangent of 0.0009, the other ones (partly) with a tanδ of 0.0013.

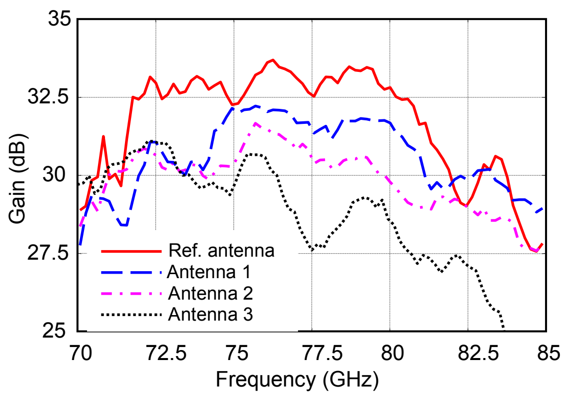

Fig. 8 Antenna gain as a function of frequency for the four tested antennas.

To identify loss contributions in more detail, some calculations were done based on the measured antenna characteristics; these data hold for a reasonable range around the center frequency (± 2 … 3 GHz), but may deviate further away:

- Influence of beamwidth: For this, theoretical gain values were calculated from the beamwidths using the approximate formula $G = 27000/(\Delta\Phi*\Delta\Theta)$, with $\Delta\Phi$ and $\Delta\Theta$ being the 3 dB beamwidths in the two planes in degrees. In fact, this formula already includes a "standard" level of sidelobes, but in this context, the resulting value is used for gain relations only. Based on this formula, the loss in gain compared to the reference antenna is determined.
- Influence of the power in the sidelobes: The radiation diagrams of reflectarray antennas with circular aperture are, to a first approach, rotational symmetric. Based on this assumption, the percentage of power in the sidelobes can be estimated by an integration over solid angle using the principle plane radiation diagrams.

Concerning the main beam, all three novel antennas exhibit a wider beamwidth accounting for additional losses in gain in the range of 1 dB. Looking at the far-off side-lobe levels of the reference antenna, this drops to about -45 dB at ±90°, while the respective value is around -40 dB for the other antennas. This, however, accounts for only about 0.1 … 0.2 dB of additional losses compared to the reference antenna. In this case, also the reference antenna suffers from some losses compared to a standard reflector antenna. What is much more difficult to check are the losses due to depolarization at the reflectarray – due to the diverging phase angles of the TE and TM wave at offset incidence, the polarization twisting deteriorates. Waves in the wrong polarization are reflected by the grid in front of the antenna (the polarization purity of the complete antenna still is good), but according to the underlying phase angle errors, these may be scattered around and even leave the antenna at the open sides. Together with phase angle errors, losses due to disturbed polarization twisting towards the antenna edges may reduce the effective antenna aperture. A first near-field check [17] of the reflectors of the reference antenna and antenna 1 alone indicate strong polarization errors for antenna 1 in those areas where a phase angle change of 360° occurs.

Some improvement seems to be possible also for the reference antenna applying the configuration with overlay substrate, but of course at the expense of additional fabrication complexity.

TABLE I
Summary of the data of the test antennas

		Ref. antenna	Antenna 1	Antenna 2	Antenna 3
Maximum Gain (dB)		33.7	31.6	31.1	32.2
Beamwidths (degrees)		3×3.2	3.3 ×3.8	3.3×3.7	3.2×3.6
$\frac{27000}{\Delta\Phi \cdot \Delta\Theta}$	Abs. (dB)	34.5	33.3	33.4	33.7
	G/G_{ref} (dB)	-	-1.2	-1.1	-0.8
Power in sidelobes	(%)	10	12	13	14
	Loss(dB)	0.45	0.55	0.6	0.65

V. Conclusions

Loss contributions have been investigated for four different designs of reflectarray antennas. Major contributions come from phase errors, resulting in increase of beamwidth and higher (far-off) sidelobe level. Some improvements concerning current losses seem possible by a specific overlay structure transforming the major current density away from the rough interface between metal and substrate.

References

[1] J. Huang, *"Microstrip reflectarray,"* IEEE Antennas and Propagation Society International Symposium, 1991. AP-S 1991, pp. 612 -615.

[2] R. D. Javor, X.-D. Wu, K. Chang, *"Design and performance of a microstrip flat reflectarray antenna,"* Microwave and Optical Technology Letters, Vol. 7 (1994), No. 7, pp. 322 - 324.

[3] D. M. Pozar, S. D. Targonski, H. D. Syrigos, *"Design of millimeter wave microstrip reflectarrays,"* IEEE Trans. on Antennas and Propagation, Vol. AP-45 (1997), pp. 287 - 296.D. Pilz and W. Menzel, "Folded reflectarray antenna," Electronics Letters, vol. 34, no. 9, pp. 832–833, Apr. 30, 1998.

[4] W. Menzel, D. Pilz, R. Leberer, *"A 77 GHz FM/CW radar front-end with a low-profile, low-loss printed antenna,"* IEEE Trans. on Microw. Theory Tech., Vol. 47, No. 12, pp. 2237 – 2241.

[5] W. Menzel, D. Pilz, and M. Al-Tikriti, *"MM-Wave Folded Reflector Antennas with High Gain, Low Loss, and Low Profile,"* IEEE AP Magazine, June 2002, pp. 24 - 29.

[6] J. A. Zornoza , R. Leberer, M. Moraga, J. A. Encinar and W. Menzel, *"A folded 3-layer printed reflectarray with shaped pattern for LMDs central station sectored antenna,"* IEEE Int. Symposium on Antennas and Propagation, Monterey, USA, July 2004, Vol. 1, pp. 5 - 8.

[7] Ansoft Designer 5.0.2, ANSYS Inc., Canonsburg, PA, USA, 2010.

[8] M. R. Chaharmir, J. Shaker, M. Cuhaci, and A. Ittipiboon, *"Broadband reflectarray antenna with double cross loops,"* Electronics Letters, vol. 42, no. 2, pp. 65–66, Jan. 19, 2006.

[9] M. R. Chaharmir, J. Shaker, M. Cuhaci, A. Ittipiboon, *"A Broadband Reflectarray Antenna with Double Square Rings as the Cell Elements,"* 1st European Conference on Antennas and Propagation (EuCAP), Nice, France, 2006.

[10] D. Cadoret, L. Marnat, R. Loison, R. Gillard, H. Legay, and B. Salome, *"A dual linear polarized printed reflectarray using slot loaded patch elements,"* in Proc. Second European Conference on Antennas and Propagation EuCAP 2007, Nov. 11–16, 2007, pp. 1–5.

[11] K. H. Sayidmarie and M.E. Bialkowski, *"Investigations into Unit Cells offering an increased Phase Range for Single Layer Printed Reflectarrays,"* Microwave and Optical Technology Letters, Vol. 50, No. 4, April 2008, 1028-1032.

[12] M. R. Chaharmir and J. Shaker, *"Broadband reflectarray with combination of cross and rectangle loop elements,"* Electronics Letters, vol. 44, no. 11, pp. 658–659, May 2008.

[13] M. E. Bialkowski, A. M. Abbosh, and K. H. Sayidmarie, *"Investigations into phasing characteristics of printed single and double cross elements for use in a single layer microstrip reflectarray,"* in Proc. IEEE Antennas and Propagation Society International Symposium AP-S 2008, Jul. 5–11, 2008, pp. 1–4.

[14] S. Dieter, C. Fischer, W. Menzel, *"Single-Layer Unit Cell with Optimized Phase Angle Behavior,"* Third European Conference on Antennas and Propagation, 2009, Berlin.

[15] W. Menzel, J. Li, and S. Dieter, *"Folded reflectarray antenna based on a single layer reflector with increased phase angle range,"* in Proc. 3rd European Conference on Antennas and Propagation EuCAP 2009, Mar. 23–27, 2009, pp. 2757–2760.

[16] G. Fischer, University of Erlangen, Germany, personal communication.

[17] S. Dieter, W. Menzel, *"High-resolution probes for near-field measurements of reflectarray antennas,"* IEEE Antennas and Wireless Propagation Letters, Vol. 8 (2009), pp. 157 – 160.