Folded Reflectarray Antenna Based on a Single Layer Reflector with Increased Phase Angle Range

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***Abstract*— Simple elementary cells for reflectarrays based on a single dielectric layer exhibit only a limited phase angle range not covering the complete 360° range, whereas multilayer substrate arrangements are not acceptable for some commercial applications with high pressure on cost. Therefore, this paper reports investigations on novel elementary reflectarray cells suitable for folded reflectarray antennas, resulting in a flat phase angle slope over geometrical dimensions as well as a phase angle range of more than 500°. A test antenna and a reference antenna with simple rectangular elementary cells were designed, built, and tested. Although the novel antenna exhibits slightly higher losses, it had a larger bandwidth and better performance at frequencies above the design frequency.**

I. Introduction

Printed planar reflectarrays [1 - 7] 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, 5] which have already been implemented into an automotive radar.

A typical printed reflectarray consists of a dielectric substrate with printed microstrip antenna patches connected to a section of transmission line providing the necessary phase shift, or of printed metal elements which adjust phase simply by their geometry, for example rectangular patch structures. The patch antenna approach can, in principle, adjust arbitrary phase shift values, according to the length of the connected transmission line, but the microstrip patch antennas always are operated in resonance, leading to increased losses. On the other hand, a disadvantage of single-layer reflectarrays with simple rectangular patches is a reduced phase angle range of only 300° … 320° which may affect antenna performance. Phase angle range may be increased by using a thinner dielectric substrate, but this leads to a very steep phase angle slope as a function of element size and, consequently, to high fabrication accuracy requirements, critically for mm-wave applications. A thicker substrate, on the other hand, results in a flatter phase angle behavior, but at the expense of a further reduced phase angle range. This problem can be overcome by dual or triple layer reflectarrays [5, 6]. The underlying principle are coupled resonances thus doubling or tripling the available range of phase angles. For some application, however, like in automotive radars, such multilayer substrates with their increased fabrication effort and cost are not acceptable.

A solution of this problem is the realization of coupled resonators on a single layer. Recently, some modified structures have been proposed for an increased phase angle range for a single polarization, e.g. [8, 9], or for polarization dependent antennas in the form of double cross loops [7].

In this paper, the idea of coupled resonators on a single layer is extended to structures where phase angles can be adjusted independently for the two polarizations to finally allow a 180° phase shift between reflected waves in the two orthogonal polarizations, and consequently realizing elements including a 90° polarization twisting necessary for folded reflectarray antennas [4].

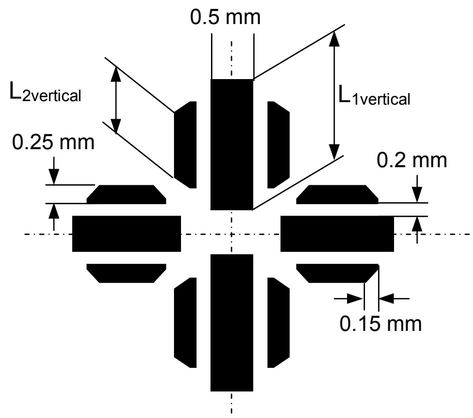

Fig. 1: Proposed reflectarray cell (L_{2vert}= 0.5 L_{1vert}, cell size 5.2 mm, substrate thickness h= 0.508 mm, ε_r= 2.22, frequency 76.5 GHz).

II. Novel Reflector Element

A novel elementary cell arrangement to fulfill the requirements as described above is shown in Fig. 1. It consists of four resonators with three patches each. Symmetry is maintained in both planes as well as within the partial structures to avoid unwanted depolarization effects. The corners of outer dipoles are mitered to allow a more compact setup. The vertically oriented dipole structures affect vertical, the horizontal ones horizontal polarization. Compared to previous single layer reflectarrays with simple rectangular patches [4], substrate thickness is doubled – for the 77 GHz frequency range as considered in the following, substrate thickness will be 0.5 mm. The ratio of the lengths of central and parasitic side resonators was optimized for optimum phase angle performance, i.e. a monotonic, flat phase angle versus length. As simulations [10] show, the respective reflection phase angle can be adjusted nearly independently for the two polarizations. Fig. 2 presents the reflection phase angle for an infinite periodic structure of such elements, covering a range of more than 500° with a relatively flat slope.

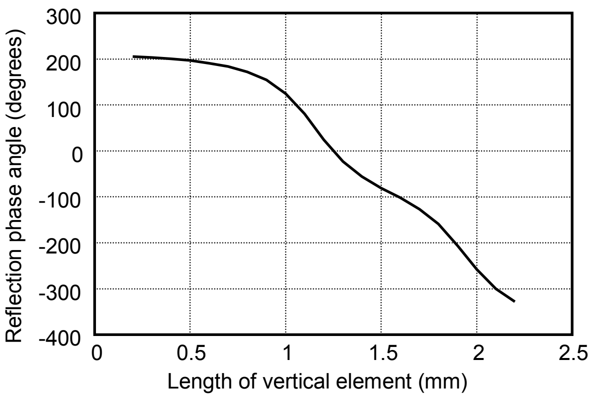

Fig. 2: Reflection phase angle of the structure in Fig. 1 for vertical polarization as a function of L_{1vert}. (L_{1horiz} = 1.2 mm, f = 76.5 GHz).

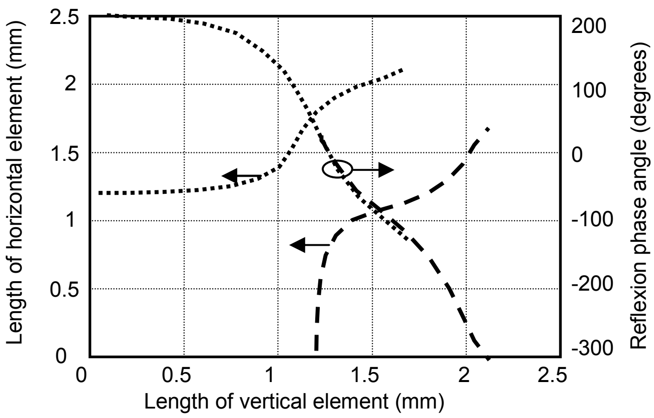

Fig. 3: Phase angle and length ratio including 180° phase shift between the two polarizations (all other dimensions as in Fig. 1, f = 76.5 GHz).

By proper selecting the lengths of vertical and horizontal dipoles, combinations can be easily found which provide a phase angle difference of ±180° between the two polarizations, necessary for polarization twisting in the folded reflectarrays. In Fig. 3, phase angle for vertical polarization (right vertical axis) and the corresponding dimension in the horizontal direction (left vertical axis) are plotted. The selection process for suitable geometrical combinations results in two sets of length combinations (according to phase shifts of +180° and -180°) of the central dipoles (L_{1vert}, L_{1horiz}), while the lengths of the coupled, shorter resonators always are related to the center ones by $L_{2x} = 0.5\ L_{1x}$ where "x" represents either the vertical or horizontal direction. Based on these design curves, a folded reflectarray easily can be designed using lengths of the vertical dipoles between 1 mm and 2 mm with a quite moderate slope of the phase angle curve, resulting in relaxed tolerance requirements even at 77 GHz.

III. Test Antennas

To test the novel reflectarray structure, two antennas were designed for a frequency of 76.5 GHz, built, and measured. One of the antennas is based on the novel structures as described above, the other one uses conventional rectangular patched [4] on a substrate of 0.254 mm thickness. The antennas have a reflector diameter of 90 mm and a distance between reflector and a polarizing slot array of 26 mm (Fig. 4). The feed is a circular waveguide and designed to give approximately a -10 dB edge illumination of the reflectarray. For the tests, only the reflectarray was exchanged to be able to compare the two antennas directly. A photograph of the reflectarray with the novel elements is given in Fig. 5.

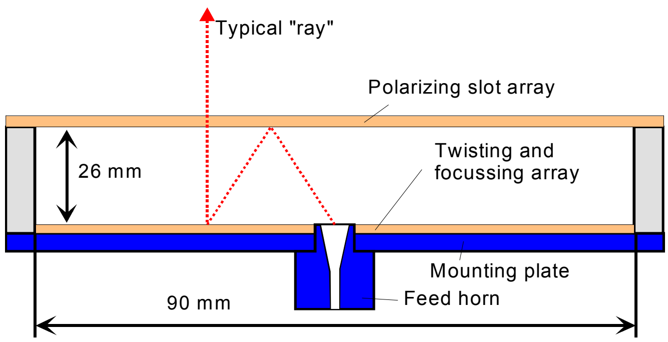

Fig. 4: Cross section of test antennas.

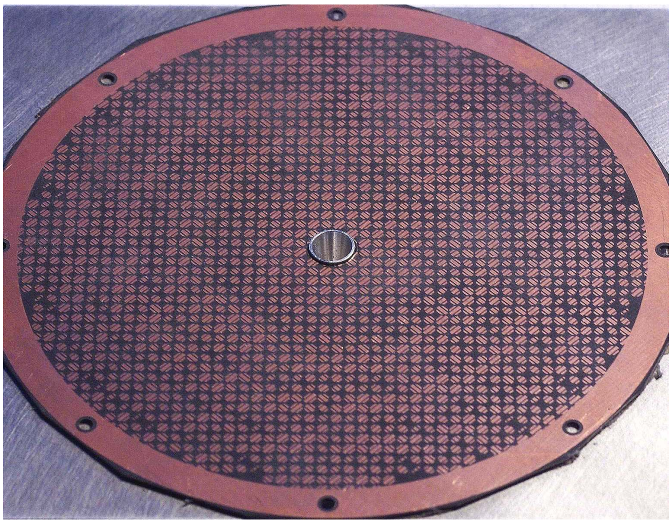

Fig. 5: Photography of the novel reflectarray.

Both antennas were tested in the 70 GHz to 83 GHz frequency range. Fig. 6 shows normalized E-plane and H-plane radiation diagrams of the two antenna at the design frequency of 76.5 GHz. Beamwidths for the novel antenna are 3.8° and 3.6° in the H-plane and E-plane, respectively, and a good maximum sidelobe level of -24 dB can be seen in both planes. The radiation diagrams of the reference antenna (with "conventional" rectangular patches) are very similar to that of the novel antenna, except that beamwidth is slightly smaller (3.4° and 3.2° in H-plane and E-plane, respectively). At the moment, no specific reason for this difference has been identified. Possibly, the difference in phase angle adjustment with gaps in the phase distribution of the reference antenna is responsible for this difference.

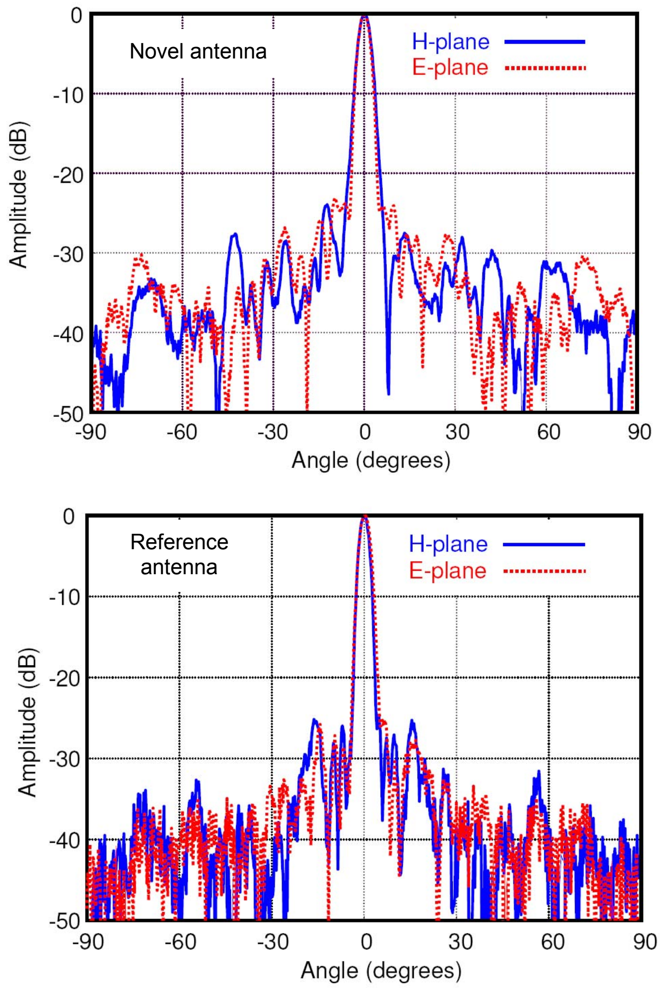

Fig. 6: E-plane and H-plane radiation diagrams of the novel antenna (top) and the reference antenna (bottom) at 76.5 GHz.

Another interesting question is the performance of the antenna as a function of frequency. Figs. 7 and 8 present a comparison of the E-plane radiation diagrams of the two antennas at 72 GHz and 80 GHz, respectively. It was known before that the folded reflectarray antenna with standard rectangular patches typically performs quite good at lower frequencies; this can be observed in Fig. 7, although the novel antenna gives good results, too. Things change with frequencies above the design frequency. Typically, the reference antenna quickly shows an increasing side lobe level – about -13 dB at 80 GHz, while the novel antenna still gives a performance close to that of the design frequency (Fig. 8).

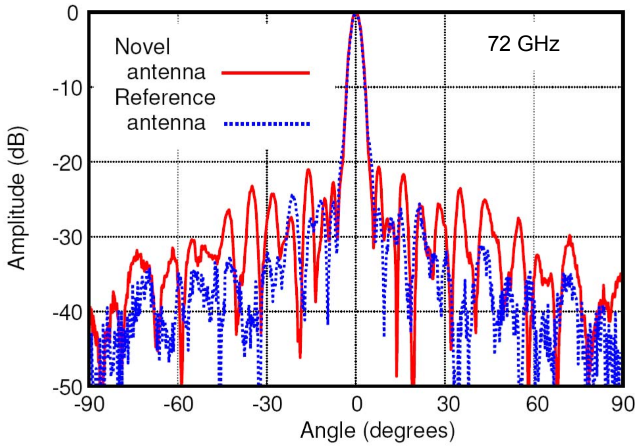

Fig. 7: E-plane radiation diagrams of the novel and the reference antenna at 72 GHz.

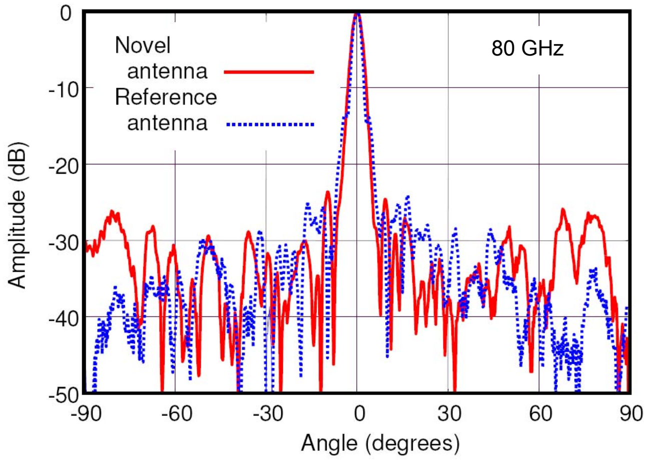

Fig. 8: E-plane radiation diagrams of the novel and the reference antenna at 80 GHz.

The gain of both antennas was measured in the 70 GHz to 83 GHz range using a comparison with a standard gain horn. The resulting values for both antennas are plotted in Fig. 9. In addition, the measured values are interpolated by polynomials using a least squares approximation. Around the center frequency, the gain of the reference antenna is higher than that of the novel antenna by about 2 dB. 1 dB are due to the narrower beamwidth of the reference antenna, and another dB is due to increased losses of the novel antenna, as the elements are quite narrow strips leading to higher current densities. Concerning the 3 dB gain bandwidth, the novel antenna exhibits 10.2 GHz compared to 9.2 GHz of the reference antenna. In addition, as shown above, the novel antenna performs better with respect to sidelobe level in the higher frequency range.

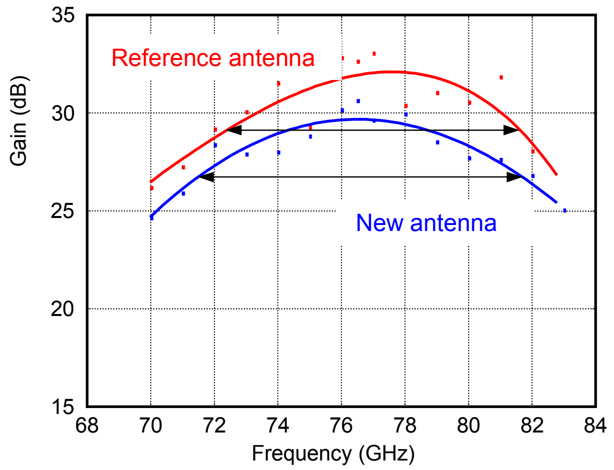

Fig. 9: Gain of the novel and the reference antenna. Dots are measured values, the curves are polynomial approximations based on a least squares method.

IV. CONCLUSIONS

As has been shown in this paper, novel elementary cell structures for folded reflectarray structure can provide both a flatter phase angle slope as well as a wider phase angle range covering more than the required 360°. Two test antennas with a center frequency of 76.5 GHz were realized – one antenna with the novel elementary cells, one with standard rectangular patch elements as reference antenna – tested, and compared to each other. Although the novel antenna exhibits a slightly lower gain due to increased losses, bandwidth is improved, and the antenna performance is improved towards higher frequencies (lower sidelobe level).

Presently, alternative structures are under investigation which might exhibit reduced losses.

In addition, the novel reflectarray elements as applied to the test antenna use a fixed ratio between the lengths of central and parasitic dipoles in each cell; this in principle can also be modified to optimize the performance of the cells over frequency [11]or with respect to other design parameters [12].

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