Single-Layer Unit Cells with Optimized Phase Angle Behavior

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Abstract— **In this paper, single-layer coupled FSS reflection type-structures for reflectarrays are investigated resulting in an increased phase range and smaller slope of the phase angle as a function of structure size. Their improved performance is also demonstrated with three test reflectarray antennas using the novel structures.**

I. Introduction

Single-layer FSS reflectors have the advantage of easier fabrication compared to stacked layer structures, but with simple patches, they suffer from a small phase angle range, usually less than 360°, and a huge slope, which leads to higher phase errors due to fabrication tolerances. In this paper, novel single-layer FSS-structures for printed reflectarrays with an extended range and reduced slope of reflection phase angles are proposed. Three types of unit cells are presented, all based on the principle of coupled structures with different resonant lengths. The design frequency is 35 GHz, and Rogers 4003C is used as substrate material. Metallization thickness is 17 µm. Recent investigations on coupled FSS-structures are given in [1]-[3].

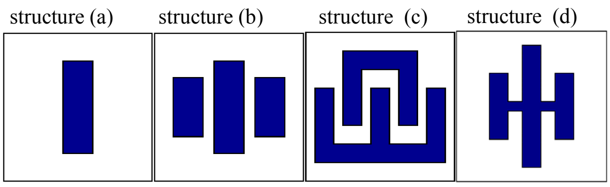


Fig. 1 Reference unit cell (a) and coupled structures (b) to (d) investigated in this paper.

In this work, FSS-structures are analyzed based on a full-wave simulation [4] with the assumption of uniform cells which are repeated and form arrays of infinite size. The phase angle curves for structures (b) to (d) in Fig.1 were optimized in simulations, and also dielectric losses are considered. An interesting point is the influence of geometrical unit cell parameters on the phase angle curve, such as coupling and resonant lengths. The main goals of these investigations are an increased phase angle range, a decreased slope of the phase angle curve and also a reduction of losses.
A standard rectangular patch (Fig. 1a) is used for comparison, exhibiting a phase angle range of 343° for the used substrate and a maximum slope of 1742° per millimeter around the resonant length of the patch. The performance of the novel structures is validated with four reflectarray antennas.

II. Theoretical Background

As a reference, standard rectangular metalized patches are used, with two free parameters l_y and l_x of the patch dimensions (Fig. 2). Here, the length l_y is parallel to the polarization of the incident wave.

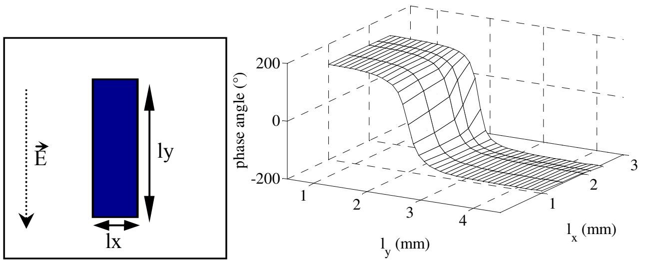


Fig. 2 Reference unit cell (a) consisting of a single-layer rectangular metalized patch and phase angle behavior for Ey-polarization.

The phase angle curve is almost independent of the second parameter l_x perpendicular to the polarization of the incident wave (Fig. 2). So here, the parameter used for phase correction is the patch length l_y.

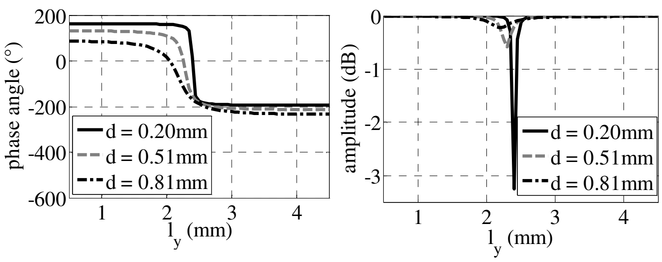


Fig. 3 Phase and amplitude characteristics over length of unit cell (a) for three different substrate thicknesses.

Fig. 3 shows the phase and amplitude characteristics versus l_y for three different substrate thicknesses. In the characteristic phase angle curve, the slope is highest at the resonant length

of the patch. Therefore, patches of these lengths give the main contribution to phase angle errors due to etching tolerances. Amplitude losses are also very high at the resonant length of the patch (Fig. 3). Both the phase errors due to the high slope and the corresponding amplitude losses would decrease, if a smaller slope in the phase characteristics could be achieved.
This is the case when substrate materials with greater thickness are used which can be obviously depicted from Fig. 3. In Table I it is made clear that the substrate with thickness 0.81 mm shows the smallest slope and losses of all. Here, the contribution of metallic losses is smaller than those of dielectric losses, in contrary to thin materials, where metallic losses prevail and the total loss is higher [5]. However, usage of thick substrates reduces the phase angle range, and therefore, again, phase errors occur because of a decreased phase angle range less than 360°.

TABLE I
PHASE AND AMPLITUDE CHARACTERISTICS FOR DIFFERENT SUBSTRATE THICKNESSES

Substrate thickness (mm)	0.2	0.51	0.81
Phase angle range (°)	356	343	320
Maximum phase slope (°/mm)	5420	1742	638
Maximum attenuation (dB)	3.25	0.59	0.22

III. SIMULATION RESULTS

One possibility to reduce the slope and, at the same time, increase the phase angle range is the usage of coupled structures, e.g. on two different layers. For easier fabrication, coupled structures on one layer are investigated here.

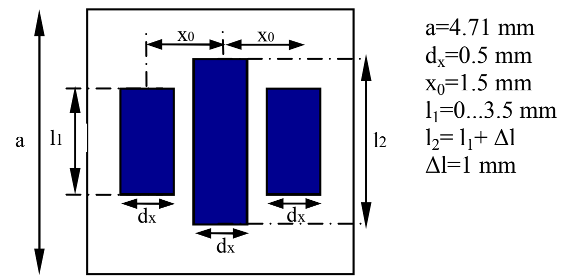


Fig. 4 Unit cell (b) based on a structure with three coupled patches and chosen parameters after optimization.

The first unit cell with coupled structures consists of patches with different resonant lengths as can be seen in Fig. 4. More degrees of freedom compared to one single patch are given by the two patch lengths l_1 and l_2 and the parameter x_0, which has influence on the coupling behavior between the patches. The parameters must not be investigated independently from each other, e.g., the patch width d_x also has an effect on the coupling behavior because of its geometrical dependencies on the slot widths.
Fig. 5 and 6 show the simulation results related to unit cell (b) of Fig. 1. The reflection phase angle and amplitude are shown as a function of the shorter patch length l_1 with a constant length difference Δl between the inner and the two outer patches. A phase angle range of 680° is achieved, and the slope is decreased compared to the reference unit cell (a) of Fig. 1. These results are similar to those of [3], maintaining, however, symmetry for improved polarization performance.
In Fig. 5 the phase angle and amplitude of the reflection coefficient of structure (b) are given for different coupling distances x_0 (Fig. 4) between the three patches. The slope of the phase angle curve at the second resonance is increasing with stronger coupling. The coupled resonators interact and together act like a resonator with higher quality factor. This is also made clear with the reflection amplitude in Fig. 5, where for small distances x_0 higher losses occur for the second resonance as an indicator for higher field strengths and currents.

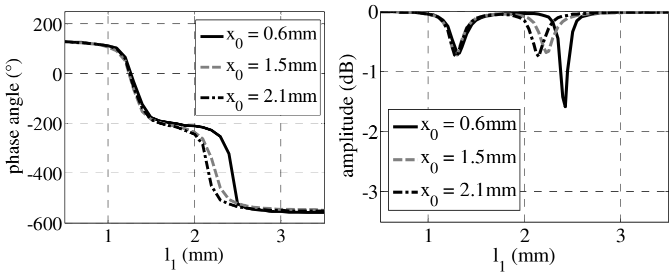


Fig. 5 Phase angle and amplitude over patch length l_1 for unit cell (b) using different patch distances x_0.

Fig. 6 shows the results of the investigation of the length difference Δl between the two patch lengths l_1 and $\Delta l = l_2 - l_1$. By changing the length difference of the two patches, their relative resonant lengths can be moved with respect to each other. The maximum phase angle slope at the resonance point does not change, but the phase curve can be influenced by shifting of the resonance point and therefore optimized for the phase angle region used for antenna design.

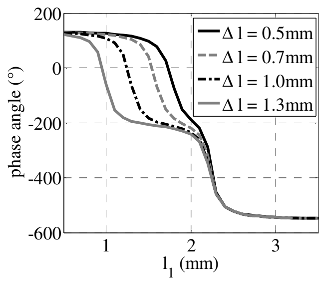
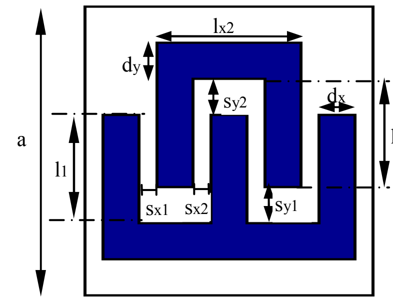


Fig. 6 Phase angle characteristics over the patch length l_1 for unit cell (b) using different patch lengths l_1 and $l_2 = l_1 + \Delta l$.

In structure (c), according to Fig. 7, even more degrees of freedom can be considered due to the multitude of geometrical dimensions within the unit cell. After optimization, this unit cell showed the best performance of all four types, a phase range of 673° and with 999°/mm the smallest slope of all.



a=4.71mm
d_x=d_y=0.5 mm
s_x=0.5 mm
s_{y2}=0.1 mm
s_{y1}=s_{y2}=0.5 mm
l_1=0...2.29 mm
l_2= l_1+ Δl
Δl=1 mm

Fig. 7 Unit cell (c) based on two coupled structures and chosen parameters after optimization.

In Fig. 7, it can be seen, that the geometrical structure has five degrees of freedom: l_1, $\Delta l=l_2-l_1$, s_{y2}, s_{x1}, s_{x2} – the other parameters are fixed by the choice of these five parameters.
As the resonance forms out along the metalized parts in y-direction, the influence of the coupling parameter s_{y2} on the phase angle curve is small (Fig. 8). In contrary, the coupling in x-direction is important for the maximum phase angle slope near the resonant lengths l_1+d_y and l_2+d_y. For smaller s_{x1} the coupling in x-direction increases and the slope of the first resonance point is smaller, whereas the second resonance is steeper for stronger coupling (Fig. 8).

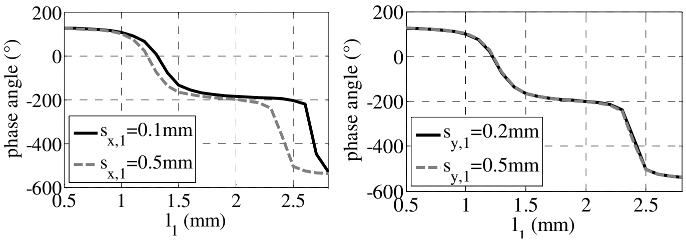


Fig. 8 Phase angle characteristics over the geometrical length l_1 for unit cell (c) using different coupling distances s_{x1} and d_y.

A modification of the length difference $\Delta l=l_2-l_1$ shifts the location of the resonances, analogue to the investigations with unit cell (b).

A further modification of structure (b) leads to structure (d), which can be seen in Fig. 9. In the middle of the structure, a metal patch with a width 0.6 mm and perpendicular to the polarization of the incoming wave is added, acting like a short-circuit. So it is possible to decrease the slope while covering the same phase angle range compared to structure (b), see Fig. 10.

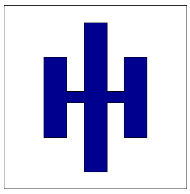


Fig. 9 Structure of unit cell (d) as a modification from unit cell (b), with a cross connection width of 0.6 mm.

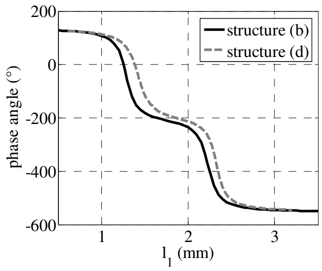


Fig. 10 Phase angle curve of unit cell (d) compared to unit cell (b).

A comparison of the phase angle curves of all four structures is given in Fig. 11. Structures (c) and (d) show the most promising results with respect to extended phase angle curves with reduced slope. An overview is also given in Table II. The phase angle slope could be reduced similar to the case of a thicker substrate, however, the phase angle range could be almost doubled at the same time to more than 670°.

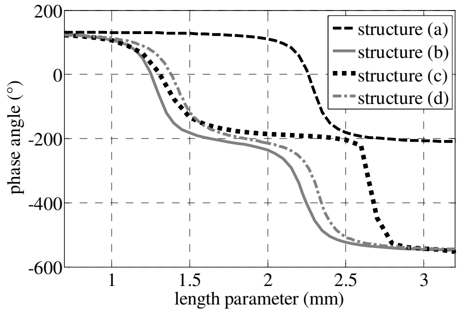


Fig. 11 Phase angle curves for unit cells (a) to (d) for a frequency of 35 GHz and after parameter optimization. Substrate thickness is 0.51 mm, the unit cell dimension is 4.71 mm × 4.71 mm.

TABLE II
COMPARISON OF PHASE CHARACTERISTICS FOR ALL STRUCTURES.

Structure	(a)	(b)	(c)	(d)
Phase angle range (°)	343	680	673	670
1. Resonance slope (°/mm)	1742	1535	999	1190
2. Resonance slope (°/mm)	-	1565	2689	1646

IV. MEASUREMENT RESULTS

To check the influence of the novel reflector structures, four reflectarray antennas have been built with the discussed structures. 24×24 unit cells are printed on the substrate, each of them having a cell size of 0.55 λ_0=4.71 mm for the operating frequency 35 GHz. The used substrate thickness is 0.51 mm. For the design of the reflectarray based on raytracing, the characteristic curves shown in Fig. 11 were used for phase angle correction. The optimized parameters for coupling distances and resonant length differences are given in the corresponding figures (Fig. 4, Fig. 7 and Fig. 9).

Fig. 12 Offset feed antenna for investigation of the structures in farfield measurements.

Fig. 12 shows the offset feed antenna with four exchangeable substrate plates for experimental comparison of the structure types (a) to (d). The phase angle differences of the geometrical paths from the feed to the positions on the reflector plane are compensated by phase angle shifts at the cells of the reflectarray substrate. The assumption of infinite repetition of one unit cell with the same geometrical dimensions was made in the simulations, but is not valid for the antenna: the reflectarray has a finite size and, because of different phase angle correction values for each point on the reflectarray, the geometrical dimensions of the structures vary from one cell to another.

For the raytracing process one degree of freedom is an absolute phase angle offset which can be added to all phase correction values of the single cells on the array, since only the phase angle difference between the unit cells is important but not their absolute value. For structures covering a phase range less than 360°, this phase offset can be used to decrease the number of patches with phase angles needed outside the achievable phase values. For structures (b) to (d) of unit cells covering a phase region more than 360°, the phase offset can be used to avoid, as far as possible, the usage of phase angle regions where losses are high, i.e., near the resonant length of the patches.

As expected by theoretical investigations, the antenna based on unit cell type (c) shows the best performance (Fig. 13) with an increased side lobe attenuation of 20.9 dB compared to 15.4 dB for the reference structure (a) in the E-plane.

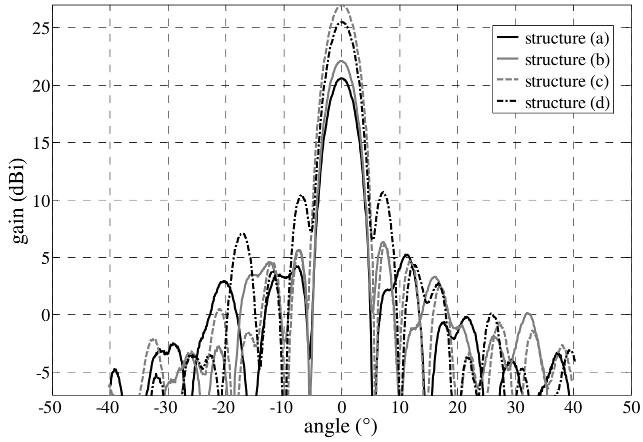


Fig. 13 Farfield measurement results in the E-plane of the offset antenna types based on structures (a) to (d).

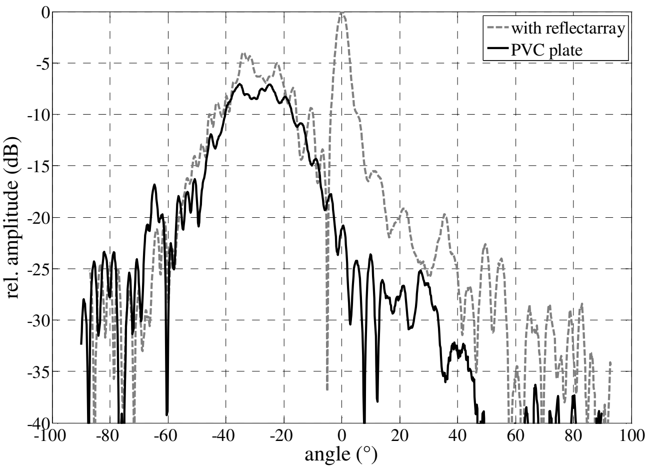


Fig. 14 Farfield measurement results in the H-plane with reflectarray and with just a PVC plate in the same setup.

In the H-plane, farfield measurement results show a high side lobe level. On the one hand, there is the architectural problem of feed blockage in the H-plane. On the other hand, an increased side lobe level at an azimuth angle of -30° is observed. This additional signal component in the farfield shows the characteristics of the feed horn, which means, there could possibly be a specular reflection for this angle. This signal component is also observed by measurement of just a PVC plate without substrate in the same setup (Fig. 14). It is no specific phenomenon of the substrate, because it was noticed both in measurements with other substrate materials and in measurements of different unit cell types. Of course this has an influence on the antenna gain which is compared in the overview in Table III.

TABLE III
FARFIELD MEASUREMENT CHARACTERISTICS FOR ANTENNAS BASED ON UNIT CELL MODELS A) TO D) .

	E-plane			
Structure	**(a)**	**(b)**	**(c)**	**(d)**
3-dB-bandwidth (°)	4.7	4.7	4.8	4.6
Gain (dB)	20.6	22.1	27	25.5
Side lobe attenuation (dB)	15.4	15.8	20.9	14.8
	H-plane			
Structure	**(a)**	**(b)**	**(c)**	**(d)**
3-dB-bandwidth (°)	4.4	4.1	4.2	3.9
Gain (dB)	19.9	21.8	25.7	25.3
Side lobe attenuation (dB)	5.6	8.5	13.7	13.9

V. CONCLUSION

The basic investigations on structures with rectangular metalized patches show the restriction of a phase angle range of less than 360° and a huge slope of the phase angle curve near the resonant length of the patch. By the use of thicker substrate materials, the phase angle range becomes smaller, but its slope and losses decrease. With different types of unit cells based on the principle of coupled structures, however, it is possible to both enlarge the phase angle range and to reduce the slope of the phase angle curve. Therefore, phase errors due to unrealizable phase angle values and due to fabrication tolerances can be reduced. Unit cell (c) shows the best performance of all four investigated types, a phase angle range of 673°, and the smallest slope of all. Four offset feed antennas were built to demonstrate the performance of reflectarrays designed on the principle of these unit cells.

These structures show the benefits of an increased phase angle range and small phase angle maximum slope at the same time, regardless of the chosen substrate material. Phase errors are reduced due to both fabrication tolerances and limited phase angle ranges less 360°.

The principle of coupled resonators can also be applied to thicker substrates and even increase the benefit. In this case the enlarged phase angle regions of these structures still will allow to provide a phase angle range of over 360°. At the same time, even smaller phase angle slopes can be achieved due to the principle of coupling and the thick substrate material.

If only the use of thin substrates is possible in an application, the phase angle curve can be flattened, and its maximum slope is reduced by coupled structures. So the main disadvantage of thin substrate materials can be reduced.

ACKNOWLEDGEMENT

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