# Design of a Folded Reflectarray Antenna Using Particle Swarm Optimization

Sabine Dieter[1], Christoph Fischer, Wolfgang Menzel

*Institute of Microwave Techniques, University of Ulm*
*D-89069 Ulm, Germany*
[1]sabine.dieter@uni-ulm.de

*Abstract*— **In this paper, a method for design and optimization of folded reflectarray antennas is proposed based on Particle Swarm Optimization (PSO). In addition to such a powerful optimization algorithm, two further requirements have to be fulfilled. The first one is a good and fast algorithm for the exact prognosis of the farfield radiation diagram, resulting from a specific element configuration on the reflector. Additionally, a good choice of the fitness function for the evaluation of the resulting radiation diagrams is necessary. In both, reflectarray related aspects such as phase truncation, reflection losses and cell discontinuities have to be considered. Antenna optimization based on this technique is presented in this paper at the example of two 77 GHz folded reflectarray antennas. The efficiency of this approach is demonstrated with these examples, and the results are verified by measurement, showing an excellent agreement with the specifications of the diagram masks.**

## I. INTRODUCTION

Planar reflectarray antennas [1] show the advantages of compact size, low weight, reduced cost and easy fabrication. The principle of folded reflectarray antennas [2] is illustrated in Fig. 1. The input wave from the feed is reflected at the polarization grid. Then, a second reflection occurs, this time on the lower reflector, which is designed as an array of reflector elements, e.g. metallized rectangular patches on a backside-metallized substrate. Due to a polarization twist on the array, the wave then passes the polarization grid. Additionally, the reflection elements act as phase shifters, which compensate for free-space phase delays and add specific phase angles. In this way, a multitude of farfield diagrams can be synthesized.

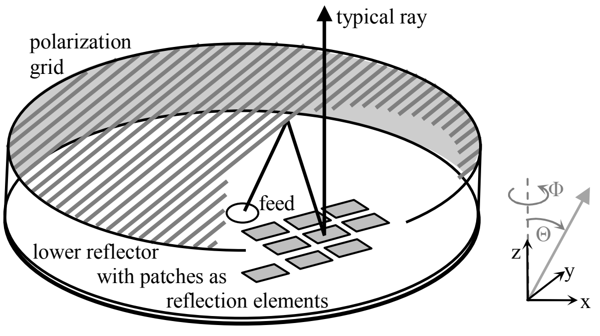



Fig. 1 Principle of a folded reflectarray antenna.

The principle of the presented optimization process for the reflectarray antenna is shown in Fig. 2. In the first step, the antenna diagram is calculated for a set of input parameters, which will be discussed in Section II. The resulting output diagram *F* should be very accurate, as the whole further proceeding will depend on the results. The difference between the desired antenna diagram (specification mask) and the calculated intermediate results is evaluated by the fitness function, see Section III. If the achieved diagram fulfills the antenna requirements given by the mask, the actual configuration could be chosen to be the final design, this would terminate the process. Otherwise, in the next iteration, the diagram calculation is restarted with a new set of input parameters. The criteria for the chosen new parameters are based on the respective optimization algorithm and also depend on already achieved results from previous iterations. The features of the used algorithm are explained in Section IV.

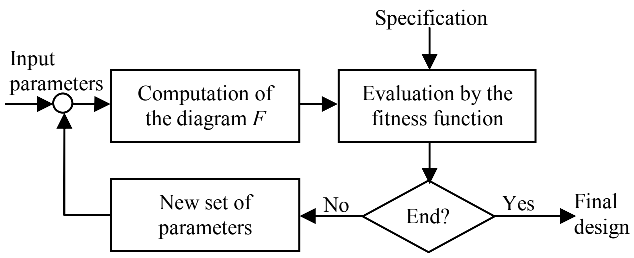



Fig. 2 Optimization process of the antenna.

## II. COMPUTATION OF THE ANTENNA DIAGRAM

Besides the chosen optimization algorithm, the realistic prediction of an antenna diagram, resulting from a given configuration of the reflector, is an important requirement for the whole process. For this purpose, a mathematical tool has been developed for the diagram extraction, which makes use of the following steps:

- The free-space phase delay of the incident electrical field on the lower reflector is calculated by quasi-optical raytracing.
- The amplitude of the incident electrical field on the lower reflector is determined. Therefore, the radiation pattern of the feed, has been incorporated in the quasi-optical model [3].
- The complex reflection coefficient for each patch on the reflector surface is computed by use of a Frequency-Selective-Surface (FSS) simulation tool [4]. Dependant on the FSS unit cell, not all phase angles can be realized. Each phase angle corresponds to a certain return loss.

According to these points, both the phase angle as well as the amplitude distribution are considered where the amplitude depends on the feed illumination and the reflection amplitude of each reflectarray cell. Tests have shown that especially the amplitude of the illumination has an important influence and must not be neglected in order to get a realistic estimation of the resulting farfield diagram.

To take into account the effect of the element diagram of each reflector element, a correction factor $cos\Theta$ is multiplied with the resulting group diagram $F_{Group}(\Theta,\Phi)$:

$$F(\Theta,\Phi) = cos\Theta\cdot F_{Group}(\Theta,\Phi) \quad (1)$$

This factor $cos\Theta$ is only a simplified assumption of the element diagram of a single patch on the reflector. However, this approximation is sufficient, as can be seen in the comparison between the simulated and measured antenna diagram (Fig. 3) of a folded reflectarray antenna with design criteria also used in Section V.

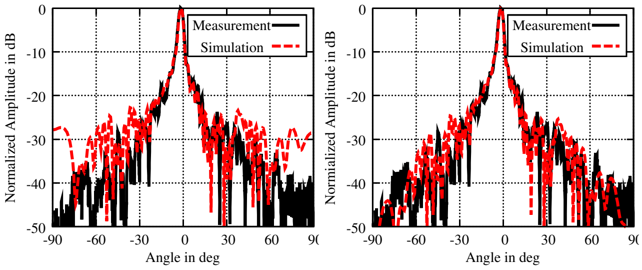



Fig. 3 Comparison between measured and simulated results of a folded reflectarray antenna without (left) and with diagram correction by the element factor (right).

## III. Fitness Function

The definition of the fitness function is an important factor for the quality of the final optimization result. Here, the fitness function evaluates the farfield diagram resulting from a given configuration of the reflector structure, as shown in Fig. 2. The output parameter is a scalar value, which stands for the deviation between the achieved diagram and an ideal reference mask.

An example of a pencil beam farfield diagram and a corresponding mask is given in Fig. 4. The fitness function evaluates the gain of the antenna, its 3 dB-beamwidth and the sidelobe suppression as well. Here, the evaluation is done by upper mask limits (e.g. -30 dB in the marked region of the sidelobes in Fig. 4.) and lower mask limits – for the pencil beam diagram in Fig. 4, only a lower limit in the region of the main beam is reasonable. The angular position of this mask determines the beamwidth.

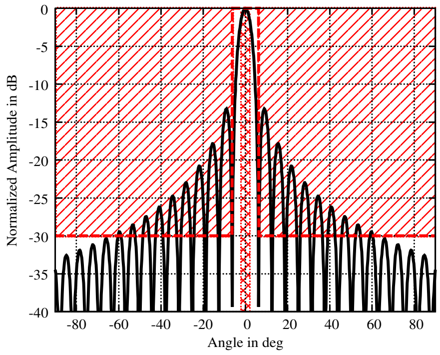



Fig. 4 Example of the antenna mask for a pencil beam diagram.

Besides the farfield diagram, in this work, the fitness function includes an additional criterion for evaluation of the reflector configuration. On the one hand, the design of a reflectarray has the freedom of an overall absolute phase angle offset. On the other hand, the phase angle range of the elements is limited, resulting in phase angle steps of 360° and large changes of geometry. This behaviour is also included in the fitness function, allowing optimal reduction of such large elements variations. Thus, by calculating geometrical differences of adjacent patch elements, the continuity of the geometrical patch dimensions on the reflector surface is taken into account.

## IV. Optimization Process

Particle Swarm Optimization (PSO) was introduced in [5] and [6] as a powerful optimization method, using a swarm of birds as a model for the algorithm. Based on this example given by nature, swarms of particles, identifying possible solutions of a problem, move through the solution space and use personal and group memory in order to find an optimum solution. There exist several publications based on this algorithm presented in [5], only a few important for this work are listed here ([6]-[8]). As this method is applicable in all fields of science, it is also suitable for optimization problems in the microwave area, e.g. in [7].

### A. The Particle Swarm Algorithm

One possibility to illustrate the procedure used in PSO for this reflectarray design, is shown in Fig. 5. Just for explanation, we assume a planar reflectarray with only three elements $j=1,2,3$ on the surface. The possible reflection phase angle values per element ($\varphi_1$, $\varphi_2$ and $\varphi_3$) should cover a region between $0°$ and $360°$ each plotted at the three axes. So all possible solutions for the synthesis, in this simple case, are located in a three-dimensional solution area, which is displayed as a cube.

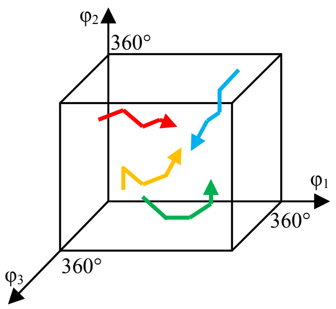



Fig. 5 Simple model for the PSO algorithm, using four particles and an antenna with only three reflection elements, each having a phase angle range of 360°.

The number of particles here is chosen to four ($i=1,2,3,4$). At initialization, they are situated at random position somewhere in the cube, each describing a possible configuration of the reflector for all three phase-shifters.

With each iteration time-step $\Delta t$, the particles move to another location in the cube $\vec{x}_{i,t+\Delta t}$, dependant on their current position $\vec{x}_{i,t}$ and current velocity vector $\vec{v}_{i,t}$ :

$$\vec{x}_{i,t+\Delta t} = \vec{x}_{i,t} + \vec{v}_{i,t+\Delta t}\Delta t \qquad (2)$$

The fitness function evaluates the quality of the solution for the reflector configuration at the particles' new position. All four particles have both a global memory vector $\vec{g}_{best}$ and a personal memory vector $\vec{p}_{best,i}$, containing the position for the best solution of all particles and the own best solutions during their movement in the cube. This stored vectors have influence on the new directions and velocities of the particles:

$$\vec{v}_{i,t+\Delta t} = w\vec{v}_{i,t} + \text{rand}_{[0,1]\times N}\ \tfrac{c1}{\Delta t}\left(\vec{p}_{best,i} - \vec{x}_{i,t}\right) + \text{rand}_{[0,1]\times N}\ \tfrac{c2}{\Delta t}\left(\vec{g}_{best} - \vec{x}_{i,t}\right) \qquad (3)$$

The expression $w\vec{v}_{i,t}$ describes the effort of the particle, trying to keep its old movement stable. Its influence on the total movement is given by the factor $w$.

This trend is changed by the two vectors $(\vec{g}_{best} - \vec{x}_{i,t})$ and $(\vec{p}_{best,i} - \vec{x}_{i,t})$, pointing to the locations of global and personal best memory. Also, their direction is slightly altered by a random vector. This memory influence on the total movement is controlled by the constants $c_1$ and $c_2$. Different values for these constants are used in literature and were also varied for this application. The values used in [7] proved to lead to very good results ($c_1=c_2=1.49445$ and $w=0.729$).

Due to this composition of the velocity vector, the particles' movement resembles that of a swarm, moving towards the optimum solution. This, in many cases, is never reached, but the process is terminated by a chosen maximum number of iteration steps. However, provided a good choice of the fitness function, of the diagram computation, of the values $w$, $c_1$, $c_2$ and of the amount of particles, it is possible to find a very good solution which is very close to the global optimum.

### *B. Boundary Conditions*

One problem within the algorithm is dealing with boundary crossing. By movement to the edge of the cube, particles tend to leave the range of values. In this work, so-called restricted boundary conditions [8] were used. This means, no particle position can exceed its maximum value and leave the cube. Instead, its position is set to the limit in the respective dimension, and its velocity vector will be adapted, so the particle gets the possibility to change its direction and will move back into the cubes' inner area. In tests within this work for antennas with up to $N=2000$ elements, this method turned out to be the most effective solution for the boundary problem.

### *C. Parameter Reduction by Use of Orthogonal Polynomials*

In Fig. 5, an intuitive choice of the parameters for reflectarray antennas is illustrated, by using the obtainable phase angle values of one single element on the reflector for each model dimension. The specification of the antenna with a multitude of single elements would extend this optimization to a problem with about $N=2000$ dimensions.

In [9], an interesting method for the synthesis of linear array antennas is proposed, suitable for direct synthesis methods or for use in optimization algorithms. This principle was adapted within this approach and could reduce the amount of parameters within the optimization process from $N=2000$ to a number of $N<8$. The idea is to describe the continuous phase angle distribution on the reflector surface by a linear combination of $N$ orthogonal polynomials. Instead of optimizing the phase of each element, only the weights of the basis functions, describing the phase distribution on the reflector, are optimized. This rigorously reduces the number of parameters and therefore enforces rapid convergence.

For example, the required phase angle curve to achieve an offset beam diagram can be described by use of the first Chebychev polynomial $T_1(x)$. So the phase $\varphi(x)$ is

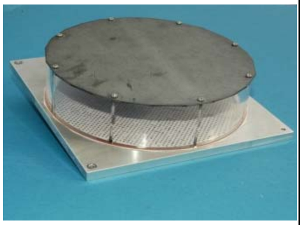
$$\varphi(x)=c_1\cdot T_1(x)=c_1\cdot x \qquad (4)$$

By this parameter modification presented in [9], the intuitive definition of the solution space, according to Fig. 5, is not possible anymore, but it is an effective way to reduce the amount of parameters. In this work, there are two differences compared to [9], regarding the influence of single patches and considering amplitude effects. Besides the optimization using polynomials for describing the phase angle on the reflector, here also the influence of the single elements is considered. In the optimization process (Fig. 2), the choice of a new set of parameters assumes a continuous phase angle distribution on the reflector by use of Chebychev polynomials. On the other hand, the computation of the antenna diagram uses single patch properties, including phase truncation and the magnitude of the reflection coefficient. Additionally, as already mentioned in Section III, in each iteration, the fitness function is evaluating both antenna diagram and the continuity between the cell geometries. So, the large number of reflection elements still has an impact on the optimization time, but does not slow down the synthesis too much. The overall process has the advantage of fast optimization, combined with a better performance due to the consideration of the single patch behavior in the antenna diagram computation and the consideration of the cell geometries.

## V. Measurement Results

The general specifications of the optimized and fabricated folded reflectarray antennas are listed in Table 1.

TABLE I
Specifications Of the Fabricated Folded Reflectarray Antennas

| | | |
|---|---|---|
| frequency | 77 GHz |  |
| reflection elements | ca. 2000 | |
| antenna diameter | 123 mm | |
| antenna height | 30 mm | |
| unit cell size on the array | 2.14 mm × 2.14 mm | |
| antenna diagrams | $cosec^2$ and offset-beam | |

First, we present an antenna design, based on the parameters in Table 1 and $cosec^2$-characteristics. The diagram mask can be seen in Fig. 6. The used substrate is RT-Duroid 5880 from Rogers with a permittivity $\varepsilon_r=2.2$ and a thickness of 0.127 mm.

Fig. 6 shows both the simulation and measurement result of the $cosec^2$-antenna. The optimization routine results in a good matching of specification and measurement. Sidelobe position and level are estimated correctly, and even the amplitude incursions (e.g. at $\Theta=10°$) can already be seen in the simulation.

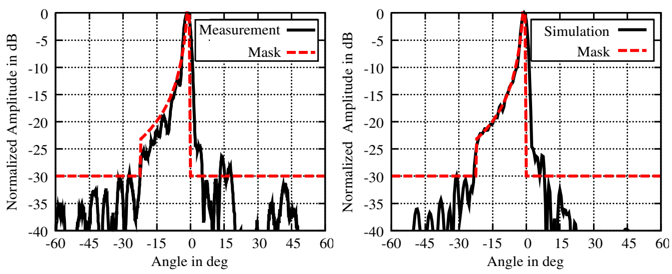



Fig. 6 Comparison between measurement and simulation for the optimized $cosec^2$-antenna at 77 GHz.

Even better results have been achieved for the design of an offset-beam antenna with main beam at $\Theta=-25°$, see Fig. 7. The chosen substrate was RO4003C from Rogers with the permittivity $\varepsilon_r=3.38$ and a thickness of 0.51mm. The results show a very good optimization performance regarding reduced sidelobe level and small beamwidth of the main beam. Fig. 7 also shows a good matching between theory and measurement results. The two curves are almost identical.

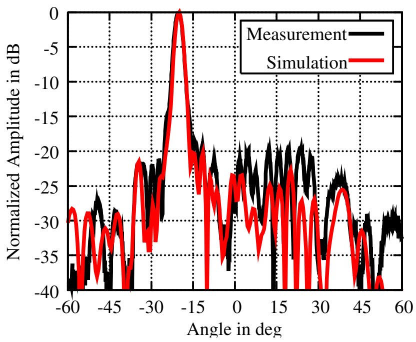



Fig. 7 Comparison between simulated diagram after optimization and corresponding measured diagram for the offset-beam antenna at 77 GHz.

## VI. Conclusions

In this paper, the design and optimization of two folded reflectarray antennas for 77 GHz was presented using Particle Swarm Optimization. It has been shown, that by use of a powerful optimization method, an accurate extraction of the antenna diagram from the reflector configuration and a reasonable choice of the fitness function, convincing optimization results can be achieved.

Besides optimizing maximum power in direction of a main beam, the shape of the whole antenna diagram can be specified, including the sidelobe level or even more detailed profiles, like e.g. a $cosec^2$-characteristic. The functionality of the optimization process is verified by two antenna designs and measurement results for 77 GHz, one offset-beam antenna and one with a $cosec^2$-pattern.

## Acknowledgment

This work has been funded by the German Research Association (DFG) under the contract ME 1016/14-2.

## References

[1] D. M. Pozar, S. D. Targonski, and R. Pokuls, "A shaped-beam microstrip patch reflectarray," *IEEE Trans. on Antennas and Propagation*, vol. 47, pp. 1167-1173, Jul. 1999.
[2] W. Menzel, D. Pilz, and M. Al-Tikriti, "Millimeter-wave folded reflector antennas with high gain, low loss, and low profile," *IEEE Antennas and Propagation Magazine*, vol. 44, pp. 24-29, June 2002.
[3] P. Feil, W. Mayer, and W. Menzel, "A 77 GHz eight-channel shaped beam planar reflector antenna," in *3rd European Conference on Antennas and Propagation (EuCAP)*, pp. 1320-1323, Mar. 2009.
[4] ANSYS, *Ansoft Designer 5.0.2.,* ANSYS Inc., Canonsburg, PA, USA, 2010.
[5] J. Kennedy, and R. Eberhart, "Particle swarm optimization," in *IEEE International Conference on Neuronal Networks*, vol. 4, pp. 1942-1948, Dec. 1995.
[6] M. Clerc, and J. Kennedy, "The particle swarm – explosion, stability, and convergence in a multidimensional complex space," *IEEE Trans. on Evolutionary Computation*, vol. 6, pp.58-73, Feb. 2002.
[7] J. Robinson, and Y. Rahmat-Samii, "Particle swarm optimization in electromagnetics," *IEEE Trans. on Antennas and Propagation*, vol. 52, pp. 397-407, Feb. 2004.
[8] S. Xu, and Y. Rahmat-Samii, "Boundary conditions in particle swarm optimization revisited," *IEEE Trans. on Antennas and Propagation*, vol. 55, pp. 760-756, Mar. 2007.
[9] R. V. Gatti, L. Maraccioli, and R. Sorrentino, "A novel phase-only method for shaped beam synthesis and adaptive nulling," in: *33rd European Microwave Conference*, pp. 739-742, Oct. 2003.