Millimeter wave reflectarrays

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Abstract

This paper is an overview of the mm-Wave reflectarrays developed at the LEAT (University of Nice Sophia Antipolis- France) since October 2004. It addresses several topics: method of conception and design constraints of mm-Wave reflectarrays, influence and limitations of the reduction of the cell size, design and realization of ultra-low lobe reflectarrays by using *prolate* horns, design of simultaneous multi-lobe antenna.
The field of application was initially the collision avoidance radar for to rescue helicopters with a design frequency of 94 GHz. The design concepts have been validated by experimental data.

1. Introduction

MM-Wave reflectarrays have been of increasing interest in the past decade [1]. R&D were pushed forward by the demand for high frequency systems due to the low-frequency spectrum congestion. In addition, the possibility to provide compact platform for high resolution by means of mm-Waves, has motivated their use for radar applications. The most well-known is the 77 GHz automotive radar [2] with a moderate 200-300m detection range whose bandwidth has been recently extended to 76-81 GHz. For long range detection, 94 GHz is better due to the lower atmospheric attenuation [3]. For the antenna designer, the requirements are similar: high gain (min. 30 dBi), low side lobes, low profile, low weight and not to be neglected low cost. The reflectarrays seem to have the better match to these constraints because they combine the advantages of quasi-optic and printed antennas.
The design methods and realizations of reflectarrays have lead to the realization of particularly compact mm-Wave antennas like the folded reflecarray [2], multi-beam antennas ,and also non conventional radiation pattern [4]. Moreover, the problem of the phase range coverage by means of varying the patch dimensions has been intensively studied with the outcome of particular patches shapes [5, 6] at lower frequencies.
This paper will focus on the following topics:

- The method of conception and design constraints of mm-Wave reflectarrays,
- The influence and limitations of the reduction of the cell size,
- The design and realization of ultra-low lobe reflectarrays by using *prolate* horns,
- The design of simultaneous multi-lobe antenna.

The design frequency of the reflectarrays is 94 GHz with single layer rectangular patches. The design concepts have been validated by radiation pattern measurements done in the anechoic chamber of the LEAT.

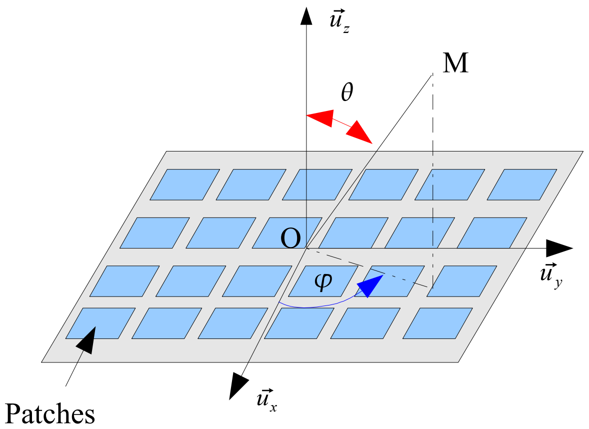
2. Conception and design constraints

The method of conception is close to the one described in [1]. It is based on the association of the determination of reflection phase by the patch using *Ansoft-HFSS,* and an equivalent aperture method for computing the radiation pattern. The design procedure is shown in figure 1, the resulting program is called *apremm* (*ap*erture *re*flectarray *mm*Wave).
The reflectarray is divided into square cells referenced by the integers *(i,j).*The complex amplitude of the far field is computed with the equivalent aperture formula [8]:

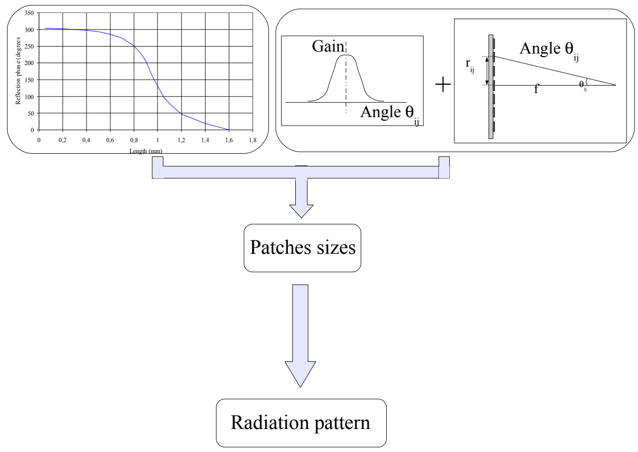
$$\vec{E}_{Ray_{ij}} = 2\mathrm{j}\,\pi\, e\,\frac{-jkr}{r}\,\vec{u}\times(\vec{E}_{TF_{ij}}\times\vec{u}_z) \quad (1)$$

where $\vec{E}_{TF_{ij}}$ is the 2D Fourier transform of the tangential electric field that is assumed to be constant on the cell and whose complex value is given by the radiation pattern of the primary source. The total far field is obtained by the superposition of the electric field of each cell. This simplified method takes into account the primary feed radiation pattern, its aperture blockage, the spillover but neglects the coupling between the cells, the edge diffraction, the ohmic and dielectric losses and the surface waves. In counterpart to the model simplicity, the simulation is very fast while keeping a good accuracy provided that the coupling is not too strong.
In addition to the following considerations, a particular attention has to be given to the fabrication tolerance at mm-wave. Indeed, the small value of the wavelength leads to patch dimensions closed to the fabrication tolerances.

Therefore, the design procedure shown in figure 1 has been modified in order to add some randomly distributed error on the patches dimensions due to the fabrication tolerances as we will see in section 3.



a. Reflectarray cells and spherical coordinates



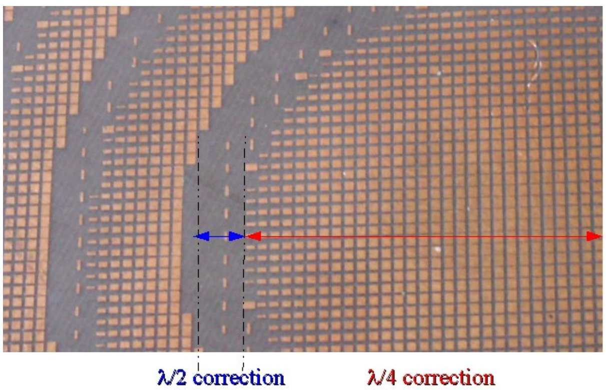
*b. Mode of operation of **apremm***

*Figure 1: Method of conception and related program **apremm***

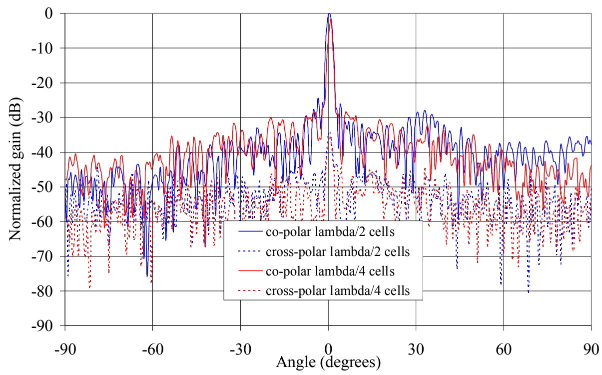
3. Reduction of the cell size

The increase of frequency bandwidth and gain are major issues for the future, especially with the bandwidth extension of automotive radars. One of the solutions consist in reducing the array lattice [8,10]. Usually, the elementary cell of the reflectarray (patch + grounded substrate) is half a wavelength in order to achieve the best compromise between the coupling and the grating lobes. If we reduce the cell size, the phase correction profile will be improved, so does the gain. In the same time, the reflectarray surface differs from a traditional design using near-resonant variable sized patches because their spacings are much smaller than λ/2, this provides also bandwidth enhancement.

The minimum cell size providing gain enhancement has been estimated at (λ/6) by a full-wave simulation with *Ansoft-HFSS* on a small 5λ*5λ reflectarray at 94 GHz. Due to fabrication constraints this reflectarray was made with (λ/4) cells and measured. The simulated gain enhancement, compared to the same array with (λ/2) cells, is 3dB whereas it is 1.5 dB in measurements. In the same time, better scan capabilities were shown with 1dB losses for ±30° scan instead of 3dB for (λ/2). The same principle has been applied to a larger antenna of 130mm diameter. Nevertheless, the phase coverages of a rectangular patches are respectively 320° for (λ/2) and 240° for (λ/4) while keeping dimensions compatible with classical printed circuits techniques. Therefore, we designed a 130m with mixed cells (λ/4 and λ/2) patches (see figure 2.a). Measurement results showed neither gain nor bandwidth improvements compared to the same diameter reflectarray with (λ/2) cells, the radiation pattern at 94 GHz is shown on figure 2.b. In order to explain this, we have chosen a fabrication error within ±50µm and applied the randomly distribution. The resulting antenna gain reduction for the (λ/4) reflectarray is 1dB instead of 0.2 dB for the (λ/2). For the future, the cell robustness toward the fabrication tolerance will have to be taken into account if we want to take advantage of the cell size reduction.



a. Photo of the 130 mm diameter reflectarray (detail)



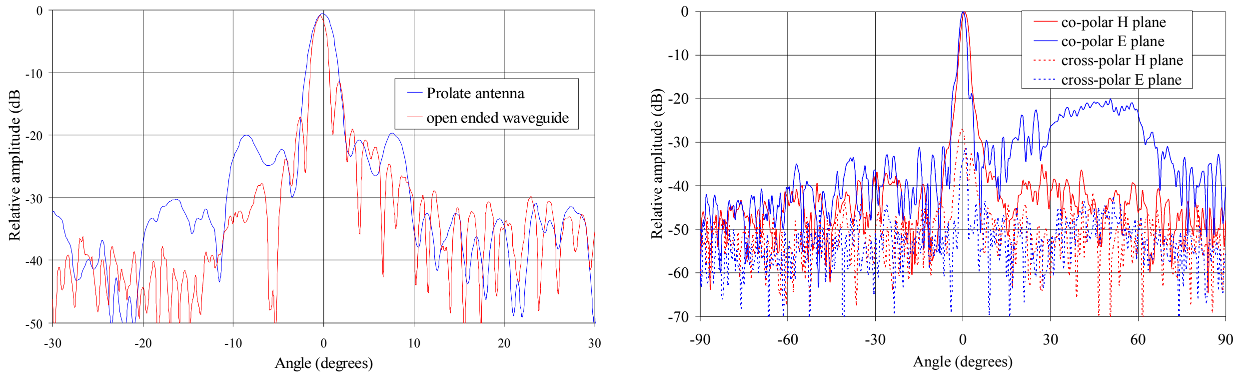
b. Measured radiation pattern at 94 GHz

Figure 2: Influence of the cell size reduction

4. Ultra-low side lobes reflectarrays

According to equation (1), the radiated field by the reflectarray is proportional to the Fourier transform of the tangential electric field, i.e the Fourier transform of the primary feed radiation pattern (if we assume that the reflectarray is in the far field of the primary source, that is, if the focal length is large enough). So the effect of the primary feed on the far field of the reflectarray is comparable to a signal processing windowing. For this purpose we use a primary feed with a radiation pattern corresponding to a prolate function. This function was found in 1961 by Slepian and Pollak [11] and achieves the lowest overall noise at the expense of the main lobe widening [12]. In other words, a diminution of the gain is expected while the “out of main lobe level” of the radiation pattern should drastically decrease. The so-called *prolate* horn is 17.5mm long with an aperture of 8.6mm. More detail can be found in [13].

In order to show the radiation pattern improvement, comparisons were conducted on a 130mm diameter centered reflectarray of focal length over diameter ratio of 0.5. A bent open-ended waveguide as primary source was used, then replaced with the prolate horn. Figure 3.a shows the measurement results at 94 GHz. As expected, the main lobe is widen whereas the near side lobe level is reduced about 10 dB. In the same time, an unexpected increase of the secondary lobes around ±10°appear with the *prolate* horn. It is due to the horn flange (21 mm diameter) that directly faces the reflectarray whereas the open-ended waveguide is bent, thus with reduced aperture blockage. In order to avoid this effect, an offset feed reflectarray was designed. The radiation pattern measurements with the prolate horn are reported on figure 3.b. The side lobe level improvement compared to an open-ended wave guide is 20 dB while the main lobe aperture at -3 dB is increased of 0.3°. On the contrary to the theory, the measured gain is 2dB higher with the prolate horn. We explain it by the improvement of the overall radiation level. In the future specular reflection improvements will have to be worked out.



a. Centered reflectarray at 94 GHz *b. Offset reflectarray at 94 GHz*

Figure 3: Use of prolate horn as primary feed

5. Multi-lobe reflectarrays

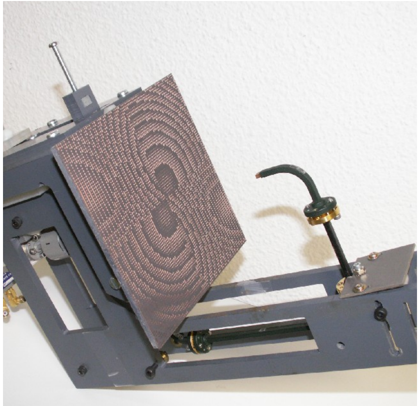
The possibility to have multi-lobes or scanning antennas is of importance for the actual and future generations of automotive radar, and more generally, to increase the radiation pattern agility in order to match the more and more complex requirements assigned to the radar. In order to demonstrate the reflectarray capabilities for this, we have designed a four simultaneous beams antenna working at 94 GHz. For this purpose, the primary feed is a centered open-ended waveguide and the phase profile is calculated with *apremm*. We chose to place arbitrary the four lobes in the φ=45° plane with the four main radiation directions for θ=-30, -0, 10 and 30°. A reflectarray picture and measurements results including comparisons with *apremm* simulations are reported on figure 4. The good agreement shows that *apremm* is a good tool for the design and simulation of such reflectarrays.

6. Conclusion

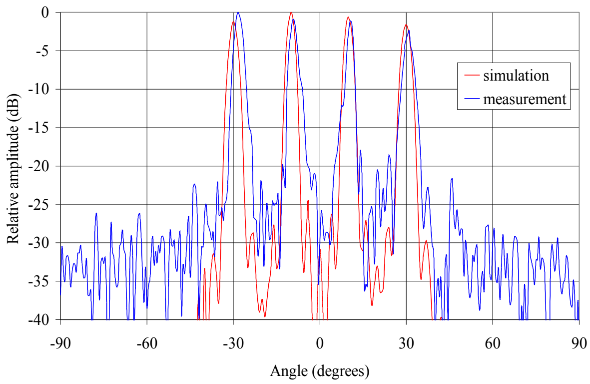
After a short description of the method of conception with the home-made program *apremm* for mm-Wave reflectarrays, this paper we has addressed the following topics:

1. The influence and limitations of the reduction of the cell on the array performance,
2. The design and realization of ultra-low lobe reflectarrays by using *prolate* horns,
3. The design of simultaneous multi-lobe antenna.

The first part has pointed out the limitations of the cell size reduction due to the fabrication constraints but further studies should be continued, especially by using full-wave simulators in order to understand better the behavior of reduced cell size reflectarrays. The second topic has shown the benefit of using so-called *prolate* horns, but the specular reflection level will have to be reduced in order to achieve a real overall low-noise radiation pattern. Finally promising results were obtained on simultaneous multi-lobes reflectarrays. This work has to be continued, especially the frequency bandwidth has to be investigated.



a. Picture of the multi-lobe reflectarray



b. Radiation pattern at 94 GHz

Figure 4: Multi-lobe 94 GHz reflectaray

7. References

1. D.M Pozar, S.D Targonski, H.D Syrigos, *Design of millimeter wave microstrip reflectarrays*, IEEE Trans. Antennas Propagat., vol.45, pp.287-295, february 1997

2. W. Menzel, D. Pilz, R. Leberer, *A 77 Ghz FM/CW radar front-end with a low profile lowloss printed antenna*, IEEE Trans. Microwave Theory and Techniques, vol.47, pp.2237-2241, december 1999

3. B.D. Nguyen, C. Migliaccio,, Ch. Pichot, K. Yanamoto, N. Yonemoto, *W-band Fresnel zoneplate reflector for helicopter collision avoidance radar,* IEEE Trans. Antennas Propagat., vol.55, pp.1452-1456, may 2007

4. J.A Zornoza, R. Leberer, J. Encinar, *W. Menzel, Folded Multilayer Microstrip Reflectarray with Shaped Beam*, IEEE Trans. Antennas Propagat., vol.54, pp.510-517, february 2006

5. P.D. Vita, A. Freni, G.L Dassano; P. Pirinoli; R.E Zich, *Broadband element for high-gain single-layer printed reflectarray antenna*, Electronics Letters, vol. 43, 8 November 2007.

6. N. Misran, R. Cahill, V.F Fusco, *Design optimization of ring elements for broadband reflectarray antenna*, IEE Proc. Microwave Antennas Propagat, vol.150, pp.440-444, 2003.

7. S. Drabowitch, A. Papiernik, H. Griffiths, J. Encinar, *Modern Antennas*, ISBN: 0412579103.

8. S. Costanzo, F. Venneri and G. Di Massa, *Bandwidth enhancement of aperture-coupled reflectarrays*, Electronics Letters , Vol.42, pp. 1320-1322, 9 November 2006.

9. D.M Pozar, *Wideband reflectarrays using artificial impedance surfaces*, Electronics Letters, Vol.43, pp. 148-149, February 2007.

10. H. Legay, B. Salome, D. Bresciani, E. Labiole, M.A. Milon, L. Moinat, R. Gillard, *Reflectarrays for Satellite Telecommunication Antennas,* EuCAP 2007 : The Second European Conference on Antennas and Propagation, 11 – 16 November 2007, EICC, Edinburg, UK.

11. D.Slepian and H.O Pollak, *Prolate Spheroidal wave functions, Fourier analysis and uncertainty I*, Bell System Technical Journal, vol. 40, pp. 43-64, January 1961.

12. R. Soummer *et al.*, *Prolate apodized coronography: numerical simulations for circular apertures*, Astronomy with High Contrast Imaging, C. Aime and R. Soummer (eds), EAS Publications Series (8) (2003), pp. 93-105.

13. J.Lanteri *et al.*, *Improvement of reflectarrays and lenses radiation pattern byprolate spheroidal functions in W band*, EUCAP 2006 : The First European Conference on Antennas and Propagation, November 2006, Nice, France.