Improvement of Reflectarray Performances at Millimeter Waves by Reduction of the Cell Size

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Abstract—In this paper we discuss the advantages and limitations of reducing the cell size of reflectarrays elements. Reflectarrays have demonstrated their utility at mm-Wave because of their compactness, flexibility and quasi-optical feed that reduces losses. Several applications have been covered such as the automotive cruise control including beam scanning. Most of them use $\lambda/2$ cell sizes. We have investigated and compared performances of reflectarrays with 15 mm and 50 mm diameters using $\lambda/2$ and $\lambda/4$ cell sizes at 94 GHz. Measurements on reduced cell size reflectarrays have demonstrated a loss of 1 dB over 60° beam scanning whereas it is of 3 dB for the $\lambda/2$ structure in the case of the smaller reflector. Nevertheless, this effect is not demonstrated on the largest one because of the phase compensation range that is limited by the variation in the patch dimensions. The maximum corrected phase values are of 320° and 240° for $\lambda/2$ and $\lambda/4$ cells respectively. Furthermore a program based on the ray tracing theory has been developed in order to evaluate the influence of the cell size on the array performances.

1. Introduction

Reflectarrays consist of printed elements, typically patches or dipoles representing the elementary cell of the array. They are designed to scatter the incident field, coming from a feeding antenna, with the proper phase required to form a planar phase surface. They have been developed in the millimeter-wave domain since over 10 years [1] in regards to their low profile and low cost. Most of the classical array characteristics have been studied in order to obtain beam scanning [2], or high aperture efficiency both for linear or circular polarization [3]. Efforts have been made for finding appropriated patch shapes for increasing the variation of the reflected phase, the bandwidth or the fabrication simplicity [4, 5].

In this paper, we investigate the influence of the cell size on the gain and beam scanning performances. The elementary cell consists in a rectangular patch printed on a thin substrate. As the patch shape is not the aim of this work, it has been chosen in order to be simple to design regarding to the cell size variation. The first section describes the measured performances of two small reflectarrays with cell sizes of $\lambda/2$ and $\lambda/4$ respectively, at the operating frequency of 94 GHz. In the second section, a program based on the ray tracing theory is presented and tested on different structures in order to demonstrate the effects of the cell size reduction. Finally limitations are discussed.

2. Influence of the Cell Reduction on a 15 mm Diameter Reflectarray

Two reflectarrays of 15 mm diameter were designed and measured at 94 GHz. They are chosen to be small (about 5λ) in order to avoid the effect of the phase compensation limitation. Indeed, when frequency increases, it becomes difficult to cover 360° of reflection phase with a square patch since its dimensions become too small to be fabricated by classical printed circuit techniques. One solution could be to use sophisticated lithography, like the one based on glass mask. It drastically increases the fabrication cost, thus decreases the competitivity of reflectarrays toward other high gain antenna systems such as dielectric lenses or parabolic reflectors.

The primary source is a standard WR-10 open waveguide that radiates a power pattern that can be approximated by $\cos^5(\theta)$. Considering the spillover and taper efficiencies relations given in [1], a diameter to focal length ratio of 2 provides spillover and taper efficiencies of 87 and 89% respectively. Thus focal length is chosen to be of 7.5 mm. Figure 1(a) and (b) show the upper side of the two reflectarrays. Patch size is optimised by numerical simulations provided by the commercial three-dimensional finite element method solver (HFSS) using the periodic structure module. The substrate is Duroid of dielectric constant 2.2 and 0.381 mm thickness. Phase range compensations are of 320° for the $\lambda/2$ cell and 240° for the $\lambda/4$ one. Nevertheless, due to the small size of the reflector, the number of rings with missing phase values is only of one. Thus their effect is decreased.

Reflectarrays are measured at 94 GHz for a scan angle up to 60° as described in Figure 2. Results are reported in Figure 3(a) and 3(b). A reflectarray with $\lambda/2$ cells performs a loss of gain of 3 dB while scan angle moves. The $\lambda/4$ cells exhibit only 1 dB loss. These results are expected due to the increase of phase accuracy. Additionally, an increase of 2.3 dB is observed on the gain when the cell size is $\lambda/4$.

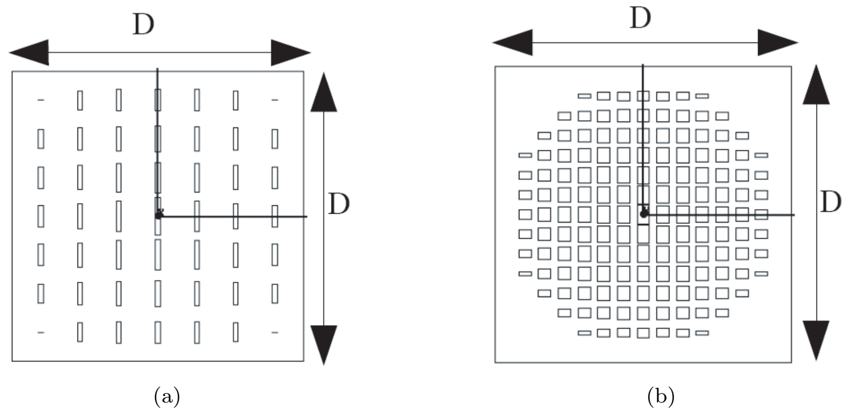

Figure 1: (a)($\lambda/2$) cell, (b)($\lambda/4$) cell.

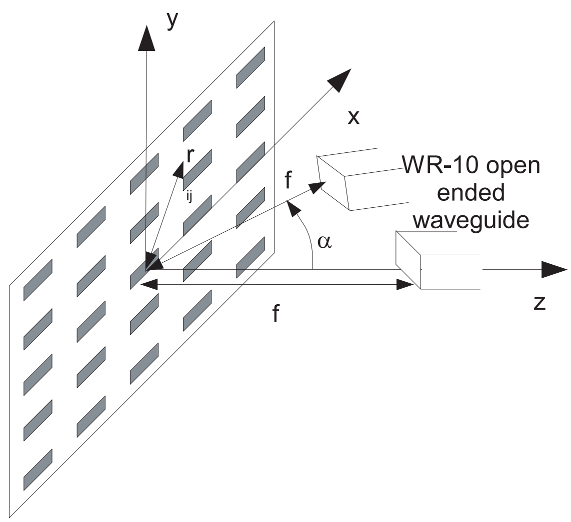

Figure 2: Measurement setup.

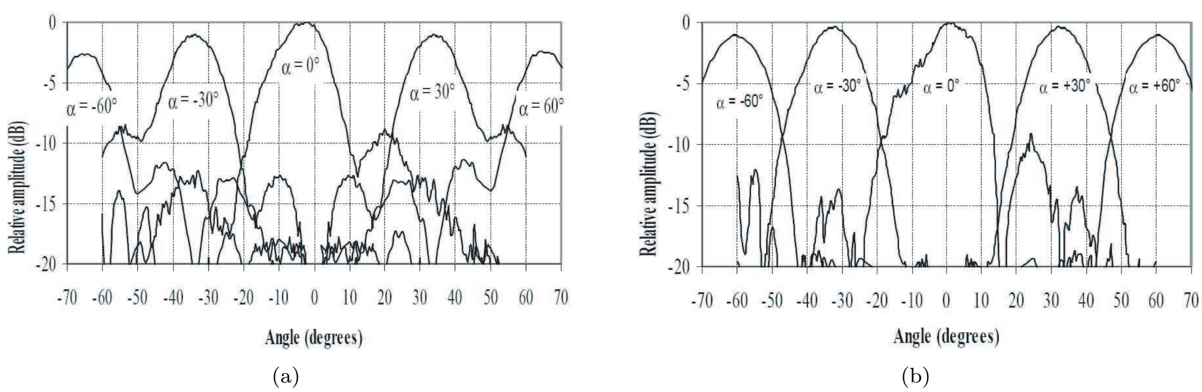

Figure 3: (a)$D = 1(\lambda/2)$ cell size, (b)($\lambda/4$) cell size.

3. Analysis Program

A program based on ray tracing theory was developed in order to investigate the influence on the cell size reduction. It was implemented using Scilab [6]. The surface of the reflectarray is divided into square cells of $\lambda/2$ or $\lambda/4$ size depending on the structure under study. Values of the desired compensation phases are calculated taking into account the directions of incident spherical and reflected plane wave, including offset feeds and scan angles as described in [1]. A complex amplitude coefficient is affected to each cell. Its module is the value of the power pattern described before. The phase is the difference between the formerly calculated one and the compensated one computed by simulations. If the 360° phase could be covered by the square patch, this difference should be of zero in the desired maximum radiation direction. A matrix of complex coefficient is generated. If we denote θ the angle with respect to the z axis described in Figure 2, power density along θ is calculated by making the sum of all the coefficients of the complex matrix for each angle θ. The advantage of using a software as scilab is the possibility to create 3D matrix whose two first dimensions represent the physically 2D reflector and the third one represents the scan angle θ. As a consequence, the time of calculation is reduced. Radiated power is calculated over the power density integration assuming that the radiation pattern is the same over the φ angle. This does not take into account the real primary source radiation pattern such as the square shape of the reflectarray. Radiation pattern is finally plotted after the normalization of the power density by the radiated power. Figure 4 shows the results for the 15 mm reflector. It is obvious that the effect on the beam scanning improvement is the same as the measured one. Gain values are much higher in the simulation. It can be explained by several factors: the simulation does not take into account the primary source blockage, neither the coupling between primary the source and the reflectarray which are both critical in regard to the very short focal length.

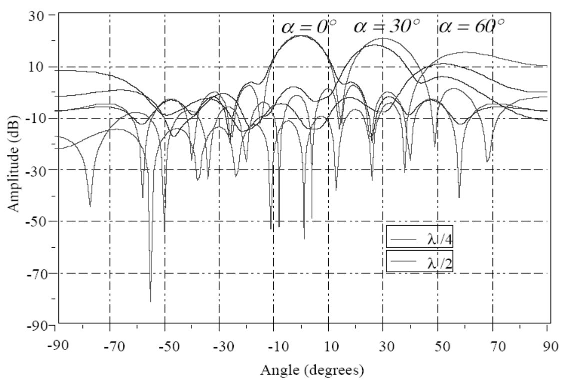

Figure 4: Simulated radiation pattern of the 15 mm reflectarray with different cell sizes.

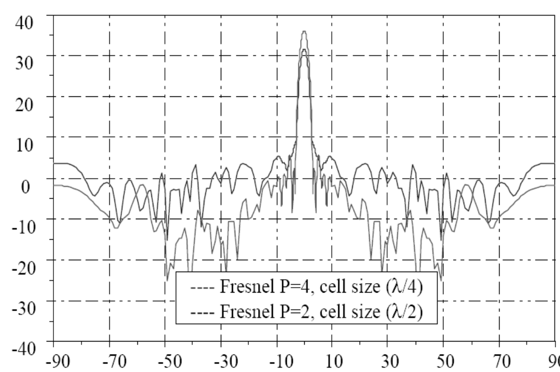

Figure 5: Simulated radiation pattern of Fresnel reflectors with $D = 100$ mm.

The same program is tested on reflector using Fresnel zones phase compensation, whose formula is reminded bellow:

$$R_n = \sqrt{\left(2n\frac{\lambda}{P}\right) + \left(n\frac{\lambda}{P}\right)^2}$$

where R_n is the radius of the Fresnel zone referred to the reflector center, λ the free space wavelength, f the focal length and P the Fresnel correction factor (for example $P = 2$ for a half-wavelength Fresnel reflector). In this case, the effect of the cell size reduction can be seen with different approaches.

First, we consider the effect on size reduction with the same Fresnel correction factor. The improvement of maximal gain is of about 1 dB for a 100 mm diameter half-wavelength reflector.

Second, the space dedicated to each Fresnel zone, defined by $(R_{n+1} - R_n)$ decreases when n increases. As a consequence, high values of P cannot be obtained because the cell size becomes larger than the space for the zone. It can be overcome by using a reduced cell size. The same reflector as described above can be simulated with $P = 4$ if $\lambda/4$ cell size is used whereas cell size of $\lambda/2$ limits P to 2. Results are plotted in Figure 5. The gain increases of 4.4 dB which corresponds to a 50% improvement due to the passage from half- to quarter-wavelength Fresnel reflector enhanced by the cell reduction.

4. Limitations

Larger reflectors of 50 mm diameter have been made and tested without performing the formerly described ameliorations. Considering the limit values of the corrected angles, which are of 320° for the $\lambda/2$ cell and 240° for the $\lambda/4$ one, the program has been modified including this limitation. The number of uncorrected rings increases in comparison to the smaller reflector as shown in Figure 6. Results are plotted in Figure 7. It is obvious that the formerly improvements disappear when the phase compensation range of 360° is not covered.

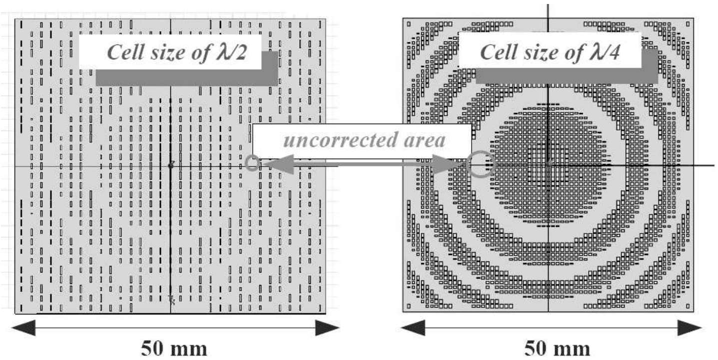

Figure 6: 50 mm diameter reflectors with uncorrected zones.

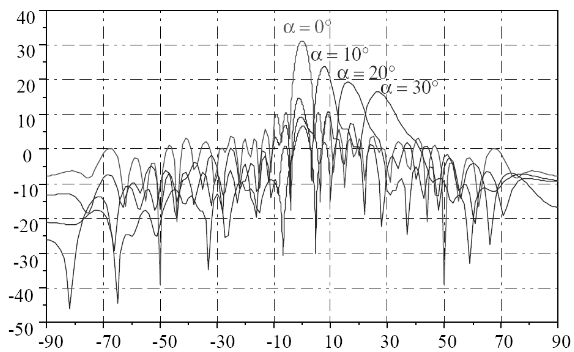

Figure 7: Simulated radiation pattern showing the limitation of cell sizes reduction.

5. Conclusion

We have shown that the cell reduction of reflectarrays provide a gain enhancement and better beam scanning for classical reflectarrays. In case of Fresnel reflectors, the increase of the gain is more important since the cell size reduction enables to increase the Fresnel correction factor P. Nevertheless, making reflectors with cell of $(\lambda/4)$ encounters the difficulty to obtain a phase reflection compensation of 360°, specially at mm-Wave. In this case, performances are strongly decreased. New patch shapes have to be investigated in order to overcome this problem.

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