PHASE ERRORS REDUCTION PROCEDURE FOR NEW ANTENNA SHAPES : APPLICATION TO WIDE SCAN ANGLE MULTI BEAM METAL PLATE LENSES

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1. Introduction

A general procedure to reduce aberrations produced by the focusing element of high-gain antennas is presented. The objective is to design such element with minimum phase errors (aberrations) to reduce side lobe levels for relatively large beam tilt angles (±30°). The procedure, based on Geometrical Optics (GO) principles in association with the Method of Moments (MoM), is described in details in the case of a metal-plate lens antenna (constrained lens), with narrow and wide field of view. The application is intended for automotive radar antennas operating at 76-77 GHz, in short range operation. Third generation of Automatic Cruise Control (ACC) radars have indeed requirements such as compactness and low –cost together with high gain antenna (25-30 dB) having a relatively large field of view. It should ensure both a long-range detection within ± 7° in the main axis and a short-range detection that requires a ± 30° angle tilt (fig. 2). In addition, side lobe levels should typically be below – 20dB for long range system to avoid false detections in any operating detection. Both phase error (aberration) and feeder illuminations are major contributions to increasing side lobe levels. Consequently, optimisation procedures should be considered (see for instance [2]). Metal plate lenses provide a good trade-off between compactness, low-cost process and performances. They include parallel metal plates illuminated by a primary source (feeder) whose electric field must be along the z-axis (fig. 1) to reduce losses. TE_1 mode operation between plates [1] ensures focusing. Hence, the equivalent local refraction index is less than unity. The plates are separated by a foam substrate of constant thickness, which was found to have an optimum value h= 2.4 mm to minimize omhic losses at 76GHz. In this paper, some investigations on this lens are presented with the objective of minimizing aberration effects.

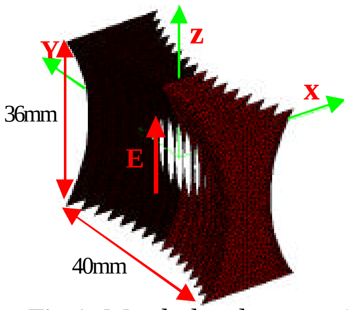

Fig 1: Metal plate lens

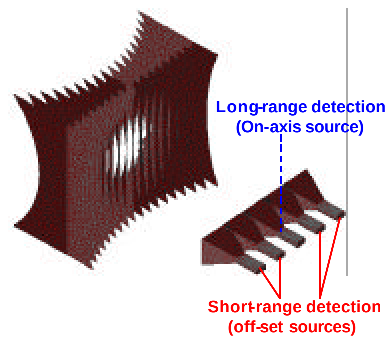

Fig 2: Structure of the antenna

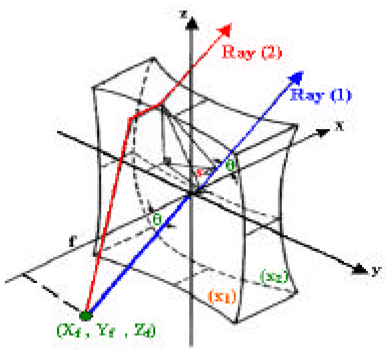

Fig 3: Ray paths of an offset source

2. Geometrical optics approach

The first step of the design is based on the Geometrical Optics (GO) principles. Hence, one has to calculate the optical path difference (OPD) between rays (fig. 2) and then to apply a method in order to minimize the phase error along the field of view. In this system, the primary sources lie in the same plane. In consequence, classical methods to reduce the aberrations (Abbé's sine condition [3], bifocal lens[4]) are limited in terms of compromise between performances and scanning range. Thus a 3D variational method is used in order to minimize the phase error along the total scanning field. The OPD between Ray(1), and Ray(2), is given by the following expression:

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$$\Delta[\mathrm{Ray}(2)-\mathrm{Ray}(1)]=\frac{2\pi}{\lambda}\left[\frac{f}{\cos(\theta)}-\sqrt{(x_1+x_f)^2+(y+y_f)^2+(z+z_f)^2}-n_0(x_2-x_1)+x_2\cos(\theta)+y\sin(\theta)\right]$$

where: n_0: refractive index between the plates, ?: angle of deviation of the primary source, (x_f, y_f , z_f): coordinates of the primary source, f: focal distance, x_1: inner shape, x_2: outer shape.

Let us first present the classical formulations of phase errors obtained by carrying the Taylor development of ? in the case of circular inner and outer lens profiles :

1) Spherical aberration and higher orders varying in $\mathbf{A_1(y^2+z^2)+A_2(y^4+z^4)+A_3(y^6+z^6)+\ldots}$ (independent on ?) produce deeper zero radiation levels and a broader main lobe.

2) Cubic aberration ('Coma') and higher orders $\mathbf{(B_1?y(y^2+z^2)+B_2?y(y^4+z^4)+B_3?^3y(y^2+z^2)+\ldots)}$ introduce the radiation pattern dissymmetry, the increase of the side lobe level on one side only and finally the gain reduction.

3) Astigmatism, field curvature and higher order: $\mathbf{(C_1?^2(y^2+z^2)+C_2?^4(z^2-y^2)+C_3?^2(y^4+z^4)+\ldots)}$ produce the same effects as the spherical aberration.

4) the Distortion factor (free of aberration): $\mathbf{D_1(?y+?^3y+?^5y+\ldots)}$ provokes a tilt of the main lobe.

In order to apply the 3D variational method, let us first remind that ? is zero for a plane wave front inclined at an angle ? (with respect to the y and z axis). Hence, it is desirable to make ? as small as possible for all feed positions and for all ray paths. Then the square of ? may be integrated over the lens aperture dimension, $2y_d$ and $2z_d$, and over the full scan angle, $2?_0$ [5], leading to :

$$\delta=\int_{-y_d}^{y_d}\int_{-z_d}^{z_d}\int_{-\theta_0}^{\theta_0}\Delta^2\left[x_1(y,z),\,x_2(y,z),\,y,\,z,\,\theta,\,\mathrm{constants}\right]d\theta\,dz\,dy$$

where the constants include the parameters of the lens (focal distance, refractive index,…).

The optimisation of the lens profiles is then carried out by assuming:

$$x_1=-f+\sqrt{f^2-a_1y^2-a_2z^2}$$

(which is an elliptical profile) and a polynomial formulation for the outer shape:

$\mathbf{x_2 = b_1y^8+ b_2y^6+ b_3y^4+ b_4y^2 + b_5z^8+ b_6z^6+ b_7z^4+ b_8z^2}$

Then the variables a_m (m=1, 2) and b_n (n=1,…,8) are determined to minimise the phase error. The problem is then reduced to a system of ten equations depending on a_m and b_n:

$$\frac{\partial\delta(y_d,z_d,\theta_0,a_m,b_n)}{\partial a_m}=0 \qquad \frac{\partial\delta(y_d,z_d,\theta_0,a_m,b_n)}{\partial b_n}=0$$

In the case of the following parameters: f = 40mm (focal distance), $2?_0$=60° (scanning angle), $2y_d$=40mm, $2z_d$=36mm (aperture dimension) and by applying the variational process, we obtained :

a_1=0.7938300828, a_2=0.6619998206, b_1=0.417452405x10^{-10}, b_2=-0.3476668444x10^{-7},
b_3= 0.1173992216x10^{-4}, b_4=0.01782319860, b_5=0.99180409x10^{-10}, b_6=-0.67358685x10^{-7},
b_7= 0.161542072x10^{-4}, b_8= 0.02161275828 .

This approach, based on the geometrical optics principles, is a preliminary step to design the shapes of the lens. The diffraction and the interaction effects are not taken into account. A full wave model [6] is then applied for a better accuracy.

3. Optimisation procedure

First, a plane wave is applied on the optical axis, in order to examine the near fields in the main planes. From the field distributions (see fig. 4 and 5), one can conclude that the energy is not focused on the point given by the GO theory, but, due to the spherical aberration, there is a zone of concentrated energy. To have the best choice for the primary source location, one has to detect the maximum E field magnitude on the optical axis (-35mm) (fig. 7). This position corresponds to the circle of least confusion (fig. 6). Once the optimal choice of the feeder is made, one has to find the optimal dimensions of the pyramidal horn used a primary source. According to Robieux's theorem [7] illustrated in fig.6, global efficiency (excluding metallic and mismatch losses) of a focusing system antennas can be calculated as the coupling factor ? between the electromagnetic fields (E_2, H_2), radiated by the primary feed located in the focal plane of the lens and the electromagnetic fields (E_1, H_1) issued from an incident plane wave crossing this lens :

$$\eta = \frac{\left| \int_S (\vec{E}_1 \wedge \vec{H}_2 - \vec{E}_2 \wedge \vec{H}_1) \circ \vec{n} \, dS \right|^2}{16 \, P_1 P_2}$$

where P_1 and P_2 correspond to the power flow in the horn aperture and the power in the focal plane S of the lens, respectively. The efficiency (η) is maximum when the electric and magnetic fields have complex conjugate values. Thus, optimal solution is found when the fields in the aperture match perfectly to that in the focal plane of the lens (same amplitude, opposite phase). To impose these conditions, one has to study first the power distribution in the focal plane (fig. 8). Then, the zone where 80% of the energy is concentrated is used to apply the matching conditions stated by Robieux's theorem. This is done by carrying out a parametric study on pyramidal horn dimensions (a, b, L in fig.8).

In the case of on-axis focusing (used mainly for long-range detection), this process allows reducing the spherical aberration (which is the only existing phase error in this case). In the case of off-axis focusing (used for short-range wide field of view detection), the position of the primary source is given by minimizing the phase errors ('coma' and astigmatism). Note that primary sources are kept in the same plane in order to facilitate the future design of planar circuits including all primary sources.

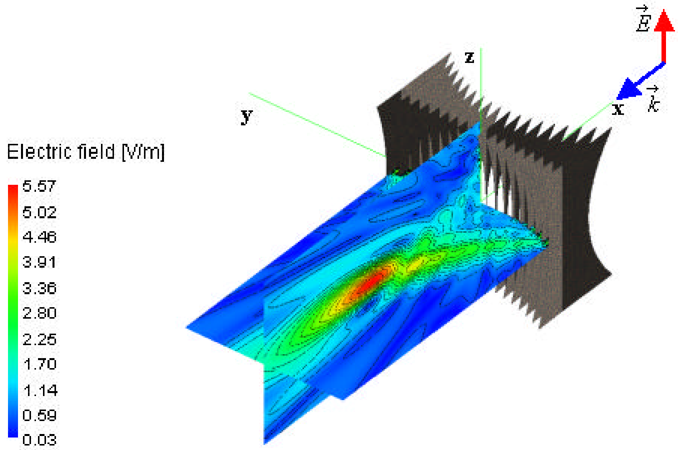

Fig. 4: E field distribution on the XZ and XY planes

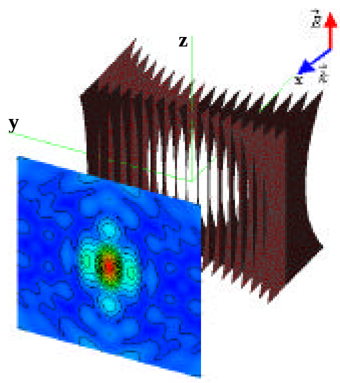

Fig. 5: E field distribution on the focal plane

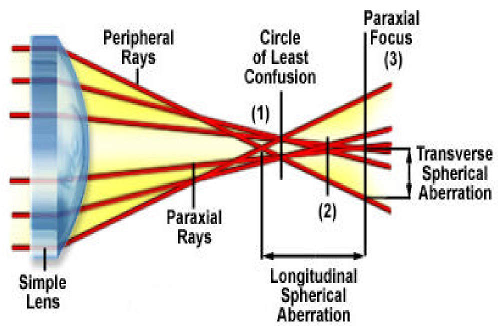

Fig 6: Spherical aberration distribution [8]

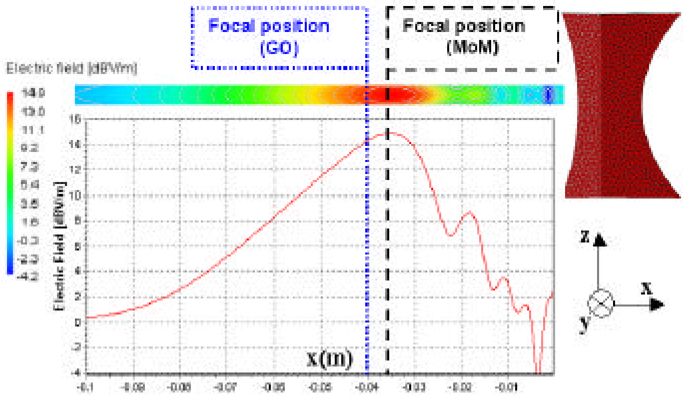

Fig 7: E magnitude along the optical axis (OX)

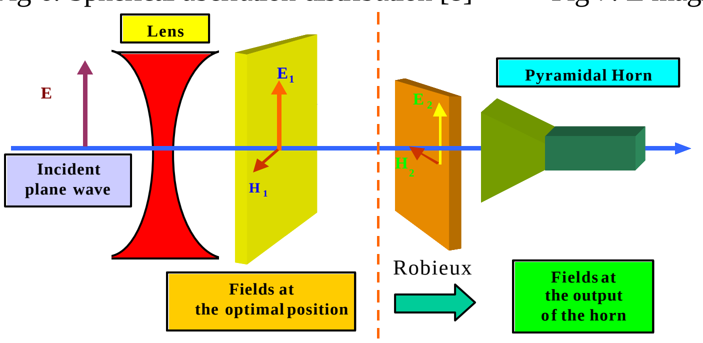

Fig 8: Illustration of Robieux' theorem

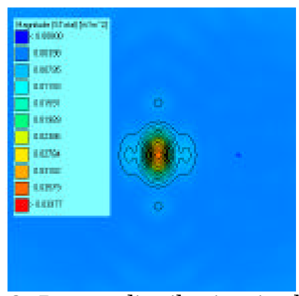

Fig 9: Power distribution in the focal plane

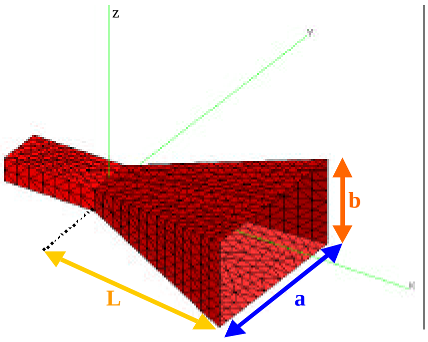

Fig 8: Pyramidal horn dimensions

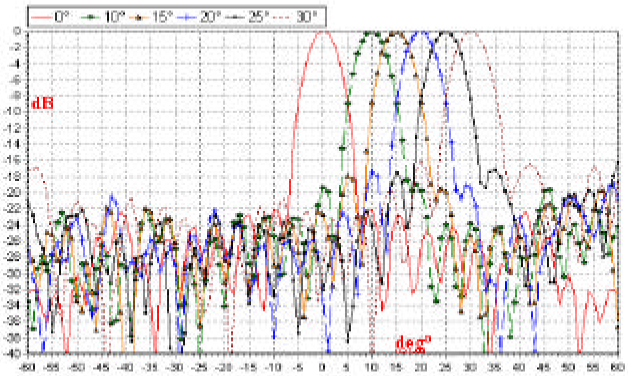

Fig 9 : Radiation pattern in the H plane (FEKO simulations [6])

The parametric study of the horn, leads to a 65% efficiency for the whole system, against 55% for a classic lens without optimisation. Side lobes rejection is around 22dB in both E and H planes, for the feeding horn at 0° (long range operation). For short-range operation, the position of the horn was modified to obtain various beam angles (fig. 9). The optimisation procedure yields an average of 17dB of side lobe rejection in the H-plane.

4. Conclusion

An efficient method to reduce aberrations involved in focusing lenses designed with classical optics was presented. It is based on a variational method to minimise the deviation function related to ray theory. Then, a full-wave approach was used to determine the optimal position of the feeder by applying Robieux's principle to obtain maximum matching between the feeder and the lens. The procedure, although general, was applied to a metal plate lens fed by a pyramidal horn for potential application to an ACC radar antenna at 76 GHz. Results show some substantial improvement as compared to non optimised structures. Current work concerns physical implementation and measurements.

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