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77 GHz Fan Beam Radiation Lens Antenna For Automotive Long-range Applications

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A B S T R A C T

This paper presents an inhomogeneous lens to radiate a control-table Fan Shaped pattern for long-range automotive applications. Fan Shaped pattern of the designed lens covers more angles in azimuth. The proposed circular aperture inhomogeneous lens is designed based on the critical angle theorem. The profile of the dielectric constant of the proposed lens changes in 3 directions of ρ, φ, and z. The lens is matched to the source and surroundings. A closed-form formula is offered for an arbitrary fan-shaped pattern lens antenna. A compact circular lens with a diameter of 20 mm and thickness of 2.25 mm is simulated in CST full-wave software to validate the design structure.

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1. Introduction

In recent years, the use of microwave radars has grown increasingly to improve driving performance. Microwave radars have significant advantages over LIDAR, sonar sensors, and cameras in that they operate accurately in adverse weather and other environmental conditions [1]. Automotive radar operates in the frequency range of 76-81 GHz [2-4]. High range resolution and high allowed equivalent radiated power (EIRP) are two features for using this frequency band in automotive radars. Today, mainly 77 GHz frequency band is considered for long-range applications [5].

Various automotive radars should not add remarkable cost to the car's overall price. Low-cost microstrip antennas are good candidates for the radar antenna [6-8]. Dielectric lenses can also be used to improve the radiation characteristics of the antenna. Dielectric lenses can align the source's beam and shape the radiation pattern. The inhomogeneous dielectric lenses are divided into isotropic [9-11] and anisotropic [12]. Ray inserting method (RIM) [13] is an analytical method based on geometrical optics to design inhomogeneous lenses. The critical angle theorem is discussed in [14] to design an inhomogeneous lens to radiate a directional radiation pattern.

Fan-shaped radiation antennas [15] are useful for short-range applications such as blind spot radars [16]. Generally, the ratio of two orthogonal 3dB beam widths is more than 5:1. The realized gain of a directional antenna is significantly more than fan-shaped radiation antennas. Directional antennas are used for long-range applications. In [17], the hemispherical lens was studied and designed. A pencil radiation beam is radiated to its axial symmetry and the shape of its circular aperture. In [18], a fan beam radiation lens is designed using a semi-elliptical lens so that the width of the beam in the vertical and horizontal planes can be formed separately.

In this paper, to cover more angles in azimuth, we present a directional fan-shaped lens antenna for long-range radar (Fig. 1). The proposed circular aperture inhomogeneous lens is designed based on

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the critical angle theorem. The profile of the dielectric constant of the proposed lens changes in 3 directions of ρ, φ, and z. The proposed lens is matched to the source and surroundings. A closed-form formula is offered for an arbitrary fan-shaped pattern lens antenna.

2. Lens antenna design

A schematic of a circular aperture lens is shown in Fig. 2. The lens' aperture in this paper is circular. Unlike the lens designed in [18], there is no control over the dimensions of the output aperture. Various factors cause a change in the radiation beam width for a fixed-size aperture [19]. The control of the amplitude distribution (such as Chebyshev and Taylor) in the radiation aperture cause higher side lobe levels and broader beam width. The amplitudes distribution has a limited effect on the half-power beamwidth. Non-uniform phase distribution on the radiation aperture increases the half-power beam width. The side lobe levels are highly dependent on the phase distribution. An unusual increase in phase distribution causes an inappropriate change in the radiation pattern [19].

In this manuscript, based on the critical angle theory, we parallelize the rays emitted from the source in the output plane of the lens. Then, by considering a non-linear distribution for the phase of the aperture in each constant φ-plane, we obtain the electric length of the rays and the dielectric coefficient of the lens with changes in two dimensions, i.e., ρ and ϕ. In the following, the dielectric coefficient of the structure will be proposed with changes in three dimensions by creating suitable matching conditions for input and output planes.

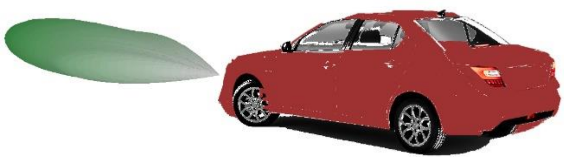

Figure 1: Use of a directional fan-shaped pattern antenna for long-range Automotive radar.

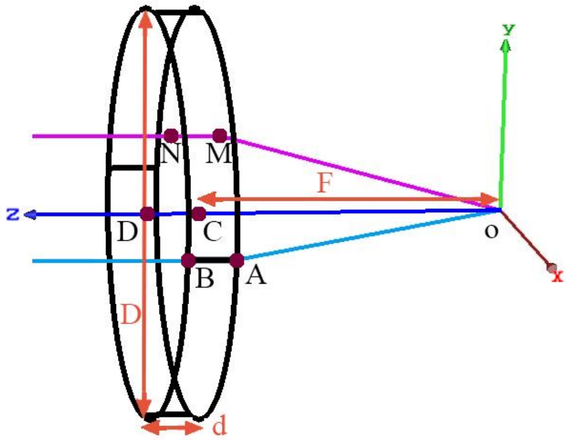

Figure 2: A schematic of a circular aperture lens

A point source is located at the origin and dielectric lens slabs are at a distance of F from the point source (see Fig. 2). A spherical wave is emitted from the source. To have a Fan-shaped radiation pattern, the equal phase distribution is considered for the constant $\varphi = 0$ plane (XZ-plane) of lens, and the phase of other constant φ-planes change with an arbitrary function of $\Phi(\varphi)$.

To create an in-phase wavefront at an angle of $\varphi = 0$, all rays should have the same effective length. If the permittivity on the AB path is considered to be One, the in-phase equation between the longest path (light blue) and the shortest path (dark blue) has been written to obtain the permittivity of the lens's center ($\varepsilon_{rcenter}$).

$$\Delta\varphi(\overline{OA}) + \Delta\varphi(\overline{AB}) = \Delta\varphi(\overline{AC}) + \Delta\varphi(\overline{CD}) \tag{1}$$

So

$$\beta_0 F + \beta_0\sqrt{\varepsilon_{rcenter}}\,d = \beta_0\left(\frac{F}{\cos(\alpha_{\max})}\right) + \beta_0\sqrt{1}\,d \tag{2}$$

where F, d, and D are the focal length, thickness, and diameter of the lens, respectively. β_0 is the wavenumber of the free space, and $\alpha_{\max}$ is $\tan^{-1}\left(\frac{F}{D/2}\right)$. By simplifying (2), $\varepsilon_{rcenter}$ is obtained.

$$\varepsilon_{rcenter} = \left(\sqrt{F^2 + (D/2)^2}\,/\,d + 1 - F/d\right)^2 \tag{3}$$

The effective phase of each ray for having a certain phase distribution at all points of the output plane, i.e., $z = F + d$, can be obtained as follows:

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$$\Delta\varphi(\overline{OM}) + \Delta\varphi(\overline{MN}) = \Delta\varphi(\overline{OC}) + \Delta\varphi(\overline{CD}) + A(\varphi)(\frac{\rho}{D/2})^2 \tag{4}$$

Where $A(\varphi)$ is an arbitrary function of phase distribution at each constant φ-plane. Different distributions are used for the phase of the aperture. In [19], the phase distribution equal to the square of location is proposed as an appropriate model for increasing the half-power beam width in the array antennas. The required permittivity of a flat lens can be obtained as follows:

$$\varepsilon_r(\rho,\varphi) = \left\{ \frac{F}{d} + \sqrt{\varepsilon_{rcenter}} - \frac{\sqrt{F^2+\rho^2}}{d} + \frac{A(\varphi)}{d}(\frac{\rho}{D/2})^2 \right\}^2 \tag{5}$$

$A(\varphi)$ should be symmetric of XZ and YZ planes.

$$A(\varphi) = \begin{cases} \Phi_0(\frac{\varphi}{\pi/2})^2 & for\ 0 \le \varphi < \pi/2 \\ \Phi_0(\frac{\pi-\varphi}{\pi/2})^2 & for\ \pi/2 \le \varphi < \pi \\ \Phi_0(\frac{\varphi-\pi}{\pi/2})^2 & for\ \pi \le \varphi < 3\pi/2 \\ \Phi_0(\frac{2\pi-\varphi}{\pi/2})^2 & for\ 3\pi/2 \le \varphi < 2\pi \end{cases} \tag{6}$$

Where Φ_0 is the maximum phase distribution on the constant $\varphi = \pi/2$-plane. This relative permittivity is independent of Z. For achieving a 3D refractive index and reducing the reflection coefficient of the input and output planes of the designed 2D lens a symmetrically tapered equation is employed for the z direction.

Ultimately 3D permittivity of the lens ($\varepsilon_r(\rho,\varphi,z)$) is obtained as follows:

$$\varepsilon_r(\rho,\varphi,z) = \sin^2\theta_i + (\cos\theta_i + (\sqrt{\varepsilon_r(\rho,\varphi,z) - \sin^2\theta_i} - \cos\theta_i)N(z))^2 \tag{7}$$

Where $\theta_i = \tan^{-1}(\frac{\rho}{F})$ and $N(z)$ is a symmetrically tapered equation. A suitable type of $N(z)$ could be:

$$N(z) = \frac{\pi}{2}\sin(\frac{\pi(z-F)}{d}) \tag{8}$$

3. Simulation

The listed values in Table 1 are considered for the dimension of the lens to simulate at the frequency of 77 GHz. The focal length to the diameter of the lens is considered equal to 0.7. A standard circular waveguide antenna with a diameter of 3.18 mm is used to excite the designed lens as the source. The permittivity profile of the lens is shown in Figs. 3. As can be seen, the maximum permittivity is 7, and the dielectric constant of the designed lens is equal to one in both the input ($z = F$) and output ($z = F + d$) planes, and it varies for constant φ –planes.

Table 1: Parameters for simulating lens structure

F (mm)	D(mm)	d(mm)
14	20	2.25

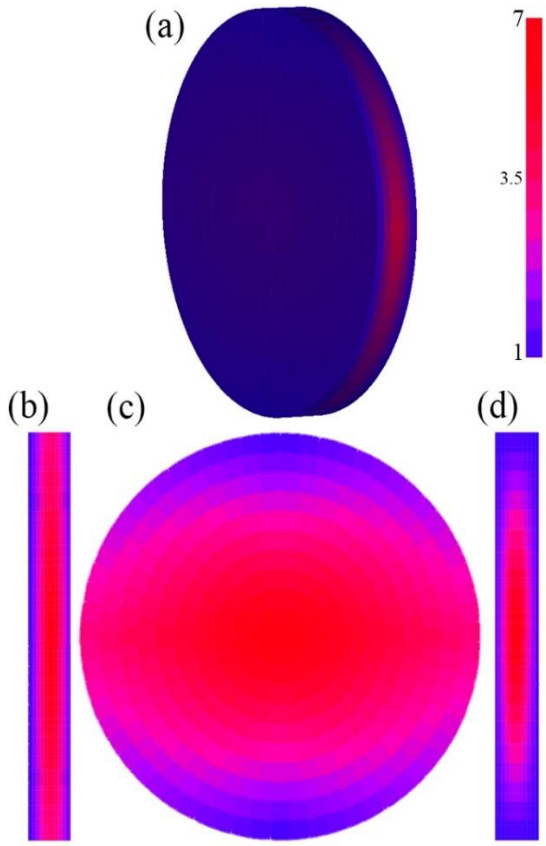

Figure 3: The permittivity profile of the presented lens, a) the 3D model, b) the YZ cut plane, c) the XY cut plane (constant $z = F + d/2$ plane), and d) the XZ cut plane.

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To validate the design procedure, the designed lens is simulated in CST commercial software. Figure 4 shows a view of a set of a lens and a feeding antenna. The reflection coefficient and the realized gain of the lens antenna are shown in Figure 5. It can be seen in Figure 5, the frequency bandwidth of the lens covers the range of 76-81 GHz for automotive applications. This lens has a suitable bandwidth, and this matching is due to the equality of the refractive index of the lens to the environment space. The realized gain of the lens antenna is 21.5 dBi at 77 GHz.

Figure 6 shows the electric field distribution in two XZ and YZ planes at the frequency of 77 GHz. The field in the XZ plane is distributed in-phased in the output plane. But according to the preliminary design, the field distribution in the YZ plane is desired and out of phase. The 3D radiation pattern of the antenna structure is shown in Figure 7.

The polar plot of the azimuth and elevation planes are shown in Fig. 8. The azimuth plane half-power beam width is 18.7 degrees, and the elevation plane half-power beam width is equal to 9.8 degrees. The side lobe level is 17.1 dB. The half-power beam width in the azimuth plane is about twice the elevation plane, which confirms using the presented technique of phase distribution to design a Fan-shaped pattern lens.

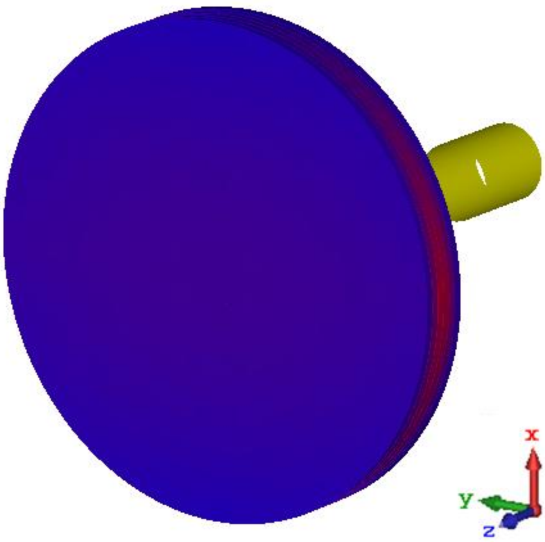

Figure 4: The designed inhomogeneous lens and the position of the feed in front of it

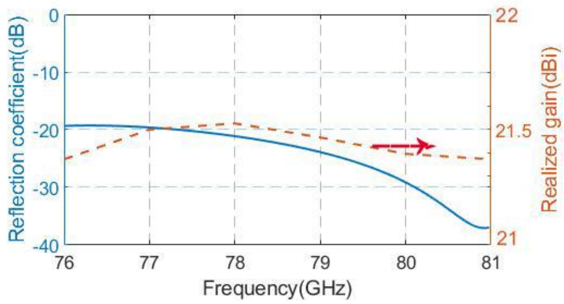

Figure 5: The reflection coefficient and the realized gain of the lens antenna

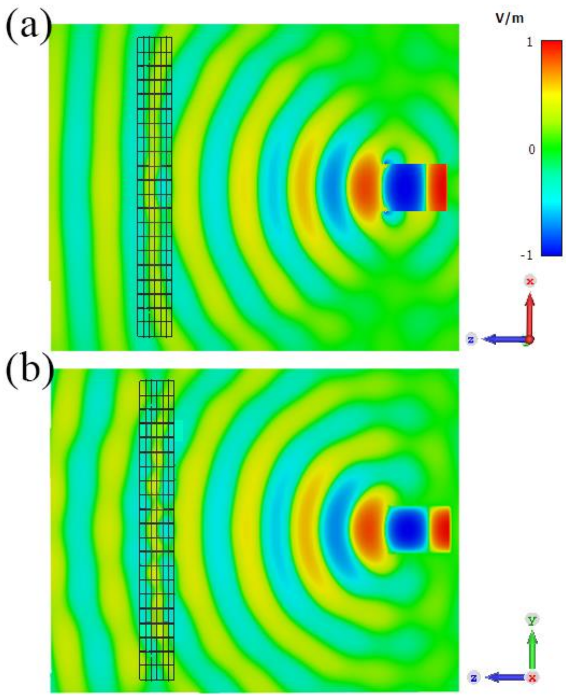

Figure 6: The electric field distribution at the frequency of 77 GHz, a) the XZ plane, and b) the YZ plane.

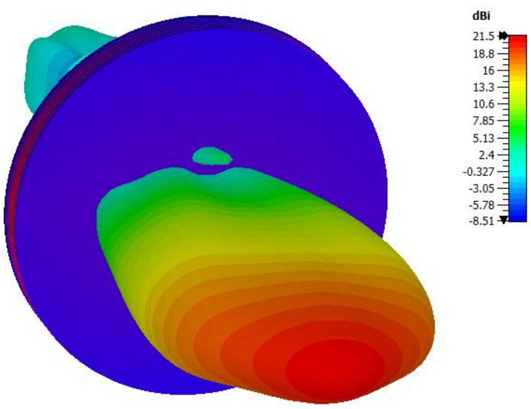

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Figure 7: The 3D radiation pattern of the antenna structure at 77 GHz

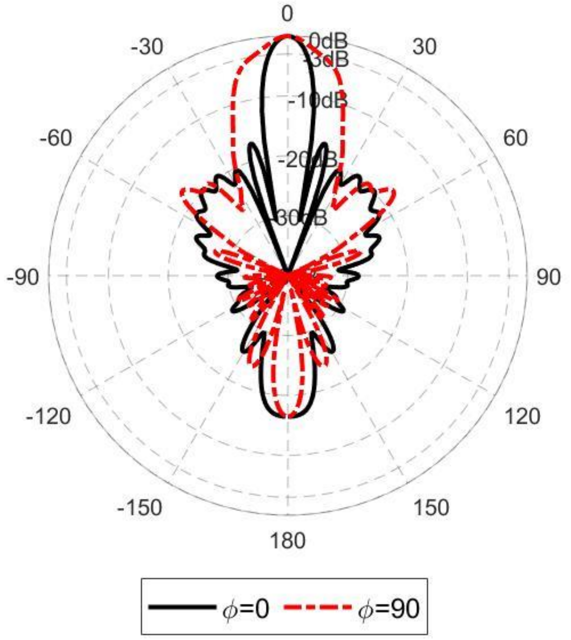

Figure 8: The polar plot of the azimuth and elevation planes

4. Conclusions

This paper has proposed a 77 GHz compact inhomogeneous lens to radiate a Fan Shaped pattern. The critical angle theorem is used to design a three-dimensional inhomogeneous lens. A closed-form formula is offered for an arbitrary fan-shaped pattern lens antenna. A compact circular lens with a diameter of 20 mm and thickness of 2.25 mm is simulated in CST full-wave software to validate the design structure. The frequency bandwidth of the lens covers the range of 76-81 GHz for automotive applications, due to the equality of the refractive index of the lens to the environment space. The realized gain of the lens antenna is 21.5 dBi at 77 GHz. The half-power beam width in the azimuth plane is about twice the elevation plane, which confirms using the presented technique of phase distribution to design a Fan-shaped pattern lens.

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