International Journal of Microwave and Wireless Technologies, 2017, 9(4), 939–944. © Cambridge University Press and the European Microwave Association, 2016
doi:10.1017/S1759078716000854

RESEARCH PAPER

Millimeter-Wave Fresnel Zone Plate Lens with new technological process

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Fresnel Zone Plate lens (FZPL) antennas working in the V and W band are reported in this paper with half and quarter phase correction respectively. A low cost and straightforward technological process is used to manufacture the dielectric lenses using only one foam material where the dielectric constant is controlled. Simulation and measurement results are in good agreement that confirms the viability of such a process to fabricate inhomogeneous structures. Good loss efficiency of 73 and 55% are obtained at 60 and 85 GHz respectively with the two different FZPL designs.

Keywords: Fresnel lens antenna, Millimeter waves, Index

Received 2 March 2016; Revised 8 July 2016; Accepted 11 July 2016; first published online 30 August 2016

I. INTRODUCTION

Many millimeter-wave communications and radar systems need antennas with a high gain to contend with the high path loss in such very high frequencies. Examples are point-to-point and point-to-multipoint links for backhaul in 60 GHz band [1] to communicate over 1 km, or long range automotive radars [2] at 77 GHz.

To achieve high gain (30–40 dBi) different low cost solutions exist such as large printed antenna arrays [3] but they can suffer from high loss due to the length of feeding line network, or reflector antennas [4]. One interesting solution is to design Fresnel Zone Plate lens (FZPL). The simplest and low cost FZPL consisting of alternate transparent and reflecting rings has rather poor efficiency (<15%). To improve efficiency, Black and Wiltse [5] proposed to replace the opaque zones by phase reversing dielectric ones and introduced a Half-Wave FZPL. In the same way, Hristov extended the design with four quarter-wave subzones [6]. The phase correcting zones can be achieved by designing single layer printed circular or annular patches [7] or by implementing a grooved dielectric Fresnel Zone plate lens [8, 9] but problem of diffractions can appear because of the difference of dielectric steps. One alternative is to design the phase correcting zones by changing their dielectric constant [6] instead of one dielectric material and different heights or steps. But in this paper, to avoid the use of different materials, the authors propose to manufacture FZPL by using a unique composite material. The dielectric constant of the different correcting phase zones in the FZPL are controlled thanks to a new technological process [10] by pressing the composite material (foam). In Section II, the authors give details about Fresnel lens design at 60 and 85 GHz respectively with half and quarter phase correction before reminding briefly the technological process used. In Section III, the simulated and measured results are presented for the design at 60 GHz (correction index $q = 2$) while the results for the second FZPL (85 GHz and correction index $q = 4$) are shown in Section IV. The results demonstrate that this technological process is well suitable for the FZPL antenna. Good accuracy is obtained between simulated and measured radiation patterns. Moreover the antenna efficiency of these two FZPL is quite interesting in millimeter waves.

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II. V-BAND FZPL DESIGN AND TECHNOLOGICAL PROCESS

The FZPL does not correct linearly the incident spherical wave fed by the primary source positioned at the focal distance F (Fig. 1) but this lens is a stepped phase transformer where q is the Fresnel correction index.

If $q = 4$ as represented in Fig. 1, it needs to have four distinct dielectric zones within the lens and they are periodically reproduced along the lens radius R. From [6] using optical theory, the radii of the different zones are given by the following formula (1):

$$r_n = \sqrt{\frac{2.n.F.\lambda}{q} + \left(n.\frac{\lambda}{q}\right)^2}, \qquad (1)$$

with λ the working wavelength and r_n the radius of the nth zone of the lens. In this context, the dielectric constant of the nth zone is given by the formula (2):

$$\varepsilon_n = \left(\sqrt{\varepsilon_{n-1}} + \frac{\lambda}{qd}\right)^2, \qquad (2)$$

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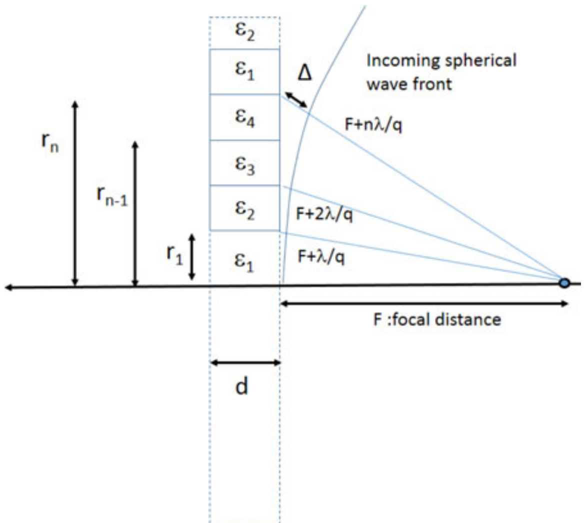

Fig. 1. FZPL principle with dielectric zones to correct phase.

with d the thickness of the lens. As we mentioned before, we fabricate this inhomogeneous lens with an innovative technological process detailed in [10]. It uses only a foam composite material [11] with an initial low dielectric constant very close to 1. This kind of foam is in fact composed of one base material with a relative permittivity in which one air or gas is injected to decrease the dielectric constant close to one. This composite material is full of air bubbles. So the innovated technological process allows to extract air bubbles from the composite by pressing it at 90°C. Depending on the thickness ratio before and after pressing, this process gives the opportunity to control the dielectric constant in order to finally design inhomogeneous structures like FZPL or Luneburg lens for example [12].

In this paper, the FZPL is manufactured from an Airex PXc 320 foam with a 1.4 basic dielectric constant.

The link between the dielectric constant and the density ratio (initial thickness over final thickness) for this material has been further investigated in [10] theoretically and experimentally.

Firstly, we decided to design a simple half wave FZPL2 with $q = 2$ at 60 GHz. So the first dielectric constant (zone 1) is 1.4 and as the thickness of the lens is chosen to be 6.25 mm, the second dielectric constant value is 2.48 from the formula (2). To obtain this value after pressing, the ratio between initial and final thickness must be equal to 2.8 [10] so the initial thickness of the areas with $\varepsilon_r = 2.48$ is 17.5 mm. The lens diameter is close to 150 mm and the focal distance is chosen to be 132 mm (F/D = 0.88).

In the Table 1, we give also the radius of each area in the FZPL2 lens.

A picture of the FZPL2 manufactured thanks to the new technological process is given in Fig. 2 before and after being pressed.

As it is well known, by increasing the Fresnel correction index q, it gives the opportunity to improve the aperture efficiency of such a FZPL. So a second design is considered in this paper with $q = 4$. To limit the thickness of the lens and to manufacture easier the FZPL with the innovative technological process, this second antenna is designed at 85 GHz with a thickness of 6.5 mm. The lens diameter is 115.9 mm and the focal distance is 101.5 mm (F/D = 0.88). In the Table 2, we give the radius of each area in the FZPL4 and the corresponding dielectric constant. As for the first lens, each dielectric constant is obtained by choosing the ratio between initial and final thickness of the foam area. A picture of this second FZPL manufactured thanks to the new technological process is given in Fig. 3 before and after being pressed. In the following section are given the measured results compared with the simulated ones in terms of radiation pattern and gain.

Table 1. V-band radii and relative permittivity obtained after computation for FZPL2.

Area number	Radius (r_i) (mm)	Dielectric constant (ε_r)
1	25.8	1.4
2	36.6	2.48
3	44.6	1.4
4	51.5	2.48
5	57.5	1.4
6	63	2.48
7	68	1.4
8	72.7	2.48

Fig. 2. FZPL ($q = 2$) manufactured with the new technological process, (a) before being pressed, (b) after being pressed.

Table 2. W-band radii and relative permittivities obtained after computation for FZPL4.

Area number	Radius (r_i) (mm)	Dielectric constant (ε_r)
1	14	1.4
2	19.8	2.65
3	24.4	2.19
4	28.2	1.77
5	31.6	1.4
6	34.7	2.65
7	37.6	2.19
8	40.3	1.77
9	42.8	1.4
10	45.2	2.65
11	47.5	2.19
12	49.8	1.77
13	51.9	1.4
14	54	2.65
15	56	2.19
16	58	1.77

III. SIMULATED AND MEASUTRED RESULTS FOR THE V-BAND DESIGN ($q = 2$)

A) Design of primary source

A rectangular horn antenna has been simulated and manufactured to effectively illuminate the FZPL2. It has been

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Fig. 3. FZPL4 ($q = 4$) manufactured with the new technological process, (a) before being pressed, (b) after being pressed.

Fig. 4. Manufactured FZPL2 fed by the optimized horn antenna with foam support.

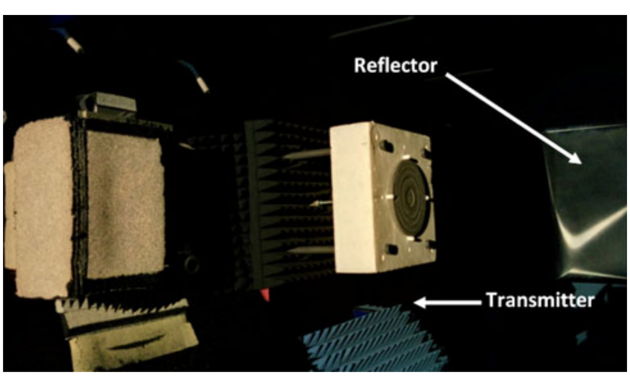

Fig. 5. Manufactured FZPL2 fed by the optimized horn antenna and positioned in the IETR CATR.

optimized to have a radiation pattern with −12 dB power level on the edges of the Fresnel zone to limit spill-over. As the focal distance is 132 mm, the illumination of the edges of the lens corresponds to an angle of 30° for the radiation pattern of the primary source. A standard rectangular waveguide WR-15 (3.8 × 1.9 mm²) is used with a length of 10 mm. This waveguide feeds a rectangular horn of length 18 mm with an aperture size 10 × 7.25 mm².

B) Simulated and measured results of the FZPL2 ($q = 2$)

The lens is fed by the optimized horn antenna (Figs 4 and 5) and simulations are performed using CST-MS and are compared with measurement results in Fig. 6 at 61 GHz concerning radiation pattern in *H*- and *E*-planes.

It is primordial to note that measurements have been performed via a new technique for Institute of Electronics and Telecommunications of Rennes (IETR) laboratory. Indeed, classical measurement needs to be performed in the far-field zone. For this large FZPL2 antenna (30 λ_o), it was impossible to measure radiation patterns with classical far-field technique because our anechoic chamber was not long enough. For that reason a Compact Antenna Test Range (CATR) has been implemented based on a reflector illuminated with a feed horn source. It allows to have a 60 cm quiet zone at relative short distance and to perform high gain antenna measurement.

In Fig. 6, radiation patterns (co and cross polarization) in both the *H*- and the *E*-planes are presented and demonstrate a good agreement between simulation and measurement results. Half power beam widths of 2° and 2.2° are measured and side lobe levels are under −22 dB compared with the main beam. The cross-polarization is also really low (−32 dB).

A relatively good stability over frequency has been observed. Only the side lobes levels are a little bit higher for lower frequencies but still good (−18 dB at 57 GHz) and cross-polarization remains low (<−20 dB). Simulated directivity, measured gain and loss efficiency are computed and given in Fig. 7. A measured gain of 33.3 dBi has been achieved at 61 GHz, which leads to a loss efficiency of 73%. The aperture efficiency of the lens is not so good (31%) if we compare its directivity (34.5 dBi) to the one obtained with the same diameter radiating aperture and given by the formula (3):

$$D_{max} = 10.\log\left(\frac{4\pi S}{\lambda^2}\right) = 39.5 \text{ dBi}, \quad (3)$$

with *S* the aperture surface.

This surface efficiency can be improved by simply using more phase correction zones (4 or 8) which is proved by designing and measuring a second FZPL4 at 85 GHz with $q = 4$ and the results are presented in the following section.

IV. SIMULATED AND MEASUTRED RESULTS FOR THE W-BAND DESIGN ($q = 4$)

This second FZPL4 is optimized to work in the W band (85 GHz) in order to avoid a too thick lens or too high dielectric constant. As mentioned before, the lens diameter is 115.9 mm and the focal distance is 101.5 mm (F/D = 0.88). The diameter is close to 30 λ_o at the corresponding frequency, the same ratio than for the precedent design. The same technological process is used to manufacture the lens (Fig. 3).

A) Design of primary source

A very similar horn antenna than for the first design at 60 GHz is optimized to illuminate this second FZPL4 at

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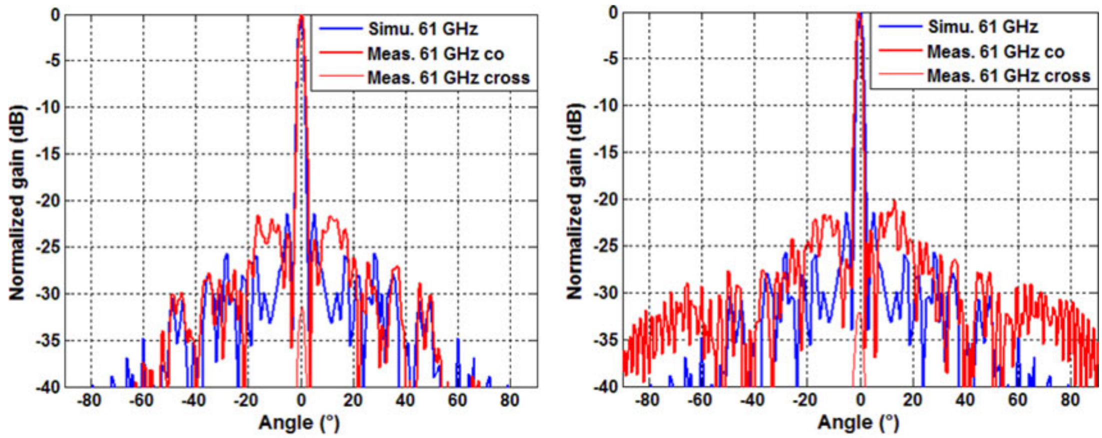


(a) (b)

Fig. 6. Simulated and measured co and cross-radiation patterns at 61 GHz in (a) *E*-Plane, (b) *H*-Plane for FZPL2.

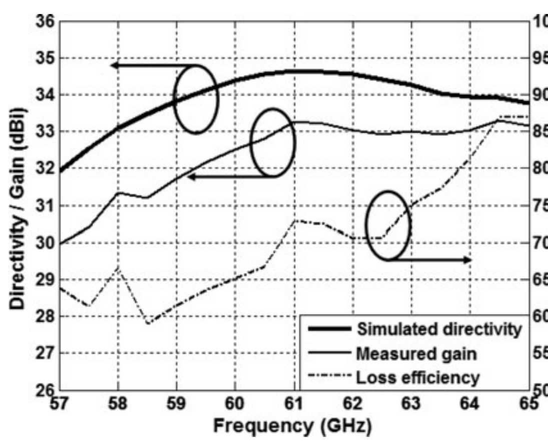


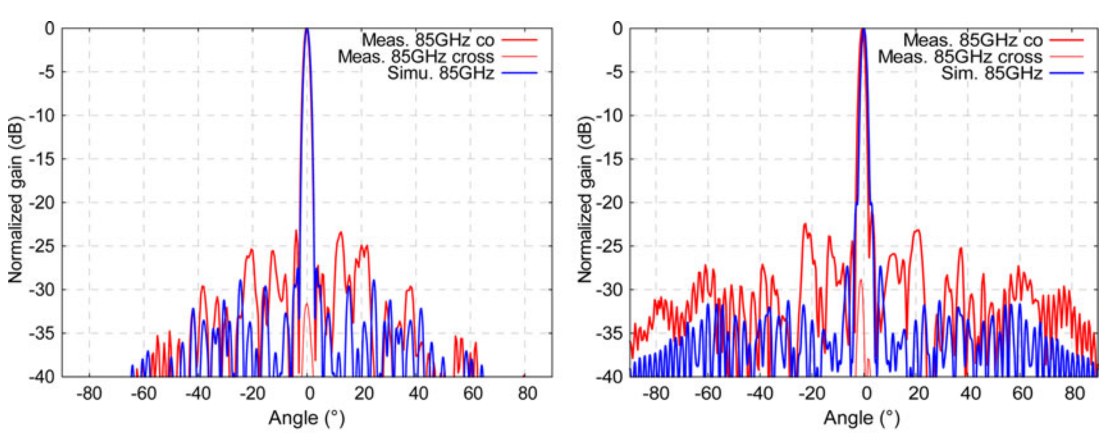
Fig. 7. Simulated directivity (CST MS), measured gain and loss efficiency for FZPL2.

85 GHz. A standard rectangular waveguide WR-10 ($2.5 \times 1.27\ mm^2$) is used with a length of 7.7 mm. This waveguide feeds a rectangular horn of length 14 mm with an aperture size $7.69 \times 5.27\ mm^2$ with a directivity of 15.3 dBi and a measured gain of 15 dBi. The beam width for a -12 dB level has been optimized in order to properly illuminate the lens. The side lobes level is less than -15 dB.

B) Simulated and measured results of the FZPL ($q = 4$)

After the manufacturing process, the FZPL4 illuminated by the feeder horn antenna is measured thanks to the CATR measurement setup. The simulated and measured radiation patterns are presented in Fig. 8 for both the *H*- and *E*-planes at 85 GHz. The beam widths are very close to 2.1° and a good accuracy is shown between simulated and measured results even if the side lobes level are quite a bit higher for the measurement. That can be explained by the dielectric constant law, which is not perfectly reconstructed with the technological process. Moreover, a small misalignment of the feeder with the plate lens can also explain this problem.

As mentioned before, by increasing the number of phase correction (4 instead of 2), the theoretical directivity is 37.3 dBi (compared with 34.5 dBi for the first design). Simulated directivity, measured gain, and loss efficiency are computed in Fig. 9. This directivity corresponds to a 52% aperture efficiency. The measured gain is maximum at 86 GHz and equals to 34.6 dBi so a 54% loss efficiency is obtained. The loss could be reduced by using lower loss foam material. Our results are consistent with current state of the art [6, 7, 13] and our technological process to manufacture FZPL4 in millimeter waves is very low cost and simple.



(a) (b)

Fig. 8. Simulated and measured co and cross-radiation patterns at 85 GHz in (a) *E*-Plane, (b) *H*-Plane for FZPL4.

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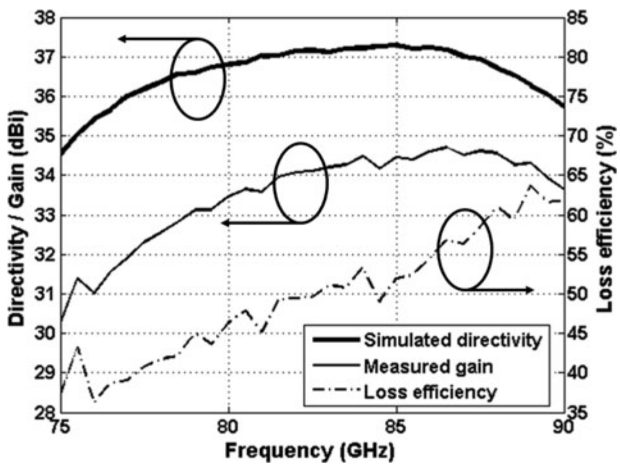

Fig. 9. Simulated directivity (CST MS), measured gain and loss efficiency for FZPL4.

V. CONCLUSION

In this paper, FZPL antennas are designed and manufactured in millimeter-wave band using a new and simple technological process. The phase correction is improved by changing periodically the dielectric constant along the diameter of the lens. Only one composite material is used (Foam) and by controlling the index of it, it becomes possible to design such an inhomogeneous structure. The first manufactured lens with only two phase corrections gives very good results in terms of radiation patterns (beam width and side lobe level) and loss efficiency (73%) in the V band. As it is well known, the aperture efficiency can be improved by increasing the number of phase correcting zones (4 or more). So the authors presented a second design with $q = 4$ at 85 GHz. The results are quite good and the measured gain increases up to 34.5 dBi.

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