Fresnel Zone Plate and Ordinary Lens Antennas: Comparative Study at Microwave and Terahertz Frequencies

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Abstract

Several realistic FZP lens antennas have been studied numericaly in the 38-GHz microwave and 625-GHz low-terahertz frequency bands, and have been contrasted to the same in aperture, focal length and feed-horn ordinary lens antenna. Both types of antennas have (i) close realized gains, (ii) similar bandwidths, (iii) comparable cross-polar isolations and (iv) input mismatch qualities. It is found that for eight FZP phase-correction levels the microwave FZP antenna give way to the ordinary lens antenna by 0.8 dB only. Shifting from the microwave to terahertz band diminishes gain efficiency about 0.5 dB and 10 %, respectively, for both 8-step FZP and ordinary lens antennas. As a reward, however, the FZP lenses are very much smaller and ligher, simpler for fabrication and have superior technology tolerance.

1. Introduction

The diffractive in nature Fresnel zone plate (FZP) lenses and based on them lens or reflector antennas have already have become elements in various microwave and millimeter-wave electronic systems [1-3]. Compared to the ordinary refractive lenses the FZP lenses are preferred whenever thinner, lighter and easier for production focusing tools are required. Despite of the fact that the FZP lenses and antennas are quite well examined theoretically their practical value is still miscalculated. This is partly due to the lack of precise comparative knowledge on similar in design and size diffractive and refractive (or reflective) devices, lenses or antennas. With the present publication the authors pretend to fill up in some extent the gaps regarding the FZP lens antennas in two distinct frequency bands: microwave and terahertz. For each band several designs of ordinary and FZP lens antennas comprising different dielectric lenses but having the same feed-horn design, aperture and focal dimensions are examined and contrasted by use of accurate electromagnetic solver [4].

2. FZP vs. Ordinary Lens Antennas

2.1 Dielectric FZP and Ordinary (Refractive) Lenses

The refractive plane-hyperbolic (Fig. 1(a)) dielectric lens has been chosen as a basic ordinary lens [5-6]. It smoothly transforms by refraction the plane wave into a spherical (focused) one and vise versa, or acts like lens antennas if designed properly. Parallel to the plane-hyperbolic lens several phase-corrected FZP lenses with reasonable radiation efficiency are selected [2-3]: two single-dielectric lenses with 4-step (Fig. 1(b)) and 8-step (Fig. 1(c)) profiles, respectively, and one planar multi-dielectric lens (Fig. 1(d)). The FZP lens makes a stepwise wave transformation by means of diffraction with a maximum allowed phase error in each wave zone equal to $2\pi/p$, where usually $p = 2$, 4, 8 or 16. For $p \to \infty$ the Fresnel zone plate is converted to the well known zoned lens. Ordinary and FZP lenses have been designed for antenna operation at *microwave* frequency f_{mw} =38 GHz (or wavelength λ_{mw} =7.89 mm) and *low-terahertz* (THz) frequency f_{thz} =625 GHz (or λ_{thz} =0.48 mm). Each microwave lens antenna has a focal length F_{mm} =180 mm (or F_{mm}/λ_{mm} =22.8). The lens/antenna aperture diameter for all lenses is the same, D_{mw} =190.7 mm (D_{mw}/λ_{mw} =24.15). Thus, the lens aspect ratio F_{mw}/D_{mw} is equal to 0.94. The single-dielectric FZP lenses (Fig. 1(a-e)) are made of low-loss dielectric material (Rexolite) with a relative permittivity ε =2.53 and a loss factor $\tan\delta_{mw}$ = 0.0003 at 38 GHz. The planar four-dielectric phase-corrected lens

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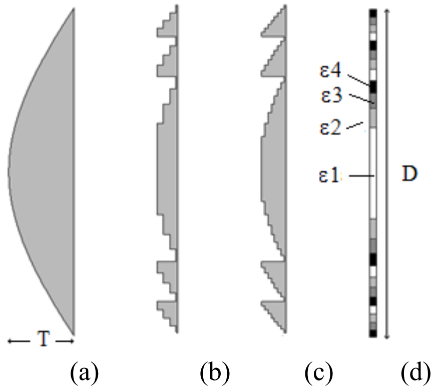


Figure 1 Dielectric lenses: (a) plane-hyperbolic, (b) 4-step FZP, (c) 8-step FZP, and (d) four-dielectric FZP

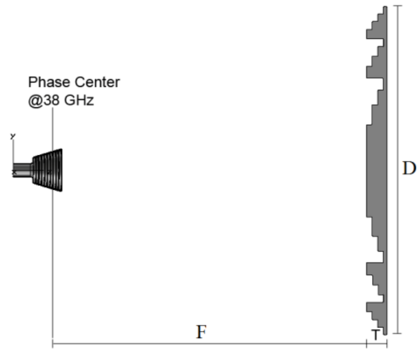


Figure 2 Lens antenna with 4-step FZP and corrugated feed-horn

(Fig. 1(d)) has been employed in addition, where the quarter-wave subzone relative permittivities are in the following order: $\varepsilon_1 = 1$ (air subzone), $\varepsilon_2 = 6.25$, $\varepsilon_3 = 4$ and $\varepsilon_4 = 2.25$. All dielectrics are supposed with a loss factor equal to that of the Rexolite. The main physical data (depth, volume and weight) of the ordinary plane-hyperbolic lens, two single-dielectric FZP with 4 and 8 phase correction steps in each wavelength zone, correspondingly, and one four-dielectric planar FZP are listed in Table 1. The antennas based on the lenses described above are fed by one and the same feed horn with aperture diameter of 24.9 mm (or $3.16\lambda_{mw}$) and axial length of 16.5 mm (or $2.09\lambda_{mw}$). The feed horn is supposed to be golden with an electric conductivity of $\sigma_{mw} = 5 \cdot 10^7$ S/m. Fig. 2 is a sketch of the lens antenna with 4-step conical corrugated horn with a phase center at the FZP focal point.

Table 1 Physical data for 38-GHz FZP and ordinary lenses

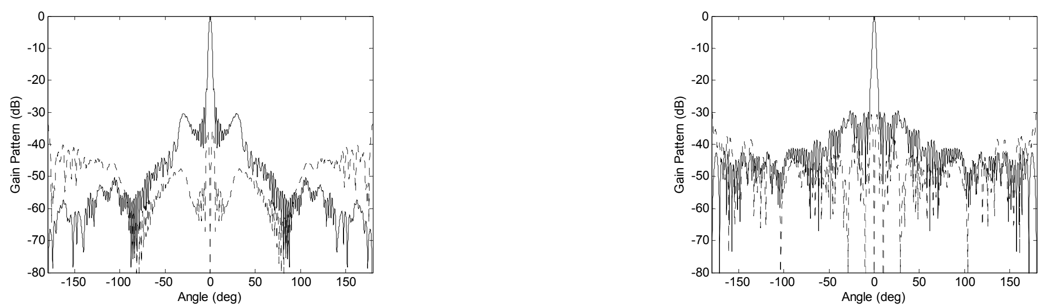
Lens	Depth (mm)	Volume (cm3)	Weight (kg)
Pl.-Hyper.	34.3	457.5	0.48
4-step FZP	11.03	170.4	0.18
8-step FZP	12.7	194.2	0.20
4-diel. FZP	3.9	115.0	-

The 625-GHz terahertz lens antennas are reduced copies of the 38-GHz microwave antennas scaled down by the linear scale factor $s = \lambda_{thz}/\lambda_{mw} = 0.0608$. Thus, the terahertz lens antenna diameter and focal length are $D_{thz} = sD_{mw} = 11.59$ mm and $F_{thz} = sF_{mw} = 10.94$ mm, respectively. Scaled copies are also the terahertz feed horn and its metal waveguide. The terahertz lens antennas are made also of Rexolite and golden metal, and both materials behave much differently at terahertz frequencies [8]. The dielectric permittivities roughly preserve their microwave values while the loss tangent is much bigger ($\tan\delta_{thz} = 0.0045$). The electric conductivity of terahertz feed-horn also different ($\sigma_{thz} = 4.1 \cdot 10^7$ S/m). Thus, the electromagnetic characteristics of terahertz and microwave lens antennas should differ only due to the distinct material loss.

2.2 Physical and Electromagnetic Comparative Results for Microwave and THz bands

The study is aimed on contrasting numerically the refractive (ordinary) and diffractive FZP lenses antennas in two very distinct frequency bands: 38-GHz microwave band and 625-GHz terahertz band. One ordinary lens and several FZP lenses, and the corresponding lens antennas have been designed, simulated and compared depending on their diverse configurations and loss influence on the antenna characteristics in the above frequency bands. As a configuration example a lens antenna having a diffractive 4-step FZP lens is sketched in Fig. 2.

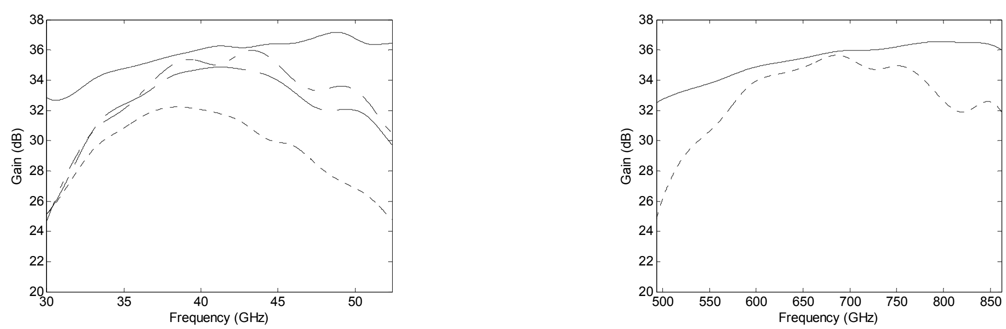
Figs. 3(a) and 3(b) illustrate respectively the gain co-polar (solid lines) and cross-polar (dash lines) radiation patterns of plane-hyperbolic lens antenna and 8-level phase-corrected FZP lens antenna simulated at the diagonal cut plane $\varphi = 45^0$ for the design microwave frequency of 38 GHz.



(a) (b)

Figure 3 Gain co-polar (solid line) and cross-polar (dot line) radiation patterns of (a) plane-hyperbolic lens antenna and (b) 8-step FZP lens antenna.

In Fig. 4 are given the realized antenna gain vs. frequency graphs in the (a) 38-GHz band (~30-50 GHz) for 2-step, 4-step, and 8-step FZP lenses, and plane-hyperbolic lens, and (b) 625-GHz band (~500-850 GHz) for 8-step FZP lens and plane-hyperbolic lens only as these lenses suffer bigger influence by the material loss change.



(a) (b)

Figure 4 Realized gain graphs vs. frequency in the: (a) microwave band for plane-hyperbolic lens (solid line), and, 8-step (dash-dot line) and 4-step (dash line) and 2-step (dot line) FZP lenses and (b) terahertz frequency band, for 8-step (dot line) plane-hyperbolic lens (solid line),

Table 2 FZP and ordinary lens antenna parameters for the microwave and terahertz bands

Lens/Antenna parameters		Greal (dB)	Eff (%)	BW (deg)	BnW (%)	Ixp (dB)	S11 (dB)
1.	38-GHz 4-step FZP	34.2	45.7	2.85	34	31	-19.1
3.	38-GHz 4-diel. FZP	34.7	51.2	2.70	23	36	-16.6
4.	38-GHz 8-step FZP	34.9	53.7	2.75	33	31	-19.7
4.1	**625-GHz 8-step FZP**	**34.4**	**47.9**	**2.90**	**32**	**29**	**-16.3**
5.	38-GHz Pl-Hyp. lens	35.7	66.6	2.75	≈ 80	35	-14.7
5.1	**625-GHz Pl-Hyp. lens**	**35.2**	**57.6**	**2.75**	**≈ 80**	**34**	**-15.3**

Table 2 summarizes the main electromagnetic parameters of 38-GHz antenna designs employing two single-dielectric FZP lenses (no. 1 and no. 4) with four or eight phase-correction steps, one four-dielectric FZP lens (no. 3), and one plane-hyperbolic lens (no. 5). Two of the 38-GHz antennas are scaled down in size (no. 4.1 and no. 5.1) to fit the 625-GHz band. The antenna parameters of interest are: (a) maximum realized co-polar gain Greal in decibels and the corresponding antenna efficiency Eff in percent around the design frequency. Greal and Eff take into account all a BnW in percents relative to the peak gain frequency, (b) minimum cross-polar isolation Ixp in decibels, antenna losses (material, mismatch, polarization, etc.), (c) half-power main lobe beamwidth BW in degrees; (d) 3-dB gain bandwidth calculated at the diagonal $\varphi = 45^0$ -plane in the θ-interval $-180^0 \le 0 \le \theta \le 180^0$, and (e) input scattering (reflection) coefficient S11 in decibels.

3. Conclusion

Several realistic microwave and low-terahertz FZP lens antennas have been numerically studied in detail in two frequency bands: microwave and terahertz. They are contrasted to the same in aperture, focal length and feed-horn ordinary lens antenna with plane-hyperbolic lens. It is found that for four or more FZP phase-correction levels (steps or different dielectrics) both antenna types, FZP and ordinary, have (i) close Greal values, (ii) similar beamwidths, and (iii) comparable cross-polar isolations and mismatch qualities. In both 38-GHz and 625-GHz bands the 8-step microwave FZP antenna give way before the ordinary lens antenna by 0.8 dB only. Our extra study has shown that the 16-step FZP antenna is closer in gain to the ordinary lens but comes at the expense of the bigger size and production complexity. Shifting from the microwave to terahertz band diminishes Greal and Eff by about 0.5 dB and 10 %, respectively, for both 8-step FZP and ordinary lens antennas.

Because the examined FZP lenses and antennas are much narrowbanded than the ordinary ones all these parameter similarities are hold in a smaller bandwidth of about 20-30%.

As a reward, however, the FZP lenses are very much smaller in depth, volume and weight than the ordinary lenses (Table 1), and this leads to a creation of significantly lighter lens antennas with a constrained frequency bandwidth. Besides, the diffractive plane-step FZP lenses are simpler and easier for production compared to the thick or zoned refractive antenna lenses. And finally, it is known that the diffractive lenses have better tolerance superiority compared to the refractive ones, which in addition ease their fabrication.

A feasible application of FZP optics similar to the studied here is envisioned in a receiver for the Atacama Large Millimeter Array (ALMA) radio telescope in Chile, for operation in the low-frequency mm-wave band between 31 GHz and 45 GHz.

4. Acknowledgments

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