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Research Article

Terahertz Harmonic Operation of Microwave Fresnel Zone Plate Lens and Antenna: Frequency Filtering and Space Resolution Properties

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This paper examines the binary Fresnel zone plate (FZP) lens frequency-harmonic and space-resolution focusing, and its application as a FZP lens antenna. A microwave FZP lens antenna (FZPA) radiates both at design (90 GHz) and terahertz (THz) odd harmonic frequencies. Frequency and space domain antenna operation are studied analytically by use of the vector diffraction integral applied to a realistic printed FZPA. It is found that all harmonic gain peaks are roughly identical in form, bandwidth, and top values. At each harmonic frequency, the FZPA has a beamwidth that closely follows the Rayleigh resolution criterion. If the lens/antenna resolution is of prime importance and the small aperture efficiency is a secondary problem the microwave-design FZP lens antenna can be of great use at much higher terahertz frequencies. Important feature of the microwave FZP lens is its broader-zone construction compared to the equal in resolution terahertz-design FZP lens. Thus, unique and expensive microtechnology for the microwave FZP lens fabrication is not required. High-order harmonic operation of the FZP lens or lens antenna could find space resolution and frequency filtering applications in the terahertz and optical metrology, imaging tomography, short-range communications, spectral analysis, synchrotron facilities, and so on.

1. Introduction

During the last two decades, a rapid exploration of terahertz waves is taking place [1–3]. Fresnel zone plate (FZP) lenses, binary and phase correcting, have already turned into essential focusing and imaging elements in the microwave and terahertz electronic systems [4–13]. At terahertz frequencies, the multilevel phase-correcting dielectric FZP lens shows better efficiency compared to the ordinary dielectric lens, and is easier and cheaper to fabricate because of its planar configuration [4–6].

If the high lens resolution and small thickness are of prime importance, the binary FZP lens consisting of free-standing or printed skinny metal rings would be preferable. Such lenses have found a lot of applications in the areas of 3D imaging tomography, electron microscopy, sensing and security systems, and synchrotron radiation facilities for beam focusing [11, 14–19]. For these purposes, a special lithography process has been developed for fabrication of high aspect ratio gold structures on silicon nitride membranes [19]. Because the classical FZP lens is acting as a diffraction grating of annular elements, it possesses very intriguing spectral periodicity [5, 9, 11, 13, 16].

Main objective of this paper is to clarify the harmonic action of binary FZP lens and antenna, and to examine them numerically in frequency and space domains with for grounding hypothetically their future employment as multi-band focusing and filtering devices.

Section 2 provides shortly the FZP lens design and resolution basics and makes physical clarification of the harmonic-mode FZP focusing mechanism.

Section 3 illustrates the microwave FZP antenna radiation geometry used in the vector Kirchoff's diffraction theory for the axially symmetric FZP lens antenna analysis and optimization. The particular 90 GHz printed FZP lens antenna design described in this section operates in a periodic way at much higher frequencies in accordance with the odd harmonic sequence $f_1, 3f_1, 5f_1$, and so forth, where $f_1 = 90$ GHz is the antenna design (first order) microwave frequency. For the first time, the FZP antenna space-domain operation is studied for finding antenna vector radiation field and resolution characteristics at the design (microwave) and higher (terahertz) harmonic frequencies.

Section 4 describes FZP lens antenna designed for the terahertz frequency of 1530 GHz. Its radiation, structural, and technological properties are observed and contrasted to those of the same-size 90 GHz microwave FZP lens antenna operating at its 15th terahertz harmonic frequency of 1530 GHz as well.

The paper is completed by a general conclusion, acknowledgement, and list of references.

2. Harmonic-Mode Operation of FZP Lens Illuminated by Plane Wave

2.1. FZP Design. In general, a FZP lens centered in the origin of Cartesian coordinate system is transforming an axially incident spherical wave front of radius $z = -F_s$ into multiple spherical waves focused on the lens axis z at multiple foci with focal distances (lengths) $z = +F_n$, where $n = 1, 3, 5, \ldots$ are odd numbers. The unusual multiple focusing action of the FZP lens is due to its diffractive nature, and this is its major distinction from the ordinary refractive lens. The first or primary focus for which $n = 1$ has a focal distance F_1 collects the largest portion of the focused field energy in the forward semispace $z > 0$. This allows the others or so-called secondary foci at $z = F_3 = F_1/3$, $z = F_5 = F_1/5$, and so on to be neglected.

Figure 1 illustrates a binary-amplitude FZP lens of diameter D illuminated along the axis z by a plane wave that corresponds to $F_s = -\infty$. With the secondary foci disregarded, the lens will have a single focus at a focal distance $F = F_1$. Such a lens is operating in the antenna receive mode. The FZP lens drawn in Figure 1 has odd zones closed (tinted in black).

The normally illuminated by a plane wave planar FZP conmprises concentric half-wave zones with zone radii $b(m)$ determined by

$$b(m) = \sqrt{m\lambda F + \left(\frac{m\lambda}{2}\right)^2}, \tag{1}$$

where λ is the design wavelength, $m = 1, 2, 3, \ldots, M$ is the current zone number, and M is the ending zone number.

In optics the following approximation of (1) is usually valid:

$$b(m) = \sqrt{m\lambda F} = b(1)\sqrt{m}, \tag{2}$$

where the term $(m\lambda/2)^2$ is neglected because the ratio $m\lambda F \gg (m\lambda/2)^2$ takes place, and $b(1) = \sqrt{\lambda F}$ is the first zone radius.

2.2. FZP Lens Resolution. By definition, the so-called Rayleigh resolution criterion for the resolving power of a circular aperture of diameter D is typically expressed by the resolving angle δ_0, in radians [20–22]

$$\delta_0 = \chi\frac{\lambda}{D}, \tag{3}$$

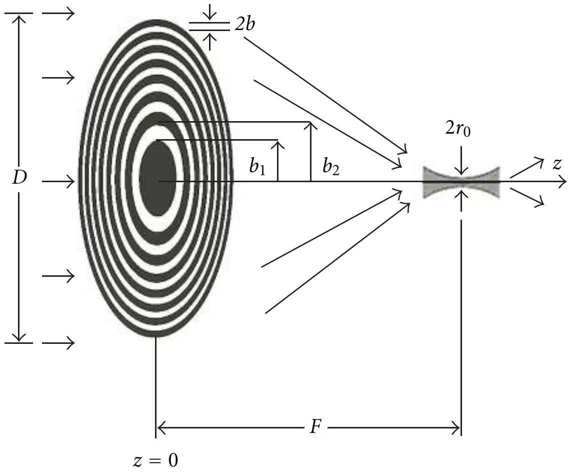

Figure 1: Plane-wave illuminated binary negative Fresnel zone plate lens.

where $\chi = 1.22$ is a constant that is valid for every open circular aperture illuminated normally by a plane wave. This can be the aperture of a circular horn, parabolic reflector, ordinary refractive, or phase-correcting FZP lens.

From (3), is evident that if the diameter D is maintained constant, the resolving angle is proportional to the wavelength λ and χ. It is said that the smaller angle δ_0 the bigger lens resolution, and vise versa.

In the case of a binary FZP, however, the constant value 1.22 of χ is valid only if the total number of zones M is bigger than about 200. For smaller M, say $M < 50$, χ differs from 1.22 and varies with M, or $\chi = \chi(M)$ [23, 24]. More exactly, $\chi(M) > 1.22$ for the positive FZP lenses (odd zones open), and $\chi(M) < 1.22$ for the negative FZP lenses (odd zones closed). In Table 1, several values of $\chi(M)$ for positive (pFZP) and negative (nFZP) lenses are listed [22, 23].

From Table 1, it is concluded that for $M \leq 50$ and the same normalized aperture diameter D/λ, the negative FZP has a smaller resolving angle δ_0 (or bigger resolution) than the positive FZP and ordinary refractive lens by 15% and 9.5%, for $M = 10$, 8% and 5.5% for $M = 20$, 5% and 3.5%, for $M = 30$, 3.5% and 2.5%, for $M = 40$, and 2.7% and 2%, for $M = 50$, respectively.

The resolving angle δ_0 is directly related to the first null radius r_0 of the FZP Airy diffraction pattern at the focal plane. The radius r_0 measures the space (distance) lens resolution and is opposite to angle δ_0 in the corresponding rignt triangle, so that $\tan\delta_0 = r_0/F$. For a high resolution, the angle δ_0 is small enough, or $\delta_0 \approx r_0/F$. Thus, taking into account (3) the resolving lens r_0 can be expressed as

$$r_0 = \chi(M)\frac{\lambda F}{D}. \tag{4}$$

The ending zone width Δb is related to the resolving lens radius as follows [11, 23, 24]:

$$r_0 = \chi(M)\Delta b \tag{5}$$

Table 1: Values of $\chi(M)$ for $M \leq 50$.

M		10	20	30	40	50
$\chi(M)$	pFZP	1.275	1.245	1.235	1.230	1.227
	nFZP	1.125	1.165	1.185	1.195	1.200

or vice versa

$$\Delta b = \frac{r_0}{\chi(M)}. \quad (6)$$

2.3. Multifrequency Focusing of FZP Lens: Physical Justification. Next, we clarify the multiple frequency-domain behavior of the binary FZP lens illuminated by a plane wave. This phenomenon is analogious to the axial multiple focusing of the same lens. Both phenomena are linked by (1) and can be easier explained by its approximation (2). From (2), it follows that for a given FZP diameter $D = 2b(M)$, the change of the focal distance F for $\lambda = \lambda_1 =$ const., or the wavelength λ for $F =$ const. will raise a multifocal or multifrequency effect, respectively, if the total number of zones M somehow changes. Here λ_1 is the design wavelength. This statement might be confusing having in mind that for a realistic FZP design, D and M are both constant quantities.

Next, it is clarified that the multifrequency phenomenon taking as an example a binary FZP lens of four Fresnel (or half-wave) zones designed for a focal length F at a frequency f_1 (or wavelength λ_1). Consider first this FZP lens illuminated by a plane wave of frequency equal to the third harmonic frequency $f_3 = 3f_1$, corresponding to the free-space wavelength $\lambda_3 = \lambda_1/3$. The radius (2) could be rewritten for the FZP diameter as follows:

$$D(M_3) = 2\sqrt{M_3 F \lambda_3}. \quad (7)$$

The maintenance of same aperture diameter D and focal length F for the three times smaller wavelength λ_3 requires three times bigger number of zones, or $M_3 = 3M$. This means that in each real zone corresponding to the design wavelength λ_1 three virtual λ_3-subzones should be enclosed: two positive (in white) and one negative (in grey). Thus, the virtual subzone radii can be calculated by the equation $b(m_3) = \sqrt{m_3\lambda_3 F} = \sqrt{3\,m\lambda_3 F}$, where m_3 is the current subzone number. The above suggestion is illustrated by Figure 2(a), where in each open realistic zone, three virtual subzones are included. The fields produced by the 2nd subzone and 3rd subzone will be canceled leaving only the 1st subzone to contribute at the focus.

Similarly, for an illuminating plane wave with a frequency $f_5 = 5f_1$, or wavelength $\lambda_5 = \lambda_1/5$, each real open zone should contain five virtual subzones: three positive and two negative, with radii found by $b(m_5) = \sqrt{5\,m\lambda_5 F}$. The two positive (3rd and 5th) and two negative (2nd and 4th) subzones will cancel at the primary focus leaving again only one, the 1st positive half-wave subzone to be productive. The above considerations are valid for all higher harmonic frequencies.

The field intensities provided at the primary focal point by all real open zones corresponding to f_1 and by all virtual constructive subzones related to any odd harmonic frequency are expected to be roughly equal. This is because the total constructive areas, the real A_1 and the virtual $A_3, A_5, \ldots$, normalized by corresponding squared wavelengths $\lambda_1^2, \lambda_3^2, \lambda_5^2, \ldots$, respectively, are about the same (or $A_1/\lambda_1^2 \approx A_3/\lambda_3^2 \approx A_5/\lambda_3^2 \approx \cdots \approx$ const.). In other words, the focusing gain G_f of all constructive zones, actually related to the design frequency, and virtually related to any harmonic frequency, could be considered equal.

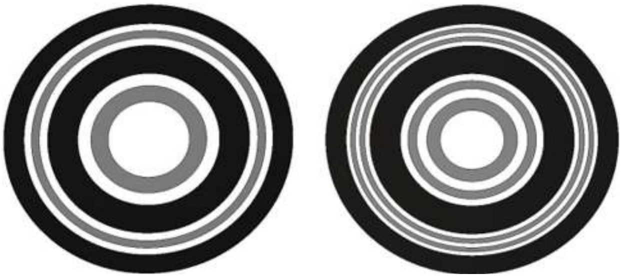

Figure 2: Harmonic-action FZP lens at (a) 3rd harmonic frequency f_3 and (b) 5th harmonic frequency f_5.

Taking into account the basic lens/antenna relation between the focusing gain and radiating aperture $G_f = 4\pi A\eta/\lambda^2$, the radiation aperture efficiency for each frequency is expressed as follows: $\eta_1 = G_f\lambda_1^2/4\pi A_1$, $\eta_3 = G_f\lambda_3^2/4\pi A_1$, $\eta_5 = G_f\lambda_5^2/4\pi A_1, \ldots$, and so forth. It is seen that the efficiency values $\eta_1, \eta_3, \eta_3, \ldots$ are directly proportional to the respective ratios $\lambda_1^2/A_1, \lambda_3^2/A_1, \lambda_5^2/A_1, \ldots$. Because the physical aperture area of the lens A_1 and the focusing gain G_f are considered constant quantities, the FZP aperture efficiencies for the 3rd, 5th, and so forth harmonics are diminishing rapidly compared to the efficiency for the design frequency, or $\eta_3 = \eta_1(1/3)^2$, $\eta_5 = \eta_1(1/5)^2$, and so on.

3. Microwave FZP Lens Antenna Operation at Terahertz Harmonic Frequencies

3.1. Radiation Characteristics Computed by Use of Vector Kirchhoff's Diffraction Theory. Consider the geometry of binary FZP lens antenna consisting of feed-horn and positive binary FZP of concentric metal rings (in grey) obstructing the even zones (Figure 3). The feed phase center coincides with the lens focal point $P_1(0,\ 0,\ -F)$. In antenna transmit mode, the spherical wave that originated from P_1 illuminates the FZP lens which odd open Fresnel zones radiate constructively along the lens axis ($\theta = 0$).

The antenna radiation characteristics have been computed by use of the vector Kirchhoff's diffraction integral solved explicitly for the axially symmetric binary FZP lens antenna [5, 8, 9].

The feed-horn field is approximated theoretically by the broadly used aperture directive gain function $G_f(\psi, n) = G_f(0, n)\cos^n\psi$ for $0 \leq \psi \leq \pi/2$, where $G_f(0, n) = 2(n+1)$, and $G_f(\psi, n) = 0$ for $\pi/2 < \psi \leq \pi$. The lens aperture field is

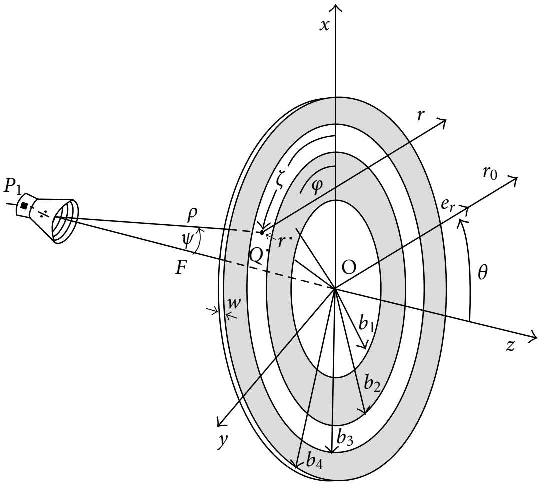

Figure 3: Radiation geometry of FZP lens antenna.

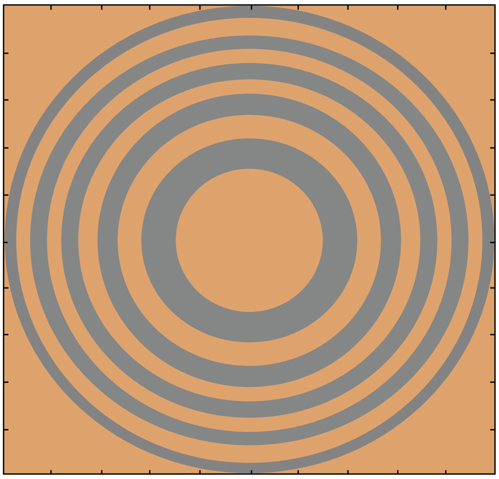

Figure 4: Binary FZP lens of FZPA-M-10 designed at microwave frequency of 90 GHz with all even zones covered by thin metal (in grey) printed on dielectric substrate (in light brown).

tapered to the edge level equal to −10 dB, or 10 dB down to the center field magnitude, $n = 8.32$ and $G_f(0) = 12.7$ dBi.

The microwave FZP lens antenna design studied in this paper is marked by the acronym FZPA-M-10, which stands for FZP Antenna designed at the Microwave frequency $f_1 = 90$ GHz and by having a FZP lens with 10 Fresnel zones in total (Figure 4). The lens has a diameter $D = 100$ mm and focal length $F = 66.7$ mm, so the lens aspect ratio is $F/D = 0.67$.

The FZP lens is made as a printed construction with metal rings of thickness t printed on a dielectric substrate of width w and a complex permittivity $\tilde{\varepsilon}_r(f) = \varepsilon_r[1 - j\tan\delta(f)]$, which is a function of frequency f. In the frequency band $\Delta f = f_{\max} - f_{\min}$, the loss tangent $\tan\delta$ of typical microwave dielectrics is roughly increased as a linear function of f in the range $\Delta\tan\delta = \tan\delta_{\max} - \tan\delta_{\min}$ and can be approximated by the next simple equation:

$$\tan\delta(f) \approx \tan\delta_{\min} + \mathrm{k}_{\Delta}(f - f_{\min}), \qquad (8)$$

where $\tan\delta_{\min}$ corresponds to $f_{\min}$, and $k_\Delta = \Delta\tan\delta/\Delta f$ is a constant specific for a given dielectric substrate. Equation (7) is an author's approximation for dielectrics with a linear conduct of the loss tangent versus frequency and is based on published measurements for some dielectrics in the millimeter-submillimer frequency bands [6]. For instance, in the $90 \div 1500$ GHz frequency band (8) matches well the loss tangent behavior of Teflon, chosen here as a FZP substrate dielectric, if $k_\Delta = 0.0104$. The Teflon real permittivity ε_r is approximately equal to 2.05 in the whole band. According to (8), for the working FZP frequencies 90, 270, and 1350 GHz, for instance, $\tan\delta$ has values $5 \cdot 10^{-4}$, $6.8 \cdot 10^{-4}$, and $17.9 \cdot 10^{-4}$, respectively.

In the studied FZP lens structure, the Teflon substrate plate is 1 mm thick, while the metal rings have a width of 0.1 mm and are supposed infinitely conductive.

The outmost (10th) zone is obstructed by a metal ring of width $\Delta b_M = 2.83$ mm, which is slightly less than the wavelength corresponding to the design frequency of 90 GHz but is about 10–15 times bigger than the wavelengths related to highest harmonic frequencies in the band for which the FZP-M-10 is studied here.

3.2. Frequency-Domain Performance of FZP Antenna. Frequency analysis of the FZP lens antenna is based on the variation of far-field directive gain versus frequency in the normal direction $f = 90$ along the z-axis (or at $\theta = 0$ deg). The main frequency characteristics of interest are the antenna directive peak gain (G_p, dBi) and the 3-dB gain bandwidth (B) around the design and harmonic frequencies.

The FZPA-M-10 has been examined numerically in the frequency band 50–1550 GHz. Figure 5 illustrates the characteristic multiband comblike FZP focusing/radiation behavior with gain peaks at the microwave frequency of 90 GHz and its odd terahertz harmonics of 270, 450, 630, …, 1350, and 1530 GHz.

The multiband FZP antenna is considered as a multitude of individual harmonic-frequency antennas radiating all or each at a time. The analysis is made on the assumption that each individual harmonic antenna is fed by a feed located at the same focal point P_1 and radiating at the respective odd harmonic. These imaginary feeds are supposed to have the same shape radiation patterns and directive gains. In fact, such an enclosure of several different sizes of feeds (feed horns, for example) in the small focal area is a very challenging construction.

Practically, the harmonic-frequency feeds could be also located off axis on a circular arc, which is the scan curve of the FZP lens antenna [20]. Another pragmatic feed might be a single frequency independent feed like the Archimedean or equiangular spiral antenna having a radiation pattern and input impedance match roughly preserved for a number of microwave/THz harmonic frequencies. And finally, same configuration narrowband feedantennas, designed for the basic and harmonic frequencies, might be positioned each at a time in the FZP focal area by a simple electromechanical

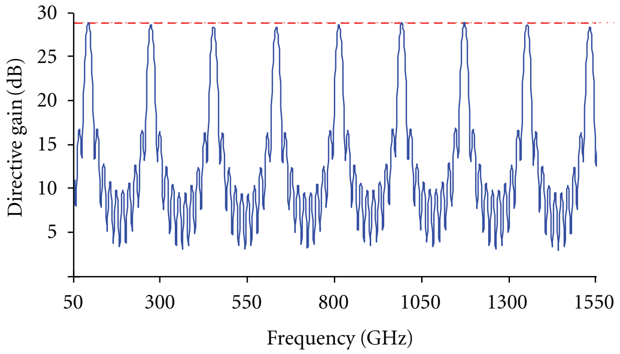

Figure 5: Frequency-domain harmonic action of binary FZP antenna: directive gain versus frequency.

Table 2: Frequency-domain radiation parameters of FZP lens antennas: microwave (M) and terahertz (T) designs.

FZP antenna $F/D = 0.67$	f (GHz)	G_p (dBi)	B (GHz)	 (%)	e (%)
FZPA-M-10 ($f_1 = 90$ GHz, $D = 100$ mm)	90	28.9	~ 16.5	18.4	9.63
	270	28.6		6.1	1.07
	1350	28.5		1.22	0.05
FZPA-T-150 ($f_1 = 1350$ GHz, $D = 100$ mm)	1350	52	16.3	1.20	7.92

device. Thus, every feedantenna will illuminate the FZP lens each at a time, or consecutively.

The essential frequency-domain parameters of the antenna FZPA-M-10 are listed in Table 2 for the design frequency $f_1 = 90$ GHz and for the two harmonic frequencies $f_3 = 270$ GHz and $f_{15} = 1350$ GHz. It is seen that the peak gain G_p (dB) has a slight fluctuation with the frequency due to the multiray transmission and absorption through the dielectric substrate, and the absolute bandwidth B (GHz) is kept almost constant or 16.5 GHz, respectively. The normalized (relative) bandwidth B (%) and aperture efficiency e quickly go down with the frequency rise.

3.3. Space-Domain or Radiation Pattern Study. Here by a space-domain antenna study, the FZP lens radiation pattern analysis at the design and harmonic frequencies is understood. Figure 6 illustrates the radiation characteristics of microwave antenna FZPA-M-10, namely: (a) copolar radiation pattern and (b) cross-polar radiation pattern in the small angular interval $\theta = 0 \div 3$ deg at the diagonal cut plane $\varphi = 45^\circ$, for the same three harmonic frequencies chosen in the previous section: 90, 270, and 1350 GHz. In addition to the peak gain value of about 29 dBi, other basic pattern parameters can be found: main lobe beamwidth BW(deg) read at a level 3 dB down to the peak gain value, first side lobe level L_s(dB), and maximum cross-polarization L_{cr} measured within the main lobe beamwidth.

The half-power (or −3 dB) antenna beamwidth BW is approximately equal to the lens aperture resolving angle δ_0 [22], or

$$BW \approx \delta_0. \tag{9}$$

For the FZP design wavelength λ_1 and for the harmonic wavelengths $\lambda_3, \lambda_5, \ldots$, and so on, (3) for the resolving angle can be rewritten as follows:

$$\delta_{0i} = \chi(M)\frac{\lambda_i}{D}, \tag{10}$$

where $i = 1, 3, 5, \ldots$ is an odd integer number.

Thus, for a known design FZP resolving angle δ_{01}, the *ith* resolving angle δ_{0i} is in a reverse proportion to δ_{01}, or

$$\delta_{0i} = \frac{\delta_{01}}{h_i}, \tag{11}$$

where $h_i = f_i/f_1$ is the harmonic scale ratio.

Similarly, for the ith harmonic resolving distance r_{0i}, (4) and (6) can be rewritten, respectively, as follows:

$$r_{0i} = \chi(M)\frac{\lambda_i F}{D}, \tag{12}$$

$$r_{0i} = \chi(M)\frac{\Delta b}{i}. \tag{13}$$

Table 3 summarizes the radiation (space) pattern characteristics of microwave antenna FZPA-M-10 at the design frequency of 90 GHz, and at its 3rd and 15th harmonics, found from Figures 6(a), and 6(b). From Table 3 several essential features of the FZP antenna space-domain behavior are discovered.

(i) Theoretical beamwidth matches very well the Rayleigh resolution criterion for all working frequencies. For example, at $f = f_1 = 90$ GHz the FZP lens

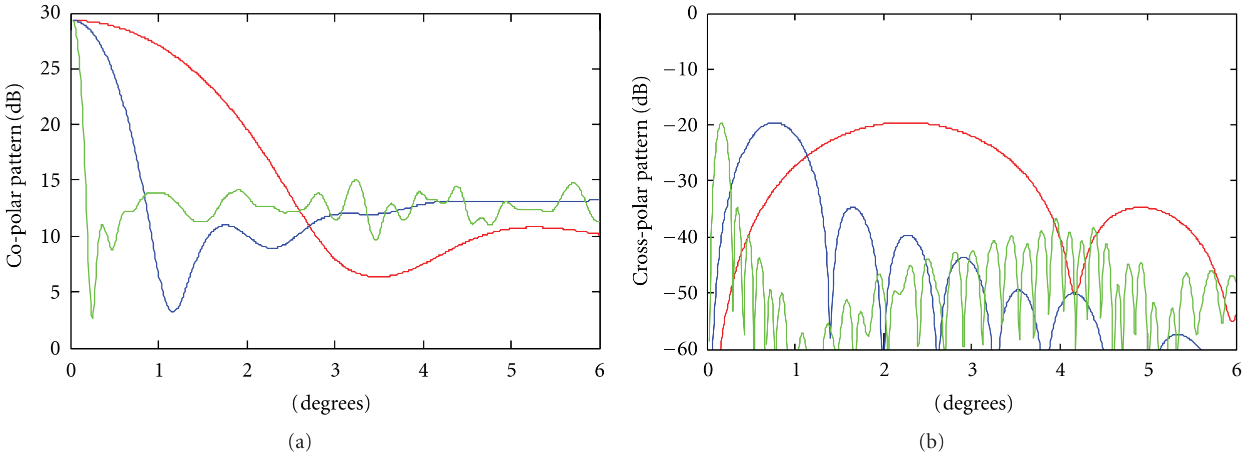

Figure 6: Radiation characteristics of FZPA-M-10 versus angle θ: (a) copolar radiation patterns, (b) cross-polar radiation patterns. Red, blue, and green lines correspond to 90, 270, and 1350 GHz, respectively.

antenna has a main lobe beamwidth 2.4 deg that is roughly equal to the lens resolving angle $\delta_{01} = 2.43$ deg. At the 3rd harmonic (270 GHz) and 15th harmonic (1350 GHz) the beamwidth is 3 and 15 times much narrow: $BW_3 = 0.78$ deg and $BW_{15} = 0.15$ deg. The same harmonic ratio 1 : 3 : 15 is valid for the corresponding values of resolving angle δ_0 and resolving distance r_0.

(ii) At all microwave and terahertz harmonics, the studied FZP lens antenna preserves roughly constant the peak gain values ($G_p = 29$ dBi), first sidelobe level ($L_s = 11$ dB), and cross-polar level within the mainlobe beamwidth ($L_{\text{cr}} = -25$ dB).

The quick drop of the FZP lens/antenna focusing/radiation efficiency with the rise of harmonic frequency deserves more discussions. The aperture antenna radiation efficiency less than 40–50% is not satisfactory, and less than 10–20% is considered small. In principle, the binary FZP lens/antenna belongs to the latter efficiency category because of noneffective amplitude and phase aperture utilization. By exploiting a proper phase correction of the aperture field like in the grooved dielectric or multidielectric FZP lenses, for instance, the corresponding FZP lens antenna easy reaches at its design (first-order) frequency the radiation efficiency of the classical aperture antennas (horn, parabolic-reflector, etc.), though in a rather smaller frequency band.

The low efficiency might be considered as a price for the unique features of the binary FZP lens or antenna: precise harmonic filtering and resolution characteristics that the usual directive-aperture antennas do not possess. Especially valuable is the big potential resolution at the much higher harmonic frequencies as it is discussed above. Similar “give and take” is met in many natural phenomena, and also in many other radioelectronic devices. Very appropriate example with a similar to the FZP multifrequency action is the harmonic-frequency multiplier. In particular, a big power-efficiency loss is produced in the process of harmonic-frequency multiplication of microwave frequencies to much higher terahertz frequencies. The output of the solid-state terahertz generators based on the frequency multiplication drops with harmonic frequency increase as about $(1/f)^3$ [3]. As is found here, the FZP lens/antenna radiation efficiency goes down like $(1/f)^2$.

It is clear that at THz harmonic frequencies, the microwave FZP lens/antenna aperture is not utilized efficiently for a focusing or radiation. Such low aperture radiation efficiency, however, is also typical for all planar frequency-independent antennas like the Archimedean and equiangular. For example, the Archimedean spiral antenna, which can radiate in a frequency band greater than 20 : 1 also shows very unproductive use of its radiation structure (aperture). At each frequency f (or wavelength λ) only a narrow annular zone in the whole circular aperture radiates actively. This radiation zone has a radius of $\lambda/2\pi$ and a circumference equal to λ. The rough calculation confirms that an Archimedean antenna designed for the microwave band 1–20 GHz at the working frequency of 10 GHz has less than 0.5% aperture utilization or efficiency of radiation [22].

4. Terahertz-Design FZP Lens Antenna: Electromagnetic and Structural Evaluation

Next are described terahertz FZP lens and antenna, designed at the terahertz frequency of 1350 GHz (Figure 7), or at the 15th harmonic of the 90 GHz microwave FZP lens. Both, terahertz-design and microwave-design lenses are equal in size, or they have $D = 100$ mm, $F = 66.7$ mm, and lens aspect ratio $F/D = 0.67$. The 1350 GHz terahertz FZP lens encloses 150 Fresnel zones totally or 15 times much more than the 90 GHz microwave FZP lens. Thus, their zone number scale ratio is 15 : 1 and is equal to the design frequency ratio 1350 : 90 GHz. The outmost zone of the terahertz FZP lens has a width $\Delta b = 185\,\mu$m.

The computed copolar and cross-polar radiation patterns of terahertz-design FZPA-T-150 versus angle θ are drawn in Figure 8, red line and blue line, respectively. The main

Table 3: Radiation pattern parameters of FZP lens antennas: microwave (M) and terahertz (T) designs.

FZP antenna F/D =0.67	f (GHz)	BW (deg)	δ_0 (deg)	r_0 (μm)	L_s (dB)	L_{cr} (dB)
FZPA-M-10	90	2.4	2.43	2835		
(f_1 = 90 GHz,	270	0.78	0.81	945	11	−25
D = 100 mm)	1350	0.15	0.16	189		
FZPA-T-150 (f_1 = 1350 GHz, D = 100 mm)	1350	0.15	0.155	226	22	−56

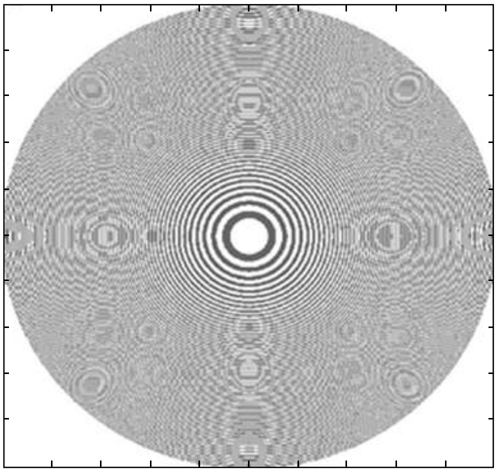

Figure 7: Terahertz-design FZP lens of FZPA-T-150 lens antenna designed at 1350 GHz.

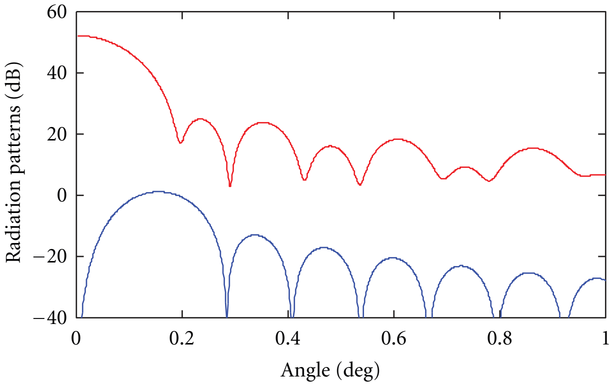

Figure 8: Radiation patterns of terahertz-design FZPA-T-150 versus angle θ: copolar radiation pattern (red line) and cross-polar radiation pattern (blue line).

frequency and radiation-pattern parameters of the 1350 GHz antenna FZPA-T-150 are also listed in Tables 1 and 2, below the analogous parameters of the 90 GHz microwave antenna FZPA-M-10.

At the same working terahertz frequency of 1350 GHz, both antennas, the microwave antenna FZPA-M-10 and terahertz antenna FZPA-T-150, have the following radiation parameters:

(a) similar absolute and relative bandwidths of about 16.5 GHz (absolute) and 1.2% (relative), respectively;

(b) comparable radiation pattern beamwidths (or angular resolutions) of about 0.15 degrees;

Naturally, the terahertz-design antenna FZPA-T-150 has a much higher gain and aperture efficiency, but a similar radiation to those of FZPA-M-10 at its design frequency of 90 GHz. At FZPA-T-150 harmonic frequencies like 4.05 THz (3rd terahertz harmonic) and 20.25 THz (15th harmonic, located in the low-infrared band), the aperture utilization efficiency of the FZPA-T-150 will again become low, about 1% and 0.05%, correspondingly.

With regards to the structural, technological, and other lens qualities, the contrast between the microwave- and terahertz-design FZP lenses shows:

(i) FZP lens used in the FZPA-T-150 antenna has very narrow ending zones. As was pointed out above, the last or the 150th zone is only 185 μm wide. For comparison, the last zone of the microwave-design FZP lens in FZPA-M-10 is 2830 μm width or about 15 times broader;

(ii) microwave-design FZP lens in the FZPA-M-10 antenna working at high-terahertz harmonics has a much simpler construction and can be easily fabricated, while the terahertz-design FZP lens needs sophisticated, precise, and costly microtechnology for its production;

(iii) narrow-zone terahertz-design FZP lenses are more fragile electrically and might not withstand high-energy illumination [18, 19].

It is fascinating that the big microwave-design antenna FZPA-M-10 could operate at frequency harmonics much higher than the terahertz frequencies or in the infrared band, for instance, for which the antenna aperture efficiency will be really extremely low (at about $10^{-4} \div 10^{-5}$%). By all criteria and applications, such efficiency values will not be pragmatic.

Instead, the terahertz lens/antenna FZPA-T-150 could be chosen for reaching the low infrared range. As is pointed out above, its 15th harmonic is the infrared frequency of 20250 GHz (or 20.25 THz) that corresponds to wavelength of 14.81 μm. For a normal operation at this infrared wavelength, the thickness of the 1350 GHz FZP has to be very thin, less than about 0.1–0.15 wavelengths, or less than 1.5–2.0 μm. The linear transverse resolution r_0 of such terahertz lens/antenna operating at the infrared frequency will be around 12 μm.

5. Conclusion

The study exposes for the first time a number of intriguing features related to the binary microwave FZP lens and antenna operating at harmonic terahertz frequencies. The harmonic gain versus frequency pattern shows a strict appearance of the peak gains in proportion to the frequency harmonic sequence 90 : 270 : 450, . . ., 1530 GHz. This antenna property makes the FZP lens antenna a frequency-domain filtering device. For a given microwave FZP design all harmonic gain peaks have roughly identical shapes, bandwidths, and top values. If the lens/antenna resolution is of major importance and the aperture efficiency is a secondary problem, or might be improved if necessary by additional amplification, the microwave-design FZP lens antenna can be of big importance. Unique and expensive microtechnology is not required for fabrication of simple and large in size microwave-design FZP lenses running at high-terahertz frequencies. Similarly, the terahertz-design FZP lens designs can be used for focusing in the infrared or higher optical bands. Also, the narrow-zone terahertz FZP lens designs are more fragile electrically if illuminated by high-energy fields.

The high-order harmonic operation of the FZP lens and antenna could find space resolution and frequency filtering applications in terahertz and optical metrology, imaging tomography, spectral analysis, short-range communications, synchrotron radiation and focusing facilities, and radio astronomy, among others.

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