Recent Advances in Fresnel Zone Plate Antenna Technology

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Abstract: *This paper outlines some of the recent advances in Fresnel zone plate antenna technology. Sidelobe reduction and control over sidelobe location are two developments which are useful for interference reduction. Another development is the focusing resolution of Fresnel zone plate antennas for sub-wavelength focal distances. Designs will be given for spatial resolutions of less than* $\lambda/2$.

1.0 Introduction

The aperture of the conventional Fresnel zone plate antenna (FZPA) is planar and consists of circular zones which alternate between air and metal as shown in Fig. 1. The FZPA is illuminated by a feed antenna located along the z-axis at a distance F from the aperture plane and the overall diameter of the antenna is D. The metal zones represent the locations on the surface of the aperture where the electromagnetic waves from the source are 180° out of phase relative to the center of the aperture. The

metal zones block the out-of-phase waves while the waves passing through the air zones combine constructively to collimate a beam in the far field. The waves that are blocked by the metal zones therefore do not contribute to the antenna radiation pattern.

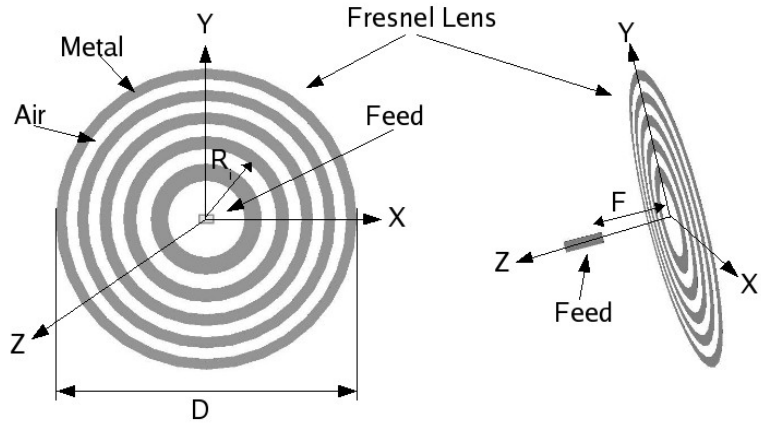


Fig. 1: Conventional FZPA in Transmission Mode

Due to overcrowding problems in the lower frequency bands and to the ever-increasing demand for more bandwidth, the Ka-band (26GHz – 40GHz) has been drawing significant attention over the last few years for future wireless applications. The migration to these higher frequencies will require new antenna technology since traditional high-gain antennas such as parabolic reflectors, shaped dielectric lenses, and planar arrays are not adequate due to either large physical volumes, high losses, or added fabrication complexity. FZPAs offer many practical advantages in the Ka-band over these traditional technologies. They are less complex to fabricate, have a reduced aperture profile, are lighter weight, and are less expensive.

The two primary disadvantages of the FZPA are low aperture efficiency (on the order of 10% for amplitude binary type), due to half the energy being reflected off the metal zones, and large physical volume, due to the location of the feed in front of the lens aperture, which is a problem also shared by reflectors and dielectric lenses. Several methods have been developed over the last few decades to

improve the aperture efficiency [1]-[6] with varying degrees of success. In [3] aperture efficiencies on the order of 30-50% were achieved using a dielectric lens with phase compensation. In [5] the aperture efficiency of the zone plate was improved to 20% by placing a reflector $\lambda/4$ behind the lens. Some attempts have also been made to reduce the volume [7][8]. In [7], focal lengths were reduced from 15λ to 3λ and in [8] the focal lengths were reduced from 3.75λ to 1.25λ.

Recent research has been devoted to improving other aspects of the FZPA radiation characteristics [9]-[12]. This paper will highlight three of these advances. The first is a design improvement which involves the effective use of a newly identified parameter, the reference phase, to lower sidelobe levels [10]. The second is a technique which involves changing the shape of the conventional FZPA zones to be polygonal so that control over the sidelobe levels and locations can be achieved [9], [12]. The last development involves determining the spatial resolution of the FZPA with sub-wavelength focal distances.

2.0 Optimal Reference Phase for FZPA

Fig. 2 illustrates the side-view of the FZPA geometry which shows an antenna of diameter D in transmit mode using a ray-tracing model. The fields radiated from the source travel varying distances before reaching the lens surface. The shortest distance traveled is F with all other paths being longer by Δ_i, the path difference. The phase of the shortest path is ϕ_o, and the fields along the lens surface, at a radius, r_i, will have a relative phase,ϕ_i.

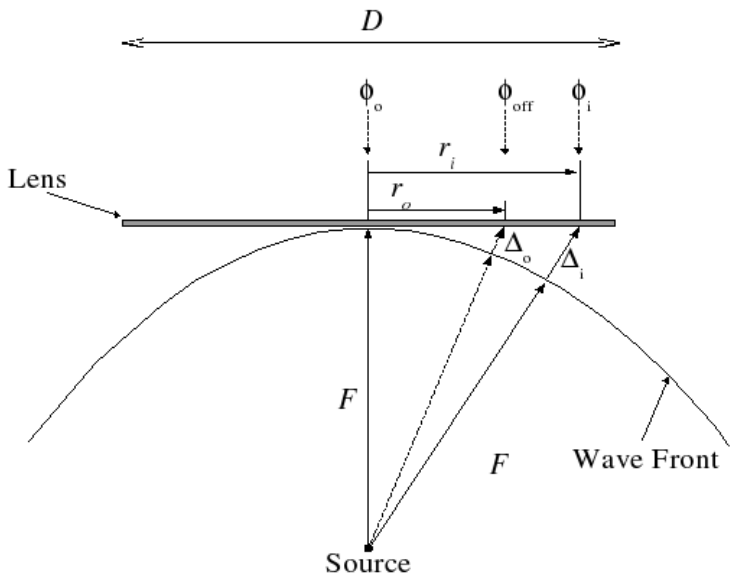


Fig 2: FZPA Diagram (Side View)

Historically, the radius of the first zone was chosen such that the phase difference, $\phi_1 - \phi_o$, was 180°. This decision was made to ensure that the out-of-phase radiation from 180° to 360° was blocked in order to achieve constructive interference in the far field. However, this phase difference does not have to be 180° and can actually be any value between 0° and 180° [13]-[15].

Changing the phase difference between ϕ_1 and ϕ_o creates a new first zone with radius r_o and offset phase ϕ_{off}, as illustrated in Fig. 2. This causes a shift in the phase of all the other zone radii such that the phase of the second zone is 180° from ϕ_{off} and the phase of the third zone is 180° from the second zone, etc... The creation of the new zone can be thought of as a form of phase correction since instead of allowing the phase difference, or error, to reach 180°, it is corrected at a value less than 180° while still maintaining constructive interference in the far field. The reference phase is defined as the sum of ϕ_o and ϕ_{off} and is represented by Φ_o.

Antenna designs take this parameter into account by including it in the computation of the Fresnel zone radii as shown in (1). This equation comes from an analysis of the trigonometry in Fig. 2 where ϕ_i

is the electrical length of Δ_i, N is the total number of zones and the zone index starts at zero instead of one in order to include the additional zone. Inspection of (1) confirms that increasing the reference phase effectively increases the radii of the Fresnel zones and hence the overall diameter of the lens. Also, it can be shown that if $\Phi_o=0^o$ the familiar expression for 180° phase sub-zones results with $r_o=0$.

$$r_i=\sqrt{\left(\left[F+\frac{\lambda}{(2\pi)}(i\pi+\Phi_o)\right]^2-F^2\right)} \qquad i=0,1,2,3,\ldots,N \qquad (1)$$

Fig. 3 show a comparison at 30GHz between H- and E-plane relative 1st sidelobe level versus the reference phase using a finite-difference time-domain (FDTD) software. The FZPA in this case has a focal distance of 3.75cm and a diameter of 15.8cm with 10 zones. The best sidelobe level was achieved when the reference phase was 60 degrees with a drop of about 6.2dB and 6.5dB in the H- and E-planes respectively when compared to the zero degree reference phase case. These results were confirmed through measurements. Thus by altering the reference phase, a significant improvement in sidelobe levels can be achieve with little degradation in peak directivity [10].

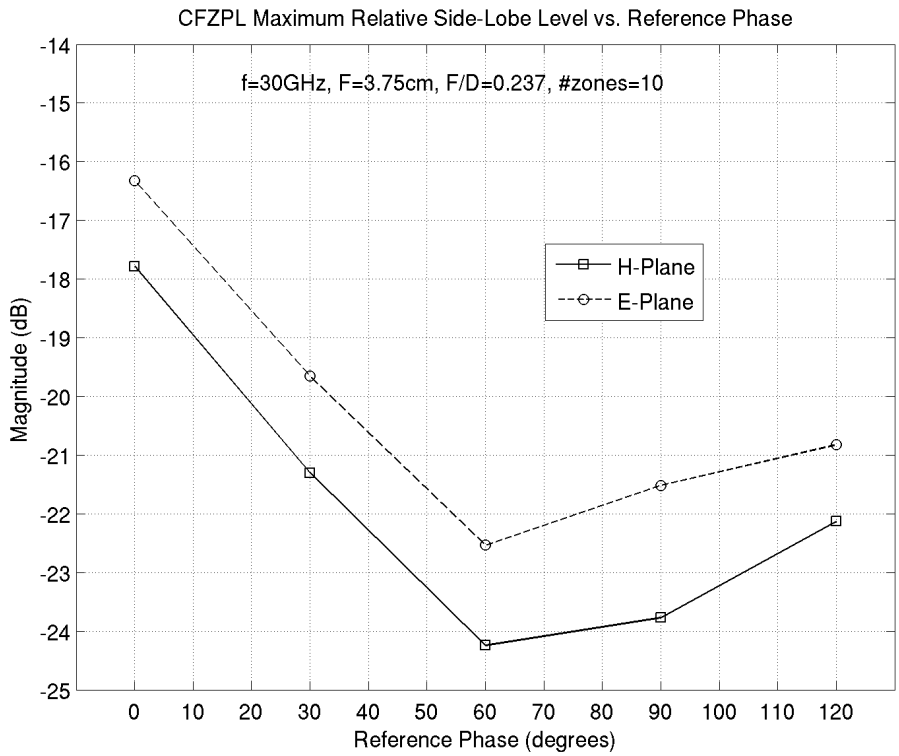
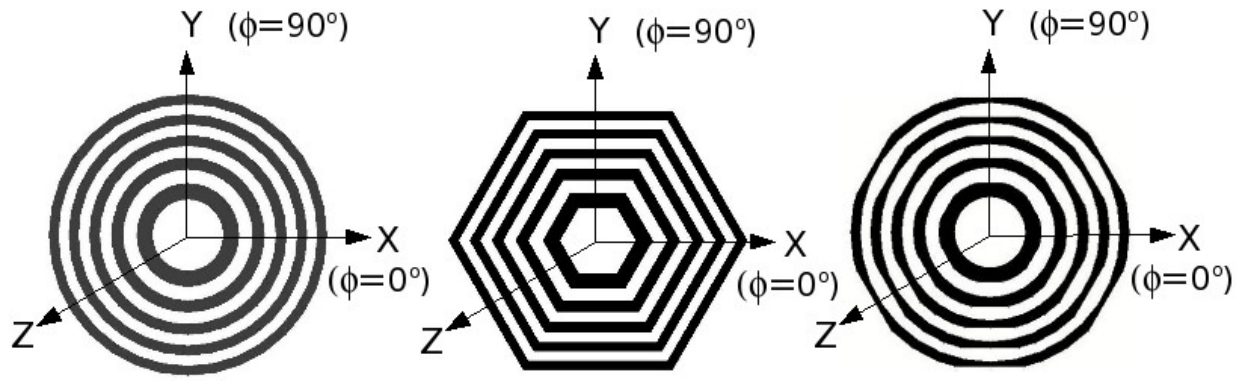


Fig. 3: Relative 1st Sidelobe Level with Varying Reference Phase (Φ_o)

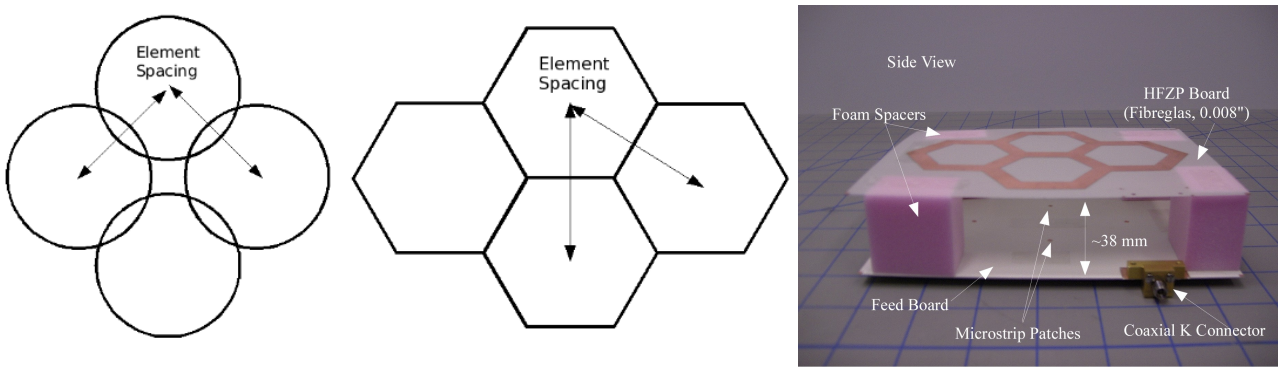
3.0 Control of FZPA Radiation Patterns

In a recent paper [9], hexagonal zones were proposed as an alternative to the conventional circular zones in the FZPA. The hexagonal geometry, shown in Fig. 4b, is interesting in that the zones are no longer circularly symmetric so that they can be rotated with respect to each other and provide control over certain characteristics of the radiation pattern [16]. The hexagonal shape is also beneficial in that it avoids overlap areas when the FZPA elements are used in an array, as shown in Fig. 5 (a) and (b). Fig. 5(c) is a picture of a single-zone hexagonal array from [17] which was a recent publication highlighting the potential of the hexagonal element in an array.



(a) (b) (c)

Fig. 4: (a) Circular Zone FZPA, (b) Hexagonal Zone FZPA, (c) Alternating Hex-Cut Zone FZPA



(a) (b) (c)

Fig. 5: Arrays of (a) Circular FZPAs, (b) Hexagonal FZPAs, (c) Prototype from [17]

However, since the hexagonal FZPA is inherently an approximation to the circular FZPA, it has a lower directivity, higher sidelobe levels, larger 3dB beamwidths, and higher cross-polarization levels compared to the circular version [9]. In order to maintain the hexagonal shape but bring the radiation characteristics closer to those of the circular FZPA, alternating hex-cut zones can be used as shown in Fig. 4(c) [12]. In this way, the hex-cut or trimmed zones maintain partial circularity but still allow for array packing and zone rotation.

The hex-cut zones were created by first making an optimal hexagon following the method described in [9] and [18]. In this way, the dimension from the center of the optimum hexagon to the hexagonal edge is actually smaller than the radius of the equivalent circular zone. The optimum hexagonal zone

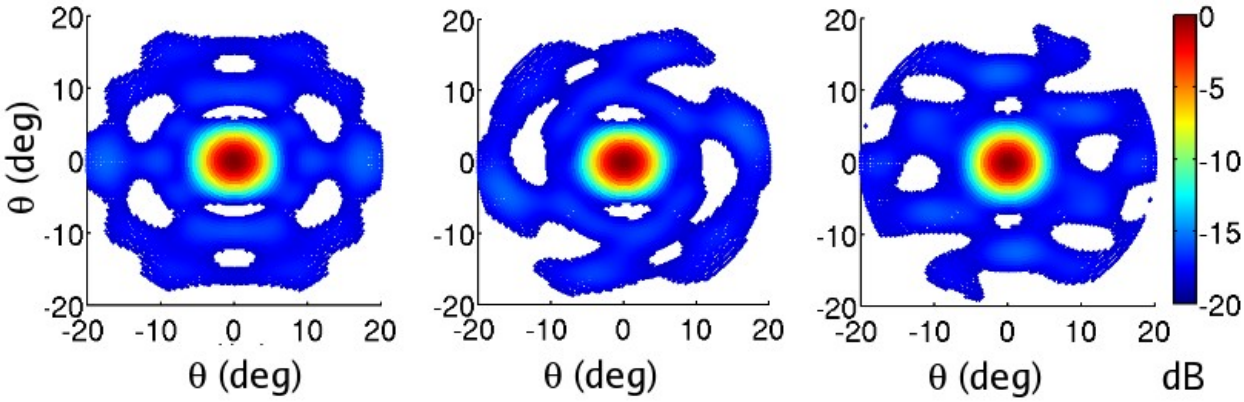
was then overlayed on the circular zone which has a radius defined in (1). Once overlayed, the perimeter of the circular zone was trimmed where it intersected the hexagonal sides. This process was applied to alternate zones of a 10-zone FZPA with F=3.75cm, F/D=0.237 and the results were compared to the conventional circular as well as the hexagonal zone FZPA cases. Table I outlines these results. Compared to the circular version, the FZPA with alternating hex-cut (AHC) zones had only a slight decrease in peak directivity and a slight increase in the maximum sidelobe (SLB) over all phi angles.

TABLE I
SUMMARY OF RESULTS

FZPA Configuration	**Peak Directivity (dB)**	**Relative Max. SLB over all ϕ (dB)**
Standard Circular Zones	24.65	-16.30
Alternating Hex-Cut Zones	24.33	-15.57
All Hexagonal Zones	21.52	-8.57

The radiation pattern control comes from rotating the zones of the AHC FZPA. The maximum angle of rotation was 60 degrees due to the symmetry of the structure. Various configurations of zone rotation were modeled using FDTD software. If the rotation was progressive from zone to zone, the sidelobes were found to smear and form a pin-wheel around the main beam. When the zone rotation was not progressive the sidelobes appeared shifted and/or tilted instead of rotated. Fig. 6 shows the contour plots of the far-field radiation pattern for three different rotation configurations of the AHC FZPA. The peak level is normalized to 0dB and the pattern contours are shown down to about -20dB. Fig. 6(a) shows a case with no rotation, Fig. 6(b) shows a case with a progressive zone rotation of 0°, 10°, 20°, 30°, 40° from outer to inner alternating zones, and Fig. 6(c) shows a case where the zone rotation was 0°, 30°, 15°, 30°, 0° from outer to inner alternating zones. This work concluded that depending on the exact zone

rotation configuration, the sidelobes can be moved and the level of the maximum sidelobe can be affected. This is useful for interference mitigation since the location of the sidelobes can be moved to avoid picking up interfering signals from specific directions.



(a) (b) (c)

Fig. 6: Effect of Zone Rotation on Sidelobes:
(a) No Rotation, (b) Progressive Rotation, (c) Non-Progressive Rotation

4.0 Resolution of FZPA with Sub-Wavelength Focal Distance

Sub-wavelength focal distances are important in order to make compact FZPAs. However, with these small focal distances the standard equations for spatial resolution given by the Rayleigh criterion [6] and the Abbe limit [19] are no longer valid. It is therefore difficult to predict what resolutions are achievable in sub-wavelength configurations and so the values have remained unknown. It was shown recently using FDTD software in [19] that a spatial resolution of less than 0.5λ could be achieved for a phase correcting dielectric Fresnel lens antenna having an $F/D < 0.2$ and $F < 2\lambda$. This resolution is significantly finer than what can be achieved from lenses with larger values of *F/D*. In [19] it was also shown that as the *F/D* decreases, the spot beam size decreases as well thus enabling a finer resolution to be achieved. These interesting results were motivation to determine whether similar spatial resolutions

could be achieved for FZPAs under similar *F/D* and focal distance conditions.

In order to observe the spatial resolution of a lens antenna, the focal fields had to be determined. This involved illuminating the lens with an incident plane wave propagating in the +z-direction and polarized in the y-direction (see coordinate system in Fig. 1). A 10-zone, F=0.5λ and F/D=0.045 FZPA at 30GHz was used for the comparison since it was the closest match to the dielectric lens from [19]. Fig. 7 shows the normalized average power density along the z-axis (x=y=0). In this figure, the lens is located at z=1.5λ and the focus is to the right of the lens at z=2.14λ.

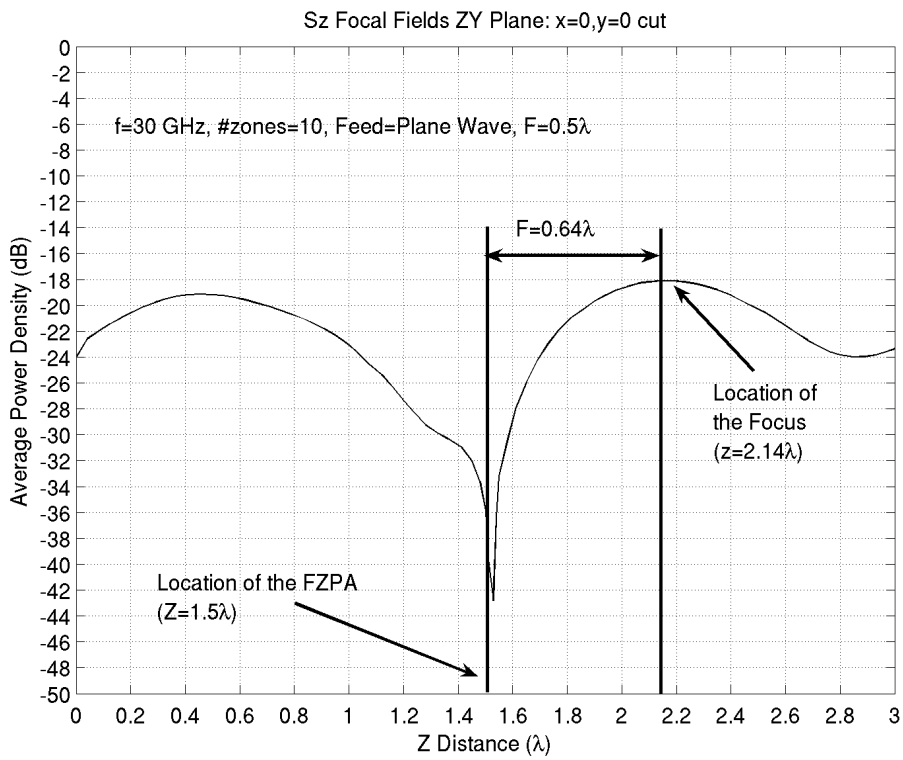


Fig. 7: Normalized Average Power Density (x=y=0)

Fig. 8 shows the normalized magnitude of the spot beam along the x and y-axes respectively. The spatial resolution was determined from these graphs by the distance between the peak and the location of the first nulls in the spot-beam pattern. These results are summarized in Table II where it can be seen that the spatial resolution of the FZPA is also under 0.5λ and is close to that of the dielectric Fresnel

lens, particularly along the x-axis.

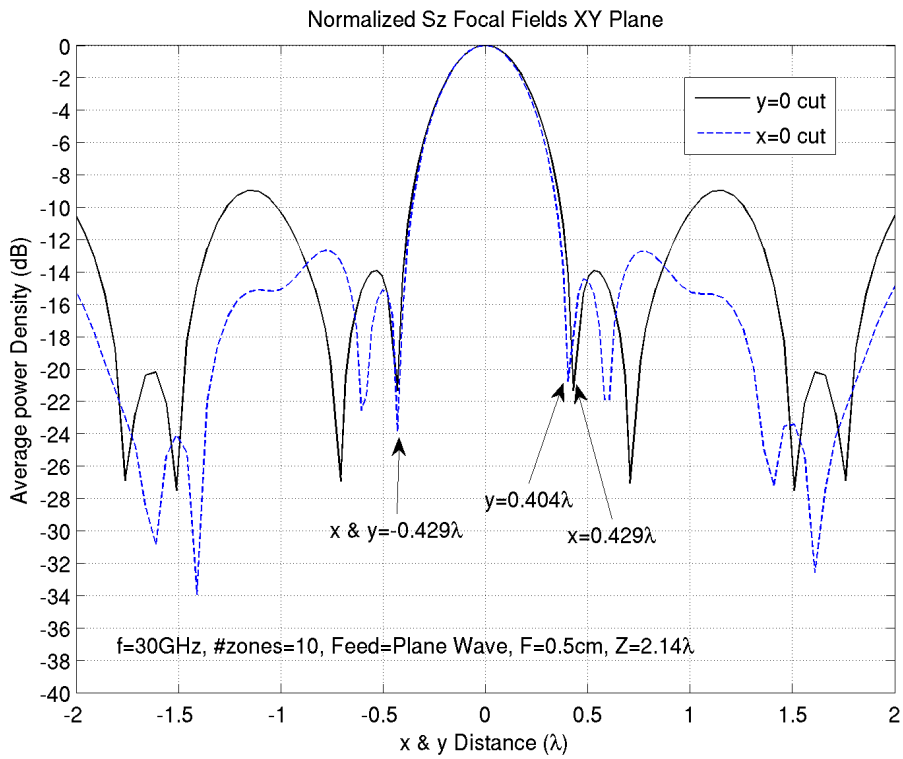


Fig. 8: Normalized Average Power Density (z=2.14cm)

TABLE II
COMPARISON OF SPATIAL RESOLUTION
BETWEEN FZPA AND DIELECTRIC FRESNEL LENS ANTENNA

Antenna Type (*F*=0.5λ)	**X-Axis Resolution (λ)**	**Y-Axis Resolution (λ) left/right**
Fresnel Zone Plate	0.429	0.429 / 0.404
Dielectric Fresnel Lens (Er=4)	0.410	0.37 (avg of left & right)

Fig. 9 shows how the peak power density varied with frequency. The maximum peak power density occurred at 34.5GHz and the 1dB peak power density bandwidth was 6.6GHz or 19%. The x-axis resolution improved to 0.404λ at 34.5GHz which was slightly better than that of the dielectric Fresnel

lens.

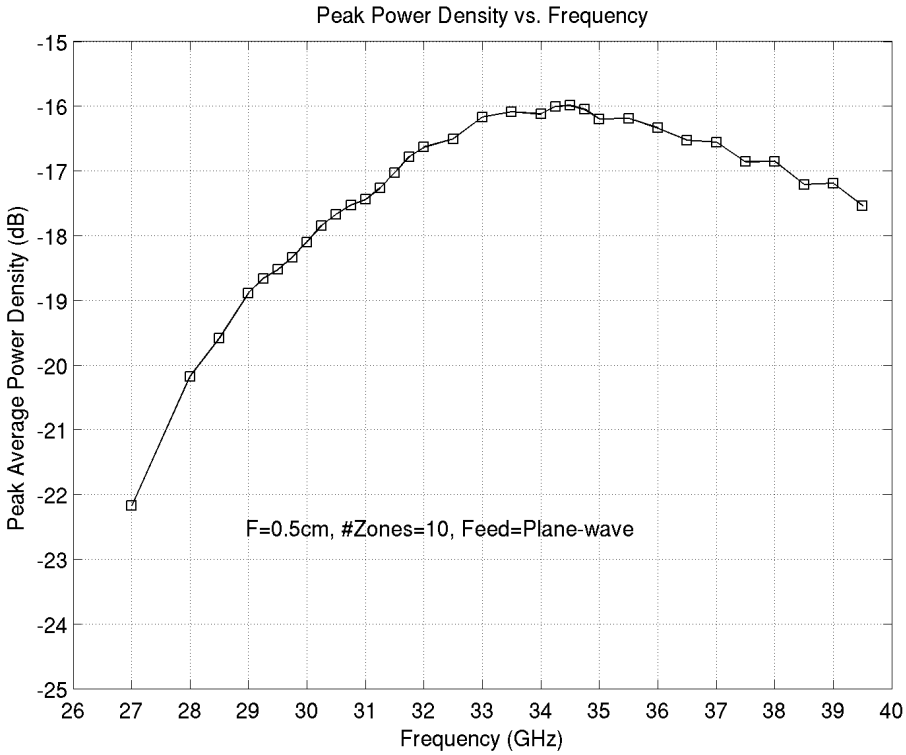


Fig. 9: Peak Power Density vs. Frequency

The ability of the FZPA to create a small spot size with sub-wavelength focal spacing is related to the fact that the operation of the antenna depends more on the near or evanescent fields than on the radiative field components used in the standard interference methods [20]. Rayleigh and Abbe's limit apply to these standard interference methods but do not apply when the near fields are involved. This explains why sub-wavelength focusing can exceed the standard limits.

The FZPA with sub-wavelength focus is an important advance since it allows designers to create very compact antennas that will be more attractive for future wireless applications in the Ka-band.

5.0 Discussion

The advances described in this paper provide enhanced capability to the FZPA making them well suited for applications in the Ka-band which require compact, high gain, and specific sidelobe templates.

Such specifications will certainly be required in future terrestrial wireless and certain satellite systems where the use of existing technology, such as microstrip patch arrays, is not adequate due to the high losses and costs at 30GHz.

6.0 Conclusions

Over the last few years, several advances have been made in the field of Fresnel zone plate antennas. Three significant advances were summarized in this paper. The first one involved making use of the reference phase of the FZPA. Careful selection of this parameter enabled a decrease in the overall sidelobe level performance and should also be applicable to various types of phase-correcting dielectric Fresnel lenses which have significantly better radiation efficiencies. The second advance involved modifying the shape of the zones from circular to hexagonal-cut. By doing this, there was no longer symmetry between the zones which meant that they could be rotated with respect to each other. This approach gives the designer some control over the location and level of the sidelobes while having very little effect on the directivity of the conventional circular FZPA. Lastly, the spatial resolution of the FZPA was shown to be nearly the same as that of the dielectric lens for sub-wavelength focal distances and small *F/D* cases. This will provide further motivation to design compact FZPAs.

7.0 Acknowledgments

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8.0 References

[1] Wiltse, J.C., “History and Evolution of Fresnel Zone Plate Antennas for Microwaves and Millimeter Waves”, *IEEE Antennas and Propagation Int, Symp. 1999*, Special Section “Status and

Future of Fresnel Zone Plate Antennas", Orlando FL, July 11-16, 1999, Symp. Digest Vol.2, pp.722-725.

[2] Guo,Y.J., and Barton, S.K., *Fresnel Zone Antennas*, Kluwer Academic Publishers, Boston, 2002.

[3] Hristov, H.D., and Herben, M.H.A.J., "Millimeter-Wave Fresnel-Zone Plate Lens and Antenna", *IEEE Trans. Microw. Theory and Tech*, 1995, 43 (12), pp.2779-2785.

[4] Zhang, Wen-Xun, "An Improved Zoning Rule of the Fresnel Zone Plate", *Microwave and Opt. Tech. Lett.*, Vol. 23, No. 2, October 20 1999.

[5] Fujita, M., Yu, J., "Design and Analysis of a Folded Fresnel Zone Plate Antenna", *Int. Journal of Infrared and Millimeter Waves*, Vol. 15, No.8, pp. 1385-1406, 1994.

[6] Minin, O.V., Minin, I.V., *Diffractional Optics of Millimetre* Waves, IOP Publishing Ltd., Boston-London, 2004.

[7] Gouker, M.A., Smith, G.S., "A Millimeter-Wave Integrated-Circuit Antenna Based on the Fresnel Zone Plate", *IEEE Trans. Microw. Theory and Tech*, 1992, 40 (5), pp.968-977.

[8] Stout-Grandy, S., Petosa, A., Minin, I.V., Minin, O.V., Wight., J.S., "Investigation of Low Profile Fresnel Zone Plate Antenna", *URSI North American Radio Science Meeting*, Ottawa Ontario, July 23, 2007, CDROM.

[9] Stout-Grandy, S., Petosa, A., Minin, I.V., Minin, O.V., Wight., J.S., "Hexagonal Fresnel Zone Plate Antenna", *ANTEM 2006*, Montreal, Canada, July 2006 pp. 511 – 514,.

[10] Stout-Grandy, S., Petosa, A., Minin, I.V., Minin, O.V., Wight., J.S., "A Systematic Study of Varying Reference Phase in the Design of Circular Fresnel Zone Plate Antennas", *IEEE Transactions on Antennas and Propagation*, Vol. 54, No12, Dec 2006, pp 3629-3637.

[11] Stout-Grandy, S., Petosa, A., Minin, I.V., Minin, O.V., Wight., J.S., "A Novel Reflector-Backed Fresnel Zone Plate Antenna", *Microwave and Optical Technology Letters*, Vol. 49, No. 12, Dec 2007, pp.3096-3098.

[12] Stout-Grandy, S., Petosa, A., Minin, I.V., Minin, O.V., Wight., J.S., "Fresnel Zone Plate Antenna with Hexagonal-Cut Zones", Accepted for publication in *Microwave and Optical Technology Letters*, March 2008.

[13] Minin, I.V., Minin, O.V., Webb, G., "Flat and Conformal Zone Plate Antenna with New Capabilities", *Proc. International Conference on Applied Electromagnetics and Communications –*

ICECOM 2005, Dubrovnik, Croatia, Oct. 11-14, pp.405-408.

[14] Minin, I.V., Minin, O.V., "Control of Focusing Properties of Diffractional Elements", *Sov. J. Quantum Electron*. Vol. 20, No. 3, pp.198-199, 1990.

[15] Minin, I.V., Minin, O.V., "Three Dimensional Fresnel Antennas", Chapter 5, *Advances on Antennas, Reflectors and Beam Control*, Research Signpost, Kerala, India, 2005, pp.15-148.

[16] Danilov E.G., Lbov G.S., Minin, I.V., Minin, O.V., "Parameter Optimization Algorithm of a New Type of Diffraction Optics Element", *Proc. 5th IEEE-Russia Conference Microwave Electronics: Measurements, Identification, Applications (MEMIA)*, Dec. 13-15 2005, Novosibirsk Russia, pp.177-185.

[17] Petosa, A., Thirakoune, S., Minin, I.V., Minin, O.V., "Array of Hexagonal Fresnel Zone Plate Lens Antennas", *IEE Electronics Letters*, Vol.42, No.15, July 2006, pp.834-836.

[18] Minin, I.V., Minin, O.V., Petosa, A., S. Thirakoune, "Improved Zoning Rule for Designing Square Fresnel Zone Plate Lenses", *Microwave and Optical technology Letters*, Vol.49, No.2, 2007, pp.276-278.

[19] Minin, I.V., Minin, O.V., Gagnon, N., Petosa, A., "Investigation of the Resolution of Phase Correcting Lenses with Small Focal Length-to-Diameter Ratios and Subwavelength Focus", *Electromagnetic Theory Symposium (EMTS) 2007*, July 26-28, 2007, Ottawa, On, Canada, CDROM.

[20] Merlin, R., "Radiationless Electromagnetic Interference: Evanescent-Field Lenses and Perfect Focusing", *Science*, Vol. 317, August 17, 2007, pp. 927-929.