Analysis of Electromagnetic Simulation Method for the Dielectric Lens Antenna

Farizah Ansarudin[1,3], Tharek Abd. Rahman[1], Yoshihide Yamada[2*], Nurul Huda Abd Rahman[2,4]

[1]Universiti Teknologi Malaysia,
 School of Electrical Engineering, Johor Bahru, 81310, MALAYSIA

[2]Universiti Teknologi Malaysia,
 Malaysia-Japan International Institute of Technology, Kuala Lumpur, 54100, MALAYSIA

[3]Universiti Kebangsaan Malaysia,
 Faculty of Engineering & Built Environment, Selangor, 43650, MALAYSIA

[4]Universiti Teknologi MARA,
 Faculty of Electrical Engineering, Shah Alam, Selangor, 40450, MALAYSIA

*Corresponding Author

Abstract: For the millimetre wave usage at 5G mobile communication system, a dielectric lens antenna will become a promising candidate for the base station antenna. In developing a dielectric lens antenna, antenna performance analysis by an electromagnetic simulator will be necessary. The structure of the proposed design is a hyperbolic dielectric lens antenna fed by a pyramidal horn at the operating frequency of 28GHz. In this paper, the abilities of a commercial electromagnetic simulator FEKO are investigated. Simulation methods of GO and MoM solvers are shown for electric field distributions on the antenna aperture and far field radiation patterns. The simulation results show that the optimum gain of lens antenna based on GO and MoM method are 26.68 dBi and 27.24 dBi, respectively. Moreover, multi beam radiation patterns and suitable feed positions are clarified for wide scanning angle. Good performance for multi beam application by using MoM is shown based on the off-focus characteristic where the antenna gain is only slightly reduced from 0.51 dBi to 4.03 dBi for 5.71° to 35.54°.

Keywords: Hyperbolic lens, refractive index, on-focus, off-focus, method of moment, geometrical optics

1. Introduction

In 5G mobile system, many new technologies are required such as millimetre wave (mm-wave), massive multiple-in multiple-out (MIMO) technology [1], multi beam base station antenna, advanced multiple access and higher order modulation and coding. 5G requires a wide frequency band to provide high-speed communications. The current microwave frequency spectrum suffers from congestion and are not able to support the demand for higher data rate mobile smartphone users due to the limitation of spectrum at these frequencies. In developing new base station antennas, significant difference from the present system is the antenna size and its beam pattern. Multiple radiating beams with high gain performance are expected for the 5G base station as one radiating beam is assigned for one user only.

This paper describes the use of dielectric lens antenna (DLA) for multi beam 5G base station application at 28 GHz based on numerical method. At this frequency, DLA is selected by considering its ability to eliminate aperture blockage by the feed, excellent multi beam shapes, good scanning performance and acceptable in size and weight for many applications [2-4]. Besides, it can be easily contoured to any reasonable shapes to produce a specified beam pattern. There are two main categories of lens antenna depending on its application; either shaped lens antenna for collimating radiated energy or cylindrical and spherical for beam scanning with single or multiple feed possibility [4].Lens shaping techniques have been investigated by many researchers based on conventional geometrical optics (GO), transformation optics (TO), analytical method combining approximation of GO and physical optics (PO) as well as genetic algorithm depending on its applications [5-7]. The GO approach is fairly accurate for structures that are large compared to the wavelength of the radiation. In this paper, the numerical methods of spherical DLA for required beam pattern of on-focus and off-focus feed using MoM and GO method will be discussed.

2. Lens Surface Equation

The analysis of lens shaping had been discussed to ensure the accuracy of the design structure for multi beam application. The lens antenna structure and coordinate system are shown in Figure 1. The lens is symmetrical around the z-axis. The x-axis corresponds to the radial direction of the lens and z-axis corresponds to the longitudinal direction. The purpose of this paper is to clarify the suitable electromagnetic simulation method for a DLA. The simplest hyperbolic lens shape is selected. The feed is set at the focal point of (0,0) coordinate. The lens inner surface is expressed by (x,z) coordinate. The distance from the focal point to the inner lens surface (S1) is expressed by r. The focal length, F and lens thickness, T are shown in Figure 1.
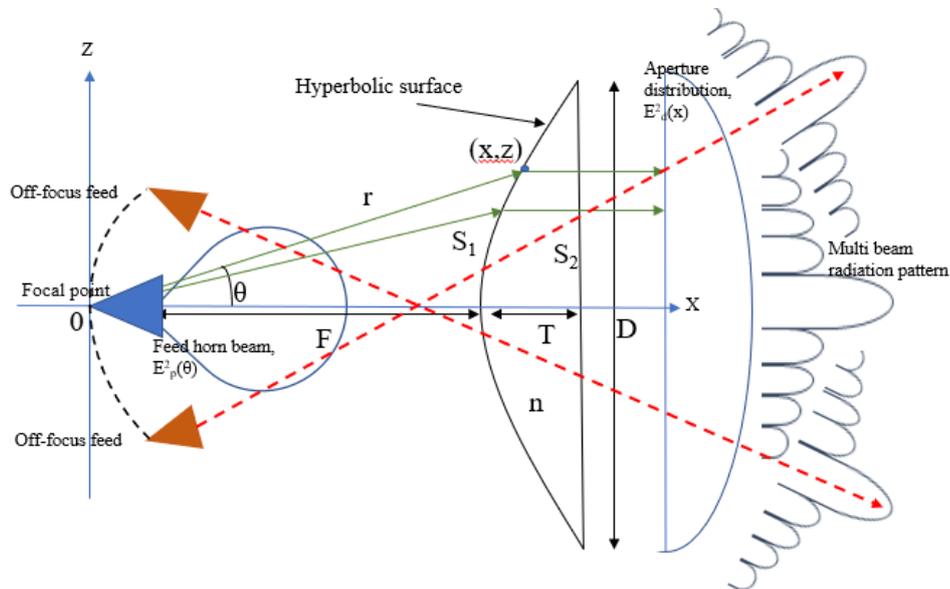

Fig. 1 - Hyperbolic lens antenna configuration and the concept of multi beam radiation pattern

When the inner surface is given by Eq. (1), (2) and (3), the refracted ray at the inner surface becomes parallel to the x-axis [8]:

$$r = \frac{(n-1)F}{n\cos\theta - 1} \tag{1}$$

$$x = r\cos\theta \tag{2}$$

$$z = r\sin\theta \tag{3}$$

where n is the refractive index of lens material and F is the focal length from radiating element to S_1. For a given diameter, D, the central thickness, T of the lens is expressed by:

$$T = \frac{1}{n+1}\left[F^2 + \frac{(n+1)D^2}{4(n-1)} - F \right] \tag{4}$$

3. Electromagnetic Simulation Model

3.1 Dielectric Lens Antenna Structure

Figure 2 shows the configurations of the hyperbolic surface of dielectric lens antenna in the electromagnetic simulator, FEKO. The lens is set symmetrical along y-axis. A pyramidal horn antenna is applied as a radiating element with maximum gain of 15.09 dBi. The lens diameter is about 10λ with 28GHz frequency employed in the system. The ratio of focal length, F and lens diameter, D =100 is F/D = 1. The hyperbolic lens surface is designed in FEKO based on Eq. (1), (2) and (3), respectively. The material used for dielectric lens antenna with permittivity value, $\varepsilon_r = 4$ and lens thickness, T is determined by Eq. (4). Table 1 shows the configuration of the dielectric lens antenna.

Table 1 - Dielectric Lens Antenna Configuration

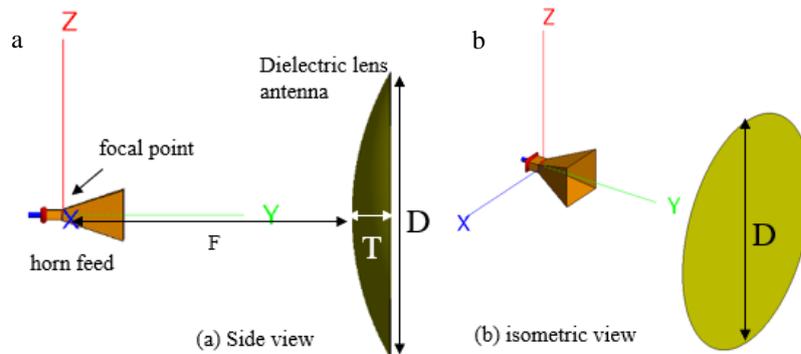| Parameter	Dimension
Diameter, D	100 mm
Focal Length, F	100 mm
Lens Thickness, T	10.76 mm
Refractive index, n	2
Maximum angle, θ_m	24.29°

Fig. 2 - The dielectric lens antenna (a) side view; (b) isometric view

Table 2 shows the several coordinate points of the surface from origin, θ=0° to maximum angle, θ_m=24.29°. All 147 data points are calculated to design lens surface in FEKO using polyline curve.

Table 2 - Lens Surface Coordinates

Angle,θ (°)	y	z
24.29	50	110.76
20.19	39.36	107.01
15.00	27.79	103.66
10.04	17.98	100.16
5.19	9.13	100.83
0	0	100

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3.2 Simulation Parameters

The specification of the super computer in the Communication System Network Laboratory, MJIIT-UTM and the simulation parameters are shown in Table 3. Two simulation methods are conducted using Method of Moment (MoM) and hybrid simulation using Ray Launching-Geometrical Optics (RL-GO)-MoM for the whole antenna system. The horn feed with Perfect Electric Conductor (PEC) material is simulated based on MoM with mesh size of $\lambda/12$. For dielectric lens antenna, mesh size of $\lambda/5$ is employed for optimum simulation by MoM and GO method, respectively.

Table 3 - The Simulation Parameter

Parameter	Specification
Computer	
Processor	Xeon 2.10 GHz
Random Access Memory	512GB
Electromagnetic Software	FEKO 2018
Lens Antenna	
refractive index, n	2
tan δ	0.0004
Mesh size	$\lambda/5$
Number of mesh	66,112
Feed Horn	
Mesh size	$\lambda/12$
Number of mesh	18,532
Calculation Time	
MoM	1H
RL-GO and MoM (Hybrid)	3H

3.3 GO Method

Multi beam characteristics based on ray tracing in this method is analysed using hybrid simulation, where two solvers, MoM and RL-GO are employed in performing the simulation of a feed horn and a DLA. The solver in FEKO that is used to produce ray tracing is RL-GO which is employed between the lens structure to the aperture plane. However, ray is not extended to the aperture plane unless other material is associated with the lens structure as shown in Figure 3. The rays can be refracted from surface 1 and surface 2 of the lens to the aperture plane by assigning an air region.
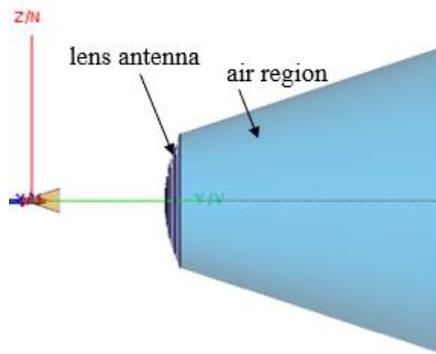

Fig. 3 - Lens antenna is associated with air region

Figure 4(a) shows all rays become parallel at on-focus feed after refracted from the lens surface. It shows that the lens concept of Figure 1 is verified clearly. In order to investigate the accuracies of GO method in FEKO, multi feed positions are simulated at $\theta_{F6} = 35.54°$ for off-focus feed as shown in Figure 4(b). It shows that the transmitted rays are almost parallel to the aperture plane and the accuracy of feed position is ensured. Figure 5 shows the radiation pattern simulated by GO method at $\theta_F = 0°$ and $\theta_{F6} = 35.54°$, respectively. The results show that there is slight reduction in gain, and the difference is observed from 26.68 dBi to 23.67 dBi for $0°$ to $35.54°$. However, the beamwidth becomes larger from $\theta_B = 6.68°$ to $\theta_B = 9.68°$ which is clearly seen that the beam is distorted due to interruption of phase distribution. The concept of collimated rays occurred in on-focus and off-focus for each beam pattern is shown with parallel and almost parallel rays, respectively.
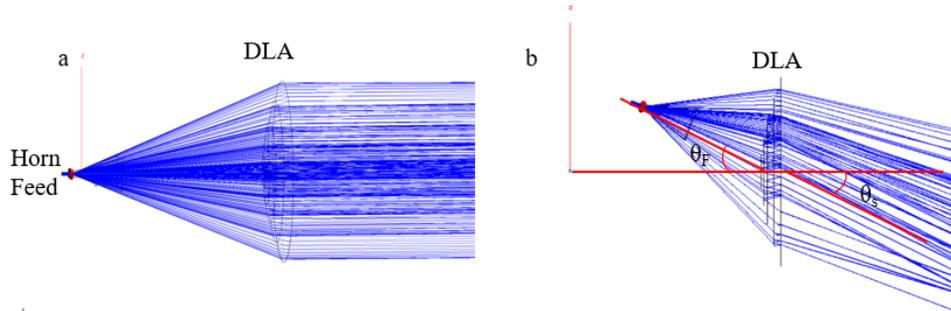
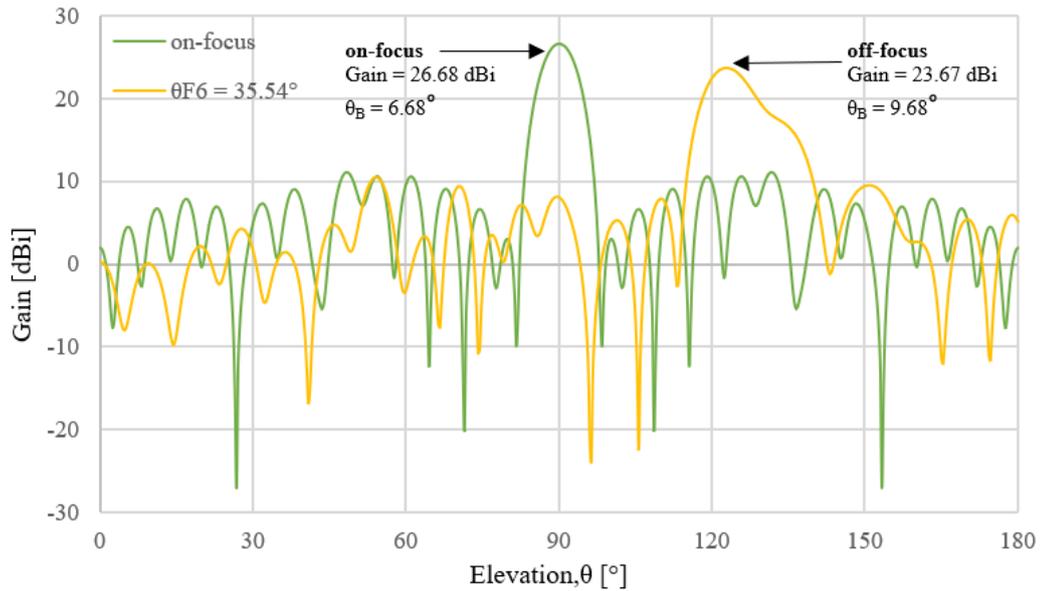**Fig. 4 - Ray tracing for different feed position (a) on-focus; (b) off-focus**

Fig. 5 - Radiation pattern by GO method

3.4 MoM Method

3.4.1 Feed Horn Structure

The horn is excited at the feed point by a waveguide source as shown in Figure 6. At the focal point from lens surface, the phase centre is at horn neck about 21mm inside from the horn aperture. The main specification in designing the feed horn is to obtain the correct radiation parameters [9-10], specifically around θ_B=7.06° beamwidth and low side-lobe level at the aperture plane that corresponds to 10λ or 100.71mm. The horn dimension is designed based on Eq. (5) to obtain -10dB edge level of lens at calculated beamwidth, θ_B=34.39°.

$$\theta_B = 57\frac{\lambda}{D} \qquad (5)$$

The simulated radiation pattern is almost symmetrical for E-plane and H-plane as shown in Figure 6. The 3dB beam width of each pattern is about 32.04° and 32.98°, respectively. There is about 1.41dBi to 2.35dBi differences between the simulated and the theoretical beamwidth. These differences might not affect the main lobe shapes because the radiated power is very small, which is less than 10dBi. The radiation angle to lens region of θ=2θ_B for both E-plane and H-plane are θ_E=56.24° and θ_H=60.21°, respectively. However, the optimization of phase centre shall be considered for the feed position in obtaining a uniform phase.
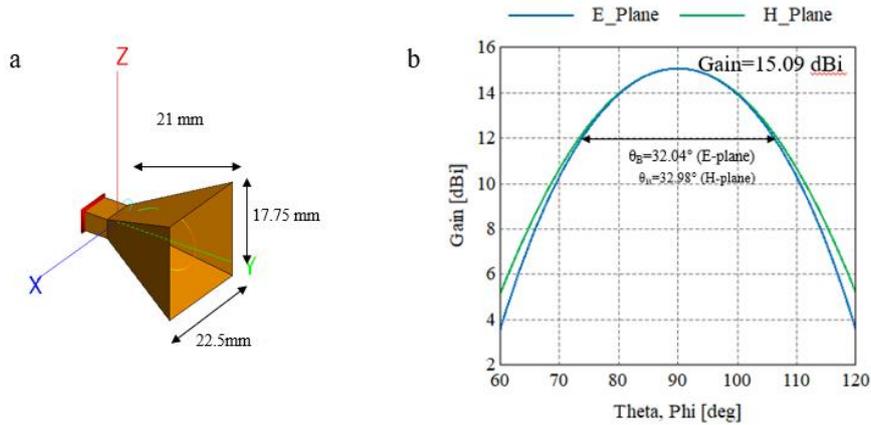
Fig. 6 - (a) Feed horn antenna; (b) Feed horn radiation pattern

3.4.2 Aperture Distribution

Antenna performance is investigated particularly according to its aperture distribution of field intensity and phase as shown in Figure 7 and Figure 8, respectively. The simulation of MoM method for the whole antenna system is employed for on-focus feed. From Figure 7, it is clearly seen that the edge level of the lens is -10dB and phase distribution is almost constant as shown in Figure 8.
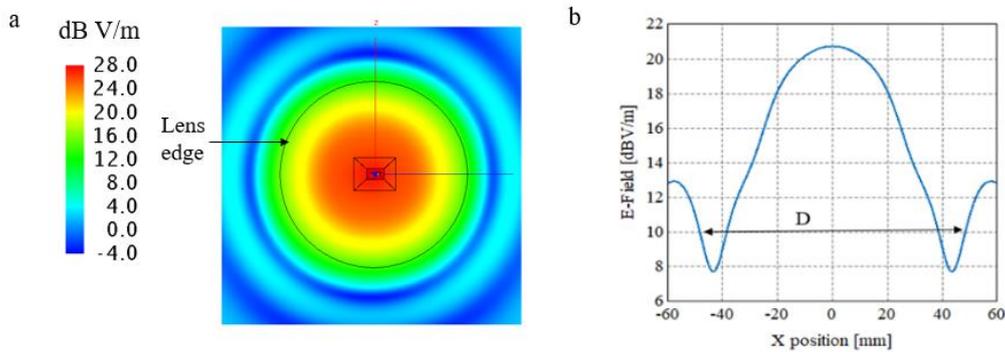

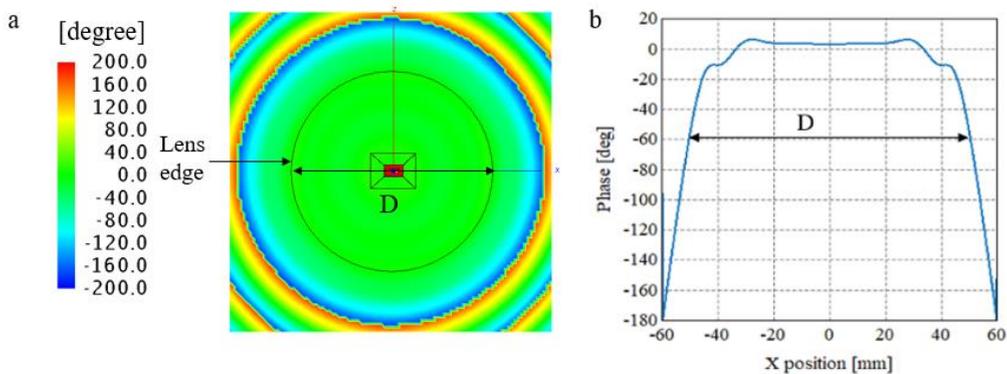**Fig. 7 - Electric field (a) intensity distribution; (b) amplitude distribution**

Fig. 8 - Electric (a) Phase contour; (b) Phase distribution

3.4.3 Radiation Pattern

The overall antenna system is simulated by electromagnetic software, FEKO using Method of Moment (MoM) and hybridization solver RL-GO with MoM at the operating frequency 28GHz. The hybrid simulation is conducted for pyramidal horn (MoM) because of PEC material and dielectric lens antenna (RL-GO) as an insulation material for

asymptotic method analysis at high frequency. The antenna is simulated for on-focus feed for F/D=1. All simulation results were compared with theoretical values of gain and beamwidth. Both theoretical gain and beamwidth are calculated using Eq. (6) and (7), respectively.

$$\theta_{BT} = 68.17 \frac{\lambda}{D} \qquad (6)$$

$$G_T = \left(\frac{\pi D}{\lambda} \right)^2 \qquad (7)$$

The comparison of far field distribution at elevation angle between MoM and GO method is shown in Figure 9. The simulation results show that the optimum gain, Gs for GO and MoM method are 26.68 dBi and 27.24 dBi, respectively. The simulated gain, $G_S = 27.24$ dBi for MoM corresponds to the aperture efficiency of $\eta = 61.67\%$ while GO of about $\eta = 54.22\%$ by comparing to the theoretical gain of $G_T = 29.34$ dBi [9]. Moreover, values of simulated beam width $\theta_{BS} = 7.01°$ and $\theta_{BS} = 6.68°$ for both methods were observed with theoretical values as tabulated in Table 4. It is shown that the MoM method is more accurate for the gain and beam width when compared to GO due to full wave analysis for deriving rigorous solution in the electromagnetic simulator. The analysis of antenna performance can be extended in next measurement process for comparison studies between simulation and measurement results.

Table 4 - Beam width and gain for dielectric lens antenna

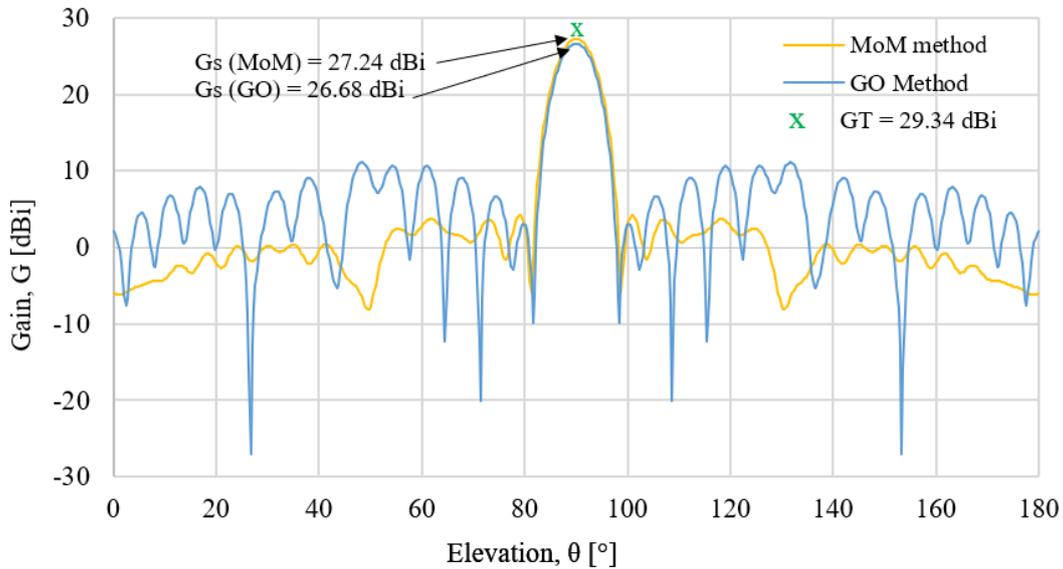| Theoretical Beamwidth θ_{BT} (°)	Simulated beamwidth θ_{BS} (°)	Theoretical Gain, G_T (dBi)	Simulated Gain, G_S (dBi)
7.3°	7.01°(MoM)	29.34	27.24 (MoM)
	6.68° (GO)		26.68 (GO)

Fig. 9 - Radiation pattern by MoM and GO method

4 Multi Beam Characteristics

4.4 Feed Position

The off-focus feeds for various angles have been employed at YZ plane as shown is Fig. 10. Feed points are typically shifted about 5° to 8° for each off-focus position. Previously, focal region was calculated through receiving mode ray tracing with caustic point as the best feed position [11-12]. In this paper, a simple linear regression is applied for off-focus feed determination. The optimum feed positions for off-focus feeds are shown in Figure 11 and Table 5. These positions are approximately expressed by Eq. (8).

$$z = 1.1619y \qquad (8)$$

It is visibly seen that the feed position is linearly increased with increasing value of incident angle. In addition, shifted beam direction, θ_s is smaller than the feed angle, θ_F for F1 to F6. This condition encounters the principle of Snell's Law when the waves are passing through between two boundaries from free space to dielectric material. The locus of feed position, R(y,z) from focal length, F can be derived as:
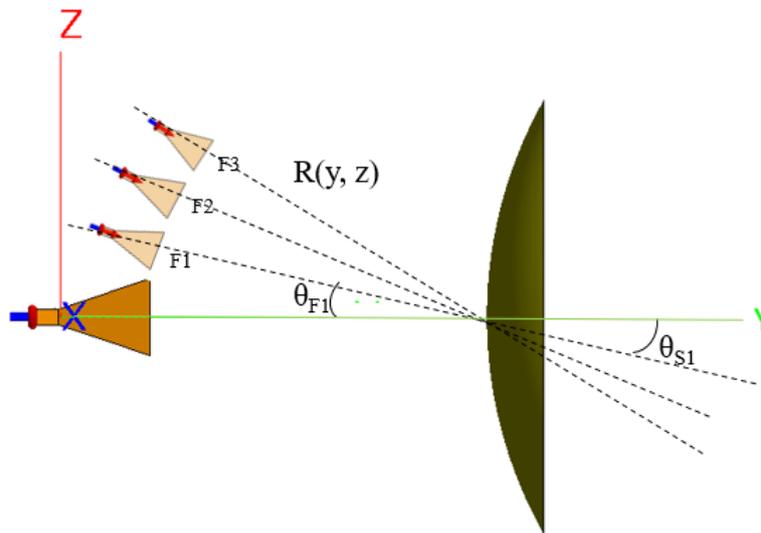
$$R(y,z) = \frac{F-y}{\cos\theta_F} \qquad (9)$$

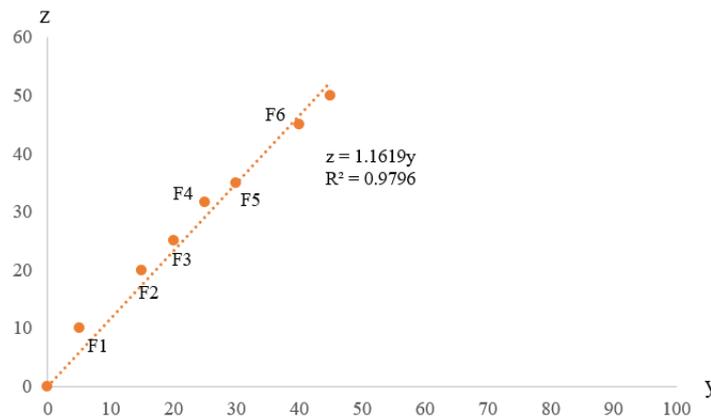**Fig. 10 - Off-focus beam scanning for various feed angle, θ_F**

Fig. 11 - Linear regression for feed horn position with R^2=0.9796

Table 5 - Feed positions for off-focus

Feed Number (off-focus)	Feed Position y	z
F1	5	5.81
F2	15	17.43
F3	20	23.24
F4	25	29.05
F5	30	34.86
F6	40	46.48

4.5 Off-Focus Radiation Patterns

The off-focus beam characteristic is shown in Fig. 12 with scanning angle from 0° to 35.54° at YZ plane using MoM method. The gain is regularly reduced from 27.24 dBi (on-focus) to 23.21 dBi (F1-F6) when the incident angle of feed position is increased. It shows that the antenna performance using MoM for on-focus and off-focus is almost accurate for multibeam characteristics with gain reduction of about 0.42-3.8dBi from F1 to F6. The beam is slightly deteriorated (F6) at maximum scanning angle due to phase delay with the difference in gain of about 3.8dBi. Table 6 shows the antenna gain performance of on-focus and off-focus feed from F1 to F6 for scanning angle from 0° to 35.54°.
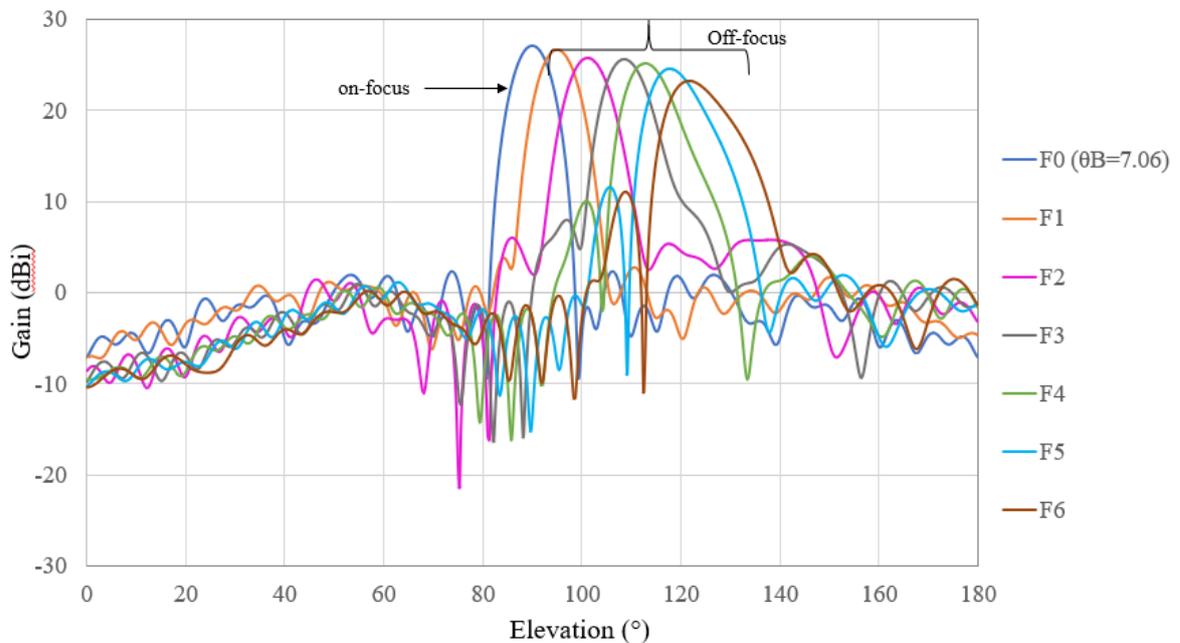

Fig. 12 - Radiation patterns for off-focus feeds at different angles

Table 6 - Off-focus feeds at different positions

Feed Position		Feed Angle, θ_F (°)	Shifted Beam Direction, θ_s (°)	Beam Width, θ_B (°)	Gain (dBi)
on-focus	F0	0	0	7.06	27.24
off-focus	F1	5.71	5.08	7.28	26.59
	F2	13.87	11.08	7.75	25.77
	F3	21.80	18.57	7.91	25.62
	F4	26.56	22.83	8.40	25.17
	F5	30.47	27.89	9.33	24.53
	F6	35.54	31.77	11.08	23.21

5 Conclusion

Lens shape for hyperbolic surface simulated at 28GHz that corresponds to 10λ diameter gives a promising beam width for base station installation. On-focus feed using hybrid method of RL-GO-MoM and MoM method provides optimum antenna performances. GO-MoM method shows that the concept of lens surface designing is ensured visibly because all rays become parallel to the aperture plane. However, multi feed position cannot be obtained accurately using ray tracing results in GO method due to the limitation of the 3D features of ray tracing plane view in FEKO. Besides, GO method is an approximation analysis for asymptotic technique for high frequency application. Conventionally, ray tracing technique for off-focus analysis can be developed by complete algorithm for computing the visibility between points [13]. The efficiency of simulated gain of MoM method is 61.67% accurate compared to GO method is only 54.2% between theoretical gain as calculated by (7). Beamwidth of MoM is slight closely to the theoretical values as calculated in (5) with difference angle of 0.29° while GO 0.62°. The results of MoM show good aperture distribution of amplitude and phase at on-focus feed for near field distribution. The off-focus beam scanning used in MoM shows that the feed position between F1 to F6 is suitable for multibeam characteristics because of low reduction in gain of about 4.03 dBi for scanning angle from 0° to 35.54°. The multi feed position is ensured based on the analytical expression (8) where the beamwidth and gain obtained are not much reduced.

Acknowledgement

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