Cylindrical Dielectric Lens Antenna for 5G Mobile Base Station

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Abstract. A wide range new technologies such as millimetre wave, massive MIMO technology, multi beam base station antenna are required in the fifth-generation (5G) mobile system. For multi beam base station application, a dielectric lens antenna is selected due to capabilities of achieving excellent radiation patterns in a wide angular range by applying the lens shaping method. A cylindrical structure is suitable for a lens antenna installation on the base station pole. In this paper, a cylindrical dielectric lens antenna is proposed and multi beam radiation patterns are investigated through the calculations by an electromagnetic simulator (FEKO) at the operating frequency of 28 GHz. As a result, good multi beam radiation patterns are achieved in the scanning angle from 0°to 30° with total gain reduction around 5dBi and antenna efficiency of about 95.9%.

1. Introduction

Nowadays, communication system which providing fast rate transmission, low latency, extremely high traffic volume density, super-dense connections and cost efficiencies are the main requirement for the deployment of 5G mobile system. At the 5G mobile, new features such as millimetre wave operation, small cell size and multi beam base station antenna to meet massive multiple-input multiple-output (MIMO) requirements [1]. To ensure high quality of services, high performance of multibeam scanning for 5G base station is required. 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, multiple radiating beams with high gain performance are expected for the 5G base station as one radiating beam is assigned for one user as shown in figure 1(a). Therefore, the base station antenna size is expected to be less than 30 cm at the mm-wave operation.

According to [2-4], the dielectric lens antenna is known to produce excellent multi beam with very low network losses, simple structure and easy to fabricate. Based on previous studies reported by [5-6], numerous methods for non-uniform of Luneburg lenses have been applied for the use of communication applications and its feeding networks. Nevertheless, the capabilities of performing wide angular scanning for multi beam applications were not discussed in detail in those works. Ray tracing method based on the Geometrical Optics (GO) [7-8] was employed for shaping lens surfaces in achieving excellent radiation patters, where lens shaping is conventionally analysed by the aperture distribution method or Abbe's sine method [2]. For the base station pole installation, cylindrical dielectric lens antenna (CDLA) structure is suitable as shown in figure 1(b). In this paper, a cylindrical dielectric lens antenna is designed and the performance of multi beam characteristics for scanning beam from 0° to 30° at the vertical plane is observed.

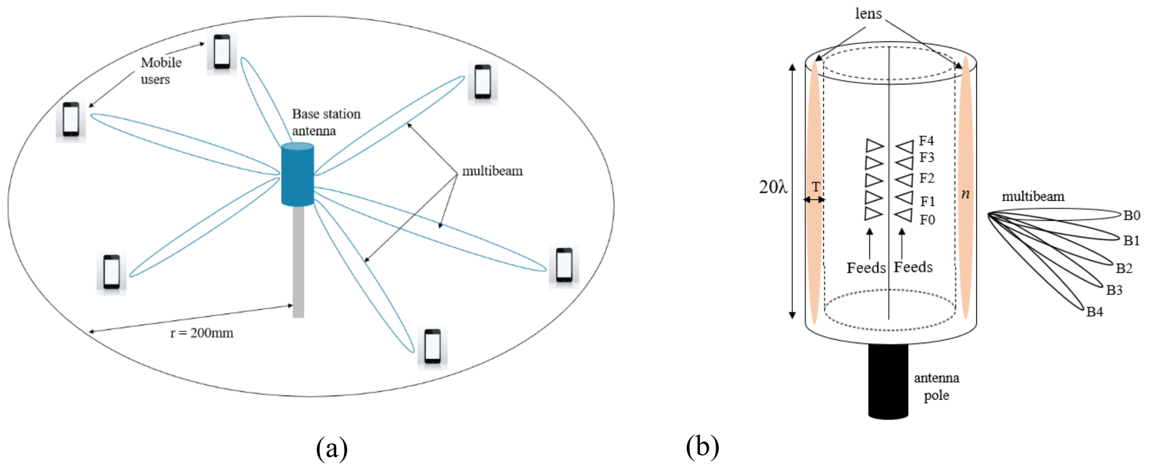


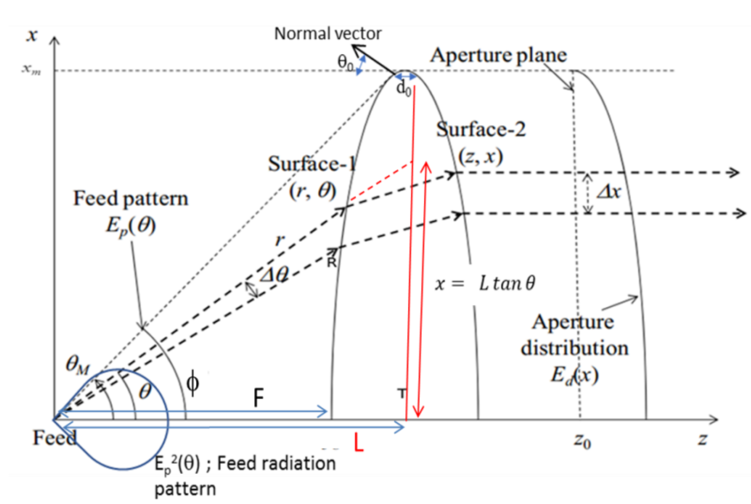
Figure 1. (a) Concept of multi beam 5G base station antenna (b) A cylindrical lens structure for the pole installation

2. Antenna Configuration and Lens Shaping Method

The principle of lens shaping is based on Snell's Law for constructing a surface 1 (S1) and surface 2 (S2), respectively. The lens design equations and function of equations are expressed all in table 1 to shape the lens structure by ray tracing method. The new design method is proposed to shape a small and this lens curvature, called as Straight-Line Condition (SLC) [9]. The simultaneous differential equations composed of Eq. (1), (2) and (5) are solved by a MATLAB program. Figure 2 shows the lens antenna configurations comprises of two surfaces, S1 and S2, respectively. The lens is symmetrically rotate at the *z*-axis the *x*-axis corresponds to the radial direction of the lens. The radiation pattern of the horn is indicated as $E_p(\theta)$ and the illumination distribution on the antenna aperture plane is shown by $E_d(x)$. The ray emitted from feed at maximum angle, θ_M reaches S1 is indicated by (r,θ). Then, the refracted ray at S1 produced by the angle, ϕ, reaches S2 at the point indicated by (z,x) and paralled to aperture plane. The shaped SLC lens by MATLAB program is shown in figure 3. From the figure, the rays are radiated from the feed point and formed to be parallel rays to the *z*-axis by the effect of lens refractions.

Table 1. Lens design equation

Subject	Equation		Function of equations
Snell's Law on S1	$\frac{dr}{d\theta}=\frac{nr\sin(\theta-\phi)}{n\cos(\theta-\phi)-1}$	(1)	r is determined for θ change
Snell's Law on S2	$\frac{dz}{d\theta}=\frac{n\sin\phi}{1-n\cos\phi}\frac{dx}{d\theta}$	(2)	z is determined for θ change
Constant electrical path length condition	$L_t=r+\frac{n(Z-r\cos\theta)}{\cos\phi}+Z_o-Z$	(3)	ϕ is given by θ
Straight-Line Condition (SLC)	$x=L\tan\theta$	(4)	
	$\frac{dx}{d\theta}=L\sec^2\theta$	(5)	$dx/d\theta$ in eq. (2) is given and x is determined for θ change



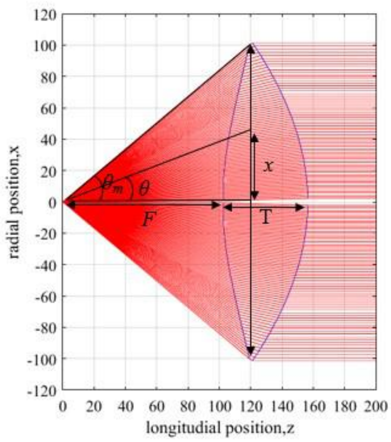


Figure 2. Lens antenna structure

Figure 3. Designed SLC lens shape

3. Electromagnetic Simulation Model

In order to provide antenna for a base station, practical installation needs to be taken into account such as economically, simple structure, high performance and reliable. In this paper, cylindrical structure is designed at the ratio of focal length to diameter (*F/D*). The electromagnetic simulator FEKO is employed. Simulation structural parameters are shown in table 2. The chosen of most suitable lens material is based on practicality of easy fabrication with small ratio of *F/D* and small lens thickness. *F/D=0.6* is selected. The lens diameter is set to *D*=200mm, approximately 20λ. As for the dielectric material, the use of TPS-PC (Polycarbonate) by Toray is considered and *n*=1.7 (ε_r=2.9) is selected. The 90-degree cylindrical SLC lens geometry is shown in figure 4.

Table 2. Structural parameters

Antenna parameter	Dimension
Operation frequency	28 GHz
Diameter, *D*	200 mm
Focal Length, *F*	119.18 mm
Thickness, *T*	51.3 m
Radius of Cylinder, L	144.88 mm
Refractive index, *n*	1.7
Angle to lens edge, θ_m	40°

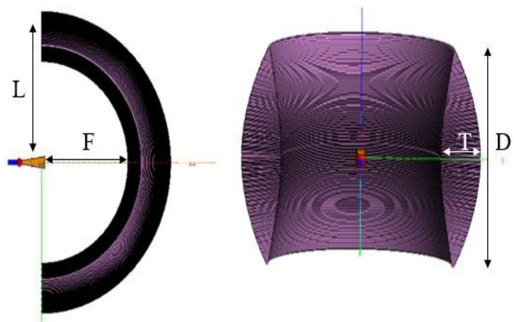


Figure 4. Cylindrical SLC antenna

4. Electric Field Distributions in the Near Field

A practical pyramidal feed horn antenna is designed with the ratio of focal length to diameter, *F/D*=0.6 to illuminate the lens edge. Figure 5 shows the horn dimension with edge level for both XZ-plane and YZ-plane of about -10.94 dB and -8.38 dB, respectively. The electric field distributions at the near field position of the lens aperture are shown in figure 6. At the position *ρ*=173 mm, the amplitude and the phase distribution are shown in figure 6(a). From the figure, small ripples are observed and aperture distribution of field intensity is well agreed between simulation (FEKO) and calculation in MATLAB at the lens edge, -12.9 dB and -12.21 dB, respectively. From figure 6(b), existence of standing waves is observed inside the lens. The reason of small ripples at the amplitude and phase distributions is

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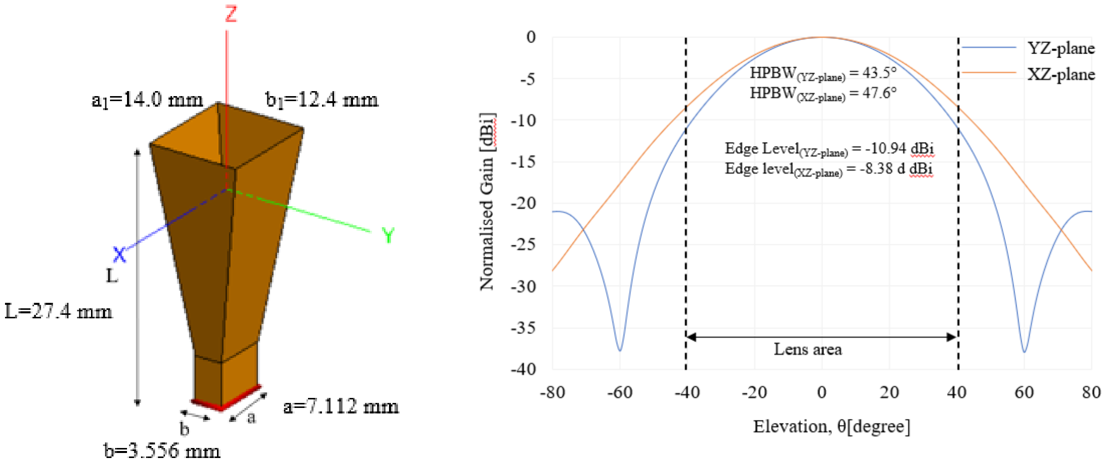
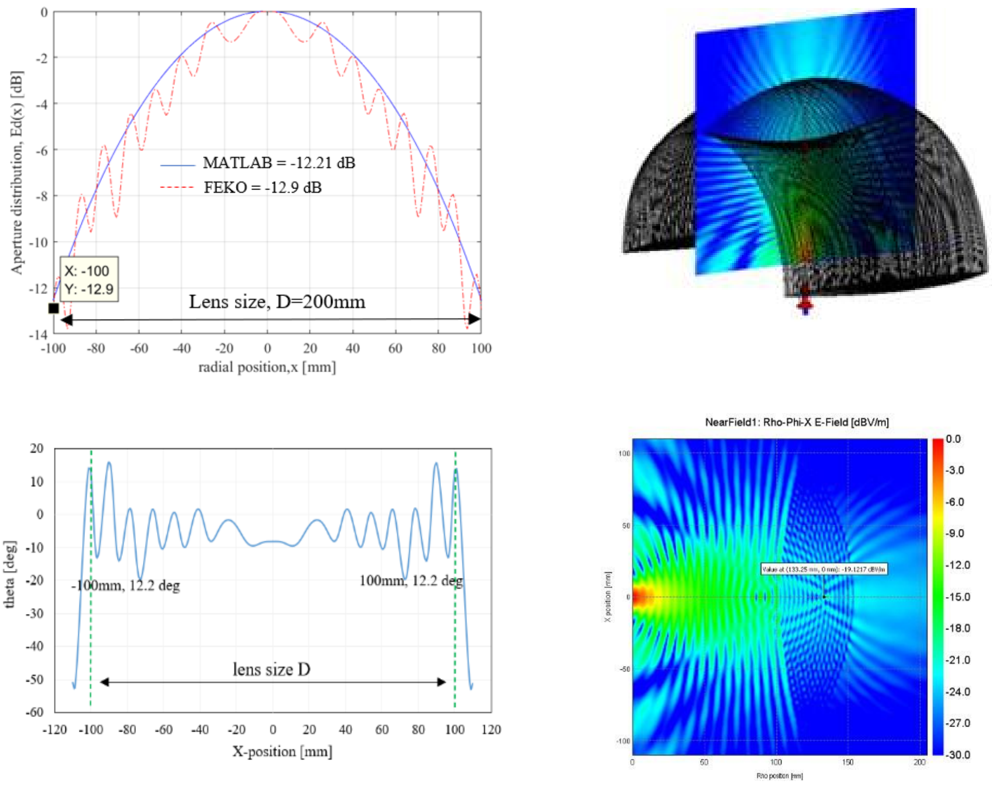
considered to be the standing waves. For elimination of the standing waves, attachment of a matching layer is effective.



(a) (b)

Figure 5. The pyramidal horn antenna for *F/D* =0.6 (a) horn dimension (b) horn radiation pattern



(a) (b)

Figure 6. (a) Amplitude and phase distributions (b) Electric field distribution

5. Multi Beam Radiation Patterns

As a fundamental data, the radiation characteristics at the on-focus feed condition is examined as shown in table 3. Gain values of MATLAB and FEKO agree well with the theoretical value with antenna efficiency around 95.9%. The calculated beam width by analytical and simulation are similar and slightly larger than the theoretical value.

Table 3. Calculated and simulated HPBW and gain for on-focus beam

Method	HPBW [θ_{3dB}]	Gain [dBi]
Theoretical	3.21°	24.86
Analytical (MATLAB)	3.21°	24.34
Simulation (FEKO)	3.28°	24.68

For multi beam performance, the feed positions are determined by the focal region ray tracing technique employed by the Ray-Launching Geometric Optic (RL-GO) solver in FEKO [10]. Figure 7 shows the the radiation patterns for on-focus feed ($\theta_F = 0°$) and scanning angle up to $\theta_F = 30°$. The performance of multi beam radiation characteristic is solved by the transmitting mode employed by Method of Moment (MoM) solver. It is observed at the feed angle from $\theta_F = 0°$ to 30°. The centre beam ($\theta_F = 0°$) shows high gain value 24.68 dBi and narrow half power beam width (HPBW) θ_{3dB}=3.28° are obtained. It is clearly seen that good multi beam radiation patterns are achieved with beam direction up to θ_S=33.1°. After the beam direction of larger than 30°, the beam deformation becomes a bit large and high side lobes appear. Table 4 shows the summary of multi beam characteristic. As a result, the cylindrical SLC lens antenna is suitable for the use of 5G mobile multibeam base station due to wider scanning beam coverage at vertical plane and low reduction in gain around 3.16 dBi at θ_F=30°

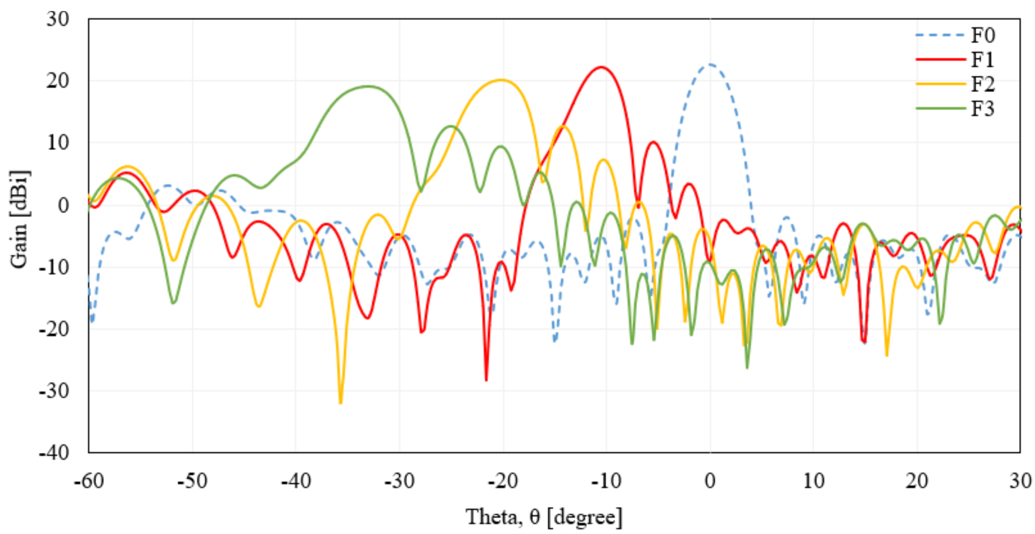


Figure 7. Multi beam radiation pattern based on locus focal region ray tracing technique

Table 4. Multi beam characteristics of cylindrical SLC lens

Feed Position	Feed Angle θ_F (°)	Beam Direction θ_S (°)	HPBW θ_{3dB}	Gain (dBi)	Gain Difference (dBi)
F0	0	0	3.28	22.68	0
F1	10	10.5	3.49	22.11	-0.57
F2	20	20.1	3.96	20.24	-1.43
F3	30	33.1	5.23	19.20	-3.16

6. Conclusion

The cylindrical lens antenna with a shaped lens surface is proposed. The lens shape is designed based on the straight-line condition (SLC). The vertical cylindrical structure with the SLC shaped cross section is simulated by the MoM solver for electromagnetic simulations. By shifting feed positions from θ_F=0° to θ_F=30°, multi beam radiation patterns are calculated. As a result, the total gain reduction around 5 dBi and good multi beam shapes are achieved for wide scanning angle. The useful of a new stucture of cylindrical SLC lens antenna is suitable for 5G multi beam base station with coverage beam up to θ_S=33.1°.

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