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Design and Simulation of a 3.5 GHz Pyramidal Horn Antenna for IoT and High Speed 5G Wireless Technology Mobile Networks.

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ABSTRACT

The wireless communication system is an imperative component of Internet of Things (IoT) framework, serving as a bridge for bidirectional connection for data gathering and control message conveyance for effective data application hence, wireless techniques has short range of IoT band and consume a lot of power. This study, design and simulation of a pyramidal horn antenna for IoT and fifth generation (5G) applications operating at 3.5 GHz is presented. The antenna is designed and simulated using MATLAB 2020a produced by MathWorks Inc The gain, bandwidth, and maximum directivity of the single element antenna is 14.1 dB, 460 MHz and 15 dBi respectively. A low simulated return loss (-15.8 dB) is obtained. Hence, the antenna has a very good efficiency. The performance after simulation of this antenna that is combined with a 3.5 GHz radio frequency module and IoT sensors. The distance of the radiating element is 5 cm, and its overall waveguide length 15 cm is obtained at a resonance frequency 3.5 GHz. the simulated antenna has the axial lengths $L_H = L_E = 4\ cm$ that suitable for short range IoT applications. All mutual-coupling (S21 to S44) characteristics between the elements lie within -27 and -84 dB, which follows the beam steering requirements perfectly. Therefore, 5G and other applications are possible with this antenna.

Key words: *Bandwidth, Fifth generation, Gain, IoT, Maximum directivity.*

I. Introduction

Technology relates to wireless sensor helping to increase device internet connectivity as well as the effectiveness of IoT application operation [1]. Various field in IoT development such as agriculture, healthcare, security, smart home and location devices associated with wireless technology going towards future and here antenna plays a vital role. One of the wireless techniques for short range IoT applications is Bluetooth low energy (BLE) under 2.4 GHz industrial, scientific, and medical (ISM) band because of its low power consumption [2, 3]. Mobile communications, on the other hand, provide longer range IoT applications, but they consume a lot of power [4]. In radio frequency microwave modules, the size reduction and improvement of the antenna performance are the key design parameters, so the horn antenna integrated on a printed circuit boards (PCBs) are suitable antennas for IoT applications [5,6,7].

Furthermore, 5G communication suffers from path-loss severely because high frequency bands (450 MHz to 52.6 GHz) will be used [8,9]. To manage this problem, high gain antenna is required. Hence, in this study, design and simulation of pyramidal horn antenna is presented. The structure of the antenna designed and simulated using MATLAB 2020a produced by MathWorks Inc operated at 3.5 GHz is presented [8,9].

II. Optimum of Horn Antenna Design

In this study, the horn antenna is implemented with center frequency of 3.5 GHz. Estimating the desired antenna gain (G) is necessary for the anticipated frequency of operation and it is the first stage in designing the pyramidal horn antenna. As a result, the goal of this study is to obtain a gain of 15 dB at 3.5 GHz, which is employed for 5G network communication. The objective of the design is to determine the dimensions of the following parameters: Wave guard (p and q)., Flaring angles (α, β)., axial lengths (L_E, L_H)., Apertures (P and Q) that will lead to an optimum gain of the antenna.[10] The whole design can be actually reduced to the solution of a single fourth-order equation. For a horn to be realizable, the following must be true:

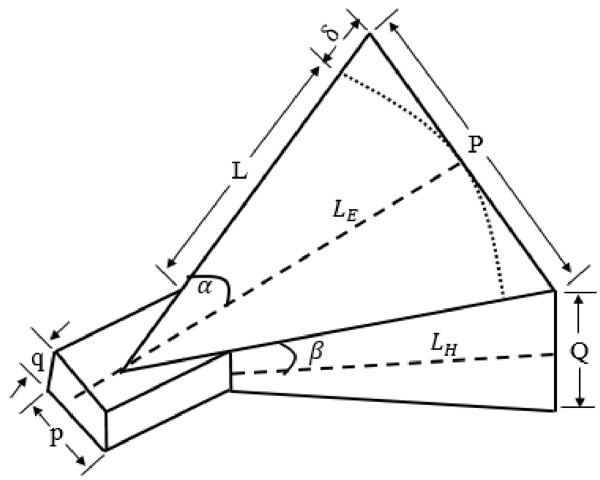

Figure. 1 Pyramidal horn

The wave guide p and q for the transverse electric and magnetic modes (TEmn and TMmn) respectively is designed by considering the cut-off frequency. The cut-off frequency, operating frequency and upper frequency are 3.15, 3.5 and 3.85 GHz respectively. The dominant mode of the waveguide is the mode with minimum value of *m* and *n* which the cut off frequency will be lowest as depicts in Equation. (1)[11,12]. In this study, the transverse electric mode is selected as dominant because it has the lowest attenuation of all modes in a rectangular wave guide.

$$F_c(mn) = \frac{1}{2\sqrt{\mu\varepsilon}}\sqrt{\left[\left(\frac{m}{p}\right)^2 + \left(\frac{n}{q}\right)^2\right]} \qquad (1)$$

The operating wavelength is obtained using the speed of electromagnetic waves in free space (3×10^8 ms^{-1}) and the operating frequency of the proposed antenna as follows:

$$\lambda = {}^{c}/_{F} = 0.0857\ m$$

$$\therefore \lambda = \cong 8.6\ cm$$

(i) Design of Waveguide

In this study, the waveguide cut-off frequency, F_c is 3.15 GHz. The waveguide cut-off wavelength is obtained as follows;

$$\lambda_c = {}^{c}/_{F_c} = 0.0952\ m$$

$$\lambda_c \cong 9.5\ cm$$

Width of the waveguide, $p = {}^{\lambda_c}/_{2} = 4.80\ cm$. Height of waveguide $q = 3.36\ cm$

The guide wavelength is designed as follows,

$$\lambda_g = \frac{\lambda}{\sqrt{1 - \left({}^{F_c}/_{F}\right)^2}} \cong 20\ cm$$

From the backside of the waveguide, the distance of the radiating element is given as,

$$l = {}^{\lambda_g}/_{4} = 5\ cm$$

The length of the radiating element is,

$$d = {}^{\lambda}/_{4} \cong 2\ cm$$

Hence, the overall length of the waveguide is

$$L = 0.75\lambda_g = 15\ cm$$

(ii) Design of Horn Aperture P and Q

Referring to figures 2(a) and 2(b) respectively, the dimension of the electric plane view YZ should be equal to the dimension of magnetic plane XZ [13].

$$L_{E2} = (Q - q)\left[\left({}^{L_E}/_{Q}\right)^2 - {}^{1}/_{4}\right]^{\frac{1}{2}} \qquad (2)$$

$$L_{H2} = (P - p)\left[\left({}^{L_H}/_{P}\right)^2 - {}^{1}/_{4}\right]^{\frac{1}{2}} \qquad (3)$$

The optimal relation between the flared height Q and the horn apex length L_E that produces the maximum possible directivity is

$$Q = \sqrt{2\lambda L_E} \tag{4}$$

Also, the optimal directivity is obtained if the relation between P and L_H is

$$P = \sqrt{3\lambda L_H} \tag{5}$$

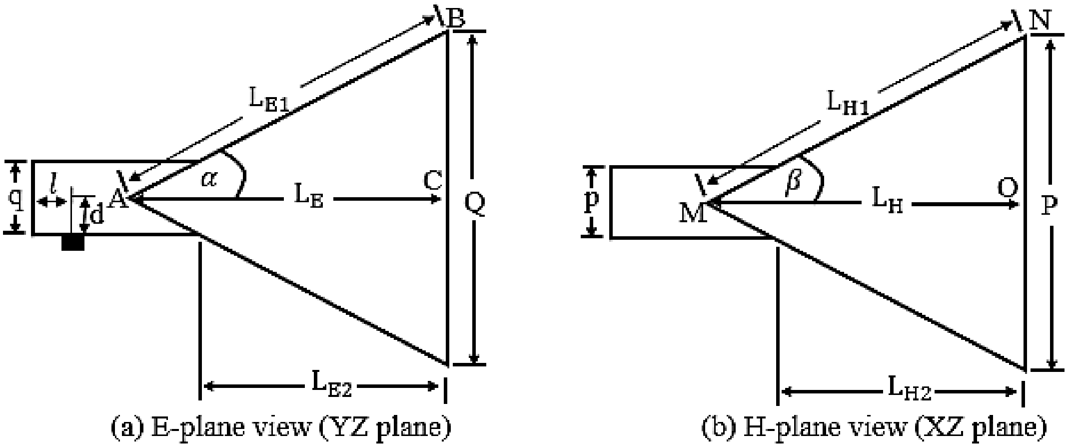

Fig 2. Pyramidal horn coordinate system.

From figure 2 (a) and (b), it can be shown that,

$$\frac{L_H}{L_{H2}} = \frac{P/2}{P/2 - p/2} = \frac{P}{P-p} \tag{6}$$

$$\frac{L_E}{L_{E2}} = \frac{Q/2}{Q/2 - q/2} = \frac{Q}{Q-q} \tag{7}$$

In the E-plane, the optimum gain condition is obtained by substituting Equation. (4) In Equation (7)

$$Q^2 - qQ - 2\lambda L_E = 0 \tag{8}$$

The physical solution to Equation (8) is,

$$Q = \frac{1}{2}\left(q + \sqrt{q^2 + 8\lambda L_E}\right) \tag{9}$$

Similarly, the peak gain condition for the H-plane geometry is obtained by substituting Equation (5) in Equation (6):

$$\mathrm{L_H} = \frac{\mathrm{P-p}}{\mathrm{P}}\left(\mathrm{P^2}/_{3\lambda}\right) \tag{10}$$

$$\mathrm{L_H} = \mathrm{P}\frac{\mathrm{P-p}}{3\lambda} \tag{11}$$

Since $\mathrm{L_H} = \mathrm{L_E}$ must be satisfied, substituting Equation.(11) in Eq.(9) this gives

$$Q = \frac{1}{2}\left(q + \sqrt{q^2 + \frac{8P(P-p)}{3}}\right) \tag{12}$$

Substituting in the equation for the horn's antenna gain,

$$G = \frac{4\pi}{\lambda^2} \times \varepsilon_{ap}(PQ) \tag{13}$$

This gives the relation between P, aperture efficiency (ε_a) and the gain of the horn antenna as follows,

$$G = \frac{4\pi}{\lambda^2} \times \varepsilon_a P \frac{1}{2}\left(q + \sqrt{b^2 + \frac{8P(P-p)}{3}}\right) \tag{14}$$

$$P^4 - pP^3 + \frac{3qG\lambda^2}{8\pi\varepsilon_a}P - \frac{3G^2\lambda^4}{32\pi^2{\varepsilon_a}^2} = 0 \tag{15}$$

Therefore, Eq. 15 is the optimum pyramidal horn antenna equation. **F**or optimum pyramidal horns antenna, the overall efficiency (including both the antenna and aperture) is 0.50. In this study, the operating wavelength is 8.6 cm and the 11 dB gain is initially proposed. The aperture P is designed using a numerical solution of Eq. (15) with the guess usually set at P(0) as follows

$$P(0) = 0.45\lambda\sqrt{G}$$

$$\therefore P = 12.80\ cm$$

The aperture Q is designed from Equation. (12), with q = 3.36 cm,

$$Q = \frac{1}{2}\left(3.36 + \sqrt{(3.36)^2 + \frac{8 \times 16.4(16.4 - 3.36)}{3}}\right)$$

$$\therefore Q = 10.80\ cm$$

(iii) Design of Axial lengths

Since axial length L_H is equal to L_E. Equation. (11) is used to design the axial length as follows:

$$L_H = 12.8 \times \frac{12.8 - 4.8}{3(8.6)}$$

$$\therefore L_H = L_E = 4.00\ cm$$

(iv) Design of Flared lengths.

The axial length L_E from the E-plane view is determine by referring to triangle ABC in figure 2 (a) using Pythagoras theorem as follows,

$${L_{E1}}^2 = {L_E}^2 + \left({}^{Q}/_{2}\right)^2$$

$$\therefore L_{E1} = 6.7\ \text{cm}$$

The flare angle α, is given by,

$$\alpha = \cos^{-1}(0.5970) = 53°$$

The axial length L_H from the H-plane view is determine in a similar manner as E-plane by considering triangle MNO in figure 2(b).

$${L_{H1}}^2 = {L_H}^2 + \left({}^{P}/_{2}\right)^2$$

$$\therefore L_{H1} = 7.55\ \text{cm}$$

$$\beta = cos^{-1}(0.5298) = 58°$$

In this study, the gain is obtained using Eq. (13)

$$G = \frac{4 \times 3.142}{8.6^2} \times 0.51(12.8 \times 10.8) = 11.98 \cong 12$$

So, this derived parameter is in good agreement with the designed value of 11 dB.

The results of the antenna designed at 3.5 GHz are summarized and presented in Table 1.

Table 1. Parameters of the designed Horn's antenna

Parameters	Value
Operating frequency	3.15 GHz
Waveguide height (q)	3.36 cm
Waveguide width (p)	4.80 cm
Waveguide length (L)	15.50 cm
Aperture (P)	12.80 cm
Aperture (Q)	10.80 cm
E-plane flared length, (L_{E1})	6.70 cm
H-plane flared length, (L_{H1})	7.50 cm
Axial lengths $L_H = L_E$	4.00 cm
E-plane flared angle, α	53°
H-plane flared angle,	58°
Radiating element (d)	2.00 cm
Distance of the radiating element (l)	5.00 cm
Overall length of the waveguide (L)	15.00 cm

Results and Discussion

Referring to Figure 3, the radiation pattern of the designed horn antenna is forward facing, indicating that it has a unidirectional radiation pattern suitable for use as a 5G antenna system. The gain is calculated in the directions of maximum radiation (Main lobe). In this study, the simulated gain 14.1 dB at 0° is achieved. The resulting 3D radiation pattern looks like a bagel with the antenna sitting in the hole and radiating energy outward with maximum directivity 15 dBi. The strongest energy is radiated outward, perpendicular to the antenna in the x-y plane as shown in figure 4. The azimuth plane pattern is formed by slicing through the 3D pattern in the horizontal plane, the x-y plane in this case, the azimuth plane pattern is non-directional, and that is, the antenna radiates its energy equally in all directions in the azimuth plane. Figure 5 and 6 shows the X-Z and Y-Z views.

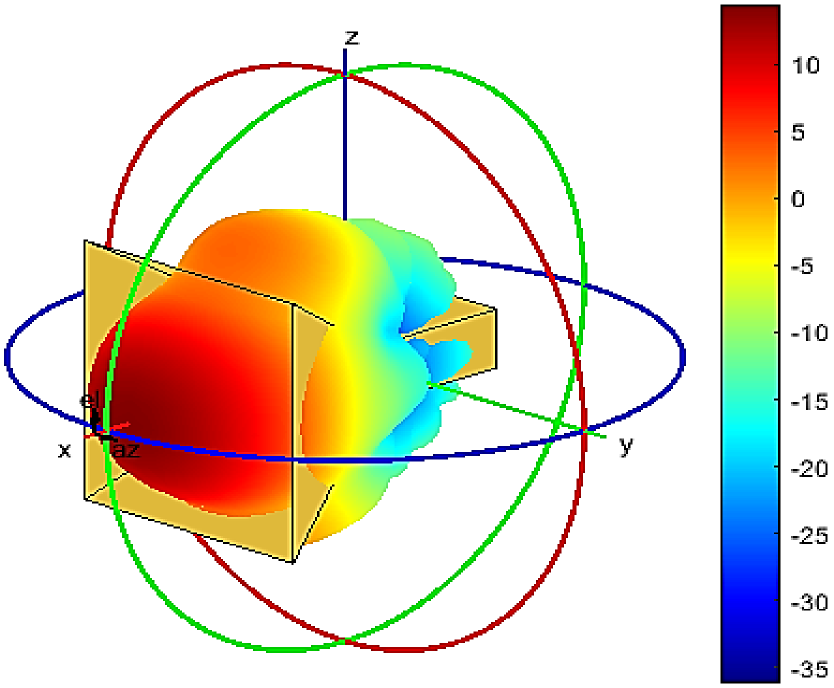

Figure 3. Far field 3D radiation pattern of Horn antenna

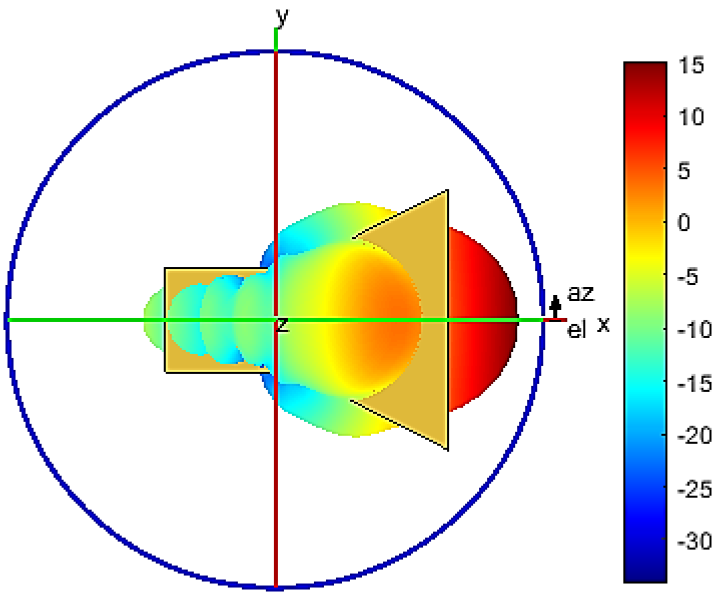

Figure 4. Azimuth plane (X-Y view)

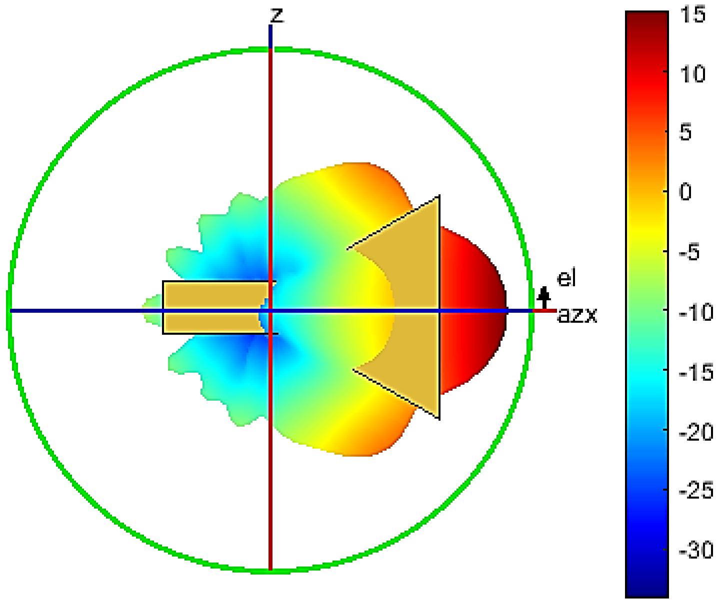

Figure. 5. Elevation plane of horn antenna (X-Z view)

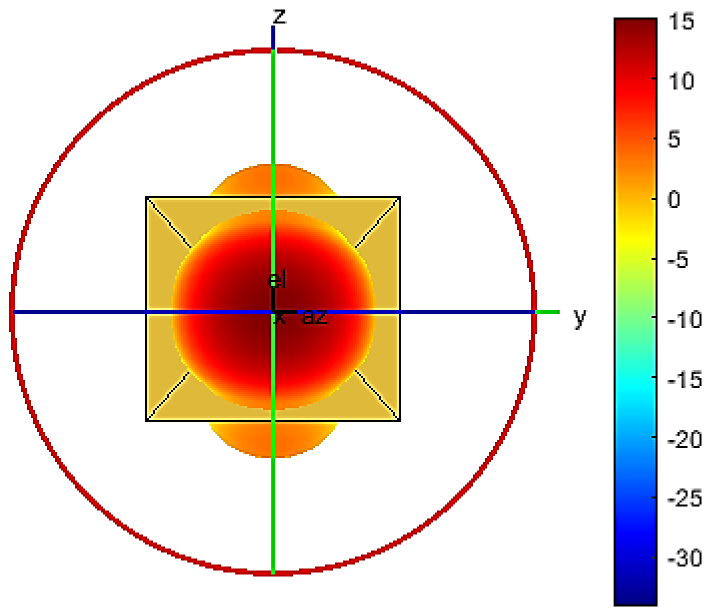

Figure. 6. Y-Z view

Figures 7 and 8 depicts the radiation patterns at specific spot frequency within the desired operating band. From the elevation plane pattern, the angular separation in which the magnitude of the radiation pattern decreases by -3 dB from the peak of the main beam, that is, half power beam with (HPBW) is 30^{o} realized gain of 14.1 dB is achieved as indicated on the pattern in Figure 7. Also, the realized gain of 14 dBi was achieved in the HPBW of the main plane azimuth at 0° which is reasonable gain for this type of commercial antenna

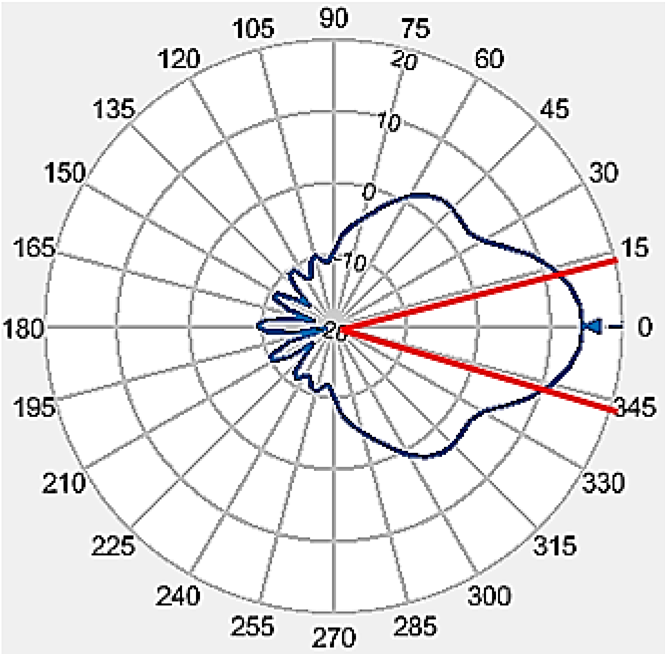

Figure 7. Horn antenna Elevation radiation plane pattern

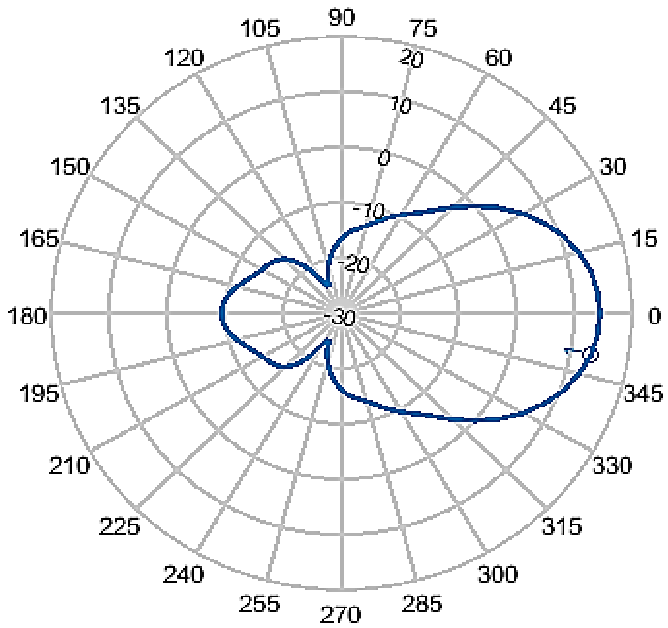

Figure. 8. Horn antenna Azimuth radiation plane pattern

By using MATLAB software, the antenna designed radiates best at the chosen operating frequency 3.5 GHz. Figure 8 depicts the return loss in dB against the frequency of operation (the simulated return loss (S11) response). Referring to Figure 8, this simulated Horn antenna can transmit an electromagnetic wave signal at operating frequency of 3.5 GHz with the signal's reflection ratio which is less than -10 dB. The figure also shows how much the feeding power that was reflected back from the antenna and the transmitter line that are not perfectly matched with the reflections at the antenna port travel back towards the source which result in standing wave. The bandwidth can be defined from the reflection coefficient graph by taking the frequency range at -10 dB. The antenna S11 at 3.5 GHz, -10dB S11 return loss and bandwidth (BW) are –15.8 dB and 460 MHz respectively. The return loss of the antenna obtained is very low, So, the antenna has a very good efficiency with 460 MHz of bandwidth.

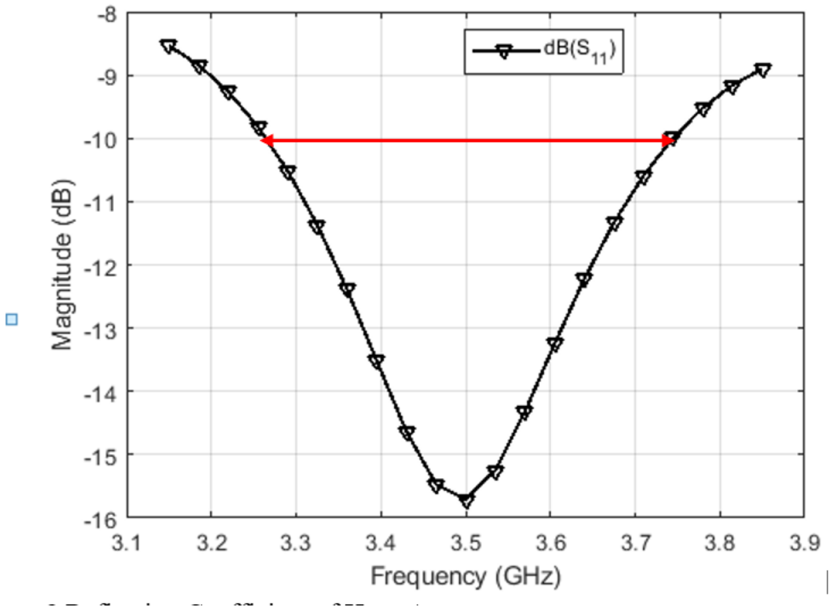

Figure. 8 Reflection Coefficient of Horn Antenna

The simulated S11 characteristics of the eight elements array design for different values of L as a function of λ_g, the guided wavelength. From the analysis, it appears that L must be equal or close to $0.75\lambda_g$ to obtain the low mutual coupling characteristics over its operating frequency range. After many iterations in MATLAB, we ended up the L value as 15 cm ~ $0.75\lambda_g$, which produce a low mutual coupling effect and high gain. With this L value, the total dimension of the antenna components for two elements up to eight-element phased array antenna can be varied. In order to obtain the high gain and wide scene of beam steering characteristics, eight antenna elements (S11 to S81) in the proposed array design were considered in this design. The simulated S parameters (S11 to S81) of the proposed array is presented in Figure.9. It can be seen that the antenna array has quite good performance regarding the S11 parameter likewise a single element antenna within the entire frequency bandwidth 460 MHz. Further, all mutual-coupling (S21 to S44) characteristics between the elements lie within -27 and -84 dB, which follows the beam steering requirements perfectly.

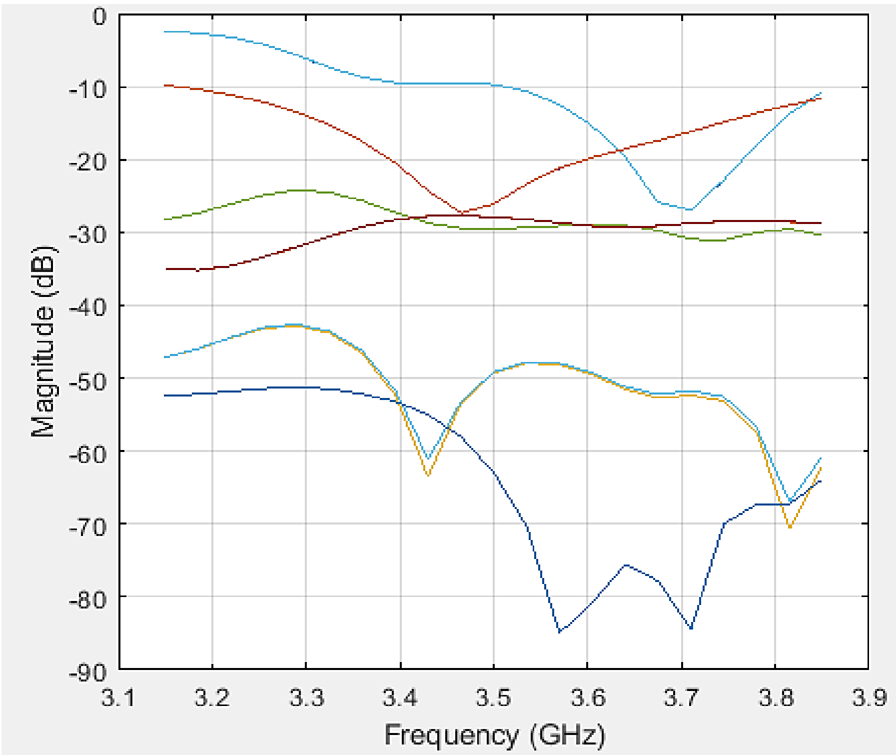

Figure 9. Simulated S-parameters

IV. Conclusion

The design and simulation of a rectangular waveguide pyramidal horn antenna using MATLAB tool operating at 3.5 GHz envisioned for 5G network applications is presented. Simulated gain of 14.1 dB is achieved at 3.5 GHz. The gain, bandwidth, and maximum directivity of the single element antenna is 14.1 dB, 460 MHz and 15 dBi respectively. A low simulated return loss (-15.8 dB) is obtained. Hence, the antenna has a very good efficiency. The performance after simulation of this antenna that is combined with a 3.5 GHz radio frequency module and IoT sensors. Having small size and high fractional bandwidth which gives a good performance in IoT application. The distance of the radiating element is 5 cm, and its overall waveguide length 15 cm is obtained at a resonance frequency 3.5 GHz. the simulated antenna has the axial lengths $L_H = L_E = 4\ cm$ that suitable for short range IoT applications. Since our current 5G design is based on the simulation only, so the future works in this study will involve the construction and experimentation at the FCC assigned operating frequency.

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