Design and Analysis of Waveguide-Fed Broad-Wall Longitudinal Log Periodic Slotted Array Antenna for 8.2 ~ 11.11 GHz Frequency Applications

Hare Ram Jha[1] and Shiva Nand Singh[2]

[1]Department of Electronics & Communication Engineering, NIT Jamshedpur, Jharkhand, India
[2]Department of Electronics & Communication Engineering, NIT Jamshedpur, Jharkhand, India

Abstract— *This paper presents Design and Analysis of Waveguide-Fed Broad-Wall Longitudinal Log Periodic Slotted Array Antenna for X-Band. Initially, seven separate 7-element Conventional Shunt Slot Array Antennas (CSSAA) have been designed for X-band in accordance with different slot lengths like 13.5mm, 14.5mm, 15.5mm, 16.5mm, 17.5mm, 18.5mm and 19.5mm and an analysis of correlated reflection coefficient data have been obtained respectively. After these have been taken CSSAA seven different slot lengths are milled on a Standard WR-90 waveguide producing Log Periodic Slot Array Antenna (LPSAA), and correlated reflection coefficient data have been obtained. The simulated data has been compared with 7 different CSSAA data, with simulated proposed LPSAA, theoretical data and proposed manufactured LPSAA measured data to validate the proposed design. The outstanding agreement obtained among the results validates the investigation. After validating the methodology, a 7-element waveguide fed LPSAA antenna has been designed, manufactured and tested for resonance frequencies (8.2 ~ 11.11 GHz). The manufactured antenna works efficiently on 8.2 ~ 11.11 GHz, providing a high peak gain of 23.18dB at 9.4GHz.*

Keywords— Array, Method of Moments, Multiple Cavity Modeling Technique, Slot and WR-90 Waveguide

I. INTRODUCTION

Studies on waveguide broad wall longitudinal slot antennas date back before World War II [1]. Due to this fact a lot of literature is available in this area. In the last five decades, considerable research work on the resonance, mutual impedance and admittance properties of structure designing has been produced [2-17]. Although, most of these analysis were run on slot array in which each slot length and breadth is fixed in dimension, more recently in 2013, Gyan and Das [18] have introduced a Method of Moments based analysis of high-gain broadband waveguide broad-wall longitudinal slot array antenna. In this paper the author has arbitrarily varied the length of slot on a waveguide that antenna provides a high peak gain as 15dB.

This paper presents Ansoft High Frequency Structure Simulator (HFSS) software based design and analysis of proposed waveguide-fed broad-wall 7-element longitudinal Log Periodic Slot Array Antenna (LPSAA) that works within the range of X-band. Initially, seven separate waveguide-fed broad-wall 7-element longitudinal Conventional Shunt Slot Array Antenna (CSSAA) have been designed and analyzed while corresponding reflection coefficient (S_{11}) data has been obtained for different slot lengths. After that, the seven different slot lengths from separate CSSAA are milled on a waveguide, resulting in a 7-element LPSAA.

II. DESIGN THEORY

A slot is generally characterized by its electrical length and offset from the center. The electrical length of the slot generally determines its resonant frequency, whereas the offset determines the power radiated from it into the half space. Let us look at the slot array, shown in fig. 1.

The array consists of radiating slot of different electrical lengths (corresponding to different resonance frequencies). Due to inherent property, each of them will resonate at their own individual resonance frequency. If the slot length and positions are chosen in such a way that the lower cut-off frequency and higher cut-off frequency of the nth slot overlaps with the higher and cut-off frequency of the (n-1)th and (n+1)th slot respectively, then the complete array is expected to give a wide band response resulting in log- periodic dipole array. The concept is similar to the log-periodic dipole array. Mathematically the condition can be written as:

$$f_{n-1} + \frac{Df_{n-1}}{2} = f_n - \frac{Df_n}{2} \tag{1}$$

$$f_n + \frac{Df_n}{2} = f_{n+1} - \frac{Df_{n+1}}{2} \tag{2}$$

Where, f_i and Df_i are the center frequency and bandwidth of the ith slot, respectively.

III. DESIGN OF THE LOG PERIODIC ANTENNA

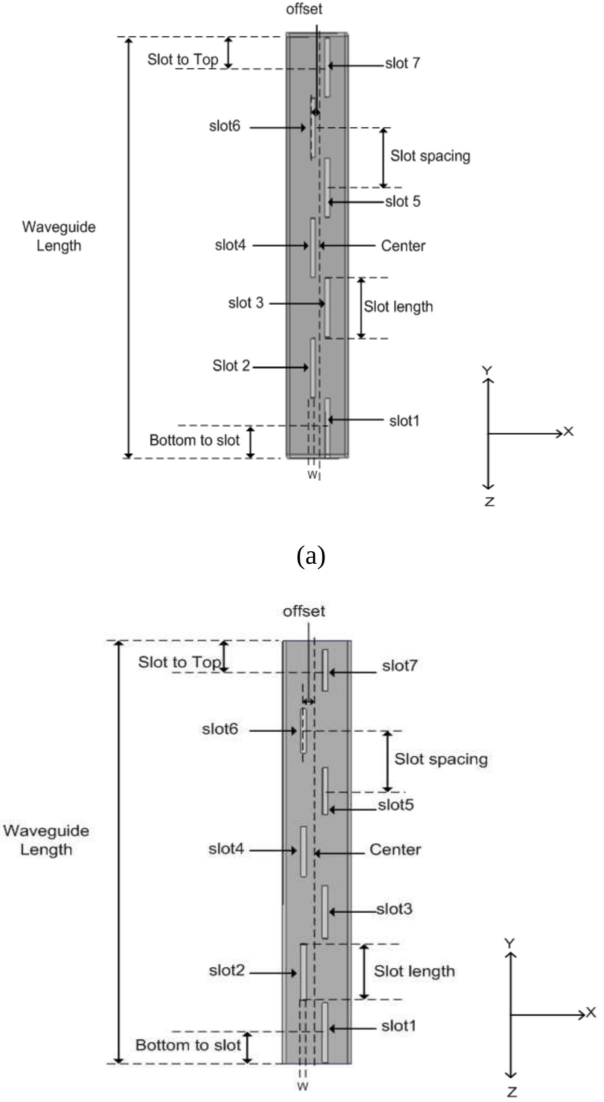
Figure 1 shows the front view of conventional shunt slot array and proposed broad-wall 7-element longitudinal log periodic slot array antenna. In the simulated computation, it is assumed that the material of the waveguide is a perfect conductor with 1.27mm thickness. The waveguide is designed to operate at 8.2 GHz to12.4GHz with TE_{10} mode. The slot lengths are designed to achieve resonance at 10.0 GHz, and the distance between adjacent slots is set equal to set $\lambda_g/2$ at this frequency [12]. Placing the solution frequency is at 10.0 GHz the standard WR-90 wave guide dimension being [Wide Sidewall: 22.86 mm (Inside Measurement), 25.40 mm (Outer Side Measurement) Short side wall: 10.16 mm (Inside Measurement), 12.70 mm (Outer Side Measurement)]. Slot to top and bottom length set at $\lambda_g/4$ and $\lambda_g/4$ respectively, where, λ_g = guided wavelength. Calculation of λ_g for TE_{10} mode X-band by guided wavelength standard formula as:

$$\lambda_g = \frac{\lambda}{\sqrt{1-\left(\frac{\lambda}{\lambda_c}\right)^2}} \qquad (3)$$

Where, λ_c= cut-off wavelength= 2× '2a' and '2a'= 22.86 mm for standard WR-90. Assigning the value of λ and λ_c gets the result of λ_g= 39.7553794 mm. Hence $\lambda_g/2$=19.8mm and $\lambda_g/4$=9.9 mm. Waveguide length is calculated after 7-element slot is milled on the broad wall face of the WR-90. Here, Waveguide length= 138.9 mm (Top to bottom) is taken into account.

Practically, slot length is usually between 0.3λ to 0.65λ, where, λ is the free space wavelength. When calculated the λ=30mm by standard formula, i.e. $\lambda = c/f$ where, c=3× $10^8\ m/sec\ and\ = 10\ GHz$. Thus the range of slot length is 9 mm to 19.5 mm. Hence, choose the slot lengths that achieve resonance at 10.0 GHz. For CSSAA slot 1 to slot 7, there is neither increment nor decrement of slot length. For instance, if we take slot-1 length as 19.5mm then it will have to accept the same slot length respectively, for slot-2, slot-3, slot-4, slot-5, slot-6 and slot-7.Designed specification of seven different cases of CSSAA is shown in table-I. The CSSAA 7th case structure is designed by HFSS tool as presented in fig. 1(a).

For LPSAA, slot-1 length is set on 19.5mm which is the utmost limit of slot length for 10.0 GHz frequency, for creating a log periodic consistently decrement of 1mm in the subsequent slot up to slot-7. The specification of slot is presented in table- II. The proposed LPSAA is designed by HFSS tool is shown in fig. 1(b).



(a)

(b)

Fig. 1. Front View of HFSS based design broad-wall 7-element longitudinal (a) Conventional Shunt Slot Array Antenna (CSSAA) and (b) proposed Log Periodic Slot Array Antenna (LPSAA) without flange.

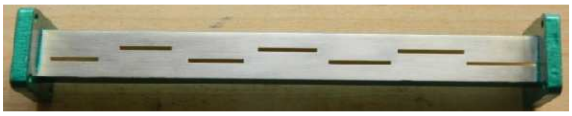


Fig. 2. Top view of fabricated 7-element longitudinal log periodic slot array antenna with flange.

IV. ANALYSIS OF THE LOG PERIODIC ANTENNA

After designing the CSSAA and PLSAA by HFSS software tool waveguide is excited for analyzing the magnitude of reflection coefficient (S_{11}) and then simulating the result with entire frequency range of X-band. After simulation, the comparison graphs of reflection coefficient in magnitude versus frequency are presented in fig 3.

In fig. 3 only proposed LPSAA reflection coefficient value is greater than zero for entire range of X-band (8.2~12.4GHz), that means antenna will work for larger frequency extent.

TABLE I
DESIGN SPECIFICATION OF CONVENTIONAL SHUNT SLOT ARRAY ANTENNA

CSSAA-#			**CSSAA-1**	**CSSAA-2**	**CSSAA-3**	**CSSAA-4**	**CSSAA-5**	**CSSAA-6**	**CSSAA-7**
Slot #	***Width (mm)***	***Offset (mm)***	***Length (mm)***	***Length (mm)***	***Length (mm)***	***Length (mm)***	***Length (mm)***	***Length (mm)***	***Length (mm)***
Slot-1	2	+4	13.5	14.5	15.5	16.5	17.5	19.5	19.5
Slot-2	2	-4	13.5	14.5	15.5	16.5	17.5	19.5	19.5
Slot-3	2	+4	13.5	14.5	15.5	16.5	17.5	19.5	19.5
Slot-4	2	-4	13.5	14.5	15.5	16.5	17.5	19.5	19.5
Slot-5	2	+4	13.5	14.5	15.5	16.5	17.5	19.5	19.5
Slot-6	2	-4	13.5	14.5	15.5	16.5	17.5	19.5	19.5
Slot-7	2	+4	13.5	14.5	15.5	16.5	17.5	19.5	19.5

TABLE II
DESIGN SPECIFICATION OF LOG PERIODIC SLOT ARRAY ANTENNA

Slot #	***Length (mm)***	***Width (mm)***	***Offset (mm)***
Slot-1	19.5	2	+4
Slot-2	18.5	2	-4
Slot-3	17.5	2	+4
Slot-4	16.5	2	-4
Slot-5	15.5	2	+4
Slot-6	14.5	2	-4
Slot-7	13.5	2	+4

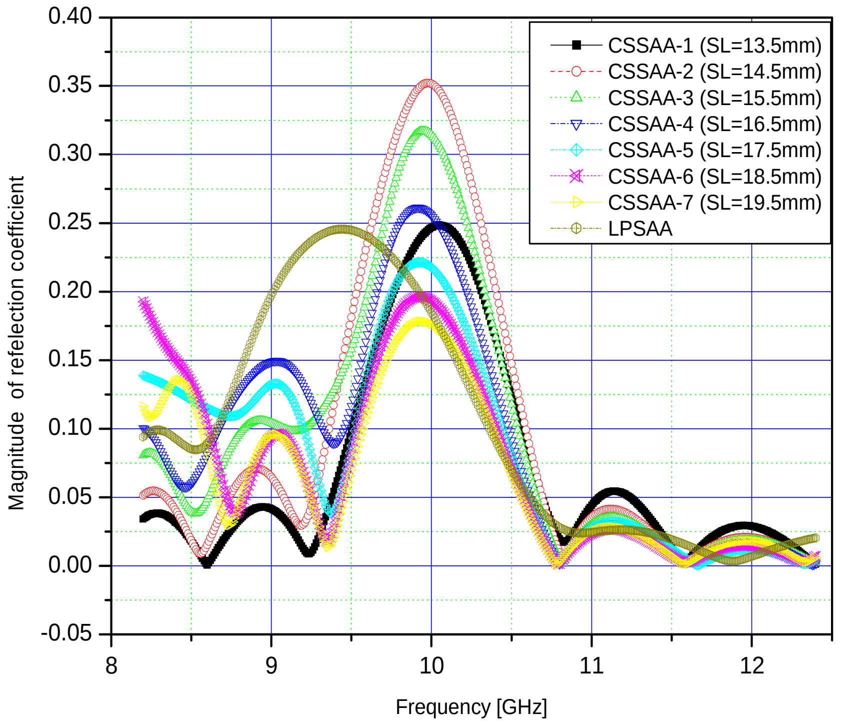


Fig. 3. Comparison of simulated data of reflection coefficient in magnitude versus frequency in X-band for different cases of CSSAA and proposed LPSAA

Theoretical analysis using multiple cavities modeling technique (MCMT):

The Top view of the two- element log periodic slot array antenna is shown in fig.4 along with details of different parameters that will be used in the analysis. The corresponding cavity modeling and details of magnetic current at the apertures are shown in fig.5.

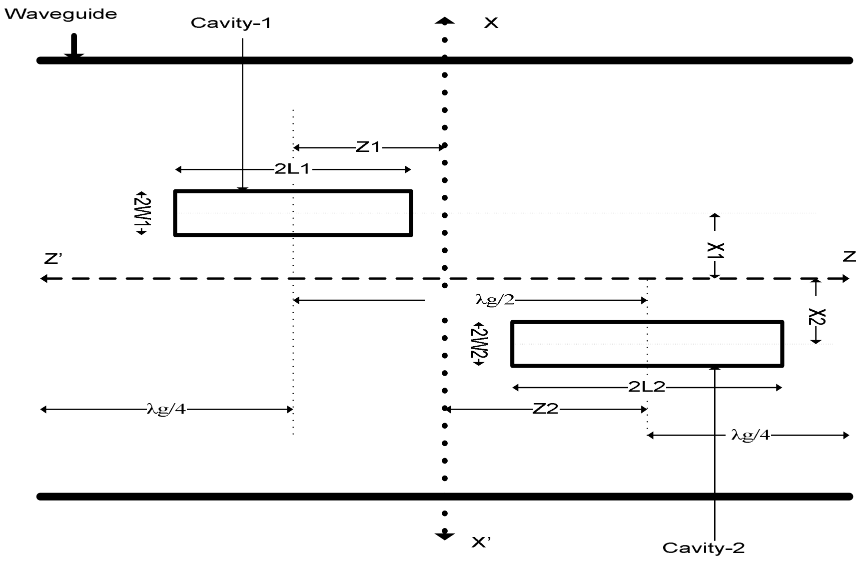


Fig. 4. Top view and detail of different parameters used in the analysis of the 2-element log periodic slot array antenna.

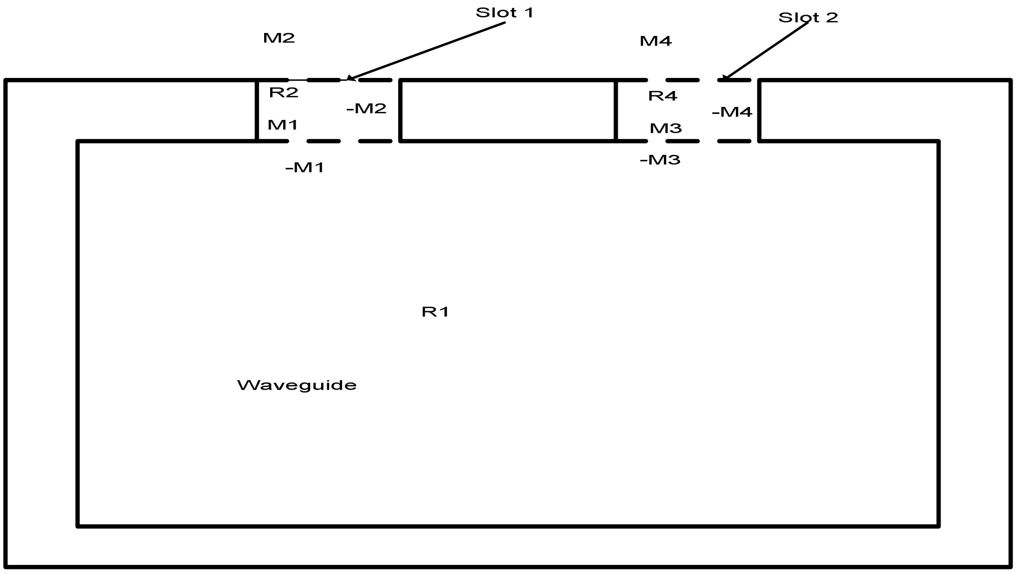


Fig. 5. Details of different regions and magnetic currents at the apertures of the 2-element log periodic slot array antenna.

The electric field at any point $(x', y,' z')$ at the slot may be assumed to be x-directed and expressed in terms of a sum "M" weighted sinusoidal basis function $\left(e^i_{p,y}\right)$ defined over the entire length of the slot as follows [16]:

$$\vec{E}^i = \hat{u}_x \sum_{p=0}^{M} E^i_{p,z} \begin{cases} \sin\left\{\frac{p\pi}{2\mathrm{L_i}}\left(\mathrm{z}' - \mathrm{Z_i} - L_i\right)\delta\left(\mathrm{y}' - \mathrm{b}\right)\right\} & \text{On aperture "i"} \\ 0 & \text{Elsewhere} \end{cases} \tag{4}$$

Where $E^i_{p,z}$ is the basis coefficient, "2L$_\mathrm{i}$" the length of the i$^{\mathrm{th}}$ slot, "2b" the guide height, and Z$_\mathrm{i}$ the offset of the i$^{\mathrm{th}}$ slot along the z-direction of propagation distance.

Using equivalence principle, electric field distribution the fictitious magnetic currents existing at apertures can be obtained.

For the proposed structure, the tangential components of magnetic field existing at different regions can be expanded [16] as:

Region 1 (R_1):

$$H_z^{wvg}\left(-M_z^1\right) + H_z^{wvg}\left(-M_z^3\right) + H_z^{inc} \tag{5}$$

Region 2 (R_2):

$$H_z^{cav\,1}\left(M_z^1\right) + H_z^{cav\,1}\left(-M_z^2\right) \tag{6}$$

Region 3 (R_3):

$$H_z^{ext}\left(M_z^2\right) + H_z^{ext}\left(M_z^4\right) \tag{7}$$

Region 4 (R_4):

$$H_z^{cav\,2}\left(M_z^3\right) + H_z^{cav\,2}\left(-M_z^4\right) \tag{8}$$

At the region of slot, the tangential components of the magnetic field should be continuous, which results in the following boundary conditions:

Aperture 1 (Region 1 = Region 2):

$$H_z^{wvg}\left(M_z^1\right) + H_z^{cav\,1}\left(M_z^1\right) - H_z^{cav\,1}\left(M_z^2\right) + H_z^{wvg}\left(M_z^3\right) = H_z^{inc} \tag{9}$$

Aperture 2 (Region 2 = Region 3):

$$-H_z^{cav\,1}\left(M_z^1\right) + H_z^{cav\,1}\left(M_z^2\right) + H_z^{ext}\left(M_z^2\right) + H_z^{ext}\left(M_z^4\right) = 0 \tag{10}$$

Aperture 3 (Region 1 = Region 4):

$$H_z^{cav\,2}\left(M_z^3\right) - H_z^{cav\,2}\left(M_z^4\right) + H_z^{wvg}\left(M_z^1\right) + H_z^{wvg}\left(M_z^3\right) = H_z^{inc} \tag{11}$$

Aperture 4 (Region 3 = Region 4):

$$H_z^{ext}\left(M_z^2\right) - H_z^{cav\,2}\left(M_z^3\right) + H_z^{cav\,2}\left(M_z^4\right) + H_z^{ext}\left(M_z^4\right) = 0 \tag{12}$$

The field components of equation (9) - (12) are given by [17, 18] as:

$$H_z^{ext}\left(M_z^i\right) = \frac{\mathrm{W_i L_i}}{\eta\kappa\pi^2} \sum_{\mathrm{p=0}}^{\mathrm{M}} E^i_{p,z} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{\kappa^2 - \kappa_\mathrm{x}^2}{\left(\kappa^2 - \kappa_\mathrm{x}^2 - \kappa_\mathrm{z}^2\right)^{\frac{1}{2}}} \,\mathrm{sinc}\,\left(\kappa_\mathrm{x} \mathrm{w_i}\right)$$

$$\mathrm{e}^{-j(\kappa_\mathrm{x}\mathrm{x1} + \kappa_\mathrm{z}\,\mathrm{z1})} \frac{\begin{cases} \mathrm{j}\sin(\kappa_\mathrm{z}\mathrm{L_i})\,\text{if p is even} \\ \cos(\kappa_\mathrm{z}\mathrm{L_i})\,\text{if p is odd} \end{cases}}{\frac{\mathrm{p}\pi}{2}\left\{1 - \left(\frac{2\mathrm{L_i}\mathrm{k_z}}{\mathrm{p}}\right)\right\}} \mathrm{e}^{\mathrm{j}\left(\mathrm{k_z z'} + \mathrm{k_x x'}\right)} \mathrm{dk_z dk_x} \tag{13}$$

$$H_z^{wvg}(M_z^i) = -\sum_{p=1}^{M} E_{p,z}^i \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{j \in_m \in_n W_i}{2\eta\kappa\gamma_{\mathrm{mn}}^2} \frac{\cos(n\pi)}{1+S^2(p)} \times$$
$$\mathrm{Cos}\left\{\frac{m\pi}{2a}(x_i+a)\right\} \sin c \left\{\frac{m\pi}{2a} W_i\right\} cos\left\{\frac{m\pi}{2a}(x+)\right\} \times$$
$$\left[\left\{k^2 - \left(\frac{\mathrm{p}\pi}{\mathrm{L_i}}\right)\right\} \sin\left\{\left(\frac{\mathrm{p}\pi}{\mathrm{L_i}}\right)(z+L_i)\right\}\left(\kappa^2 + \right.\right.$$
$$\left.\left.\gamma_{\mathrm{mn}}^2\right) S(p) e^{-\gamma_{mn}L_i} \begin{Bmatrix} -\sinh(\gamma_{\mathrm{mn}}\mathrm{Z}) \text{ if p even} \\ +\cosh(\gamma_{\mathrm{mn}}\mathrm{Z}) \text{ if p odd} \end{Bmatrix}\right] \cos\left\{\frac{n\pi}{2b}(y+b)\right\} \qquad (14)$$

When $z_1 = 0$

$$H_z^{inc} = -j \sin\left(\frac{\pi x}{2a}\right) e^{-j\beta z} \qquad (15)$$

Where “2a” is the guide width, “2t” the slot/waveguide wall thickness, and

$$S(p) = p\pi/(2L_i\gamma_{mn}) \qquad (16)$$

$$H_z^{cav}(M_z^i)$$
$$= -\frac{\mathrm{j}\omega\varepsilon}{\kappa^2}\sum_{\mathrm{p}=1}^{\mathrm{M}} E_{p,z}^i \sum_{m=p=1}^{\infty} \left\{k^2 - \left(\frac{m\pi}{2L_i}\right)^2\right\} \sin\left\{\left(\frac{\mathrm{m}\pi}{\mathrm{L_i}}\right)(z+L_i)\right\}$$
$$\times \cos\left\{\frac{n\pi}{2W_i}(x+W_i)\right\} \frac{(-1)}{\Gamma_{mn}\{\sin 2\Gamma_{mn}\}}$$
$$\times \begin{cases} \begin{pmatrix} \cos\{\Gamma_{mn}(y-t)\}\cos\{\Gamma_{mn}(y'+t)\}\; y > y' \\ \cos\{\Gamma_{mn}(y'-t)\}\cos\{\Gamma_{mn}(y+t)\}\; y > y' \end{pmatrix} & \left| \begin{array}{l} \text{for m = p} \\ \text{and n = 0} \end{array} \right. \\ 0 & Otherwise \end{cases} \qquad (17)$$

The method of moments is applied with Galerkin’s specialization [19] to solve equation (9)-(12) and hence to enable the determination of the $E_{p,z}^i$.

For the 7-element log periodic slot array, the fields existing at different regions can be expressed as:

Region 1: Waveguide

$$H_z^{inc} - \sum_{i=1,3,\dots\dots,13} H_z^{wvg}(M_z^i) \qquad (18)$$

Region n: cavity n

$$H_z^{cav}(M_z^{2n-1}) + H_z^{cav}(-M_z^{2n}) \qquad n = 1,2,\dots\dots,7 \qquad (19)$$

Region 3: Half space

$$\sum_{i=2,4,\dots..14} H_z^{ext}(M_z^i) \qquad (20)$$

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Equating the tangential components of magnetic field for different regions, as before 14 boundary conditions for the 14 apertures can be obtained. On solving these boundary conditions using Glarkins specialization method of moments, the electric field distribution at different apertures can be obtained. Once the electric field apertures have been found, different network parameters can be easily obtained. On the basis of the formulation Mat Lab codes have been written to compute Reflection Coefficient (S_{11}) and Transmission Coefficient (S_{21}) parameters of 7 elements longitudinal log periodic slot arrays. For validating the result, proposed LPSAA design is manufactured as shown in fig. 2 and tested using the Agilent Network Analyzer-5071C (300MHz~20GHz).

The comparison graph among measured, theoretical using MCMT and HFSS simulated of reflection coefficient and transmission coefficient in magnitude is shown in fig.6. Indicating that excellent agreement among simulated, theoretical and measured data results of seven- element log periodic slot array antenna validates the analysis.

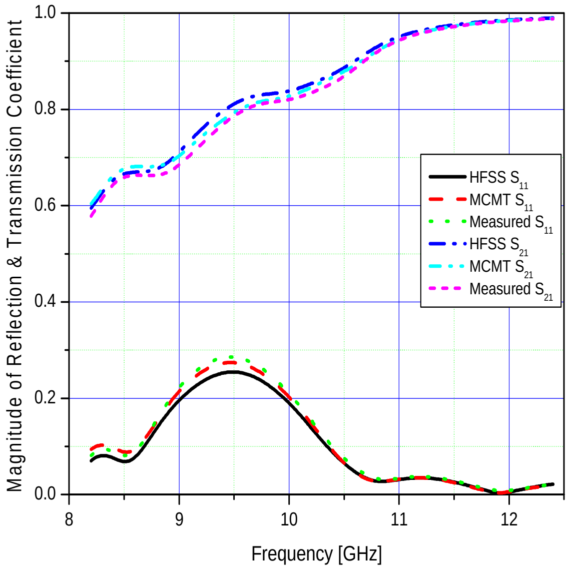

Fig. 6. Comparison of HFSS simulated data of the magnitude of Reflection & Transmission Coefficient versus frequency with theoretical and measured data for seven-element log periodic slot array antenna.

Experimental setup of manufactured LPSAA for calculating the gain in dB of seven-element LPSAA is shown in fig. 7.

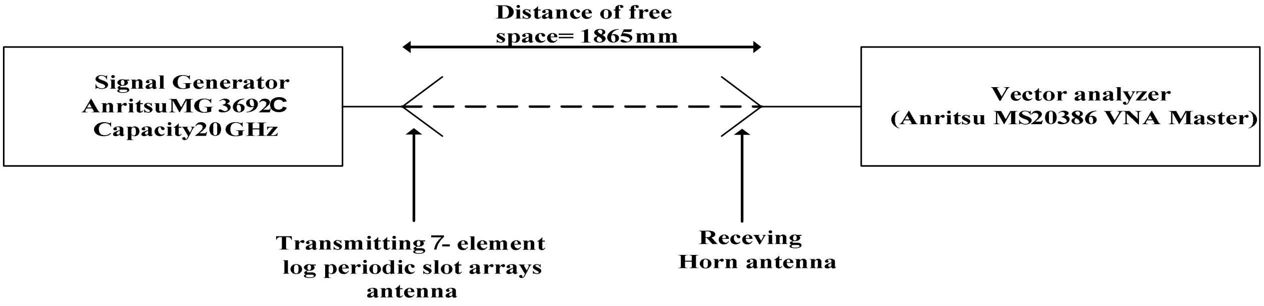

Fig. 7. Block diagram of experimental set up for measurement of gain of the seven-element log periodic slot array antenna.

V. RESULTS AND DISCUSSION

The connection is established in the laboratory according to fig. 7 and input power is set 5dbi on signal generator when solution frequency is 10 GHz with the help of signal generator corresponding radiated power is received with the help of horn antenna and resultant radiated power is displayed on the spectrum analyzer according to different frequency like us (8.2~12.4GHz) when theta and Phi [20] both are in 0^0 direction. The simulated data and measured data graph between frequencies versus gain of proposed LPSAA with simulated different case of CSSAA for X-band is shown in fig. 8.

Fig. 8 shows that the peak gain of proposed LPSAA is reaching up to 23.18dB that falls down to20.80% in respect of CSSAA-2 and increases up to 54.53% in respect of Gyan and Das [18] high-gain broadband waveguide broad-wall longitudinal slot array antenna. The gain radiation pattern of YZ- plane (E-plane) and XZ-plane (H-plane) of proposed LPSAA at frequencies 8.2GHz, 8.5GHz, 9.0GHz, 9.5GHz, 10.0GHz, 10.5GHz, 11.0GHz, 11.5GHz, 12.0GHz and 12.4GHz are shown in fig. 9. The E-plane as well as H-plane at different frequencies (8.2, 8.5, 9.0, 9.5, 10.0, 10.5, 11.0, 11.5, 12.0 and 12.4 GHz) has been studied. The H-plane radiation patterns are almost omnidirectional, whereas the E-plane radiation patterns are almost in the broadside direction for high frequencies. The proposed LPSAA gain is more than 0 dB in the entire range of X-band (8.2~12.4GHz). Hence we can say that proposed LPSAA bandwidth has increased in respect of CSSAA and high gain with respect to Gyan and Das [18] design antenna.

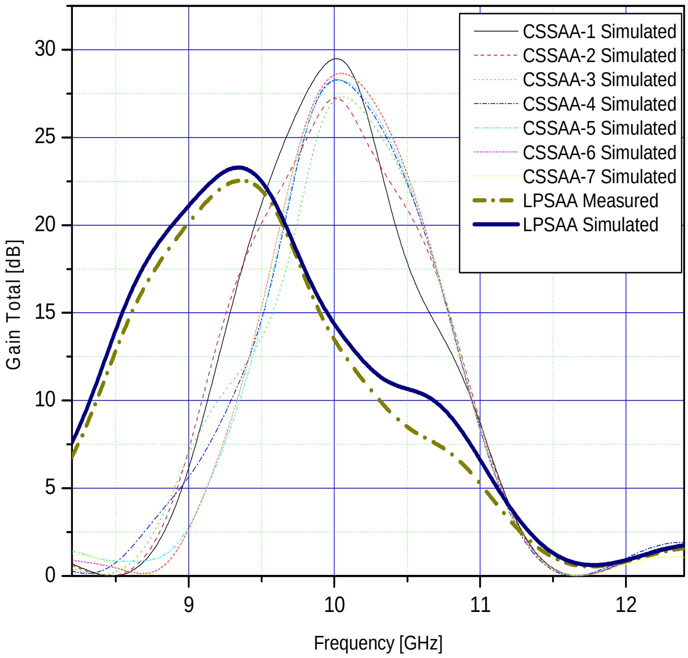

Fig. 8. Comparison of the simulated data Gain with respect to frequencies (8.2~ 12.4 GHz) at Theta = 0^0 and Phi= 0^0 directions for the proposed LPSAA with different case of CSSAA and measured data gain of proposed LPSAA.

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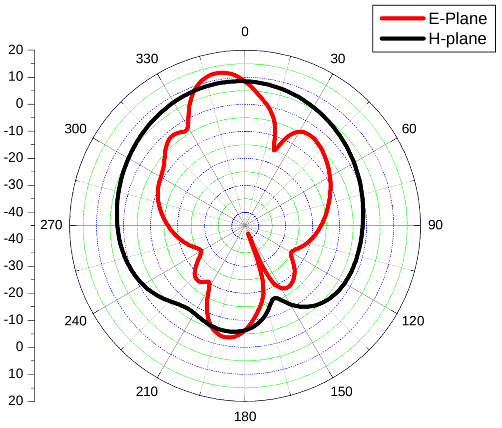
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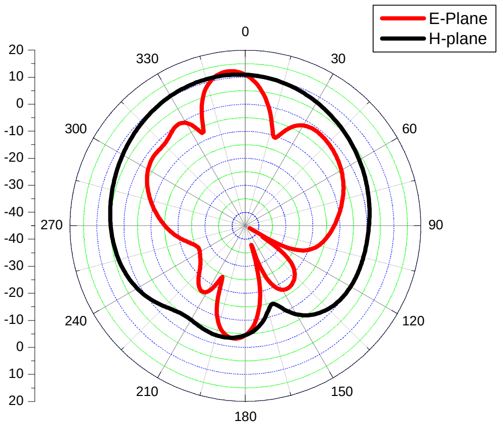
(a)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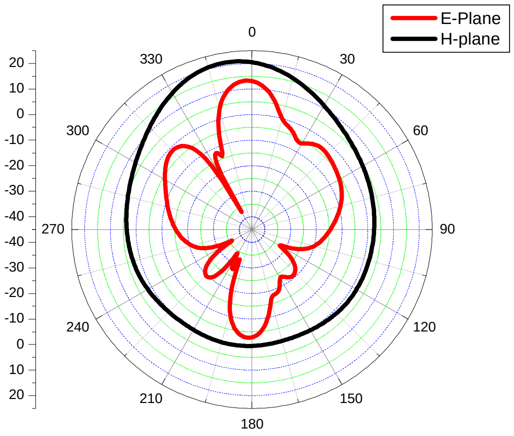
(b)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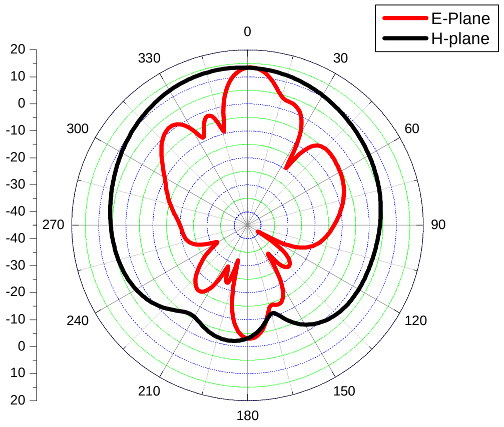
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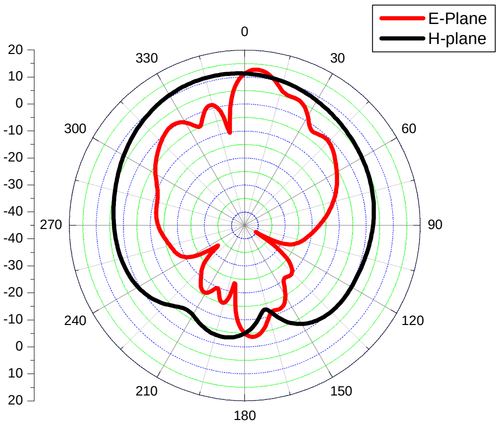
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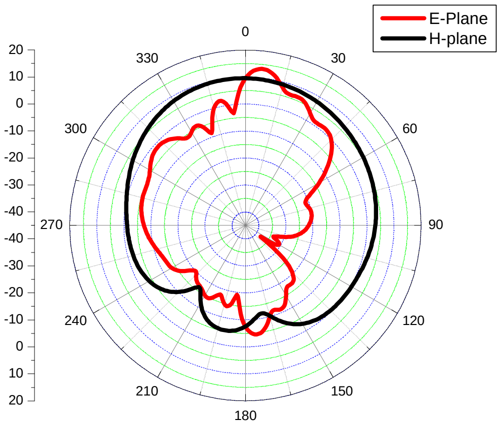
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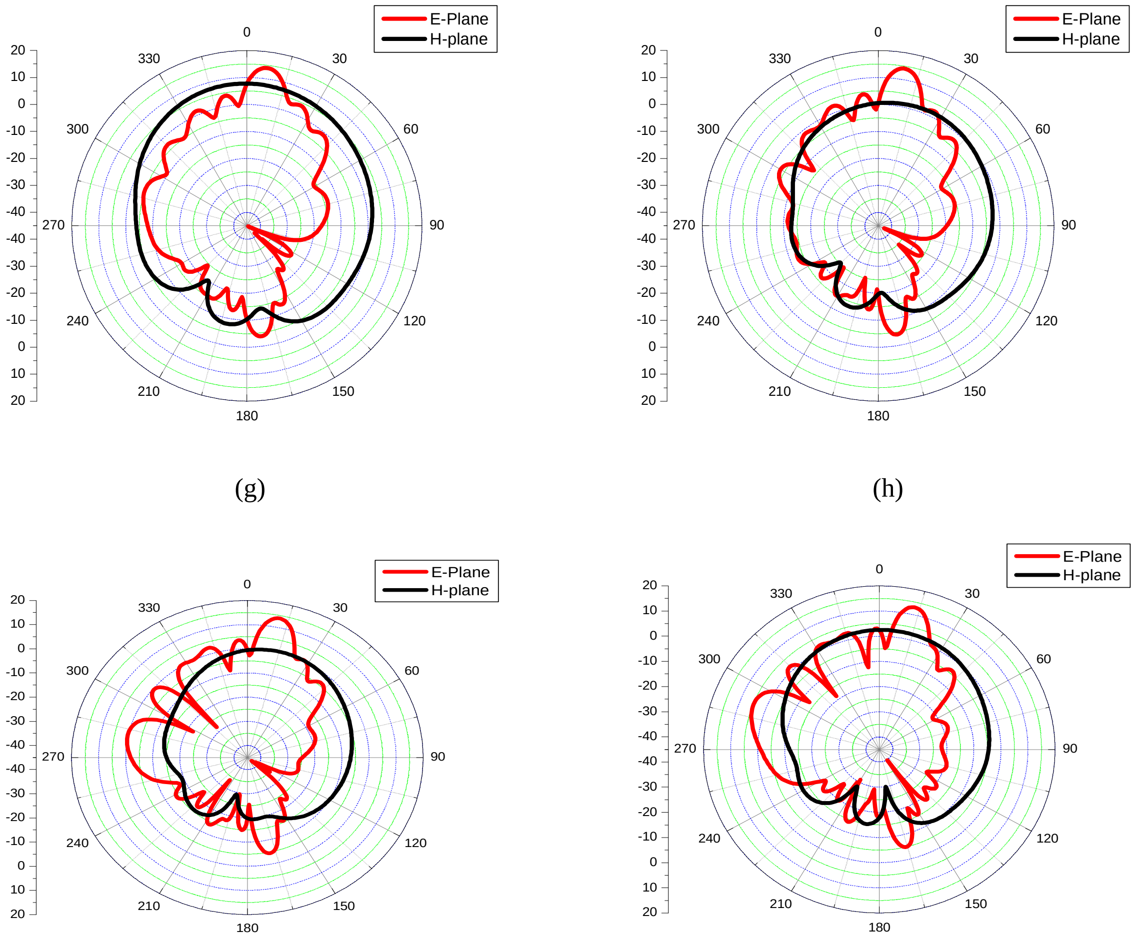
(f)



(g) (h)

(i) (j)

Fig. 9. Gain radiation patterns of the proposed LPSAA (a) 8.2GHz. (b) 8.5 GHz. (c) 9.0 GHz. (d) 9.5. (e) 10.0GHz. (f) 10.5GHz. (g) 11.0GHz. (h) 11.5GHz. (i) 12.0GHz. (j) 12.4 GHz.

VI. CONCLUSION

The proposed LPSAA has been manufactured as well as measured. The S-parameter, gains and radiation patterns have been reported. The antenna provides a gain as high as 23.18dB at 9.4GHz and as low as 0.61dB at 11.79 GHz and average 8-20dB, 6-7dB, 1-5dB across 8.2GHz to 10.97GHz, 10.98 GHz to 11.11GHz, 11.12GHz to 12.4GHz respectively are shown in fig. 8. The frequency range 11.12~12.4GHz average gain is poor that is 1-5dB ,therefore this frequency region antenna do not work efficiently, That's why this frequency region cannot be considered for broadband application of the proposed antenna. The obtained radiation characteristics at different frequencies are in the broadside direction with a good omnidirectional radiation in the H-plane of the antenna. There is excellent agreement between the simulated and experimental results. Therefore, we can say that the proposed LPSAA works or radiates on 8.2~11.11GHz in desired direction.

It may be noted that the geometrical offset position of the designed slot array antenna are not optimized. Here our objective was only to show that a log periodic slot array with varying length can have high gain at 8.2~11.11GHz frequencies. To design a high-gain slot array antenna with a desired radiation pattern, we can use the same antenna synthesis procedure that is used to design a standard shunt slot array antenna. This is an additional advantage of the proposed structure.

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