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# A HIGH-GAIN BROAD-BAND WAVEGUIDE LONGITUDINAL SLOT ARRAY ANTENNA

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**Abstract**—This paper presents method of moments based analysis of high-gain broad-band waveguide broad-wall longitudinal slot array antenna. Initially a basic two-element slot array antenna has been analyzed, and corresponding scattering parameter data have been obtained. The theoretical data have been compared with experimental data and Ansoft HFSS's simulated data to validate the proposed method. The excellent agreement obtained between the results validates the analysis. After validating the methodology, attempts have been made to design a broad-band high-gain slot array antenna. An 18-element slot array antenna has been designed, fabricated and tested. The fabricated antenna provides a high gain over large band width.

## 1. INTRODUCTION

Studies on waveguide broad-wall longitudinal slot antennas date back before World War II. Since then a number of workers have carried out considerable investigations on the resonance and admittance properties of the structure, and a detailed review of it will be a literature of its own. A brief survey of these literatures has been provided in [1]. However, most of these analyses were carried out for a single-slot element. In 1983, Elliott [2] presented an improved design procedure for small arrays of shunt slots. In this paper, he generalized an earlier design procedure that was valid for arrays of longitudinal slots fed by air-filled rectangular waveguide for application in dielectric filled waveguide. This work resulted in a simpler and more direct derivation of the design equations. In 1993 Sangster and Wang [3] presented resonance properties of omnidirectional slot doublet in rectangular waveguide. In this paper, moment method

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was employed to analyze a longitudinal slot doublet in both air-filled and dielectric-filled rectangular waveguides in which the slot radiators were located in the opposite broad faces of the waveguide. Two years later, in 1995, they presented another paper on moment method analysis of a horizontally polarized omnidirectional slot array antenna [4]. In this paper, an entire domain moment method analysis of an omnidirectional linear array antenna, in which the radiating elements are slot doublets in a rectangular waveguide, was developed. In 2004 Bastani and Rashed-Mohassel [5] presented analysis of planar slotted-waveguide array antennas with longitudinal slots using the method of moments. The effects of various mutual couplings, thickness of the waveguide walls, and waveguide proximity were taken into account in this analysis. Chen, Liao, and Wei [6], in 2010, presented an unequally spaced and excited resonant slotted-waveguide antenna array based on an improved resonant-slot coupled cavity chain composite right/left-handed waveguide. The proposed array produced a lower peak sidelobe level (PSLL) with comparison to the equally spaced but unequally excited resonant slotted-waveguide antenna array. In 2011 Ghaem et al. [7] presented design, optimization and VSWR improvement of a standing wave longitudinal slot array on a rectangular waveguide. The method that was applied in this paper is based on the Elliot's design formulas. It utilizes a three-term error function including the two-term Elliot's design formulas, input impedance matching and pattern synthesis at three different frequencies. By minimizing the error function, the optimum values of different parameters were derived. Advantages of the proposed method over other design methods are the ability to find proper parameters to improve VSWR and relatively increase the bandwidth in addition to the synthesis of a pattern with desirable properties. More recently, in 2013, Daliri et al. [8] presented a spiral shaped slot as a broad-band slotted waveguide antenna. In this paper, the bandwidth of the radiating elements was made to match with that available in the waveguide using a spiral shaped slot cut through the broad-wall of a rectangular waveguide. The predicted total efficiency and peak realized gain were found to be relatively uniform across the entire bandwidth. The antenna patterns for the manufactured spiral shaped slots in waveguides were shown to be similar to those predicted.

This paper presents method of moments based analysis of high-gain broad-band waveguide broad-wall longitudinal slot array antenna. Initially a basic two-element slot array antenna has been analyzed, and corresponding scattering parameter data have been obtained and validated. After validating the methodology, attempts have been made to design a broad-band high-gain slot array antenna. An 18-element

**Figure 1.** Fabricated 18-element slot array antenna.

slot array antenna as shown in Figure 1 has been designed, fabricated, and then tested.

## 2. PROBLEM FORMULATION AND ANALYSIS

The top view of the two-element array is shown in Figure 2 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 Figure 3.

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 of "$M$" weighted sinusoidal basis functions ($e^i_{p,z}$) defined over the entire length of the slot as follows [1]:

$$\vec{E}^i(x',y',z') = \hat{u}_x \sum_{p=1}^{M} E^i_{p,z} \begin{cases} \sin\left\{\dfrac{p\pi}{2L_i}\left(z'-Z_i+L_i\right)\right\}\delta\left(y'-b\right) & \text{On aperture "}i\text{"} \\ 0 & \text{Elsewhere} \end{cases}$$

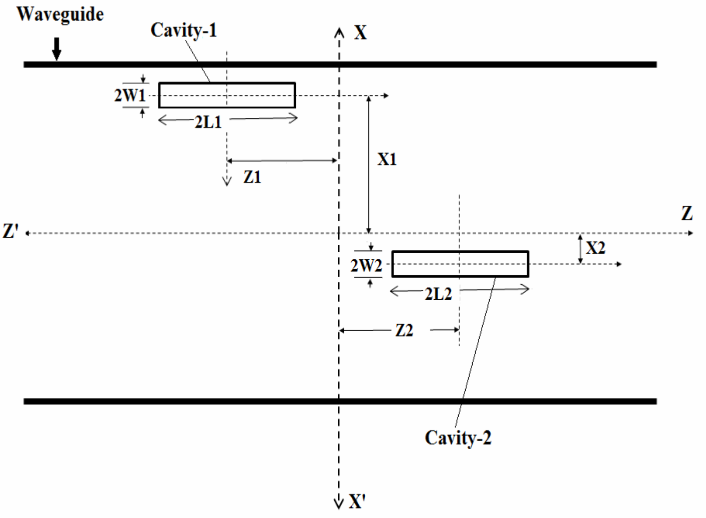


**Figure 2.** Top view and detail of different parameters used in the analysis of the two-element slot array.

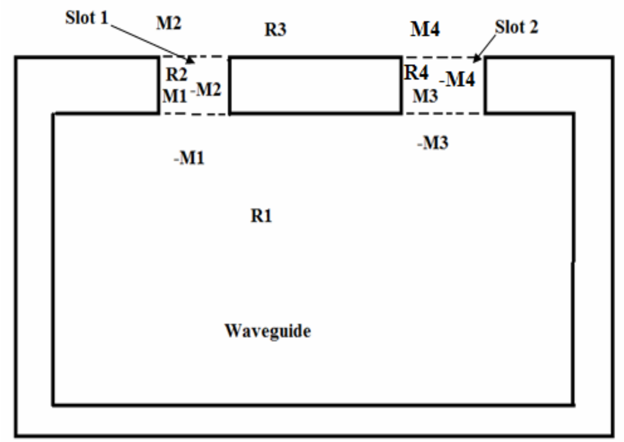


**Figure 3.** Details of different regions and magnetic currents at the apertures of the two-element slot array.

where $E^i_{p,z}$ is the basis coefficients, "$2L_i$" the length of the $i$th slot, "$2b$" the guide height, and $Z_i$ the offset of the $i$th slot along the $z$-direction or propagation direction.

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

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

Region 1 ($R_1$): $H_z^{wvg}\left(-M_z^1\right) + H_z^{wvg}\left(-M_z^3\right) + H_z^{inc}$
Region 2 ($R_2$): $H_z^{cav1}\left(M_z^1\right) + H_z^{cav1}\left(-M_z^2\right)$
Region 3 ($R_3$): $H_z^{ext}\left(M_z^2\right) + H_z^{ext}\left(M_z^4\right)$
Region 4 ($R_4$): $H_z^{cav2}\left(M_z^3\right) + H_z^{cav2}\left(-M_z^4\right)$

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)

$$H_z^{wvg}\left(M_z^1\right) + H_z^{cav1}\left(M_z^1\right) - H_z^{cav1}\left(M_z^2\right) + H_z^{wvg}\left(M_z^3\right) = H_z^{inc} \quad (1)$$

Aperture 2 (Region 2 = Region 3)

$$-H_z^{cav1}\left(M_z^1\right) + H_z^{cav1}\left(M_z^2\right) + H_z^{ext}\left(M_z^2\right) + H_z^{ext}\left(M_z^4\right) = 0 \quad (2)$$

Aperture 3 (Region 1 = Region 4)

$$H_z^{wvg}\left(M_z^1\right) + H_z^{wvg}\left(M_z^3\right) + H_z^{cav2}\left(M_z^3\right) - H_z^{cav2}\left(M_z^4\right) = H_z^{inc} \quad (3)$$

Aperture 4 (Region 3 = Region 4)

$$H_z^{ext}\left(M_z^2\right) - H_z^{cav2}\left(M_z^3\right) + H_z^{cav2}\left(M_z^4\right) + H_z^{ext}\left(M_z^4\right) = 0 \qquad (4)$$

The field components of Equations (1)–(4) are given by [9, 10]

$$H_z^{ext}\left(M_z^i\right) = -\frac{W_i L_i}{\pi^2 k\eta}\sum_{p=1}^{M} E_{p,z}^i \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{k^2 - k_x^2}{\left(k^2 - k_x^2 - k_z^2\right)^{1/2}} \operatorname{sinc}\left(k_x W_i\right)$$
$$e^{-j(k_x x_1 + k_z z_1)} \frac{\begin{cases} j\sin\left(k_z L_i\right) & \text{if } p \text{ is even} \\ \cos\left(k_z L_i\right) & \text{if } p \text{ odd} \end{cases}}{\frac{p\pi}{2}\left\{1 - \left(\frac{2L_i k_z}{p\pi}\right)^2\right\}} e^{j\left(k_z z' + k_x x'\right)} dk_z dk_x$$

$$H_z^{wvg}\left(M_z^i\right) = -\sum_{p=1}^{M} E_{p,z}^i \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{j\varepsilon_m \varepsilon_n W_i}{2k\eta\gamma_{mn}^2 ab} \frac{\cos(n\pi)}{1+S^2(p)} \cos\left\{\frac{m\pi}{2a}\left(x_i + a\right)\right\}$$
$$\operatorname{sinc}\left(\frac{m\pi}{2a}W_i\right)\cos\left\{\frac{m\pi}{2a}(x+a)\right\} \times \left[\left\{k^2 - \left(\frac{p\pi}{2L_i}\right)\right\}\sin\left\{\frac{p\pi}{2L_i}\left(z + L_i\right)\right\}\right.$$
$$\left. + \left(k^2 + \gamma_{mn}^2\right) S(p)\, e^{-\gamma_{mn} L_i} \begin{cases} -\sinh\left(\gamma_{mn} z\right) & \text{if } p \text{ even} \\ +\cosh\left(\gamma_{mn} z\right) & \text{if } p \text{ odd} \end{cases}\right]$$
$$\cos\left\{\frac{n\pi}{2b}(y + b)\right\}$$

when $z_1 = 0$

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

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

where "$2a$" is the guide width, "$2t$" the slot/waveguide wall thickness, and

$$S(p) = p\pi/\left(2L_i\gamma_{mn}\right)$$

The method of moments is applied with Galerkin's specialization [11] to solve Equations (1)–(4) and hence to enable the determination of the $E_{p,z}^i$.

For the 18-element slot array, the fields existing at different regions can be expressed as:

Region 1: Waveguide

$$H_z^{inc} - \sum_{i=1,3,\ldots,35} H_z^{wvg}\left(M_z^i\right)$$

Region $n$: Cavity $n$

$$H_z^{cavi}\left(M_z^{2n-1}\right) + H_z^{cavi}\left(-M_z^{2n}\right) \quad n = 1, 2, \ldots, 18$$

Region 3: Half Space

$$\sum_{i=2,4,\ldots,36} H_z^{ext}\left(M_z^i\right)$$

Equating the tangential components of magnetic field for different regions, as before a total of 36 boundary conditions for the 36 apertures can be obtained. On solving theses boundary conditions using Galerkin's specialization method of moment, the electric field distribution at different apertures can be obtained. Once the electric fields at the apertures have been found, different network parameters and antenna parameters can be easily obtained.

## 3. RESULTS AND DISCUSSION

On the basis of the formulation, MATLAB codes have been written to compute scattering parameters of a two-element linear slot array. The results are presented below.

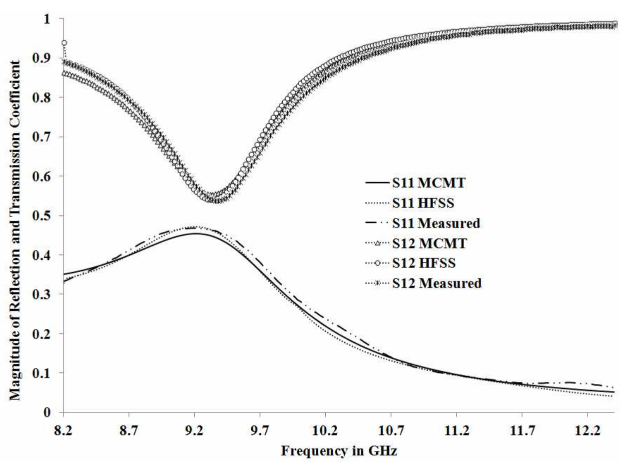


**Figure 4.** Comparison of theoretical data of the magnitude of reflection coefficient and transmission coefficient with HFSS and measured data for a two-element slot array.

The magnitude of the $S$-parameters of a two-element slot array with slot length = 16 mm, width = 1 mm, thickness = 1.27 mm, offset $X_1 = 8.43$ mm and $X_2 = -8.43$ mm and slot distance along the propagation direction = 0 mm have been obtained and compared with HFSS and measured data in Figure 4 over a frequency range 8.2 GHz to 12.4 GHz. The excellent agreement obtained between them validates the analysis.

The magnitudes of $S$-parameters for a four-element slot array with non-uniform slot lengths = 18.75 mm, 18.75 mm, 12.5 mm and 12.5 mm width = 1 mm, thickness = 1.27 mm, offset $X_1 = 5.5$ mm, $X_2 = -5.5$ mm, $X_3 = 5.5$ mm, $X_4 = -5.5$ mm and slot distance along the propagation direction = 32.75 mm, 31.30 mm, 29.85 mm milled on a waveguide with $2a = 22.86$ mm, $2b = 10.16$ mm are plotted with frequency in Figure 5 and Figure 6, respectively. The frequency responses of the magnitude of the $S$-parameters for two more slot arrays but now with uniform slot length (18.75 mm, 18.75 mm & 12.5 mm, 12.5 mm, respectively) and slot offset along propagation direction = 32.75 mm, 29.85 mm, respectively are also plotted in the respective figures. The graphs reveal that the frequency response of the slot array with non-uniform slot length closely follows the envelope of the overlapped frequency response of the two slot arrays of uniform slot length. This implies that there is a possibility of designing a broadband slot array using slots of non-uniform slot lengths. To explore this

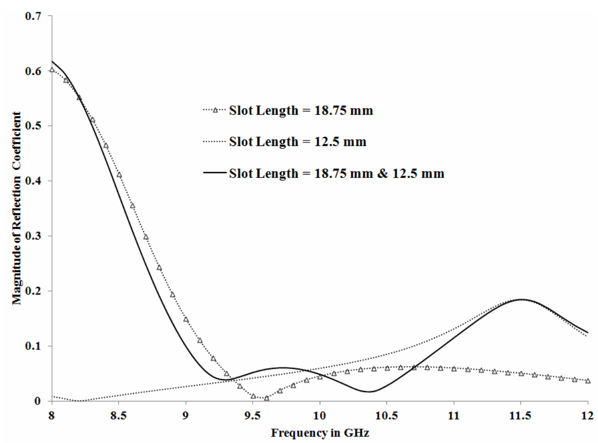


**Figure 5.** Variation of magnitude of reflection coefficients with frequency for three slot array antennas, one with non-uniform length (18.75 mm & 12.5 mm) and two with uniform lengths (18.75 mm & 12.5 mm respectively).

property, the gain response of the three-slot arrays, mentioned above, have been studied in Figure 7 for $\theta = 0°$ and $\varphi = 0°$. Here we also note that the gain response of the slot array of non-uniform slot length is closely following the envelope of the overlapped gain response of the

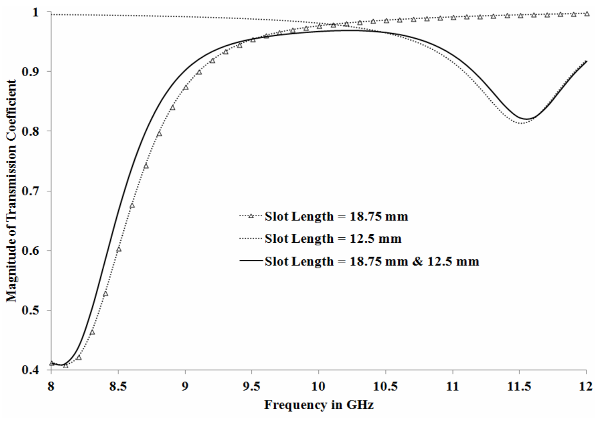


**Figure 6.** Variation of magnitude of transmission coefficients with frequency for three slot array antennas, one with non-uniform length (18.75 mm & 12.5 mm) and two with uniform lengths (18.75 mm & 12.5 mm respectively).

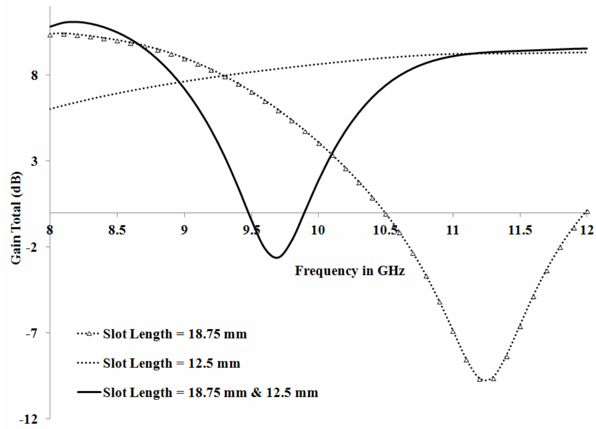


**Figure 7.** Plot of gain versus frequency at Theta = 0 and Phi = 0 direction for three slot array antennas, one with non-uniform length (18.75 mm & 12.5 mm) and two with uniform lengths (18.75 mm & 12.5 mm respectively).

slot arrays with uniform slot lengths.

Inspired by the above results, next an 18-element slot array with slot width = 1 mm, thickness = 1.27 mm, offset $X_i$ = ±5.5 mm, (alternatively) and slot lengths = 18.75 mm, 18.75 mm, 17.65 mm, 17.65 mm, 16.67 mm, 16.67 mm, 15.79 mm, 15.79 mm, 15 mm, 15 mm, 14.29 mm, 14.29 mm, 13.64 mm, 13.64 mm, 13.04 mm, 13.04 mm, 12.5 mm, 12.5 mm milled on a waveguide with $2a = 22.86$ mm, $2b = 10.16$ mm has been designed, fabricated and tested. The measurement set up is shown in Figure 8, and the measured gain response is shown in Figure 9. In the designed array, the slot lengths are chosen such that each of them resonates at any one of the frequencies 8, 8.5, 9, 9.5, 10, 10.5, 11, 11.5, and 12 GHz. The gain response of nine two-element slot arrays, corresponding to the above nine resonance frequencies, are

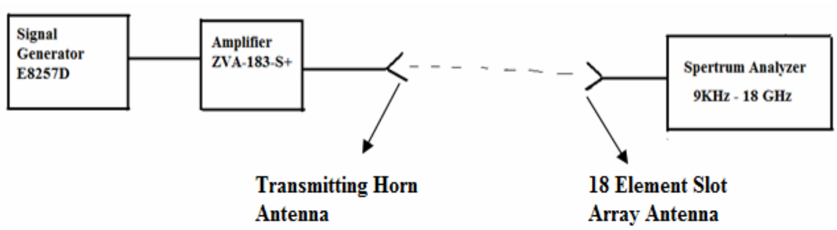


**Figure 8.** Block diagram of the experimental setup for measurement.

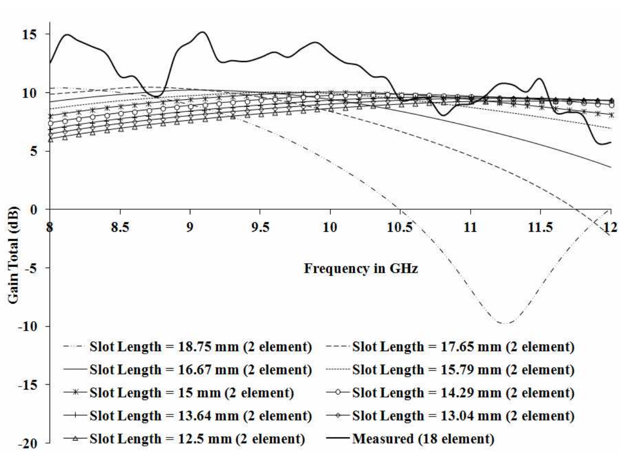


**Figure 9.** Plot of gain as a function of frequency at Theta = 0 and Phi = 0 direction for the 18-element slot array and nine other two-element slot arrays corresponding to resonance frequencies 8, 8.5, 9, 9.5, 10, 10.5, 11, 11.5 and 12 GHz respectively.

also plotted in the same figure for comparison. The results show that the designed antenna has both higher gain and higher bandwidth than the uniform arrays except for the 12 GHz. The decrease in gain at few intermediate bands such as near 8.8 GHz and between 10.5 to 11 GHz is due to measurement error that occurred as results of reflections from ground and nearby objects. The $\theta$-plane radiation patterns of the above slot arrays are compared in Figure 10.

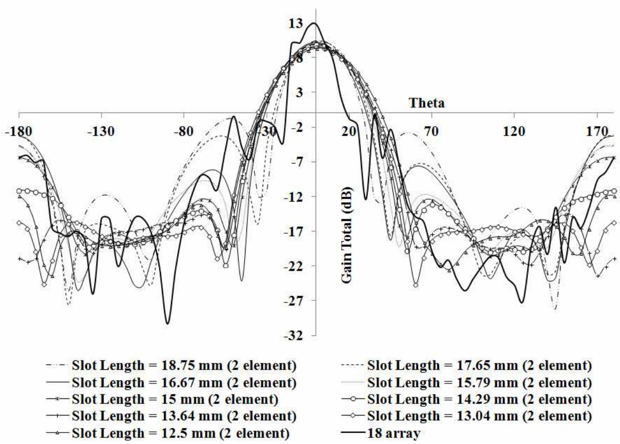


**Figure 10.** Plot of gain versus theta over Theta = $-180°$ to $180°$ direction for the 18-element slot array and nine other two-element slot arrays corresponding to resonance frequencies 8, 8.5, 9, 9.5, 10, 10.5, 11, 11.5 and 12 GHz respectively.

## 4. CONCLUSION

This paper presents the analysis of a high-gain broad-band slot array antenna. The methodology has been verified with measured data. The antenna provides a gain as high as 15 dB and average 12–13 dB over 8 to 10.5 GHz band width at $\theta = 0°$ and $\varphi = 0°$. Between 10.5 GHz and 11.5 GHz, the average gain is almost equal to its corresponding two-element array with uniform slot length.

It may be noted that the geometrical parameters of the designed slot array antenna are not optimized. Here our objective was only to show that a slot array with varying slot length can have a high gain and also broad band. To design a high-gain broad-band 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 extra advantage of the proposed structure.

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