Study of Slotted Array Waveguide with High Peak Gain Antenna for Data Communication

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Abstract

Objectives: This article manifests a study of high peak gain of a slotted array waveguide antenna. At first, two similar slot lengths 2-elements shunt slotted array antenna structures (i.e. Case-1) and two dissimilar slot lengths 2-elements shunt slotted array antenna structures (i.e. Case-2) are designed one by one. Methods/Statistical Analysis: The Multiple Cavity Modeling Technique (MCMT) has been applied in both cases of structural antennas. The scattering parameters (i.e. $|S_{11}|$ and $|S_{21}|$) data have been computed for both cases of 2-element shunt slotted array antenna. The MCMT $|S_{11}|$ and $|S_{21}|$ data graphs have been compared with Ansoft High Frequency Structure Simulator (HFSS) simulated data graphs. Comparison results signify that a slight difference between computed and simulated data. Findings: Subsequently, the HFSS simulated gains total of the both cases of design structures antenna are obtained. The outcome found in 2-element shunt slotted array with similar slot length gains higher total rather than dissimilar slot length 2-element shunt slotted array antenna. In order to achieve further increases in gain a 2-elements lotted array antenna up to optimal point was extended up to seven slots. Analysis was done to compare the results with theoretical and simulated HFSS results. Application/Improvement: The antenna finds its application in high speed data communication system in the area of aircraft.

Keywords: Multiple Cavity Modeling Technique (MCMT), Peak Gain, Slot Array, Scattering Parameters, Waveguide

1. Introduction

The Slotted Waveguide Antennas (SWA) comprise with two important things waveguide and slot antenna. The waveguide is basically a device (“a guide”) for transporting electromagnetic energy from one region to another region. It is available in two forms rectangular and circular. The waveguide is often used at microwave frequencies. Slot antenna is such type of antenna in which a slot cut into the wall of the waveguide. In this regard, several papers were published in this region. A good number of them are used, one slot for radiating element for computing reflection and transmission coefficient by various methodologies. Some of the works were published for efficient and accurate evaluation of external mutual coupling between two longitudinal slots. In recent decade, a small number of works were also published for computing reflection and transmission coefficient parameters by using MCMT in which multi slots are used for radiating element.

Although, micro strip patch antenna is very popular due to very small size and low cost design, but they suffer high peak gain problem in X-band. Now-a-days, high gain antennas are very much required to reach a high signal to noise (S/N) ratio for point-to-point high-speed data-communication systems in the millimeter-wave band. In addition, speedy data-communication systems SWA is very essential. Generally, the present communication system needs high peak gain for high speed data transferring. Slot antenna is useful in various applications, especially where low profile or flush mountings are required as, for example, on high speed aircraft for data communication.

The performance of SWA can be measured by a number of parameters such as radiation pattern, gain,
directivity, bandwidth, scattering parameters and Voltage
Standing Wave Ratio (VSWR).

2. Design of SWA

Generally, rectangular waveguide comprises with two
broad walls and two narrow walls. In fact, the waveguide
is a hollow metal box that is made from perfect conduc-
tor material as shown in Figure 1. In slotted waveguide
antenna, longitudinal slots are cut on waveguide. These
slots start discontinuities inside the conductor and stop
the flow of current along the waveguide. In its place, the
current must flow in the region of the edges of the slots,
causing them to work as dipole antennas.

In this paper initially two longitudinal slots with
similar size lengths cut on one face of broad wall of a
standard waveguide (WR-90) and also dissimilar size
lengths cut on one face of broad wall of another WR-90
respectively for designing 2-element shunt slotted array
antenna. Here, only two designs have been prepared as
shown in Figure 2. Design constraint of 2-element shunt
slotted array antenna is exposed in Table 1. A design both
slots are similar in length size, i.e. considered as a Case-
1. Another design both slot length sizes are dissimilar as
considered for Case-2. The design procedure of standard
waveguide slot arrays was presented by Elliott in11–13
and it is adopted here. In this Case-1 and Case-2, we keep
the distance between slots as $\lambda_g/2$ such that the slots will be
fed in the same phase (spacing between the slots at $\lambda_g/2$
intervals in the waveguide is an equivalent electrical spac-
ing of 180°. Therefore, each slot is exactly out of phase
with its neighbors, so their radiation cancelled each other.
On the other side, slots on opposite sides of the center
axis of the guide are out of phase (180°), so we can swap
the slot displacement around the center axis and have a
total phase difference of 360° between slots, putting them
back in phase) and the beam will not be inclined14,15. From
the position of the initial/last slot, the center of the slot
is kept at guiding quarter wavelength away from the ini-
tial/closed end of the waveguide. The guided wavelength
$\lambda_g$ is calculated 39.75mm at 10 GHz cut off or central
frequency as adopted here as2. The Case-1 and Case-2
structures are made in HFSS software separately. The per-
fected conductor material is used for designing the shunt
slot array antenna. Simulated the structures and com-
puted the electric field for Case-1 and Case-2 as shown in
Figure 3. Subsequently, scattering parameters of Case-1
and Case-2 are obtained respectively, when both ports of
the waveguide are excited by wave port.

Table 1. Design constraint of similar and dissimilar
2-element shunt slotted array antenna

| Case-# | Case-1 | Case-2 |
|-------|-------|-------|
| Slot-# | Width (mm) | Offset (mm) | Length (mm) | Length (mm) |
| Slot-1 | 2 | +3.5 | 16 | 19.5 |
| Slot-2 | 2 | -3.5 | 16 | 13.5 |

![Figure 1. Waveguide photograph.](image)

![Figure 2. Diagram with parameters detail of (a) two similar size lengths of slots milled on a WR90 with ± 3.5mm offset (b) two dissimilar size lengths of slots milled on a WR90 with ± 3.5mm offset.](image)
3. Problem Formulation

Reflection Coefficient i.e. represented by $S_{11}$ or $\Gamma$ and Transmission coefficient i.e. represented by $S_{21}$ or $T$ are computed by the MCMT as described as follows:

The MCMT design of 2-element shunt slotted array antenna with interrelated specifications is shown in Figure 4. The related aperture information of magnetic current in dissimilar region of MCMT is revealed in Figure 5.11-12.

Figure 3. HFSS simulated electric field image for (a) Case-1 and (b) Case-2.

Figure 4. The MCMT design structure of 2-element shunt slotted array antenna.

Figure 5. MCMT region information drawing of 2-element shunt slotted antenna.

Here, let us consider lot electric field is x-directed at a point $(x', y', z')$ and represented terms for the entire slot length into basis function $E_{p,z}^{i}$ as 16, in which ‘M’ indicates the weighted sum.

$$E = \sum_{p} E_{p,z}^{i} \sin \left( \frac{p \pi}{2L_i} (z' - Z_i) \right) \delta(y - b)$$

where, $E_{p,z}^{i}$ indicates basis coefficient, ‘2b’ represents the height of the waveguide, ‘2L’ shows length of the $i$th slot and $Z_i$ reflects the offset of the $i$th slot.

By the use of the equivalence principle, pretended magnetic currents lying on apertures may be obtained. The components of tangential magnetic field for 2-element shunt slotted structures are occurring at regions may be articulated as:

$$\text{Region 1}(R_1) : H_z^{wv}(-M_1^i) + H_z^{wv}(M_1^i) + H_z^{inc}$$

$$\text{Region 2}(R_2) : H_z^{cav}(M_2^i) + H_z^{cav}(-M_2^i)$$

$$\text{Region 3}(R_3) : H_z^{ext}(M_3^i) + H_z^{ext}(M_3^i)$$

$$\text{Region 4}(R_4) : H_z^{cav}(M_4^i) + H_z^{cav}(-M_4^i)$$

The boundary conditions at the different region are expressed as:

For aperture1: equating region $R_1$ and $R_2$, we get

$$H_z^{wv}(M_1^i) + H_z^{cav}(M_1^i) - H_z^{cav}(M_1^i) + H_z^{wv}(M_2^i) = H_z^{inc}$$

For aperture2: equating region $R_2$ and $R_3$, we get

$$-H_z^{cav}(M_2^i) + H_z^{cav}(M_2^i) + H_z^{ext}(M_3^i) + H_z^{ext}(M_3^i) = 0$$

For aperture3: equating region $R_1$ and $R_4$, we get

$$H_z^{cav}(M_4^i) - H_z^{cav}(M_4^i) + H_z^{cav}(M_3^i) + H_z^{cav}(M_3^i) = H_z^{inc}$$

For aperture4: equating region $R_4$ and $R_3$, we get

$$H_z^{cav}(M_4^i) - H_z^{ext}(M_4^i) + H_z^{ext}(M_4^i) + H_z^{ext}(M_4^i) = 0$$
The equation (6) - (9) are given by\(^{11-12}\) as:

\[
H^{\text{inc}}_z(M_i') = \frac{W_L k_w}{\eta k \pi} \sum_{p=1}^{N_z} E_p \sum_{k=0}^{\infty} \left( \frac{k^2 - k_z^2}{k^2 - k_w^2} \right) \sin c(k_z W_i') \times e^{j(k_z z + \kappa_x x + \kappa_y y)} d\kappa_x d\kappa_y
\]

(10)

\[
H^{\text{ext}}_z(M_i') = -\frac{W_L k_w}{\pi k} \sum_{p=1}^{N_z} E_p \sum_{k=0}^{\infty} \left( \frac{k^2 - k_z^2}{k^2 - k_w^2} \right) \sin c(k_z W_i') \times e^{j(k_z z + \kappa_x x + \kappa_y y)} d\kappa_x d\kappa_y
\]

Here, four boundary conditions are obtained for four apertures of regions of 2-element shunt slot array waveguide antenna. Similarly, fourteen boundary conditions may be obtained in accordance with fourteen apertures on behalf of 7-element shunt slotted array antenna. The entire boundary conditions are solved by the Glarksins specialized moments method. The dissimilar apertures electric field can be obtained as\(^{3}\). Subsequently, reflection and transmission coefficient parameters can be simply obtained by equation (18) and (19). Where, '2L_i' = i\(^{th}\) slot length, '2a' = waveguide width, '2t' = wall thickness of slot/waveguide, and '2b' = waveguide height, '2W_i' = i\(^{th}\) slot width, 'x_i' = offset of the i\(^{th}\) slot, '\beta_i' = propagation constant, 'k' = wave number and \(E^{i}_{p,z}\) = electric field of i\(^{th}\) slot.

\[
\Gamma = \frac{\pi W_i}{4a' b' k' \eta W_i} \sin \left( \frac{\pi y}{2a} \right) \sin \left( \frac{\pi x}{2b} \right) E_p \sum_{m=1}^{N_z} S(p) \left[ j \sinh (\lambda \beta_i) \frac{y}{y_{p,even}} \right]
\]

(18)

\[
\mathcal{T} = 1 + \frac{\pi W_i}{4a' b' k' \eta W_i} \sin \left( \frac{\pi y}{2a} \right) \sin \left( \frac{\pi x}{2b} \right) E_p \sum_{m=1}^{N_z} S(p) \left[ j \sinh (\lambda \beta_i) \frac{y}{y_{p,even}} \right]
\]

(19)

\[4. \text{Numerical Results and Discussion}\]

Accordance with formulation \(S_{11}\) and \(S_{21}\) codes have been written in Mat Lab of Case-1 and Case-2 respectively. The MCMT \(|S_{11}|\) and \(|S_{21}|\) data of Case-1 and Case-2 are compared through HFSS simulated \(|S_{11}|\) and \(|S_{21}|\) data more than the range of 8.2-12.4 GHz (X-band) respectively in Figure 6(a) and Figure 6(b). Figure 6 exposes that small variations between theoretical MCMT and HFSS simulated data graph. In another word, we can say that Figure 6 shows the validation of analysis. Subsequently, in HFSS Theta and Phi are kept zero degree and total gain data are obtained over 8.2-12.4 GHz frequency for Case-1 and Case-2 are shown in Figure 7. Figure 7 shows that Case-1 carry on high gain (greater than 5dB) in whole X-band and gain total is achieved up and about to 8.14dB at 10.8 GHz. Whereas, Case-2 is not achieved up to high gain in a whole X-band. However, form dual band characteristic inside in X-band, one band works on 8.2 GHz to 10 GHz another band works on 10.5 GHz to 12.4 GHz. These things were also reflected in\(^{12}\). But 8.14dB is not sufficient for high speed data communication. Usually for high data communication rate 10dB or more than 10dB gain is required. For achieving the high gain, the Case-1 slot element is extended up to seventh for designing 7-element shunt slotted array antenna. The design constraint of 7-element shunt slotted array antenna is shown in Table 2. In accordance with Table-2 constraint, 7-element
shunt slotted array antenna is made in HFSS software i.e. shown in Figure 8. Excited both ports by wave port of 7-element shunt slotted array antenna at 10 GHz central frequency, then found that the simulated electric field shown in Figure 9, magnitude of reflection and transmission coefficient as shown in Figure 10 and also reflection and transmission coefficients in decibel (dB) as shown in Figure 11. Figure 10 represents that magnitude of reflection is close to zero and the magnitude of the transmission coefficient nearer to 1. Similarly, in Figure 11 shows that a reflection coefficient falls down -10dB point and transmission coefficient above than -10dB point in entire X-band respectively. Compared the magnitude of reflection and transmission coefficient HFSS data to theoretical MCMT data and got a good agreement between them to validate the analysis as shown in Figure 12.

Figure 6. Comparison graphs between MCMT theoretical and HFSS simulated (a) $|S_{11}|$ (b) $|S_{21}|$ of Case-1 and Case-2 in accordance with the 8.2-12.4 GHz frequency band.

Figure 7. Case-1 and Case-2 simulated gain total graph in accordance with 8.2-12.4 GHz frequency band.

Figure 8. HFSS image of proposed 7-element shunt slotted array antenna with radiation boundary.

Figure 9. The electric field image of proposed 7-element shunt slotted array antenna.

directivity represents are in dB over the 8.2-12.4 GHz frequency band as shown in Figure 13. Peak gain and directivity both are high more 12 dB in entire X-band frequency. Maximum peak gains 15.6 dB is reached on 10 GHz frequency.

Subsequently, peak gain and directivity are computed in the HFSS software environment for proposed 7-element slot array waveguide antenna. Peak gain and
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Figure 10. The simulated graph image of $|S_{11}|$ and $|S_{21}|$ of proposed 7-element shunt slotted array antenna in accordance with 8.2-12.4 GHz frequency band.

Figure 11. The Simulated graph image of $S_{11}$ and $S_{21}$ represented in dB of proposed 7-element shunt slotted array antenna in accordance with 8.2-12.4 GHz frequency band.

Figure 12. Comparison graphs between MCMT theoretical and HFSS simulated $|S_{11}|$ and $|S_{21}|$ of proposed 7-element shunt slotted array antenna in accordance with 8.2-12.4 GHz frequency band.

Figure 13. Graph image of Peak Gain and Peak Directivity in dB for proposed 7-element shunt slotted array antenna in accordance with 8.2-12.4 GHz frequency band.

Table 2. Design constraint of 7-element shunt slotted array antenna

| Slot-# | Length (mm) | Width (mm) | Offset (mm) |
|--------|-------------|------------|-------------|
| Slot-1 | 16          | 2          | +3.5        |
| Slot-2 | 16          | 2          | -3.5        |
| Slot-3 | 16          | 2          | +3.5        |
| Slot-4 | 16          | 2          | -3.5        |
| Slot-5 | 16          | 2          | +3.5        |
| Slot-6 | 16          | 2          | -3.5        |
| Slot-7 | 16          | 2          | +3.5        |

5. Conclusion

In this paper slotted waveguide antenna has been developed with high gain. The study was initiated with a structure having two shunt symmetrical slot (similar slot length dimension) and two shunt unsymmetrical (dissimilar slot length dimension) milled on one broad wall face separately. The result obtained in this antenna was compared with two techniques, namely HFSS and MCMT. They were in agreement with each other in terms with scattering parameters. A further study was carried out with the optimum symmetrical with high peak gain structure up to seven slots in order to achieve the gain factor more than 12dB as required like aircraft data communication systems.

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