Assessment of Input Impedance of an Axial Slot Antenna on a Sectoral Cylindrical Cavity Excited by Probe using Method of Moments

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Abstract

This paper presents the assessment of input impedance of a sectoral cylindrical cavity-backed slot antenna excited by a probe. This antenna is proposed to be an element of array that can be assembled to be the antenna for UHF TV broadcasting system. The integral equations are derived based on boundary conditions of the proposed structure and are expressed in terms of dyadic Green's functions and unknown currents. The unknown current densities are solved by the Method of Moments and the input impedance is derived subsequently. Numerical results show the variation of input impedance, for the specified dimensions of the antenna, as a function of frequency. This result is validated by measurement and found that the result is sufficiently accurate. The result from this study is useful for the design of a sectoral cylindrical cavity-backed slot antenna excited by a probe.

1.Introduction

Broadcasting system has been extensively and continuously used for distributing information over wide range of the service area. The antenna applied for the broadcasting station of the ultra high frequency television (UHF TV) requires either unidirectional or omnidirectional beam with sufficient gain and high power handling. The bandwidth of each channel is 6 MHz [1]. Moreover, the antenna should possess physically strong structure, low windload, easy fabrication and cost effectiveness.

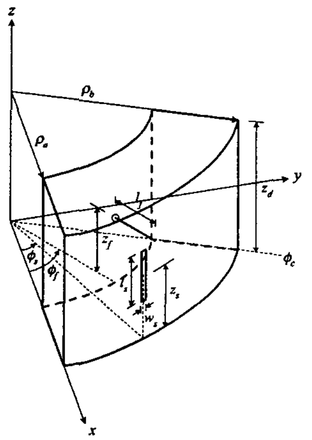
Most manufacturers offer configurations that can be used to broadcast a wide variety of azimuth and elevation patterns at either low or high power with their simple feeding system, low windload, and ability to be side- or top-mounted. Conventionally, the versatile and popular antenna utilized for this purpose is the coaxial slot antenna. Its disadvantages include narrow bandwidth and pattern distortion when side-mounted [2]. UHF panel system is another type of antennas that contains horizontally polarized dipoles as an array arrangement. Panel systems are large and not self-supporting. They require an external spine to support them and their often complex and fully feed systems and also produce higher windload than coaxial slot antenna of the same gain and pattern shape. The other popular one is superturnstile antenna which combines the omnidirectionality of the top-mounted slot antennas with the full UHF bandwidth of a panel antenna. The combination of these features makes the superturnstile to be the alternative choice when both wide bandwidth and omnidirectional pattern are required. However, their disadvantages are feeding systems. In broadband panel systems, mechanical structure is made of small radiating elements. So, it is not self-supporting. Therefore, this type of antenna must be enclosed in a structural radome that supports the antenna. The weight of a high power superturnstile is about one third of an equivalent top-mounted slot antenna. However, because of the large radome diameter, the superturnstile will generate higher windload.

From these aforementioned literatures of the conventional UHF TV broadcasting antennas, it is obvious that the antenna which possesses simple feeding system, high power handling, low windload is desirable. An antenna made of concentric sectoral cylindrical cavity backed slot array antenna is an attractive one since a single feed is used in each linear array and when multiple of them are combined to be the circular array, the structure looks like a compact cylindrical antenna. This structure can be easily fed from power divider. This results in a very simple structure, high power handling and low windload as described. In addition, the wide response of the frequency of this antenna might be controlled by various parameters of the antenna. Therefore, a concentric sectoral cylindrical cavity-backed slot array antenna excited by a probe is proposed. Moreover, the design of the array of these sectoral structures is simpler than using annular cylindrical structure.

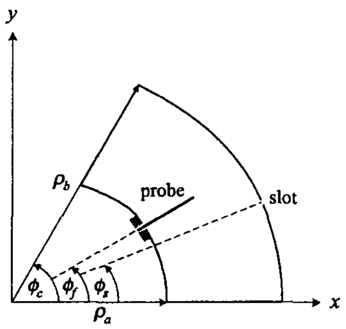
Most of substantial works related to the sectoral cylindrical structure have been done about the concentric sectoral cylindrical waveguide. Lin and Omar [3] determined the cutoff wavelength of this structure. The equivalent parameters for the slot on a sectoral waveguide was presented by Lue *et al.* [4]. Fan and Jin [5] obtained radar cross section of cylindrically slotted waveguide array antenna. Besides these, Tam *et al.* investigated annular sector dielectric resonator antenna geometry [6] and Richard *et al.* [7] presented a theoretical and experimental investigation of annular, annular sector and circular sector microstrip antennas. As far as we know, there is no information about the cavity structure excited by probe which is necessary for the structure that requires the simple feeder and high power handling. Since impedance is the important characteristics that determines the efficiency of the antenna. Therefore, this paper focuses on impedance of a sectoral cylindrical cavity-backed slot antenna excited by a probe. Theoretical background of this antenna is determined by using Method of Moments. The integral equations are first formulated by using field equivalent principle and boundary conditions. The dyadic Green's functions in all canonical regions are derived. The integral equations are subsequently solved by using Method of Moments to determine the unknown current densities. Then, the input impedance of the antenna at the feeding probe are determined and validated by measurement.

2. Antenna Configuration

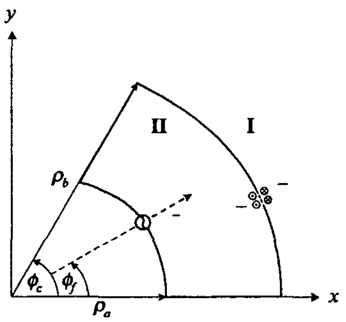
The structure of a sectoral cylindrical cavity-backed slot antenna is composed of a narrow slot cut on an outer surface of the sectoral cylindrical cavity as shown in Fig.1 (a). The slot of the length l_s and the width w_s is aligned along z direction at which the center of this slot is located at (ρ_b, ϕ_s, z_s). The dimension of the cavity is made up from the concentric conducting circular cylindrical structure of the inner and outer radii of ρ_a and ρ_b, respectively. This structure is surrounded by the conducting surface at an angle $\phi = 0$ and $\phi = \phi_c$ and shorted at the both ends ($z = 0$ and $z = z_d$). This cavity wall is considered to be a perfect electric conductor and the thickness is negligible. The cross-sectional view of the antenna is illustrated as shown in Fig.1(b). The excitation probe is located at the center of the inner surface of the cavity $(\rho_f = \rho_a, \phi_f = \phi_c/2, z_f = z_d/2)$. The length of the probe is l_f and it is assumed to be very thin so as to disregard the diameter.



(a) perspective view



(b) cross-sectional view



(c) equivalent analysis model

Fig.1 Antenna structure

3. Method of Moments Formulations

The coupling of the energy from the probe and the subsequent radiation from the slot can be formulated by enforcing the boundary conditions on the slot aperture and the excited probe. The structure is divided into two regions: the region outside the sectoral cylinder (region I) and the cavity region (region II), as illustrated in Fig.1(c). In accordance with the field equivalent principle, the fields in the two regions can be decoupled by covering the aperture with a perfectly conducting surface and introducing equivalent magnetic current above and below the perfectly conducting surface. Denoting the equivalent magnetic current above aperture as $\bar{M}$ and that below one as $-\bar{M}$. For the excited probe, it can be represented by removing the excited probe out and introducing equivalent electric current around it as $\bar{J}$. Therefore, the field in region I is due to $\bar{M}$, the field in region II is due to $-\bar{M}$ and $\bar{J}$ from the slot and the excited probe, respectively.

The input impedance of a sectoral cylindrical cavity-backed slot antenna fed by a probe will be assessed by using Method of Moments [8]-[9]. The integral equations of two unknown currents, viz., an electric current at the probe and a magnetic current sheet over the slot, can be formulated base on the field equivalent principle in addition to the enforced boundary conditions at the probe and the slot. Those boundary conditions are that the tangential magnetic fields inside and outside the cavity are continuous throughout the slot aperture. The integral equations of the two unknown currents are

$$j\omega\varepsilon_0 \iint_{S_s} \left\{\bar{\bar{G}}^{in}_{HM}(\bar{R},\bar{R}') + \bar{\bar{G}}^{out}_{HM}(\bar{R},\bar{R}')\right\} \cdot \bar{M}(\bar{R}')\,dS' + \int_{L_f} \bar{\bar{G}}^{in}_{HJ}(\bar{R},\bar{R}') \cdot \bar{J}(\bar{R}')\,dL' = 0 \tag{1}$$

and

$$\iint_{S_s} \bar{\bar{G}}^{in}_{EM}(\bar{R},\bar{R}') \cdot \bar{M}(\bar{R}')\,dS' + j\omega\mu_0 \int_{L_f} \bar{\bar{G}}^{in}_{EJ}(\bar{R},\bar{R}') \cdot \bar{J}(\bar{R}')\,dL' = \delta(\bar{R}') \tag{2}$$

where $\bar{\bar{G}}^{in}_{EM}$ denotes dyadic Green function of the electric fields in region II due to the magnetic current source, $\bar{\bar{G}}^{in}_{EJ}$ denotes the dyadic Green function of the electric fields in region II due to the electric current source, $\bar{\bar{G}}^{out}_{HM}$ and $\bar{\bar{G}}^{in}_{HM}$ denote the dyadic Green function of the magnetic fields in region I and II, respectively, due to the magnetic current source and $\bar{\bar{G}}^{in}_{HJ}$ denotes the dyadic Green function of the magnetic fields in region II due to electric current source. All of them are dyadic Green's functions in the corresponding regions, where $\bar{R}$ denotes the position vector of a field point or that of observer, $\bar{R}'$ is the position vector of a source point. S_s and L_f denote the surface of the slot and length of the excited probe, respectively. The dyadic Green's functions can be derived by using the eigenfunction expansion method. The resultant of the dyadic Green's functions inside the cavity are expressed as [10]-[12]

$$\bar{\bar{G}}_{HM}(\bar{R},\bar{R}') = -\frac{1}{k}\hat{z}\hat{z}\delta(\bar{R}-\bar{R}') + \sum_{m=0}^{\infty}\sum_{n=1}^{\infty}\frac{(2-\delta_m)}{\phi_c}$$
$$\left\{\frac{1}{k_h^2 I_h k_{gh}\sin(k_{gh}z_d)}\left[\bar{N}_{h,odd}(z_d-z)\bar{N}'_{h,odd}(z) + \bar{N}_{h,odd}(z)\bar{N}'_{h,odd}(z_d-z)\right] - \frac{1}{k_e^2 I_e k_{ge}\sin(k_{ge}z_d)}\left[\bar{M}_{e,even}(z_d-z)\bar{M}'_{e,even}(z)+\bar{M}_{e,even}(z)\bar{M}'_{e,even}(z_d-z)\right]\right\} \quad (3)$$

$$\bar{\bar{G}}_{HJ}(\bar{R},\bar{R}') = \sum_{m=0}^{\infty}\sum_{n=1}^{\infty}\frac{(2-\delta_m)}{\phi_c}\left\{\frac{1}{k_h^2 I_h k_{gh}\sin(k_{gh}z_d)}\left[\bar{M}_{h,odd}(z_d-z)\bar{N}'_{h,odd}(z)+\bar{M}_{h,odd}(z)\bar{N}'_{h,odd}(z_d-z)\right] - \frac{1}{k_e^2 I_e k_{ge}\sin(k_{ge}z_d)}\left[\bar{N}_{e,even}(z_d-z)\bar{M}'_{e,even}(z) + \bar{N}_{e,even}(z)\bar{M}'_{e,even}(z_d-z)\right]\right\} \quad (4)$$

$$\bar{\bar{G}}_{EM}(\bar{R},\bar{R}') = \sum_{m=0}^{\infty}\sum_{n=1}^{\infty}\frac{(2-\delta_m)}{\phi_c}\left\{\frac{1}{k_h^2 I_h k_{gh}\sin(k_{gh}z_d)}\left[\bar{N}_{h,odd}(z_d-z)\bar{M}'_{h,odd}(z)+\bar{N}_{h,odd}(z)\bar{M}'_{h,odd}(z_d-z)\right] - \frac{1}{k_e^2 I_e k_{ge}\sin(k_{ge}z_d)}\left[\bar{M}_{e,even}(z_d-z)\bar{N}'_{e,even}(z) + \bar{M}_{e,even}(z)\bar{N}'_{e,even}(z_d-z)\right]\right\} \quad (5)$$

$$\bar{\bar{G}}_{EJ}(\bar{R},\bar{R}') = -\frac{1}{k}\hat{z}\hat{z}\delta(\bar{R}-\bar{R}') + \sum_{m=0}^{\infty}\sum_{n=1}^{\infty}\frac{(2-\delta_m)}{\phi_c}$$
$$\left\{\frac{1}{k_h^2 I_h k_{gh}\sin(k_{gh}z_d)}\left[\bar{M}_{h,odd}(z_d-z)\bar{M}'_{h,odd}(z) + \bar{M}_{h,odd}(z)\bar{M}'_{h,odd}(z_d-z)\right] - \frac{1}{k_e^2 I_e k_{ge}\sin(k_{ge}z_d)}\left[\bar{N}_{e,even}(z_d-z)\bar{N}'_{e,even}(z)+\bar{N}_{e,even}(z)\bar{N}'_{e,even}(z_d-z)\right]\right\} \quad (6)$$

The normalization factor, I_e and I_h are given by

$$I_e = \frac{1}{2k_e^2}\left[\rho^2\frac{\partial B_\upsilon(k_e\rho)}{\partial\rho}\right]_{\rho_a}^{\rho_b} \quad (7)$$

$$I_h = \frac{1}{2k_h^2}\left\{(k_h^2\rho^2-\upsilon^2)\left[B_\upsilon(k_h\rho)\right]^2\right\}_{\rho_a}^{\rho_b} \quad (8)$$

where $k_{gh}=\sqrt{k^2-k_h^2}$, $k_{ge}=\sqrt{k^2-k_e^2}$, δ_m denotes the Kronecker delta, in which $\delta_m=1$ for m or $n=0$, and $\delta_m=0$ for otherwise.

The dyadic Green's function outside the cavity is readily derived in reference [4] and can be written as

$$G^{out}_{HM,zz} = -\frac{1}{2\pi^2\rho_b}\int_\Gamma\sum_{m=0}^{\infty}\frac{1}{1+\delta_m}\cos m(\phi-\phi')\frac{1}{k_k}\frac{H_m^{(2)}(k_k\rho_b)}{H_m'^{(2)}(k_k\rho_b)}e^{-jt|z-z'|}dt \quad (9)$$

where $k_k = \begin{cases}\sqrt{k^2-t^2} & , k\geq t\\ -j\sqrt{t^2-k^2} & , k<t\end{cases}$,

By following the Method of Moments, the unknown magnetic current sheet over the slot is expanded. The entire domain sinusoidal basis function is chosen as

$$\bar{M}(\bar{R}') = a_s\hat{m}_s = \hat{z}a_s\frac{1}{w_s}\sin\frac{\pi}{l_s}\left(z'-\frac{l_s}{2}\right). \quad (10)$$

The basis function on the feed probe is given by

$$\bar{J}(\bar{R}') = b_f\hat{j}_f = \hat{\rho}b_f\left\{\sin\frac{\pi}{2l_f}(\rho'-\rho_a+l_f)\right\}, \quad (11)$$

where a_s and b_f are the coefficients of the magnetic current over the slot and the electric current at the probe which must be determined. These basis functions provide the efficient computation with the acceptable accuracy [8]. After the current distributions are known, the input impedance can be obtained from the ratio of the excited voltage to the unknown currents.

4. Numerical Results

From the preliminary study it was found that the outer cylindrical radius of the structure should be 1.575λ so that the omnidirectional pattern of these six elements array could be obtained. For illustration, the antenna was designed to operate at the center frequency of *3* GHz. The dimensions of the antenna are listed in Table I. The computer program was fabricated to calculate the input impedance of the antenna as described in the previous section. The solid line in Fig.2 shows the theoretical value of input impedance when the frequency is varied from $0.9f_o$ to $1.1f_o$ (f_o is the center frequency) which is *20%* bandwidth. It is observed that at the lower frequency, this antenna has inductive impedance with low resistance and reactance. The resistance has its constant low value as the frequency is increased to about $0.95f_o$ whereas the reactance increases continuously. Then, the resistance and reactance increase in accordance with the frequency. The antenna resonates at a frequency slightly lower than the center frequency and the impedance at the center frequency is capacitive impedance with resistance about *70* Ω. Then, the capacitive reactance decreases as the frequency is increased to $1.1f_o$. It is noted that this antenna is almost matched to *50* Ω.

Table I Antenna parameters used in the model

Antenna parameters	Physical size at *3* GHz
Outer cylindrical radius (ρ_b)	*15.75* cm
Inner cylindrical radius (ρ_a)	*8.75* cm
Angle of sector (ϕ_c)	*60.0°*
Cavity length (z_d)	*15.00* cm
Slot length (l_s)	*4.60* cm
Slot width (w_s)	*0.30* cm
Slot offset (ϕ_s)	*22.5°*
Slot offset (z_s)	*7.50* cm
Probe length (l_f)	*2.50* cm
Probe location (ϕ_f)	*30.0°*
Probe location (z_f)	*7.50* cm

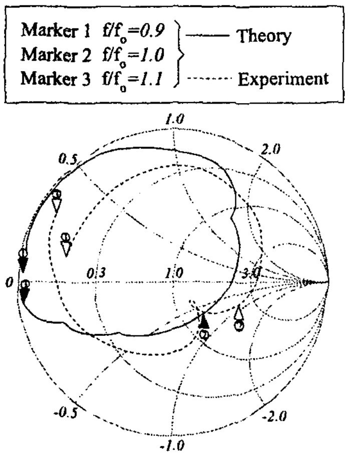


Fig.2 Input impedance of a sectoral cylindrical cavity backed slot antenna excited by probe

Fig.3 Photograph of the prototype of the antenna

To validate the theoretical calculation, the antenna *with the dimension in* Table I was fabricated and the input impedance was measured by using an HP8720C Network Analyzer. The photograph of the fabricated antenna is shown in Fig.3. The measured results are superimposed as dashed line in Fig.2. It should be pointed out that the good agreement between theory and experiment can be observed in the range from $0.95f_o$ to $1.05f_o$ which is *16%* bandwidth. Some errors take place because the external Green's function in (9) is belonged to the infinite whole cylindrical structure. In addition, a single term entire domain basis function is accurate when the frequency is close to the resonance frequency when the probe length is 0.25λ. However, the accurate result within this 10% bandwidth is sufficient for many applications including the TV broadcasting.

5. Conclusions

Input impedance is an important characteristic that affects the antenna efficiency. It must be well investigated so that the matched antenna can be designed. This paper focuses on the input impedance characteristics of a so-called sectoral cylindrical cavity-backed slot antenna excited by probe. This antenna is developed to be an UHF TV broadcasting antenna due to its simple feeding system, high power handling and low windload. In order to investigate input impedance of this antenna, the straightforward procedure is applied. Starting from formulations of integral equations of the structure based on boundary conditions, then the dyadic Green's functions are derived. The entire domain basis function is used in the Method of Moments to solve for the electric current density on the probe and the magnetic current density on the slot. The input impedance can be found from these currents subsequently. From numerical results, the frequency response of input impedance can be investigated. We can predict it accurately within a bandwidth of *10%*, which is sufficiently wide for general applications. Characteristics of several slots on this structure are under investigation.

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