Forced Resonant Type Cutoff Cavity-Backed Aperture Antennas Loaded with a Single External Reactance

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Abstract

This paper presents the basic characteristics of a cutoff cavity-backed aperture antenna with a feed post and a parasitic post inserted parallel to the aperture. It is shown that this type of antenna forcibly resonates the cutoff cavity by adding a single external reactance to the parasitic post. The Galerkin's method of moments is used to analyze integral equations for the unknown electric current on each post and the aperture electric field on the aperture. The value of an external reactance for forced resonance is analytically obtained by deriving a determining equation. Also the current distribution on each post, aperture electric field distributions, and the radiation patterns are discussed. The theoretical analysis is verified by the measured return loss and radiation patterns.

Key words : Cavity-backed Aperture Antenna, Forced Resonance, Reactance Loading.

Ⅰ. Introduction

Cavity-backed slot antennas have been used in different types of applications within the microwave band, including satellite communications, aircraft and spacecraft communications, and rectenna/spacetenna for microwave power transmission in the SPS(Solar Power Satellite) system. Their low profile is an important characteristic, especially for aircraft and spacecraft applications, because they can be flush-mounted on the surface of airborne vehicles. Cavity-backed slot antennas have been investigated by many researchers[1]~[7]. For the microwave power transmission, cavity-backed slot antennas were proposed, of which the slot is normal to the feed post[6]. Therefore microwave circuits are placed at the bottom of the cavity accounted for the ease of manufacturing. The early efforts to analyze cutoff cavity-backed slot antennas using two external reactances were presented by Kim and Tokumaru[3].

This paper proposes a cutoff cavity-backed aperture antenna with only one external reactance to obtain the impedance matching easily. Since the cavity is under a cutoff condition, the cavity size becomes smaller than the usual cavity-backed slot antenna. Therefore microwave circuits may be attached to the lateral wall of the volume-reduced cavity for the rectenna/spacetenna applications. The antenna is analyzed as a boundary value problem, which is a set of coupled integral equations for the current distributions on the post and electric field distributions on the aperture. The coupled integral equations for the unknown electric current and aperture electric fields on the aperture are solved by Galerkin's method of moments[8]. The determining equation for a reactance value giving the forced resonance is derived by considering the antenna as a two-port network as mentioned in [9]. And the current distribution on each post, aperture electric field distributions, and the radiation patterns in forced resonance are investigated. Numerical results show that we can obtain forced resonance of the proposed antenna with one reactance element. To check the validity of the theoretical analysis, the return loss and the radiation patterns for the model antenna are compared with those of experiments.

Ⅱ. Theoretical Analysis

2-1 Integral Equations

Fig. 1 shows the geometry and coordinate system of a forced resonant type cutoff cavity-backed aperture antenna with one reactance element. The aperture of length a and width b is in the infinite plane of a perfect electric conductor at z=0 and is backed by a conducting rectangular cavity of depth c. A feed post(#1) of radius r is at x=d and $z=-s$, and the external reactance jX is connected to a parasitic post(#2) of radius r at x=e and $z=-s$ to obtain forced resonance of the cavity antenna. Both posts are connected to the upper wall of the cavity. Note that the cavity dimensions are chosen such that the cross section of the cavity $a\times b$ corresponds to the

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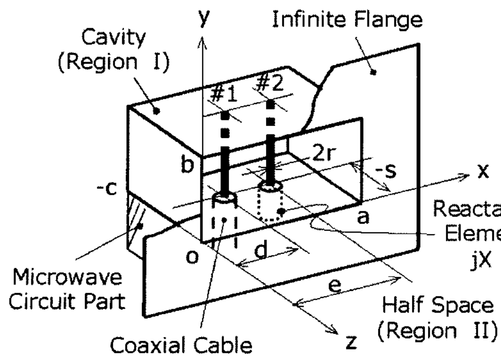


Fig. 1. Geometry and coordinate system of the cutoff cavity-backed slot antenna.

cutoff condition for the waveguide of the same cross section when the cavity is empty. The hatched region of the lateral wall of the cavity shown in Fig. 1 is reserved for microwave circuits especially for the application of rectenna/spacetenna.

To derive integral equations, the antenna is divided into two regions as shown in Fig. 1, a cavity(region I) and a half space(region II). The voltage V_1 is applied at $z=-s$, $y=0$ and $x=d$, and the external reactance element is loaded at $z=-s$, $y=0$ and $x=e$. If the cavity antenna is fed by a delta gap generator as the voltage source, the simultaneous integral equations for the unknown electric currents J_1 and J_2 on the feed post and parasitic post, respectively, and for the unknown aperture electric field E_a on the aperture can be written as

$$\frac{1}{j\omega\varepsilon_0}\oiint_{S_1'}\bar{K}^{I}_{11e}(r,r')\cdot J_1(r')dS_1' + \frac{1}{j\omega\varepsilon_0}\oiint_{S_2'}\bar{K}^{I}_{12e}(r,r')\cdot J_2(r')dS_2' + \iint_{S_a'}\bar{K}^{I}_{1am}(r,r')\cdot[\hat{z}\times E_a(r')]dS_a' = -V_1\delta(y)\hat{y} \tag{1}$$

$$\frac{1}{j\omega\varepsilon_0}\oiint_{S_1'}\bar{K}^{I}_{21e}(r,r')\cdot J_1(r')dS_1' + \frac{1}{j\omega\varepsilon_0}\oiint_{S_2'}\bar{K}^{I}_{22e}(r,r')\cdot J_2(r')dS_2' + \iint_{S_a'}\bar{K}^{I}_{2am}(r,r')\cdot[\hat{z}\times E_a(r')]dS_a' = jXI_2(0)\delta(y)\hat{y} \tag{2}$$

$$\hat{z}\times\left\{\oiint_{S_1'}\bar{K}^{I}_{a1e}(r,r')\cdot J_1(r')dS_1' + \oiint_{S_2'}\bar{K}^{I}_{a2e}(r,r')\cdot J_2(r')dS_2' + \frac{1}{j\omega\mu_0}\iint_{S_a'}\bar{K}^{I}_{aam}(r,r')\cdot[\hat{z}\times E_a(r')]dS_a'\right\} = \hat{z}\times\frac{1}{j\omega\mu_0}\iint_{S_a'}\bar{K}^{II}_{aam}(r,r')\cdot[-\hat{z}\times E_a(r')]dS_a' \tag{3}$$

where the superscripts I and II denote region I and region II. The subscripts 1, 2, and a represent a feed post, a parasitic post, and an aperture, respectively. $\hat{y}$ and $\hat{z}$ are unit vectors in the y and z direction. $\delta(\cdot)$ is the delta function and ω represents the angular frequency. And position vectors r and r' are the observation and the source point, respectively. The J_1 and J_2 represent the surface current density on each post, $dS_{1,2}'$ and dS_a' denote an element of an area on the surface of the posts and the aperture, respectively, and $I_2(0)$ is the current at the loading position of the external reactance jX. The time dependence $exp(j\omega t)$ is assumed and omitted throughout this paper. In (1)~(3), the kernels are listed in the Appendix.

If the radius r of the post is sufficiently small compared to the operating wavelength, the current density may be considered to be uniform around the periphery of the post. Thus the integral equations (1)~(3) are simply represented as the y direction integral only since $J_{1,2}=\hat{y}I_{1,2}/2\pi r$. To solve the simultaneous integral equations for the unknowns, the electric currents J_1, J_2 and the aperture electric field E_a are expanded as

$$J_1(y)=\hat{y}\sum_{u=0}^{U}I_{1u}\cos\frac{u\pi y}{b} \tag{4}$$

$$J_2(y)=\hat{y}\sum_{v=0}^{V}I_{2v}\cos\frac{v\pi y}{b} \tag{5}$$

$$E_a(x,y)=\hat{x}\sum_{p=0}^{P}\sum_{q=1}^{Q}E_{xpq}\cos\frac{p\pi x}{a}\sin\frac{q\pi y}{b} + \hat{y}\sum_{p=1}^{P}\sum_{q=0}^{Q}E_{ypq}\sin\frac{p\pi x}{a}\cos\frac{q\pi y}{b} \tag{6}$$

where I_{1u}, I_{2v} and E_{xpq} are E_{ypq} complex expansion coefficients. Substituting the assumed basis functions (4)~(6) into the integral equations (1)~(3) and employing Galerkin's method of moments[8], we obtain a set of linear equations for the unknown expansion coefficients expressed in the matrix form:

$$\begin{bmatrix} Z_{u'u} & Z_{u'v} & B^x_{u'pq} & B^y_{u'pq} \\ Z_{v'u} & Z_{v'v} & B^x_{v'pq} & B^y_{v'pq} \\ C^x_{p'q'u} & C^x_{p'q'v} & Y^x_{xp'q'pq} & Y^x_{yp'q'pq} \\ C^y_{p'q'u} & C^y_{p'q'v} & Y^y_{xp'q'pq} & Y^y_{yp'q'pq} \end{bmatrix}\begin{bmatrix} I_{1u} \\ I_{2v} \\ E_{xpq} \\ E_{ypq} \end{bmatrix} = \begin{bmatrix} V_{u'} \\ V_{v'} \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

where $V_{u'}$ and $V_{v'}$ are the excitation vectors, and the matrices Z, B, C, and Y are known.

2-2 Determining Equation for Reactance Value

There are generally two different methods to obtain the forced resonance of the antenna[9]. One is the perfect matching which is totally matched to the transmission line. The other is the partial matching which is partially matched to the transmission line. We just use the partial matching because one loaded-reactance can achieve the similar characteristic of the perfect matching with the adjustment of the location of a parasitic post.

The input impedance of the cavity-backed aperture antenna in Fig. 1 can be controlled by adjusting one external reactance value. The resonant condition at the feed point is given by

$$\mathrm{Im}\{Z_{in}(y_{ij}, jX)\} = 0 \tag{8}$$

where Z_{in} is the input impedance of the antenna, the symbol Im{ · } taking the imaginary part of { · }. We represent the input impedance as (9) by treating the antenna as a two-port network with the applied voltage at port 1 and the reactance element at port 2 using admittance parameters $y_{ij}(i, j=1, 2)$.

$$Z_{in} = \frac{y_{22} + (1/jX)}{y_{11}[y_{22} + (1/jX)] - y_{12}^2}. \tag{9}$$

The admittance parameters y_{ij} are given by $y_{ij}=I_i/I_j$ where V_j is a voltage source applied to port j and I_i is the current in the short circuit at port i[8]. It should be noted that we can calculate these admittance parameters numerically by the method of moments. Substituting (9) into (8), we obtain a determining equation for a forced resonant reactance, as given by

$$X = \frac{2y_{11}^I}{(-E \pm D)} \tag{10}$$

where

$$D = \sqrt{E^2 - 4y_{11}^I G}, \tag{11}$$

$$E = (y_{12}^I)^2 - 2y_{22}^I y_{11}^I - (y_{12}^R)^2, \tag{12}$$

$$G = y_{11}^I (y_{22}^R)^2 + y_{11}^I (y_{22}^I)^2 - 2y_{22}^R y_{12}^R y_{12}^I - y_{22}^I (y_{12}^I)^2 + y_{22}^I (y_{12}^R)^2, \tag{13}$$

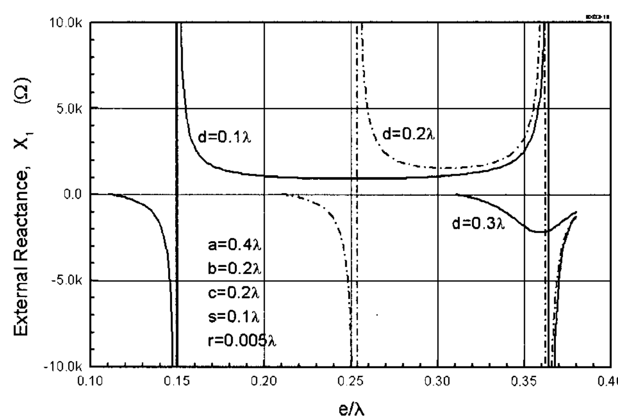
and y_{ij}^R and y_{ij}^I denote the real part and imaginary part of the y_{ij}, respectively. In (10), a positive and a negative sign of D in the denominator give rise to a series and a parallel resonance, respectively. We represent X_1 for the series resonance(plus sign) and X_2 for the parallel resonance(minus sign), respectively.

The enforcement of the reactance obtained from (10) makes the imaginary part zero resulting in resonance of the cutoff cavity-backed aperture antenna. Also a perfect impedance matching at the feed point might be obtained by controlling the input resistance. The real part of the input impedance can be controlled by adjusting the location of the parasitic post(#2) connected with the reactance element. The selection of the post position and the determination of the reactance value should be made simultaneously. The results are discussed in Section III.

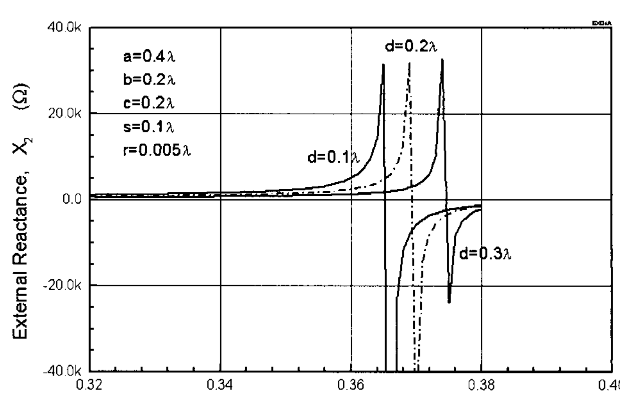
Ⅲ. Numerical Results and Discussion

Fig. 2 shows the external reactance value that satisfies the resonance condition(8), when the position of the parasitic post(#2) is shifted. By enforcing the calculated reactance value at the parasitic post, we can realize the forced resonance of the cutoff cavity-backed aperture antenna. The external reactance X_1 that determines the reactance value as shown in Fig. 2(a) is for the positive sign of D in (10) and is for the series resonance. The external reactance X_2 that determines the reactance value as shown in Fig. 2(b) is for the negative sign of D in (10) and is for the parallel resonance. The parallel resonance is not useful in practice, because the input resistance becomes very large and the input impedance can not be matched to the characteristic impedance of the feed line. Therefore, in this paper we discuss only the case of a series resonance.

Fig. 3 describes the input impedance characteristics dependent on the position of the parasitic post as a parameter of feed post position when the external reactance in Fig. 2(a) is loaded at the parasitic post. As



(a) Series resonance



(b) Parallel resonance

Fig. 2. Resonant external reactance value versus parasitic post position.

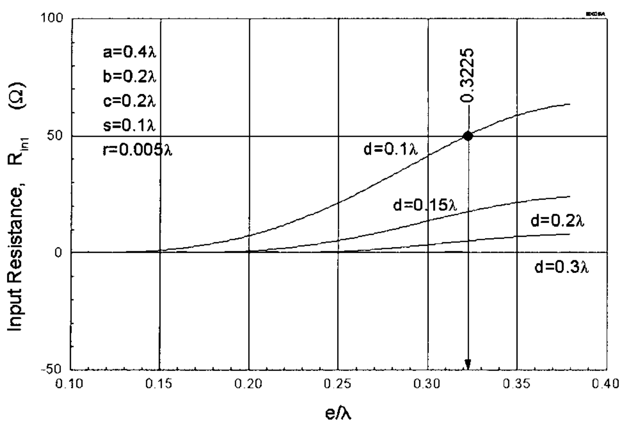


Fig. 3. Input impedance versus parasitic post position in resonance as the parameter of feed post position.

shown in Fig. 3, the parasitic post should be placed at e=0.3225 λ when d=0.1 λ for the input impedance to be matched perfectly when the characteristic impedance of the feed line is 50 Ω. The loading reactance value in this case would be X_l=1267.8 Ω as shown in Fig. 2(a).

Fig. 4 shows the input impedance characteristics dependent on the position of the parastic post as a parameter of cavity height when the external reactance in Fig. 2(a) is loaded at the parasitic post. As can be seen from Fig. 4, for the narrow aperture height b=0.1 λ, the input resistance is lower than 50 Ω. As shown in Figs. 3 and 4, the input resistance is dependent on the position of the parasitic post.

Fig. 5 represents the current distribution on each post when the external reactance X_l=1267.8 Ω is loaded on the parasitic post. As shown in Fig. 5, the current amplitude on the feed post is almost uniform and is 20 mA, but much larger resonant currents flow on the parasitic post.

Fig. 6 shows the electric field distributions on the aperture along the center line of the aperture when the

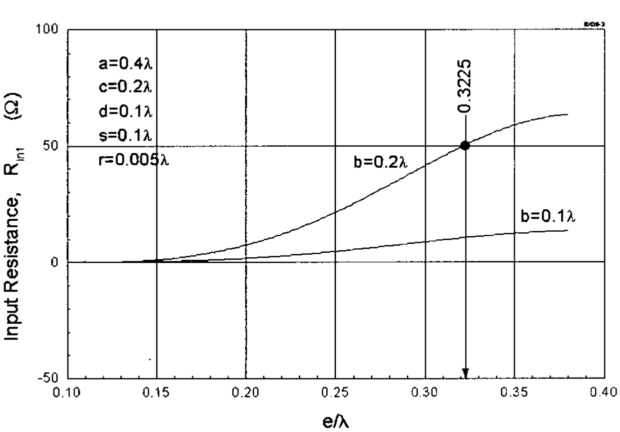


Fig. 4. Input impedance versus parasitic post position in resonance as the parameter of cavity height.

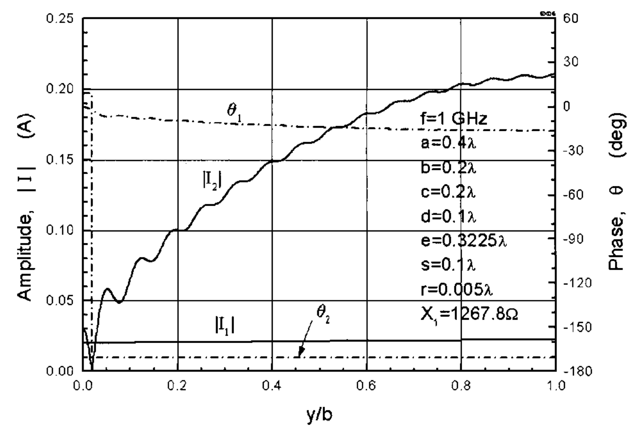


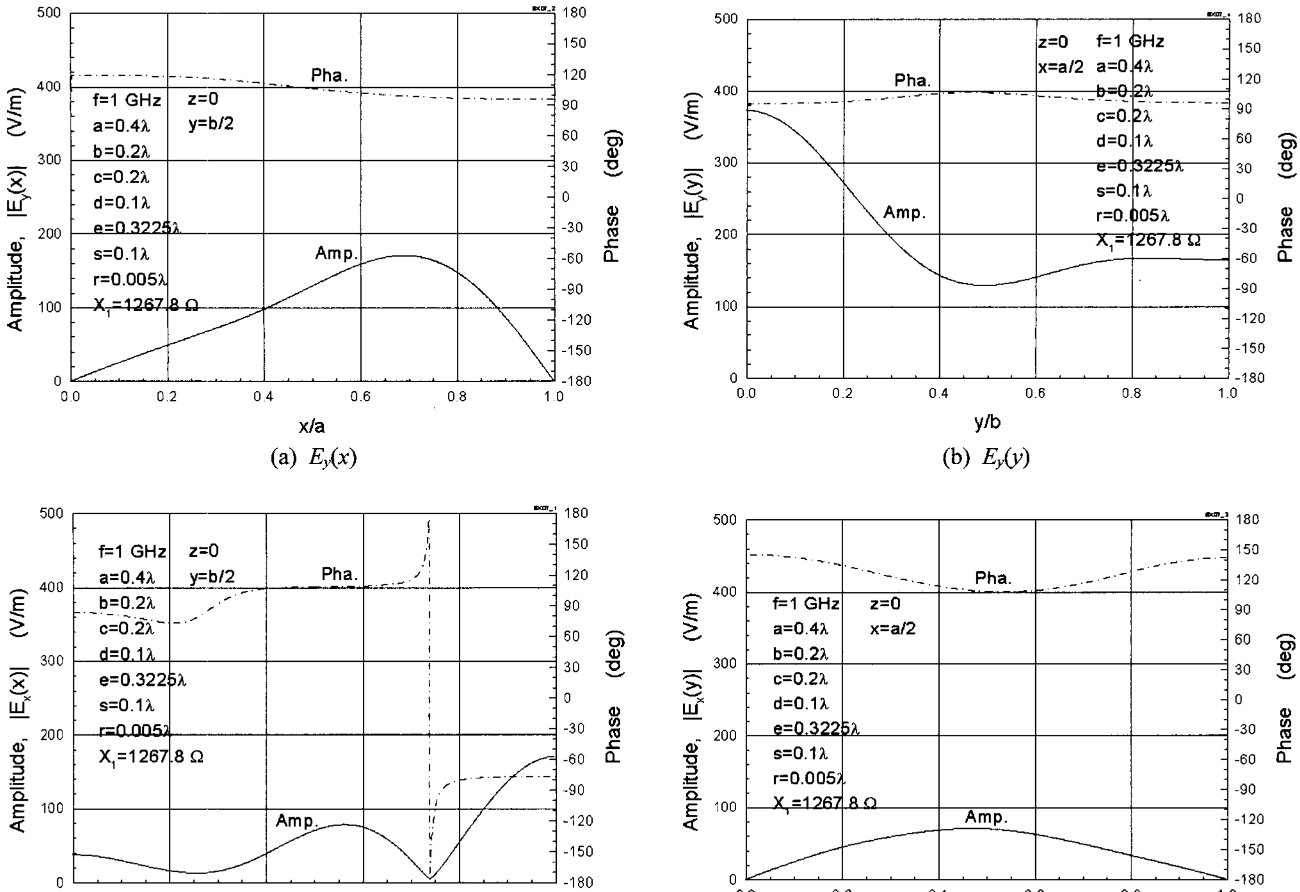
Fig. 5. Current distributions on the posts in resonance.

external reactance X_l=1267.8 Ω is loaded on the parasitic post(#2). It is found from these results that the amplitude peak of $\boldsymbol{E}_y$ is maximum at y=0 when the cutoff cavity is resonated. In Fig. 6(c), the change of the phase at $x \approx 0.75a$ is due to the current on the parasitic post.

Fig. 7 shows the frequency characteristics of the voltage standing wave ratio(VSWR) when external reactance X_l=1267.8 Ω is loaded on the parasitic post. The bandwidth of the cavity-backed aperture antenna is approximately 0.5 MHz with VSWR≤2. As shown in this figure, the use of external reactance element for impedance matching leads to narrow bandwidth. Expanding the proposed cavity-backed aperture antenna element to a broad bandwidth is still remained and this deserves as a future work.

Fig. 9 presents the radiation patterns of the cutoff cavity-backed aperture antenna. As shown in Fig. 9, the main beam of the antenna faces the front side of the slot. To reduce the cross polarization appearing in H-plane, either the slot width b should be decreased or both the feed and parasitic post should be moved to the deep inside of the cavity to reduce the higher-order-mode radiation.

To verify the analysis in Section II, the return loss characteristics and radiation patterns of a model antenna are presented, together with their experimental results. A measurement setup comprises a Wiltron 37225A vector network analyzer and a cutoff cavity-backed aperture antenna with a 2×4 m metal ground plane inside the microwave anechoic chamber. The cavity-backed aperture antenna made of a Cu plate is designed, and has the following parameters: a=12 cm, b=6 cm, c=6 cm, d=3 cm, e=9.7 cm, s=3 cm, and r=1.5 mm. The N-type connector(straight jack flange receptacle) made by Kukje Connector Co.(model no. K345-410) is used as an external reactance element. Since the open-circuited transmission line with characteristic impedance Z_0 and length



(a) $E_y(x)$ (b) $E_y(y)$

(c) $E_x(x)$ (d) $E_x(y)$

Fig. 6. Aperture electric field distributions in resonance.

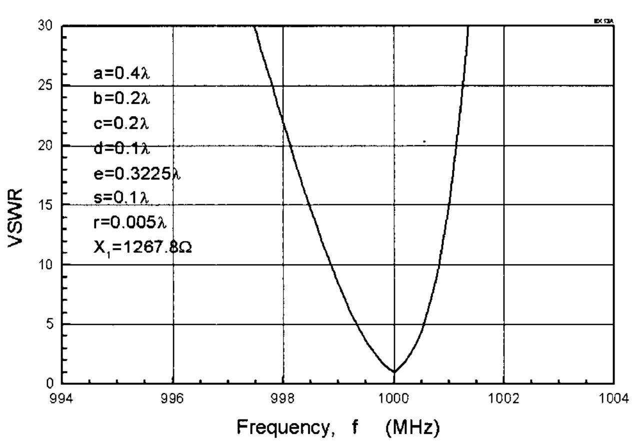


Fig. 7. Frequency characteristics of VSWR.

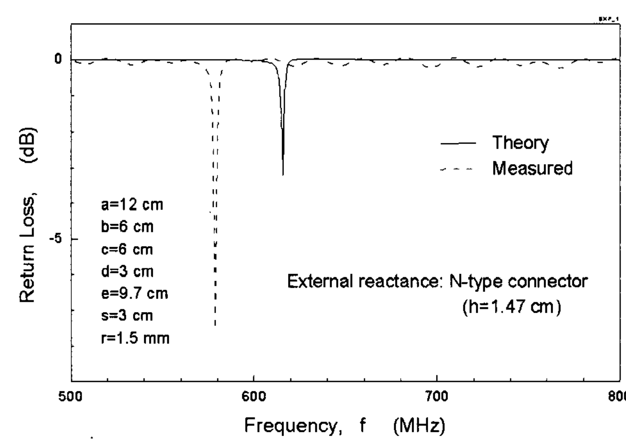
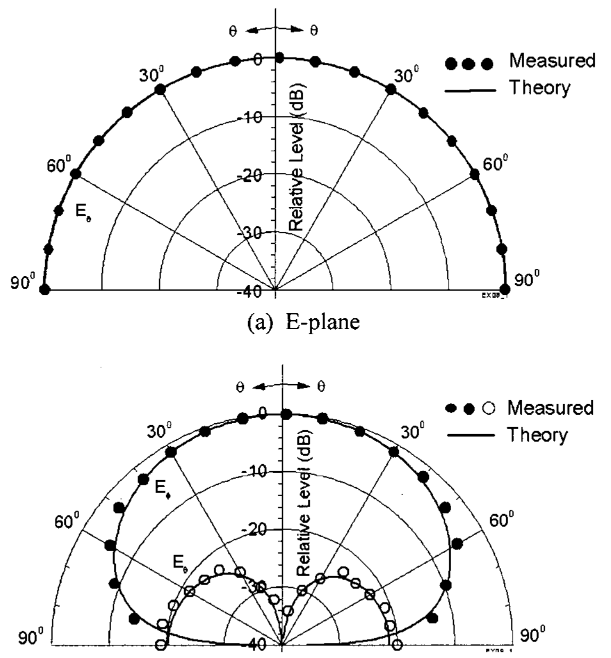


Fig. 8. Frequency characteristics of return loss.

h constitutes the reactance element, the reactance can be expressed as $X=-Z_0\cot(\beta h)$, where β is the propagation constant of the transmission line. In this case the N-type connector has Z_0=50 Ω and h=1.47 cm.

Figs. 8 and 9 present the frequency characteristic of the return loss and the radiation patterns for the coaxial line with the characteristic impedance of 50 Ω. In Fig. 8, the deviation of 6 % exists between the theoretical and experimental return loss and this deviation is almost equal to those of [3]. The cause of the deviation may be due to the value of the external reactance and the position of the parasitic post. As shown in Fig. 9, the



(a) E-plane

(b) H-plane

Fig. 9. Radiation patterns.

calculated radiation patterns are in good agreement with the experimental results.

Ⅳ. Conclusion

We have described a forced resonant type cutoff cavity-backed aperture antenna that has a feed post and a parasitic post in a cutoff cavity, and suggested the use of one reactance element to obtain a forced resonance of the antenna. The basic characteristics of the antenna are investigated using the Galerkin's method of moments. As the results, it is found that the forced resonant type cutoff cavity-backed aperture antenna can be realized by loading only one reactance element. The structural advantages are that the cavity might be downsized and microwave circuits can be attached to the lateral wall of the volume-reduced cavity. The antenna can be used as an element in a rectenna/spacetenna for microwave power transmission and aircraft and spacecraft communications. Expanding the proposed cavity-backed aperture antenna element to an array is still remained and this deserves as a future work.

Ⅴ. Appendix

This Appendix lists the kernels of the integral equations (1)~(3) and the dyadic Green's functions.

5-1 Kernels of the Integral Equations

In the integral equations (1)~(3), the kernels $\bar{K}_e^I$ and $\bar{K}_m^{I,II}$ are expressed as follows:

$$\bar{K}_{ije}^I(r,r') = (\bar{I}k_0^2 + \nabla\nabla)\cdot\bar{G}_e^I(r,r') \tag{14}$$

$$\bar{K}_{iam}^I(r,r') = \nabla\times\bar{G}_m^I(r,r') \tag{15}$$

$$\bar{K}_{aie}^I(r,r') = \nabla\times\bar{G}_e^I(r,r') \tag{16}$$

$$\bar{K}_{aam}^I(r,r') = (\bar{I}k_0^2 + \nabla\nabla)\cdot\bar{G}_m^I(r,r') \tag{17}$$

$$\bar{K}_{aam}^{II}(r,r') = (\bar{I}k_0^2 + \nabla\nabla)\cdot\bar{G}_m^{II}(r,r') \tag{18}$$

where $\bar{I}$ is a unit dyadic, and i, j=1, 2. In (14)~(18), $\bar{G}_e^I$ and $\bar{G}_m^I$ are the dyadic Green's functions for the cavity, $\bar{G}_m^{II}$ is the dyadic Green's function of the half space.

5-2 Dyadic Green's Functions in Region I

For the rectangular cavity of length a, width b and depth c, the dyadic Green's functions $\bar{G}_e^I$ and $\bar{G}_m^I$ are expressed as follows and their derivation is based on Reference 10:

$$\bar{G}_e^I(r,r') = -\hat{y}\hat{y}\sum_{n=1}^{\infty}\sum_{m=0}^{\infty}\frac{2\varepsilon_m}{ab\Gamma_{nm}^I}\sin\frac{n\pi x}{a}\cos\frac{m\pi y}{b}\sin\frac{n\pi x'}{a}\cos\frac{m\pi y'}{b}\cdot\begin{cases}\dfrac{\sinh\Gamma_{nm}^I(z'+c)}{\sinh\Gamma_{nm}^I c}\sinh\Gamma_{nm}^I z, & z\ge z' \\ \dfrac{\sinh\Gamma_{nm}^I z'}{\sinh\Gamma_{nm}^I c}\sinh\Gamma_{nm}^I(z+c), & z\le z'\end{cases} \tag{19}$$

$$\bar{G}_m^I(r,r') = \sum_{n=1}^{\infty}\sum_{m=0}^{\infty}\frac{2\varepsilon_m}{ab\Gamma_{nm}^I}(\hat{x}\hat{x}N_x + \hat{y}\hat{y}N_y)\cdot\begin{cases}\dfrac{\cosh\Gamma_{nm}^I(z'+c)}{\sinh 2\Gamma_{nm}^I c}\cosh\Gamma_{nm}^I(z-c), & z\ge z' \\ \dfrac{\cosh\Gamma_{nm}^I(z'-c)}{\sinh 2\Gamma_{nm}^I c}\cosh\Gamma_{nm}^I(z+c), & z\le z'\end{cases} \tag{20}$$

where

$$N_x = \sin\frac{n\pi x}{a}\cos\frac{m\pi y}{b}\sin\frac{n\pi x'}{a}\cos\frac{m\pi y'}{b} \tag{21}$$

$$N_y = \cos\frac{n\pi x}{a}\sin\frac{m\pi y}{b}\cos\frac{n\pi x'}{a}\sin\frac{m\pi y'}{b} \tag{22}$$

$$\Gamma_{nm}^I = \sqrt{\left(\frac{n\pi}{a}\right)^2 + \left(\frac{m\pi}{b}\right)^2 - k_0^2} \tag{23}$$

and ε_m=1 for m=0 and 2 for $m \ge 1$.

5-3 Dyadic Green's Function in Region II

The dyadic Green's function $\bar{G}_m^{II}$ in Region II is expressed as follows:

$$\bar{G}_m^{II}(r,r') = \bar{I}\frac{e^{-jk_0R_s}}{2\pi R_s} \tag{24}$$

where

$$R_s = \sqrt{(x-x')^2+(y-y')^2+(z-z')^2}\,. \tag{25}$$

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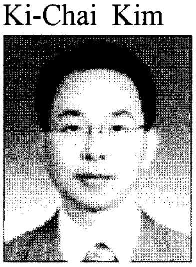

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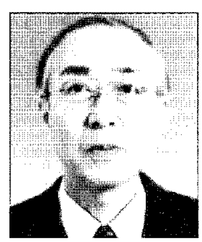

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