Forced Resonant Type Cutoff Cavity-Backed Slot Antenna Elements for Electromagnetic Power Transmission

Ki-Chai Kim[1] · Ick-Seung Kwon[2]

Abstract

This paper presents the basic characteristics of a cutoff cavity-backed slot antenna, for the application of spacetenna, with a feed post and a parasitic post inserted parallel to the slot. This type of antenna might effectively excite the slot and forcibly resonate the cavity by adding 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 electric field in the slot. The value of external reactance for forced resonance is discussed by deriving a determining equation, the current distribution on each post and the radiation patterns are considered. The analysis is in excellent agreement with the experiment for the radiation patterns.

Key words : cavity-backed slot antenna, forced resonance, reactance loading, electromagnetic power transmission

Ⅰ. INTRODUCTION

The solar power satellite (SPS) concepts enable microwave energy to be beamed from space to earth where it would be converted to electricity, and they are researches in progress [1]. For the microwave power transmission, cavity-backed slot antennas were proposed, of which the slot is normal to the feed post[2],[3]. Therefore microwave circuits are placed at the bottom of the cavity accounted for the ease of manufacturing (see Fig. 1(b)). This paper proposed a cutoff cavity-backed slot antenna, for the application of spacetenna, with a feed post and a parasitic post inserted parallel to the slot[4]. This type of antenna might effectively excite the slot and forcibly resonate the electrically small cavity by adding external reactance to the parasitic post. Because of structural advantage of being small sized, microwave circuits can be attached to the lateral wall of the volume-reduced cavity (see Fig. 1(a) and (c)).

The proposed antenna was analyzed by solving integral equations for the unknown electric current on each post and aperture electric field in the slot with the employment of Galerkin's method of moments[5]. The value of external reactance for forced resonance is discussed by deriving a determining equation, the current distribution on each post and the radiation patterns are considered. Also the effect of the cavity depth on input characteristics of the antenna is investigated. To check the validity of the theoretical analysis, the calculated radiation patterns are compared with expriments.

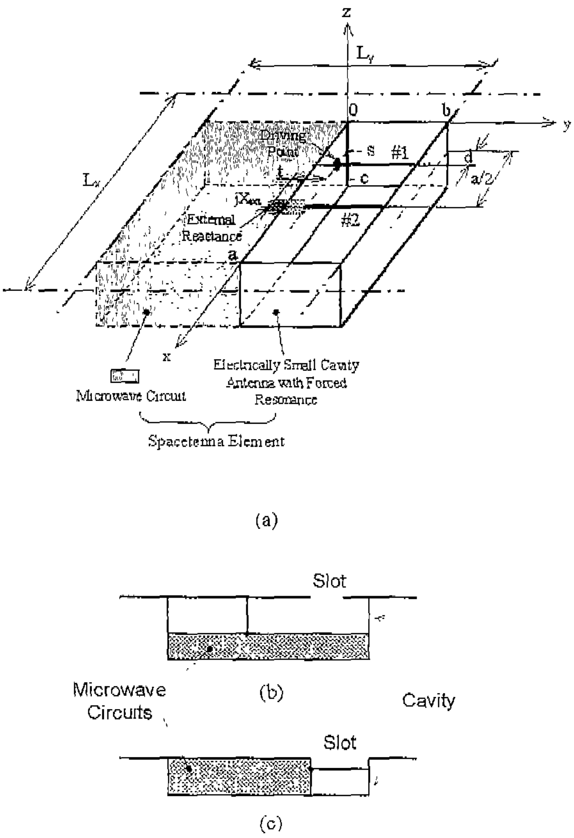

Fig. 1. Geometry and coordinate system of the antenna.

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Ⅱ. THEORETICAL ANALYSIS

2-1 Integral Equations

Fig. 1(a) and (c) shows the geometry and coordinate system of a forced resonant type electrically small-sized cavity-backed slot antenna. The slot of length a and width b is in the infinite plane of 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 $x=d$, $z=-s$ and the external reactance jX_{ext} is connected to a parasitic post (#2) of radius r at $x=a/2$, $z=-s$ to obtain forced resonance of the cavity antenna. Both posts are short ended to the wall of the cavity. The cavity dimensions are chosen such that the cross section of the cavity $a \times b$ corresponds to the cutoff condition for the waveguide of the same cross section when the cavity is empty. For this reason we name it cutoff cavity.

The element spacing of $L_x \times L_y$ which do not generate a grating lobe in beam scanning is chosen as $L_y \leq 0.67\lambda$ and $L_x \leq 0.78\lambda$[2]. The shaded region of the lateral wall of the cavity shown in Fig. 1 is reserved for microwave circuits.

To derive integral equations, the antenna is divided into two regions as illustrated in Fig. 1(a), a cavity (region I) and a half space (region II). The voltage V_I is applied at $y=0$, $x=0$ and the reactance element is loaded at $y=0$, $x=a/2$. If the cavity antenna is fed by a delta gap generator as the voltage source, the simultaneous integral equations for the unknown electric currents $\boldsymbol{J}_1$ and $\boldsymbol{J}_2$ on the feed post and parasitic post, respectively, and for the unknown aperture electric field $\boldsymbol{E}_a$ in the slot can be written as

$$\frac{1}{j\omega\varepsilon_0}\int\int_{s_1'}\overline{\boldsymbol{K}}^I_{11e}(\boldsymbol{r},\boldsymbol{r}')\cdot \boldsymbol{J}_1(\boldsymbol{r}')dS_1' + \frac{1}{j\omega\varepsilon_0}\int\int_{s_2'}\overline{\boldsymbol{K}}^I_{12e}(\boldsymbol{r},\boldsymbol{r}')\cdot \boldsymbol{J}_2(\boldsymbol{r}')dS_2' + \int\int_{s_a'}\overline{\boldsymbol{K}}^I_{1am}(\boldsymbol{r},\boldsymbol{r}')\cdot[\hat{z}\times \boldsymbol{E}_a(\boldsymbol{r}')]\,dS_a' = -V_1\hat{y}\delta(y) \tag{1}$$

$$\frac{1}{j\omega\varepsilon_0}\int\int_{s_1'}\overline{\boldsymbol{K}}^I_{21e}(\boldsymbol{r},\boldsymbol{r}')\cdot \boldsymbol{J}_1(\boldsymbol{r}')dS_1' + \frac{1}{j\omega\varepsilon_0}\int\int_{s_2'}\overline{\boldsymbol{K}}^I_{22e}(\boldsymbol{r},\boldsymbol{r}')\cdot \boldsymbol{J}_2(\boldsymbol{r}')dS_2' + \int\int_{s_a'}\overline{\boldsymbol{K}}^I_{2am}(\boldsymbol{r},\boldsymbol{r}')\cdot[\hat{z}\times \boldsymbol{E}_a(\boldsymbol{r}')]\,dS_a' = jX_{ext}\,\hat{y}I_2(o)\,\delta(y) \tag{2}$$

$$\hat{z}\times\left\{\int\int_{s_1'}\overline{\boldsymbol{K}}^I_{a1e}(\boldsymbol{r},\boldsymbol{r}')\cdot \boldsymbol{J}_1(\boldsymbol{r}')dS_1' + \int\int_{s_2'}\overline{\boldsymbol{K}}^I_{a2e}(\boldsymbol{r},\boldsymbol{r}')\cdot \boldsymbol{J}_2(\boldsymbol{r}')dS_2' + \frac{1}{j\omega\mu_0}\int\int_{s_a'}\overline{\boldsymbol{K}}^I_{aam}(\boldsymbol{r},\boldsymbol{r}')\cdot[\hat{z}\times \boldsymbol{E}_a(\boldsymbol{r}')]dS_a'\right\}$$
$$=(-\hat{z})\times\frac{1}{j\omega\mu_0}\int\int_{s_a'}\overline{\boldsymbol{K}}^{II}_{aam}(\boldsymbol{r},\boldsymbol{r}')\cdot[-\hat{z}\times \boldsymbol{E}_a(\boldsymbol{r}')]dS_a' \tag{3}$$

where

$$\overline{\boldsymbol{K}}^I_{ije}(\boldsymbol{r},\boldsymbol{r}') = (\overline{I}k_0^2+\nabla\nabla)\cdot\overline{\boldsymbol{G}}^I_{ije}(\boldsymbol{r},\boldsymbol{r}') \tag{4}$$

$$\overline{\boldsymbol{K}}^I_{iam}(\boldsymbol{r},\boldsymbol{r}') = \nabla\times\overline{\boldsymbol{G}}^I_{iam}(\boldsymbol{r},\boldsymbol{r}') \tag{5}$$

$$\overline{\boldsymbol{K}}^I_{aie}(\boldsymbol{r},\boldsymbol{r}') = \nabla\times\overline{\boldsymbol{G}}^I_{aie}(\boldsymbol{r},\boldsymbol{r}') \tag{6}$$

$$\overline{\boldsymbol{K}}^I_{aam}(\boldsymbol{r},\boldsymbol{r}') = (\overline{I}k_0^2+\nabla\nabla)\cdot\overline{\boldsymbol{G}}^I_{m}(\boldsymbol{r},\boldsymbol{r}') \tag{7}$$

$$\overline{\boldsymbol{K}}^{II}_{aam}(\boldsymbol{r},\boldsymbol{r}') = (\overline{I}k_0^2+\nabla\nabla)\cdot\overline{\boldsymbol{G}}^{II}_{m}(\boldsymbol{r},\boldsymbol{r}') \tag{8}$$

$\overline{I}$ is unit dyadic, and i, $j=1$ or 2. The superscripts $\boldsymbol{I}$ and $\boldsymbol{II}$ denote region I and region II, the subscripts 1, 2, and a represent feed post, parasitic post, and aperture, respectively. $\hat{y}$ and $\hat{z}$ are a unit vector in the y and z direction. $\delta(\cdot)$ is the Dirac delta-function, $k_0=\omega\sqrt{\varepsilon_0\mu_0}$, and ω represents the angular frequency. And position vectors $\boldsymbol{r}$ and $\boldsymbol{r}'$ are for the observation and source points, respectively. The $\boldsymbol{J}_1$ and $\boldsymbol{J}_2$ represent the surface current density, $dS_{1,2}'$ and dS_a' denote an element of 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_{ext}. In (4)~(8), $\overline{G}^I_e$ and $\overline{G}^I_m$ are the dyadic Green function of the electric and magnetic type for the cavity, $\overline{G}^{II}_m$ is the dyadic Green function of the half space. The time dependence $exp(j\omega t)$ is assumed and omitted throughout this paper.

If the radius r of the post is sufficiently small, 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 $\boldsymbol{J}_1$, $\boldsymbol{J}_2$ and the aperture electric field $\boldsymbol{E}_a$ are expanded as

$$J_1(y)=\hat{y}\sum_{u=0}^{U} I_{1u}\cos\frac{u\pi y}{b} \tag{9}$$

$$J_2(y)=\hat{y}\sum_{v=0}^{V} I_{2v}\cos\frac{u\pi y}{b} \tag{10}$$

$$\boldsymbol{E}_a(x,y)=\hat{x}\sum_{p=0}^{P}\sum_{q=1}^{Q}E_{xpq}\cos\frac{p\pi x}{a}\sin\frac{q\pi y}{b} + \hat{y}\sum_{p=1}^{P}\sum_{q=0}^{Q}E_{ypq}\sin\frac{p\pi x}{a}\cos\frac{q\pi y}{b} \tag{11}$$

where I_{1u}, I_{2u}, E_{xpq} and E_{ypq} are complex expansion coefficients. Substituting the assumed basis functions (9)~(11) into the integral equations (1)~(3) and employing Galerkin's method of moments[5], we obtain a set of linear equations for the unknown expansion coefficients.

2-2 Forced Resonant Condition and Determining Equation for Reactance Value

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

$$I_m\{Z_{in}(y_{ij}, jX_{ext})\} = 0 \tag{12}$$

where Z_{in} is the input impedance of the antenna, the symbol $Im\{\cdot\}$ taking the imaginary part of $\{\cdot\}$. We represent the input impedance as (13) 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 $y_{ij}(i, j = 1, 2)$.

$$Z_{in} = \frac{y_{22} + (1/jX_{ext})}{y_{11}[y_{22} + (1/jX_{ext})] - y_{12}^2} \tag{13}$$

The admittance parameters y_{ij} are given by $y_{ij} = I_i / V_j$ where V_j is a voltage source applied to port j and I_i is the current in the short circuit at port i [5]. It should be noted that we can calculate these admittance parameters numerically by the method of moments. Substituting (13) into (12), we obtain a determining equation for forced resonant reactance, as given by

$$X_{ext} = \frac{2y_{11}^I}{(-E \pm D)} \tag{14}$$

Since the short-circuited transmission line with characteristic impedance Z_0 and length t constitutes the external reactance, the expression for the value of reactance, $jX_{ext} = jZ_0 \tan(kt)$ should be put into (14) to obtain the expression for the length of the reactance for forced resonance. The resonant length of the reactance element, which makes the antenna resonate forcefully, can be expressed as

$$t = k^{-1}\tan^{-1}\left(\frac{2y_{11}^I}{Z_0(-E \pm D)}\right) \tag{15}$$

where k is the propagation constant of the transmission line,

$$D = \sqrt{E^2 - 4y_{11}^I G} \tag{16}$$

$$E = (y_{12}^I)^2 - 2y_{22}^I y_{11}^I - (y_{12}^R)^2 \tag{17}$$

$$E = y_{11}^I (y_{22}^R)^2 + y_{11}^I (y_{22}^I)^2 - 2y_{22}^R y_{12}^R y_{12}^I - y_{22}^I (y_{12}^I)^2 + y_{22}^I (y_{12}^R)^2 \tag{18}$$

and y_{ij}^R and y_{ij}^I denote the real part and imaginary part of the y_{ij}, respectively. In (14) and (15), a positive and a negative sign of D in the denominator give rise to a series and a parallel resonance, respectively. We represent t_1 for the series resonance (plus sign) and t_2 for the parallel resonance (minus sign), respectively. The enforcement of reactance obtained from (14) and (15) makes the imaginary part zero resulting in resonance of the cutoff cavity-backed antenna. Also a perfect impedance matching at the feed point might be obtained by controlling the input resistance.

Ⅲ. NUMERICAL RESULTS AND DISCUSSION

Fig. 2 shows the length of the external reactance element and its reactance value that satisfies the resonance condition (12), when the position of the feed post (#1) is shifted. By enforcing the calculated reactance value at the parasitic post (#2), we can realize the forced resonance of the antenna. The length t_1 of the external reactance that determines the reactance value as shown in Fig. 2 is for the positive sign of D in (15) and for the series resonance. In this paper, we discussed the case of a series resonance since the input resistance of the antenna becomes larger when a parallel resonance occurs. The parallel resonance is not useful in practice, because the input impedance can not

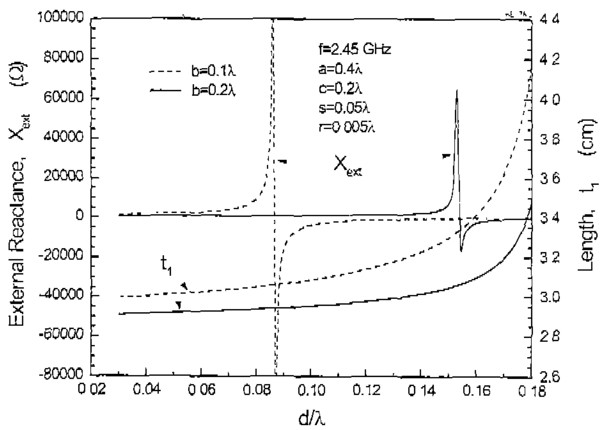


Fig. 2. Resonant external reactance value and length versus feed post position.

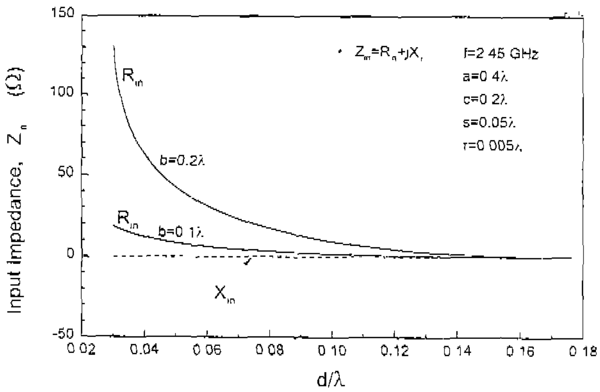


Fig. 3. Resonant input impedance versus feed post position.

be matched to the characteristic impedance of the feed line.

Fig. 3 describes the input impedance characteristics dependent on the position of the feed post (#1) when the external reactance in Fig. 2 is loaded at the parasitic post (#2). As shown in Fig. 3, the feed post should be placed at $d = 0.0455\lambda$ when $b = 0.2\lambda$ for the input impedance to be matched perfectly when the characteristic impedance of the feed line is 50Ω. The loading reactance value in this case would be $X_{ext} = 677.4\Omega$ as shown in Fig. 2. As can be seen from the Fig. 3, for the narrow slot width $b = 0.1\lambda$, the input resistance is lower than 50Ω. The input resistance is dependent on the position of the feed post (#1).

Fig. 4 represents the current distribution on each post when the external reactance $X_{ext} = 677.4\Omega$ is loaded on the parasitic post (#2). As shown in Fig. 4, the current on the feed post (#1) is almost uniform of 20 *mA* but much larger resonant current flows on the parasitic post (#2). Fig. 5 shows the characteristics of voltage standing wave ratio dependent on the cavity depth when the external reactance of $X_{ext} = 529.2\Omega$ is connected at the parasitic post. The value of external reactance of 529.2Ω is calculated at the cavity depth $c = 3\lambda$ in order to discuss the effect of the cavity depth. In this case the feed post should be placed at $d = 0.0374\lambda$ when $c = 3\lambda$ for the input impedance to be matched to the feed line with the characteristic impedance of 50Ω. The result shows that, above $c = 0.37\lambda$ with VSWR$\leq$2.5 : 1, the input characteristics are independent on the end wall of the cavity. From the results of Fig. 5, if a cavity depth is moderately chosen, we do not need the end wall of the cavity to obtain impedance matching (see Fig. 6(b)). Fig. 6 represents the structure of the antenna with end wall (Fig. 6(a); short structure) and without end wall (Fig. 6(b); open structure).

Fig. 7 shown the frequency characteristics of the input impedance obtained when external reactance $X_{ext} = 677.4\Omega$ is loaded on the parasitic post (#2). The bandwidth of the cavity-backed antenna is about 2.5 MHz with VSWR $\leq$ 1.5 : 1, and 4.3 MHz

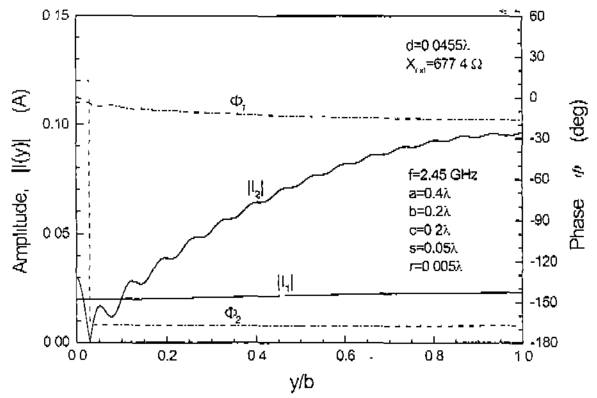


Fig. 4. Current distributions on the posts in resonance.

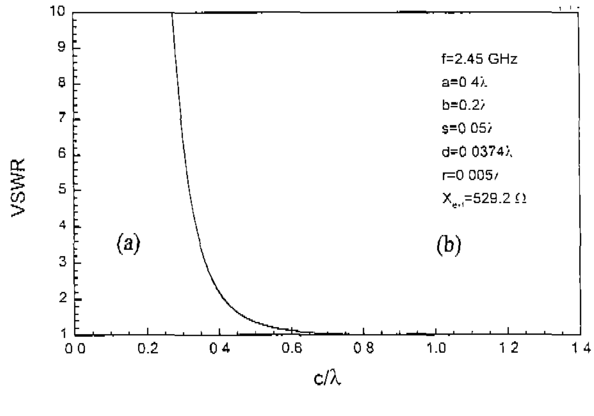


Fig. 5. VSWR versus depth of end wall.

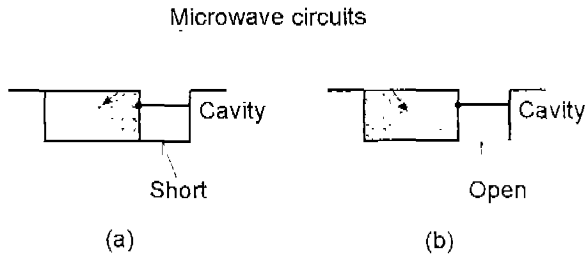


Fig. 6. Short and open structure of the cavity.
(a) Short structure, (b) Open structure.

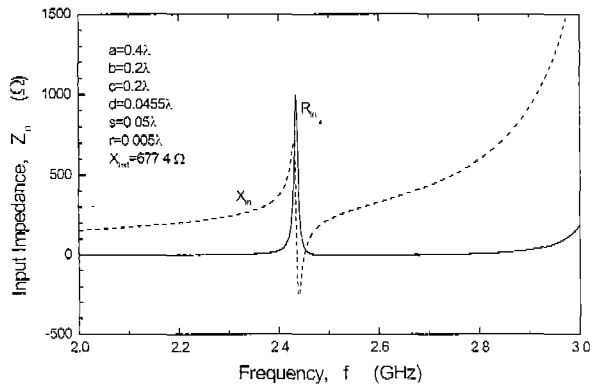
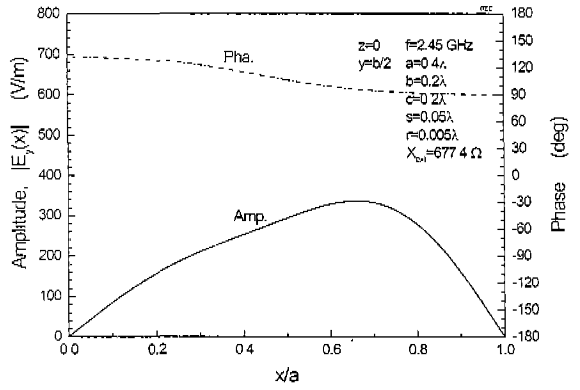


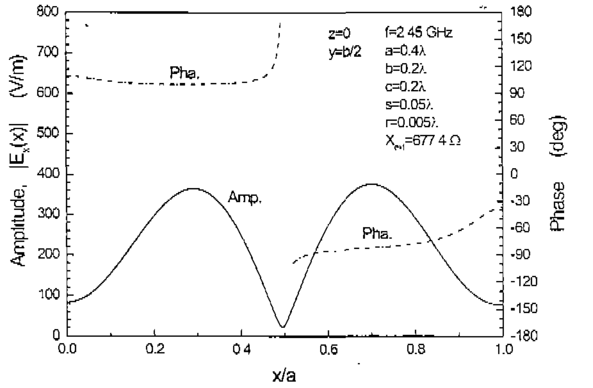
Fig. 7. Frequency characteristics of the input impedance.

with VSWR $\leq$ 2.0 : 1.

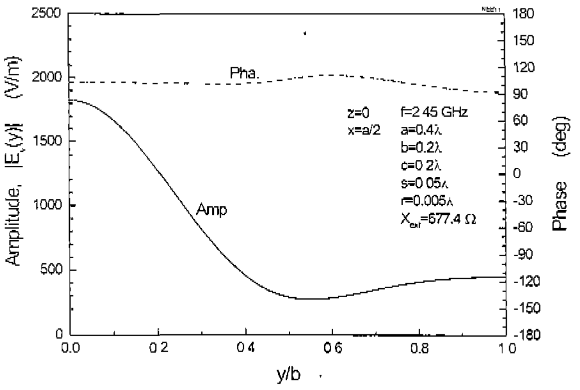
Fig. 8 shows the electric field distributions on the aperture along the center line of the aperture when the external reactance $X_{ext} = 677.4\Omega$ is loaded on the parasitic post. It is found from these results that the amplitude peak of E_y is maximum at when the cutoff cavity is resonated. Fig. 9 represents the radiation pattern of the cavity-backed antenna in resonance. As shown in Fig. 9, the main beam of the antenna faces the front



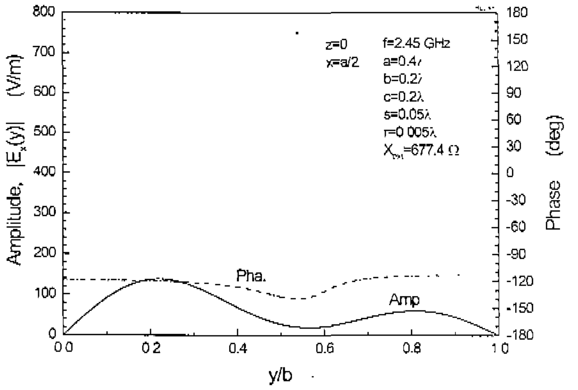
(a) $E_y(x)$



(c) $E_x(x)$



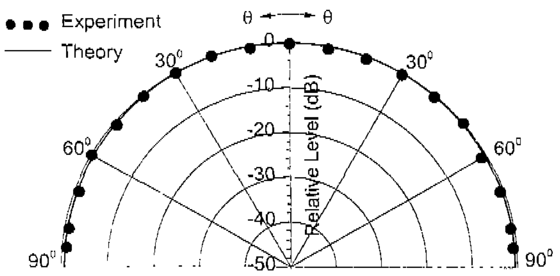
(b) $E_y(y)$



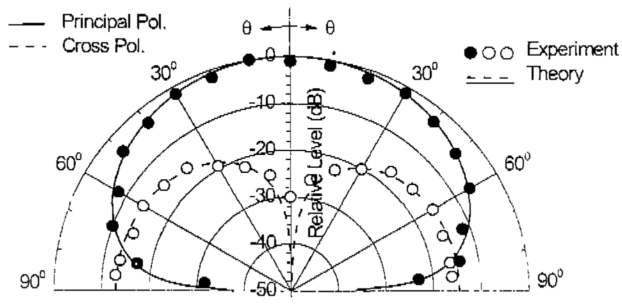
(d) $E_x(y)$

Fig. 8. Electric field distributions on aperture.

side of the slot. To reduce the cross polarization appearing in H-plane, either the slot width should be decreased or both the feed and parasitic post should be moved to the far inside of the cavity from the aperture.



(a) E-plane



(b) H-plane

Fig. 9. Radiation patterns.

To check the validity of the numerical calculations, the radiation patterns of the antenna were compared with those of experiments. These results are plotted in Fig. 8(a) and (b). It is shown that the calculated radiation patterns are in good agreement to experimental results. A measurement setup comprised of an HP8510C vector network analyzer and an electrically small cutoff cavity-backed slot antenna with 2 × 4 m metal ground plane inside the microwave anechoic chamber. The cavity-backed slot antenna made of C_u plate was designed for operation around $f = 2.45$ GHz, and has the following parameters: $a = 4.9$ cm, $b = 2.45$ cm, $c = 2.45$ cm, $d = 5.6$ mm, $s = 6.1$ mm, and $r = 0.6$ mm.

Ⅳ. CONCLUSIONS

We have described a forced resonant type cutoff cavity-backed slot antenna element that has a feed post and a parasitic post in an electrically small-sized cavity, and suggested the use of external reactance to obtain a forced resonance for the application of spacetenna. The basic characteristics are investigated using the method of moments. As the results, it is found that the forced resonant type cutoff cavity-backed slot antenna can be realized by loading only one reactance element. Moreover if a cavity depth is moderately chosen, we do not need the end wall of the cavity to obtain impedance matching. 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. Expanding the proposed spacetenna element to an array still remains and this deserves further work.

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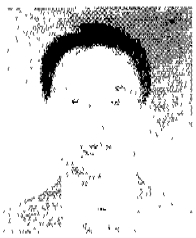

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