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FDTD ANALYSIS OF STACKED MICROSTRIP ANTENNA WITH HIGH GAIN

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Abstract—The finite-difference time-domain (FDTD) method is applied to the probe-fed square patch microstrip antenna stacked a parasitic patch for high gain. The input impedance, the directivity, the far field radiation patterns and the near field distributions are calculated and the relation between the antenna structure and the high gain is investigated The calculated input impedance and radiation patterns agree well with the experimental values. When the size of parasitic patch is nearly equal to the fed patch and the distance between the fed patch and the parasitic patch is about a half wavelength, the maximum gain of 9.43 dBi is obtained. In this case, the region between the fed patch and the parasitic patch forms a resonator. Then, the amplitude of current distribution on the parasitic patch becomes large and its phase is opposite to the current on the fed patch. The amplitude of electromagnetic fields of the space between the patches are increased.

1. INTRODUCTION

Although a microstrip antenna has practical advantages such as low-profile and light weight, a single patch antenna has a low gain (5−8 dBi) and a narrow bandwidth. By stacking a parasitic patch on a microstrip patch antenna, the antenna with high gain or wide bandwidth can be realized [1]. These characteristics of stacked microstrip antenna depend on the distance between a fed patch and a parasitic patch. When the distance is about 0.1λ (wavelength), the stacked microstrip antenna has a wide bandwidth [1, 2]. The stacked microstrip antenna has been analyzed numerically by using the spectral domain method [2–5]. In these papers, the impedance characteristics of the stacked microstrip antenna is mainly discussed. It has been experimentally shown that the stacked microstrip antenna has a high gain when the distance between the fed patch and parasitic patch is 0.3 to 0.5λ [1, 6, 7]. However, there is no paper what explain relations between the gain enhancement and near field distributions of the stacked microstrip antenna.

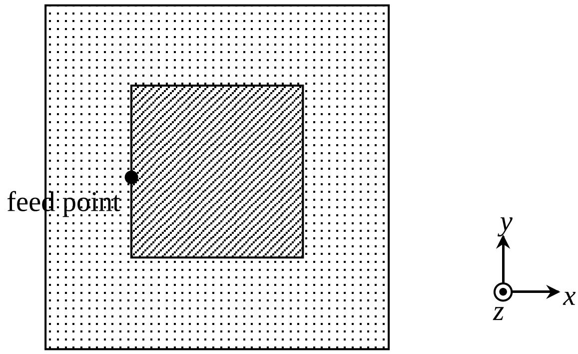
In this paper, the finite-difference time-domain (FDTD) method is applied to the stacked microstrip antenna with high gain [8]. The input impedance, the directivity, the far field radiation pattern and the near field distribution are calculated and the relations between the gain enhancement and the calculated field distributions on the patches are discussed.

2. MODEL FOR ANALYSIS

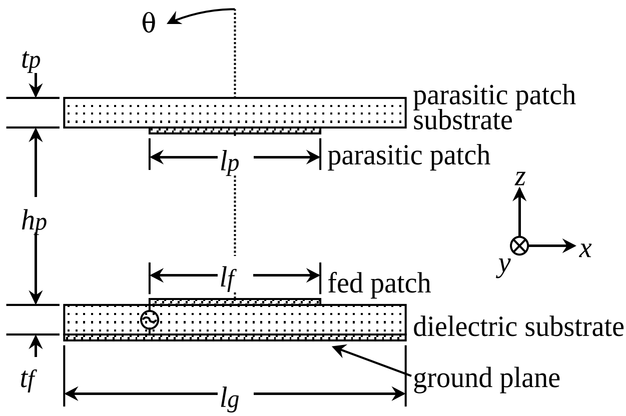
Figure 1 shows the geometry of the stacked microstrip antenna. This microstrip antenna is composed of the probe-fed square patch antenna and the parasitic square patch. The width of fed patch and parasitic patch are l_f and l_p, respectively. The fed patch is designed to have a resonant frequency of 7.5 GHz. These patches are etched on a dielectric substrate (length l_g, the relative dielectric constant $\varepsilon_r = 2.15$, the thickness $d = 0.8$ mm). The parasitic patch is stacked at the height h_p above the fed patch and supported by the foam spacer with low dielectric loss. The substrate of the parasitic patch is above the parasitic path and used as cover.

For practical use, a cover is necessary to protect antennas. In this paper, We suggest the stacked microstrip antenna adding a cover at the upside of the parasitic patch (Figure 1) and calculate the characteristics of covered antennas for the cover's parameters.

The FDTD method introduced by Yee is used to analyze the stacked microstrip antennas [8]. Berenger's perfectly matched layer (PML) with 10 cells is applied as the absorbing boundary condition



(a) Top view



(b) Side view

Figure 1. Structure of stacked microstrip antenna.

[9]. The space steps used in the FDTD formulation are $\Delta x = \Delta y = 0.615\,\text{mm}$ and $\Delta z = 0.8\,\text{mm}$ and the size of free space is $60\Delta x \times 60\Delta y \times 60\Delta z$. The time step is taken to be $\Delta t = 1.2744\,\text{ps}$ to satisfy the Courant stability condition. The size of the ground plane and the fed patch are $40\Delta x \times 40\Delta y\,(24.6 \times 24.6\,\text{mm})$ and $20\Delta x \times 20\Delta y\,(12.3 \times 12.3\,\text{mm})$, respectively.

The far field is calculated from the equivalent electric and magnetic currents on the surface defined 3 cell inside of the absorbing boundary [10]. The equivalent electric and magnetic currents in the spectral domain are calculated by using Fourier Transform of the time-domain results after FDTD simulation.

The antenna is excited by a Gaussian pulse electric field in the feed point gap $(i_f, j_f, k_f + 1/2)$;

$$\begin{aligned} E_z^n\left(i_f, j_f, k_f + \frac{1}{2}\right) &= E_z^{n-1}\left(i_f, j_f, k_f + \frac{1}{2}\right) \\ &\quad + \frac{\Delta t}{\epsilon \Delta x}\left\{H_y^{n-\frac{1}{2}}\left(i_f + \frac{1}{2}, j_f, k_f + \frac{1}{2}\right)\right. \\ &\quad \left. - H_y^{n-\frac{1}{2}}\left(i_f - \frac{1}{2}, j_f, k_f + \frac{1}{2}\right)\right\} \\ &\quad - \frac{\Delta t}{\epsilon \Delta y}\left\{H_x^{n-\frac{1}{2}}\left(i_f, j_f + \frac{1}{2}, k_f + \frac{1}{2}\right)\right. \\ &\quad \left. - H_x^{n-\frac{1}{2}}\left(i_f, j_f - \frac{1}{2}, k_f + \frac{1}{2}\right)\right\} \\ &\quad - \frac{\Delta t}{\epsilon} J_f^{n-\frac{1}{2}} \end{aligned} \tag{1}$$

$$\begin{aligned} J_f^n &= A_s \exp\left(\frac{\Delta t n - T}{0.29T}\right)^2 \sin(2\pi f_c \Delta t n), \\ T &= \frac{0.646}{f_0}, \end{aligned}$$

where f_c, f_0 and A_s are the center frequency, 3 dB bandwidth and the amplitude of the input source J_f, respectively.

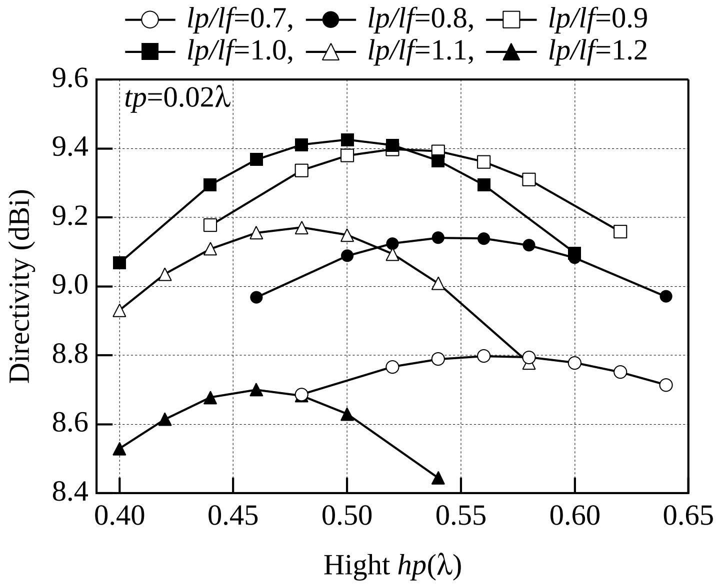
The input impedance Z_{in} is calculated by the equation

$$Z_{in}(f) = \frac{V(f)}{I(f)}, \tag{2}$$

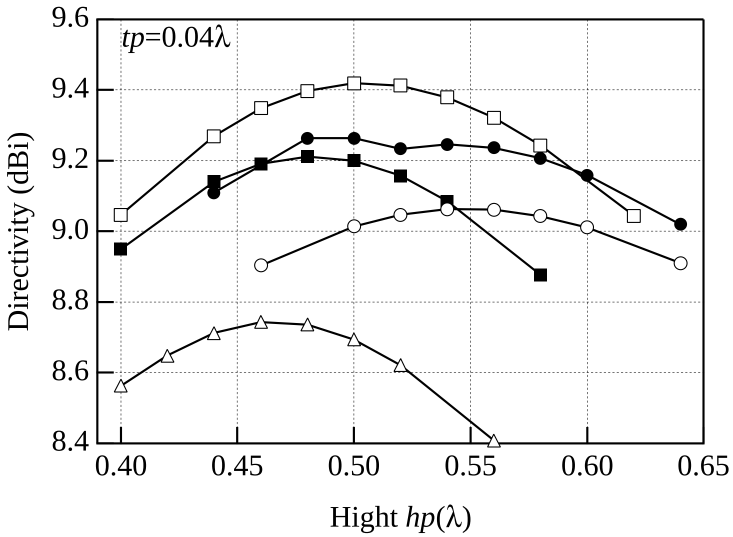
where the voltage $V(f)$ and the current $I(f)$ are Fourier transforms of time-dependent voltage $V(t)$ and current $I(t)$ at the feed point $(i_f, j_f, k_f + 1/2)$. $V(t)$ and $I(t)$ are expressed as follows.

$$V(t) = -E_z^n\left(i_f, j_f, k_f + \frac{1}{2}\right)\Delta_z, \tag{3}$$

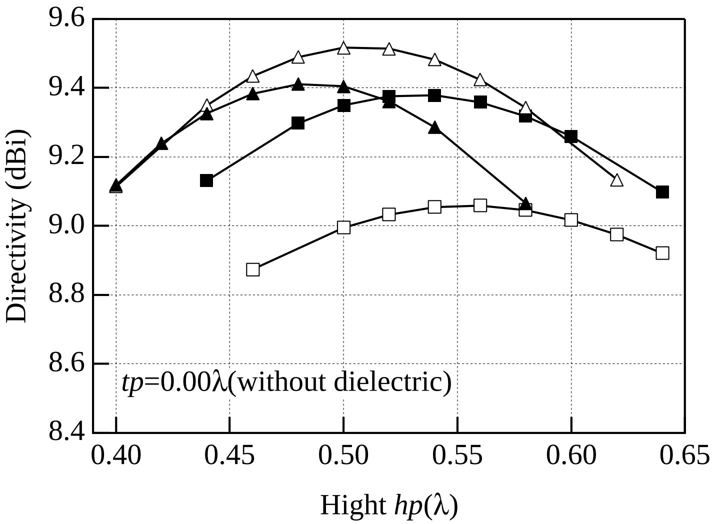
$$\begin{aligned} I(t) &= \left\{H_y^{n-\frac{1}{2}}\left(i_f + \frac{1}{2}, j_f, k_f + \frac{1}{2}\right)\right. \\ &\quad \left. - H_y^{n-\frac{1}{2}}\left(i_f - \frac{1}{2}, j_f, k_f + \frac{1}{2}\right)\right\}\Delta y \\ &\quad - \left\{H_x^{n-\frac{1}{2}}\left(i_f, j_f + \frac{1}{2}, k_f + \frac{1}{2}\right)\right. \\ &\quad \left. - H_x^{n-\frac{1}{2}}\left(i_f, j_f - \frac{1}{2}, k_f + \frac{1}{2}\right)\right\}\Delta x. \end{aligned} \tag{4}$$



(a) $t_p = 0.02\lambda$



(b) $t_p = 0.04\lambda$



(c) $t_p = 0.00\lambda$ (without parasitic patch substrate)

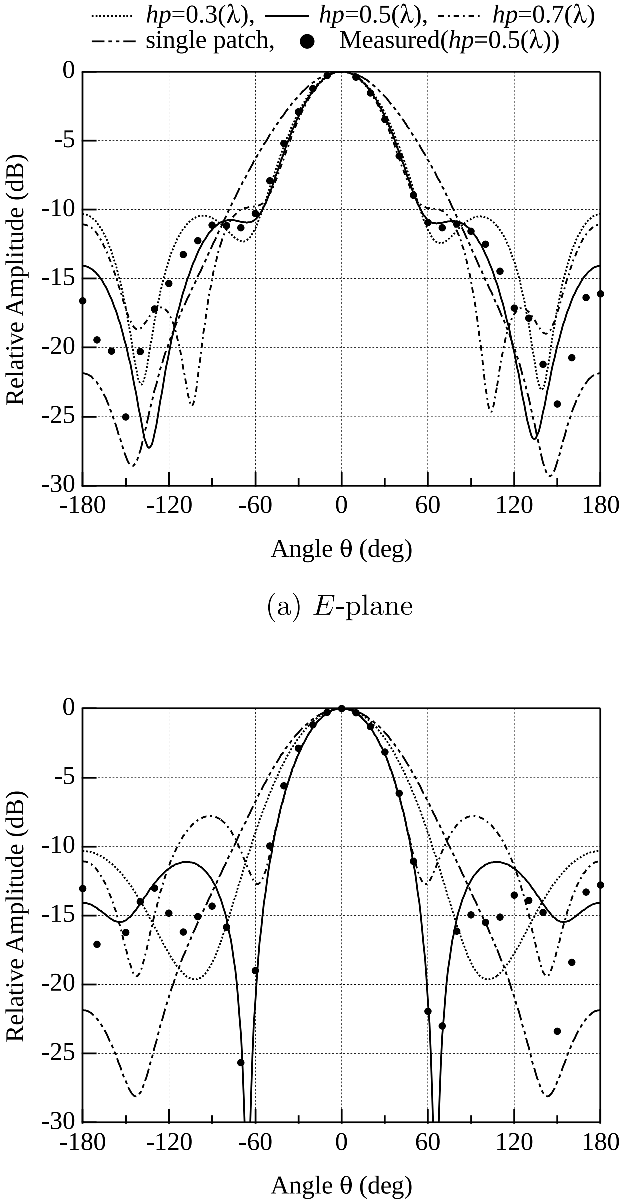
Figure 2. Directivity as a function of h_p. (Frequency = 7.5 GHz)

3. CHARACTERISTICS OF THE STACKED ANTENNA

Figure 2 shows the calculated directivities of the stacked microstrip antenna as a function of the spacing h_p between the fed patch and the parasitic patch. Figure 2(a) and (b) show the directivities of the antenna whose the parasitic patch substrate thickness t_p are 0.02λ and 0.04λ, respectively. Figure 2(c) shows the directivities of the antenna without dielectric substrate of parasitic patch ($t_p = 0$).

The directivity increases by stacking the parasitic patch. The higher gain is obtained when the height and the size of parasitic patch are about a half wavelength ($h_p \simeq 0.5\lambda$) and same as one of fed patch ($l_p/l_f = 1.0$), respectively. By increasing the thickness of parasitic substrate, the directivity decreases and the size of parasitic element to obtain the maximum gain becomes large.

Figure 3(a) and (b) show the electric field radiation patterns in E- and H-plane, respectively. The calculated results agree well with the experimental values. Although the beamwidth becomes narrow by stacking the parasitic patch, the back lobe level increases. In this antenna the electromagnetic field from the fed patch reflects at the parasitic patch and the standing wave occurs between the fed patch and the parasitic patch. Since the reflected field at the parasitic patch



(a) E-plane

(b) H-plane

Figure 3. Electric field radiation patterns in E- and H-plane. (Frequency 7.5 GHz, $l_p/l_f = 1.0$, $t_p = 0.02\lambda$)

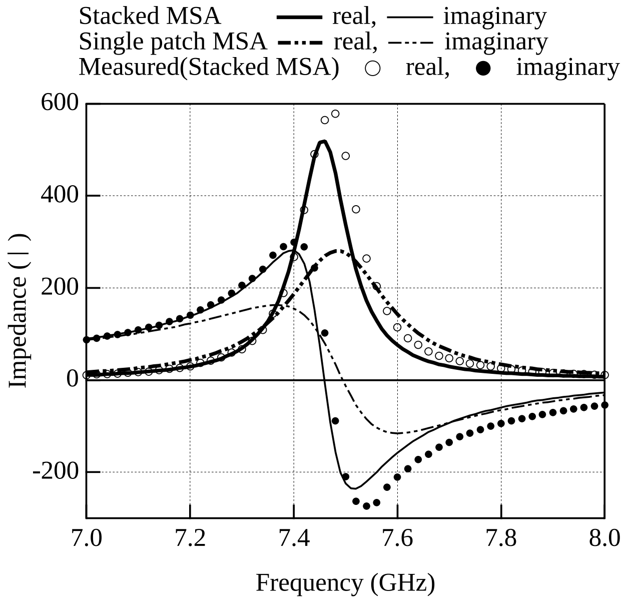


Figure 4. Frequency characteristics of input impedance. ($l_p/l_f = 1.0,\ h_p = 0.5\lambda,\ t_p = 0.02\lambda$)

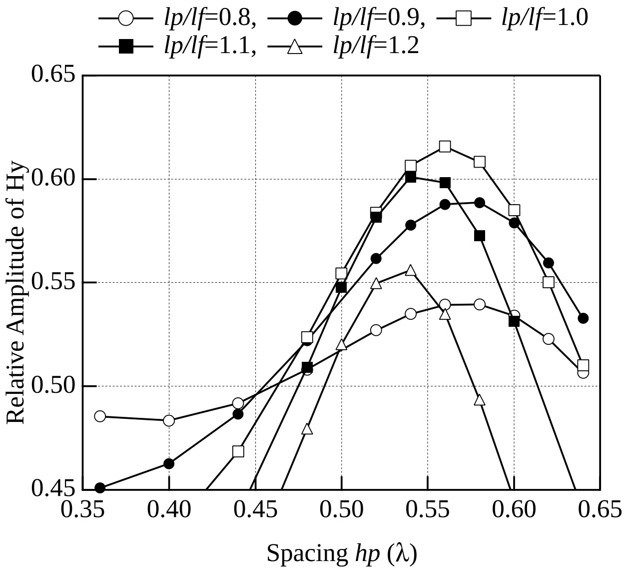
radiates backward, the back lobe level increases.

Figure 4 shows the frequency characteristics of input impedance of the stacked microstrip antenna. In the figure, the input impedance of the single patch antenna is also shown to be compared with those of the stacked microstrip antennas. The calculated impedances of the stacked microstrip antenna agree well with the experimental values. Since the region between the fed patch and parasitic patch forms a resonator when h_p is about 0.5λ, the bandwidth becomes narrow.

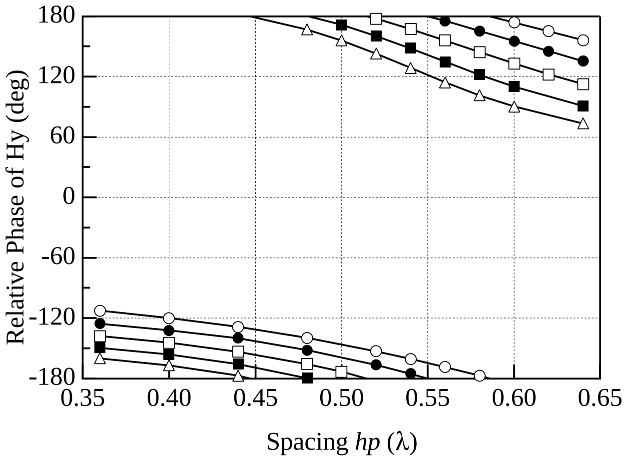
4. DISCUSSION

Figure 5 shows the near field distribution of H_y on the center of upper surface of parasitic patch as a function of the height of the parasitic element h_p. These H_y are expressed in the relative values to the H_y on the center of fed patch. The maximum amplitude of H_y is obtained at $h_p = 0.56\lambda$ and $l_p/l_f = 1.0$. The phase difference of 180° is obtained at $h_p \simeq 0.5\lambda$ and at $l_p/l_f = 1.0$.

The gain becomes the maximum at $h_p = 0.5\lambda$ and $l_p/l_f = 1.0$. The relative phase is 180° when the maximum directivity is obtain for each the size of parasitic element (vid. Figurer 2(a)). However,



(a) Amplitude



(b) Phase

Figure 5. Relative values of H_y above parasitic patch. (Frequency $= 7.5\,\text{GHz},\ t_p = 0.02\lambda$)

the maximum amplitude of H_y on the parasitic patch of the antenna is not obtained at these parameters. The reason for this difference may be that the electromagnetic field is radiated from not only the patch conductors but also the the side aperture of cavities between the ground plane, the fed patch and the parasitic patch in this antenna. We will have to study on this in detail.

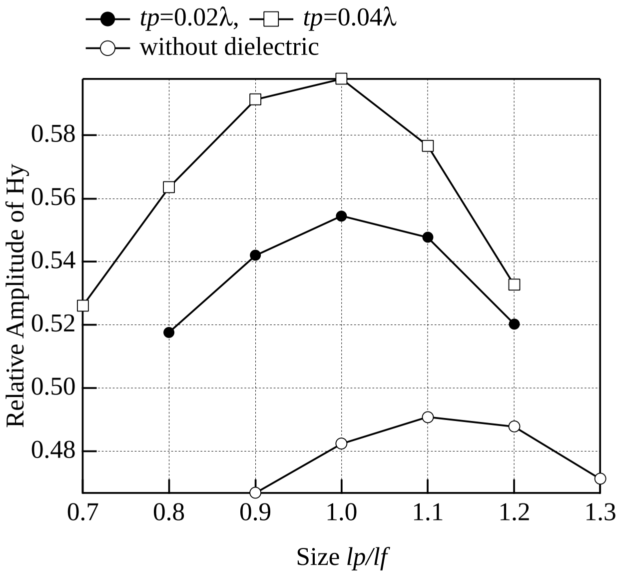
Figure 6 shows the near field distribution of H_y on the center of upper surface of parasitic patch as a function of the size of the parasitic element l_p. These H_y are expressed in the relative values to the H_y on the center of fed patch. When the maximum directivity is obtained for the all parasitic substrate thickness t_p, the relative amplitude become large and the relative phase is about 180°. The relative amplitude of H_y becomes large as increasing the thickness of the parasitic substrate t_p. However, the directivity is decreases.

Figure 7 and 8 show the E_x, and H_y distributions in the z-direction including the center of antenna, respectively. The amplitude of the each distribution of the antennas are normalized by its input power. The E_x are normalized by the maximum amplitude at $h_p = 0.5\lambda$, and the amplitude of H_y are expressed in the relative values to the fed element. The phase of E_x and H_y at the fed element are set to be zero.

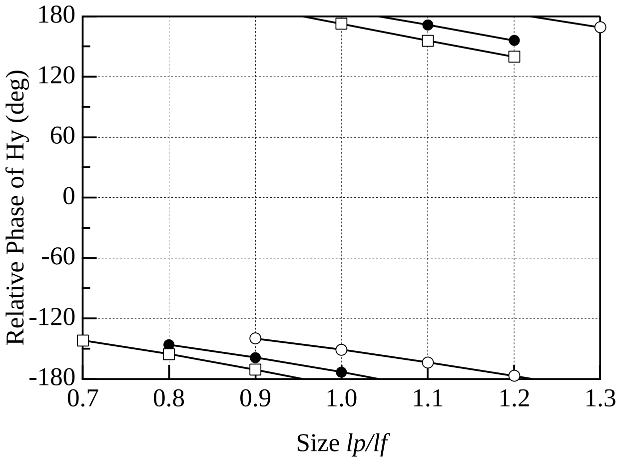
When the height of parasitic element is $h_p = 0.5\lambda$, the directivity becomes the maximum. When h_p is 0.3λ and 0.7λ, the gain decreases from the maximum value. There is the standing wave between the fed element and the parasitic element. The space between the fed element and parasitic element forms the resonator.

For the E_x distributions, when the hight h_p is 0.5λ, the E_x amplitude is the maximum and the E_x phase remains constant. Increasing the height h_p to 0.7λ or decreasing the height h_p to 0.3λ, the amplitude are deceased and the phase does not remain constant and the effect of the resonator fade away. Electromagnetic fields energies are stored at the cavities between the patches. When the maximum gain are obtained, the stored energies become large.

For the H_y distributions, decreasing the hight h_p, the H_y amplitude becomes large. However, the phase difference of the H_y on elements is not 180°. The current phase difference and the space distance between the patches are 180° and a half wavelength, respectively. In the main lobe direction, a phase of a wave radiated from the fed patch agree with one from the parasitic patch, so that the waves overlap each other and the gain is increased. When the maximum gain is obtained, the amplitude of E_x distribution between the fed element and the parasitic element is large and the phase difference of H_y on the elements is 180°.

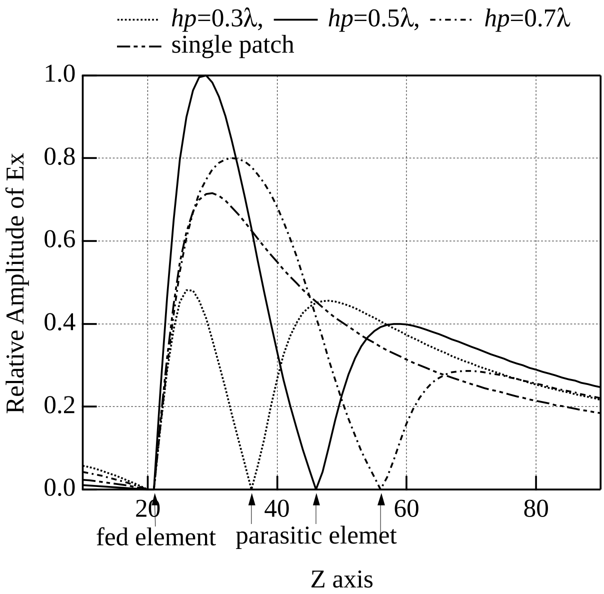


(a) Amplitude

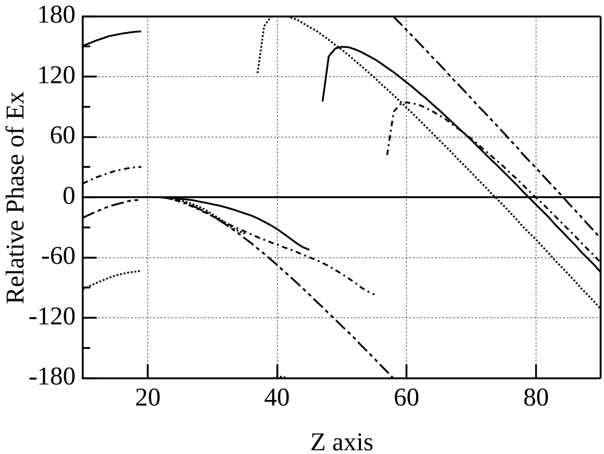


(b) Phase

Figure 6. Relative values of H_y above parasitic patch. (Frequency $= 7.5\,\mathrm{GHz}$, $h_p = 0.5\lambda$)

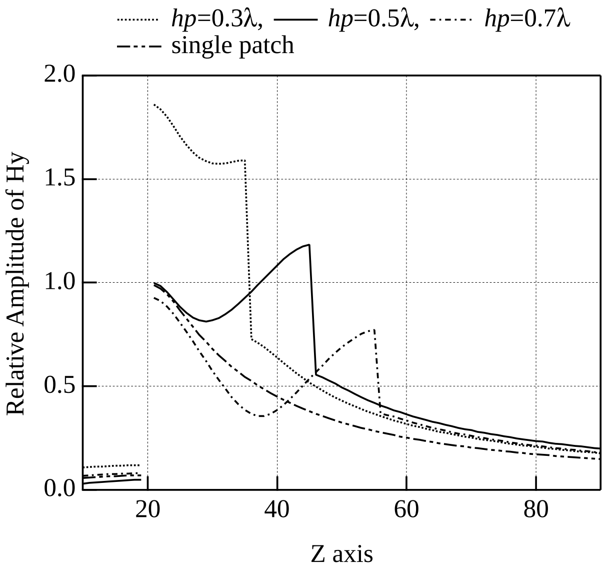


(a) Amplitude

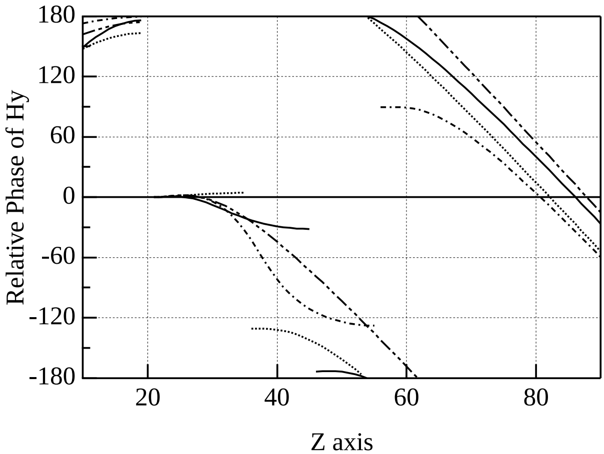


(b) Phase

Figure 7. Distributions of E_x in the z-direction. (Frequency $=$ $7.5\,\mathrm{GHz}$, $l_p/l_f = 1.0$, $t_p = 0.02\lambda$)



(a) Amplitude



(b) Phase

Figure 8. Distributions of H_y in the z-direction. (Frequency $=$ $7.5\,\mathrm{GHz}$, $l_p/l_f = 1.0$, $t_p = 0.02\lambda$)

5. CONCLUSION

The probe-fed square patch microstrip antenna with a stacked parasitic patch for high gain has been calculated by using FDTD method and compared with the measured results. The input impedance, the directivity, the far field radiation patterns and the near field distributions have been calculated and the relation between the gain enhancement and the antenna structure has been investigated. The calculated radiation patterns and input impedance by FDTD simulation agree well with the experimental results.

When the size of parasitic patch is nearly equal to the fed patch and the distance between the fed patch and the parasitic patch is about a half wavelength, the maximum gain of 9.43 dBi is obtained. The highly accurate near field analysis by the FDTD method makes it clear that the space between the fed patch and the parasitic patch forms the resonator.

When the higher gain is obtained, the amplitude of electric fields in the cavity between patches becomes large, and the amplitude of current distribution on the parasitic patch becomes also large and its phase is opposite to the current on the fed patch.

Since the length of ground plane of fed patch is twice of fed patch, the back lobe becomes large compared with the single patch antenna. If the ground plane with larger size will be used, the backward radiation would be suppressed and the higher gain could be expected.

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