Home

Mutual Coupling Effects Between Patch Elements of Microstrip Planar Antenna Arrays

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Abstract - Radiation from the microstrip patch elements was studied. Expressions were derived for the far field radiation assuming the current variation is only along the length of the patch. Mutual coupling effects between the microstrip patches were studied and analytical expressions for near fields and mutual impedances were derived. Results show that the coupling effects change the current distribution on the patch and the far field radiation of the antenna array where the elements are placed close to each other.

I Introduction

Microstrip antennas are very popular for their low profile and lightweight. Deschamps first proposed the concept of microstrip radiators as early as 1953 [1]. However, these arrays were not fabricated as better theoretical models and photo-etch techniques for copper or gold-clad dielectric substrates with a wide range of dielectric constants were not developed. The first practical microstrip antenna was built in the year 1970 by Howell and Munson [2].

Radiation from microstrip antennas can be understood by considering the simple case of a rectangular patch spaced a small fraction of a wavelength above a ground plane. Assuming that field varies only along the patch length, which is about half a wavelength ($\lambda/2$). Radiation may be ascribed mostly to the fringing fields at the open-circuited edges of the patch. The fields at the end can be resolved into normal and tangential components with respect to the ground plane. The normal components are 180^0 out of phase because the patch line is $\lambda/2$ long; therefore the far field produced by them cancel in the broadside direction. The tangential components (those parallel to the ground plane) are in phase, and the resulting fields combine to give maximum radiated field normal to the surface of the structure; i.e., broadside direction.

Chen proposed a phased array [4]. Chen and others studied mutual coupling effects in microstrip patch phased linear antenna array; results were presented with and without mutual coupling. They concluded that mutual coupling can also be the cause of blind scan angles, which should always be avoided within the scan range of the phased array. Far fields **E** and **H** can be calculated from the vector potential **A**, which is a function of the current distribution of the microstrip patch. However in an array where the elements lie close to each other, the coupling effects change the effective current distributions on the individual elements and must be taken into consideration while calculating the far field electromagnetic radiations of the microstrip patch antenna.

Daniel et al [5] discuss the flexibility of the printed technology and offer the possibilities of innovative radiating structures well suited to various applications. Academic researchers of the laboratory were focused on the corner fed square patch and the array design of such elements.

Alfaouri in his paper [6] describes a study of the relative performance of the far field radiation pattern using different methods from the viewpoint of reducing the side lobes. He discusses the implementation of the fractional change for nonuniform spacing to reduce the side lobe levels. A detailed analysis of patch arrays with corporate feed networks incorporating non-isolating splitters is described in [7]. A small array of microstrip patches is presented in [8]. It has been designed, fabricated and tested by Wojciech Sadowski and others to be used in a GSM 1800 base station antenna. A partial compensation of the free space attenuation along a sector cell is provided.

In this study we derive expressions for the far field radiation assuming the current variation is only along the length of the patch. Mutual coupling effects were taken into consideration by deriving analytical expressions for the near fields and mutual impedances for the elements shown in Figure (1). The results are given for an 8x8 patch antenna array patterns with and without mutual coupling.

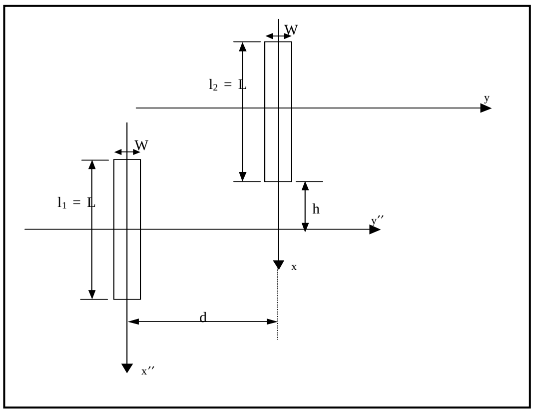

Fig. 1. Geometry of two microstrip patches for mutual coupling calculations

Results show that the coupling effects change the current distribution on the patch and the far field radiation of the antenna array where the elements are placed close to each other.

II. Mutual coupling between two microstrip patch antennas

When two patch elements are brought in the vicinity of each other, current in each element changes in both amplitude and phase. The amount of change depends on the mutual coupling between the elements. As now the currents are changed, the far-fields due to these elements change. Mutual coupling expressions can be derived from the near field calculations. From the expressions of self and mutual impedances, the effective current distributions on the patches can be obtained. Form the effective current distribution the far fields can be calculated which is the effective far field radiation of the two patch elements located close to each other.

$\mathbf{E_x}$ is used for mutual coupling calculations and is given by the following equations.

$$\Rightarrow E_x = \left\{ \begin{array}{l} \dfrac{\eta}{4\pi}\dfrac{I_0}{W}\dfrac{1}{k}\left[\begin{array}{l} \dfrac{(y+W/2)}{L_1{}^2-(x+L/2)^2}e^{-jkL_1} - \dfrac{(y-W/2)}{U_1{}^2-(x+L/2)^2}e^{-jkU_1} \\ + \dfrac{(y+W/2)}{L_3{}^2-(x-L/2)^2}e^{-jkL_3} - \dfrac{(y-W/2)}{U_3{}^2-(x-L/2)^2}e^{-jkU_3} \\ -2\cos\left(\dfrac{kL}{2}\right)\left(\dfrac{(y+W/2)}{L_2{}^2-x^2}e^{-jkL_2} - \dfrac{(y-W/2)}{U_2{}^2-x^2}e^{-jkU_2}\right) \end{array} \right] \\ + \dfrac{j\eta}{ky}H_\theta \end{array} \right\} \tag{1}$$

where,

$$H_\theta = \frac{I_0}{8\pi jW}\left\{ \begin{array}{l} e^{jk(x+L/2)}\left[Ei[-jk(L_1+x+L/2)]-Ei[-jk(U_1+x+L/2)]\right] \\ +e^{-jk(x+L/2)}\left[Ei[-jk(L_1-x-L/2)]-Ei[-jk(U_1-x-L/2)]\right] \\ +e^{jk(x-L/2)}\left[Ei[-jk(L_3+x-L/2)]-Ei[-jk(U_3+x-L/2)]\right] \\ +e^{-jk(x-L/2)}\left[Ei[-jk(L_3-x+L/2)]-Ei[-jk(U_3-x+L/2)]\right] \\ -2\cos\left(\dfrac{kL}{2}\right)e^{jkx}\left[Ei[-jk(L_2+x)]-Ei[-jk(U_2+x)]\right] \\ -2\cos\left(\dfrac{kL}{2}\right)e^{-jkx}\left[Ei[-jk(L_2-x)]-Ei[-jk(U_2-x)]\right] \end{array} \right\} \tag{2}$$

$$U_1 = \sqrt{(x+L/2)^2+(y-W/2)^2} \quad ; \quad L_1 = \sqrt{(x+L/2)^2+(y+W/2)^2}$$
$$U_2 = \sqrt{x^2+(y-W/2)^2} \quad ; \quad L_2 = \sqrt{x^2+(y+W/2)^2}$$
$$U_3 = \sqrt{(x-L/2)^2+(y-W/2)^2} \quad ; \quad L_3 = \sqrt{(x-L/2)^2+(y+W/2)^2}$$

Therefore the mutual and the self impedances are calculated from these near fields and are given by the following expressions.

$$Z_{21m} = -\frac{30}{Wk(d+W/2)}I_1 + \frac{30}{Wk(d-W/2)}I_2 - \frac{15}{Wkd}I_3 \tag{3}$$

where,

$$I_1 = \int_{-L/2}^{L/2} \sin\left[k\left(\frac{L}{2}-|x|\right)\right]\times\left[e^{-jkL_1}+e^{-jkL_3}-2\cos\left(\frac{kL}{2}\right)e^{-jkL_2}\right]dx$$

$$I_2 = \int_{-L/2}^{L/2} \sin\left[k\left(\frac{L}{2}-|x|\right)\right]\times\left[e^{-jkU_1}+e^{-jkU_3}-2\cos\left(\frac{kL}{2}\right)e^{-jkU_2}\right]dx$$

$$I_3 = \int_{-L/2}^{L/2} \sin\left[k\left(\frac{L}{2}-|x|\right)\right]\times S(x)\,dx$$

and

$$S(x) = \left\{ \begin{array}{ll} & e^{jk(x-h)}\left[Ei[-jk(L_1+x-h)]-Ei[-jk(U_1+x-h)]\right] \\ + & e^{-jk(x-h)}\left[Ei[-jk(L_1-x+h)]-Ei[-jk(U_1-x+h)]\right] \\ + & e^{jk(x-h-L)}\left[Ei[-jk(L_3+x-h-L)]-Ei[-jk(U_3+x-h-L)]\right] \\ + & e^{-jk(x-h-L)}\left[Ei[-jk(L_3-x+h+L)]-Ei[-jk(U_3-x+h+L)]\right] \\ - & 2\cos\left(\dfrac{kL}{2}\right)e^{jk(x-h-L/2)}\left[\begin{array}{l} Ei[-jk(L_2+x-h-L/2)] \\ -Ei[-jk(U_2+x-h-L/2)] \end{array} \right] \\ - & 2\cos\left(\dfrac{kL}{2}\right)e^{-jk(x-h-L/2)}\left[\begin{array}{l} Ei[-jk(L_2-x+h+L/2)] \\ -Ei[-jk(U_2-x+h+L/2)] \end{array} \right] \end{array} \right\}$$

$$\therefore Z_{11m} = -\frac{1}{I_m{}^2}\int_{-L/2}^{L/2} E_{x11} I_1(x)\,dx\Big|_{y\to W/2} \tag{4}$$

where

$$E_{x11}(x) = 30\frac{I_0}{W}\frac{1}{k(y+W/2)}\left\{e^{-jkL_1}+e^{-jkL_3}-2\cos\left(\frac{kL}{2}\right)e^{-jkL_2}\right\}$$

$$-30\frac{I_0}{W}\frac{1}{k(y-W/2)}\left\{e^{-jkU_1}+e^{-jkU_3}-2\cos\left(\frac{kL}{2}\right)e^{-jkU_2}\right\}$$

$$+15\frac{I_0}{W}\frac{1}{ky}\left\{ \begin{array}{l} e^{jk(x+L/2)}\left[Ei[-jk(L_1+x+L/2)]-Ei[-jk(U_1+x+L/2)]\right] \\ +e^{-jk(x+L/2)}\left[Ei[-jk(L_1-x-L/2)]-Ei[-jk(U_1-x-L/2)]\right] \\ +e^{jk(x-L/2)}\left[Ei[-jk(L_3+x-L/2)]-Ei[-jk(U_3+x-L/2)]\right] \\ +e^{-jk(x-L/2)}\left[Ei[-jk(L_3-x+L/2)]-Ei[-jk(U_3-x+L/2)]\right] \\ -2\cos\left(\dfrac{kL}{2}\right)e^{jkx}\left[Ei[-jk(L_2+x)]-Ei[-jk(U_2+x)]\right] \\ -2\cos\left(\dfrac{kL}{2}\right)e^{-jkx}\left[Ei[-jk(L_2-x)]-Ei[-jk(U_2-x)]\right] \end{array} \right\}$$

III. Far field array pattern of microstrip patch antenna array

The array pattern of a microstrip patch array can be obtained by multiplying the array factor of the array and the element pattern of the microstrip patch. However the array factor is calculated taking the mutual coupling into account. The array pattern of 8×8 element microstrip taking coupling effects into consideration is given by equation 5.

Top

$$[I]=[Z]^{-1}[V]$$

$$AP_{8\times8}=\sum_{n=-1}^{-4}\left[\sum_{m=-1}^{-4}EP\times I_{m,n}\exp\left(-j\left(\left(\frac{2m+1}{2}\right)\Psi_x-ph_{mn}\right)\right)+\right.$$
$$\left.\sum_{m=1}^{4}EP\times I_{m,n}\exp\left(-j\left(\left(\frac{2m-1}{2}\right)\Psi_x-ph_{mn}\right)\right)\right]\times\exp\left(-j\left(\frac{2n+1}{2}\right)\Psi_y\right)$$

$$+\sum_{n=1}^{4}\left[\sum_{m=-1}^{-4}EP\times I_{m,n}\exp\left(-j\left(\left(\frac{2m+1}{2}\right)\Psi_x-ph_{mn}\right)\right)+\right.$$

$$\left.\sum_{m=1}^{4}EP\times I_{m,n}\exp\left(-j\left(\left(\frac{2m-1}{2}\right)\Psi_x-ph_{mn}\right)\right)\right]\times\exp\left(-j\left(\frac{2n+1}{2}\right)\Psi_y\right) \qquad (5)$$

where

$$EP=\sqrt{(E_\theta)^2+(E_\phi)^2}$$

$$E_\theta=-j\eta\frac{\exp(-jkr)}{\pi r}\frac{\sin\left(\frac{kW}{2}\sin\theta\sin\phi\right)}{kW\tan\theta\tan\phi}\frac{\left[\cos\left(\frac{kL}{2}\sin\theta\cos\phi\right)-\cos\left(\frac{kL}{2}\right)\right]}{\left(1-\sin^2\theta\cos^2\phi\right)}$$

$$E_\phi=j\eta\frac{\exp(-jkr)}{\pi r}\frac{\sin\left(\frac{kW}{2}\sin\theta\sin\phi\right)}{kW\sin\theta}\frac{\left[\cos\left(\frac{kL}{2}\sin\theta\cos\phi\right)-\cos\left(\frac{kL}{2}\right)\right]}{\left(1-\sin^2\theta\cos^2\phi\right)}$$

$$V_{mn}=\sum_u\sum_v Z_{mn,uv}I_{uv}$$

where

$Z_{mn,mn}$ are self impedances $Z_{mn,uv}$ for $mn\neq uv$ are mutual impedances

IV. Results

The array pattern of a microstrip patch array can be obtained by multiplying the array factor of the array and the element pattern of the microstrip patch. However the array factor is calculated taking the mutual coupling into account. The array pattern of 8×8 element microstrip taking coupling effects has been derived and used to obtain the actual radiation characteristics of the planar array with and without the mutual coupling effects.

The coupling effects were studied and analytical expressions were derived. The results of mutual impedance variation with separation were obtained. The effect of mutual coupling on the far field radiation pattern is illustrated by considering an 8×8 element microstrip array and comparing its radiation patterns with and without coupling. Typical results of the array patterns with and without mutual coupling are shown in Figures(2-3).

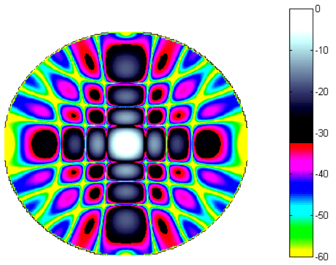

Fig. 2. The 3-D array pattern of 8×8-element array without coupling

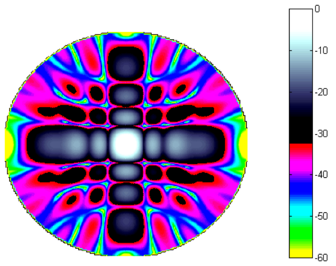

Fig. 3. The 3-D array pattern taking mutual coupling into account

The results show that the mutual coupling between the elements of the array changes the far field pattern considerably and therefore have to be taken into account when designing closely spaced microstrip arrays. It is also worth noting that there is considerable variation in the pattern along the element axis compared to the variation in the direction normal to the axis.

V. Summary and Conclusions

From the results it can be concluded that the mutual coupling between the elements of the array changes the far field pattern considerably and therefore must be taken into account when designing closely spaced microstrip arrays. It is also worth noting that there is considerable variation in the pattern along the element axis compared to the variation in the direction normal to the axis. All the expressions were derived with the assumption of sinusoidal current distribution along the length of the patch to show the results of the effect of mutual coupling effects on array far field radiation.

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Top