공간체감된 구형 위상어레이의 성능에 미치는 상호결합의 영향

장병건*

MUTUAL COUPLING EFFECTS ON THE PERFORMANCE OF A SPACE-TAPERED RECTANGULAR PHASED ARRAY

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이 논문은 2004년도 인천대학교 멀티미디어연구센터에서 연구비를 지원받았음

요 약

어레이 소자의 방사 또는 수신 특성은 소자 상호결합 효과 때문에 고립된 소자의 특성과 달라지게 되며, 따라서 어레이 성능은 고립된 소자를 가정하여 설계할 경우의 성능과 다르게 된다. 접지판 위에 위치한 삼각형 격자 구조를 가진 직사각형 다이폴 어레이에 미치는 상호 결합의 영향을 소자패턴을 고려하여 논의하였다. 소자 이득 함수를 이용하여 소자가 균일하게 분포되거나 소자간격이 체감된 어레이에서 부엽(sidelobe)에 미치는 소자 상호결합 효과의 영향을 점검하였다. 상호결합 효과가 존재할 때, 소자간격이 체감된 어레이에서의 부엽의 성능이 소자간격이 균일하게 분포된 어레이와 비교하여 향상되는 것을 보여주었다. 컴퓨터 시뮬레이션을 제시하였다.

ABSTRACT

The radiating or receiving characteristics of array elements (i.e., antennas) are changed from those of isolated elements due to mutual coupling effects and the array performance becomes different from those originally designed by assuming isolated elements. The effects of mutual coupling on the performance of a rectangular array with triangular grid geometry of dipoles above a ground plane are discussed with respect to element pattern. The concept of element gain function is used to examine the effects of mutual coupling on the array performance in terms of sidelobe level in the uniformly spaced and space-tapered rectangular arrays with triangular grid geometry of dipoles. It was shown that the sidelobe performance improved in the space-tapered array compared to the uniformly spaced array in the presence of mutual coupling effects. Computer simulation results are presented.

키워드

mutual coupling, sidelobe, triangular grid, dipole, space-tapered

1. Introduction

A portion of energy radiated from a phased array couples between antenna elements and introduces mutual coupling effects in the array environment. The mutual coupling effects are

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접수일자 2004. 12. 20

one of the major problems in the design of a phased array. The mutual coupling generally depends on the type of antenna element, inter-element spacing, and array geometry. Since the radiating and receiving characteristics of array elements are changed from that of isolated elements because of mutual coupling effects, the array performance becomes different from that originally designed with isolated elements. The methods to reduce the mutual coupling effects have been widely investigated in the literature [1-4]. The element gain function was effectively employed to analyze the mutual coupling effects in a rectangular dipole array with rectangular grid geometry [2]. It is well known that the array with triangular grid geometry is practically efficient in the sense that it provides an array performance comparable to that by a rectangular grid geometry with fewer number of elements. Thus the array design cost is reduced with the triangular grid geometry. Also, it is known that the sidelobe level gets lowered in the space-tapered array [5]. Another advantage of the space tapering approach is that the mutual coupling between elements is reduced because the number of elements in the space-tapered array is less than in the normal uniform array and thus the inter-element spacing is larger in the space-tapered array compared to the normal array.

In this paper, a space-tapering approach with triangular grid geometry has been proposed to reduce the mutual coupling effects. The element gain function has been used to analyze the mutual coupling effects in a rectangular phased array with triangular grid geometry of dipoles above a ground plane. The mutual coupling effects are analyzed in terms of element pattern in a passively terminated array environment. It is assumed that the array is above a ground plane which is sufficiently large such that there are no edge effects due to the ground plane. Also, it is assumed that each dipole is identical and driven by an independent constant voltage generator and, for convenience, the transmission line is of zero length. The gain function of the center dipole as a typical element has been examined in terms of array parameters in the presence of mutual coupling and used to approximate the array performance with respect to sidelobe level. Also, the edge effects in a finite array have been investigated using the element gain function in the presence of mutual coupling effects.

It is shown that the sidelobe level gets lowered and also the edge effects decrease with the proposed approach.

2. Element Behavior in a Rectangular Phased Array

In a rectangular phased array, the mutual coupling affects the element pattern differently depending on the element location in the array because of geometrical asymmetry. As a result, the patterns of edge or corner elements are more asymmetrical than those of the elements around the array center. One way of evaluating this phenomenon is to examine the gain function of the dipole elements. It is assumed that all dipoles have the same self-impedance and all generator impedances are equal. A practical way of measuring the element pattern in an array environment is to drive a single element while all other elements are terminated with their generator impedances [4]. Then the array pattern of a rectangular array with triangular grid geometry of dipoles can be represented by

$$H(\Theta,\phi)=\sum_{n}\sum_{m} f_{nm}(\Theta,\phi)\, i_{nm} e^{-j\beta(p_n d_x u + q_m d_y v)} \qquad (1)$$

where

$$u = \sin\Theta\cos\phi \qquad (2)$$

and

$$v = \sin\Theta\sin\phi \qquad (3)$$

$f_{nm}(\Theta,\phi)$ is the pattern of the nmth dipole per unit current and i_{nm} is the current in the nmth dipole, with all other dipoles passively terminated, p_n and q_m are scale factors related to the array geometry, d_x and d_y are the inter-element spacings on the E and H plane respectively, $\beta=2\pi/\lambda_c$, λ_c is the wave length corresponding to array center frequency, and Θ and ϕ are the elevation and azimuth angles respectively. To find an analytic expression for the element pattern when one dipole is driven with all other dipoles passively terminated, the array pattern need to be considered in terms of two perspectives. One perspective is that the array pattern is determined entirely by the pattern of the driven dipole and its current as defined in (1). Therefore if the nmth dipole is driven with other dipoles passively terminated, the array pattern is given by

$$H(\Theta,\Phi)=f_{nm}(\Theta,\Phi)i_{nm}e^{-j\beta(p_n d_x u+q_m d_y v)} \qquad (4)$$

From the definition of i_{nm} (Equation (1)), we have

$$i_{nm}=Y_{nm,nm}V_{g,nm} \qquad (5)$$

where $Y_{nm,nm}$ is the self-admittance of the nm th dipole and $V_{g,nm}$ is the generator voltage of the nmth dipole. Substituting (5) into (4), we have the array factor as

$$H(\Theta,\Phi)=f_{nm}(\Theta,\Phi)Y_{nm,nm}V_{g,nm}e^{-j\beta(p_n d_x u+q_m d_y v)} \qquad (6)$$

The second perspective for the array pattern is that it can be obtained by measuring the short-circuit (parasitic) current induced in all the dipoles by the coupled energy from the driven element. The parasitic current at the klth dipole is given by

$$i_{kl}=Y_{kl,nm}V_{g,nm} \qquad (7)$$

where $Y_{kl,nm}$ is the mutual admittance between the klth and nmth dipoles. If the klth element is not affected by other elements except the driven dipole such that other dipoles look like an open circuit, we can use an isolated dipole pattern $f_i(\Theta,\Phi)$ to calculate the beam pattern assuming all dipoles have an identical isolated pattern. Thus the beam pattern results in

$$H(\Theta,\Phi)=f_i(\Theta,\Phi)\sum_k\sum_l i_{kl}e^{-j\beta(p_k d_x u+q_l d_y v)} \qquad (8)$$

Substituting (7) into (8), we have

$$H(\Theta,\Phi)=f_i(\Theta,\Phi)V_{g,nm}\sum_k\sum_l Y_{kl,nm}e^{-j\beta(p_k d_x u+q_l d_y v)} \qquad (9)$$

Comparing (6) and (9), the pattern of the nm th dipole is approximately given by

$$f_{nm}(\Theta,\Phi)=\frac{f_i(\Theta,\Phi)}{Y_{nm,nm}}\sum_k\sum_l Y_{kl,nm}e^{-j\beta[(p_k-p_n)d_x u+(q_l-q_m)d_y v]} \qquad (10)$$

The dipole pattern is simply the isolated pattern modified by the self-admittance and the vector sum of phased mutual admittances. It can be shown that the gain of the nmth dipole with other dipoles passively terminated is given by

$$g_{nm}(\Theta,\Phi)=\frac{4\pi\,|f_{nm}(\Theta,\Phi)i_{nm}|^2}{|V_{g,nm}|^2/(4R_g)} \qquad (11)$$

where $|V_{g,nm}|^2/(4R_g)$ is the maximum power available to the array from the generator and R_g is the generator resistance. Substituting (5) into (11), we have

$$g_{nm}(\Theta,\Phi)=16\pi R_g|f_{nm}(\Theta,\Phi)|^2|Y_{nm,nm}|^2 \qquad (12)$$

Also, the maximum gain of the isolated dipole can be expressed as

$$g_{i,\max}(\Theta,\Phi)=\frac{4\pi|f_i(\Theta,\Phi)i_i|^2}{|V_g|^2/(4R_s)} \qquad (13)$$

where R_s is the real part of the self-impedance of each element. If the isolated dipole is matched, the current is given by

$$i_i=V_g/(2R_s) \qquad (14)$$

From (13) and (14), we have

$$|f_i(\Theta,\Phi)|^2=\frac{R_s}{4\pi}g_{i,\max}(\Theta,\Phi) \qquad (15)$$

Substituting (10) and (15) into (12), we get the gain function of the nmth dipole as

$$g_{nm}(\Theta,\Phi)=4R_sR_g\left|\sum_k\sum_l Y_{kl,nm}e^{-j\beta[(p_k-p_n)d_x u+(q_l-q_m)d_y v]}\right|^2 g_{i,\max}(\Theta, \qquad (16)$$

To find the mutual coupling effects on the gain function, the gain functions of dipoles (1,1), (1,6) and (5,6) in an 8×12 uniformly spaced (d_x=0.656λ_c, d_y=0,7572λ_c) rectangular array of dipoles in Fig. 1 are plotted in Figs. 2-4 in the E- and H-plane with the maximum gain of an isolated dipole above a ground plane as given in the following[ ]

$$g_{i,max}(\Theta,\Phi) = \frac{480}{R_s}\frac{\sin^2(\beta h\cos\Theta)\cos^2(\pi\sin\Theta\cos\Phi/2)}{1-\sin^2\Theta\cos^2\Phi} \tag{17}$$

where h is the height of the array above the ground plane, which is assumed to be $0.25\lambda_c$. It is shown that the gain function is symmetrical if the geometry of the dipole is symmetrical with respect to the E or H-plane (i.e., H-plane patten of (1,6); E and H-plane patterns of (5,6)) while it is not symmetrical if the dipole geometry is asymmetrical (i.e., E and H-plane patterns of (1,1); E-plane pattern of (1,6)).

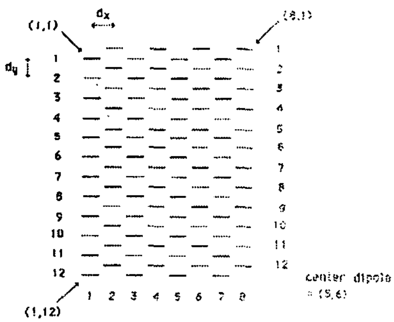

Fig. 7 An 8×12 rectangular array of dipoles with triangular grid geometry.

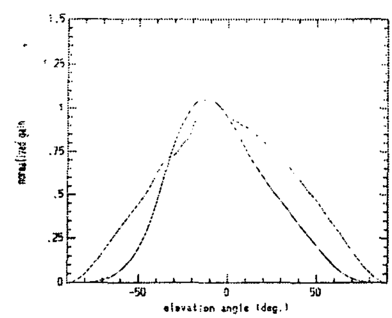

Fig. 7 Normalized gain functions of (1,1): E-plane (solid line); H-plane (dashed line).

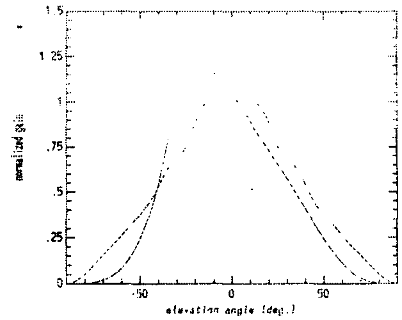

Fig. 8 Normalized gain functions of (1,6): E-plane (solid line); H-plane (dashed line).

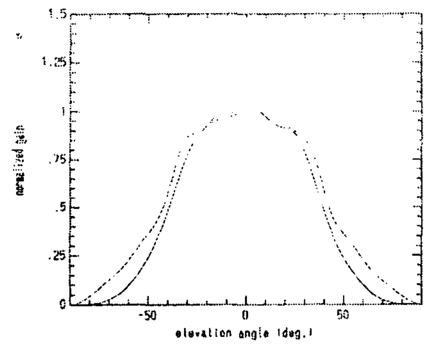

Fig. 9 Normalized gain functions of (5,6): E-plane (solid line): H-plane (dashed line).

One way of reducing the geometrical asymmetry of the edge or corner elements (or edge effects) is to taper the element spacing such that the inter-element spacing increases toward the edges in the x and $y$axis with specified center spacings. Two cases for d_{xc}=0.6λ_c, d_{yc}=0.7λ_c;d_{xc}=0.55λ_c, d_{yc}=0.65λ_c were used as the center spacings in the simulation. The array is space-tapered in such a way that the element spacings increase linearly and also symmetrically toward the four array sides. To illustrate, the spacings between neighboring elements n and $(n+1)$ from the center in the x and y directions are given by

$$d_{xn}=(1+n\,a_x)d_{xc} \tag{18}$$

and

$$d_{ym}=(1+n\,\alpha_y)d_{yc} \tag{19}$$

respectively. The ratios α_x and α_y are obtained from a given array size and center spacing d_{xc} and d_{yc} specified for each axis and are given by

$$\alpha_x=4(n_x-1)(d_x/d_{xc}-1)/[n_x(n_x-2)] \tag{20}$$

and

$$a_y=4(n_y-1)(d_y/d_{yc}-1)/[n_y(n_y-2)] \tag{20}$$

where n_x and n_y are the number of elements in the x and $y$axis respectively and assumed to be even and greater than two, and d_x and d_y are the inter-element spacings in the uniform array. The gain functions of dipoles (1,1), (1,6), and (5,6) in the space-tapered array are compared with the gain functions of the corresponding dipoles in the uniformly spaced array in the E-plane in Figs. 5-7. It is found that the extent of the asymmetry of the gain functions for the edge or corner dipoles reduces while the symmetry of the center dipole is maintained with reduced gain. The similar phenomena were observed in the H-plane.

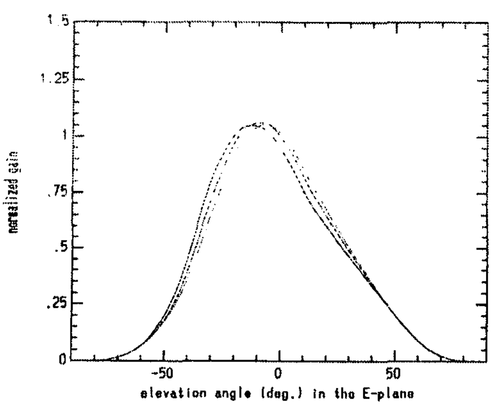

Fig. 10 Normalized gain functions of (1,1) in the E-plane; uniformly spaced (solid line); $d_{xc}=0.6\lambda_c$; $d_{yc}=0.7\lambda_c$ (dashed line); $d_{xc}=0.55\lambda_c$, $d_{yc}=0.65\lambda_c$ (dotted line).

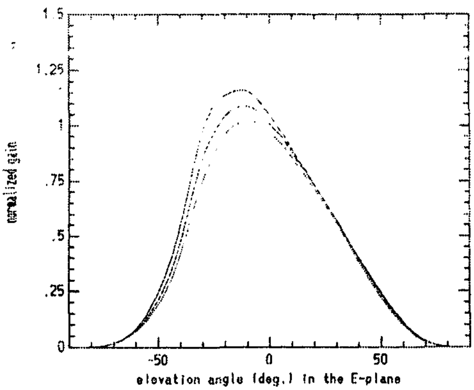

Fig. 11 Normalized gain functions of (1,6) in the E-plane; uniformly spaced (solid line); $d_{xc}=0.6\lambda_c$; $d_{yc}=0.7\lambda_c$ (dashed line); $d_{xc}=0.55\lambda_c$, $d_{yc}=0.65\lambda_c$ (dotted line).

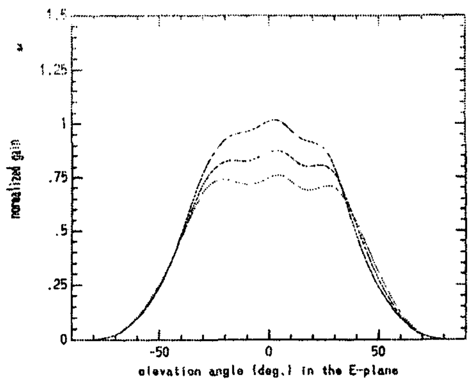

Fig. 12 Normalized gain functions of (5,6) in the E-plane; uniformly spaced (solid line); $d_{xc}=0.6\lambda_c$; $d_{yc}=0.7\lambda_c$ (dashed line); $d_{xc}=0.55\lambda_c$, $d_{yc}=0.65\lambda_c$ (dotted line).

3. Effects of Element Pattern on Beam Pattern

If the array is steered to (Θ_o, Φ_o), the generator voltage at the nmth dipole is given by

$$V_{g,nm}=a_{nm}e^{j\beta(p_n d_x u_o+p_m d_y v_o)} \tag{21}$$

where a_{nm} is a real amplitude at the nmth dipole.

Substituting (5) with (21) into (1), the array pattern is expressed as

$$H(\theta,\phi)=\sum_{n}\sum_{m} f_{nm}(\theta,\phi)\, Y_{nm,nm}\, a_{nm}\, e^{-j\beta[p_n d_x(u-u_o)+p_m d_y(v-v_o)]} \quad (22)$$

The beam pattern was generated by combining all the dipole patterns and the array factor over the array visual range. Another expression for the beam pattern can be obtained by substituting the dipole pattern in (10) into (22). Then we get

$$H(\theta,\phi)= f_i(\theta,\phi)\sum_{n}\sum_{m}\sum_{k}\sum_{l} a_{nm} Y_{kl,nm}\, e^{-j\beta[(p_k-p_n)d_x u+(q_l-q_m)d_y v]}\, e^{-j\beta[p_n d_x(u-u_o)+q_m d_y(v-v_o)]} \quad (23)$$

Assuming that a unit voltage is generated in each dipole, it can be shown that the beam pattern is given by

$$H(\theta,\phi)= f_i(\theta,\phi)\sum_{n}\sum_{m}\sum_{k}\sum_{l} Y_{kl,nm}\, e^{-j\beta[(p_k-p_n)d_x u+(q_l-q_m)d_y v]}\, e^{-j\beta[p_n d_x(u-u_o)+q_m d_y(v-v_o)]} \quad (24)$$

The beam patterns with mutual coupling effects based on (24) are compared with those without mutual coupling effects in the E-plane in Figs. 8-10. It is shown that the performance of sidelobe level improved and also the difference between the sidelobe level without and with mutual coupling effects increased as the extent of space-tapering increased. The beam patterns of the uniformly spaced and space-tapered arrays are compared in the E and H-plane in the presence of mutual coupling effects in Figs. 11. It is observed that the overall sidelobe level gets lowered in the space-tapered array while the first sidelobe is reduced more significantly than other sidelobes in the space-tapered array compared to the uniformly spaced array.

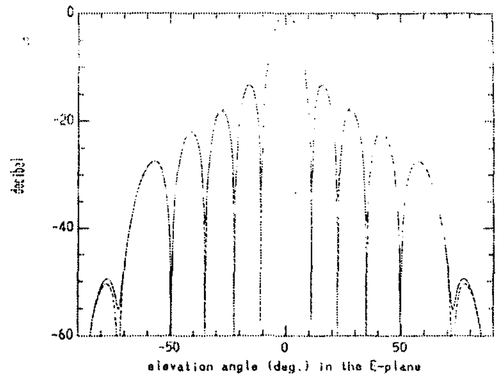

Fig. 13 Beam patterns in the E-plane for uniformly spaced dipoles; without (dashed line) and with (solid line) mutual coupling effects.

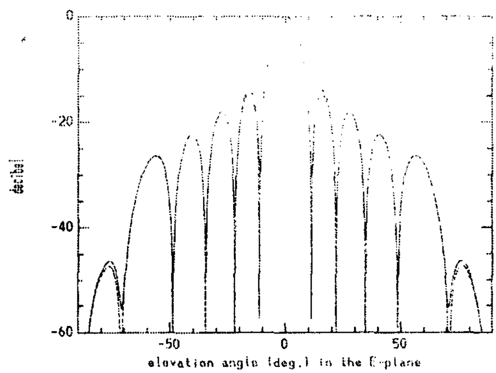

Fig. 14 Beam patterns in the E-plane for d_{xc}=0.6λ_c, d_{yc}=0.7λ_c; without (dashed line) and with (solid line) mutual coupling effects.

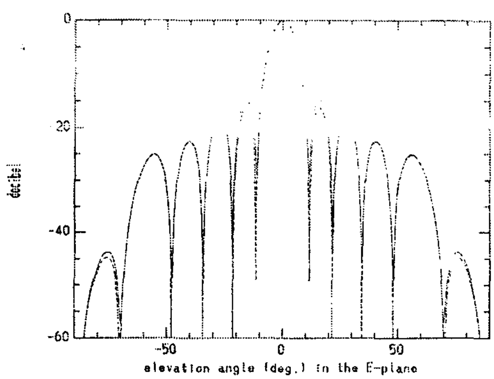

Fig. 15 Beam patterns in the E-plane for d_{xc}=0.55λ_c, d_{yc}=0.65λ_c; without (dashed line) and with (solid line) mutual coupling effects.

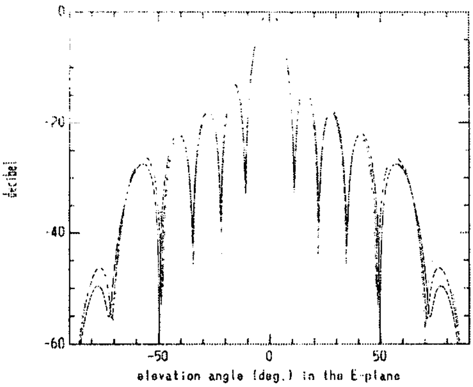

Fig. 16 Beam patterns with mutual coupling in the E-plane; $(\theta_o, \phi_o)=(0°, 0°)$. uniformly spaced dipoles (solid line); $d_{xc}=0.6\lambda_c$, $d_{yc}=0.7\lambda_c$(dashed line); $d_{xr}=0.55\lambda_r$, $d_{yr}=0.65\lambda_r$(dotted line).

4. Conclusions

Mutual coupling effects in a rectangular phased array of dipoles with triangular grid geometry above a ground plane were investigated in terms of element pattern and sidelobe level. The dipole gain function was examined to find the mutual coupling effects in a finite array geometry. It was shown that the element pattern became asymmetrical due to the array geometry.

A space tapering approach was introduced to improve the sidelobe performance. It was shown that the edge effects were reduced and the sidelobe level decreased in the space-tapered array compared with the uniformly spaced array. It was shown that the sidelobe level variation was not much noticeable around the mainbeam in the presence of mutual coupling in the uniformly spaced array while the mutual coupling effects are more evident in the space-tapered array.

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