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Mutual-Coupling Compensation in Time-Modulated Antenna Arrays for Flat-Top Pattern Synthesis

GANG LI,[1] SHIWEN YANG,[1] GUICHANG WANG,[1] and
ZAIPING NIE[1]

[1]Department of Microwave Engineering, School of Electronic Engineering
University of Electronic Science and Technology of China, Chengdu,
P.R. China

Abstract *A method that can be used to compensate for the mutual-coupling effect in time-modulated antenna arrays for synthesizing flat-top patterns is proposed in this article. Based on the measured complex embedded element patterns, the differential evolution algorithm is employed to optimize time sequences and phase excitation of each element in the array and to suppress the sideband level, leaving the amplitude excitations to be uniform. A −20-dB sidelobe level flat-top pattern is successfully synthesized in which the ripple level of the mainlobe is lower than 0.5 dB and the sideband level is lower than −10 dB. An S-band eight-element printed dipole with a double-layered structure linear array is used in the experiment to verify the proposed method, and the measured results are in good agreement with the simulated results.*

Keywords antenna arrays, time modulation, mutual coupling, differential evolution

Introduction

The problem of synthesizing an antenna pattern for a particular application has been receiving much attention since antennas were first introduced at the end of the 19th century. In recent years, shaped patterns are widely used in communication systems and electronic countermeasures. Numerous methods have been proposed over the years for synthesizing shaped patterns such as the Orchard method (Orchard et al., 1985), the Woodward-Lawson method (Stutzman & Thiele, 1998), and the optimization methods (Cid et al., 1999; Gies & Rahmat-Samii, 2003). However, such methods usually have higher amplitude excitation dynamic range ratios for synthesizing patterns with low sidelobe levels (SLLs), which may lead to stringent error tolerance requirements in practical implementation.

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Address correspondence to Shiwen Yang, Department of Microwave Engineering, School of Electronic Engineering, University of Electronic Science and Technology of China (UESTC), Chengdu, 610054, P.R. China. E-mail: swnyang@uestc.edu.cn

Time-modulated antenna arrays were proposed for synthesizing low sidelobe patterns since they only require very low excitation dynamic range ratios or even a uniform excitation as compared to conventional antenna arrays (Kummer et al., 1963; Bickmore, 1966; Yang et al., 2004, 2005a, 2005b). Moreover, time-modulation technology can be used to synthesize shaped patterns with low excitation amplitude ratios (Yang et al., 2003). However, the performance of shaped patterns of time-modulated antenna arrays is still strongly affected by the existence of the mutual-coupling effect among array elements, similar to those issues in the conventional arrays. The amplitude and phase characteristics of the antenna array elements are affected by the mutual coupling, which will distort the shaped power patterns. Thus, the compensation of mutual coupling in time-modulated antenna arrays should be taken into consideration.

In conventional antenna arrays, many methods have been proposed to compensate the mutual-coupling effects. Steyskal and Herd (1990) proposed a simple mutual-coupling compensation method by assuming that the element currents may change in amplitude but not in shape. Thus, only the input impedances of the array elements are different from each other, and the principle of pattern multiplication still applies. The mutual-coupling coefficients can be obtained by using Fourier decomposition of the measured array element patterns. Fletcher and Dean (1996) proposed a point-matching technique by using experimental data of element patterns. By point matching, the nulls of a desired pattern in the presence of mutual coupling and the complex weights of the elements can be determined. Yang and Nie (2005) adopted the differential evolution (DE) algorithm to compensate mutual-coupling effects for the synthesis of low sidelobe sum patterns in time-modulated antenna arrays. By using measured complex embedded element patterns, a −30-dB SLL discrete Taylor pattern was successfully realized in the experiment (Yang & Nie, 2005).

In this article, the DE algorithm (Qing, 2003; Chen et al., 2008) is employed to compensate the mutual-coupling effects in the time-modulated linear array for synthesizing a flat-top pattern that matches a standard flat-top pattern. An S-band eight-element linear array with the center frequency $f_0 = 3.25$ GHz and $\lambda/2$ space between elements was used to validate the proposed method. A target pattern of a −20-dB SLL flat-top pattern is successfully realized, in which the ripple level of the flat top is lower than 0.5 dB and the sideband level (SBL) is lower than −10 dB.

Compensation Method

Let us consider an N-element linear array of equally spaced identical dipole elements in which each element is controlled by a high-speed radio frequency (RF) switch. Suppose that the time-modulation period is T_p; the far-field power pattern of the array can be written by (Yang et al., 2005a)

$$E(\theta, \varphi, t) = e_0(\theta, \varphi) e^{j2\pi f_0 t} \sum_{k=1}^{N} A_k e^{j\alpha_k} U_k(t) \cdot e^{j(k-1)\beta d \sin\theta}, \tag{1}$$

where f_0 is the center frequency of the antenna array, A_k and α_k are the static excitation amplitude and phase of the kth element, respectively, d is the element spacing, $\beta = 2\pi f_0/c$, c is the velocity of light in free space, θ is the angle measured from broadside, $e_0(\theta, \varphi)$ is the element pattern factor, and $U_k(t)$ is the periodic switch-on time sequence.

The time-modulation scheme of the variable aperture size (VAS) is adopted in this article, and $U_k(t)$ is given by (Yang et al., 2004)

$$U_k(t) = \begin{cases} 1, & 0 \le t \le \tau_k \\ 0, & \text{otherwise} \end{cases}, \tag{2}$$

where τ_k is the switch-on time interval of the kth element. Due to that, $U_k(t)$ is a periodic function of time, the space and frequency response of Eq. (1) can be obtained by decomposing it into a Fourier series, and each frequency component has a frequency of n/T_p ($n = 0, \pm 1, \ldots, \pm\infty$). The nth order Fourier component is given by

$$E_n(\theta, \varphi) = e_0(\theta, \varphi) \sum_{k=1}^{N} a_{nk} \cdot e^{j[(k-1)\beta d \sin\theta + \alpha_k]}, \tag{3}$$

where the complex amplitude a_{nk} can be expressed as

$$a_{nk} = \frac{A_k \tau_k}{T_p} \cdot \frac{\sin[\pi n \tau_k / T_p]}{\pi n \tau_k / T_p} \cdot e^{-j\pi n \tau_k / T_p}. \tag{4}$$

At the center frequency ($n = 0$), we have

$$a_{nk} = \frac{A_k \tau_k}{T_p}. \tag{5}$$

Thus, shaped patterns can be synthesized at the center frequency.

However, the above analysis does not take into account mutual coupling. When synthesizing actual patterns, the mutual-coupling effects should be considered. According to Eqs. (3) to (5), the complex weighting of each element at the center frequency can be given by

$$g_k = A_k \frac{\tau_k}{T_p} e^{j\alpha_k}. \tag{6}$$

Suppose that $\tilde{A}_k$, $\tilde{\alpha}_k$, and $\tilde{\tau}_k$ are the compensated static amplitude, phase, and switch-on time interval of the kth element, respectively; then the compensated complex weighting can be written by (Yang & Nie, 2005)

$$\tilde{g}_k = \tilde{A}_k \frac{\tilde{\tau}_k}{T_p} e^{j\tilde{\alpha}_k}. \tag{7}$$

Consequently, the complex excitation vector $\mathbf{g} = \{\tilde{g}_k, (k = 1, 2, \ldots, N)\}$ should be determined. For a uniform static amplitude excitation, the amplitude excitation $\tilde{A}_k$ for all elements are the same. When $\mathbf{g}$ is determined, $\tilde{\tau}_k$ and $\tilde{\alpha}_k$ can be obtained accordingly.

In order to determine **g**, the complex pattern measurement of each embedded element in the array should be taken when all the other elements terminated with matched loads. Consequently, the entire array pattern after compensating mutual coupling can be obtained as a linear summation of the measured element patterns, given by

$$E(\mathbf{g}, \theta) = \sum_{k=1}^{N} \tilde{g}_k E_k(\theta). \tag{8}$$

The DE algorithm can be used to match the actual pattern with the desired pattern $E_d(\theta)$ in the H-plane in order to suppress the SLLs lower than a specified level and to keep the SBLs as low as possible. Thus, the optimized complex weighting vector $\mathbf{g}$ can be obtained with the cost function given by

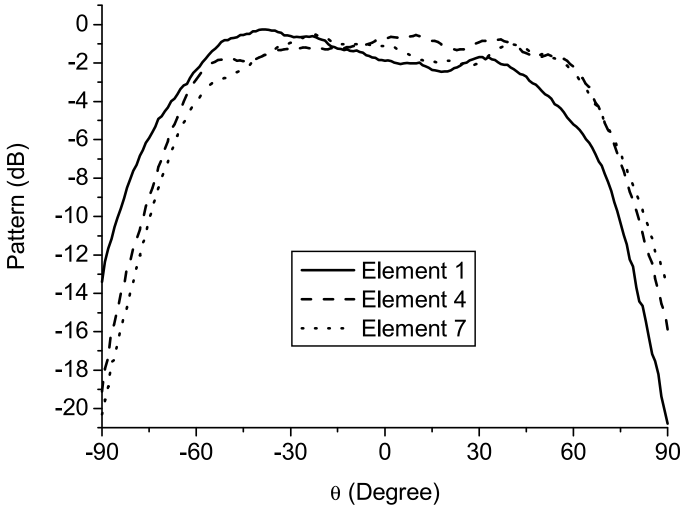
$$f^{(n)}(\mathbf{g}) = w_1 \cdot \sqrt{\sum_{i=1}^{M} |E_d(\theta_i) - E^{(n)}(\mathbf{g}, \theta_i)|^2} \\ + w_2 \cdot (SLL_{\max}^{(n)}(\mathbf{g}) - SLL_0)|_{f_0} + w_3 \cdot SBL_{\max}^{(n)}(\mathbf{g})|_{f_0+f_p}, \qquad (9)$$

where n is the number of evolution generations, M is the number of specified elevation angles within the interested range, and $f_p = 1/T_p$. $SLL_{\max}$ is the calculated maximum SLL at the center frequency, and SLL_0 is the specified SLL. $SBL_{\max}$ is the calculated maximum SBL. The corresponding weighting factors for each term are represented by w_1 to w_3, in which w_2 will be zero when $SLL_{\max}$ is lower than SLL_0 in flat-top patterns.

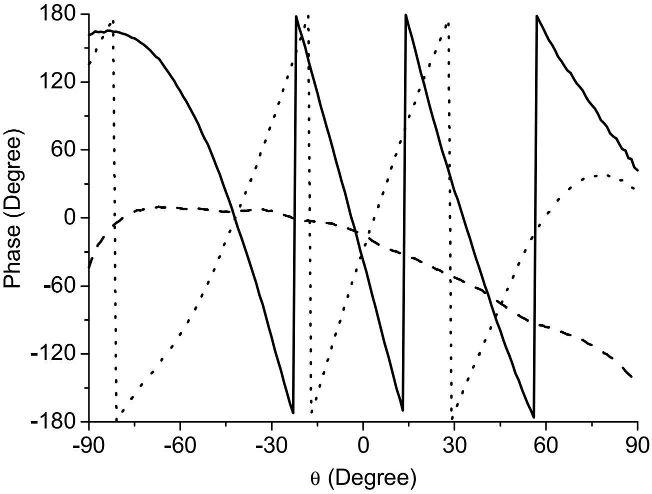
Experimental Results

To validate the proposed method, an S-band eight-element linear array with a center frequency of 3.25 GHz and $\lambda/2$ spacing between the adjacent dipole elements was used. The element used in the array is a printed dipole with a double-layered structure (Zhou et al., 2007). The feed network was composed of a power divider, eight attenuators, eight phase shifters, and eight high-speed RF switches. The single-pole–single-throw absorptive RF switch has a switching time of less than 15 ns, and the isolation is greater than 50 dB when it is off. A digital complex programmable logic device (CPLD) card generates the required time sequences to control the high-speed RF switches.

The time-modulated linear array with static uniform amplitude excitation is used to realize a −20-dB SLL flat-top pattern in which the ripple level is lower than 0.5 dB. First, the eight complex embedded element patterns were measured to show the mutual-coupling effect in time-modulated antenna arrays. Figure 1 plots the measured amplitude and phase patterns of three elements numbered 1, 4, and 7. Obviously, each of the element patterns is different, and the patterns of the edge elements become asymmetric. Thus, the effects of mutual coupling can be observed clearly. In addition, some fabrication error and measurement error also contributed to the asymmetry of the measured complex embedded element patterns, which should also be considered in pattern synthesis. Then, the mutual-coupling compensation method is applied to realize the target pattern using the measured complex embedded element patterns. The time-modulation period T_p is set to be 10 μs. The compensated switch-on time sequences in one period and compensated phase excitations are plotted in Figures 2(a) and 2(b), respectively. It is observed that the compensated switch-on time sequences are not symmetric about the array center. The comparison of the simulated and measured far-field pattern with mutual-coupling compensation at 3.25 GHz for a target −20 dB SLL flat-top pattern is shown in Figure 3. As can be seen, the measured pattern is in good agreement with the simulated pattern. The measured relative SLL is −20.1 dB, which is quite close to the target SLL of −20 dB, and the measured ripple level of the flat-top is less than 0.5 dB. The first two sideband patterns were also measured. The measured



(a)

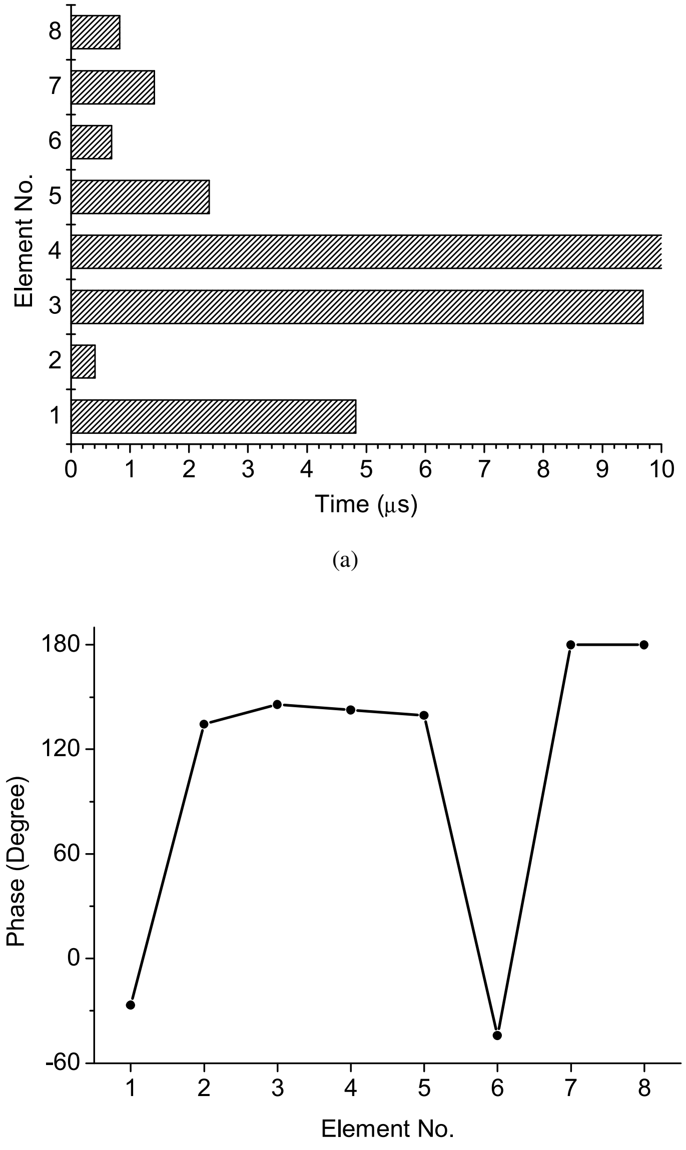


(b)

Figure 1. Measured complex embedded element patterns: (a) normalized amplitude patterns and (b) phase patterns.

relative sideband patterns at $f_0 + f_p$ and $f_0 + 2f_p$, in comparison with those simulated patterns with mutual-coupling compensation, are shown in Figure 4. The measured results are also in good agreement with simulated results. The measured SBL of the compensated time-modulated linear array is 9.7 dB, which is just 0.3 dB greater than the simulated SBL.

In order to demonstrate the effectiveness of the mutual-coupling compensation method, the time-modulated linear array is excited with uniform amplitude without mutual-coupling compensation. Figure 5 shows the switch-on time sequences and phase



(a)

(b)

Figure 2. Compensated excitations of the time-modulated linear array: (a) compensated switch-on time sequences and (b) compensated phases.

excitations determined using the approach proposed in Yang et al. (2003) for synthesizing a −20-dB SLL flat-top pattern. The simulated and measured flat-top patterns at 3.25 GHz without mutual-coupling compensation are shown in Figure 6. It is observed that there is a distinct difference between the measured pattern and the target pattern, especially at the sidelobe region. The measured SLL is −18.4 dB, and the measured mainlobe is not flat enough as compared to the simulated results.

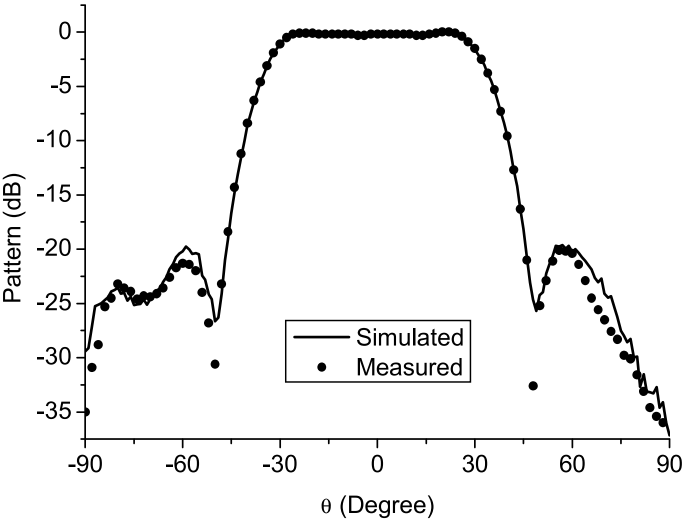


Figure 3. Comparison of the measured pattern and the simulated pattern with mutual-coupling compensation at 3.25 GHz.

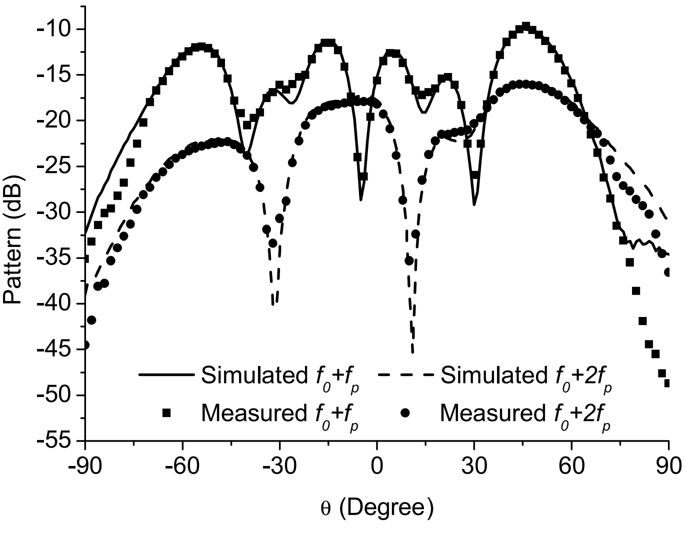


Figure 4. Comparison of the measured sideband patterns and the simulated sideband patterns.

Conclusions

A mutual-coupling compensation method for synthesizing a flat-top pattern is proposed in this article. The measured complex embedded element patterns are used to determine the compensated switch-on time sequences and phase excitation by the DE algorithm. An S-band eight-element two-layered printed dipole linear array is used to verify the proposed method. A −20-dB SLL flat-top pattern with a 0.5-dB ripple level is successfully obtained in the experiment, thus confirming the effectiveness of the mutual-coupling

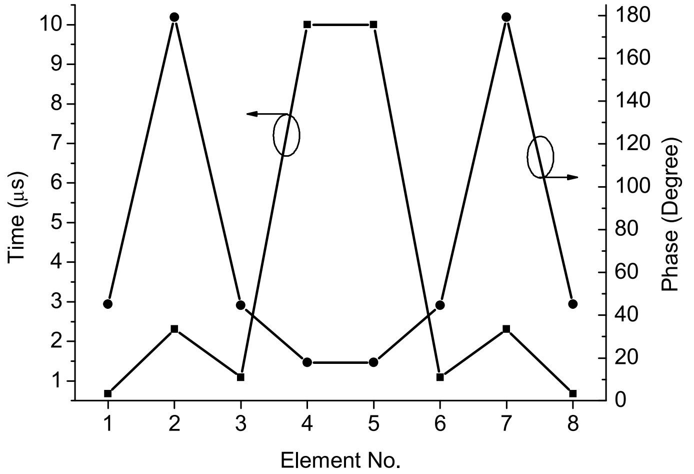


Figure 5. Switch-on time sequences and phase excitation of the time-modulated linear array for a −20-dB SLL flat-top pattern without mutual coupling.

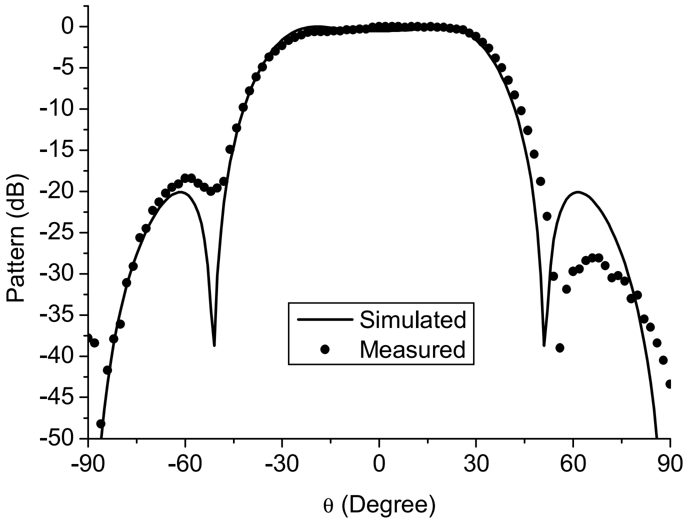


Figure 6. Comparison of the measured pattern and the simulated pattern without mutual-coupling compensation at 3.25 GHz.

compensation approach for the synthesis of flat-top patterns from time-modulated antenna arrays.

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