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RESEARCH ARTICLE

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Shaped patterns synthesis in time-modulated antenna arrays with static uniform amplitude and phase excitations

Abstract A novel approach for the synthesis of shaped beam patterns in time-modulated antenna arrays (TMAAs) with static uniform amplitude and phase excitations is proposed in this paper. Based on the sideband radiation in TMAAs, shaped beam patterns can be realized by only controlling the switch-on time sequences of the TMAAs. Differential evolution (DE) algorithm is adopted to optimize the time modulation parameters to obtain the desired flat-top and cosecant-squared beams and to suppress the sidelobe levels (SLLs). Simulation results of a time-modulated linear array (TMLA) and a time-modulated semicircular array (TMSA) demonstrate the effectiveness of the proposed approach for the synthesis of shaped beam patterns from TMAAs.

Keywords antenna arrays, time modulation, shaped pattern, differential evolution

1 Introduction

As one of the most important issues in many applications including radar systems and wireless communications, the problem of shaped beam patterns synthesis has been receiving much attention over several years, and various techniques have been presented to solve this problem [1–9]. The main idea of these techniques is to determine element positions, amplitude, and/or phase excitations by which the radiation pattern can well approximate a desired pattern. However, for synthesizing certain patterns with some stringent requirements, such as low sidelobe levels (SLLs) and sharp transitions, the dynamic range ratio of their amplitude excitations is usually quite high, which results in stringent error tolerance requirements in practice. Furthermore, the phase shifters widely used in phased arrays to control phase excitations of each element not only have higher insertion loss but also bring the problem of quantization errors of phase shift. To overcome these problems, the time modulation technique is utilized to synthesize shaped patterns in this paper.

Time-modulated antenna arrays (TMAAs) were first proposed to synthesize low SLLs patterns, which can be used to reduce the dynamic range ratios of amplitude excitations considerably [10,11]. In recent years, many studies on TMAAs have been proposed due to their attractive features in the design of low/ultra-low SLLs [12–19]. In TMAAs, each element is connected with a high-speed radio frequency (RF) switch, which can be used to control the time modulation parameters easily and flexibly. Due to the time modulation, there are many sideband signals spaced at multiples of the time modulation frequency, which imply that part of the radiated or received energy is shifted to the sideband. It is generally agreed that sideband signals may not be desirable and should be suppressed to improve the efficiency of the antenna array [11–20]. However, sideband signals are not always harmful to TMAAs. By designing appropriate time sequences of each element, sideband radiation can be used in some special applications. Reference [21] proposed a simultaneous scanning operation based on time modulation technology where the beams at different sidebands were used to point at different directions. A two-element time-modulated antenna array with direction finding properties was proposed in Ref. [22]. By adjusting the switching on times of the both elements, the electronic null scanning can be realized at the first sideband. In a type of hybrid analog-digital beamforming structure based on time-modulated linear arrays (TMLAs), the adaptive beamforming can be achieved at the first sideband [23].

This paper presents a new approach for the synthesis of flat-top beam and cosecant-squared beam patterns in TMLAs and time-modulated semicircular arrays (TMSAs) with uniform static amplitude and phase excitations. The

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synthesis can be achieved at the first sideband by only using RF switches to control the switch-on time instant and the duration of "on" times without using phase shifters, which is substantially different from the method proposed in Ref. [13], where the phase shifters are needed to achieve phase excitations in TMLAs to synthesis shaped patterns. Differential evolution (DE) algorithm [24–30] is used to optimize the time modulation parameters to make the synthesized power patterns closely approximate the desired patterns.

2 Theory

In this section, the approach for synthesizing shaped patterns in TMLAs and TMSAs with uniform static amplitude and phase excitations is presented, and the cost functions used in the DE algorithm are introduced.

2.1 Shaped beam patterns synthesis in TMLAs

Consider an N-element linear array of equally spaced isotropic elements, which is shown in Fig. 1. It is assumed that each element is connected with a high-speed RF switch, and the array factor can be written as [11]

$$F^l(\theta,t) = \mathrm{e}^{\mathrm{j}2\pi f_0 t}\sum_{k=1}^{N} A_k \mathrm{e}^{\mathrm{j}\alpha_k} U_k(t) \mathrm{e}^{\mathrm{j}(k-1)\beta d\sin\theta}, \tag{1}$$

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 denotes the element spacing of the array; $\beta = 2\pi f_0/c$, c is the velocity of light in free space; θ is the angle measured from the broadside direction of the array; and $U_k(t)$ is the time switching function. As shown in Fig. 2, the time switching function $U_k(t)$ for the kth element within one time modulation period T_p is given by

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

where t_{0k} is the switch-on time instant, and τ_k is the duration of "on" times.

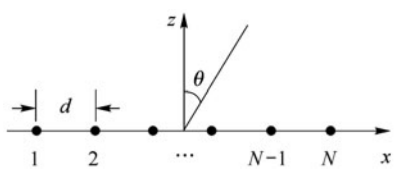

Fig. 1 Geometry of an equally spaced N-element linear array

Due to the periodicity of $U_k(t)$, the space and frequency response of Eq. (1) can be obtained by decomposing it into Fourier series, and each frequency component has a

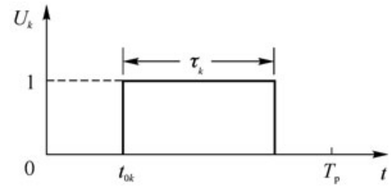

Fig. 2 Scheme of time switching function

frequency of n/T_p ($n = 0,\pm1,\pm2,\ldots,\pm\infty$). The nth order Fourier component can be written as

$$F_n^l(\theta,t) = \mathrm{e}^{\mathrm{j}2\pi(f_0+nf_\mathrm{p})t}\sum_{k=1}^{N} a_{nk}\cdot\mathrm{e}^{\mathrm{j}[(k-1)\beta d\sin\theta+\alpha_k]}, \tag{3}$$

where $f_\mathrm{p} = 1/T_\mathrm{p}$; a_{nk} is the complex amplitude and is given by

$$a_{nk} = A_k f_\mathrm{p}\tau_k \frac{\sin(n\pi f_\mathrm{p}\tau_k)}{n\pi f_\mathrm{p}\tau_k}\mathrm{e}^{-\mathrm{j}n\pi f_\mathrm{p}(2t_{0k}+\tau_k)}. \tag{4}$$

According to Eqs. (3) and (4), the array factors at the center frequency ($n = 0$) and the first sideband ($n = 1$) can be written as

$$F_0^l(\theta,t) = \mathrm{e}^{\mathrm{j}2\pi f_0 t}\sum_{k=1}^{N} A_k f_\mathrm{p}\tau_k\cdot\mathrm{e}^{\mathrm{j}[(k-1)\beta d\sin\theta+\alpha_k]}, \tag{5}$$

$$F_1^l(\theta,t) = \frac{\mathrm{e}^{\mathrm{j}2\pi(f_0+f_\mathrm{p})t}}{\pi}\sum_{k=1}^{N} A_k\sin(\pi f_\mathrm{p}\tau_k)\mathrm{e}^{-\mathrm{j}\pi f_\mathrm{p}(2t_{0k}+\tau_k)} \cdot\mathrm{e}^{\mathrm{j}[(k-1)\beta d\sin\theta+\alpha_k]}, \tag{6}$$

respectively.

In this paper, TMLAs are excited with the uniform static amplitude and phase distribution. Without loss of generality, let $A_k = 1$ and $\alpha_k = 0$ ($k = 1,2,\ldots,N$). The time modulation parameters t_{0k} and τ_k can be normalized in a time modulation period T_p. Thus, Eqs. (5) and (6) become

$$F_0^l(\theta,t) = \mathrm{e}^{\mathrm{j}2\pi f_0 t}\sum_{k=1}^{N} \xi_k\cdot\mathrm{e}^{\mathrm{j}[(k-1)\beta d\sin\theta]}, \tag{7}$$

$$F_1^l(\theta,t) = \frac{\mathrm{e}^{\mathrm{j}2\pi(f_0+f_\mathrm{p})t}}{\pi}\sum_{k=1}^{N}\sin(\pi\xi_k)\mathrm{e}^{-\mathrm{j}\pi(2\upsilon_k+\xi_k)}\cdot\mathrm{e}^{\mathrm{j}[(k-1)\beta d\sin\theta]}, \tag{8}$$

where $\xi_k = \tau_k/T_\mathrm{p}$ and $\upsilon_k = t_{0k}/T_\mathrm{p}$. By observing Eq. (7), the array factor at the center frequency f_0 is independent of υ_k, and the corresponding radiation pattern has its maximum at $\theta = 0°$. On the other hand, the terms $\sin(\pi\xi_k)$ and $\mathrm{e}^{-\mathrm{j}\pi(2\upsilon_k+\xi_k)}$ in Eq. (8) can be considered as the equivalent amplitude and phase excitations of the kth element, respectively. Thus, various iterative synthesis techniques or stochastic optimization algorithms can be applied in Eq. (8) to determine ξ_k and υ_k for synthesizing desired shape patterns.

2.2 Shaped beam patterns synthesis in TMSAs

In this section, the time modulation technology is extended to semicircular array for synthesizing shaped patterns in the plane of the array.

Consider a semicircular array of N isotropic elements equally spaced on the x-y plane shown in Fig. 3.

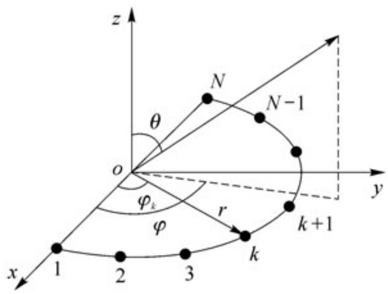

Fig. 3 Geometry of an N-element semicircular array with uniform spacing

Each element in the semicircular array is also connected with a high-speed RF switch, and the array factor can be written by

$$F^{\mathrm{s}}(\theta,\varphi,t)=\mathrm{e}^{\mathrm{j}2\pi f_0 t}\sum_{k=1}^{N}A_k\mathrm{e}^{\mathrm{j}\alpha_k}U_k(t)\cdot\mathrm{e}^{\mathrm{j}kr\sin\theta\cos(\varphi-\varphi_k)},\quad(9)$$

where r is the radius of the semicircular array; φ_k is the angular position of the kth element on the x-y plane and is given by

$$\varphi_k=\frac{k-1}{N-1}\pi.\quad(10)$$

Other parameters are the same as those in Eq. (1). By decomposing Eq. (9) into Fourier series, the array factor at the center frequency and the first sideband can be obtained and are written by

$$F_0^{\mathrm{s}}(\theta,\varphi,t)=\mathrm{e}^{\mathrm{j}2\pi f_0 t}\sum_{k=1}^{N}A_k f_{\mathrm{p}}\tau_k\cdot\mathrm{e}^{\mathrm{j}[kr\sin\theta\cos(\varphi-\varphi_k)+\alpha_k]},\quad(11)$$

$$F_1^{\mathrm{s}}(\theta,\varphi,t)=\mathrm{e}^{\mathrm{j}2\pi(f_0+f_{\mathrm{p}})t}\sum_{k=1}^{N}\frac{A_k}{\pi}\sin(\pi f_{\mathrm{p}}\tau_k)\mathrm{e}^{-\mathrm{j}\pi f_{\mathrm{p}}(2t_{0k}+\tau_k)}\cdot\mathrm{e}^{\mathrm{j}[kr\sin\theta\cos(\varphi-\varphi_k)+\alpha_k]}.\quad(12)$$

Considering the condition of uniform static amplitude and phase excitations, and by normalizing τ_k and t_{0k} in a time modulation period, Eqs. (11) and (12) become

$$F_0^{\mathrm{s}}(\theta,\varphi,t)=\mathrm{e}^{\mathrm{j}2\pi f_0 t}\sum_{k=1}^{N}\xi_k\cdot\mathrm{e}^{\mathrm{j}[kr\sin\theta\cos(\varphi-\varphi_k)]},\quad(13)$$

$$F_1^{\mathrm{s}}(\theta,\varphi,t)=\frac{\mathrm{e}^{\mathrm{j}2\pi(f_0+f_{\mathrm{p}})t}}{\pi}\sum_{k=1}^{N}\sin(\pi\xi_k)\mathrm{e}^{-\mathrm{j}\pi(2\upsilon_k+\xi_k)}\cdot\mathrm{e}^{\mathrm{j}[kr\sin\theta\cos(\varphi-\varphi_k)]}.\quad(14)$$

By observing Eq. (13), the direction of maximum radiation at the center frequency is at $\theta=0°$ but not in x-y plane. Comparing Eq. (14) to Eq. (8), it is obvious that they have the similar form, and by designing appropriate ξ_k and υ_k, the shaped patterns can be synthesized in the x-y plane.

2.3 Differential evolution algorithm

DE algorithm is a type of evolution algorithm that can be used to perform global optimization, and it has already been proven to be an efficient optimization approach in many areas, such as electromagnetic inverse scattering [25], array pattern synthesis [26,27], and some design problems [28–30].

In this paper, DE algorithm is adopted to optimize time modulation parameters (ξ_k and υ_k) to synthesize flat-top and cosecant-squared beam patterns. Thus, the optimization parameter vector is $v=\{\xi_k,\upsilon_k\}$. The search range of ξ_k is [0, 0.5], which can guarantee that $\sin(\pi\xi_k)$ in Eqs. (8) and (14) varies in the range of [0, 1]. In order to make sure that $-\pi(2\upsilon_k+\xi_k)$ varies from $-\pi$ to π that the search range of ξ_k should be $[-0.5, 0.5]$. For synthesizing flat-top and cosecant-squared beam patterns, the cost functions in DE algorithm are selected as

$$f_{\text{flat-top}}^{(n)}(v)=w_1\mathrm{Ripple}_{\max}^{(n)}(v)+w_2\frac{\beta_{\mathrm{TRANS}}^{(n)}(v)}{90^{\circ}}+w_3[\mathrm{SLL}_{\max}^{(n)}(v)-\mathrm{SLL}_0],\quad(15)$$

$$f_{\mathrm{cosec}^2}^{(n)}(v)=w_1\mathrm{Ripple}_{\max}^{(n)}(v)+w_2\frac{\beta_{\mathrm{TRANS}}^{(n)}(v)}{90^{\circ}}+w_3[\mathrm{SLL}_{\max}^{(n)}(v)-\mathrm{SLL}_0]+w_4[\beta_{\mathrm{c}}^{(n)}(v)-\beta_0],\quad(16)$$

where n denotes the nth generation evolution; $\mathrm{Ripple}_{\max}$, β_{TRANS}, and $\mathrm{SLL}_{\max}$ are calculated maximum ripple level, transition width, and SLL at the first sideband, respectively; β_{c} is the calculated direction of the maximum power radiation; SLL_0 and β_0 are desired sidelobe level and direction of maximum radiation in desired plane; w_1-w_4 are the corresponding weighting factors of each term.

3 Numerical results

First, consider a 20-element TMLA with a uniform element space of $\lambda/2$. The target is to synthesize a flat-top beam pattern of 40° in width at the broadside, with a ripple level $\leqslant$ 0.5 dB, the narrowest transition, and SLL $\leqslant$ −20 dB. Figure 4 shows the DE optimized time sequences for the target flat-top beam pattern, where the shaded bars indicate that the RF switch is on. The corresponding power patterns are shown in Fig. 5. As can be seen, the power pattern at the first sideband successfully satisfies the design requirements.

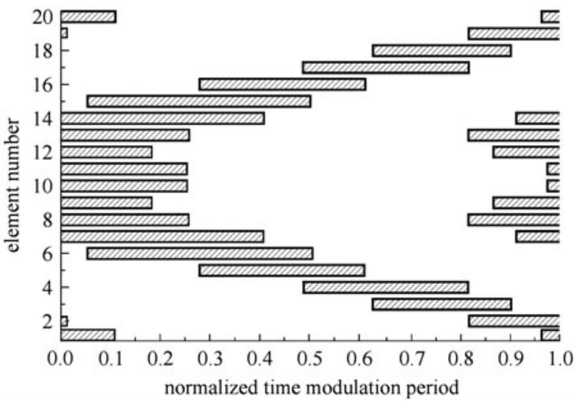

Fig. 4 DE optimized time sequences for a flat-top beam pattern in TMLA

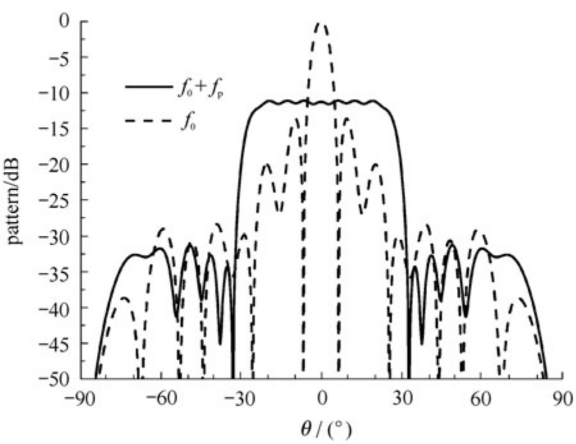

Fig. 5 Normalized power patterns at the center frequency and the first sideband with time sequences in Fig. 4

The next desired shaped pattern to be synthesized in the TMLA is a cosecant-squared beam pattern with ripple level $\leqslant$ 0.5 dB, SLL $\leqslant$ −20 dB, the narrowest transition, and the 3 dB beamwidth is 45°. The time sequences optimized by DE algorithm for the cosecant-squared beam pattern are shown in Fig. 6, and the normalized power patterns at the center frequency and the first sideband are plotted in Fig. 7. It is observed that the required shaped pattern is

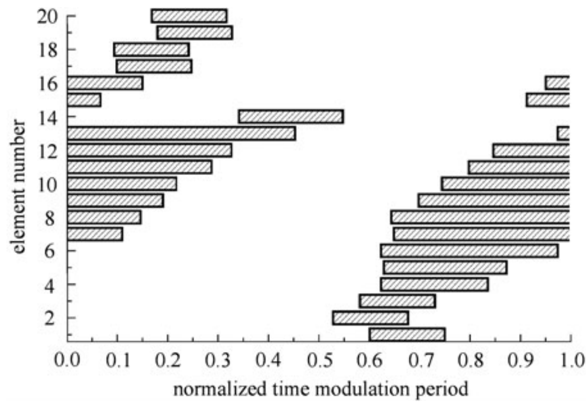

Fig. 6 DE optimized time sequences for a cosecant-squared beam pattern in TMLA

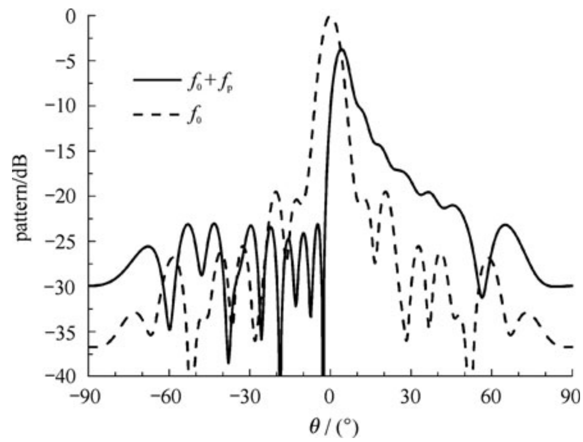

Fig. 7 Normalized power patterns at the center frequency and the first sideband with time sequences in Fig. 6

successfully synthesized at the first sideband, and the maximum sideband level (SBL) is only −3.7 dB as compared to the pattern at the center frequency. In practical application, the signals received by the patterns at the center frequency and the first sideband in TMLA can be separated and drawn by using band-pass filters as long as the time modulation frequency f_p is not lower than the bandwidth of the received signal.

Second, a $\lambda/2$-spaced TMSA of 20 isotropic elements is considered. The flat-top and cosecant-squared beam patterns with the same requirements as those in previous examples are synthesized in TMSA. Figure 8 shows the DE algorithm optimized time sequences of each element for synthesizing the flat-top beam pattern at the first sideband, and the corresponding power patterns are plotted in Fig. 9. It can be seen that desired flat-top beam pattern is obtained in TMSA by using the proposed approach, the SBL is only 2.3 dB lower than that at the center frequency in x-y plane.

Figures 10 and 11 present the time sequences obtained by DE algorithm for a cosecant-squared beam pattern and

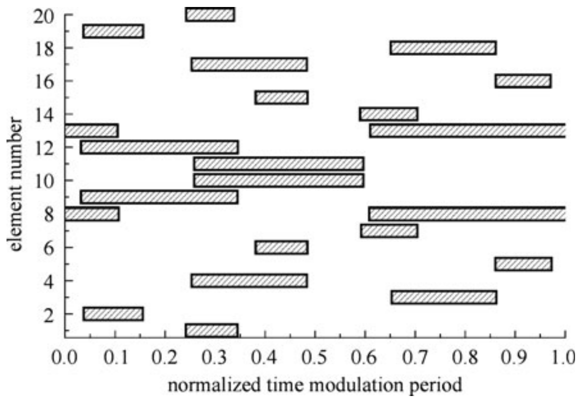

Fig. 8 DE optimized time sequences for a flat-top beam pattern in TMSA

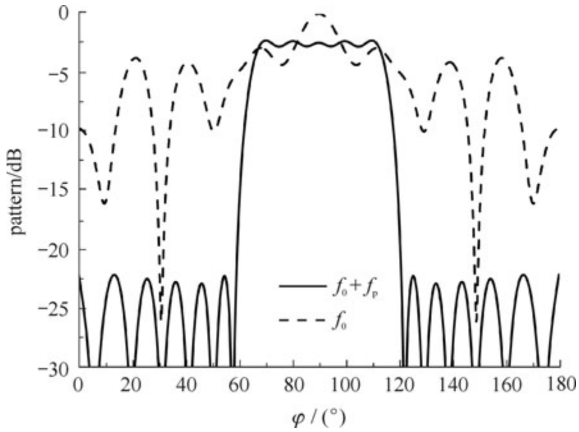

Fig. 9 Normalized power patterns at the center frequency and the first sideband with time sequences in Fig. 8

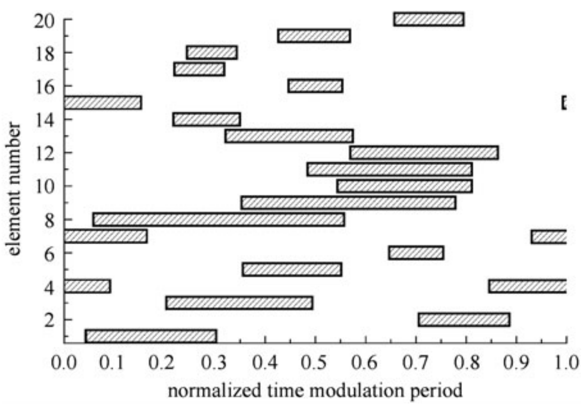

Fig. 10 DE optimized time sequences for a cosecant-squared beam pattern in TMSA

their corresponding power patterns, respectively. The desired pattern is also successfully synthesized. According to Eqs. (13) and (14), when the shaped beam pattern is synthesized at the first sideband in TMSA in *x-y* plane, the mainlobe of the pattern at the center frequency is always at $\theta = 0°$, which is perpendicular to that of the pattern at the first sideband. Thus, the patterns at the center frequency and the first sideband can be used to receive signals arriving from different directions, and they can also be separated and drawn according to the discussion in the examples of TMLA.

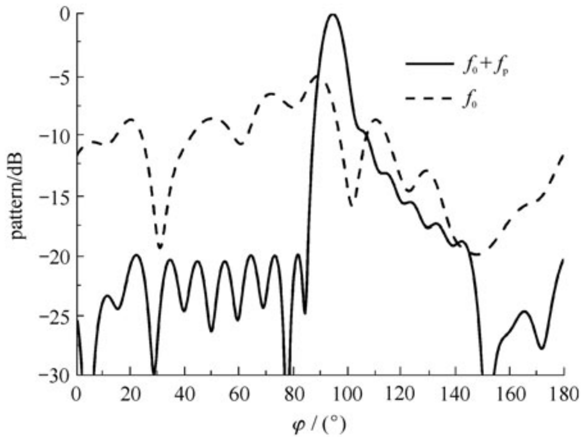

Fig. 11 Normalized power patterns at the center frequency and the first sideband with time sequences in Fig. 10

4 Conclusion

In this paper, the time modulation technique is applied to linear arrays and semicircular arrays for synthesizing fat-top and cosecant-squared beam patterns with the uniform static amplitude and phase distributions. By only controlling the time modulation parameters (switch-on time instant and duration of "on" times), the desired patterns can be synthesized at the first sideband. Theoretical analysis shows that the time modulation can be used to provide equivalent amplitude and phase excitation at the first sideband for pattern synthesis, which can also be used to simplify the feed network of antenna arrays. Numerical simulation results show that flat-top and cosecant-squared beam patterns can be successfully synthesized at the first sideband, thus demonstrating the effectiveness of the proposed approach.

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