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Review

Time Modulated Array Antennas: A Review

Wen Wu, Qiaoyu Chen, Jin-Dong Zhang, Tongde Huang, and Da-Gang Fang

Laboratory of Near-Range RF Sensing ICs & Microsystems (NJUST), Ministry of Education, School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

Corresponding author: Wen Wu, Email: wuwen@njust.edu.cn.
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Abstract — Time-modulated array (TMA) antennas, introduce the dimension of time into antenna design to control the radiation patterns and frequency spectral characteristics, thus improve the reconfigurability of array antennas and provide multiple functionalities. They have great application potential in military and civilian fields, such as precision guidance and mobile communication, and are currently a hot spot of academic research. This article provides a review on the fundamentals and applications of TMAs. First, the basic theory and mathematical formulations of TMAs are introduced. Second, the most important applications of TMAs, namely time-modulated phased arrays (TMPA), are discussed from the perspectives of harmonic suppression and harmonic utilization, which are used for single-beam and multibeam radiation. Then, we survey the combination of TMA with various types of novel antenna arrays, such as single-channel digital beamforming (DBF) arrays, frequency diverse arrays (FDAs), and retrodirective arrays, to create new hardware implementation methods and enhance their performance. Next, recent advances in dedicated integrated chips for TMA, which have played a significant role in driving the progress of TMAs from academic research to practical applications, are presented. Finally, the challenges and prospects for TMAs are discussed, including new research directions and emerging application scenarios.

Keywords — Time modulated array, Phased array, Single RF channel digital beam forming, Frequency diversity array, Retrodirective arrays, Chips.

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I. Introduction

Time-modulated array (TMA) antennas [1]–[4], also known as 4D array antennas, introduce the time dimension into operation of antennas based on three-dimensional principles. This approach allows the antenna elements to be controlled by a time-modulated circuit, which affects their radiation and frequency spectral characteristics. Unlike conventional antennas, TMAs are modulated by programmable periodic time sequences generated by field programmable gate array (FPGA) circuits, enabling high-precision amplitude and phase weighting. These signals control corresponding time modulators, such as radio frequency (RF) circuits or chips, to achieve modulation of the antenna elements, as shown in Figure 1. A specific time modulator is designed for various application scenarios, and each popular design offers its own unique features and advantages. In general, by introducing additional dimensions, TMAs have greater degrees of freedom and can provide simpler hardware structures, lower costs, more functions, and greater reconfigurability than conventional antenna arrays.

The concept of TMA was introduced in the 1960s [5], where the time dimension was used as an additional variable to control the radiation pattern. In TMAs, each antenna can simultaneously operate in multiple modes with different harmonics, thus achieving radiation characteristics different from those of conventional antennas. The theory of simultaneous multibeam scanning based on time modulation techniques generated by stepped pulse excitation was subsequently proposed in [6]. An experimental receiving array antenna was designed using time-modulated slot radiators [7] and achieved ultralow sidelobe levels (SLLs) below –40 dB using preprogramming switches. However, the implementation of time modulation techniques was challenging due to hardware limitations, particularly the need for practical high-speed RF switches. In addition, a large number of unavoidable and undesired harmonics generated by time modulation resulted in significant power loss and interference. As a result, the early development of TMA technology was slow. Since the beginning of this century, sig-

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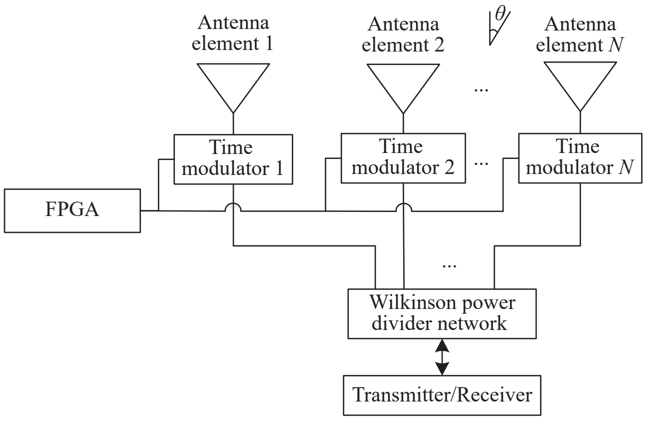

Figure 1 Diagram of TMA

nificant advances have been made in RF devices, particularly in the switching speed of RF switches, which has now reached the order of nanoseconds. Moreover, the performance of TMAs also depends on the design of the time-modulated signals. In the early stages of TMA time sequence design, only basic strategies were used, such as adjusting the time delay between elements [6] or controlling the pulse duty cycle to manage amplitude weighting [7]. However, these methods were unable to overcome the impact of numerous undesired harmonics and did not take advantage of the greater degrees of freedom offered by the TMA approach.

In 2002, a TMA using a differential evolution algorithm to suppress undesired harmonics [8] was proposed. This resulted in the suppression of the harmonic beams in the radiation pattern to below −30 dB. Since then, time modulation technology has made significant progress in theoretical analysis and circuit design. Theoretical research includes performance parameter analysis [9]–[12], instantaneous characteristic analysis [13], and full-wave analysis [14], [15]. This research has contributed to the establishment of a solid theoretical foundation for time modulation technology. From the perspective of antenna synthesis, various optimization algorithms have been applied to TMAs, including differential evolution algorithms [8], simulated annealing algorithms [16], artificial bee colony algorithms [17], particle swarm optimization algorithms [18], and convex optimization algorithms [19]. Moreover, several studies have developed unique time sequence schemes based on TMA characteristics to reduce computational complexity, such as moving phase center modulation [20], subsectional optimized time steps [21], and multifrequency modulation [22]. In addition to the conventional linear TMA, further research has been conducted on time-modulated planar arrays [23], nonuniform arrays [24], circular arrays [25], sparse arrays [26], and heterogeneous arrays [27]. Research on TMAs at this stage is primarily focused on improving rectangular time-modulated signals through optimization algorithms.

During this phase of TMA research, although the hardware is based on single-pole single-throw (SPST) switches with smaller degrees of freedom, the introduction of optimization algorithms has significantly improved the performance of TMAs. As a result, TMAs have become widely used in many application scenarios, such as multiple-input multiple-output (MIMO) arrays [28], orbital angular momentum (OAM) arrays [29], [30], direction of arrival (DOA) estimation [31]–[34], secure communication [35], [36], wireless power transmission (WPT) [37], [38], and antenna array calibration [39].

However, the hardware constraints of SPST switches make it difficult to achieve further improvements in this type of TMA. Consequently, some research has explored nonrectangular time-modulated signals [40], [41], including trapezoidal waves and raised cosine waves. Some complex signals have also been designed, such as weighted cosine waveforms (SWCs) [42] and trapezoidal bipolar waveforms [43]. While these approaches offer greater degrees of freedom, the time-modulated signals are no longer discrete. As a result, it is more challenging and less stable to implement these signals, compared to those of conventional TMAs. To balance the feasibility of hardware implementation, recent research on TMAs has combined RF switches, phase shifters, and attenuators to form time modulators, which can produce discrete time-varying amplitudes or discrete time-varying phases. Such enhancements provide new opportunities to improve the performance and extend the functionality of TMAs. In this review, we discuss recent developments in TMAs through hardware improvements and time-modulated signal design and present various application scenarios.

The remainder of this review is organized as follows. Section II discusses foundational theory and mathematical formulations of TMAs. Section III discusses the development of the time-modulated phased arrays (TMPA) from the perspectives of harmonic suppression and harmonic utilization. Section IV presents the research progress on time-modulated single-channel DBF systems. Sections V and VI present some novel antenna arrays that are combined with TMAs, including FDA and retrodirective arrays. Section VII presents an exploration of the advances in dedicated integrated chips for TMA. Finally, Section VIII presents our conclusions and a forward-looking perspective on the future of TMA.

II. Basic Theory of the TMA

As illustrated in Figure 1, the difference between a time-modulated phased array and a conventional phased array lies in the use of time modulators, such as RF switches, instead of conventional digital attenuators and digital phase shifters for amplitude and phase weighting. Controlled by an FPGA, time modulators can generate time-modulated signals $U_n(t)$ to modulate the corresponding antenna element. The array factor can be represented as

$$\mathrm{AF}(\theta,t)=\mathrm{e}^{\mathrm{j}2\pi f_0 t}\sum_{n=1}^{N}U_n(t)\cdot\mathrm{e}^{\mathrm{j}\beta(n-1)d\sin\theta} \tag{1}$$

where f_0 represents the frequency of the carrier signal, $\beta = 2\pi/\lambda_0$ denotes the free-space wavenumber, $\lambda_0 = c/f_0$ is the wavelength of the carrier signal, c is the speed of light in vacuum, d refers to the antenna element spacing, and $U_n(t)$ is the modulation pulse function with a period of T_p. Through Fourier transform, $U_n(t)$ can be decomposed as

$$U_n(t) = \sum_{m=-\infty}^{+\infty} a_{mn} \cdot e^{j2\pi m \cdot f_p t}, \quad m \in \mathbb{Z} \tag{2}$$

Subsequently, equation (1) can be rewritten as

$$\mathrm{AF}(\theta, t) = \sum_{m=-\infty}^{+\infty} e^{j2\pi(f_0 + m f_p)t} \cdot \sum_{n=1}^{N} a_{mn} \cdot e^{j\beta(n-1)d\sin\theta} \tag{3}$$

where $f_p = 1/T_p$ is the time modulation frequency, a_{mn} represents the equivalent complex excitation of the nth element in the mth sideband, and its value can be determined by the following equation:

$$a_{mn} = \frac{1}{T_p}\int_0^{T_p} U_n(t) e^{-j2\pi m \cdot f_p t} dt \tag{4}$$

Therefore, a_{mn} depends on $U_n(t)$ of the nth time modulator. By adjusting the magnitude and phase of the a_{mn}, the radiation pattern of the TMA can be controlled as desired. In a conventional TMA, the time modulation circuit is an SPST switch, and it can generate $U_n(t)$ with only two states, 0 and 1, corresponding to the on and off states of RF switches, respectively. As a result, the waveform of $U_n(t)$ exhibits a rectangular modulation signal, as shown in Figure 2(a) [44]. If the start time of $U_n(t)$ for the nth element is t_n and its duration is τ_n, a_{mn} can be calculated according to (4) as

$$a_{mn} = \begin{cases} \tau_n/T_p, & m = 0 \\ \tau_n/T_p \operatorname{sinc}(\pi m \tau_n / T_p) e^{-j\pi m(2t_{1n}+\tau_n)/T_p}, & m \neq 0 \end{cases} \tag{5}$$

With the advancement of time modulator hardware, $U_n(t)$ is no longer confined to be rectangular modulation signals. It can now switch between more amplitude states and phase states. Moreover, the corresponding complex weighting values, a_{mn}, can still be calculated by (4).

Different harmonics have different amplitudes and phases. By adjusting the duration τ_n, namely, the duty cycle, the desired amplitude weighting of the TMA can be achieved. Simultaneously, all harmonics other than the carrier contain phase components $e^{-j\pi m(2t_{1n}+\tau_n)/T_p}$, so the TMA can achieve phase weighting by adjusting t_n. Consequently, the direction of the beam can be controlled, as shown in Figure 2(b). When the beam of the mth harmonic is required to point at θ_0, $U_n(t)$ should satisfy

$$\frac{2t_{1n} + \tau_n}{T_p} = \frac{(n-1)\beta d \sin\theta_0}{m\pi} \tag{6}$$

The carrier beam always points in the normal direction. The remaining harmonics point in different directions to form multibeams because their phase difference is proportional to the harmonic order. In most cases, their specific directions cannot be controlled independently.

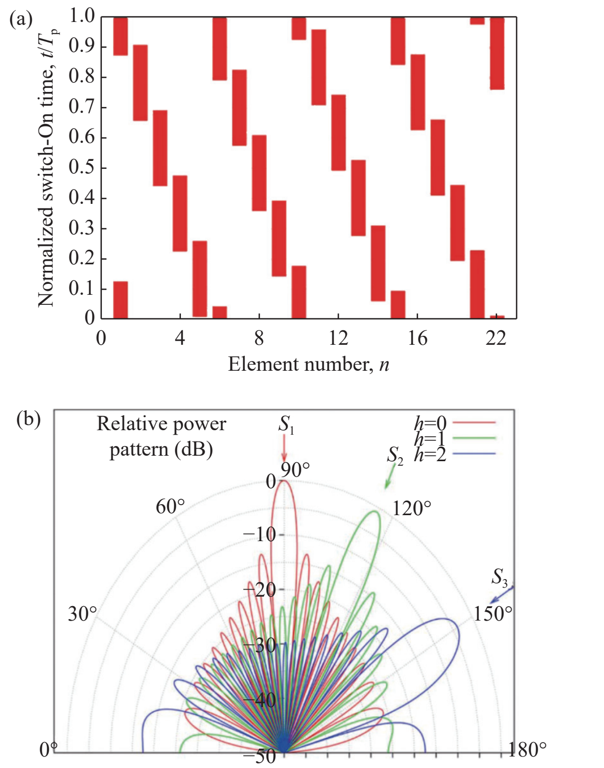

Figure 2 TMA based on SPST switches [44]. (a) Time sequence (b) Radiation pattern at carrier frequency and the 1st and 2nd sidebands.

In the early stages, TMAs primarily used carriers to achieve ultralow sidelobes by controlling the duty cycle and using optimization algorithms to suppress other undesired harmonics [6], [8]. However, when the direction of the beam changes, the suppression of undesired harmonics also changes, and repeated optimization is required during beam scanning. This results in performance instability and significant time consumption. Therefore, TMA research has attempted to design different hardware for time modulators and appropriate $U_n(t)$ to meet various requirements.

The losses in a TMA can be mainly classified into two categories: harmonic losses and feeding network losses, corresponding to the harmonic efficiency η^H and feeding network efficiency η^F, respectively. η^H is defined as the ratio of the operating harmonic power to the total output power, reflecting the loss caused by undesired sidebands. η^F refers to the ratio of the output power to the input power, reflecting the power loss from the feeding network of the time modulator. The overall efficiency of the TMA is expressed as $\eta^T = \eta^H \cdot \eta^F$.

The efficiency of conventional TMAs based on SPST switches is determined by the duty cycle. However, with the development of TMA, the shape of $U_n(t)$ changes, and two types of efficiencies of the nth time modulator in the array can be represented as

$$\eta_n^H = \sum_{m\in\Omega} |a_{mn}|^2 \Bigg/ \sum_{m=-\infty}^{+\infty} |a_{mn}|^2 \tag{7}$$

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$$\eta_n^{\mathrm{F}} = 1/T_{\mathrm{p}} \cdot \int_0^{T_{\mathrm{p}}} |U_n(t)|^2 \, \mathrm{d}t \tag{8}$$

where Ω is the set of all operating harmonics. The harmonic efficiency depends on the a_{mn} of the nth time modulator, whereas the feeding network efficiency is based on $U_n(t)$. Because the magnitude of the output signal is proportional to the value of $U_n(t)$, the feeding network efficiency depends on the integral of $|U_n(t)|^2$ over its period T_p. Under a uniform amplitude distribution, the efficiency of the time-modulated array is equal to that of each individual time modulator. When the amplitude distribution is nonuniform, η^{F} of the TMA is the average of the feeding network efficiency of each modulator. The η^{H} of the TMA depends on the frequency spectrum of the entire TMA, which is calculated by [10]

$$A_m = \sum_{n=1}^{N} \sum_{s=1}^{N} \{\mathrm{sinc}[\beta d(n-s)] \cdot a_{mn} a_{mn}^*\} \tag{9}$$

The efficiency described here is the internal efficiency of the time modulation. Although the time modulator can replace certain circuits in conventional antenna arrays, thereby simplifying its structure, the overall efficiency of the antenna array is still influenced by a variety of other factors. These include aspects such as the feed network, which is unrelated to time modulation, and the radiation efficiency of the array. Therefore, when evaluating the efficiency of TMAs, it is imperative to consider not only the efficiency of the time modulator, but also other efficiency factors that are integral to conventional antenna arrays.

III. Time-Modulated Phased Array

Phased array antennas, which comprise numerous elements with independent phase and amplitude control, can rapidly shift beam directions to provide high-precision beam control. They have been widely applied in aerospace, navigation, radar, and other applications. Conventional phased arrays typically use transmit/receive (T/R) modules to control corresponding antenna elements, which can adjust the amplitude and phase of the elements by changing the states of digital phase shifters and digital attenuators. However, this approach can be expensive, especially for use in high-resolution beam scanning. This high cost occurs because the complexity and cost of the phase shifters increase significantly, which limits the beam angle resolution of phased arrays. Moreover, accurate amplitude and phase control over a wide bandwidth becomes challenging.

In recent years, TMA has attracted attention as a nonconventional phased array technology [45]. Phase control in TMAs is primarily accomplished by using relative time delays between the time modulation signals of each element, whereas amplitude control is based on the duty cycle. This trend signifies that the high resolution of the time-modulated phased array (TMPA) depends on the resolution of the time control, which is mainly determined by the performance of the FPGA circuits. Compared with conventional phased arrays, which require increased hardware complexity to achieve higher resolution, the TMPA can achieve superior resolution without improving the RF circuits. This innovation allows components in the T/R module to be replaced with time-modulated circuits, resulting in a reduction in system cost. On the other hand, conventional phased arrays typically require the construction of Butler matrices or digital phased array systems for multibeam radiation, which significantly increases hardware complexity. However, the TMPA can generate different beams by using different sidebands, which requires only modulation signal adjustments rather than hardware changes. These attributes demonstrate the advantages of the TMPA, such as its low cost, high reconfigurability, and multiple functionalities.

Even so, the TMPA faces challenges similar to those of the conventional TMA [45]. In particular, the periodic modulation of the antenna elements generates a large number of sidebands, leading to sideband interference and reduced efficiency. These undesired sidebands can result in aliasing effects, especially for wideband signals. These problems limit the practicality of the TMPA and have attracted the attention of many researchers for possible solutions. According to statistics [4], the number of studies on sideband suppression and utilization is almost equal. Therefore, we mainly focused on the development of TMPAs from these two perspectives.

1. Suppressing sidebands

The suppression of undesired sidebands in a TMPA is critical to maintaining spectrum purity and preventing interference from other sidebands. The sideband level (SBL), which represents the ratio of the maximum undesired sideband to the operating sideband, serves as a key performance indicator for this aspect. The SBL is usually described as the ratio of the gain of the corresponding sideband in the radiation pattern. However, it is time-consuming to repeatedly optimize SBL during beam scanning of the TMPA. Hence, in studies on enhanced time modulators, the SBL is often optimized based on the power of the sidebands in the frequency spectrum, which avoids the reoptimization of the time-modulated signals when the beam direction changes. In the following discussion, the SBL discussion is mainly based on the frequency spectrum. Another important parameter that reflects TMA characteristics is the allowable signal bandwidth without aliasing. For a conventional TMA, which cannot eliminate extra sidebands, the allowable bandwidth is equal to the time modulation frequency f_{p}. As long as the modulation frequency is increased, wideband signals can be modulated without an aliasing effect. For an improved time modulator, which can eliminate some undesired sidebands, the allowable bandwidth can be increased, which is usually an integer multiple of f_{p}. However, the complete elimination of undesired sidebands is only theoretical. In practice, it is usually the bandwidth where the SBL is guaranteed to be below a certain value, such as −30 dB.

To improve the SBL and allowable signal bandwidth without aliasing, several improvements in time modulators for the TMPA have been proposed. According to their mechanisms, they can be divided into two types: harmonic-based and carrier-based.

Harmonic-based TMPA uses its harmonic as the operating frequency, which is unusually the first sideband. Theoretically, its corresponding time-modulated signal should be $e^{j2\pi f_p t}$, which is a unit circle in the complex plane. As a phased array, it is straightforward to calculate the delay of the time-modulated signals to achieve the required phase shift of each element for beam scanning. Therefore, the focus is on how to generate $e^{j2\pi f_p t}$. A practical time modulator can only generate discrete time-modulated signals, not continuous signals, which leads to the presence of undesired sidebands. The greater the number of sampling points on the unit circle is, the smaller the SBL and the wider the allowable signal bandwidth. The earliest hardware improvement scheme used 0/180° phase shifters [46] to realize two-point sampling of the unit circle. This scheme generates "−1/1" rectangular pulses to eliminate the carrier frequency and even sidebands. Moreover, the signal bandwidth without aliasing is extended to $2f_p$. The single-sideband time-modulated phased array (STMPA) was proposed in [47] by using in-phase/quadrature (I/Q) modulation, as shown in Figure 3. This scheme uses a 0/180° phase shifter and a fixed 90° phase shifter to achieve four-point sampling of the circle. As a result, only the $(4k+1)$th sidebands are reserved, and the signal bandwidth is extended to $4f_p$.

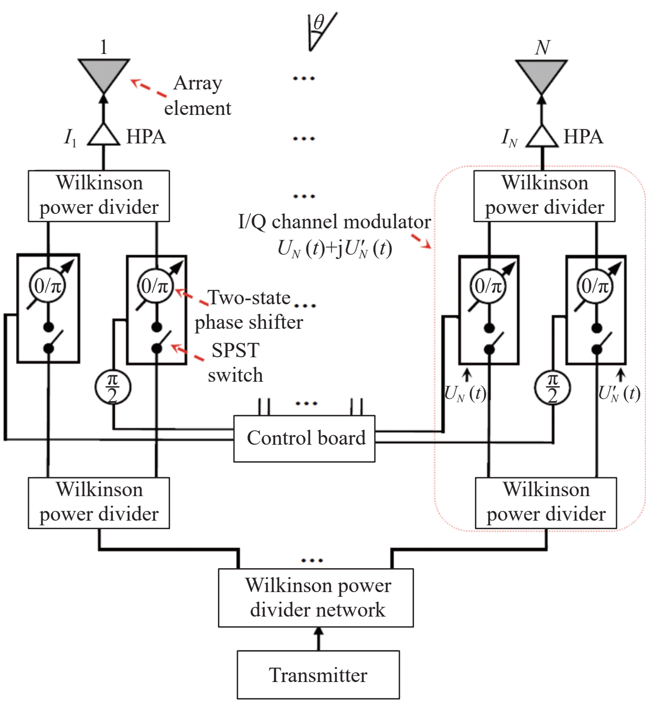

Figure 3 Configuration of STMPA with I/Q modulation [47].

To further increase the number of sampling points, one of the approaches is to provide more phase states, which is also known as phase modulation [48], [49]. A periodic time modulation signal can be evenly divided to obtain linearly increasing phase shifts, as shown in Figure 4(a) [48]. These phase shifts are generated by the circuit shown in Figure 4(b). By dividing 2π into M phase states and switching between them with equal duration within one period, only the $m = kM+1$ sideband is preserved, and the signal bandwidth without aliasing increases to Mf_p. The value of M is the number of sampling points on the circle in the complex plane. For $M=4$, the structure maintains the minimum I/Q modulation [50]–[52], which is simple and practical. A photograph of the time modulator with four phase states (0, $\pi/2$, π, $3\pi/2$) is shown in Figure 5. Moreover, the phase modulation provides a high theoretical efficiency (which approaches 100%) due to the time-invariant amplitude, which prevents power loss during the off-state of RF switches. On this basis, a high-resolution amplitude and phase control (HRAPC) method is proposed by varying the time delay between control signals [52], which is particularly suitable for scenarios with high modulation frequencies.

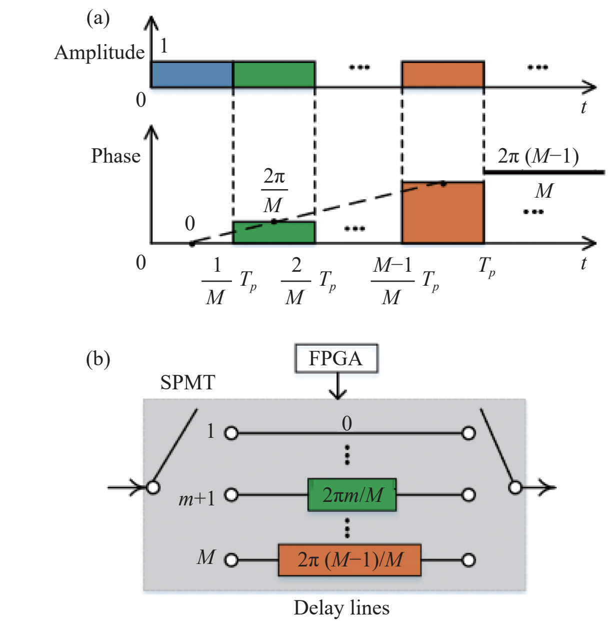

Figure 4 Diagram of phase modulation [48]. (a) Time sequences; (b) Configuration of the time modulator.

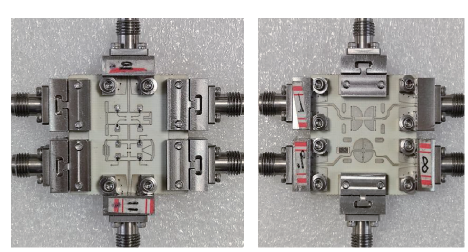

Figure 5 Photograph of phase modulator with four phase states (0, $\pi/2$, π, $3\pi/2$) [50].

Another approach includes amplitude modulation, which generates time-modulated signals with time-varying amplitudes instead of phases. Based on Euler's formula $e^{j2\pi f_p t} = \cos(2\pi f_p t) + \sin(2\pi f_p t)$, the rectangular wave in the

STMPA [47] can be improved to approximate sinusoidal waveforms with discrete waveforms. The more steps the discrete waveform has, the more sampling points there are on the unit circle, which is theoretically equivalent to phase modulation. Earlier studies [53], [54] used power dividers to achieve two-step time-modulated waveforms, followed by multistep waveforms using digital attenuators [55]–[57], as shown in Figure 6. By increasing the number of steps and generating multistep waveforms with equal step durations, more undesired sidebands can be suppressed. When the total number of steps is S, the sidebands of $m = 4kS + 1$ in the spectrum can be eliminated, and the signal bandwidth without aliasing will also increase to $4S \cdot f_p$. In [56], the theory of Haar wavelets was applied to discuss this type of STMPA. Its performance is the same as that of phase modulation when $M = 4S$ because the 4 phase states of I/Q modulation (0, π/2, π, 3π/4) are still needed for amplitude modulation. The time-varying amplitude is achieved by adjusting the attenuation value, which inevitably leads to power loss. In I/Q modulation, the efficiency is always less than 50%. However, the I/Q channels can independently generate time-varying amplitudes, providing greater degrees of freedom. For example, being limited to the exact sampling of the unit circle but with a certain deviation, 4-step waveforms can be optimized to achieve SBL below −30 dB over the entire spectrum [57], which is suitable for suppressing the aliasing effect of wideband signals. In comparison, the SBL generated by the accurate sampling scheme with the same hardware complexity is only −24 dB. A waveform design with greater degrees of freedom can provide the STMPA with other new functions, such as the correction of hardware imperfections [58] and more convenient amplitude weighting schemes [59]. In addition to stepped waveforms, sinusoidal pulse width modulation (PWM) is another interesting approach for the TMPA [60]. It uses a time-varying duration to achieve sinusoidal waveform characteristics with simple hardware but longer periods.

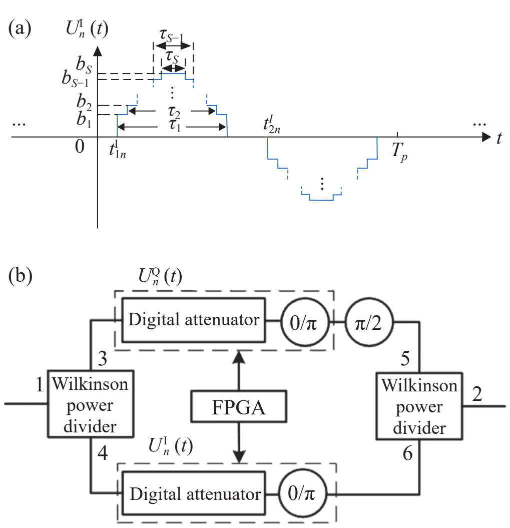

Figure 6 STMPA with multisteps waveform [55], [57]. (a) Time modulating waveform in the in-phase channel; (b) Block diagram.

A carrier-based TMPA operates at the carrier frequency ($m = 0$), which was initially considered unsuitable for phased array implementation because the beam corresponding to the carrier always points in the normal direction. However, with the introduction of phase modulation, the phase of the carrier can also be adjusted by changing the time modulation signal [61]. Simultaneously, the carrier has many characteristics that are different from those of sidebands, so there are many innovative schemes for suppressing undesired sidebands. For example, the TMPAs in [62] and [63] operate at carrier frequencies and use multifrequency modulation to suppress SBL. Moreover, they use the properties of phase modulation to ensure beam scanning, which cannot be achieved by conventional multifrequency time modulation [22], [64]. In [63], the phase of the carrier component was no longer achieved by optimization algorithms alone. Instead, it was proposed to obtain the baseband phase by vector superposition of multiphase states (0, π/2, π, 3π/4) with different durations. This greatly simplified the design of time-modulated signals for beam scanning in carrier-based TMPA. However, the complexity remains greater than that of harmonic-based TMPAs, which only require adjustments of the time delays.

Pseudorandom modulation [65]–[67] is a more recent development in carrier-based TMPA that breaks the periodicity of the time modulation to achieve sideband suppression. The pseudorandom time sequence is shown in Figure 7(a) [65], where the states of the four phase states and the off state are pseudorandomly placed. As a result, most of the power in the frequency spectrum is concentrated at the carrier frequency, as shown in Figure 7(b). This approach provides robust sideband suppression and avoids the need for repeated optimization during beam scanning to realize amplitude-phase weighting and suppress the SBL to below −30 dB. In another example [66], only the on-off pseudorandom control sequence is preserved and combined with amplitude-controlled excitation to achieve beam scanning. This approach significantly simplifies the time-modulated signals and hardware. However, pseudorandom modulation requires repeated and rapid switching of the time modulator, placing greater demands on the hardware. Hence, each state of the pseudorandom sequence in [65], [66] is designed to last 2 μs, which can alleviate the hardware constraints. Simultaneously, pseudorandom sequences can contain hundreds to thousands of states to maintain their pseudorandom characteristics. Thus, it is currently suitable for scenarios with continuous and stable signals. With the development of hardware, pseudorandom modulation could also be used in time-sensitive application scenarios.

2. Utilizing harmonics

TMAs inherently generate a large number of harmonics. However, these harmonics can be strategically used to enable multibeam generation from the same antenna aperture. The theory of multibeam TMAs was proposed in the 1960s [6], but it has only been implemented in recent years because of related advancements in RF technology. By using

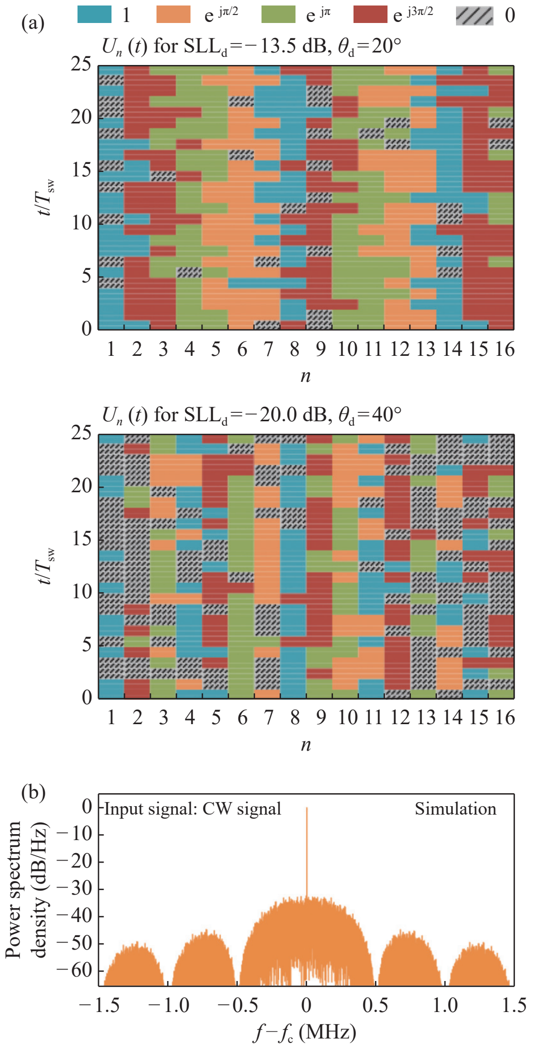

Figure 7 Pseudorandom modulation [65]. (a) Time sequence; (b) Frequency spectrum.

optimization algorithms, TMAs can use harmonics to simultaneously generate multiple beams in the desired directions while forming nulls in other beam directions to achieve mutual isolation [44], [68]–[69]. As a result, multibeam TMAs have found applications in secure communication [69] and space-division multiple access (SDMA) communication [70], [71]. In comparison to conventional SDMA systems implemented via Butler matrix beamforming or digital beamforming, time-modulated SDMA systems use a single RF channel. This approach offers advantages in terms of hardware complexity and cost. However, conventional multibeam TMAs use rectangular modulating pulses to modulate antenna elements via RF switches. Although this hardware implementation is relatively simple, it leads to performance limitations, such as low efficiency and poor gain consistency. Moreover, undesired beams from residual harmonics still exist and cannot be suppressed significantly, especially the beams of negative order harmonics, which have the same gain and symmetric directions as positive order harmonics. Their existence could lead to interference from undesired beams.

To achieve flexible multibeam design and suppress the presence of undesired beams, the design of time modulation waveforms has become crucial for replacing conventional rectangular modulating pulses. One related approach is to utilize analog time modulation waveforms achieved through the variable gain amplifiers (VGAs), as shown in Figure 8(a). For example, SWC pulses [42], which can reserve specific harmonics while suppressing undesired harmonics, have been proposed for multibeam TMAs. The radiation patterns of the multibeam TMA generated by this method are illustrated in Figure 8(b). On this basis, the technology of I/Q time modulation [47] has also been introduced to suppress negative order harmonics [72], which enables the required operating sidebands to be freely selected to meet various requirements for multibeam pointing. To increase the number of multibeams, periodic Nyquist pulses have been proposed [73]. This design exhibits favorable scalability, and the number of multibeams can be increased robustly.

These designs [42], [72], [73] significantly improve the performance of multibeam TMAs, but they have not been verified by measurements. The generation of ideal analog time modulation waveforms remains a challenge for existing RF circuits. Several practical circuits composed of different types of RF switches have been proposed to enhance multibeam TMAs [74]. This design achieves two independent beams at the carrier frequency and +2 sidebands by cascading an I/Q modulator operating at the +1 sideband with a modulator operating at the +1/−1st sideband. The time delays are independent of each other so that the directions of the two beams can be controlled separately. However, their suppression of undesired sidebands does not match the performance of those using analog time modulation waveforms.

Recently, a multibeam TMA design using multistep

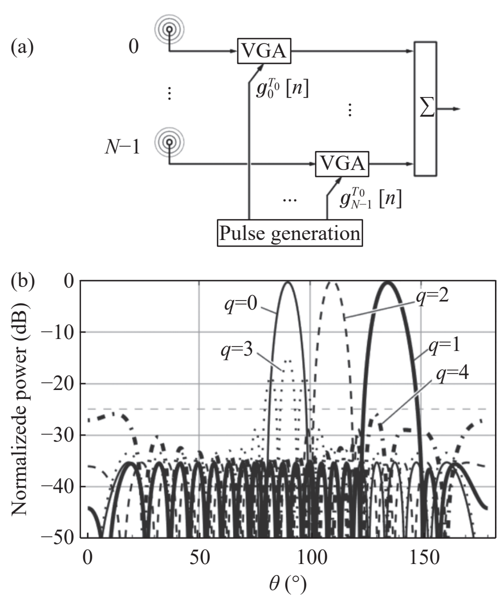

Figure 8 Multibeam TMA with SWC pulses [42]. (a) Configuration of the TMA with VGA; (b) Radiational patterns at different sidebands.

time modulation waveforms was proposed in [75], as shown in Figure 9(a). This design uses stepped waveforms to approximate analog time modulation waveforms, such as the SWC pulse. As a result, it can preserve certain sidebands while suppressing others, which is also reflected in the beam patterns as shown in Figure 9(b) and (c). Consequently, the required time-modulated waveforms can be designed accordingly and generated by a time modulator composed of a digital attenuator and a 0/π phase shifter. For example, five beams are generated by this type of time modulator, including the carrier and ±1, ±2 harmonics. This method effectively suppresses the SBL to −31.20 dB, and the operating sideband power variation is maintained at 0.68 dB.

IV. Time-Modulated Single-Channel DBF

Digital beam forming (DBF) uses advanced signal processing technology to arbitrarily process array antenna signals. Compared with analog beam forming, DBF has significantly superior flexibility and anti-jamming capability, making it a core technology for future digital array radar and smart antennas. However, conventional architectures require each element of the antenna array to be equipped with a dedicated RF channel and an analog-to-digital converter (ADC). With the increasing demand for performance and the increasing scale of antenna arrays, the use of many RF channels and ADCs have led to extremely high system complexity, accompanied by high hardware cost and high power consumption, severely limiting the development of DBF antenna arrays.

In recent years, significant efforts have been made to address the aforementioned challenges. One approach is to use integrated circuit technology to reduce the size and power consumption of each RF channel. The rapid advancement of semiconductor technology has offered some relief by mitigating the issues arising from the large number of channels. However, it is important to note that all semiconductor technologies have inherent physical limitations. As the application frequency transitions from millimeter waves to terahertz radiation, the spacing between elements decreases, posing notable challenges related to heat dissipation and coupling after multichannel integration. Aside from manipulating the integrated circuit technology, another development approach is to reduce the number of RF channels and even use a single RF channel to achieve DBF. This approach entails transmitting all the information through a single RF channel and subsequently restoring the original signal for each array element. By fundamentally reducing the complexity of DBF, this method has become a popular research topic. Compared with multichannel architectures, single-channel DBF technology has advantages in terms of compact size and cost effectiveness. This section presents a review of the existing research achievements in the single-channel DBFs and their integration with time-modulated technology.

One such scheme is the time diversity single-channel DBF. From 2002 to 2010, a time division multiplexing

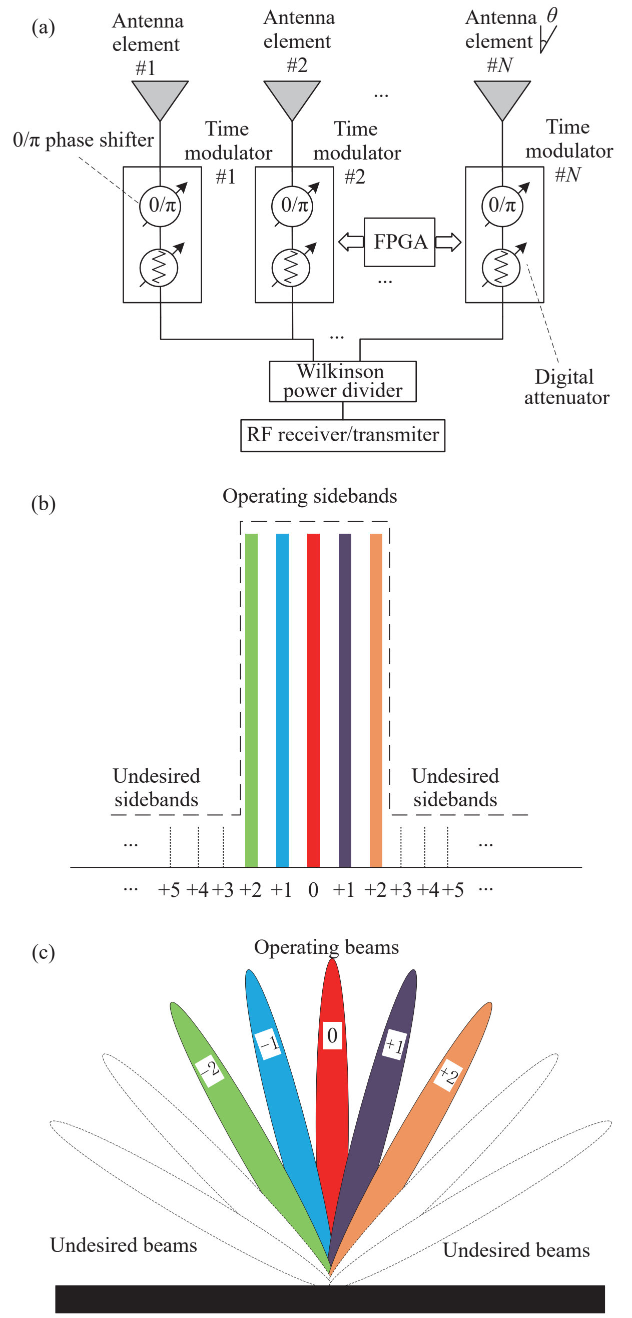

Figure 9 Multibeam TMA with stepped waveforms [75]. (a) Configuration of an N-element multibeam TMA; (b) Frequency spectrum; (c) Radiational pattern.

single-channel receiver scheme called spatial multiplexing of local elements (SMILE) was proposed [76], [77]. This system significantly reduced the complexity of DBF systems and introduced a novel approach. In 2014, another single-channel DBF scheme based on delay lines was proposed [78]. The core concept of this scheme is to connect delay lines of different lengths behind each array element, enabling the transformation of the signal simultaneously reaching the antenna array from a parallel configuration to a serial configuration, thereby transmitting it through a single RF channel. In [77], a method was proposed to further solve the problem of low distance resolution by combining delay lines and phase shifters [79]. In 2018, single-channel radar imaging was achieved and experimentally verified in [80]. Subsequently, the space code agility-based space-time coded array was proposed in 2019 [81], which effectively improves beam distortion in the range and angle domains. Additionally, in 2022, a new method based on single-channel and 1-bit time modulation was proposed [82], enabling simultaneous calculation of sum and difference beams and expanding the bandwidth of the maximum transmissible signal. In [83], a 24-GHz FMCW radar system is proposed, as shown in Figure 10, where the receiving antennas are periodically switched to a single receiving channel. This method uses beamforming methods to estimate the angle, range, and velocity.

The second scheme is the frequency diversity single-channel DBF. Through frequency conversion, different array elements occupy different frequency bands within a single channel for transmission. This method offers advantages in detecting moving targets and avoids the challenges associated with compensating for moving targets in time division multiplexing with a single channel. In 2004, the concept of a frequency division multiplexing single-channel adaptive antenna array was proposed [84]. In 2021, a 4-element frequency division multiplexing single RF channel MIMO receiver was implemented [85], as shown in Figure 11. However, this method still faces significant challenges in implementation. Indeed, although it is theoretically feasible and offers numerous advantages, relatively few results are available because of these challenges.

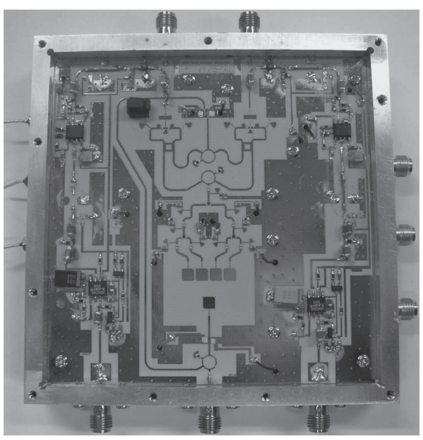

Figure 10 A 24-GHz switch-antenna array FMCW radar [83].

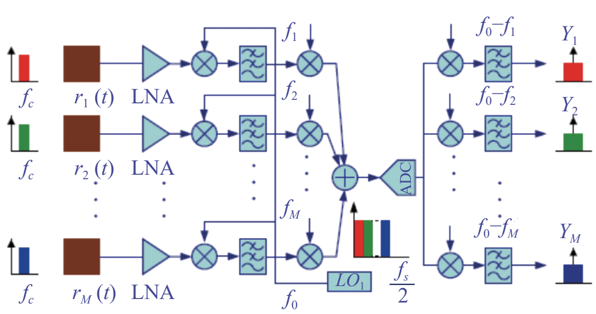

Figure 11 The method of frequency diversity single RF channel [85].

The third scheme is the code diversity single-channel DBF. Compared with other methods, code division multiplexing offers advantages in terms of anti-interference capabilities. In 2009, a single-channel RF method based on code division multiplexing was proposed to reduce the size and cost of MIMO systems [86]. In 2014, an interchannel code division multiplexing scheme was introduced [87]. From 2015 to 2017, extensive research on code division multiplexing using single RF channels was conducted [88], [89], verifying the feasibility of this single-channel DBF approach in ultrawideband and high-frequency applications. In 2020, a four-element single-channel MIMO receiver using 65 nm CMOS technology was presented [90]. Moreover, a single-channel MIMO radar system based on code division multiplexing for millimeter-wave security inspection imaging was introduced [91]. In 2021, this approach to the field of interferometric imaging was further extended [92].

The fourth scheme is the pattern diversity single-channel DBF [93]. Using this technology, a conventional phased array radar can achieve angular superresolution without altering its original hardware structure [94]. This technique can also readily achieve sum and difference patterns [95]. In 2012, a single-channel DBF antenna based on TSPW was successfully realized [96], as shown in Figure 12. An effective online error correction method [97] was also introduced. In 2013, [93] proposed an array signal recovery algorithm based on a pseudoinverse function and applied it to a three-sided antenna array. Motion compensation and real-time processing are two challenges in TSPW single-channel array antenna systems. In 2014, [98] proposed a compressive sensing-based single-channel robust adaptive beamforming algorithm. In 2017, [99] presented a low-cost nested-MIMO array for large-scale wireless sensor applications. Furthermore, their concept was extended to a space-time two-dimensional compressed sensing array antenna and developed a corresponding signal processing algorithm [100].

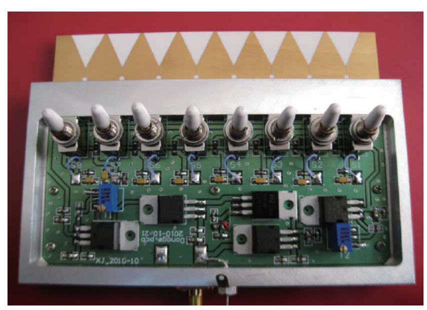

Figure 12 TSPW single RF channel digital beamforming for multibeam antenna array [96].

Although numerous studies on single-channel DBFs have been reported, several challenges remain. For example, the aperture complex field distribution will be contaminated when the radar targets are moving. Therefore, motion compensation must be conducted in this case. The rise of TMA in recent years has opened new opportunities to address these challenges. Several technical characteristics absent in conventional antenna arrays make TMAs a promising solution to the challenges associated with single-channel DBFs. Notably, TMAs offer the following: 1) Unique harmonic beams: unlike conventional methods, TMAs can generate distinctive harmonic beams. 2) Soft handover capabilities: TMAs can achieve diverse functionalities through soft handover. For example, they can use time differences to generate high-precision phase shifts [47], [57] and adjust signal frequencies by changing modulation frequencies [75], [101]. In the past two years, several achievements have been made in combining time modulation technology with single-channel research [102], [103], demonstrating the potential of TMAs in this field.

In addition to the above schemes, there are many promising topics that deserve further research. For example, beam diversity by using harmonic simultaneous multibeams and frequency diversity by using nonuniform periodic modulation significantly reduce hardware complexity and avoid motion compensation, which is important for realizing real-time processing.

V. Time-Modulated Frequency Diverse Array

FDA antennas, which are also known as frequency time-modulated array antennas, are a relatively new category of antennas that have been introduced in recent years. The concept of FDA antennas was initially proposed in 2006 [104]. By introducing small frequency offsets from the center frequency for each antenna element, the beam pointing becomes a four-dimensional function of the angle, range, and time. These advanced arrays can be used to improve signal processing in radar and navigation applications [105], [106].

Theoretical implementations of FDA antennas [107], [108] achieve small frequency offsets using RF mixers. However, this approach has several drawbacks related to the nonlinear properties of mixers, such as image frequency and possible spurious frequencies. To solve this problem, linear frequency modulated continuous wave (LFMCW) signals have been introduced for implementing FDA [109]. The LFMCW signal is generated by a source and fed to series-fed antennas. The delay between the antennas converts the time-dependent frequency at the source into diverse frequency feeding for individual antenna elements. Although this method has been validated through fabrication and measurement, its characteristics, such as small frequency offsets, depend on the series-fed network, which lacks reconfigurability.

In contrast to conventional antenna array systems that require various complex methods to achieve the small frequency offsets required by the FDA, TMAs are inherently suitable for this task because they can simply shift the input RF signal from the carrier frequency to the sideband. Moreover, the time-modulated signals can be freely adjusted, which also provides a greater degree of freedom for the FDA. This concept is used in the TMA-FDA, which was proposed in [110] and is shown in Figure 13. The TMA-FDA uses a variable-period time modulated technique (VPTMT) scheme controlled by an FPGA control circuit. By adjusting the modulation period of the switches, the TMA-FDA achieves different frequency offsets without requiring additional frequency sources. Additionally, TMA provides adjustable phase shifts through time delays, making TMA-FDA a simple and flexible approach to achieve desired frequency offsets and phase shifts by editing the program in the FPGA. This strategy enables TMA-FDA to effectively support various FDA strategies. In [111] and [112], SPTD modules of the TMA were used to generate stepped waveforms for the FDA, resulting in dot-shaped beam patterns [111] and two-beam steering [112]. These modules replace variable phase shifters (VPSs) and mixers while achieving high efficiencies. To address the tradeoff between beam collection efficiency (BCE) and half-power beamwidth (HPBW), Kaiser windows were used in [111]. Furthermore, the phase modulation technology of TMA has also been used by the FDA [113]. This FDA based on phase modulation transmitting and receiving TMA-FDA is designed for transmit-receive beamforming using 2-bit phase shifters, achieving improved sidelobe levels over the entire observation area.

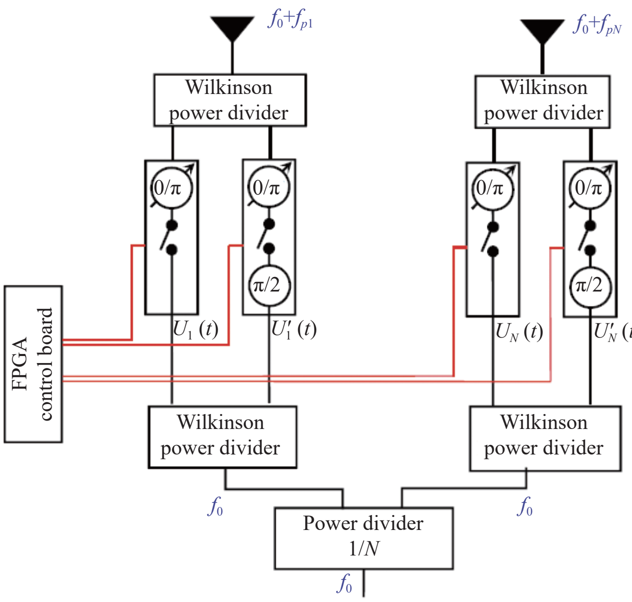

Figure 13 Configuration of the proposed FDA using VPTMT [110].

In addition to implementing the FDA using existing time modulation circuits, the category of time modulation FDA can be further extended. In 2014, Khan proposed an FDA with time-varying linear frequency offsets, where the frequency offset at each antenna element is a function of time [114]. These FDA antennas based on time-modulated frequency offsets belong to the generalized TMA. By using time-modulated nonlinear frequency offsets, the distance-angle coupling in the FDA is suppressed. On this basis, a time-modulated optimized frequency offset (TMOFO) in the FDA was proposed to achieve time-invariant spatial focusing beampatterns [115]. TMOFO-FDA has been further improved for multitarget focusing applications in long- and short-range scenarios [116], [117] and used to optimize a sparse FDA with a minimum number of elements [118]. However, the feasibility of achieving time-invariant spatial focusing has been questioned [119], [120], as the focusing point of antennas always moves with the velocity of wave propagation in the far field. The fundamental errors in [115]–[118] stem from their inaccurate definition of the frequency offset for electromagnetic waves emitted in the far field from the FDA. These studies incorrectly assumed that the frequency offset could be arbitrarily varied to meet specific requirements. This assumption violates a basic principle: after electromagnetic waves are emitted from the antenna, their frequency and other parameters in the far field are no longer under the control of the source. Instead, these waves maintain their emission frequency as they propagate into the far field. The concept of a time-invariant spatially focused beampattern arises only under this incorrect definition and represents a phenomenon that does not conform to the laws of physics. This mischaracterization has reported in numerous publications, mainly because the research on the FDA is often theoretical, and the potential formula error cannot be found through experimental validation. Nevertheless, the optimization methods for determining the frequency offset and the methods for multitarget and short-range focusing proposed in [115]–[118] are interesting and useful [119], [121]. Subsequent discussions [121], [122] have supported the idea that time-invariant spatial focusing beams are impossible, but the introduction of time-varying frequency offsets is worth further research. Moreover, many researchers have presented theoretical analyses to address this issue [123]–[125]. Their research has shown that a time-modulated FDA cannot achieve a time-invariant spatial focusing beampattern. Signal models are reestablished to discuss the time–range or frequency–phase relationship, which has been neglected in previous studies. The FDA beampattern time-variance should be used to enhance the application performance rather than suppressing the time-variance [126]. Additionally, a misconception related to the time index within the pulse and the actual time is identified as the root of the problem in [125]. However, this finding has sparked controversy regarding the unity of time [127], [128]. Therefore, further research is still necessary to advance the theory and application of time-modulated FDA.

VI. Time-Modulated Retrodirective Array

Retrodirective array antennas [129],[130] have attracted significant attention from the academic and industrial communities because of their unique self-tracking beam scanning characteristics. For example, these antennas can automatically track the direction of incoming waves without prior knowledge of the incoming wave direction and without complex digital signal processing algorithms. Between 2006 and 2008, Itoh *et al.* proposed time-shared retrodirective array antennas to simplify the array structure and reduce manufacturing costs. By connecting an SPST high-speed RF switch to each antenna element and controlling the time sequences, retrodirective or self-tracking beam scanning can be achieved by using only a single time-shared phase conjugator [131]–[133]. Nevertheless, there is still unused time redundancy information within time-shared retrodirective array antennas that can be exploited. As a result, further research is required to apply time-modulated antenna technology in retrodirective array antennas.

In [134], time modulation technology and retrodirective technology are combined to create a reconfigurable co-aperture antenna array, as shown in Figure 14. The co-aperture antenna array incorporates absorptive single-pole triple-throw (SP3T) switches that can generate time modulation sequences while enabling reconfigurable functionalities, termed as single-band time modulated/retrodirective/time-modulated retrodirective arrays. Because of its high reconfigurability, the system can also achieve dual-band and triband time-modulated retrodirective arrays based on a synthesized transmission line (STL) [135], [136]. Additionally, this system can be used as a TM-based interference re-

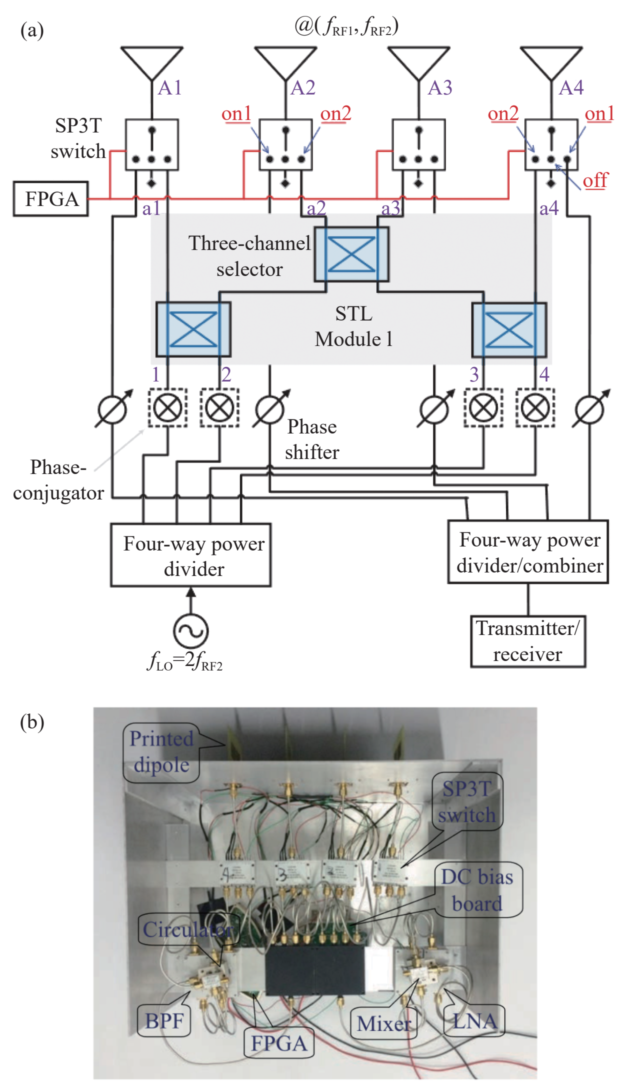

Figure 14 Reconfigurable time-modulated coaperture array antennas [134]. (a) Block diagram; (b) Photograph.

jection retrodirective array by generating a time-modulated null-steering beam that points in the direction of the retrodirective beam. This feature enables the system to transmit retrodirective signals carrying information data and self-nulling signals carrying dummy data, making it suitable for secure communication applications. A major advantage of this reconfigurable co-aperture antenna array is its high flexibility and versatility. The device can achieve multiple functionalities without the need for additional independent arrays, which distinguishes it from other retrodirective arrays with similar functionalities [137], [138].

In [139], a time-modulated retrodirective antenna array is presented, which uses an improved directional modulation technique for secure communication. This innovative approach enables the elimination of sideband signals in the direction of the legitimate receiver, resulting in wideband signals being received without distortion. Using this method, legitimate receivers can receive clear and undistorted signals from the configured direction. Conversely, in other directions, an aliasing effect caused by time modulation occurs, resulting in incorrect demodulation of the signals. This interference can effectively disrupt attempts by illegal users to receive and interpret signals, thereby increasing the security of the communication system. In [140], a retrodirective array modulated by a rectangular waveform was used to generate jamming in synthetic aperture radar (SAR) imaging. The presence of false targets is observed in both the range profile and azimuth profiles.

In conclusion, TMAs enable the integration of arrays with different functionalities into a reconfigurable co-aperture array. Compared with conventional antenna designs, this approach greatly simplifies the structure of the antenna system, reduces costs and saves space resources. Although there have been some studies combining time modulation techniques with retrodirective technologies, such studies remain relatively small in number. Furthermore, existing research in this area often relies on conventional SPST switches for time modulation hardware. However, by integrating recent advances in time modulation techniques with retrodirective technologies, it is possible to enhance system performance and expand the range of potential application scenarios.

VII. Integration of the TMA

In recent years, the integrated circuit industry has experienced unprecedented development. In particular, increasing applications in RF and mm-wave frequencies have demonstrated significant market potential. Phased array systems have become critical parts of precision guidance, navigation systems, aerospace, and other fields. However, conventional phased array antenna systems rely on precise phase shifters in the feed network to achieve the desired radiation characteristics by controlling feed amplitudes and phases. Phase shifters can be categorized into three types based on their operating principles: switch-type phase shifters [141], reflection-type phase shifters [142], and vector-sum phase shifters [143]. Switch-type phase shifters use multiple phase-shifting units with different phase angles. Reflection-type phase shifters typically feature a 90° hybrid coupler circuit with variable loads connected to its through and coupled ports. Vector-sum phase shifters usually consist of an orthogonal signal generator and two variable-gain amplifiers, which allow for different phase-shifted output signals by adjusting the gain levels in the I and Q paths. However, the design of on-chip phase shifters in the RF or mm-wave frequency range is challenging because of their complexity and limited phase-shifting accuracy. Achieving higher phase accuracy often requires a larger number of phase-shifting units, resulting in increased size and losses. Moreover, the limited accuracy of on-chip inductance and capacitance values, as well as the influences of process, voltage, and temperature (PVT) variations, make it difficult to achieve higher phase accuracy. In the millimeter-wave frequency range, parasitic effects become more prominent, further degrading the phase-shifting precision of the phase shifter, particularly because of the impacts of parasitic capacitance and inductance.

Compared with a conventional phase shifter, time-modulated phase shifting offers the advantage of achieving mutual decoupling between channel loss and phase-shifting accuracy. Its digital phase-shifting function can reduce channel loss, making it particularly suitable for millimeter-wave systems. The introduction of an enhanced STMPA [53] further enhances the efficiency and extends the signal bandwidth. by adopting the stepped time-modulated pulse waveform. However, the current design approach predominantly involves the assembly of discrete modules on a printed circuit board (PCB), resulting in a low level of integration. Moreover, existing time-modulated phased array systems primarily focus on sub-10 GHz frequencies and do not incorporate an RF front-end module (FEM). The cascading of modules on the PCB using 50 Ω transmission lines leads to limited integration and requires lengthy matching networks. This limit makes it difficult to demonstrate the advantages of the time-modulated phase shifting in millimeter-wave phased array systems. In millimeter-wave system design, the high-order effects of switch control and phase compensation units play a significant role, and the influence of parasitic effects cannot be neglected. Additionally, losses in microstrip lines and mismatches introduced by bonding wires can cause a sharp deterioration in the performance of phased arrays. It is essential to integrate and miniaturize the design of time-modulated phased arrays to cover a wider range of application scenarios, especially in the millimeter-wave frequency range.

Integrated circuit design solutions, including those using silicon-based CMOS and gallium nitride (GaN) technologies, offer notable advantages. Silicon-based technology is highly mature, cost-effective, and enables high integration density. However, there are challenges in meeting the increasing demands of phased array systems for transmitting and receiving signals. The limitations of silicon-based technology are evident in terms of linearity and power handling capabilities. On the other hand, GaN provides a higher power density and improved linearity. Its material properties, such as a high breakdown field and thermal conductivity, allow for the handling of higher power signals, making it suitable for high-power applications. Moreover, GaN exhibits excellent high-frequency characteristics, making it suitable for applications in the millimeter-wave and terahertz frequency ranges.

To address these issues, a 28 GHz fully integrated GaN-enhanced single-sideband time-modulated monolithic microwave integrated circuit (MMIC) for a phased array system was proposed in [144]. This innovative design offers several advantages over conventional analog phase shifters. The phase-shifting accuracy is primarily determined by digital pulse control, which is not limited by the number of analog control bits. The proposed design exploits various advantages of GaN transistors, including their high cutoff frequency and power density. By integrating both the FEM and a time-modulated phase shifter on a single chip, the design achieves a high level of integration and miniaturization for a high-efficiency single-sideband time-modulated phased array.

Figure 15(a) and (b) shows the block diagram and a photograph of the MMIC fabricated in the 0.1 μm GaN process. The MMIC consists of a time-modulated circuit and an RF FEM. The time-modulated circuit includes a numerically controlled attenuator, a reconfigurable power divider, $0/\pi$ phase shifters, and power dividers. A schematic of the 25–29 GHz FEM is shown in Figure 15(c). The FEM includes a power amplifier (PA), a low noise amplifier (LNA), single-pole double-throw (SPDT) switches, and two combined networks (Rx_out/Tx_in and Rx_in/Tx_out), as shown on the gray background. The purpose of this device is to amplify the signal generated by time-modulated MMICs. The input/output matching of both the LNA and PA is jointly designed and embedded in the input/output combined network. These combined networks, which bridge the receiver and transmitter channels, have been optimized effectively to minimize the undesired loading effect between them. Consequently, a transformer-based combined network has been designed to achieve the lowest possible noise figure and input return loss for the receiver channel while also attaining the optimal load impedance for the transmit channel. The isolation of the switch is greater than 20 dB from 26 to 29 GHz, the insertion loss is less than 1.1 dB, and the input $P_{0.3\mathrm{dB}}$ is approximately 35 dBm at 28 GHz.

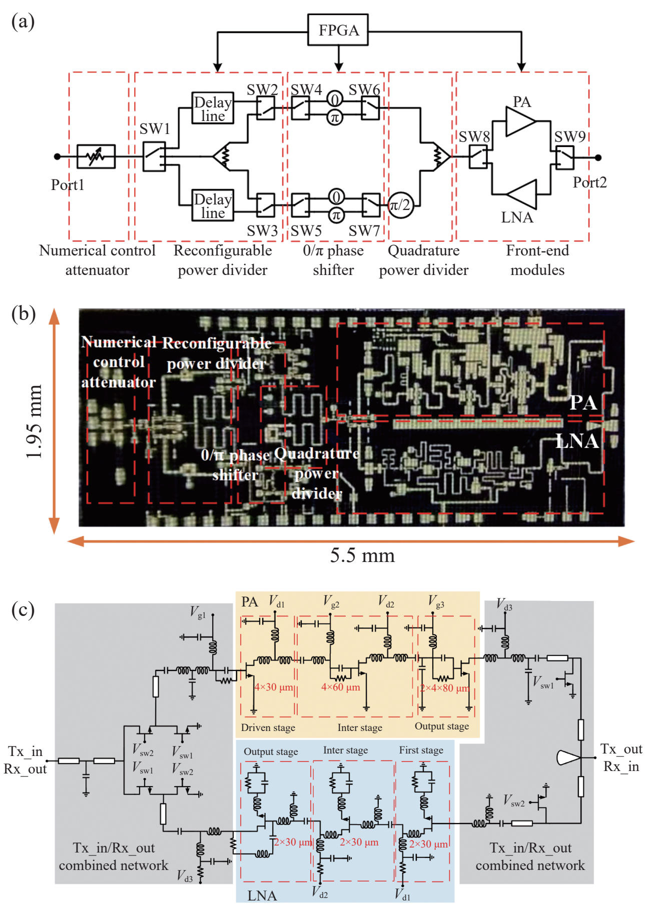

Figure 15 Time-modulated MMIC [144]. (a) Block diagram; (b) Photograph; (c) Schematic of the FEM.

Based on the aforementioned MMIC, a proposed STMPA with four elements was fabricated, as shown in Figure 16. The spectrum results indicate that the proposed STMPA has a relatively high suppression level of −16 dB at the positive fifth sideband and a suppression of over −17.5 dB for all other sidebands. The beam direction of the STMPA is determined by the time difference between the modulation waveforms of each element, which can be directly controlled by the FPGA. Experimental measurements of the scanned beams demonstrate that the STMPA is capable of achieving beam sweep angles ranging from −50° to 50°.

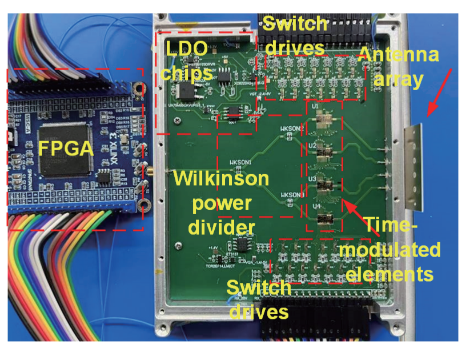

Figure 16 Photograph of the designed four-element STMPA [144].

The GaN-based time-modulated MMIC offers several advantages. This device satisfies the linearity and power requirements of radar signals, providing high transmission power while maintaining low noise levels. Additionally, the time-modulated circuit has the potential for further optimization to reduce the area as well as improve sideband suppression.

VIII. Conclusion and Future Prospects

This paper reviews TMAs and presents several applications of time modulation technology in phased array, single-channel DBF, FDA, and retrodirective arrays. The combination of TMAs with various conventional or novel antenna arrays can create new hardware implementation methods and improve their performance. In addition, recent advances in dedicated time-modulated chips, which have played a significant role in driving the progress of TMAs from academic research to practical applications, are also presented. While various application scenarios are discussed, the general principles of TMA design are summarized as follows.

The main factors in the design of TMAs are time and frequency, which represent design dimensions that are not available to normal antennas. In the time domain, this opportunity is reflected in the waveform and period of the time-modulated signal, while in the frequency domain, it is reflected in the amplitude and phase of both the operating and undesired sidebands, as well as their distribution within the spectrum. Furthermore, this review specifically focuses on hardware improvements in TMAs. In these designs, there are four additional factors to consider compared with conventional TMAs, and there is an additional need to consider four factors: flexibility, reconfigurability, hardware complexity, and efficiency. Flexibility affects the practical waveforms of the time-modulated signals generated by the time modulators. Reconfigurability reflects the ability to switch between different functionalities. The better these two factors are, the better the performance and the more functionalities that can be achieved by the TMA, but they are constrained by hardware complexity and efficiency. The hardware complexity depends on the components used in the time modulator, while the efficiency is determined by the RF power loss. The design of TMAs should be based on the requirements of the application scenario in both the time and frequency domains. This process involves designing the corresponding spectral characteristics and time-modulated signal waveforms. On this basis, the final hardware structure and the actual time-modulated signal are determined by balancing factors such as flexibility, reconfigurability, hardware complexity, and efficiency.

To best leverage these advances, various challenges need to be addressed to enable broader implementations of TMAs. In certain applications, such as Wi-Fi and Bluetooth communications, the current level of time modulation can achieve acceptable suppression levels of −30 dB to −40 dB for undesired sidebands. However, in more demanding scenarios such as radar, where there are stringent requirements for in-band spurious signals, the current level of time modulation has not yet satisfied the technical requirements. Although it is theoretically possible to design more complex time modulation circuits and corresponding modulation waveforms to further suppress undesired sidebands, the benefits of increasing hardware complexity at the current level are relatively limited. The conventional approach of sideband suppression appears to have reached a bottleneck. To address this issue, new approaches must be explored. The use of rising and falling edges in time modulation has long been a subject of research. Although these characteristics have been theoretically and experimentally validated, their practical application to further improve sideband suppression in TMAs has been limited primarily because of hardware constraints. However, with recent in-depth research on dedicated time modulation chips, the use of rising and falling edges is gradually becoming more practical. This development opens up new avenues for corresponding timing design and optimization that are of significant research value. By exploiting these advances, it may be possible to overcome the existing limitations and achieve higher levels of sideband suppression in TMAs.

Moreover, the development of high-frequency time modulation represents another important direction of this research progress. This approach has the potential to enhance the bandwidth of the transmitted signal and improve the response time of the system, thereby significantly enhancing the practicality of TMAs. However, it also imposes greater demands on the circuits responsible for time modulation and even on the circuits involved in generating control signals. To explore this opportunity, it is crucial to break away from the conventional approach and design innovative methods for signal control and hardware implementation specifically tailored for high-frequency time modulation. Currently, the highest achievable frequency for time modulation is approximately 10 MHz. However, if the frequency can be further increased to match that of the RF carrier signal, there would be numerous challenges in the corresponding hardware implementation, and it would render past theoretical analyses of time modulation obsolete. Addressing these challenges and understanding the complexities associated with high-frequency time modulation warrant further in-depth research.

Another promising research direction is the design of time-modulated circuits that are specifically based on antenna elements. Current TMAs use time modulators that are designed independently of the antenna elements, and the performance of the time modulation is also independent of the antenna element type. While this approach simplifies the theory and design of time modulation, it concurrently constrains the design flexibility, which is otherwise a key advantage of TMAs. Integrating the time modulator with the antenna element could provide control over the field distribution of the antenna element in the time dimension, thereby increasing design flexibility. Exploring the combination of various types of antenna elements with time modulation, along with their corresponding time-modulated circuits, yield new TMA characteristics. In fact, existing research on time-modulated metasurfaces [145]–[148] has already probed this area, providing a valuable reference for further advancing TMA technology.

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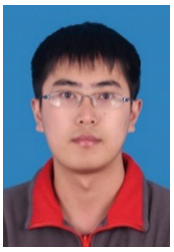
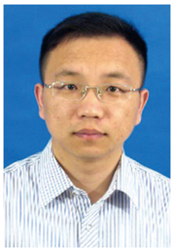
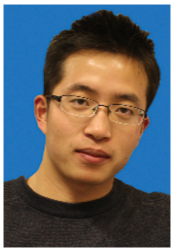
Wen Wu received the Ph.D. degree in electromagnetic field and microwave technology from Southeast University, Nanjing, China, in 1997. He is currently a Professor with the School of Electronic Engineering and Optoelectronic Technology, Nanjing University of Science and Technology, where he is also an Associate Director with the Ministerial Key Laboratory of JGMT. He has authored or coauthored more than three hundred journal and conference papers and has submitted more than thirty patent applications. His current research interests include microwave and millimeter-wave theories and technologies, microwave and millimeter-wave detection, and multimode compound detection. Dr. Wu was a recipient of six times of Ministerial and Provincial-Level Science and Technology Awards.
(Email: wuwen@njust.edu.cn)



Qiaoyu Chen was born in Jiangsu Province, China, in 1991. He received the B.E. and Ph.D. degrees in optical engineering and communication engineering from Nanjing University of Science and Technology (NJUST), Nanjing, China, in 2014 and 2021, respectively. He is currently a Post-Doctoral Researcher with NUST. His research interests include the design of time-modulated arrays, low-profile antennas with end-fire radiation and dual-band dual-circularly polarized antennas.
(Email: chenqiaoyu1213@njust.edu.cn)



Jin-Dong Zhang received the B.S. and Ph.D. degrees in optical engineering and communication engineering from the Nanjing University of Science and Technology, Nanjing, China, in 2005 and 2012, respectively. From 2015 to 2016, he was a Research Fellow with the Faculty of Science and Technology, University of Macau, Macau, China. He is currently an Associate Professor with the School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing, China. His current research interests include microwave and millimeter-wave theories and technologies, phased array, multibeam antenna and low-cost smart antenna.
(Email: zhangjd@njust.edu.cn)



Tongde Huang received the Ph.D. degree from the Department of Electronic and Computer Engineer, Hong Kong University of Science and Technology, Hong Kong, China, in 2013. From 2014 to 2016, he was a Research Fellow with Chalmers University of Technology, Gothenburg, Sweden. From 2016 to 2017, he was a Researcher with the Microwave Electronics Laboratory, Chalmers University of Technology, Gothenburg, Sweden. Currently, he is an Associated Professor with the School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing, China. His current research interests are GaN MMICs and CMOS RFIC including front-end, ultralow power and oscillator circuits.
(Email: tongdeh@njust.edu.cn)

Da-Gang Fang graduated from the Graduate School, Beijing Institute of Posts and Telecommunication, Beijing, China, in 1966. He has been a Professor at the Nanjing University of Science and Technology, Nanjing, China since 1986. His research interests include computational electromagnetics and microwave integrated circuits and antennas. He is a Fellow of the Chinese Institute of Electronics, IAC Co-Chair of iWEM'2016, General Co-Chair of ICMMT'2008, Vice General Chair of PIERS 2004, the recipient of the certificates from the IEEE Antennas and Propagation Society for his exceptional performance as a reviewer of *IEEE Trans. on AP* 3 times since 2015, the recipient of the technical excellence award from the 2021 International Applied Computational Electromagnetics Society Symposium in China, the recipient of the National Outstanding Teacher Award, the People's Teacher Medal, and the Provincial Outstanding Teacher Award. He has published 85 papers in IEEE journals. His name has been listed as the top 2% researchers in the 2023 updated science-wide author databases of standardized citation indicators.
(Email: fangdg@njust.edu.cn)