A NOVEL DIGITAL TRANSCEIVER MODULE STRUCTURE FOR MULTI-FUNCTIONAL ACTIVE PHASED ARRAY SYSTEMS

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Abstract

This paper proposes a transceiver (T/R) module structure for the multi-functional active phased array (APA) systems (including radar and wireless communication systems). The proposed structure uses a full digital interface and applies a GaN supply-modulated power amplifier (SMPA) to improve the power efficiency. In particular, the paper proposes a solution that combines the direct digital synthesis (DDS) with IQ modulation to perform flexibly the functions of phase shifting and amplitude level controlling of the transmitted signals with high resolution for antenna beamforming and scanning. The proposed solution not only eliminates RF attenuator and phase shifter that are commonly used in antenna beamforming but also flexibly configures system functions. The experimental results of designing and manufacturing DDS and IQ modulation parts demonstrate the ability of the proposed structure to generate several common signal types used in radar and communication systems as well as verifies the ability to control the phase and the amplitude level of the transmitted signal.

Index terms

Active phased array (APA), active electronically scanned array (AESA), GaN supply-modulated power amplifier (SMPA), direct digital synthesis (DDS), IQ modulation

1. Introduction

Multi-functional radio systems are normally a combination of multiple functions in a radar system [1] or a combination of wireless communication and radar functions on a single radio system [2]. Multi-functional radio systems have been researched and developed for a long time [3], [4] to share the frequency resource, reduce electronic interference between devices [5], [6], and improve system efficiency as well as reduce the number and life cycle costs of devices [7]. Along with the increasing demand for communication systems and the commercialization of radar systems, multi-functional radio systems are paid more and more attention in research and development.

The main functions of the multi-functional radio systems can be mentioned such as radio communications, navigation radar, weather radar, electronic warfare, and so on.

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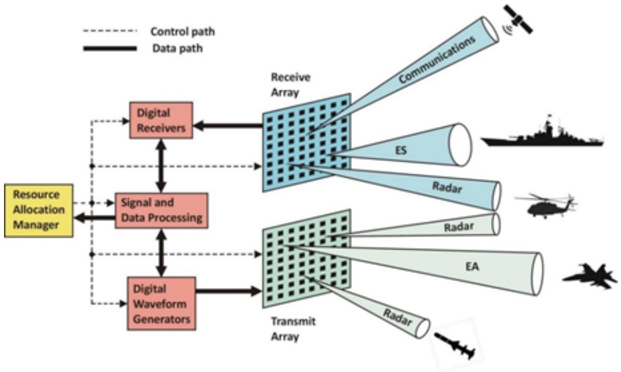

Fig. 1. The architecture of a typical multi-functional radio system.

To accommodate multiple functions simultaneously, multiple-input and multiple-output (MIMO) technology and active electronically scanned array (AESA) technology are critical in multi-functional radio systems [7].

Figure 1 depicts a typical construction for an onboard multi-functional radio system [8]. In Fig. 1, each opening part of the antenna array can be used to simultaneously synthesize independent antenna beams for use in different system functions.

Besides the advantages that were mentioned above, there are also potential risks and challenges when merging many functions on one system.

Since many different system functions are merged on a single hardware system, the failure of the device can result in the inability to perform all functions performed by the system. This is much more severe than the case where each function is performed by a separate system.

In addition, like the phased array antenna systems and digital beam pattern synthesis, the multi-functional radio system is also built on a set of transceiver modules that play a decisive role in this system. However, the system is facing some problems such as a large number of transceiver modules, layout space limitation, the efficiency of power amplifiers, cost, cooling, and so on.

In this paper, a new transceiver (T/R) module structure that meets these requirements of a multi-functional active phased array (APA) radio system is proposed in Section 2. The proposed architecture is a fully digital interface and combines both direct digital synthesis (DDS) and IQ modulation techniques to generate the transmitted signal. This solution allows the T/R module can perform various system functions and is capable of generating a variety of signals with wide bandwidth. In Section 3, the experimental results of the proposed solution are presented to demonstrate the ability to generate and synchronize transmitted signals, also to control the phase and amplitude level of the transmitted signal.

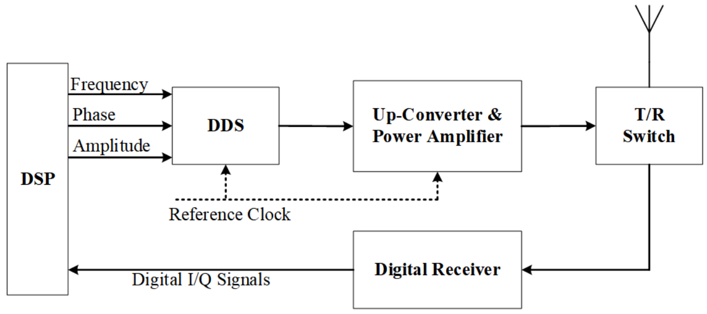

Fig. 2. DDS based a T/R module structure.

2. The transceiver module structure

2.1. The digital T/R module for multi-functional systems

The T/R module plays a key role in an active phased array system. Especially in multi-functional systems, the requirements for features and flexibility in setting up operating modes and parameters are more demanding. Except for the requirements of phase shifting and amplitude controlling for beam pattern synthesis, it is especially important to generate different types and bandwidths of signals that correspond to different features in a multi-functional radio system.

Several T/R module architectures for multi-functional systems have been studied and published in [9], [10], [11], [12]. In [9], the isolation properties of the circular polarizer are used to isolate the receiver functions of the communication system and radar. A based DDS T/R module structure for multi-functional systems is presented in [10].

In Fig. 2, each T/R module has a DDS unit to generate the transmitted signal. The phase, amplitude, and frequency data of the transmitted signal are fed to the inputs of the DDS unit. The output signal of DDS is controlled and synchronized by the digital signal processor (DSP) and the common reference clock signals.

In [11], the authors proposed a T/R module structure for multi-functional radar and radio communication systems that are employed in future intelligent transport systems. By using a solution that creates I/Q signals directly from DSP and the digital-to-analog converter (DAC) before sending to IQ to generate the transmitted signal. A similar solution is presented in [12] with the T/R module structure shown in Fig. 3.

It is easy to see that the beamforming of the multi-functional APA systems using digital T/R modules is almost based on the phase-shifting and amplitude controlling characteristics of the IQ modulator or DDS to combine the transmitted signal.

The IQ modulation allows controlling the phase and amplitude levels with higher resolution than the traditional individual RF phase shifter and amplitude attenuator. However, the DSP (usually FPGA-based implementation) will experience a limited clock frequency and signal bandwidth due to the limited operating frequency of FPGA units.

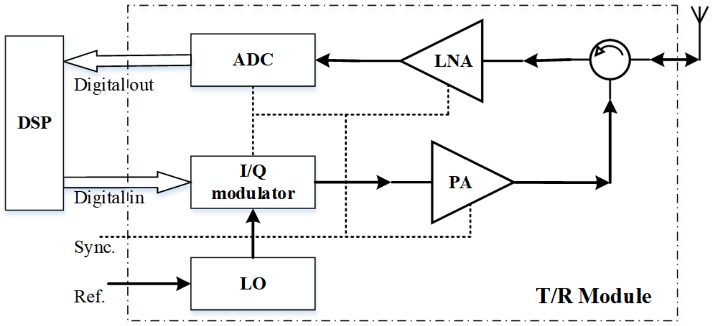

Fig. 3. The digital T/R module block diagram in [12].

This problem is solved by using directly DDS or DDS in conjunction with VCO-PLL. However, the disadvantage of using the DDS solution is that each T/R module must have its own DDS and PLL. In addition, synchronizing and controlling a large number of DDS will be difficult for the control and process system.

2.2. The proposed T/R module structure

This paper proposes a T/R module structure for multi-functional active phased array systems that combines the advantages of DDS and IQ modulation techniques. The main purpose of the proposed T/R module structure is to apply to APA systems with radio communication, radar, and electronic warfare functions. The proposed T/R module architecture is depicted in Fig. 4. Accordingly, four T/R modules (DTRM 1 to DTRM 4) are integrated into a basic unit that employs a slice architecture. The unit is the basic block for the integration of the active phased array system.

In the proposed structure, the IQ modulator is individually arranged per each T/R module, while the DDS unit and local oscillator (LO) signals (IF_LO and RF_LO) are shared for all four modules. The DDS output signal can be mixed with an IF_LO signal or used directly as the LO signal of the IQ modulator. Because of the parameter control capabilities of both the DDS and the IQ modulator, the parameters of the output signal of the IQ modulator can be controlled by both the DDS and the IQ modulator. Therefore, this solution allows us to flexibly choose whether to use either the IQ modulator or the DDS unit to generate the transmitting signal according to the system function. In particular, the DDS unit is preferred to generate the transmitted signals that require a fast speed or wide bandwidth, e.g., fast frequency-hopping signals, FMCW signals, etc.

The generation of the transmitted signal as well as the control of its amplitude and phase parameters is performed by both the IQ modulator and the DDS unit. The generated IF transmitted signal will be filtered and amplified (using the low-pass filter (LPF), amplifier, and attenuator (AMP/ATT)) before being mixed up to the operating RF frequency (MIX RF). The RF signal will be amplified using the drive amplifier (DRA), and the high power amplifier (PA) before sending to the antenna through the circulator (CIR). Due to the multi-functionality, the system can use wide bandwidth sig-

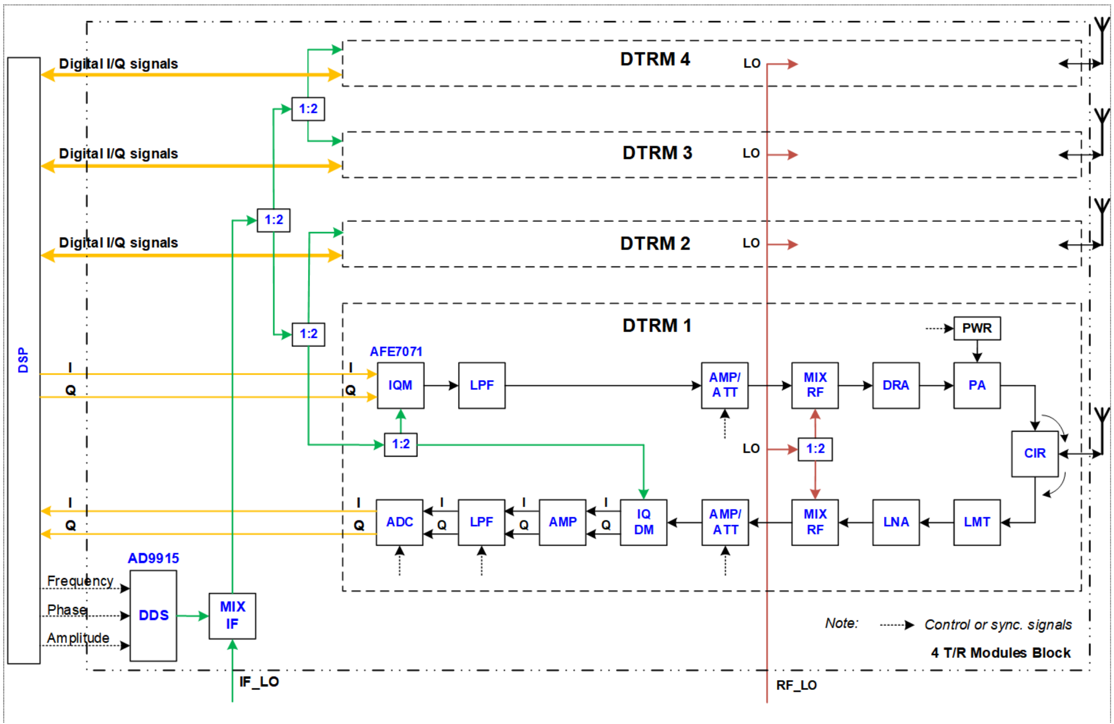

Fig. 4. The proposed T/R module structure diagram.

nals or multiple signals simultaneously. So, the transmitter applies 2 stages of frequency converter to reject the interferences and the image noise.

To improve the power efficiency, the GaN supply-modulated power amplifier (SMPA) is employed [13], [14]. Accordingly, the supply voltage for the power amplifier will change following the input power level (or the required output power level) to ensure optimal power efficiency of the power amplifier. In addition, a digital attenuator is set in the intermediate frequency (IF) stage to control the overall power of the system that can increase or decrease corresponding to the required power that is accorded to the operating distance to improve the power efficiency of the whole system [14]. The simulation results in [14] show that the GaN SMPA can achieve and maintain high efficiency in a wide range of output backoff power. The systematic PAE can increase about 14 $\sim$ 18% at the same condition of the array amplitude distribution and array scales by using GaN SM PA.

In the receiver, frequency converter technical and IQ demodulation are used before digitizing the received RF signal. The signal received from the antenna passes through the circulator (CIR), the limiter (LMT), and the low noise amplifier (LNA), then go to the down-mixer (MIX RF). The received IF signal passed through the IF amplifier (IF AMP), the attenuator (ATT), and sent to the IQ demodulator (IQ DEM). The output signals of IQ DEM are baseband signals on two I/Q channels. The I/Q signals are amplified (AMP), filtered (LPF), and converted to digital (ADC) before sending to the

DSP. The difference is in the intermediate frequency stage. A real-time controlled (RTC) digital attenuator is placed in this stage to quickly control the amplitude of the receive signal to avoid saturation and increase the dynamic range of the receiver in the case of closed or large targets, or when it is actively interfered with. This is especially important when performing radar functions.

The DDS output signal can be mixed with the IF_LO signal to reach a frequency high enough for easy removal of the high-order harmonics. The mixed signal is used as the LO signal for both the IQ modulator and the IQ demodulator. To avoid DC offset in the receiver, the I/Q signals could be configured to produce a sinusoidal signal at a fixed low-frequency to corresponding to the function and the demand of the system.

2.3. Generating waveform and control on phase and amplitude parameters of the transmitted signal

In this section, the paper focuses on analyzing the waveform generation and the control on phase and amplitude of the transmitted signal in detail. As shown in Fig. 4, the transmitted signal and phase, amplitude parameters can be synthesized and controlled by using the IQ modulator. However, this method only allows generating the signals whose bandwidth is limited by the data rate and the clock of DAC that is fed from DSP.

To maximize the advantages of both the DDS unit and IQ modulator in the proposed T/R module structure, the transmitted signal is generated by a combination of both the DDS unit and the IQ modulator. In which, the DDS plays the role of generating waveforms while the IQ modulator performs phase and amplitude control of the signal. The DDS is a well-known frequency synthesizer method used in waveform generation [15], [16]. It allows generating almost desired signal types with superior wide bandwidth and high speed and great efficiency compared with the solution that employs the I/Q signals from DSP (or FPGA). For example, the DDS AD9915 of Analog Devices with a 2.5 Gsps sampling rate and a 12-bit DAC allows generating a signal up to 800 MHz [17]. The control of phase and amplitude of the transmitted signal is performed through the control of phase and amplitude of the I/Q signals.

Assume that the output signal of DDS $s_{DDS}(t)$ is given as:

$$s_{DDS}(t) = \sin(2\pi f_{DDS} t + \varphi_{DDS}) \quad (1)$$

where φ_{DDS} is the initial phase of the DDS output signal.

The typical structure of an IQ modulator is shown in Fig. 5.

As shown in Fig. 5, the digital input signals are converted into analog signals by the DACs. The output signal of the DAC on the I channel (I signal) is mixed directly with the LO signal (that is the output signal of the DDS unit). On the Q channel, the output signal of the DAC (Q signal) is mixed with the 90-degree phase-shifted LO signal. And then, the output signals of the mixers on two channels are in phase with each other and are combined to produce the IF transmitted signal.

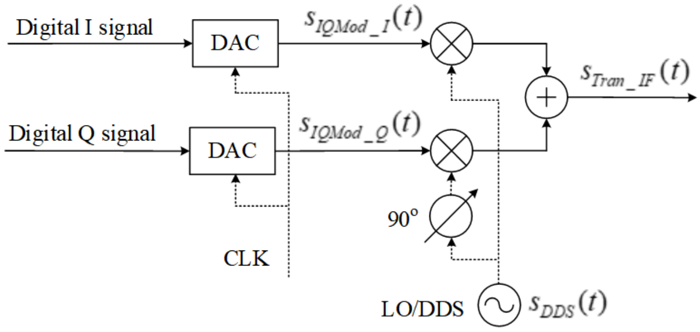

Fig. 5. The typical structure of an I/Q modulator.

Accordingly, the I/Q signals are represented by:

$$s_{IQMod\_I}(t) = A_{IQ} \times \sin(2\pi f_{IQ}t + \varphi_{IQ}) \tag{2}$$

$$s_{IQMod\_Q}(t) = A_{IQ} \times \cos(2\pi f_{IQ}t + \varphi_{IQ}) \tag{3}$$

where A_{IQ} and φ_{IQ} are the initial amplitude and phase of the I/Q signals, respectively.

So that, the IF transmitted signal at the output of the IQ modulator is then:

$$s_{Tran\_IF}(t) = A_{IQ} \times \cos(2\pi f_{Tran\_IF}t + \varphi_{Tran\_IF}) \tag{4}$$

where f_{Tran_IF} and φ_{Tran_IF} are the frequency and the initial phase of the transmitted signal, respectively.

The frequency f_{Tran_IF} and initial phase φ_{Tran_IF} are calculated as:

$$f_{Tran\_IF} = f_{DDS} + f_{IQ} \tag{5}$$

$$\varphi_{Tran\_IF} = \varphi_{DDS} + \varphi_{IQ} \tag{6}$$

According to Equations (4) and (6), the amplitude level of the transmitted signal is controlled via the amplitude level of the I/Q signals, and the phase can be controlled via the initial phases of the I/Q signals or the DDS signal. In Fig. 4, since four T/R modules shared a common DDS unit, thus the phase control feature of the DDS is only used for generating the waveform and correcting the phase error of the transmitted signal between T/R module slices. The phase shifting of the transmitted signals for beam-forming and beam-scanning is set up via the initial phase of the I/Q signals.

Because the IQ modulator uses DACs to convert the input digital data into quadrature analog signals, then the amplitude and phase resolutions are dependent directly on the data bits' number of DACs. With a linear N - bits DAC, the amplitude resolution (or amplitude step) $\Delta\alpha$ is determined by as follows:

$$\Delta\alpha = \frac{A_{DAC}}{2^{N-1}} \tag{7}$$

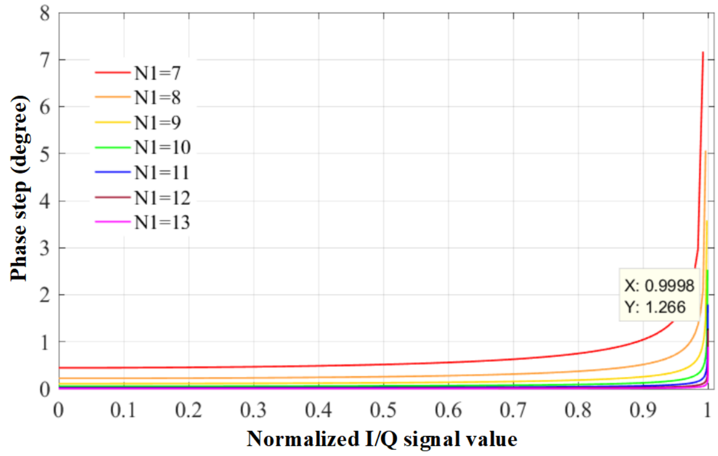

Fig. 6. Phase step vs normalized I/Q signal values.

where A_{DAC} is the maximum output voltage amplitude of DAC.

For the phase resolution, we consider the phase step caused by the amplitude step $\Delta\alpha$ at the amplitude level A_{IQ} of I/Q signals, and defined in the following equation:

$$\Delta\varphi = \left|\operatorname{arsin}\left(\frac{s_{IQMod\_I}(t) + \Delta\alpha}{A_{IQ}}\right) - \operatorname{arsin}\left(\frac{s_{IQMod\_I}(t)}{A_{IQ}}\right)\right| \tag{8}$$

where $\Delta\varphi$ [rad.] is the phase step.

If the I/Q signal frequency equals zero ($f_{IQ} = 0$), Equation (8) is written as:

$$\Delta\varphi = \left|\operatorname{arsin}\left(\frac{k+1}{2^{N_1}}\right) - \operatorname{arsin}\left(\frac{k}{2^{N_1}}\right)\right| \tag{9}$$

where N_1 is the number of bits of the DAC corresponding to the amplitude level $A_{IQ}, k = 0 \div (2^{N_1} - 1)$ is the number of steps corresponding to the value of $s_{IQMod\_I}(t)$.

From Equation (8), the phase step $\Delta\varphi$ is dependent on the values of N_1 and k. The simulation results of the phase step $\Delta\varphi$ when $N = 14$ and $N_1 = 7 \div 13$ are shown in Fig. 6. The higher the bits number N_1, the smaller the phase step $\Delta\varphi$. From the figure, the phase step gets the maximum value when the value of I/Q signals is equal to the signal amplitude (A_{IQ}). The simulated results show that the maximum phase step is about 7^o with $N_1 = 7$, and less than 1^o with $N_1 = 13$. The phase step is less than 1^o while the I/Q signal value is less than $0.9 \times A_{IQ}$. Therefore, to achieve the required phase resolution, the amplitude level A_{IQ} of the I/Q signals must be greater than a specified value corresponding to the number of bits $N_1 = N_0$. Combined with the dynamic range requirement, the minimum number of DAC bits $N_{\min}$ is given by:

$$N_{\min} = N_0 + M \tag{10}$$

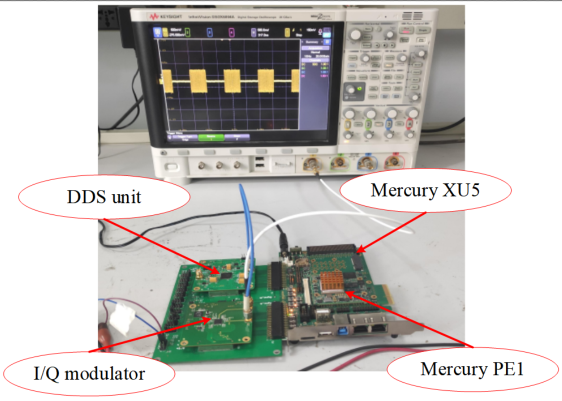

Fig. 7. The IQ modulator and DDS unit prototypes.

where M is corresponding to the amplitude dynamic range (DR) of the transmitted signal that is given as:

$$DR = 20\log_{10}2^{M} = 6 \times M(\text{dB}) \tag{11}$$

The dynamic range of the transmitted signal amplitude includes the dynamic range of amplitude distribution for beamforming and the dynamic range of operation distance adjustment. Therefore, the DACs must have a sufficient number of bits to ensure the resolutions of phase, amplitude, and the dynamic range of the transmitted signal.

3. The experimental results

In this section, the IQ modulator and DDS unit prototypes have been implemented to evaluate the ability of the proposed T/R module structure. In which, the IQ modulator has been designed and manufactured employing Texas Instruments AFE7071 device [18]. The DDS component used in the DDS unit is Analog Devices AD9915 [17]. The IQ modulator and the DDS unit on the test bench are shown in Fig. 7.

The FPGA-based blocks used to control and synchronize the operations of these prototypes have been designed in Vivado Design Suite and synthesized in Xilinx® Zynq Ultrascale+™ MPSoC on Enclustra PE1 [19] and Mercury XU5 boards [20]. The Keysight testing instruments (DSOX6004A oscilloscope (4 channels, 1 GHz bandwidth, and 20 GSa/S sampling rate) [21] and N9343C spectrum analyzer [22]) are used to measure the generated signals parameters.

Barker code and FMCW signals were generated and measured to evaluate the performance of the proposed structure on the waveform generation. Fig. 8 depicts the measurement result of the generated Barker code signal with the "0001101" codeword by the oscilloscope. The signal frequency is set at 150 MHz and the sub-pulse width is 96 ns. From the figure, the measured signal is correct with the modulation codeword and the required parameters.

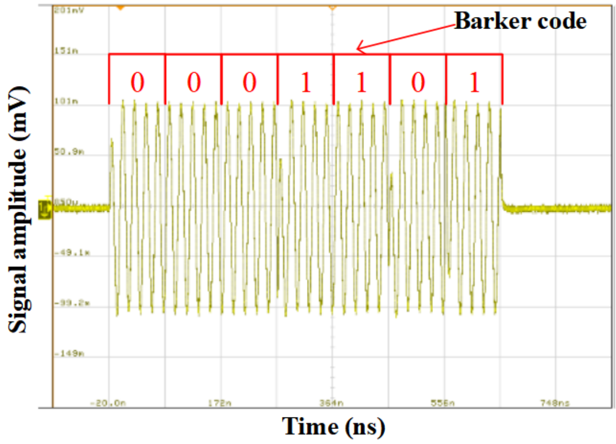

Fig. 8. The generated Barker code signal.

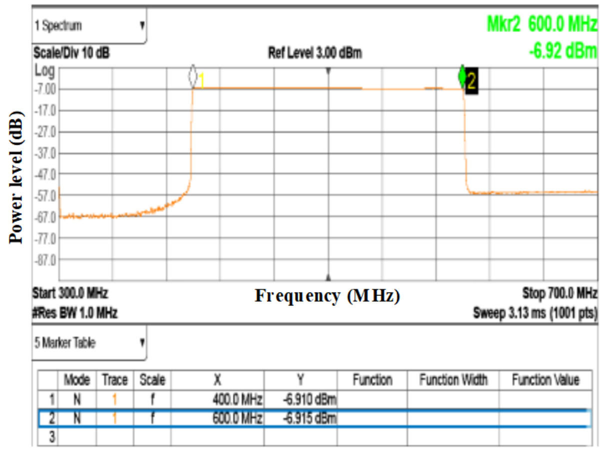

Fig. 9. The spectrum of FMCW signal with 200 MHz bandwidth.

The test results show that the values between consecutive code bits are the same, the phase and amplitude of the signal between the corresponding sub-pulses are stable. In the case of having a change in values between consecutive code bits, the phase of the signal is inverted according to the change. However, due to the characteristics of the components in DDS, when there is a change in the frequency, phase, or amplitude of the modulated signal, the device needs a small amount of time to stabilize the parameters of the output signal. With DDS AD9915, the experimental results show that this time interval is less than 15ns. This restricts the width of the smallest modulation pulse that can be generated.

A wideband FMCW signal is generated by the prototypes. The required parameters of the signal are 500 MHz center frequency, 200 MHz bandwidth, and a 10 ms repetition period. The measured spectrum of the generated FMCW signal is shown in Fig. 9.

As shown in the figure, the synthesized signal fully meets the requirements of frequencies and bandwidths. We can see that over the entire bandwidth, the power level of the transmitted signal is relatively flat with a ripple across the bandwidth of about 0.01 dB. These results demonstrate that the proposed approach is capable of synthesizing complex and wide-band signal types.

The control on amplitude and phase of the transmitted signal is evaluated by synthesizing and scanning the beam with a linear array antenna. The considered array antenna consists of 16 microstrip-type elements spaced equally by a half wavelength. The Taylor distribution is applied to obtain a side-lobe level of -30 dB. The initial phases of the elements are calculated to form the beams at 5, 15, and 25-degree angles. The PCAAD tool of Antenna Design Associates [23] is used to calculate the amplitude and initial phase values and synthesize the antenna patterns. The results of antenna patterns are shown in Fig. 10.

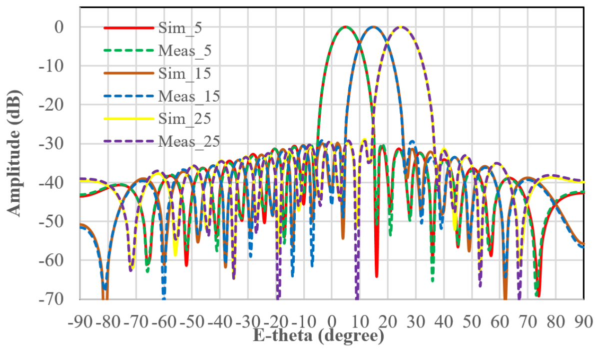

Fig. 10. Simulated antenna pattern plots.

In the figure, solid lines represent antenna patterns corresponding to parameters calculated by the PCAAD tool (simulated patterns), while the dashed lines depict antenna patterns synthesized from actual measured values (measured patterns). The figure shows that the simulated patterns and measured patterns almost coincide with all three values of the main beam angle surveyed. This result is due to the errors of amplitude and phase are very small. The measurement results show that the phase error is less than one degree and the maximum amplitude error is 0.15 dB.

In fact, the phase and amplitude errors are larger due to existing errors of phase and amplitude on the transmission line of the I and Q channels inside/outside of the IQ modulator. However, the IQ modulator AFE7071 is designed with the built-in amplitude and phase error compensators of the I/Q signals with very high resolution (gain and phase are controlled and corrected by 11 bits and 10 bits to implement the range of 0 $\sim$ 2 dB and -22.5 $\sim$ 22.5 degrees, respectively), as well as the ability to adjust the offset of the LO. This helps to minimize the phase and amplitude errors of the generated medium-frequency signal compared to the required values.

4. Conclusion

The paper proposes a T/R module structure that can be used in the multi-functional active phased array systems of communications and radar. In particular, the proposed structure combines the DDS unit and I/Q modulator to synthesize the transmitted signal. This approach not only can synthesize flexibly and easily different types of transmitted signals according to the function of systems but also can control the phase and the amplitude of the generated signal with high resolution to meet the requirements of beam-forming and beam-scanning.

The DDS unit and the IQ modulator of the proposed T/R module are designed and experimentally tested. The test results demonstrate the efficiency of the proposed structure in generating and controlling the phase and the amplitude of the transmitted signal. The DDS is useful to synthesize the complexity and wideband signals. The IQ modulator allows controlling the phase and amplitude parameters of the transmitted signal with high precision. In addition, using a common DDS unit for multiple T/R modules helps to reduce the cost, layout space, and power consumption of the system. A solution of GaN supply-modulated power amplifiers according to the required output power level is also mentioned to improve the power efficiency. Thus, the proposed T/R module is suitable for multi-functional active phased array systems.

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MỘT CẤU TRÚC MÔ-ĐUN THU/PHÁT SỐ MỚI DÙNG CHO CÁC HỆ THỐNG MẠNG PHA TÍCH CỰC ĐA CHỨC NĂNG

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Tóm tắt

Bài báo đề xuất một cấu trúc mô-đun thu/phát (T/R) cho hệ thống mạng pha tích cực (APA) đa chức năng (bao gồm các hệ thống ra-đa và thông tin vô tuyến). Cấu trúc đề xuất sử dụng giao tiếp số hoàn toàn và sử dụng bộ khuếch đại công suất công nghệ GaN và kỹ thuật điều chế nguồn (GaN SMPA) để cải thiện hiệu suất công suất. Đặc biệt, bài báo đề xuất một giải pháp kết hợp giữa bộ tổng hợp số trực tiếp (DDS) và bộ điều chế IQ để thực hiện linh hoạt các chức năng điều khiển xoay pha và mức biên độ của các tín hiệu phát với độ phân giải và chính xác cao cho tổng hợp và quét búp sóng ăng-ten. Giải pháp đề xuất không chỉ loại bỏ các bộ suy giảm, bộ xoay pha cao tần thường được sử dụng trong tổng hợp búp sóng ăng-ten mà còn linh hoạt trong cấu hình các chức năng hệ thống. Các kết quả thực hiện của thiết kế và chế tạo các thành phần bộ DDS và bộ điều chế IQ cho thấy khả năng của cấu trúc đề xuất trong tạo ra một số dạng tín hiệu phổ biến được sử dụng trong các hệ thống ra-đa và thông tin liên lạc, cũng như chứng minh khả năng điều khiển pha và mức biên độ của tín hiệu phát.