A Novel 28 GHz Phased Array Antenna for 5G Mobile Communications

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Abstract: A novel phased array antenna consisting of 256 elements is presented and experimentally verified for 5G millimeter-wave wireless communications. The antenna integrated with a wave control circuit can perform real-time beam scanning by reconfiguring the phase of an antenna unit. The unit, designed at 28 GHz using a simple patch structure with one PIN diode, can be electronically controlled to generate 1 bit phase quantization. A prototype of the antenna is fabricated and measured to demonstrate the feasibility of this approach. The measurement results indicate that the antenna achieves high gain and fast beam-steering, with the scan beams within ±60° range and the maximum gain up to 21.7 dBi. Furthermore, it is also tested for wireless video transmission. In ZTE Shanghai, the antenna was used for the 5G New Radio (NR) test. The error vector magnitude (EVM) is less than 3% and the adjacent channel leakage ratio (ACLR) less than −35 dBc, which can meet 5G system requirements. Compared with the conventional phased array antenna, the proposed phased array has the advantages of low power consumption, low cost and conformal geometry. Due to these characteristics, the antenna is promising for wide applications in 5G millimeter-wave communication systems.

Keywords: 5G mobile communications; millimeter wave; phased array antenna

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1 Introduction

5G wireless communication systems are actively tested and deployed worldwide now. They are supposed to enable extremely fast communication speed of up to 10 Gbit/s[1–2]. Compared with 1G to 4G wireless communications, 5G systems are mostly concerned with the channel capacity, power consumption, and system cost. They provide multiple application scenarios, such as enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (uRLLC), and massive machine type communications (mMTC). 5G will affect every aspect of our lives, implementing the virtual reality (VR), Internet of Things (IoT), smart home, and so on. A lot of challenges need to be overcome to realize the above goals, including those in the transmission network.

Antennas are critical components in 5G wireless transmission networks[3]. While a lot of efforts have been devoted to antenna designs in mobile devices, here we focus on antennas on base stations. Gain and coverage are two critical requirements for base station antennas; however, they contradict each other: a higher gain results in a narrower beamwidth and hence a limited coverage area. To solve this problem, multiple beams and beam scanning techniques, usually realized by phase array antennas, provide a feasible solution.

This paper presents a novel phased array antenna operating at 28 GHz for 5G wireless communications. The phased array design method is introduced first, and the element and array configuration are discussed next. The measured results of the antenna array and the communication test of 1 transmitter-1 reciever (1T-1R) and 1 transmitter-2 recievers (1T-2R) systems are presented to demonstrate the promising potential of the proposed mm-wave phased array for 5G systems. In addition, the antenna was used for the 5G NR test of ZTE Shanghai, which shows good performance in the error vector magnitude (EVM) and adjacent channel leakage ratio (ACLR).

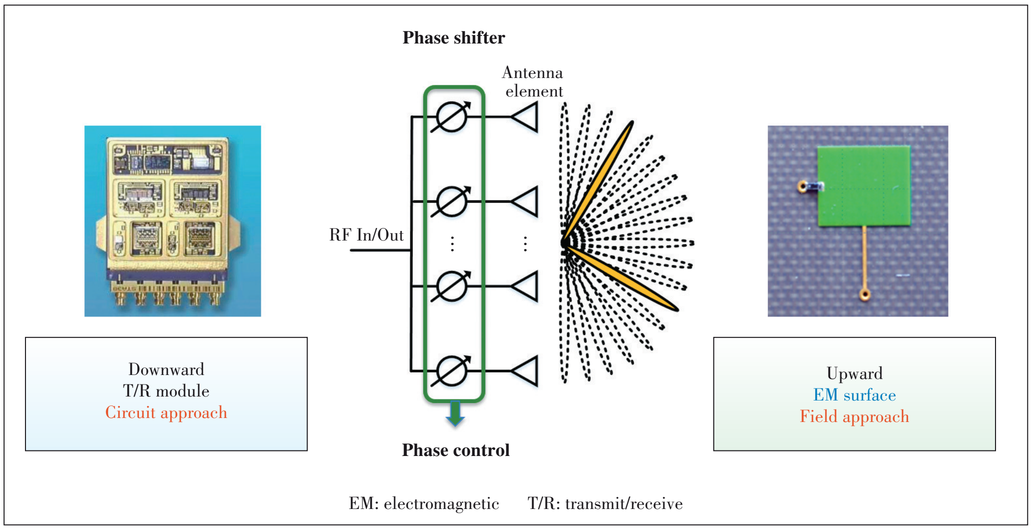
2 Design Methods for Phased Arrays

To achieve the beam scanning capability in an antenna array, the excitation phase of each element needs to be tunable in order to form a coherent phase front at the desired beam direction. As shown in **Fig. 1**, the phase control method is the key point in the design of phased arrays and two different methods can achieve phased arrays.

The major trend in phased array development is based on the microwave and millimeter-wave integrated circuit (MMIC) technology. The phase control function is realized from the antenna element "downward" and a representative device is a transmit/receive module connected to each element. This circuit approach has a lot of advantages, such as excellent radiation performance and flexible radiation beam; however, the power efficiency, antenna weight, and system cost are major concerns, especially for those large-scale and high-frequency phased arrays.

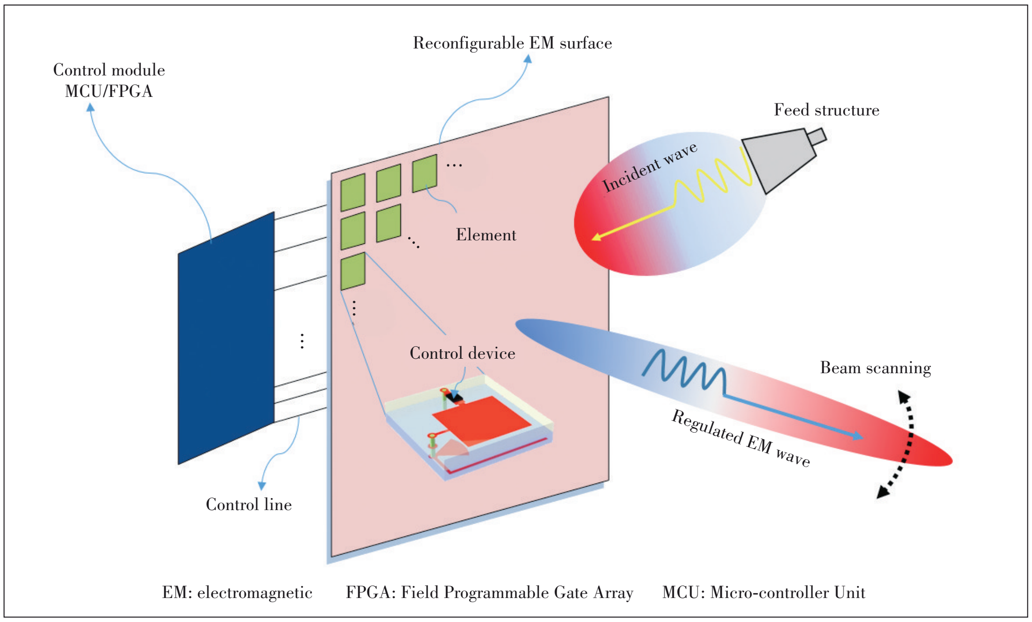
A novel alternative approach is to move the phase control function "upward" from antenna element and an example is a reconfigurable reflective surface. As shown in **Fig. 2**, when electromagnetic wave impinges on this surface, an additional reflection phase is added upon reflection, which can be tuned by active components such as PIN diodes and varactor diodes. In this field approach, both "radiation" and "phase control" functions are integrated onto the surface. This new approach has attracted growing interests because of its high efficiency, conformal geometry, feasibility for millimeter-wave and tera hertz operation, and low system cost.

The phased array using the field approach consists of three major components: a reconfigurable surface, a control module,



EM: electromagnetic T/R: transmit/receive

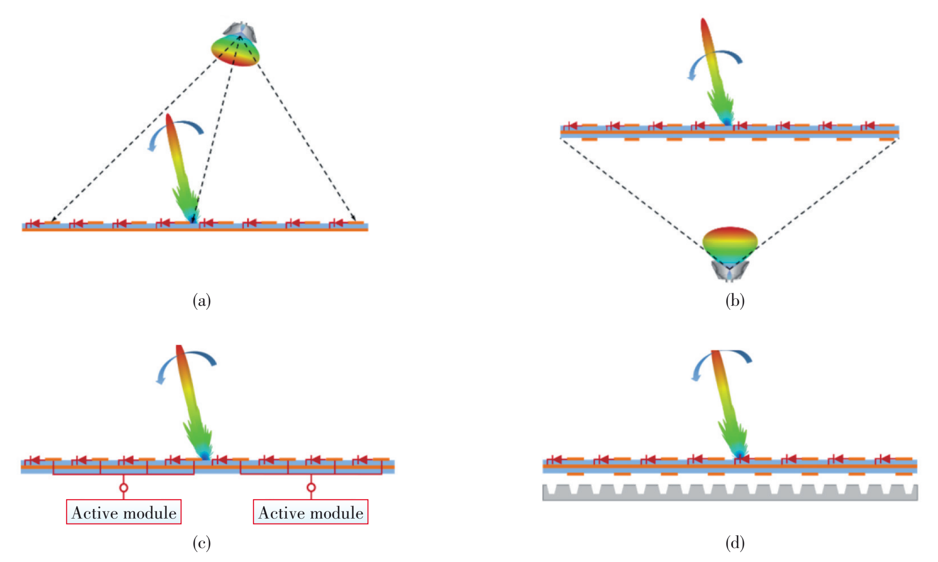
▲Figure 1. Design approaches for phased array antennas: circuit approach using T/R modules and field approach using reconfigurable electromagnetic surfaces.



EM: electromagnetic FPGA: Field Programmable Gate Array MCU: Micro-controller Unit

▲Figure 2. Structure of the novel phased array antenna.

and a feeding structure[4–6]. An array of patch elements are arranged on the surface, and each element is integrated with control devices, such as PIN diodes, varactor diodes, MEMS switches and mechanic actuators. The statuses of these devices are determined by a control module, usually a Micro-controller Unit (MCU) or a Field Programmable Gate Array (FPGA) board. To transmit/receive wave to/from the surface, a feed structure is necessary, which can be a horn in the far field[7], a passive array in the near field, or even a constrained feed network connected to the surface, as shown in **Fig. 3**.

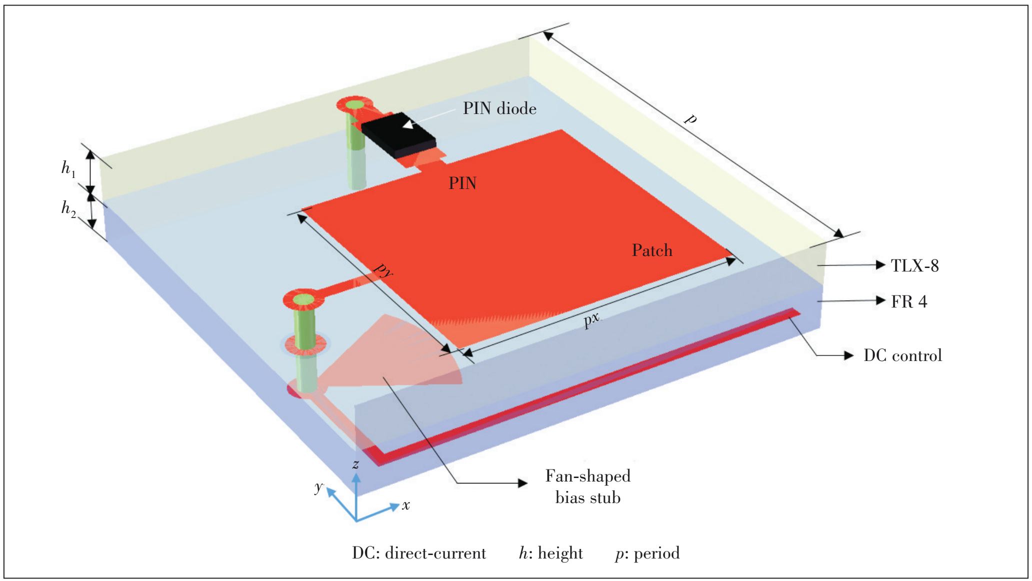


▲**Figure 3. Various structures of reconfigurable EM surface: (a) reflectarray with horn antenna; (b) transmitarray with horn antenna; (c) transmitarray with active module; (d) transmitarray with coupling network.**

3 A Novel Mm-Wave Phased Array Antenna Design and Measurement

3.1 Electromagnetic Surface Element

A phased electromagnetic surface antenna operating at 28 GHz for 5G millimeter-wave communications is designed and tested. The element geometry, array configuration, and measurement results for both the antenna radiation and system throughput are presented in this section.



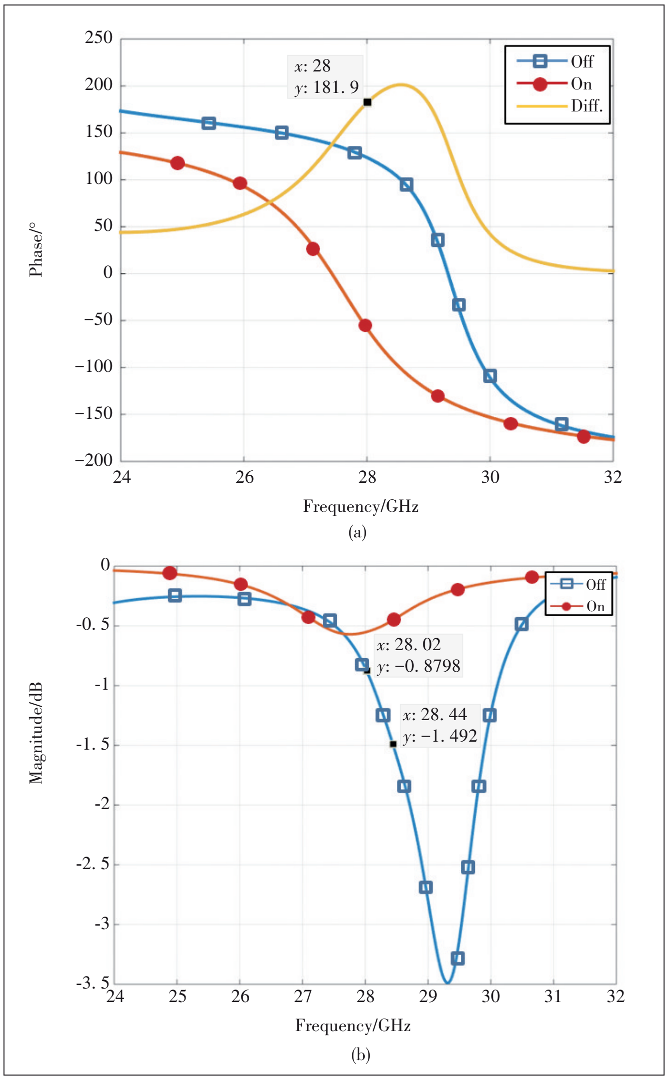
▲**Figure 4. Geometry of a reconfigurable element designed at 28 GHz: p=5.35 mm; px=3.15 mm; py=3.025 mm; h_1=0.508 mm; h_2=0.500 mm.**

Fig. 4 shows the geometry of a reconfigurable element, which consists of a patch layer, a ground layer, and a biasing line layer. A PIN diode is connected to the patch to control its reflection phase at 28 GHz. One side of the PIN diode is grounded directly, and the other side is connected to a DC biasing voltage through the patch and the biasing line. A fan-shaped stub is used to isolate the DC and RF interference. The element dimensions are listed in the caption of Fig. 4 and the element is carefully designed to obtain a 180° phase difference between PIN On-Off statuses at 28 GHz. Moreover, the reflection loss of the element is less than 1 dB at 28 GHz, as shown in **Fig. 5**.

3.2 Phased Array Antenna Design

Based on element design and simulation, a phased array consisting of 16 × 16 patch elements is designed. In space-fed array designs, the reconfigurable reflective surface is usually placed in the far-field region of the feed. The magnitude of incident wave on the surface is related to the radiation pattern of feed, as well as the spatial distance between the feed and each element.

In this paper, a horn antenna is designed as the feed. The −10 dB beam width of the feed is ±30°, so the chosen distance between the phase center of feed horn and the reflective surface is 66 mm to balance spillover efficiency and illumination efficiency.



▲ **Figure 5. Simulated results of element: (a) phase result; (b) magnitude result.**

For a reconfigurable reflective surface, the required compensation phase ϕ_{rmn} for the (m, n)th element is computed by

$$\phi_{rmn} = \phi_{imn} - k \times \widehat{u_0} \times \overrightarrow{r_{mn}} + \Delta\phi, \quad (1)$$

where ϕ_{imn} is the incident phase of the (m, n)th element, k is the free space wavenumber, $\widehat{u_0}$is the unit vector in the main beam direction, $\overrightarrow{r_{mn}}$is the position vector of the (m, n)th element, and $\Delta\phi$ is an additional optimized phase[8]. If we use reconfigurable elements with 360° full-phase coverage, the required compensation phase for each element will be continuous. For a 1 bit phased array, there are only two-phase states for each element and they are controlled by PIN On or Off. Therefore, the required compensation phase should be quantized. As simulated in Fig. 5 at 28 GHz, PIN Off means 130° and PIN ON means −50°. We use Eq. (2) to quantize the continuous phase into 1 bit compensation phase.

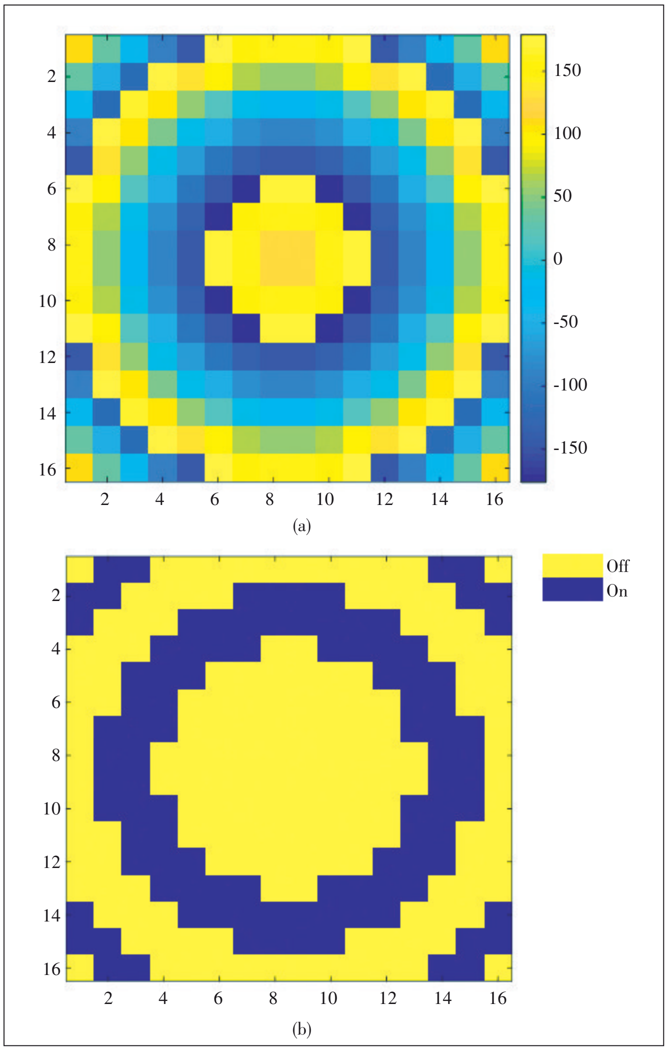
$$\phi_{rmn\_quantized} = \begin{cases} 130^\circ, \phi_{rmn\_continous} \in [40^\circ, 220^\circ) \\ -50^\circ, \phi_{rmn\_continous} \in \text{others} \end{cases}. \quad (2)$$

The phase distribution on the electromagnetic reflective surface of the boresight beam is calculated, **Fig. 6a** shows the continuous compensation phase and **Fig. 6b** shows the quantized phase.

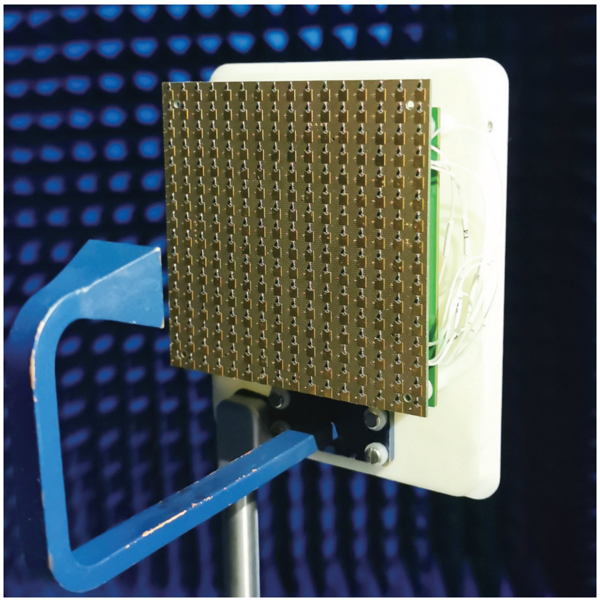
3.3 Phased Array Antenna Measurement

A phased array antenna prototype is built (**Fig. 7**). It consists of 256 patch elements and each is individually controlled by an FPGA board behind the array surface. A horn antenna is designed as the feed for this antenna and the waveguide structure minimizes the feed loss.

The antenna prototype is measured in an anechoic chamber at Tsinghua University. **Fig. 8a** shows the measured patterns at representative scanning angles: 0°, 15°, 30°, 45° and 60°,



▲ **Figure 6. Boresight beam phase distribution on the electromagnetic reflective surface: (a) continuous phase distribution; (b) 1 bit quantized phase distribution.**



▲**Figure 7. Photo of a 256-element phased array prototype for 5G mm-Wave communications.**

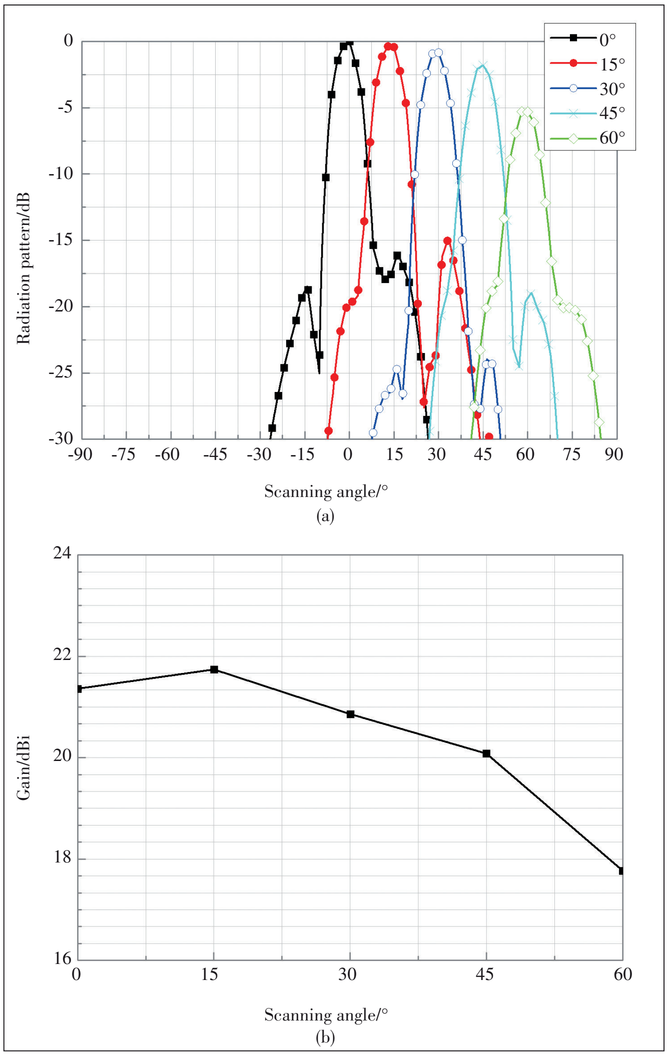
and **Fig. 8b** shows the measured gains of different scanning beams. It is observed that by reconfiguring the elements' statuses on the surface, the antenna beam can be scanned to the desired direction. In addition, the antenna is also measured from 27 GHz to 29 GHz, which shows the −3 dB gain-bandwidth of the phased array.

After measuring the phased array antenna, a wireless communication system is also built. A National Instrument (NI) millimeter-wave transceiver works at 28 GHz with a bandwidth of 800 MHz. We use 64 Quadrature Amplitude Modulation (64QAM) modulation cooperating with 7/8 turbo coding to build two test scenarios for video data transmission: 1T-1R and 1T-2R. The phased array produces one switching beam for the 1T-1R test and dual beams for the 1T-2R test. The bit rate of both scenarios can achieve up to 2.87 bit/s when the distance between transmitter and reciever(s) is 6 m.

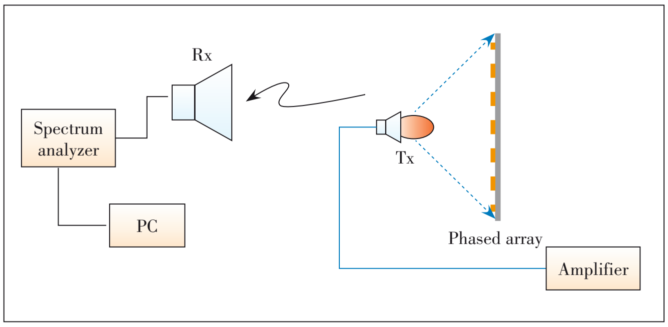
3.4 5G NR Measurement

In order to verify the communication performance of the phased array in mm-Wave band, 5G NR measurement was conducted in the chamber of ZTE Shanghai. **Fig. 9** shows the connections of NR test system.

As depicted in Fig. 9, the phased array acts as the transmitter antenna, and the horn antenna connected with the spectrum analyzer acts as a receiver antenna. The EVM and ACLR were measured by this system. EVM is usually used as a mark to measure the linear performance of transmitter, as well as the transmitter antenna. ACLR indicates interference of transmission signal leakage to the same or similar communication system. After tested by the ZTE 5G NR system, the EVM and ACLR indices (**Tables 1** and **2**) show that the antenna can be used in 5G wireless communications, and it provides comparable performance to the existing products of ZTE.



▲**Figure 8. Measured results of the 256-element phased array: (a) beam scanning measurement at 28 GHz; (b) gain measurement at 28 GHz.**



▲**Figure 9. 5G New Radio (NR) test of the phased array.**

4 Conclusions

The demand of phased array antennas for 5G millimeter-

▼Table 1. EVM measurement results

Frequency/GHz	EVM/64QAM
27.05	2.97%
27.85	3.2%
28.15	2.5%
28.95	3%

64QAM: 64 Quadrature Amplitude Modulation   EVM: error vector magnitude

▼Table 2. ACLR measurement results

Frequency/GHz	Flatness/dB	ACLR/dBc
27.2	0.78	−35.13
28	0.93	−35.8
28.8	2.4	−35.16

ACLR: adjacent channel leakage ratio

wave wireless communications has been increasing in recent years. This paper introduces a novel phased array approach using reconfigurable electromagnetic surface, which shows good performance in wireless fast data transmission. A 1 bit 256-element phased array operating at 28 GHz band is thoroughly investigated with measurements. The measured beams can scan ±60° and the maximum gain achieves up to 21.7 dBi. The array also achieves dual beams for 1T-2R wireless video transmission successfully. In addition, the array was tested for 5G NR system successfully and the EVM and ACLR indices also show good performance. Because the array only uses PIN diodes to control beam scanning, the power consumption is very low when it provides comparable performance to conventional phased arrays. The measured results show that the phased array is suitable for base stations and have a promising future for 5G millimeter-wave communication systems.

References

[1] MAHMOUD K R, MONTASER A M. Synthesis of multi-polarised upside conical frustum array antenna for 5G mm-wave base station at 28/38 GHz [J]. IET microwaves antennas & propagation, 2018, 12(9): 1559 – 1569. DOI: 10.1049/iet-map.2017.1138

[2] MALLAT N K, ISHTIAQ M, REHMAN AUR, et al. Millimeter-wave in the face of 5G communication potential applications [J]. IETE journal of research, 2020: 1 – 9. DOI: 10.1080/03772063.2020.1714489

[3] BASAR E, DI RENZO M, DE ROSNY J, et al. Wireless communications through reconfigurable intelligent surfaces [J]. IEEE access, 2019: 116753 – 116773. DOI: 10.1109/ACCESS.2019.2935192

[4] YANG H H, YANG F, CAO X Y, et al. A 1600-element dual-frequency electronically reconfigurable reflectarray at x/ku-band [J]. IEEE transactions on antennas and propagation, 2017, 65(6): 3024 – 3032. DOI: 10.1109/TAP.2017.2694703

[5] HUM S V, PERRUISSEAU-CARRIER J. Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: a review [J]. IEEE transactions on antennas and propagation, 2014, 62(1): 183 – 198. DOI: 10.1109/TAP.2013.2287296

[6] NAYERI P, YANG F, ELSHERBENI A Z. Beam-scanning reflectarray antennas: a technical overview and state of the art [J]. IEEE antennas and propagation magazine, 2015, 57(4): 32 – 47. DOI: 10.1109/MAP.2015.2453883

[7] WANG M, XU S H, YANG F, et al. Design and measurement of a 1-bit reconfigurable transmitarray with subwavelength H-shaped coupling slot elements [J]. IEEE transactions on antennas and propagation, 2019, 67(5): 3500 – 3504. DOI: 10.1109/TAP.2019.2902676

[8] YANG H H, YANG F, XU S H, et al. A 1-bit 10×10 reconfigurable reflectarray antenna: design, optimization, and experiment [J]. IEEE transactions on antennas and propagation, 2016, 64(6): 2246 – 2254. DOI: 10.1109/TAP.2016.2550178

Biographies

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XU Shenheng received the B.S. and M.S. degrees from Southeast University, China in 2001 and 2004, respectively and the Ph.D. degree in electrical engineering from the University of California at Los Angeles (UCLA), USA in 2009. From 2000 to 2004, he was a research assistant with the State Key Laboratory of Millimeter Waves, Southeast University, China. From 2004 to 2011, he was a graduate student researcher and then became a post-doctoral researcher with the Antenna Research, Analysis, and Measurement Laboratory, UCLA. In 2012, he joined the Department of Electronic Engineering, Tsinghua University, China, as an associate professor. His current research interests include novel designs of high-gain antennas for advanced applications, artificial electromagnetic structures, and electromagnetic and antenna theories.

ZHANG Jiannian received the B.S degree from Tsinghua University, China. He has 20 years of experience in system development. He was a senior engineer with the State Key Laboratory of Microwave and Digital Communication of Tsinghua University. He was the head of the System Department of Analogix Semiconductor, Inc., USA. Now he is the CEO of Beijing Actenna Technology Co., Ltd.