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A Wide-Angle Beam Scanning Antenna in E-plane for K-band Radar Sensor

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ABSTRACT In this paper, a K-band antenna with ±60° beam scanning is proposed for a mmWave (millimeter-Wave) radar sensor. Especially, we take advantages of the magnetic dipole principle, and design the antenna by employing via holes in three sides, so as to form a cavity which can be equivalently considered as magnetic dipole, resulting in the 3 dB beam width as wide as 140° in E-plane. We cascade the mmWave antenna to 1×4 and 4×4 arrays for radar transmitting and receiving, respectively. The antenna array is fabricated and implemented to a K-band radar and its wide-angle beam scanning performance is evaluated by the radar's distance and angular detections.

INDEX TERMS Wide-angle beam scanning, antenna array, magnetic current antenna, K-band radar.

I. INTRODUCTION

Radar was commonly used for military applications in the past decades. Recently, with the development of integrated circuit and antenna technologies, the small form-factor portable FMCW (Frequency Modulated Continuous Wave) radar sensors become popular for various civilian's applications such as autonomous vehicle [1], [2], intelligent security [3], indoor and outdoor monitoring and beyond [4]–[6]. Depending on the radar's application scenarios, the radar antenna needs to be designed differently. For longer distance and accurate speed detection, high gain, narrow beam width antenna array is preferred. For wide angle object detection, the antenna array with wide beam width is required, and to further improve it, the antenna beam is designed to scan from angle to angle with the assistance of Radio Frequency (RF) or digital circuits, called beam scanning radar.

Wide beam scanning characteristics could be achieved or improved by many methods, such as wide-beam antennas [7]–[9] and pattern-reconfigurable antennas (PRAs) [10]–[13]. Reference [8] proposes a wide-beam microstrip antenna with metal walls, and realizes beam scanning from −70° to +70°. In [13], a reconfigurable technique is used to reconfigure the resonant modes to cover the scanning from −75° to +75°. These wide-angle scanning antennas are not suitable for K-band radar sensor because of their large size or fabricating complexity. Patch antenna possesses the low profile but cannot easily achieve the wide-angle beam scanning due to its narrow beam width [14]–[16]. For instance, the traditional patch antenna array for radar system proposed by [15] can achieve a beam scanning only within ±45°. Recently, lens antenna is proposed for W-band radar system [17] with obtaining scanning angles within ±85°, but for K-band radars, its size is too large to be miniaturized [18]. Therefore, designing well-performed beam scanning K-band radars still needs new antenna solutions for both wide-angle beam scanning and engineering implementation.

In this paper, a wide-angle beam scanning antenna array for K-band radar sensor is proposed based on the principle of equivalent magnetic dipole. First, a wide-beam antenna element is designed at 24 GHz with 600 MHz impedance bandwidth and wide beam width of ±70° on the E-plane. Second, based on this antenna element, a 1×4 transmitting antenna sub-array is designed for the radar sensor to achieve properties of 1 GHz bandwidth, 8-dBi gain, side-lobe level less than −15 dB and 140° wide beam width at E-plane, while for radar receiver, a 4×4 antenna array is formed with achieving wide beam scanning angle of ±60° on the E-plane. Finally, relative radar sensing experiments are carried out and a good detection performance is obtained.

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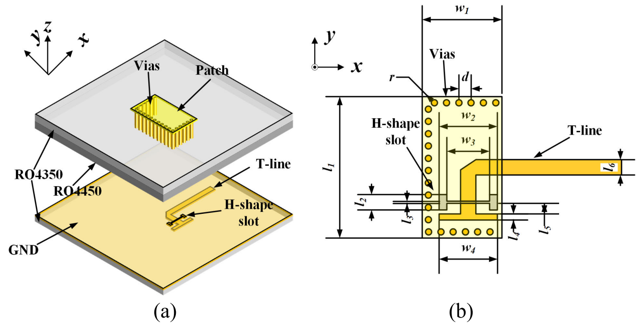

FIGURE 1. **Layout of the proposed magnetic dipole antenna. (a) boom view (b) parameters of proposed antenna (mm): $w_1 = 2.6$, $w_2 = 1.7$, $w_3 = 1.3$, $w_4 = 1.9$, $d = 0.4$, $r = 0.1$, $l_1 = 4.6$, $l_2 = 0.4$, $l_3 = 0.1$, $l_4 = 0.3$, $l_5 = 0.35$, $l_6 = 0.5$.**

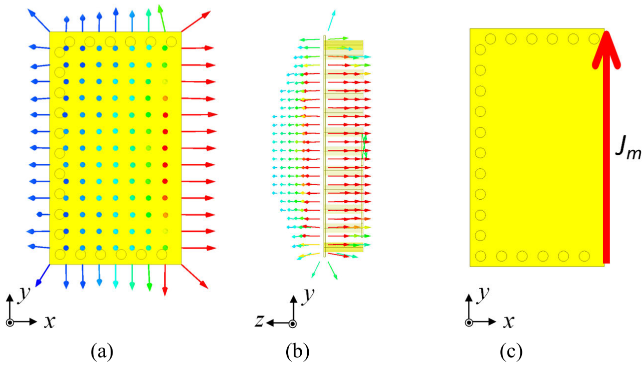

FIGURE 2. **Electric field distribution of the proposed magnetic dipole antenna at 24 GHz. (a) top view (b) side view (c) equivalent magnetic current.**

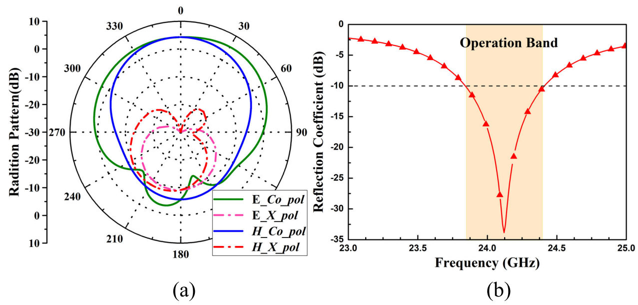

FIGURE 3. **Simulated antenna element radiation pattern and S_{11} at 24 GHz. (a) radiation patterns (b) S_{11}.**

The paper is organized as follows. Section II presents the magnetic dipole antenna design. Section III demonstrates the magnetic dipole antenna array with 1×4 and 4×4 for radar transmitting and receiving, respectively. Section IV implements a radar sensor with the proposed antenna arrays. Section V provides the conclusions.

II. MAGNETIC DIPOLE ANTENNA DESIGN

The design of the wide-angle antenna is shown in Fig. 1. A metallic patch is patterned on the top of the two substrates Rogers4350B ($\varepsilon_r = 3.66$, $\tan\delta = 0.0037$, thickness 0.254 mm) and Rogers4450F as the prepreg ($\varepsilon_r = 3.52$, $\tan\delta = 0.004$, thickness 0.202 mm), and a RF ground is under the 2nd substrate. To excite the antenna by a microstrip-slot coupling feed structure, we design an H-slot in the middle of the ground, and locate another substrate Rogers4350B ($\varepsilon_r = 3.66$, $\tan\delta = 0.0037$, thickness 0.254 mm) underneath with a T-shape feed line on the bottom layer. Especially, three edges of the top-layer patch are shorted to the ground plane by evenly positioned metal via holes, remaining one side open, which is similar to the substrate integrated waveguide (SIW) structure. Thus, the three sided via holes, the top-layer patch and the RF ground plane together form a semi-open metal cavity, while the open side is equivalent to the cavity gap. Overall, the whole structure forms a semi-open cavity with the length $l_1 = \lambda_g$ (λ_g is the wavelength in the substrate at 24 GHz) and the width only $w_1 = \lambda_g/2$, More specifically, when the cavity is excited, the main resonance mode is the TE_{01} mode. As shown in Fig. 2(a) & (b), the electric field direction is mainly parallel to the -z direction between the top-layer patch and the ground plane, while the field intensity remains consistent along the z direction and sinusoidal along the$y$ direction. According to the equivalent theory [19]-[20], the electric field at the edge of the open circuit can be equivalent to the magnetic current $\boldsymbol{J}_{my}$ that can be expressed as

$$\boldsymbol{J}_{my} = \boldsymbol{n}_x \times \boldsymbol{E}_{-z}. \tag{1}$$

where $\boldsymbol{J}_{my}$ is the equivalent magnetic current in the y direction, namely, the cross-product of a normal vector $\boldsymbol{n}_x$ along the x direction and the electric field along the-z direction $\boldsymbol{E}_{-z}$.

Fig. 2(c) depicts the equivalent magnetic current schematic diagram. Due to the equivalently magnetic current at the edge of the open circuit, this design can be effectively considered as a magnetic dipole antenna, which possesses wider beam width in E-plane than that of an electrical dipole antenna. This equivalent magnetic dipole principle also explains the narrow beam issue of E-plane existing in conventional patch antennas design: a regular patch antenna can be equivalently considered as a binary array of two co-directional magnetic dipole elements with half-wavelength spacing in the y-direction [17], thereby making the beam width of E-plane to be more narrower. Thanks to the magnetic dipole antenna that has the merits of wide beam width in E-plane and low profile characteristics, as in Fig. 3(a), the beam width is ±45° in the H-plane, but ±70° in the E-plane. In addition, it has the 4-dBi gain, a linear polarization, and the cross-polarization ratio lower than 40 dB. Furthermore, in this design we apply a coupled slot-feeding structure (Fig. 1(b)) to enhance impedance bandwidth. As shown in Fig. 3(b), the proposed magnetic dipole antenna covers the frequency range from 23.8 GHz to 24.4 GHz.

III. WIDE-ANGLE BEAM SCANNING

A. 1 × 4 ANTENNA ARRAY FOR RADAR TRANSMITTING

Based on the designed antenna, we cascade the antenna along y-direction with the distance 7.17 mm, so as to form

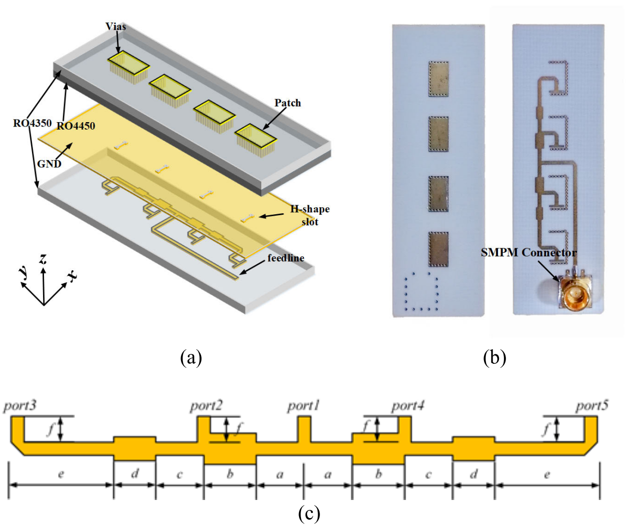

FIGURE 4. 1×4 sub-array configuration. (a) boom view (b) the fabricated sample. (c) the feeding network for the 1×4 sub-array.

TABLE 1. Parameters of the power splitter.

Symbol	Impedance	Electrical length
a	50Ω	1.85 mm
b	28Ω	1.77 mm
c	50Ω	2.02 mm
d	35Ω	1.85 mm
e	50Ω	1.62 mm
f	50Ω	1.75 mm

a 1×4 sub-array with enhanced gain [22] and wide-angle beam scanning as the transmitting antenna in our radar sensor. As illustrated in Fig. 4(a) & (b), the fabricated 1×4 sub-array has the very similar layout as that of the element demonstrated in Fig. 2(a): magnetic dipole antenna on the top with two substrates, a coupling-type feed network with another substrate on the bottom. Fig. 4(c) shows feeding network with power splitter for supplying the four elements of the 1 × 4 antenna array. More specifically, the power is input to port 1, then split to each of the four elements via ports 2∼5 respectively. The input impedance of all ports is 50 Ω. In order to reduce the side lobes of the antenna array, the Chebyshev synthesis method is used to calculate the ratio of the voltage amplitude of each port, hence, determine the feeding network with a ratio of 1:1.33:1.33:1 [23]. Relative parameters of the network are shown in Tab. 1. The series type feeding network is adopted due to it has the advantages of simple structure, compact size and smaller loss compared with the parallel type feeding network.

To improve the antenna impedance bandwidth, the feeding network is designed at 23.5 GHz with 500 MHz offset from the antenna resonant frequency of 24 GHz, as a result, two resonances appear around 24 GHz. The simulated and measured S_{11} are shown in Fig. 5, which illustrates a −10 dB bandwidth from 22.8 GHz to 24.1 GHz(5.4%).

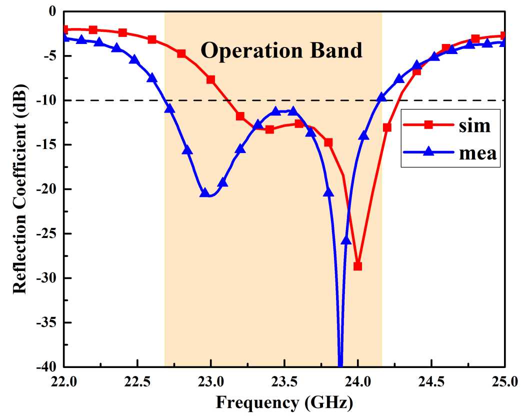

FIGURE 5. Simulated and measured S_{11} of the 1×4 sub-array.

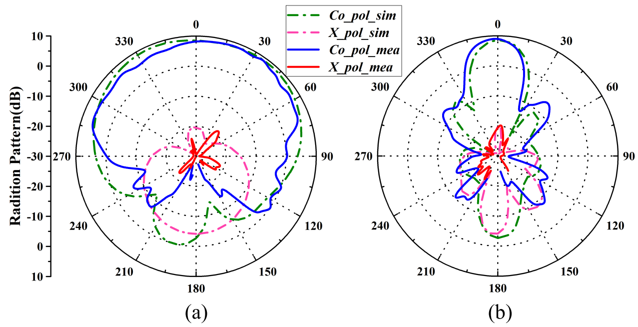

FIGURE 6. Simulated and measured radiation patterns of the 1×4 sub-array at 24 GHz. (a) E- plane (b) H-plane.

The measurement is slightly shifted from the simulation due to the fabrication accuracy. The simulated and measured radiation patterns at 24 GHz are compared in Fig. 6, and it illustrates that the cross-polarization ratio is lower than −25 dB, side-lobe level is reduced to −15dB and the beam width in the E- plane still keeps ±70°. Due to four antenna units are arranged along *y*-direction, its H-plane beam width decreases from 90° to 30°, resulting in gain enhancement with 6 dB. This array can be utilized as the transmitter in the further radar sensor.

B. 4 × 4 ANTENNA ARRAY FOR RADAR RECEIVING

The design of wide-angle scanning 4×4 antenna array, as show in Fig. 7, has the similar multi-layer configuration as the 1×4 array, and it is formed by cascading four 1×4 sub-arrays with a spacing of $d = 6$ mm. Other layout and design are exactly the same as the 1×4 sub-array in Fig. 4. In the fabricated prototype, as in Fig. 8(a), four SMPM connectors are utilized to connect the four sub-arrays. In terms of experimental implementation, first, relative S-parameters are measured, thus, to make sure all the ports are well matched and the de-coupling level among adjacent ports is acceptable. As in Fig. 9(a) and Fig. 9(b), it is seen that S_{11} parameters of all the four-port, though are not exactly consistent, cover the frequency spectrum of 23.5 GHz to 24 GHz ($S_{11} < -10$ dB). The inconsistency of S_{11}-parameters among all the four ports

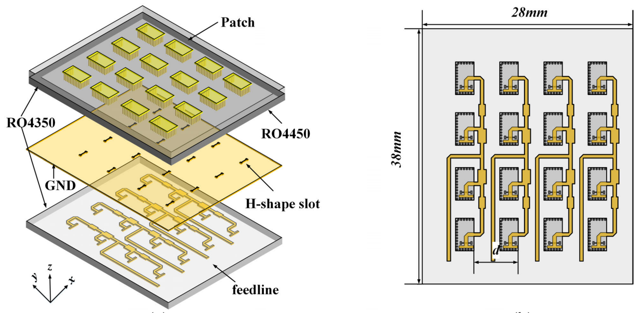

FIGURE 7. Layout of the 4×4 array. (a) boom view (b) bottom view.

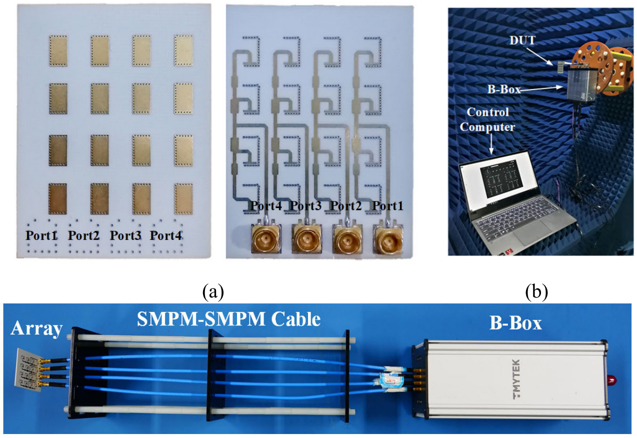

FIGURE 8. 4×4 antenna array and measurement details. (a) fabricated 4×4 array, (b) experimental set up in the microwave anechoic chamber. (c) the array is connected to the B-Box, which is the active component for providing phase shifting to the four ports.

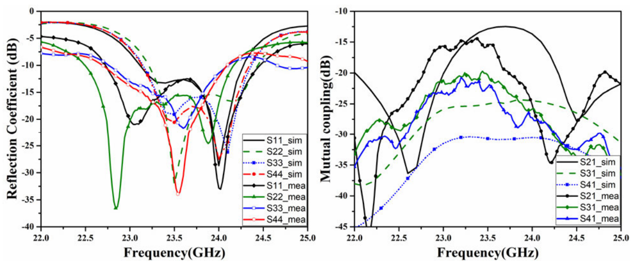

FIGURE 9. (a) Simulated and measured S_{11} of the 4×4 array. (b) Simulated and measured mutual coupling of the 4×4 sub-array.

is due to their different coupling levels, which is measured and illustrated as in Fig. 9(b). It is seen that port 1 and 2 have the strongest coupling due to they are located closest to each other, but still below −12 dB, while the coupling between other ports are as good as less than −20 dB. There exist slight variations between simulations and measurements, which might be due to in the 24 GHz band, fabrication and measurement deviations are more sensitive.

Since S-parameters of all ports are confirmed, second, the radiation patterns measurement are set up as shown

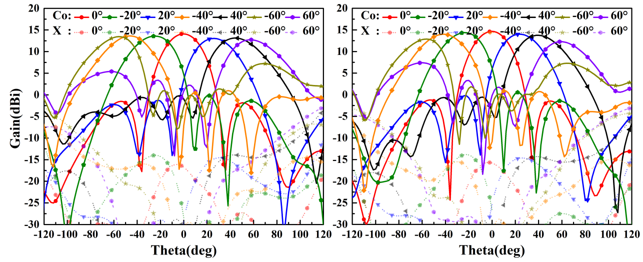

FIGURE 10. Simulated scanning radiation patterns of the 4×4 array at two resonant frequencies: (a) 23.6 GHz (b) 24 GHz.

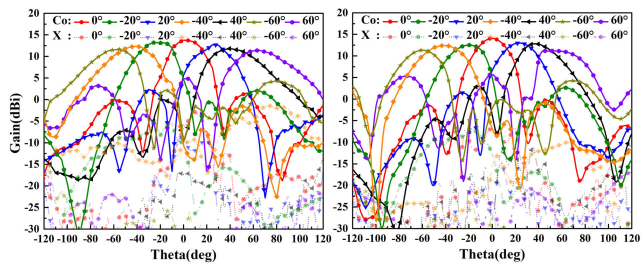

FIGURE 11. Measured scanning radiation patterns of the 4×4 array at two resonant frequencies: (a) 23 GHz (b) 24 GHz.

in Fig. 8(b). In the anechoic chamber test, a PC is used to control the active RF module for supplying the antenna array. Particularly, B-Box with four ports (TYMTEK Company, as schematic shown in Fig. 8(c)) is employed, which functions as phase shifter for providing shifted phases to the four ports, such that each array unit can be fed independently with the certain phase. In such a method, we can measure the scanning beams. In the operating frequency band, two typical frequencies 23.6 GHz and 24 GHz are selected to show the scanning radiation patterns. The simulated and measured scanning radiation patterns are shown in Fig. 10(a) & (b) and Fig. 11(a) & (b) respectively. It demonstrates very wide beam scanning from −60°, −40°, −20°, 0° to 20°, 40°, and 60° at both 23.6 GHz and 24 GHz, respectively. As beams scan to the position 0° and ±60°, the peak gains are 13 dBi and 10 dBi respectively, implying very good beam scanning performance with gains varied less than 3 dB in the 120° dynamic scanning range. In general, the measured results are in good agreement with the simulated ones. This array is utilized as the receiver in our radar sensor.

IV. RADAR SENSOR SYSTEM

To demonstrate the performance of the proposed wide-angle beam scanning antenna, a K-band radar sensor system has been developed to investigate its angle and distance detection capability. Fig. 12 illustrates the block diagram of the proposed K-band radar sensor system. This radar has one transmitting and four receiving antennas that are connected through the SMPM connectors with the chips. Phase-locked loop circuit, composed of phase detector, loop filter and

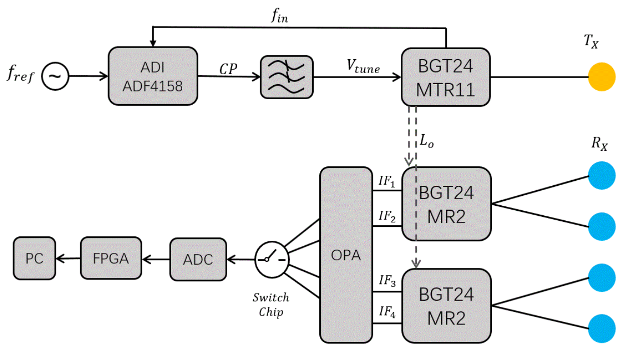

FIGURE 12. The block diagram of the K-band radar sensor system.

TABLE 2. Parameters of K-band radar sensor system.

Tx Power	7 dBm	R x antenna gain	13 dB
Tx bandwidth	500MHz	Center frequency	23.75 GHz
Chirp repetition period	1ms	Baseband Sampling rate	40 MHz
Range resolution	0.3m	Power consumption	2.0 W

voltage-controlled oscillator (VCO) in transmitter chip, generates frequency modulated continuous wave (FMCW) signal. In the receiving path, the two-channel zero IF receiver, consisting of two chips for supporting four receiving antennas, is utilized, then, the IF signals of four channels are amplified, filtered and sampled. Different from traditional receiving channels of MIMO systems, this radar chooses switch chips to reduce the number of ADC while still get same performance. The signal is digitized by the ADC then entered into the FPGA. After the low pass filtering, it is downsampled before finally sent to the data packaging module and PC. The parameters of K-band radar sensor system are listed in Table 2: the transmitting power is about 7 dBm with a center frequency of 23.75 GHz; the bandwidth of the chirp signal is 500 MHz, and the chirp repetition period is 1 ms. By combing the two channels ADC in LTC2292, the maximum sampling rate can reach 40 Msps. This radar is supplied by 5-V dc voltage, and its average power consumption is about 2.0 W.

Fig. 13(a) is the photograph of the proposed short-range and wide-angle radar system. The entire radar prototype has a size of 12 cm × 11 cm. It consists of antenna board, RF circuits, baseband circuits, signal processing units, terminal control and display. In Fig. 13(b), two corner reflectors with same cross section are placed at front site that are 60° offset from the radar sensor at different distances of 6 m and 3 m, respectively. In this radar sensor, phase shifting is performed in the digital domain [24], thus, the radar sensor can get range and azimuth information by processing the echo signal of each corner reflector. The measurement results in range and azimuth direction is plotted in Fig. 13(c), which shows that the 60° offset corner reflector can be clearly detected, briefly verifying that the proposed magnetic dipole antenna array

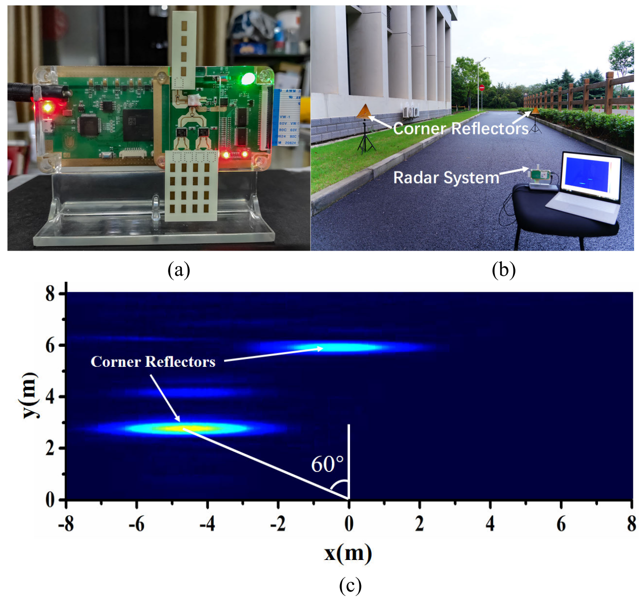

FIGURE 13. K-band radar sensor system. (a) the radar prototype. (b) measurement scenario. (c) measurement result in range and azimuth direction.

with large-angle beam scanning enables the radar sensor to possess the capability of wide-angle detection.

V. CONCLUSION

A wide-angle beam scanning magnetic dipole antenna array and its radar sensor system are designed, fabricated and tested. The prototype of the proposed 4×4 antenna array has demonstrated a bandwidth of 5.5% from 22.8 GHz to 24.1 GHz, 13-dBi gain and a beam scanning angle of the ±60° in E plane, which makes it a very promising antenna candidate for K-band radar sensor systems.

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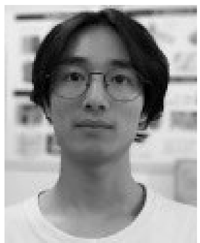

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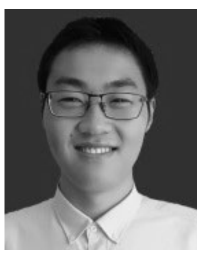

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