A Fixed-Beam Leaky-Wave Cavity-Backed Slot Antenna Manufactured by Bulk Silicon MEMS Technology

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***Abstract*— A fixed-beam leaky-wave slot antenna with an air-filled back cavity is proposed in the millimeter-waveband. The antenna is fabricated based on the bulk silicon microelectromechanical systems micromachining technology. This micromachining process can etch silicon wafers and plate them with gold. Because all surfaces of the proposed antenna are plated with gold, electromagnetic waves can transmit in the air medium without any other dielectric. The air-filled structure contributes to achieving a leaky-wave slot antenna with fixed beam as operating frequency varies. A prototype of the proposed antenna is fabricated to verify the design strategy. The measured results show that the impedance bandwidth of the proposed antenna is 55–67 GHz and within the operating frequency band, the main beam direction only varies from 48° to 53°, which confirms the fixed-beam characteristic. The measured peak gain varies from 9.1 to 10.5 dBi in the operating frequency band.**

***Index Terms*— Air-filled structure, bulk silicon microelectromechanical systems (MEMS) micromachining technology, fixed-beam leaky-wave slot antenna, millimeter wave.**

I. Introduction

OVER the past few decades, millimeter-wave antennas have attracted much attention for the promising applications in the fields such as imaging systems, sensors, radars, and communication systems [1]–[3]. In the millimeter-waveband, the demands for high gain, low loss, and less complexity challenge the antenna design strategy. The leaky-wave antenna is a popular candidate for high-performance applications [4]–[10]. Leaky-wave antennas can achieve high directivity, large bandwidths, and simple design because of their traveling-wave nonresonant property [4]. When it comes to the control of the beam direction of leaky-wave antennas, main beams of leaky-wave antennas are drifting as working frequency changes. This phenomenon is the result of the dispersive leaky propagation mechanism [11]. Realizing a fixed-beam leaky-wave antenna over a wide bandwidth is a difficult task, and only few works have been published on this topic [12]. In [13], the researchers use phase shifters between radiating elements to perform a continuous phase shift between the radiating elements and maintain the beam direction over the operating bandwidth. Negative-refractive-index transmission-line metamaterial unit cells are utilized in leaky-wave antenna design to reduce beam squinting in [14]. The radiation angle varies 56° over its operating frequency. In [15], the slot mode is proposed to propagate with free-space phase-change coefficient over the operating frequency band. The slot mode is a second mode of the slotted rectangular waveguide, and it is excited based on a quarter-wavelength back cavity. Another design to achieve fixed-beam leaky-wave antenna is leaky lens [11]. The lens antenna is proposed with a slot etched at the interface between the air and a dense dielectric lens. The peculiar structure of the lens contributes to maintaining a constant beam direction and a wide bandwidth. However, the fabrication process of the dielectric lens is complicated.

In the millimeter-waveband, using air medium is a popular method, and several process technologies have been utilized to design antennas with the air layer. Hollow waveguide is an effective method to design high-performance slot antenna array [16], [17]. Substrate integrated waveguide (SIW) has advantages in terms of cost, weight, and compactness, and it is another popular candidate in designing millimeter-wave antenna [18], [19]. To reduce dielectric loss in the millimeter-waveband, an air-filled SIW antenna has been proposed, and the air layer also increases the average power handling capability [20]. Low-temperature co-fired ceramics (LTCC) is widely used to fabricate multilayer circuit and integrate RF circuit with the antenna [21]–[26]. In the millimeter-waveband, the LTCC also suffers the problem of dielectric loss, and the method of using air layer is utilized to mediate the loss issue [27]–[29]. However, most of the air-filled leaky-wave antennas are based on the waveguide mode, which transmits fast wave, and it is not suitable for designing the fixed-beam antenna. Besides the abovementioned technologies, the microelectromechanical system (MEMS) bulk silicon micromachining technology is also utilized to design air-filled antenna by employing the multilayer structure [30], [31].

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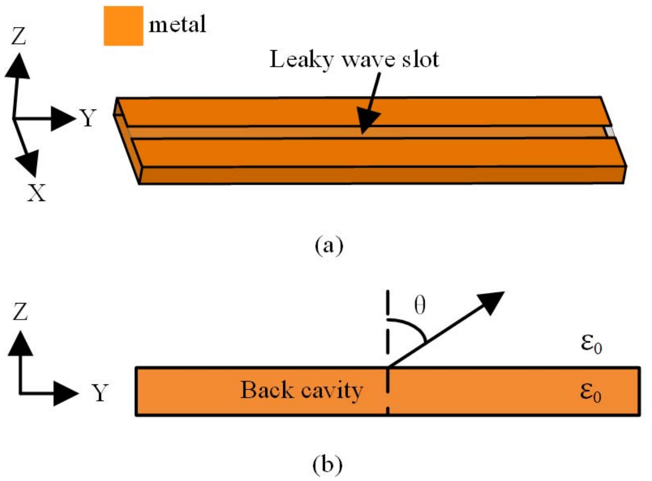

Fig. 1. Configuration of the leaky-wave slot antenna. (a) Perspective view. (b) Side view.

Bulk silicon micromachining technology can fashion the single-crystal silicon wafers by selectively etching and plating the wafers [32], [33]. Using this technology, the antenna can be simply designed by staking multilayers to achieve air-filled structure without any other dielectric [30].

In this paper, a fixed-beam leaky-wave slot antenna is proposed based on the bulk silicon micromachining technology. An air-filled back cavity is utilized in the proposed antenna to achieve unidirectional fixed-beam property. The mechanism of the fixed-beam leaky-wave slot antenna is analyzed and a prototype is fabricated to verify the feasibility. The measured results show that the impedance bandwidth of the proposed antenna is 55–67 GHz. Within the operating frequency band, the main beam direction only varies from 48° to 53°, which confirms the fixed-beam characteristic, and measured peak gain varies from 9.1 to 10.5 dBi.

II. Principle of the Fixed-Beam Property

Fig. 1 illustrates the simplified configuration of the leaky-wave slot antenna. According to [34], θ_m, which is the angle of maximum radiation, can be approximately determined by

$$\theta m \cong \arcsin\left(\frac{\beta}{k0}\right). \tag{1}$$

In (1), β is the phase constant in leaky-wave antenna, and k_0 is the propagation constant in free space. For the conventional leaky-wave slot antennas with waveguide mode, the electromagnetic wave transmits in TE_{10} mode, and the phase constant is [34]

$$\beta\mathrm{TE10} = \sqrt{k^2 - \left(\frac{\pi}{a}\right)^2}. \tag{2}$$

Applying (2) into (1) shows that the radiation direction θ_m is the function of operating frequency which means the antenna main beam steers as operating frequency varies. In this paper, we use slotline mode instead of waveguide mode to design the leaky-wave slot antenna. The ratio between phase constant β and k_0 is almost constant because the slotline leads to a quasi-TEM type of mode [35], and the direction of the main beam

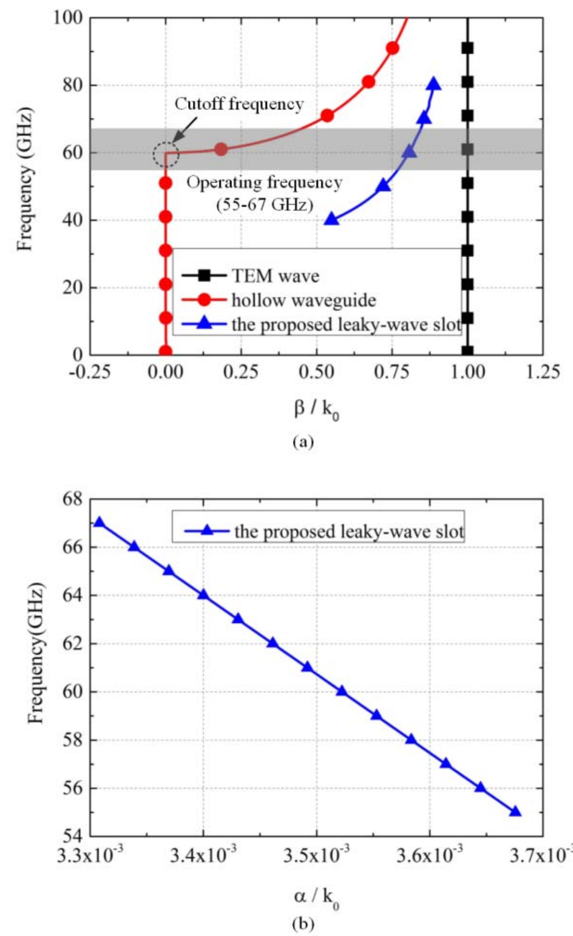

Fig. 2. Normalized attenuation and phase constants. (a) Normalized phase constants for TEM wave, hollow waveguide, and the proposed leaky-wave slot antenna. (b) Normalized attenuation constant of the proposed leaky-wave slot versus operating frequency.

would not change with frequency variation. It is necessary to mention if there is dielectric in the slot, the electromagnetic wave in the dielectric would be slower than the wave in the free space, and the electromagnetic wave cannot radiate into the free space [11]. So the leaky-wave slot antenna with air-filled back cavity is proposed in this paper to achieve fixed-beam property.

The phase and attenuation constants versus operating frequency are illustrated in Fig. 2. Fig. 2(a) shows the phase constant comparison between TEM wave, TE_{10} mode in a hollow waveguide, and the proposed leaky-wave slot. The width of the hollow waveguide is 2.5 mm, so the cutoff frequency is 60 GHz. The comparison shows that mode in the proposed leaky-wave is different from the rectangular waveguide. The normalized phase constant of the leaky-wave mode changes slightly in the operating frequency, which means the radiation angle is fixed according to (1). The nondispersive TEM mode appears as a vertical line with respect to the frequency. The normalized phase constant of the proposed leaky-wave slot is less than the TEM wave because the field is slightly distorted by the back cavity. Fig. 2(b) depicts the relation between the operating frequency and the normalized attenuation constant of the proposed leaky-wave slot. As frequency increases, the normalized attenuation constant decreases.

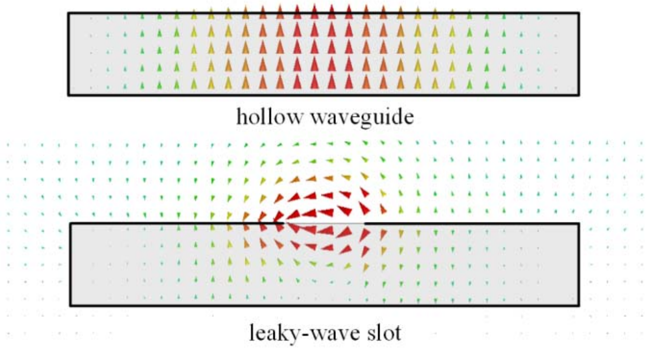

Fig. 3. Electric field vector distribution at the cross section of the hollow waveguide and the proposed leaky-wave slot.

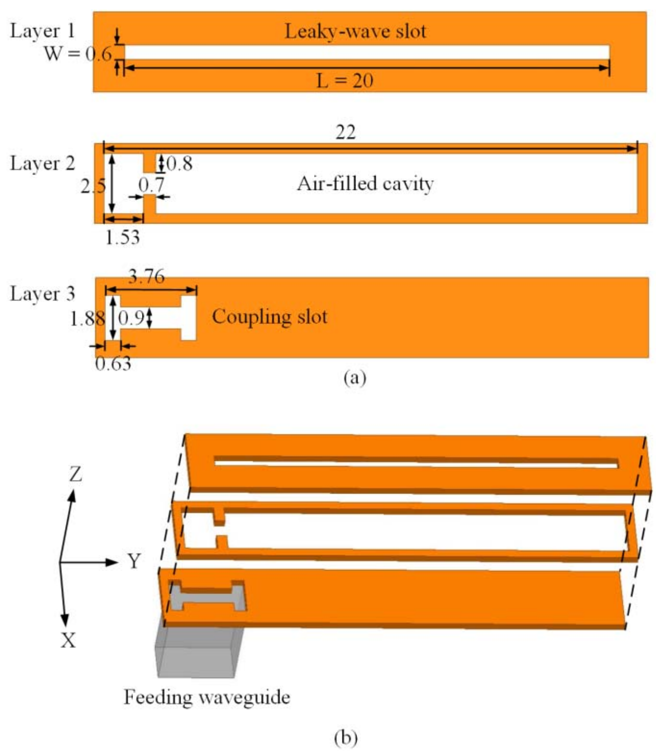

Fig. 4. Geometry of the proposed antenna. (a) Front view of every layer. (b) Exploded view (unit: mm).

To further clarify the mode of the proposed antenna, Fig. 3 depicts the electric field distribution in the cross section of a hollow waveguide and the proposed leaky-wave slot. The electric distribution shows that the electromagnetic wave in the proposed slot is different from the TE_{10} mode in a hollow waveguide. Moreover, the electric field distribution also shows that the leaky-wave slot operates in a quasi-TEM type of mode and verifies the fixed beam property.

III. Antenna Design

Fig. 4 depicts the geometry of the proposed antenna. As shown in Fig. 4(a), the proposed antenna is composed of three layers. Every layer is fabricated by the bulk silicon micromachining technology that etches silicon wafer and plates all surfaces with gold. The height of every layer is 0.4 mm. Layer 1 contains the leaky-wave slot, which is the radiation element. Layer 2 is the air-filled back cavity with two perturbing stubs for matching. Because the slot radiates a bidirectional pattern, the air-filled cavity is also utilized to achieve unidirectional radiation [12]. Layer 3 contains the H-type slot to couple electromagnetic wave from the feeding waveguide to the proposed antenna. The polarization in the feeding waveguide is along the x-axis direction, which excites the quasi-TEM type of mode in the leaky-wave slot.

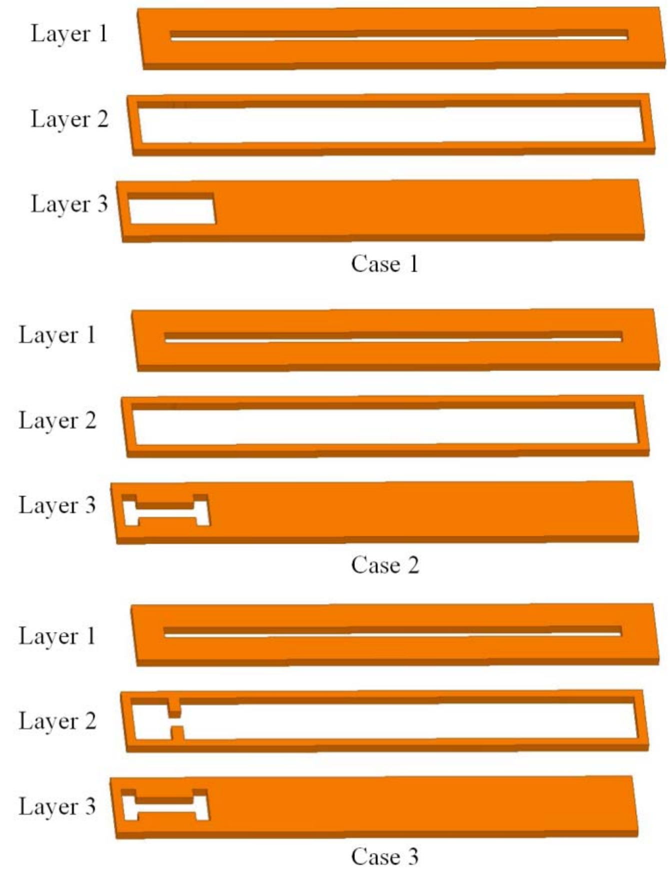

Fig. 5. Evolution of the proposed antenna matching structure.

The parameters L and W determine the length and width of the leaky-wave slot. When L or W increases, the size of the slot will increase and the antenna radiates more energy. However, increasing size also means occupying more space, and if the width of the slot is too large, the radiation of the slot will be disturbed. So the length and width of the leaky-wave slot in layer 1 are determined as $L = 20$ mm and $W = 0.6$ mm, considering the radiation property and the size of the proposed antenna.

Because the conventional slot antennas are based on the waveguide mode, we need to propose a novel matching structure to couple electromagnetic wave from the feeding hollow waveguide to the leaky-wave slot and excite the quasi-TEM type of mode. Fig. 5 depicts the evolution of the matching structure of the proposed antenna. As shown in Fig. 5, case 1 consists an air-filled cavity in layer 2 and a slot, whose size is the same with the feeding waveguide, in layer 3. However, most of the input energy is reflected by the metal surface

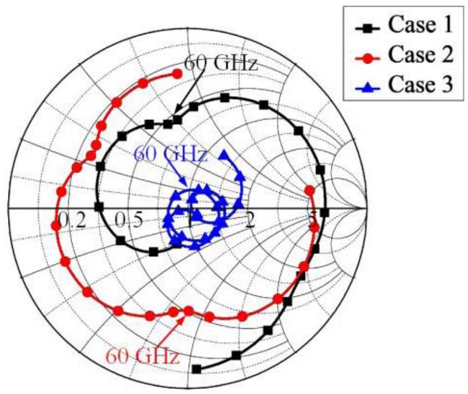

Fig. 6. Simulated results of normalized Smith chart for different cases.

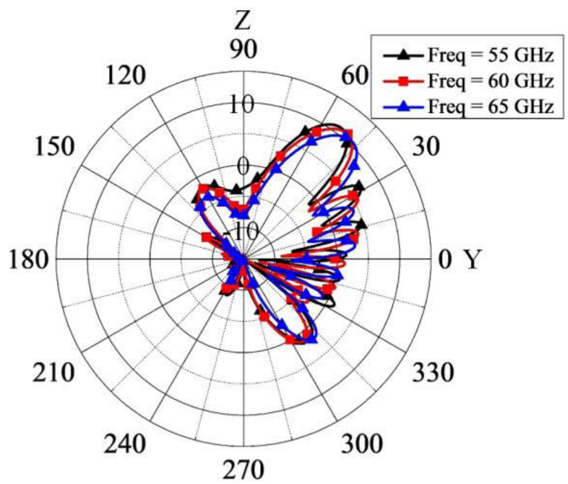

Fig. 7. Simulated radiation pattern results of the proposed antenna at different operating frequency.

of layer 1. To improve the impedance match, the slot in layer 3 is transformed into the H-type slot in case 2. However, the impedance improvement is not effective by only using the H-type slot. In case 3, two perturbing stubs are added in the cavity of layer 2, and the input impedance matches well in a wide frequency band. The principle of the impedance matching is further illustrated in Fig. 6, which shows the simulated Smith chart results of the three cases. As shown in Fig. 6, the results are normalized to the wave impedance of the feeding waveguide. One can observe that although from case 1 to case 2, the antenna input impedance mismatches, the curve moves downward to the bottom of the circle, which means the H-type coupling slot increases the series capacitor load to the input port. From case 2 to case 3, the curve moves upward, which means the perturbing stubs work as the shunt inductor. Finally, most of the curves occur around the center of the Smith chart, and the matching purpose is realized as a result of using the H-type slot and the perturbing stubs.

Fig. 7 depicts the simulated results of the proposed antenna in the yz-plane with different operating frequencies. At 55, 60, and 65 GHz, the maximum radiation direction points at 48°, 50°, and 53°, respectively. Although there is some difference between the maximum radiation directions, the phenomenon

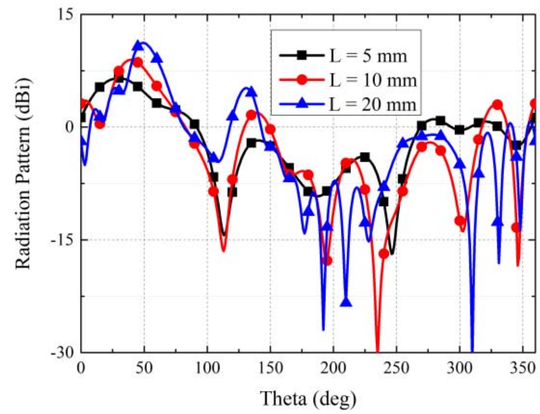

Fig. 8. Simulated radiation pattern results of the proposed antenna in the yz-plane with different values of L.

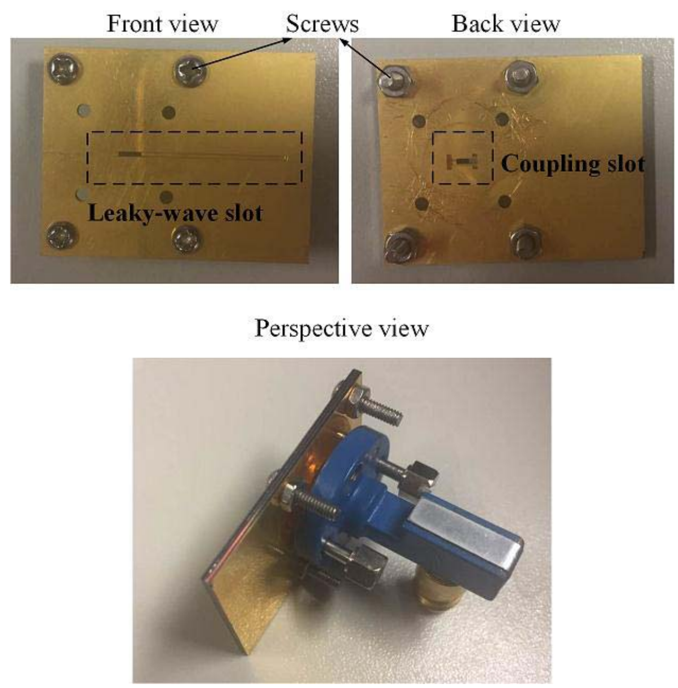

Fig. 9. Photographs of the proposed air-filled cavity-backed antenna.

verifies the fixed-beam property of the proposed antenna. The reason for the direction difference is that the electromagnetic wave in the leaky-wave slot is a quasi-TEM mode instead of a perfect TEM mode, and the residual dispersive effect of the quasi-TEM mode contributes to the radiation direction difference.

As shown in Fig. 8, the parameter study is illustrated to show the design strategy of the radiation angle. According to Fig. 4(a), the parameter L represents the length of the proposed leaky-wave slot. Fig. 8 depicts that the radiation angle increases with L. According to (1), the radiation angle of the array factor is at end-fire direction because the proposed leaky-wave antenna operates in a quasi-TEM mode. However, the individual source of the proposed leaky-wave slot antenna is equivalent short magnetic current, which radiates at broadside direction and has pattern nulls at an end-fire direction. According to the principle of pattern multiplication,

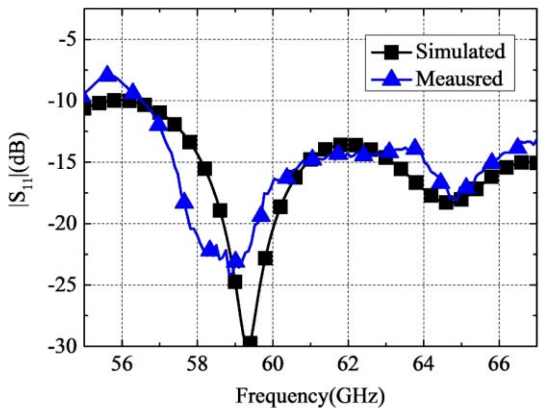

Fig. 10. Simulated and measured impedance match results of the proposed antenna.

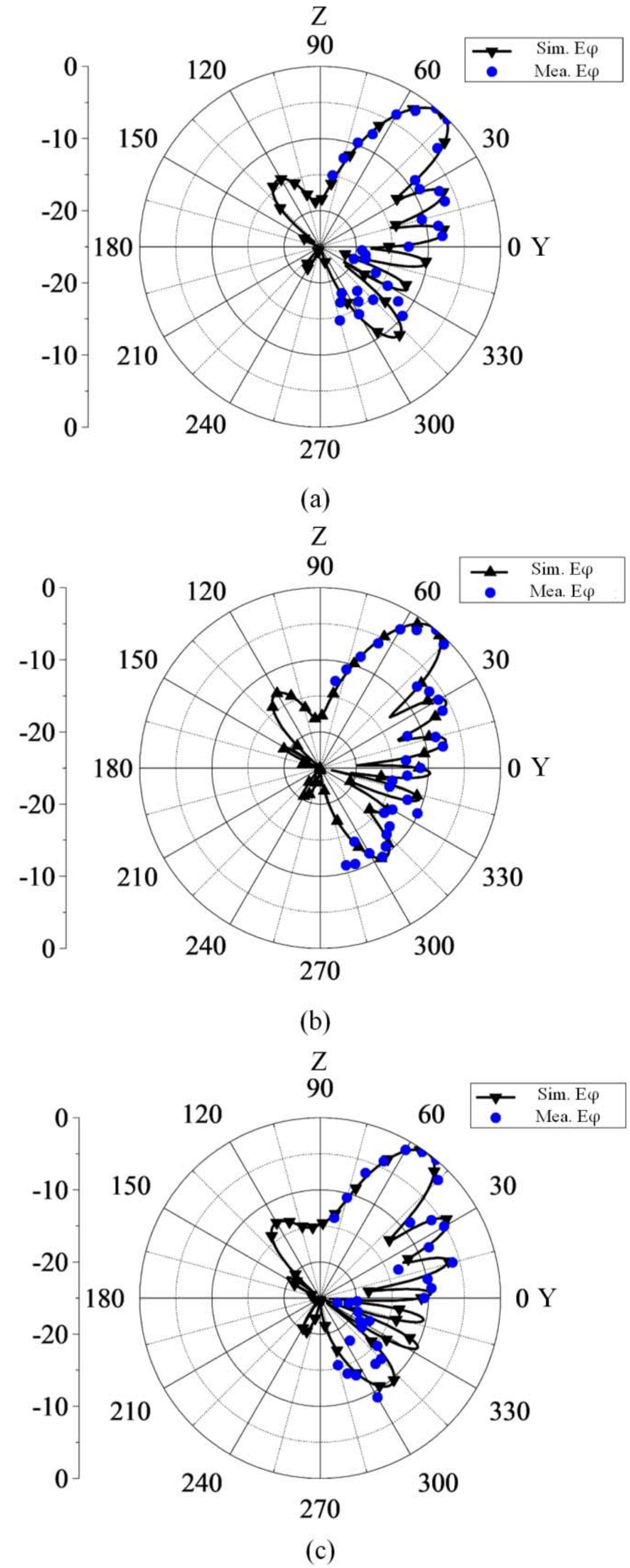

Fig. 11. Normalized H-plane (yz-plane) radiation patterns. (a) 55, (b) 60, and (c) 65 GHz.

the radiation pattern of the proposed antenna tilts away from the end-fire direction. Moreover, as the length of the leaky-wave slot increases, the gain of the array factor increases, and its beamwidth decreases, so the radiation angle of the proposed antenna tilts toward the end-fire direction.

IV. Experimental Results

Fig. 9 shows the photographs of the proposed antenna, which is fabricated by the bulk silicon MEMS micromachining technology. This technology can etch and plate the 400-μm-thick silicon wafer to form the structure of the antenna. Because the proposed antenna needs to assemble with the flange of the feeding waveguide, some holes are designed for the screws and the location pins.

Fig. 10 depicts the simulated and measured reflection coefficient of the proposed antenna. The measured result agrees well with the simulated ones. In most of the measured frequency band (from 55 to 67 GHz), the measured reflection coefficient is lower than -10 dB. Only at 56 GHz, there is some discrepancy between the measured and simulated results which is due to the assembly errors. Moreover, it is necessary to mention because the antenna is measured by the N5247A vector network analyzer (10 MHz–67 GHz), the highest frequency of the measured result is limited at 67 GHz, and the simulated result shows that at the band higher than 67 GHz, the antenna can also work well.

Fig. 11 shows the simulated and measured results of the normalized H-plane (yz-plane) radiation patterns of the proposed antenna. As illustrated in Fig. 11 (a)–(c), the simulated and measured co-polarization ($E\varphi$) patterns are depicted at 55, 60, and 65 GHz, respectively. The simulated and measured main lobes agree well with each other, and the maximum radiation direction only varies from 48° to 53°. Due to the measurement limitation, the backward radiation and the cross-polarization are not measured. The simulated cross-polarization is less -25 dB, which is not shown in Fig. 11 for simplicity.

The simulated and measured antenna gains are plotted in Fig. 12. In the operating band, the antenna gain varies from 9.1 to 10.57 dBi, and the maximum measured gain is 10.57 dBi at 59 GHz. At 61 GHz, the measured gain is lower than simulation for 1.6 dBi which is due to the assembly and measurement errors. Due to the measurement limitations, we only present the simulated radiation efficiency in Fig. 12. The simulated results show that the radiation efficiency of

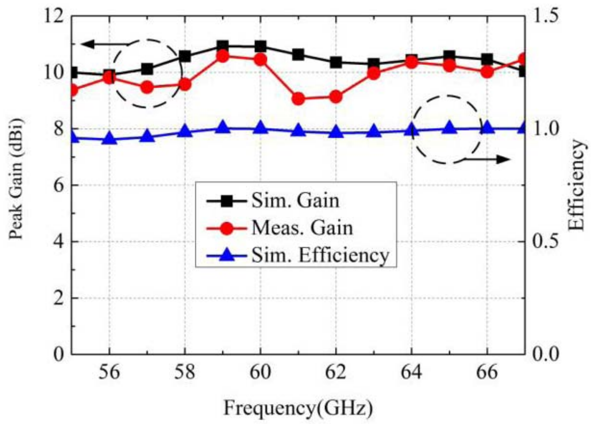

Fig. 12. Peak gain and radiation efficiency of the proposed leaky-wave antenna.

the proposed antenna is higher than 0.95 over the operating frequency.

V. Conclusion

In this paper, a novel leaky-wave slot antenna with fixed beam is proposed. The slot antenna is based on the air-filled cavity. Compared with conventional leaky-wave slot antenna, the proposed slot antenna excites quasi-TEM type of mode and uses air as the medium, which contributes to maintaining the maximum radiation direction fixed. The proposed antenna is stacked by three silicon layers, and every layer is fabricated by the bulk silicon MEMS micromachining technology. A prototype of the proposed antenna is fabricated, and the measured results show that the impedance bandwidth is 55–67 GHz, the gain varies from 9.1 to 10.5 dBi, and the maximum radiation direction is fixed at about 50°.

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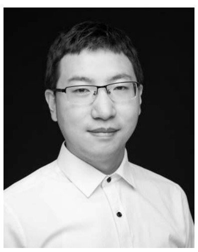
His current research interests include antenna design and theory, particularly antenna arrays based on leaky-wave antenna, massive multi-in multi-out antenna array, and millimeter-wave antenna array.



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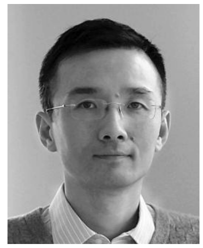

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