Cylindrical Conformal Array Antenna with Fan-shaped Beam for Millimeter-wave Application

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***Abstract*—A millimeter-wave cylindrical conformal array with 120° flat-top broad beam and a stable 30° downward tilted-angle is demonstrated, fabricated and measured in this paper. A 32-element longitudinal slots array antenna is selected as the radiating element of the cylindrical conformal array, which is wrapped around the cylindrical in the circumferential direction. A 1-to-8 unequal power divider and a compact phase compensating network are developed as the feed network for the designed 8×32 slot array. Measured results show that a 120° flat-top broad beam with stable 30° downward angle is achieved over the operating frequency band. The proposed new conformal array antenna can be used in millimeter wave base station system.**

Keywords—Conformal antenna, fan-shaped beam, Substrate integrated waveguide

I. Introduction

A conformal antenna is an antenna that conforms to a prescribed shape, such as the surface of a cylinder, sphere or cone, whose shape was determined by aerodynamic or similar reasons other than electromagnetic [1]. Conformal antennas possess the potential advantage of a wide angle coverage, which makes it is more applicable to wireless communication base station antenna than planar antenna.

In conformal design, radiating structures must possess the characteristics of good flexibility and low profile. Microstrip patch antenna has been widely used in the design of conformal antenna because of the merits of low weight, low profile and conformal ability [2-3]. However, in millimeter-wave band, microstrip patch antenna suffers from the serious the loss of surface wave and long microstrip feed line. Moreover, the structure of the microstrip patch antenna is semi-open, so the stray radiation and the mutual coupling will decrease its performance sharply. The metal waveguide has closed structure, but its profile is very high in general, which limits its application in millimeter-wave conformal antenna. As a new waveguide structure, substrate integrated waveguide (SIW) keeps most of the merits of microstrip and rectangular waveguide, such as lower profile, low insertion loss, high power capacity and ease of integration. It is very suitable for the millimeter-wave conformal antenna application [4-6]. A conformal SIW leaky-wave antenna [4] and a conformal SIW traveling-wave antenna [5] realized 70° and 10° beam-scanning with the changing of frequency, respectively. Another SIW conformal antenna array presented in [6] has a flat-top fan beam with 75° half power beam width in E-plane. However, all these approaches are facing the challenge of wide coverage (greater than 120°) and small gain ripple (less than 3 dB) if they were used for millimeter-wave base station antenna. And more importantly, tilted radiation pattern needs to be developed for the mobile communications

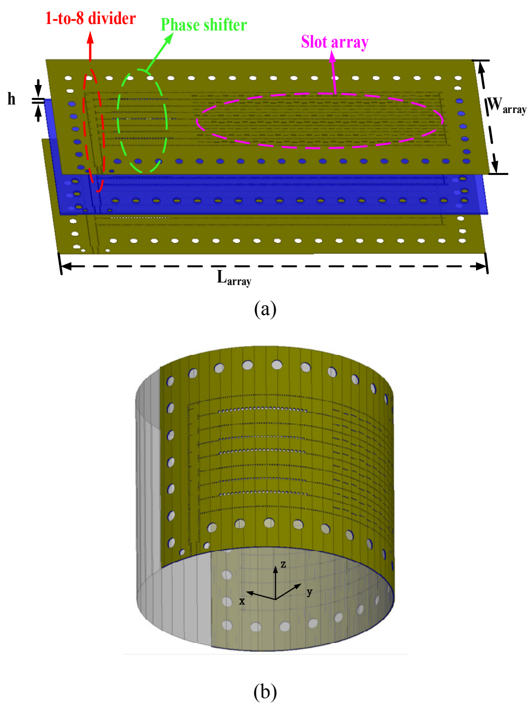


Fig1. Perspective view of the proposed antenna array; (a) 3D view of planar SIW slot array antenna; (b) 3D view of conformal SIW slot array antenna.

In this paper, a millimeter-wave SIW conformal antenna with 120° fan-shaped flat-top beam and a stable 30° downward tilted-angle is developed, the center frequency is 42.5 GHz. As the perspective and 3-D views shown in Fig. 1, the proposed conformal antenna is composed of a 1-to-8 unequal power divider, eight self-compensated phase shifters and eight 1×32 slotted waveguide antenna arrays. The whole array can be easily realized by using standard PCB technology and then wrapped on the surface of the cylinder.

II. SIW Conformal Antenna Design

In conformal antenna design, the propagation characteristic of a conformal SIW must be firstly analyzed. The fundamental mode propagation constant is calculated by using both closed-form expression and full-wave simulation. The comparison results show that it was almost keeps unchanged when the cylindrical radius to wavelength ratio is greater than 2. So it is

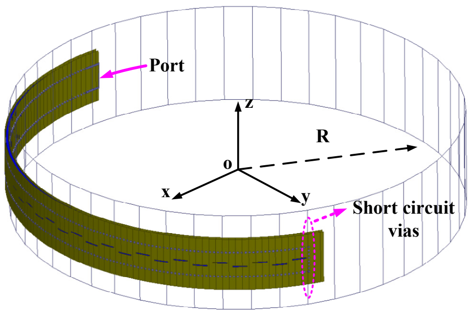


Fig. 2. Configuration of a 1×32 slot array circumferentially curved on a cylindrical surface.

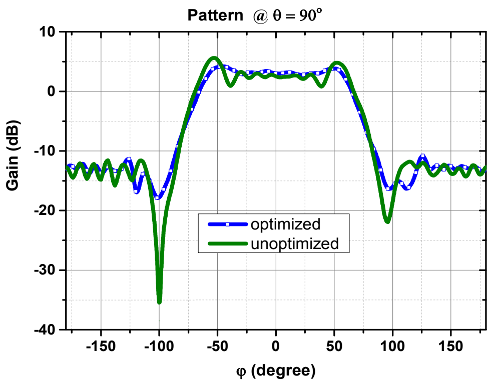


Fig. 3. Simulated Gain pattern of the conformal 1×32 slot array at the design frequency of 42.5 GHz. The green line denotes simulated result for the radiating slots have the same offset, while the blue line denotes simulated result for the slot offsets were optimized

not need to consider the change of the propagation constant in the SIW conformal antenna design.

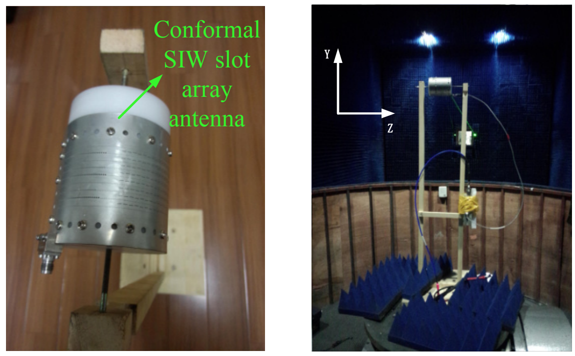
A. Design of Radiating Structure

The radiating structure is composed of eight SIW longitudinally slotted conformal antenna arrays, and each of them has 32 longitudinally slots on the broad wall. We take the longitudinally slotted array as a circular array when it was wrapped on a cylindrical surface along the circumferential orientation as shown in Fig. 2. The far-field radiation function for the circular array in the azimuth plane can be represented as,

$$E(\phi) = \sum_n V_n EL(\phi - n\Delta\varphi) e^{jkR\cos(\phi - n\Delta\varphi)} \quad (1)$$

Where R is the radius of the cylindrical and k is the wavenumber in free space, $k = 2\pi/\lambda$, $\Delta\varphi$ is the inclined angle between the two adjacent radiating slots, so the radiating slots are spaced $R\Delta\varphi$ along the circle, V_n and $EL(\phi - n\Delta\varphi)$ are the excitation amplitude and element factor for the nth radiating element.

The excitation amplitude V_n are the dominant factors affecting the flatness of the fan-shaped beam. A flat-top fan-shaped beam with maximum Gain ripple less than 1.3 dB can be quickly obtained by using a rapid approach combing Genetic algorithm optimization with full-wave simulation as shown in Fig. 3.



(a) (b)

Fig. 4. (a) photograph of the conformal antenna curved on a cylinder with R=34.7mm, (b) photograph of the measurement setup for measuring its radiation pattern.

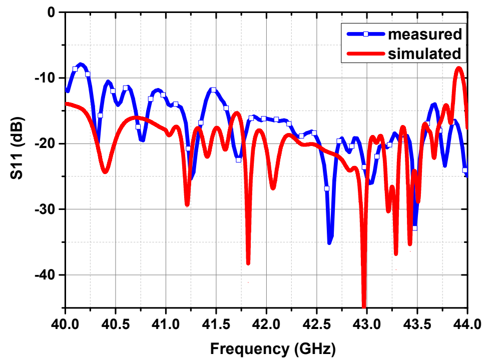


Fig. 5. The measured and simulated reflection coefficients at different frequencies.

B. Design of the Conformal Feed Network

The conformal feeding network is composed of one 1-to-8 unequal power divider and eight phase shifters. The 8 way unequal power divider is designed for achieving a -25 dB maximum side-lobe level beam in the elevation plane. The excitation amplitude of power divider output ports following the -25 dB linear Taylor distribution. The phase compensated network was adopted to compensate the output phase of the power divider, and provide stable input phase differences for the adjacent input ports of the eight SIW longitudinally slotted conformal antenna arrays over the frequency band of 42-43 GHz. Thus a stable 30° downward tilted-angle beam radiation can be achieved.

The required phase shift can be realized by adjusting the widths and the lengths of the phase shifters, however, the antenna dimension and the loss will be increased if the lengths of the phase shifters are too long, and the impedance matching will be deteriorated if the lengths are too short and the widths are too narrow, so a length of $4\lambda_g$ is selected as the original parameters in the phase shifter design.

III. FABRICATION AND MEASUREMENT

The designed 8×32 conformal SIW slot array was fabricated on a 0.508-mm-thick Rogers 5880 substrate (permittivity: 2.2, loss tangent: 0.0009) by using the low cost PCB process and occupies a volume of $188 \times 206 \times 0.508\ mm^3$. The fabricated antenna is curved on a cylindrical surface with the radius of 34.7mm in the circumferential

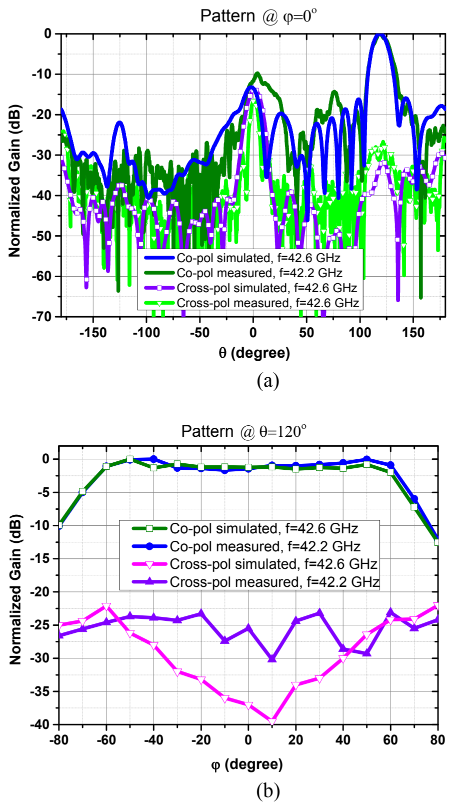


Fig. 6. The radiation patterns in elevation plane (E-plane) and in azimuth plane (H-plane) at the frequency of 42.2GHz for measurement and 42.6GHz for simulation. (a) elevation plane, (b) azimuth plane.

direction as shown in Fig. 4(a). A transition between the coplanar waveguide and substrate integrated waveguide (SIW) was used to connect the input port and the feed network, which is demonstrated in [7].

A. Return loss measurement

As shown in Fig. 5, the measured return losses of the proposed conformal antenna is compared with simulation, they are in close agreement except a small frequency deviation of about 0.3 GHz to the low frequency, which may due to the fabrication tolerance or the change of relative permittivity. The measured return loss is below to -10 dB within 40.25-44 GHz.

B. Radiation pattern measurement

The measurement setup and the test environment are shown in Fig. 4(b). The proposed conformal antenna radiates a conical beam, the maximum beam direction is points to downward and the angle between the maximum beam direction and the horizontal plane is 30°, the flat-top broad beam cannot be achieved directly by measuring the radiation pattern in azimuth plane. The information of the maximum gain ripple, beam-tilt angle and the side-lobe level can be extracted from the measured radiation patterns in elevation plane with different azimuthal angles.

The simulated radiation pattern at $\varphi = 0^o$ in elevation plane at the frequency of 42.6 GHz is shown in Fig. 6(a). The measured result at 42.2 GHz is also shown for comparison. The simulated and measured results show that the beam of the antenna has a 30° downward angle in elevation plane, the side-lobe level is less than -15 dB, the cross-polarization is lower than -26 dB at the main beam direction. As shown in Fig. 6(b), the radiation patterns at θ=120° in azimuth plane are plotted by extracting the main beam pointing angle and the maximum gain in elevation plane with different azimuthal angles, the 3 dB beamwidth is 126° (-64° to 62°), the measured cross-polarization within flat-top region is less than -22.5 dB and the maximum gain ripple is less than 1.8 dB.

IV. CONCLUSION

In this paper, a millimeter wave conformal slot array antenna with a flat-top broad beam is proposed at 42.5 GHz. The design is validated by measuring a 8×32 conformal slot array antenna, and good agreement is obtained between the designed goals and measured results. With merits of low profile, ease of integration and high compatibility with millimeter-wave circuit, the proposed antenna provided a good choice for conformal antenna in millimeter-wave application.

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