

Low-Profile, Low-Cost Substrate Integrated Waveguide Cavity-Slot Millimeter-Wave Antenna with Improved Gain and Efficiency

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Abstract—A single-layer low-cost millimeter-wave antenna with enhanced gain and efficiency is proposed by using a novel multi-slot substrate integrated waveguide (SIW) cavity structure. The antenna mainly comprises a single layer SIW cavity with multiple slots etched on the top layer and a probe as the feed approximately at the center. The position of the feed is slightly shifted away from the center to excite higher-order modes and multiple slots are etched intentionally to excite the radiation in-phase, leading to an improved gain and antenna efficiency. As a result, the conventional feeding networks of an antenna array can be removed. The antenna can realize an impedance bandwidth from 25.4 to 28 GHz with an efficiency, basically over 90%. The front-to-back (F/B) ratios are better than 27 dB. The proposed work can be a good candidate for low-profile, high efficiency millimeter-wave applications.

I. INTRODUCTION

With the requirements for higher data rates and lower latency, millimeter-wave communication technology has attracted intensive research interest and it is widely believed the millimeter-wave antenna is a critical component in the fifth/sixth-generation (5G/6G) wireless applications [1]. Recently, many types of antennas with various properties have been investigated. In [2], a dual-polarized antenna array with a broad bandwidth and high gain up to 13.1 dBi is proposed. On the other hand, the phased array with high gain and wide coverage has been studied intensively to avoid high free space loss in the millimeter-wave frequency [3]. In [4], a magnetoelectric dipole fed by substrate integrated waveguide has been investigated. Besides, it is important to improve the isolation among antenna elements to avoid co-band and cross-band interruption. In [5], the proposed antenna adapted the SICL feed structure, which significantly enhanced the isolation. However, due to complicated multiple layers and blind holes, the recently developed millimeter-wave antennas are suffering from high insertion loss and fabrication cost. With the expansion of the antenna array scaling, millimeter-wave antenna with high efficiency is a critical issue.

In this paper, an innovative, single-layer, low-cost, high-gain, high efficiency SIW cavity-slot antenna is proposed for millimeter-wave applications. The SIW cavity is designed to work in the higher modes and multiple slots are etched to realize the in-phase radiation, and hence, improved gain and efficiency can be achieved without assorting a conventional feeding network. As a result, the complexity and losses of the antenna can be significantly reduced. Furthermore, the planar and single-layer structure allows for easier fabrication and integration with

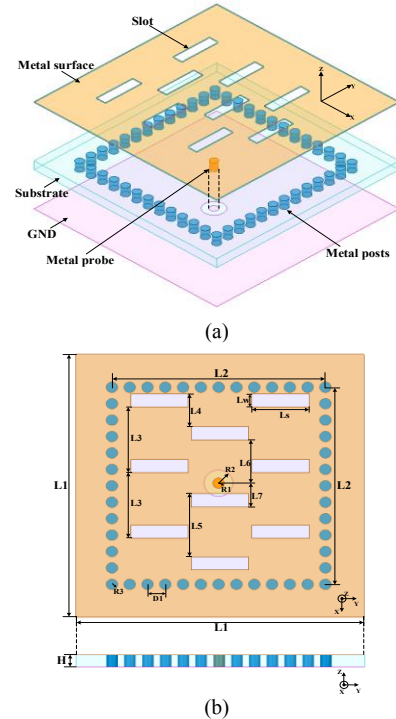


Fig. 1. Construction of proposed mm-wave feeding structure for MIMO applications. (a) Perspective view. (b) Top view and side view of the structure. $L1 = 20$, $L2 = 14.82$, $L3 = 5$, $L4 = 2.5$, $L5 = 4.8$, $L6 = 3.3$, $L7 = 1.8$, $R1 = 0.38$, $R2 = 0.6$, $R3 = 0.4$, $D1 = 1.25$, $H = 0.813$. (Unit: mm)

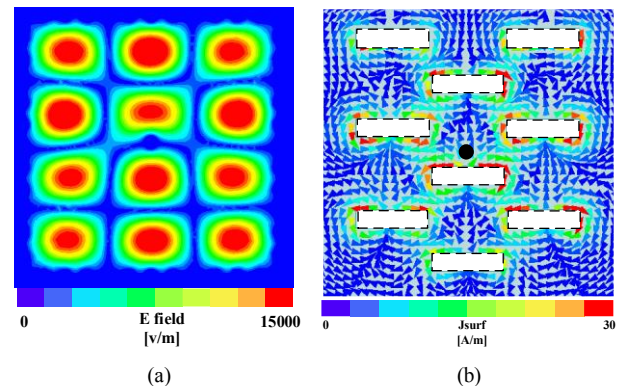


Fig. 2. Simulated field distributions: (a) E-field distribution of the cavity without slots etched, (b) current distribution with slots etched on the top layer.

other circuits, featuring a significant reduction of cost as compared with traditional millimeter-wave array antennas.

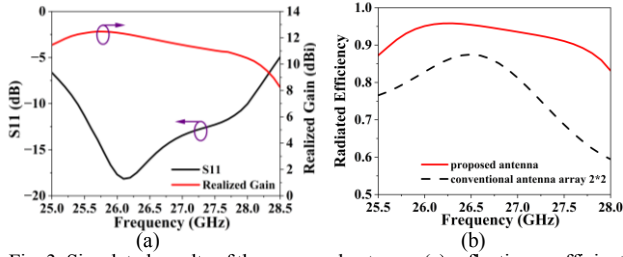


Fig. 3. Simulated results of the proposed antenna: (a) reflection coefficients and realized gain, (b) comparison of the antenna efficiency between the proposed antenna and a conventional patch antenna array.

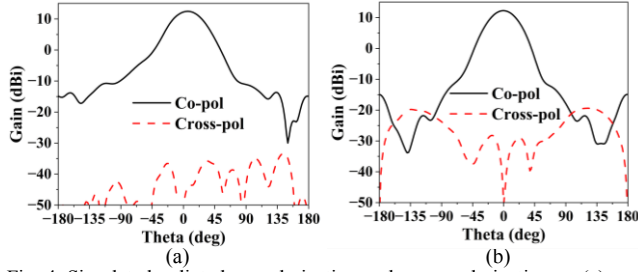


Fig. 4. Simulated radiated co-polarization and cross-polarization on (a) xoz-plane and (b) yoz-plane.

II. CONSTRUCTION AND PRINCIPLE

A. Configuration

The proposed SIW-cavity antenna is shown in Fig. 1(a). It consists of only one single substrate Rogers 4003 ($\epsilon_r = 3.55$, $\tan\delta = 0.0027$) with a thickness of 0.813mm. The antenna is working at the higher mode of the SIW cavity, which is excited by a probe. There are nine slots etched on the top layer of the SIW cavity, which can radiate linear polarization in the x-axis direction. It is noted that the position of the probe is slightly shifted away from the center position for better exciting the high modes of the cavity, as shown in Fig. 1(b). The positions of the nine slots are well selected according to the mode distribution, so that all of the slots can be excited in phase, forming the broadside radiation. The proposed antenna is designed and optimized using the High Frequency Structure Simulator (HFSS) with the key physical dimensions of the antenna listed in the caption of Fig. 1.

B. Principles

To illustrate the principles of the antenna, an SIW cavity without slots etched on the top layer is initially studied. By well tuning the position of the feeding probe, higher-order modes can be excited, as presented in Fig. 2(a). As can be seen, the SIW cavity is working at its TM_{430} mode from the electric field distribution analysis. Then, the nine slots are etched in the top layer according to the field distribution. The current distribution with etched slots is presented in Fig. 2(b). The position of slots is confirmed by selecting the positions where the current flows along the slots in phase. As a result, all of the slots can be excited in phase, leading to broadside radiation. Besides, the width, length, and position of the slots can be adjusted to achieve a better radiation performance. Thus, the proposed antenna is based on high-order modes excitation without resorting to

additional feeding networks, leading to a high efficiency as compared with traditional array antenna.

III. RESULTS AND ANALYSIS

Fig. 3(a) shows the simulated reflection coefficients and gain of the proposed antenna. The antenna exhibits an impedance bandwidth from 25.4 to 28.0 GHz (FBW = 9.7%), which can be used in 5G mm-wave applications. The simulated peak antenna gain is approximately 12.4 dBi in the band of interest. Fig. 3(b) shows the simulated antenna efficiency of the proposed antenna and a traditional microstrip array antenna. As observed, the simulated efficiency of the proposed antenna is basically higher than 90% with the maximum efficiency as high as 95.5%. Compared with the traditional patch array, the efficiency can be improved by 10% basically.

The radiation patterns of the proposed antenna are presented in Fig. 4. As can be seen, the proposed antenna exhibits broadside radiation pattern with the cross-polarization levels in both the E-plane and H-plane are lower than -20 and -30 dB, respectively. In addition, the antenna performs exceptionally good front-to-back ratio of exceeding 27 dB.

IV. CONCLUSION

In this paper, a single-layer SIW cavity-backed slot antenna with extremely low profile and high efficiency is proposed for millimeter-wave applications. The antenna structure features a single-layer, planar structure, enabling easy fabrication and integration with other circuits. A slight perturbation in the feed position is used to excite higher-order cavity modes and by selecting the positions of the slots by purpose, an improved gain and antenna efficiency can be achieved without employing traditional power-splitting networks, resulting in a reduced loss and high efficiency. Simulation results validate the concept of the antenna design, highlighting its potential for low-cost and high efficiency mm-wave applications.

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