Substrate Integrated Waveguide Cavity Backed Slot Antennas for Millimeter-Wave Applications

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***Abstract*—A low-cost single-layer substrate-integrated waveguide (SIW) cavity-backed slot antenna is proposed for millimeter-wave applications. The structure is designed to operate at the W-band. The T-shaped slot antenna is placed on the back-side of the SIW and fed by a grounded coplanar waveguide (GCPW) transmission line. A transition between the (GCPW) and the SIW is also designed. The simulated results provide that the antenna has a stable gain over the frequency range (98.79-100.56) GHz with a maximum value of around 6 dBi also high radiation efficiency.**

***Index Terms*—W-band, cavity backed-slot antenna, grounded coplanar waveguide(GCPW), millimeter-wave applications.**

I. Introduction

With the rise of wireless data traffic, the demand for much higher data rate wireless communication has been increased. The evolution of wireless channels shows that data rates of wireless channels have risen considerably and, they are quickly approaching the capacity of wired communication systems. It is predicted that they will reach ultra-high data rates up to 1 Tbps by 2030 [1]. Going by this trend, sub-Terahertz communication is a key to support this requirement, given the immense bandwidths available in this band (100-300) GHz. One of the fundamental components in the evolution of millimeter-wave systems is the antenna. The antenna design is a key component in determining the performance of the system and chosen materials may dictate the production cost and flexibility in penetration of the technology. A suitable technology to meet the requirements of millimeter-wave applications is substrate-integrated waveguide technology (SIW), which supports a complete integration of antenna and circuits within the same substrate using the same processing technique with high quality-factor, low loss, and low cost.

Either SIW cavity-backed patch antenna or a cavity-backed slot antenna have been investigated largely for mm-wave communications, owing to their easy integration in a complete system, low profile, high efficiency, besides low cost, compared to its counterparts. For example, a traditional cavity-slot-backed antenna has a high profile and low integration with planar circuits. A variety of feeding techniques can be used for the excitation of SIW cavity-backed antenna (CBA) including, microstrip line, coplanar waveguide (CPW), grounded coplanar waveguide (GCPW), probe, and waveguide [2].

Several techniques have been introduced in SIW-CBA design, such as excitation of higher-order modes in the backed cavity and introducing a double slot in the backed cavity [3] [4]. Co-planar waveguide (CPW) line with a metalized via is used as feeding for SIW cavity-backed E-shaped patch antenna in [5]. An array of 2×2 was designed, for operation at (37.5-46) GHz, a bandwidth of 34.4% and gain of 12.5 dBi with a radiation efficiency of 88 % have been obtained. In [6] four L-shape slots based SIW are demonstrated for dual W-band radar sensing and communication applications. The slots are placed on the top metal, and hybrid high-order modes are excited to solve the resolution and variation constraints of a standard PCB. The antenna has a gain of 8 dBi at 77 and 90.5 GHz frequencies but, it has low radiation efficiency, and the bandwidth is narrow in both frequencies. Also, there are high discrepancies between the simulated and measured results. Based on PCB technology, dual-layer SIW cavity-backed L-shaped slots antenna array was proposed in [7] for 79 GHz automotive radar applications. The 2×4 antenna array is manufactured using SIW-WR10 transition. The structure has a stable gain with variation less than 1 dB within the band of 75–82 GHz and acceptable bandwidth. However, the fabrication increases substantially with the number of layers.

Most SIW antenna structures use a multilayer- technology or an array to achieve high radiation performance, which increases the manufacturing cost with a complex fabrication process. So far, few studies have been investigated the design of antenna-based SIW technology for this frequency range (90-110) GHz.

In this paper, a single-layer SIW cavity-backed slot antenna is proposed. The size of the T-shaped slot antenna is adjusted to arrange two bands around the operation frequency of 100 GHz and making two exciting modes close to each other for increased bandwidth operation. Additionally, to further enlarge the bandwidth and improve gain and efficiency, a GCPW transmission line is adopted, and a transition between the grounded coplanar waveguide (GCPW) and the SIW is selected, which facilitates the measurement process.

The paper is divided into four sections. The subsequent section deals with the configuration and design procedure. The following section presents a parametric analysis and the results of the proposed antenna. The last section provides the conclusions and discussion of future work.

II. Configuration and Design Procedure

A. Substrate Integrated Waveguide Structure

The integration of technologies, rectangular waveguides, and planar circuits into a unified design leads to the rise of SIW technology. It is characterized by its high ability to integrate all active and passive components on a single substrate, with the same processing technique, high quality-factor, high power-handling capability, low loss, and low manufacturing cost [8]. A substrate-integrated waveguide is emanated from a dielectric-filled waveguide (DFW). This technology does not support TM mode (Transverse Magnetic), and it only permits the propagation of TE_{n0} modes (Transverse Electric) because of the presence of the vias. Only the vertical component of the electric current density exists along the sidewalls. The main parameters of SIW are the width W_{siw}, the diameter of the vias (d), and the center to center distance between the vias or post (p). These parameters are represented in the diagram of Fig. 1 (left). Based on empirical criteria, d and p should satisfy the following conditions:

$$d < \frac{\lambda_g}{5} \tag{1}$$

$$p \leq d, \tag{2}$$

where λ_g is a guided wavelength is expressed as:

$$\lambda_g = \frac{2\pi}{\sqrt{(\frac{\omega\sqrt{\epsilon_r}}{c})^2 - (\frac{\pi}{a})^2}} \tag{3}$$

in which c and ϵ_r represent a speed of light in vaccum and the permittivity of the substrate, respectively.

B. Grounded coplanar waveguide feed to SIW Transition

A transition SIW to grounded coplanar waveguide (GCPW) is designed for coupling the signal into the waveguide. Undesired radiation can be created by the transition, interfering with the radiation pattern. A grounded coplanar waveguide (GCPW) is chosen since it exhibits low radiation and dispersion in a high-frequency band and provides an easy interface through commercially available connectors (e.g., Southwest Microwave 2492-04A-6), facilitating the measurement procedure.

The model is composed of two parts, a coupling slot, and the impedance transformer. A tapered coupling slot is made by combining the coupling slot and its impedance transformer to achieve a wide-band transition. The sidewalls of the waveguide are tapered along with a triangle-shaped coupling slot in such a way that the direction of the electric field on the coupling slot is always perpendicular to the SIW sidewalls [9]. To cancel the parallel plate mode in GCPW, the vias are set along the GCPW. Additionally, to guarantee a single-mode operation on the side of the CPW, the condition (4) should be considered in the design [10]:

$$W + 2S + 2D < \frac{c}{2f_{max}\sqrt{\epsilon_r}} \tag{4}$$

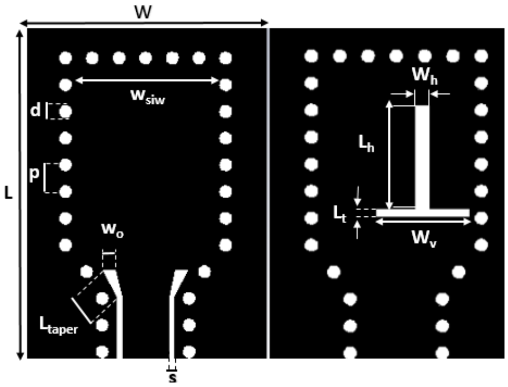

Fig. 1. Top and bottom views of the proposed SIW cavity-backed slot antenna.

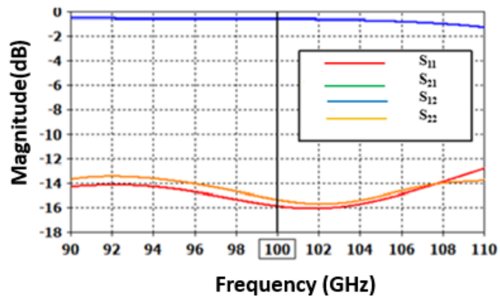

Fig. 2. S-parameters of GCPW to SIW transition.

where W is the strip width, S is the gap between the line and adjacent ground plane, and D is the distance between the gap and vias.

By locating port 1 on the GCPW transmission line side and port 2 on the SIW side, the model of this transition is designed and simulated using the substrate height of 0.381 mm, the width and gap for the GCPW line were W= 0.71 mm and S = 0.1 mm, respectively. The taper coupling slot length is selected around $\frac{\lambda}{4}$ at the center frequency. The simulation results of the S-parameters are shown in Fig. 2, in which a return loss is higher than 15 dB, and an insertion loss is lower than 0.61 dB.

C. Proposed SIW Cavity-Backed Slot Antenna

A SIW based cavity-backed slot antenna (CBA) can be obtained using single or multilayer substrate. The conditions $P/d \geq 0.5$ and $d/\lambda_0 \leq 0.1$ must be met so that a SIW cavity is equivalent to the conventional metallic cavity. The proposed structure consists of single-layer Rogers 5880 laminate with a thickness of 0.381 mm and a relative permittivity of $\epsilon_r = 2.2$. To guarantee effective isolation from any parasitic radiation produced from the feeding [11], the proposed inverted T-shape slot antenna is placed on the bottom of the structure as shown in Fig. 1 (right). The transition grounded coplanar waveguide (GCPW) to SIW cavity is adopted as feeding for the SIW cavity slot antenna.

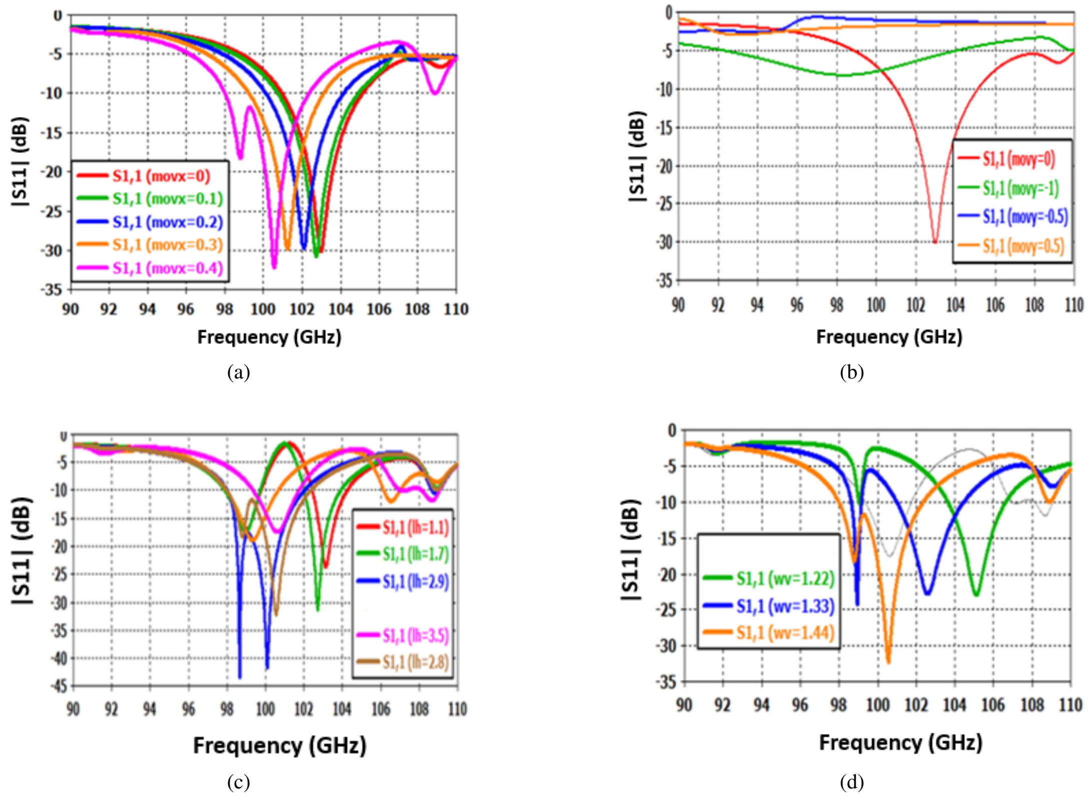

Fig. 3. Reflection coefficient (S11) for several cavity positions and sizes (a) vertical position movx, (b) horizontal position movy ,(c) length Lh and (d) width Wv.

III. Results and Discussion

A. Parametric Studies

A set of analyses was conducted to examine the impact of the cavity slot size and location of the performance of the antenna.

- It can be observed from Fig. 3a that by changing the vertical position of the slot (movx) the resonance frequency decreases and the bandwidth increases. The horizontal position (movy) for this structure affects the resonance frequency and the matched impedance, as depicted in Fig. 3b.
- When the length (Lh) is increased, it can be noted from Fig. 3c an evident decrease in the resonant frequency of the higher frequency mode.
- Increasing the width (Wv) leads to shifting the resonance of the higher modes to lower frequencies, with improvement in the bandwidth as shown in Fig. 3d.

From the results, it can be seen that the vertical position and width of the slot antenna have a strong influence on the bandwidth.

B. Results

Among the fundamental design of the SIW cavity-backed slot antenna is a suitable location of vertical slot, which controls the bandwidth. After a parametric sweep, the optimum dimensions for the proposed structure are selected and summarized in Table I. The results obtained from the simulation are set out in Fig. 4: a reflection coefficient below -15 dB was obtained with a bandwidth of 4.36 GHz ranging from 98 to 102.36 GHz. As can be seen from Fig. 5, the proposed SIW-CBA reaches a gain of about 6 dBi at 98.79 GHz with stable behavior over the frequency range (98.79-100.56) GHz.

TABLE I
Dimensions of SIW-cavity backed slot antenna

Par.	L_h	L_t	W_h	W_v	W_s	W
Value (mm)	1.65	0.15	0.24	1.44	2.36	3.88
Par.	L	W_0	L_{taper}	p	d	s
Value (mm)	5.36	0.24	0.51	0.43	0.22	0.1

Fig. 6 shows the simulated 3D radiation patterns at 98.79 and 100.56 GHz. The SIW to GCPW transition also participates in the radiation, which can affect the sidelobe level (SLL) of the structure. Overall, these results indicate that the suggested SIW- CBA is suitable for operation.

A comparison between the proposed antenna and some previous work is reported in Table II. It can be seen that acceptable performances are obtained, in terms of bandwidth (4.36 GHz), gain (about 6 dBi), and efficiency (96%) for the proposed antenna with compact size, low cost, and simple structure.

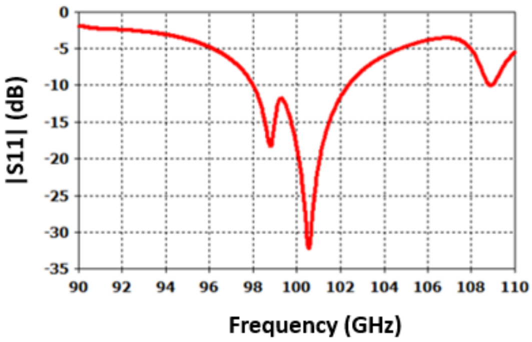

Fig. 4. Simulated reflection coefficient magnitude of SIW-CBA.

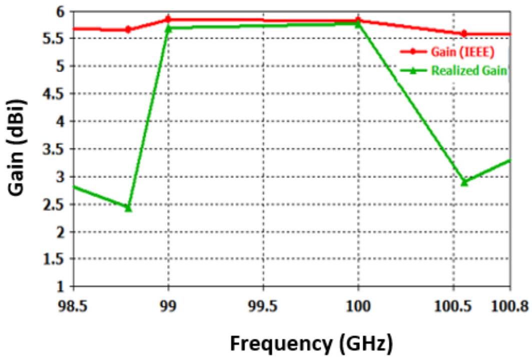

Fig. 5. Simulated gain of the proposed SIW-CBA.

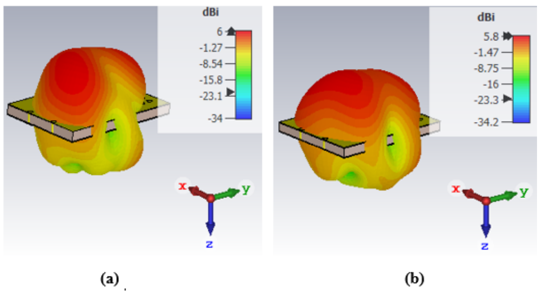

Fig. 6. 3D-Radiation patterns (a) at 98.79 GHz,(b) at 100.56 GHz.

TABLE II
COMPARISON OF THE PROPOSED ANTENNA WITH PREVIOUS REPORTED WORK

Ref	Antenna/ Array	Freq (GHz)	ϵ_r	Gain (dBi)	BW (GHz)	Eff(%)
[12]	antenna	38	2.2	7.8	7.7	83.9
[13]	antenna	60	2.2	-	2.57	70
[14]	multilayer antenna	70	3.22 3.37	7.15*	12*	83*
[6]	antenna	77 90.5	3.55	8* 8.2*	3* 1.5*	58.6* 59.4*
This work	antenna	100	2.2	6	4.36	96

−Parameters not mentioned,* Measured

IV. Conclusion

A single-layer SIW cavity-backed slot antenna is proposed. This work uses the GCPW line and tapered GCPW–SIW transition, which provides a wideband transition between the SIW feeding and antenna measurements. The position and dimensions of the slot antenna are analyzed. The results present a good compromise between high radiation performance and low-cost fabrication with a compact antenna. A flat gain around 6 dBi within a frequency range of (98.79-100.56) GHz with a radiation efficiency of 96% and bandwidth of 4.36 GHz is obtained. The small antenna size did not allow achieving large bandwidth, which requires further enhancement. As future work, the proposed antenna will be manufactured and measured.

Acknowledgment

This work was supported by FCT (Fundação para a Ciência e a Tecnologia, Portugal), through the Ph.D. grant PD/BD/137424/2018.

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