Planar Slot Antenna Backed by Substrate Integrated Waveguide Cavity

Guo Qing Luo, *Member, IEEE*, Zhi Fang Hu, Lin Xi Dong, and Ling Ling Sun, *Senior Member, IEEE*

***Abstract*—A novel design method of low profile cavity backed planar slot antenna has been described in this paper. The whole antenna including backed cavity and feeding element is completely constructed at a single substrate by using substrate integrated waveguide technique and grounded coplanar waveguide. An example with 1.7% bandwidth has been presented, which has 5.4 dBi gain, 16.1 dB front-to-back ratio and -19 dB maximum cross polarized radiation level with its total thickness less than $\lambda_0/50$. The proposed antenna keeps good radiation performance of conventional cavity backed antenna and has advantages of conventional planar antenna including low profile, light weight, easy fabrication with low cost and convenient integration with planar circuit.**

***Index Terms*—Cavity backed, grounded coplanar waveguide (GCPW), low profile, slot antenna, substrate integrated waveguide (SIW).**

I. Introduction

WITH RAPID development of wireless communication, low profile antenna with good radiation performance are in great demand, especially in space applications such as satellite, aircraft and radar in some military platforms. Slot antennas, for their attractive characteristics such as low profile, conformability to planar or curved surfaces, easy integration with planar circuits and better isolation from feed network, are very suitable for these applications and have been extensively studied by many researchers.

One evident drawback of slot antenna is its bidirectional radiation because slot etched at metal plate can radiate freely to both sides. In practical application metal reflector or shallow cavity is used to eliminate backside radiation. The optimal distance from slot to reflector or cavity bottom is roughly one-quarter wavelength. A simple short-end waveguide is usually served as backed cavity in slot antenna [1], [2]. Size reduction of cavity backed slot antennas by dielectric or ferrite loading in the cavity have been fully investigated by simulated and measured results in [3]. Another size reduction method is proposed in [4], in which specific metallic pattern is used to replace the solid metal plate around the radiating slot. With proper metallic pattern the size of the cavity backed slot antenna can be greatly reduced to a half. But all backed cavities used in above references are conventional metallic cavities and they are still bulky for some practical applications.

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Low profile cavity backed slot antenna entirely realized by multilayer printed circuit board (PCB) structure has been firstly proposed in [5], in which cavity is constructed by two rows vias connecting upper and lower ground plane, slot is etched at one ground plane and stripline is located in the middle layer as feeding structure. Another similar structure is studied in [6], which is also composed by two substrate layer. Microstrip fed slot antenna with a shorting via is fabricated at top substrate. Thin cavity is constructed by properly spaced conducting vias at bottom substrate. All above presented cavity backed slot antennas have good radiation performance with their profiles greatly reduced.

In this paper we present cavity backed slot antenna based on substrate integrated waveguide (SIW) technique combined with grounded coplanar waveguide (GCPW) structure. SIW technique is firstly proposed by Wu [7], [8], which is similar to early presented "laminated waveguide" [9] and "post-wall waveguide" [10]. In these concepts metallized vias array are adopted to construct conventional metal waveguide at planar substrate. Up to now antennas based on these concepts are open-end waveguide radiator [11] and waveguide slot antenna [10], [12]. Here we firstly take SIW technique into cavity backed slot antenna design. The proposed antenna combines advantages of conventional cavity backed antenna and planar patch or slot antennas. It behaves good radiation performance and offers advantages of low cost, low profile, easy integration with planar circuit and convenient fabrication by ordinary single layer PCB process.

II. Design Procedure

Configuration of the proposed SIW cavity backed planar slot antenna is shown in Fig. 1. The proposed antenna is completely constructed at a single substrate. Its square backed SIW cavity is realized by four rows metallized vias arrays. In order to make the SIW cavity be equivalent to conventional metallic cavity, the conditions of $d/d_p \geq 0.5$ and $d/\lambda_0 \leq 0.1$ must be satisfied, where λ_0 denote free space wavelength [7]–[9]. When these guidelines are met, attenuation constant is little enough and leakage from clearance between two neighboring vias can be neglected. Radiating slot is etched at ground plane then parasitic radiation generated by feeding network can be effectively isolated. 50 Ω GCPW is adopted as feeding element to stimulate the SIW cavity. For measurement convenience a section of 50 Ω microstrip line is added at the end of inner conductor of the GCPW with the same width.

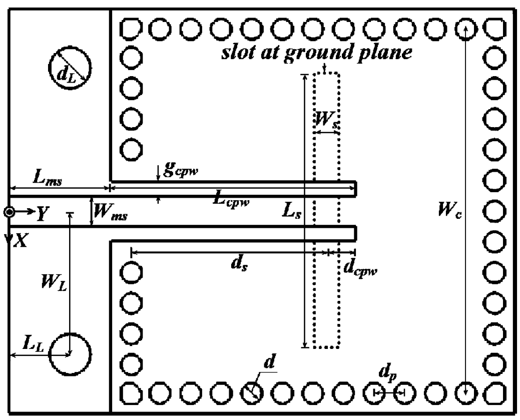

Fig. 1. Geometry of the proposed SIW cavity backed planar slot antenna.

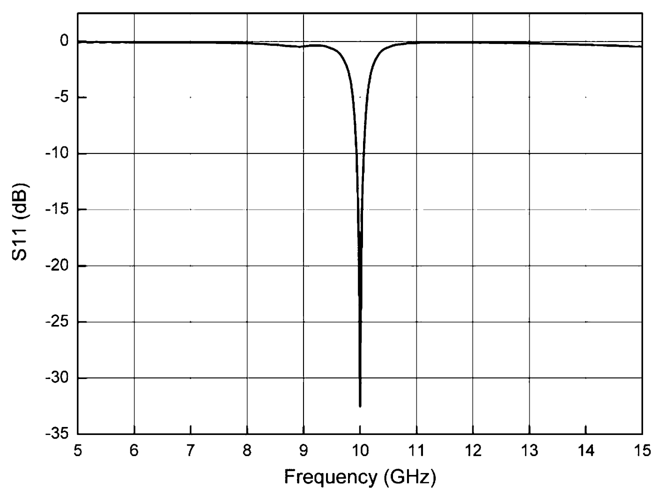

Fig. 2. Simulated S11 of the proposed antenna.

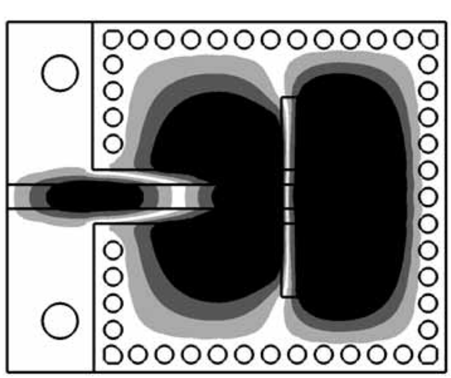

Fig. 3. Electric field profiles of the proposed antenna at 10 GHz.

The proposed antenna is studied by using finite element method. Its simulated return loss has been plotted in Fig. 2, in which dielectric and conductor losses have been counted. From the figure we can find that radiation is only generated at the required frequency within a wide frequency range. This characteristic makes it suit for some applications in which highly isolated antenna is required for rejecting interference signal at out-band. Electric field diagram of the proposed antenna at 10 GHz is given in Fig. 3. The radiation is generated by TE_{120} resonance in SIW cavity. It is far different from that

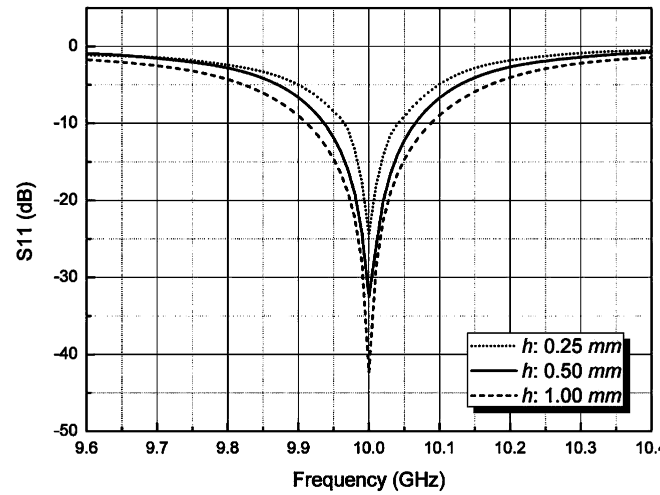

Fig. 4. S11 of the proposed antenna versus cavity height.

of conventional cavity backed antennas in which the backed cavities just behave as closely spaced reflectors. When the SIW cavity is in TE_{120} resonance, dominant electric field at two sides of the slot has opposite phase, and then there is transverse electric field across the slot, thus energy can radiate into space by the slot.

It should be noted that the proposed antenna is a narrow band antenna with fractional bandwidth about 1.4%. This is an inherent drawback of the proposed antenna for its low profile configuration and unique responding mechanism. In order to improve bandwidth some methods can be adopted. From cavity backed antenna theory we know that matching impedance bandwidth is directly proportional to cavity depth. Similarly, impedance bandwidth of the proposed antenna can be gradually improved with substrate thickness h increasing, which is shown in Fig. 4. Some other methods such as slot with inductive or capacitive load, and adding matching circuit in feeding network can be used to improve bandwidth too. But for its unique responding mechanism it is hard to make the proposed antenna have enough bandwidth for broadband application.

Severed as radiator, slot is an important tuning element of the proposed antenna. Slot width W_s can be used to slightly improve impedance bandwidth. But its effect on impedance bandwidth is far less than that of substrate thickness h. Slot length L_s has notable effects on operating frequency and radiation efficiency. Though operating frequency of the proposed antenna is primarily determined by cavity size W_c, it can be tuned by slot length L_s to a certain degree. From Fig. 5 it can be observed that operating frequency of the proposed antenna is in inverse proportion to its slot length L_s. Slot length has great effect on radiation efficiency. When slot is in resonance, energy can radiate in space to the utmost extent by the slot. In order to get high radiation performance including radiation efficiency and gain, it is better to set slot length L_s be half wavelength at the required frequency in which TE_{120} cavity mode generates. From Fig. 5 it also can be found that maximum radiation efficiency is obtained when the slot is in resonance. Within impedance matching frequency range, radiation efficiency is higher than 75%. The largest radiation efficiency of the proposed antenna can be reached is about 86%.

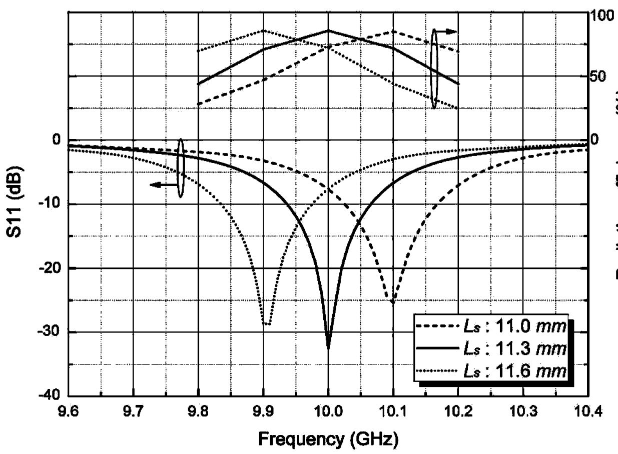

Fig. 5. S11 and radiation efficiency of the proposed antenna versus slot length.

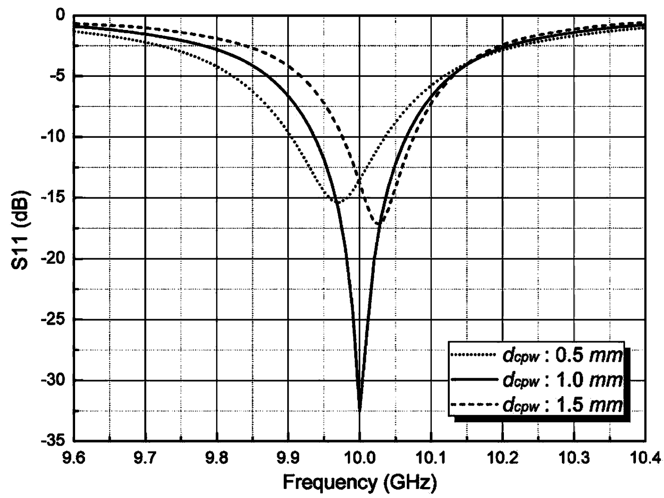

Fig. 6. S11 of the proposed antenna versus tuning GCPW length $d_{\rm cpw}$.

Once the slot length and cavity size are determined, the input impedance can be slightly adjusted by tuning GCPW length $d_{\rm cpw}$. In order to stimulate $\rm TE_{120}$ resonance in SIW cavity completely, GCPW must be set across the slot. Tuning length $d_{\rm cpw}$ is set from slot to the end of GCPW, which is labeled in Fig. 1. Its effect on S11 is demonstrated by Fig. 6. Variation of $d_{\rm cpw}$ has little influence on operating frequency, but it can evidently affect impedance matching. Large or small $d_{\rm cpw}$ would lead to matching impedance bandwidth decrease.

III. Antenna Performance

In order to validate the proposed design method, a sample of the proposed antenna has been fabricated on Rogers Duroid 5880 substrate with permittivity of 2.2 and loss tangent of 0.001. The substrate thickness h is 0.5 mm resulting in cavity height less than $\lambda_0/50$, which make the proposed SIW cavity backed antenna's profile far less than that of conventional metallic cavity backed antenna with height about $\lambda_0/4$. Detailed geometrical parameters of the measured sample are listed in Table I. The sample's photograph is shown in Fig. 7, whose whole size is 19.8 mm × 23.8 mm × 0.5 mm.

Measured S11 of the proposed SIW cavity backed planar slot antenna is plotted in Fig. 8 compared with full wave simulated

TABLE I
Geometrical Parameters of the Proposed SIW Cavity Backed Planar Slot Antenna

L_{ms} (mm)	5.0	W_{ms} (mm)	1.45
L_{cpw} (mm)	11.0	g_{cpw} (mm)	0.7
L_s (mm)	11.3	W_s (mm)	1.0
d_s (mm)	10.0	d_{cpw} (mm)	1.0
d (mm)	1.0	d_p (mm)	1.5
L_L (mm)	3.0	W_L (mm)	7.0
d_L (mm)	2.0	W_c (mm)	17.8

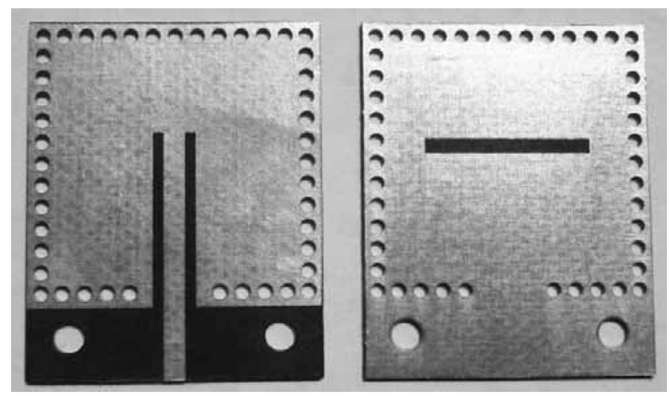

Fig. 7. Photograph of the proposed SIW cavity backed planar slot antenna. (Left: front side; Right: back side).

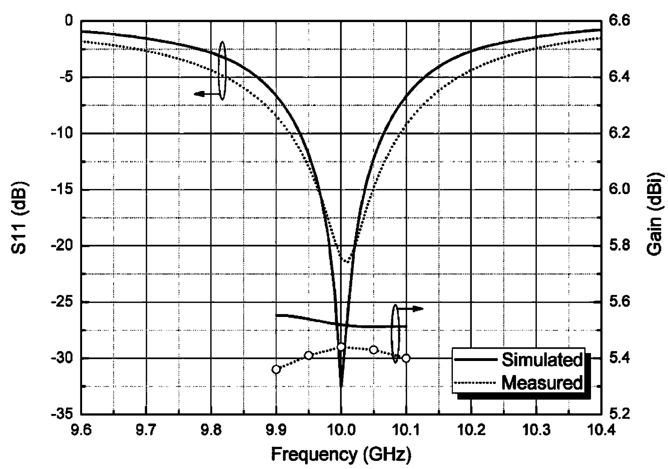

Fig. 8. Comparison between measured and simulated results of S11 and gain at boresight direction of the proposed antenna.

result. It can be found that measured result is in good agreement with the simulated. Measured bandwidth 170 MHz is more than the predicted 140 MHz. This slight discrepancy maybe attributed to some errors which can not be counted in simulation, such as roughness of metal surface, fabrication errors and transition loss. Because the proposed antenna is a high Q-value resonator, little errors would lead to an evident degradation of Q-value.

Radiation patterns measurement was carried out in microwave anechoic chamber, in which no large metal plate has been used as ground plane. Measured and simulated gain of

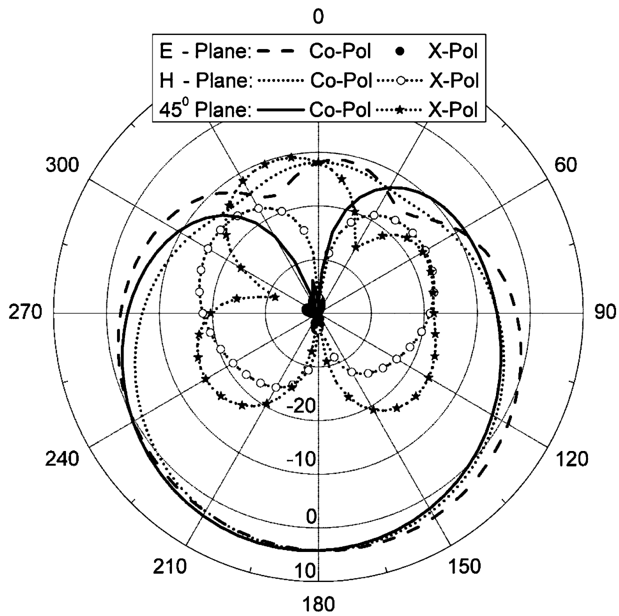

Fig. 9. Measured radiation patterns in different cut-planes at 10 GHz.

the proposed antenna at boresight direction ($\theta = 180^\circ$) varied with frequency is also plotted in Fig. 8. Both the simulated and measured results show that the proposed antenna has a high gain which is more than 5.3 dBi within the observing frequency range.

The far-field co-polarized and cross-polarized radiation patterns of the proposed SIW cavity backed planar slot antenna have been measured at 10 GHz in three different cut-planes, which are corresponding to E-plane ($y - z$ plane, $\phi = 90^\circ$), H-plane ($x - z$ plane, $\phi = 0^\circ$) and 45° -plane (diagonal plane, $\phi = 45^\circ$) respectively. The measured radiation patterns are shown in Fig. 9. It can be observed that the proposed antenna has nearly identical co-polarized radiation patterns at positive radiating direction ($90^\circ \leq \theta \leq 270^\circ$) in these three cut-planes. The largest radiation direction of the proposed antenna is offset from boresight direction by 10° for its structure asymmetry in y direction. Measured results show that the proposed antenna has very low level cross-polarized radiation. At positive radiating direction ($90^\circ \leq \theta \leq 270^\circ$) the largest cross-polarized radiation emerges at $\theta = 240^\circ$ in 45° -plane, which normalized value is -19 dB. Cross-polarized radiation at two principal planes is very low, especially in E-plane for its structure symmetry in x -direction. Measured front-to-back ratio (FTBR) of the antenna is about 16.1 dB.

From the measured radiation performance it can be found that the proposed SIW cavity backed planar slot antenna keeps high radiation performance of conventional cavity backed antenna with its profile greatly reduced. Its radiation performances including gain, FTBR and cross polarization level are far better than that of conventional planar patch and slot antennas with the same low profile. In our proposed antenna, for metallized vias array existing, surface wave propagation in substrate is prohibited. Power leakage is greatly reduced, and edge diffraction effect is effectively suppressed. Thus its radiation performance such as directivity, FTBR and cross polarization level is evidently improved. Moreover, in practical application, the proposed antenna's radiation performance can be further improved because its ground plane would be enlarged when it is integrated with follow-up planar circuits. It is well known that antenna's backside radiation can be suppressed by increasing its ground plane size. Then antenna's radiation performances including directivity, FTBR, cross polarization level etc. can be improved.

IV. Conclusion

A new design method of low profile cavity backed planar slot antenna is presented in this paper. The whole antenna including backed cavity and feeding element is completely constructed at a single substrate by using SIW technique and GCPW structure. Experiment was carried out to validate this design concept. The fabricated antenna has 1.7% bandwidth and keeps high radiation performance of conventional cavity backed antenna such as high gain, high FTBR and low cross polarization level. It still has advantages of conventional planar antennas such as low profile, light weight, good conformability and seamless integration with planar circuit. It can be easily fabricated by ordinary single layer PCB process with very low cost.

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