Hybrid Electromagnetic and Non-Linear Modeling and Design of SIW Cavity-Backed Active Antennas

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Abstract **─** This paper presents the modeling and implementation of planar passive and active cavity-backed antennas in substrate integrated waveguide (SIW) technology. The cavity-backed topology helps suppressing the undesired surface-wave modes and may provide better phase noise performance in the antenna oscillator. The use of SIW technology allows for a compact and cost-effective implementation of the structure. The design of the active antenna involves both electromagnetic full-wave modeling for the radiating structure and nonlinear analysis of the active circuitry through harmonic balance and transient simulations. Single substrate prototypes of both passive and active antennas operating in X band are presented and measured, showing good agreement with simulated results.

Index Terms **─** Active antenna, cavity-backed antenna, harmonic-balance technique, substrate integrated waveguide (SIW).

I. INTRODUCTION

In the last years, a large number of wireless applications have emerged, spurring a great demand for low-profile antennas, for applications ranging from space communications to biomedical imaging and automotive radars. In this scenario, active integrated antennas represent a new paradigm for modern millimeter-wave systems, where compactness, light weight, low cost, low power consumption, and possibility to integrate multiple functions are required [1].

Substrate integrated waveguide (SIW) technology is the most promising candidate for the realization of low-profile active antennas, since it allows for the cost-effective and high performance implementation of waveguide-like structures using conventional fabrication techniques and permits their easy integration with planar circuitry and active devices [2–5]. A large number of SIW components have been proposed in the literature, including filters, couplers, power combiners and dividers, oscillators, and antennas [5]. Current research trends in SIW technology aim to the integration of complete systems on the same substrate, according to the system-on-substrate (SoS) approach [3, 4].

Among the different topologies for the implementation of low-profile active antennas, cavity-backed antennas appear to be a particularly suitable solution. Cavity-backed antennas have been widely studied in the literature [6–8], as they offer several design advantages such as increased efficiency due to surface-wave suppression, as well as adequate metal surface to dissipate heat from active devices required in large array implementations. Furthermore, cavity-backed antenna oscillators permit to improve phase noise performance [9].

This paper presents the design and the implementation of cavity-backed antennas in SIW technology. In particular, compact, single substrate cavity-backed passive and active antennas using a SIW cavity are presented. The paper is organized as follows: Sec. II presents the design and experimental verification of a passive cavity-backed SIW antenna operating in X band. The modeling is performed by using a full-wave electromagnetic analysis tool, based on the finite element method (FEM). Sec. III presents the active counterpart of the cavity-backed SIW antenna. In this case, the modeling is based on the combined use of a full-wave FEM analysis and of non-linear analysis tools, based on the harmonic-balance (HB) technique and transient simulations. Conclusions are discussed in Sec. IV.

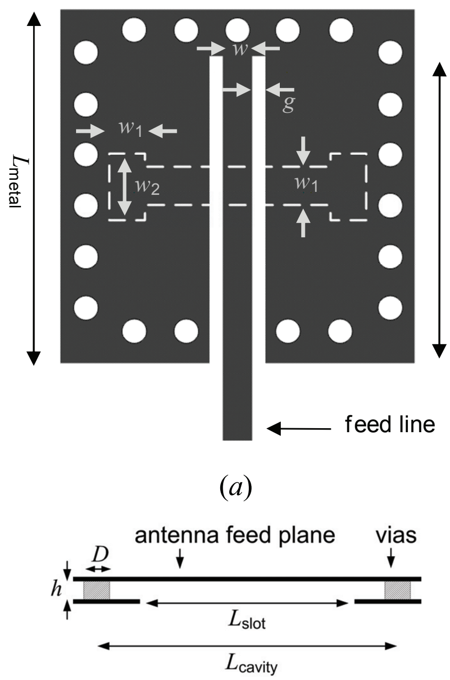

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Fig. 1. Geometry of the passive SIW antenna: (*a*) front view; (*b*) side view.

II. PASSIVE SIW ANTENNA

The passive cavity-backed SIW antenna is presented in this Section. It comprises a slot antenna backed by a SIW cavity, excited by a coplanar line (Fig. 1). This topology follows the one presented in [7], where the SIW cavity is obtained by four rows of metal cylinders in a dielectric layer with dual metallization. The radiating element is a slot etched in the ground plane. An input grounded coplanar line is used to excite both the cavity mode and the slot. This antenna topology permits to isolate the feeding circuitry and the radiating slot, since they are located on opposite sides of the dielectric substrate (Fig. 1*b*).

Table 1. Geometrical dimensions of the passive cavity-backed SIW antenna.

parameter	*dimension* [mm]
D	1.00
L_{cavity}	11.80
L_{slot}	10.00
L_{metal}	13.80
i	12.00
w_1	1.40
w_2	2.60
o	0.20
w	1.16
g	0.50

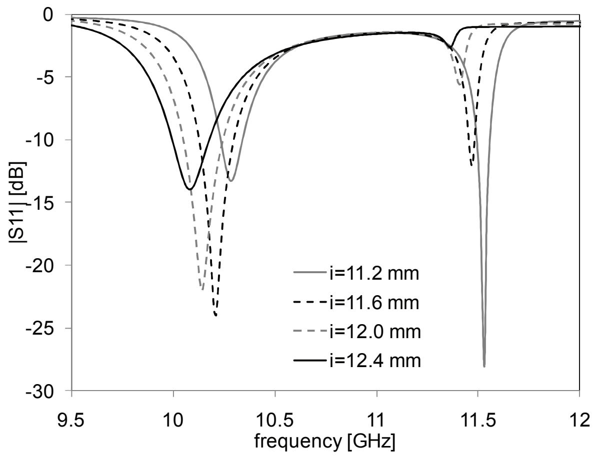
With respect to the antenna proposed in [7], the major differences are the use of a smaller cavity and of a “dogbone” slot, which allows for a more compact structure. The “dogbone” shape of the slot has been used in order to obtain the desired length within the available cavity space (Fig. 1*a*).

A. Electromagnetic modeling

The design of this passive structure has been carried out with a FEM-based full-wave simulator (Ansoft HFSS).

The antenna was designed on Arlon 25N substrate, with thickness h=0.508 mm and relative dielectric permittivity of 3.38 at 10 GHz. The SIW cavity is included between two copper planes connected by metal vias with diameter D=1 mm and spacing 2 mm, in order to avoid lateral radiation leakage [5]. In particular, the slot and the cavity have been dimensioned for broadside radiation and optimal input matching at 10 GHz. The cavity size has been selected to resonate on the TM_{120} mode. The feed line is a 50 Ω microstrip line outside the SIW cavity, whereas it turns into a coplanar line inside the cavity.

Parametric analyses have been carried out in order to investigate the dependence of the frequency response of the structure on certain



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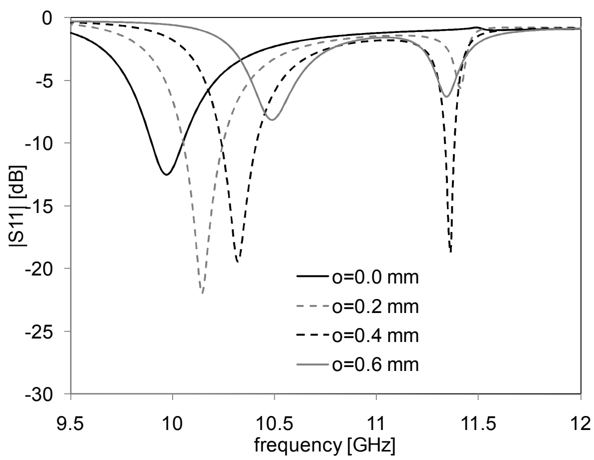

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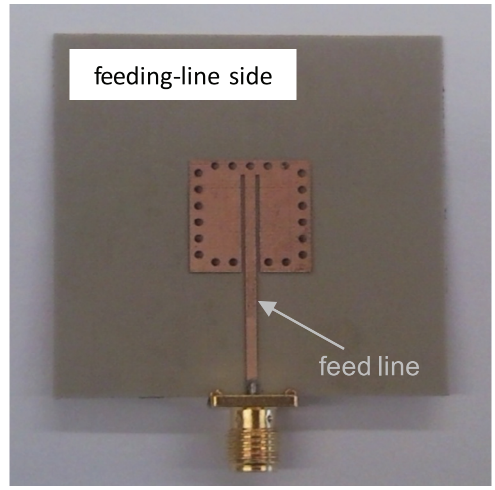
Fig. 2. Parametric study of the input matching of the passive SIW antenna.

geometrical parameters. Figure 2 shows the effect of the length of the coplanar feed line *i* and of the offset of the slot *o* on the frequency response of the antenna. Both parameters strongly affect the input matching around the first resonance (10 GHz) as well as the presence of a second resonance at 11.5 GHz. The second resonance can be attributed to the half-wavelength resonance of the coplanar feed line. More specifically, Fig. 2*a* shows that increasing the length of the coplanar line permits to minimize the effect of the second resonance. Nevertheless, if the value of *i* is larger than 12 mm, the input matching around the first resonance degrades. Similarly, Fig. 2*b* permits to identify an optimal value for the offset of the slot: if *o*=0, there is a negligible effect of the



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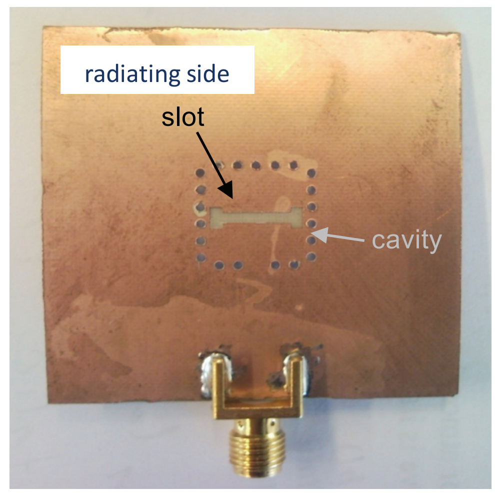

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Fig. 3. Photographs of the passive SIW antenna prototype: (*a*) feeding-line side; (*b*) radiating side.

second resonance but also a poor matching of the first resonance, whereas values of *o* larger than 0.2 mm lead to a strong effect of the second resonance.

On the basis of the parametric analysis shown in Fig. 2, the final dimensions of the geometrical parameters involved in the design have been selected and they are listed in Table 1.

B. Experimental results

A prototype of the passive cavity-backed SIW antenna has been fabricated and tested. Figure 3 shows photographs of the feed-line side and of the radiating side of the antenna.

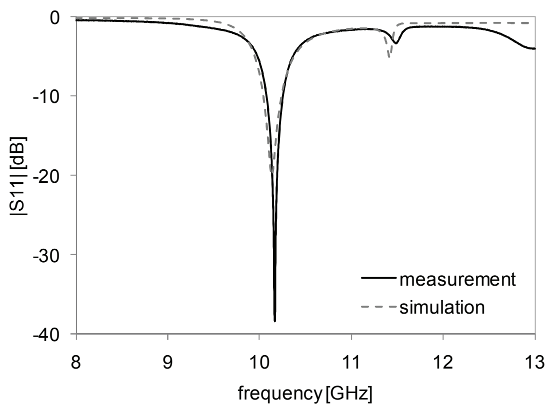


Fig. 4. Simulated and measured input matching of the passive SIW antenna.

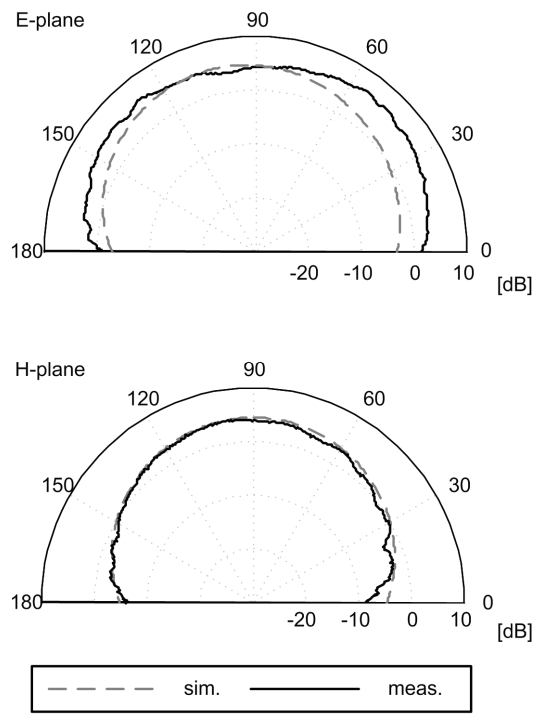


Fig. 5. Simulated and measured radiation pattern of the passive SIW antenna at the main resonance.

Figure 4 shows the simulated and measured input matching of the antenna, which exhibit a very good agreement over the entire frequency band. In particular, the simulation results predict a resonance at 10.14 GHz, whereas the measured results show a minimum of $|S_{11}|$ at 10.17 GHz.
The simulated and measured radiation patterns of the passive antenna are shown in Fig. 5, for both

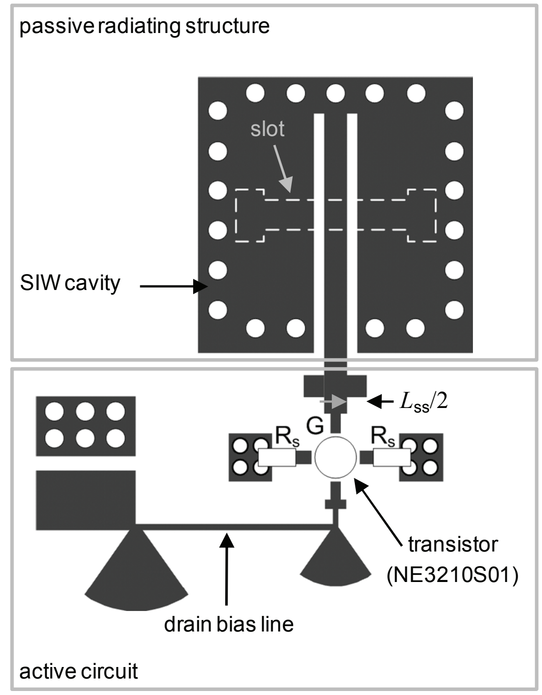


Fig. 6. Geometry of the active SIW antenna.

E-plane and H-plane cuts. The simulated gain of the final design was 4.2 dB at broadside, while the measured gain was 4.1 dB. The two patterns were obtained at the frequency of minimum reflection coefficient, namely 10.14 GHz for the simulated pattern and 10.17 GHz for the measured (Fig. 4). The asymmetry in the E-plane of the measured gain is potentially attributed to the feed line and connectors in the measurement setup.

III. ACTIVE SIW ANTENNA

The passive antenna discussed in the previous section has been used as the starting point for the design of an active cavity-backed SIW antenna. The active antenna consists of the combination of the passive antenna and a reflection oscillator, which uses the SIW cavity as the resonant element (Fig. 6). A similar cavity-backed slot antenna oscillator topology has been presented in [10]. In the present work, however, the cavity consists of a SIW resonator leading to a single substrate implementation of both the antenna and the cavity, and the slot is placed on a separate side from the active circuit, thus minimizing the effects of the active components and bias lines in the radiation pattern of the slot.

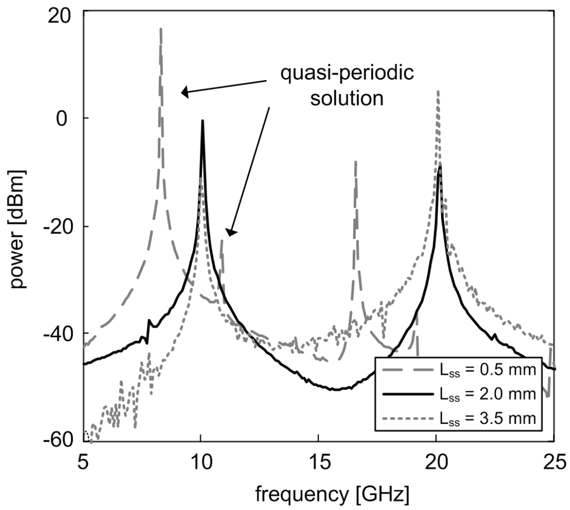
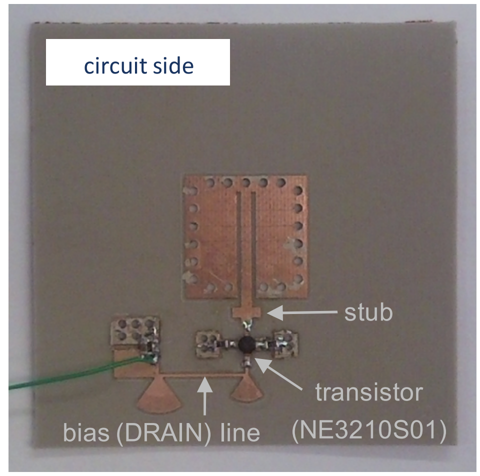


Fig. 7. Transient simulations of the active antenna, showing the effect of the stub length L_{ss}.

A. Electromagnetic and non-linear modeling

Once the design of the cavity-backed antenna has been completed, the oscillator circuit is designed using a commercial harmonic-balance simulator available from Agilent ADS. The S-parameters of the passive antenna obtained from the full-wave electromagnetic simulation are used in the HB analysis. The reflection oscillator is obtained by connecting the gate of an active pHEMT device (NE3210S01) to the cavity feed line (Fig. 6). Two 16 Ω resistors are then placed between the source terminals of the device and ground, in order to self-bias the circuit. The resulting structure is optimized to obtain an oscillation near the cavity resonance frequency of 10.14 GHz. In order to avoid the convergence to the trivial DC solution, the HB simulator was made to converge to the oscillating steady state using a properly defined ideal probe, as described in [11] and references therein. The probe consists of an ideal voltage source in series with an ideal band-pass filter. It is connected in parallel to a circuit node, in this case to the gate of the transistor. This auxiliary generator helps forcing the simulator to find an oscillating solution with non-zero amplitude at the desired frequency. Once the oscillating steady state solution has been obtained a transient simulation is used to study its stability.

One of the main parameters involved in the optimization of the active circuit is the stub length L_{ss} (Fig. 6). Changing this length allows to modify the input impedance seen from the transistor looking into the cavity; it can be seen that this design parameter can be used to optimize the oscillation frequency and eliminate unwanted parasitic oscillations. As shown in Fig. 7, for L_{ss}=0.5 mm the oscillator exhibits a quasi-periodic behavior with two fundamental frequencies (namely, at 8.3 GHz and 10.9 GHz). As L_{ss} increases, it is possible to obtain the desired oscillation frequency near the cavity resonance. For L_{ss}=3.5 mm, though, the second harmonic content of the oscillation grows. The selected value of L_{ss}=2 mm allows to find a good trade-off between the harmonic purity and the desired oscillation frequency, corresponding to 10.1 GHz.



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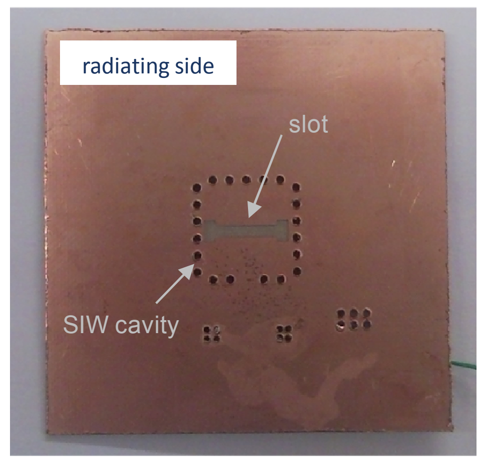

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Fig. 8. Photographs of the active SIW antenna prototype: (*a*) circuit side; (*b*) radiating side.

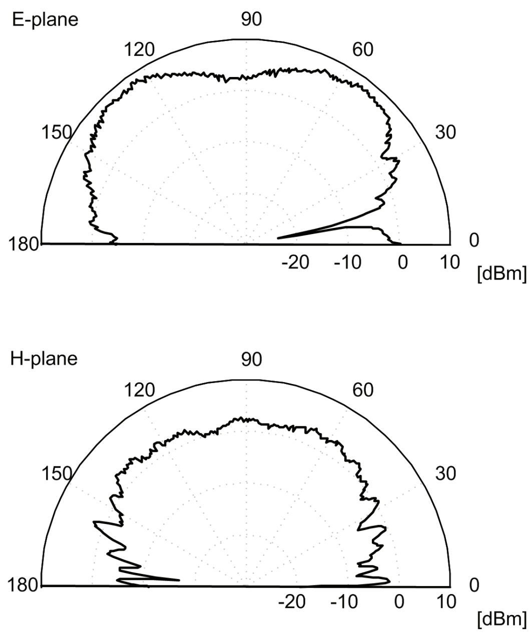

Fig. 9. Measured effective isotropic radiated power (EIRP) of the SIW active antenna.

B. Experimental results

The active cavity-backed SIW antenna was fabricated and experimentally characterized. Pictures of the prototype are shown in Fig. 8. The measured oscillation frequency of the active antenna was 9.8 GHz. Figure 9 shows the measured E-plane and H-plane radiation patterns of the active antenna, in the form of effective radiated power (i.e., gain and power product). The measured effective radiated power at broadside was 2.2 dBm.

The measured radiation pattern permits to estimate the overall radiated power, which is 0.65 mW. Since the power consumption from a DC power supply is 10.5 mW, the estimated DC-to-RF conversion efficiency results in 6.2 %.

Finally, using a probe to capture the radiated signal, the phase noise of the oscillator was measured to be -98 dBc/Hz at 1 MHz offset. The phase noise spectrum exhibited a 30 dB/dec slope up to and beyond 1 MHz offset indicating $1/f$ noise.

IV. CONCLUSION

A novel active SIW antenna has been designed and experimentally verified. It consists in the combination of a cavity-backed SIW slot antenna and a reflection oscillator, which shares the same SIW cavity with the antenna. This antenna results in a single-substrate, compact circuit topology, featuring the slot antenna and active circuitry on different sides of the substrate, thus allowing for high integration and low-cost fabrication methods.

The combined use of full-wave electromagnetic simulation tools and non-linear circuit analysis has been required for the design of this active antenna. More specifically, a full-wave FEM simulator has been adopted for the design of the antenna, whereas harmonic-balance and transient simulations have been used for the design of the oscillator.

X-band prototypes of both the passive SIW antenna and of the complete active antenna have been fabricated and measured, showing a good agreement with simulation data.

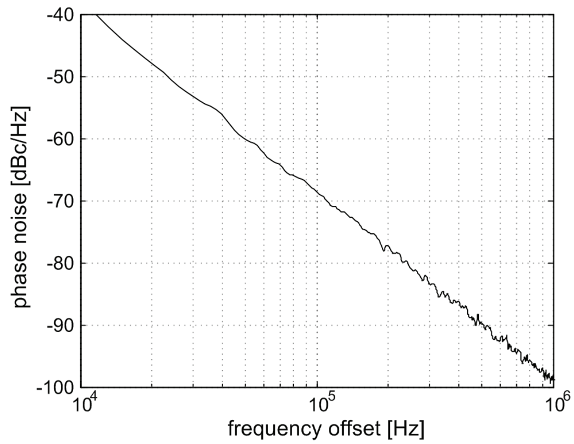

Fig. 10. Measured phase noise of the active antenna.

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