

Ultra-Wideband and Substrate-Independent AFSIW Cavity-Backed Slot Antenna for High-Performance Smart Surfaces

Kamil Yavuz Kapusuz, Sam Lemey, Piet Demeester, Hendrik Rogier

Department of Information Technology, IDLab/Electromagnetics Group, Ghent University/IMEC, Ghent, Belgium
 {KamilYavuz.Kapusuz, Sam.Lemey, Piet.Demeester, Hendrik.Rogier}@UGent.be

Abstract—A novel ultra-wideband substrate-independent air-filled substrate integrated waveguide (AFSIW) cavity-backed slot antenna that enables straightforward integration into common planar surface materials is proposed for the realization of high-performance smart surfaces. A prototype of the antenna is fabricated, integrated into furniture, and validated. In free-space stand-alone conditions, an impedance bandwidth of 1.2 GHz (or 21.8%), a total efficiency higher than 90%, and a gain higher than 5.1 dBi are achieved. Measurements prove that the antenna facilitates integration into a worktop with only a minor influence on its impedance bandwidth, gain and efficiency.

Keywords—Air-filled substrate integrated waveguide (AFSIW), cavity-backed slot antenna, circular cavity, Internet of Things (IoT), smart surface, substrate-independent, ultra-wideband.

I. INTRODUCTION

Significant momentum has started to build around the Internet of Things (IoT). The IoT network demands massive device connectivity, higher data rates, higher capacity, lower end-to-end latency, sustainable cost, and consistent quality of experience [1], [2]. For IoT radio access infrastructure, such as wireless nodes, the antenna system plays a crucial role in establishing and sustaining a robust and reliable wireless link [3], [4], [5], [6]. It should guarantee a stable and high radiation efficiency when deployed in different environments, minimize detuning due to varying environmental conditions and facilitate invisible integration into an everyday object without significantly increasing cost [7], [8].

Since exploiting the materials available in everyday objects to realize an antenna topology leads to a significant cost and area reduction, several antenna topologies have been recently developed to provide high-performance wireless communication for the IoT while adopting these readily available materials. [9] proposes two ultra-wideband cavity-backed slot antenna designs implemented on particle board and cork material. [10] relies on a circular patch antenna with four shorting vias, connecting the patch to the ground plane, in low-cost, lightweight, and flexible textile materials, enabling reliable communication between a body-worn node and an interrogator located in a smart floor/ceiling. [11] presents a dual semi-circular microstrip patch antenna implemented on a biodegradable substrate for smart domotics. Nonetheless, the adoption of general purpose materials as antenna substrate comes at the cost of

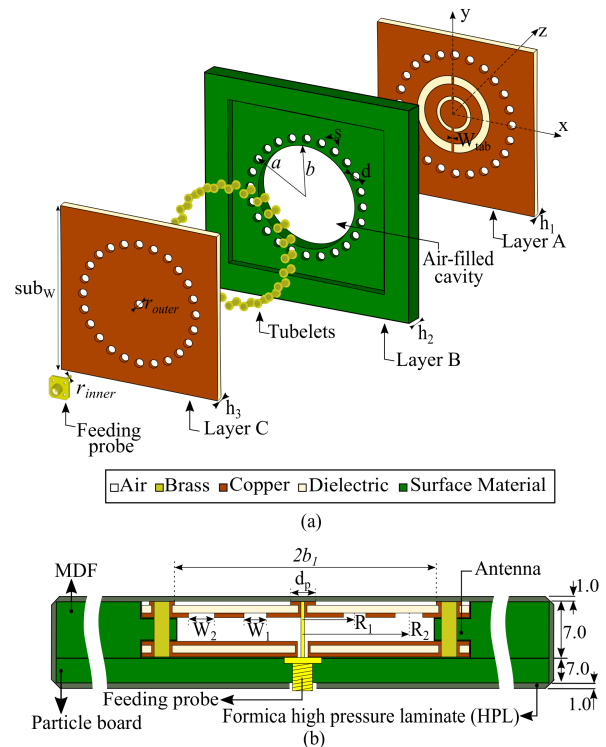


Fig. 1. (a) Exploded view of linearly-polarized AFSIW cavity-backed slot antenna. (b) Cross-sectional view after integration inside a commonly used board material to manufacture furniture. Optimized dimensions: $sub_w = 75.0$ mm, $a = 27.25$ mm, $b = b_1 = 24.53$ mm, $R_1 = 7.55$ mm, $W_1 = 1.7$ mm, $R_2 = 16.3$ mm, $W_2 = 4.0$ mm, $W_{tab} = 0.2$ mm, $h_1 = h_3 = 0.25$ mm, $h_2 = 6$ mm, $d = 4.0$ mm, $d_p = 2.3$ mm, $s = 5.7$ mm, $r_{inner} = 1.3$ mm, $r_{outer} = 4.3$ mm. Substrate parameters at 5.5 GHz: Layers A and C are implemented in I-Tera ($\epsilon_r = 3.43$, $\tan\delta = 0.014$), Layer B is implemented in MDF material ($\epsilon_r = 2.21$, $\tan\delta = 0.06$), and the cover layer is implemented in HPL material ($\epsilon_r = 3.56$).

a more complex and elaborate antenna design that takes into account the frequency-dependent material characteristics and accommodates for potential batch-to-batch variations.

In this contribution, a new cavity-backed slot antenna topology is combined with substrate-independent air-filled substrate integrated waveguide (AFSIW) technology, based on the framework in [12], to realize a high-performance, low-cost antenna design, facilitating invisible integration inside common objects. The proposed antenna was optimized for

operation in the [5.15 - 5.85] GHz Unlicensed National Information Infrastructure (U-NII) radio bands. To the authors' best knowledge, this is the first paper that describes the direct and invisible integration of a highly-efficient and low-cost AFSIW antenna inside the worktop of a desk composed of MDF/particle board and Formica High-Pressure Laminate (HPL).

II. REALIZATION OF AFSIW TECHNOLOGY

The improved AFSIW structure in [12] enables a straightforward integration of high-performance non-radiating microwave components into a wide range of general purpose commercially available surface materials. Fig. 1 shows the proposed cavity-backed slot antenna and its integration scenario by adopting this AFSIW technology [12]. The antenna consists of two layers of high-frequency laminate (Layer A and Layer C), one layer of surface material (Layer B), and low-cost conductive tubelets. On Layer A, a metallic frame and the antenna slot plane is implemented on a standard high-frequency laminate. The bottom conducting ground plane of the cavity is realized by Layer C. Next, a well-defined air cavity is created by removing parts of the surface material. To avoid that electromagnetic fields penetrate the lossy surface material, sidewalls are implemented by creating via holes in the surface material, at locations that are very close to the edges of the air cavity. These holes are then metalized by punching conductive tubelets through them, thereby joining all layers. Fig. 1 shows that a small portion of the dielectric material (Layer B) remains inside the air cavity for mechanical integrity. Yet, the lower-order modes in a cavity have their highest electric field sufficiently far away from the cavity sidewalls. Near the edge, where a small portion of lossy dielectric remains present, serving as support for the tubelets, the field values remain small. Therefore, those remaining dielectric slabs only introduce a very small loss. In [13], it is shown that for ratios of a/b above 0.9, this loss is almost independent of the dielectric properties of Layer B for the lower-order modes. In that case, any dielectric surface material can be applied as Layer B.

III. AFSIW CAVITY-BACKED SLOT ANTENNA

A. Antenna Topology and Operation Principle

The proposed ultra-wideband AFSIW cavity-backed slot antenna topology, depicted in [Fig. 1(a)], is designed by adopting the design procedure in [13]. It is composed of a top aperture plane, a circular AFSIW cavity and a bottom ground plane. Two concentric annular slots, both split in two by shorting tabs that create a virtual electric wall, are created on the top of the aperture plane. Note that the angular location of the shorting tabs defines the direction along which the electric field is linearly polarized, given the symmetry of the structure. These shorting tabs with the center-fed antenna topology enable the generation of a $TE_{11,slot}$ even mode in both parts of each annular slot [Fig. 2(a) and (b)], giving rise to a conical radiation pattern [Fig. 2(c) and (d)]. Yet, remark that the radiation pattern is not fully omnidirectional in the azimuth

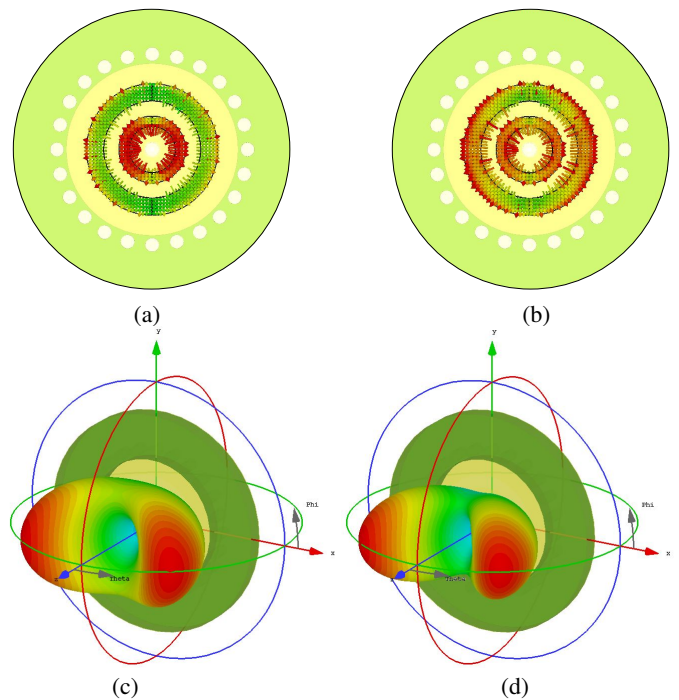


Fig. 2. Simulated hybrid mode profiles: electric field [V/m]. Horizontal cross sections of the proposed antenna at (a) 5.15 GHz and (b) 5.85 GHz. 3D gain pattern on a linear scale. In all gain patterns, the $|E_\theta|$ is the main component of the electric field ($|E_\phi| \ll |E_\theta|$): (c) 5.15 GHz and (d) 5.85 GHz.

plane as the electric field distribution in the apertures is no longer rotationally invariant due to the shorting tabs [13], [14]. Ultra-wideband performance is then achieved by judiciously positioning two concentric annular slots, resonating at distinct frequencies, into one single antenna footprint.

B. Integration into Furniture

The invisible integration of the antenna inside a commonly used worktop material is depicted in Fig. 1(b) and Fig. 3(d). The worktop consists of a $25 \times 25\text{-cm}^2$ sheet of 7-mm-thick MDF and particle board layers, sandwiched between two layers of 1-mm-thick Formica high-pressure laminate (HPL). First, the exact shape of the air-filled regions of the antenna is removed by standard CNC laser cutting in the MDF layer [Fig. 1(b)]. Next, a recess is milled out in the same MDF layer to accommodate for Layer A and Layer C. After assembling Layers A, B and C according to the procedure described in Section II, a 7-mm-thick particle board layer is glued below the MDF-layer implementing the proposed AFSIW antenna. Finally, two HPL layers are thermally bonded to the MDF/particle board stack to achieve invisible integration in contrast to [13] and [14].

C. Measurement Results

The fabricated prototype of the ultra-wideband substrate-independent AFSIW cavity-backed slot antenna is shown in Fig. 3. All the measurements are performed with an Agilent N5242A PNA-X Microwave Network Analyzer and an NSI-MI near-field antenna measurement system. The

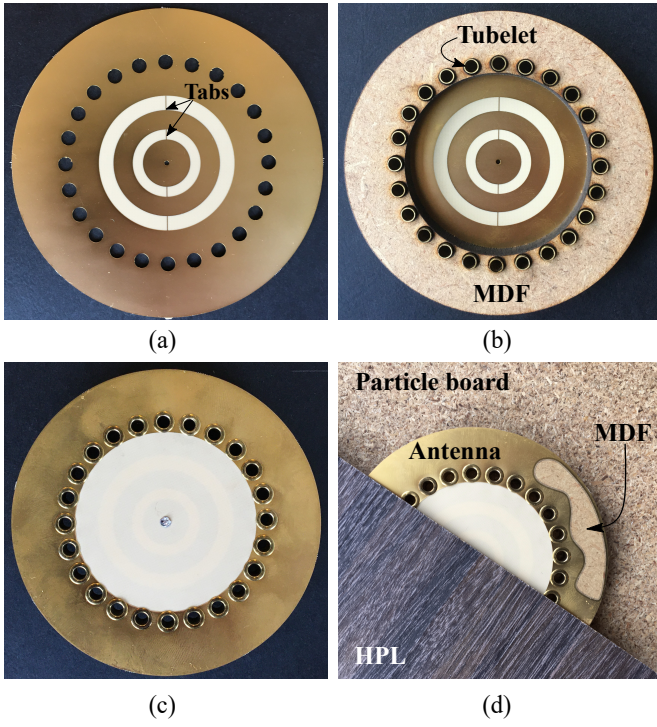


Fig. 3. (a) Back side of Layer A. (b) Integrated Layer A inside Layer B. (c) Prototype of fabricated antenna. (d) Antenna integrated inside a commonly used worktop material.

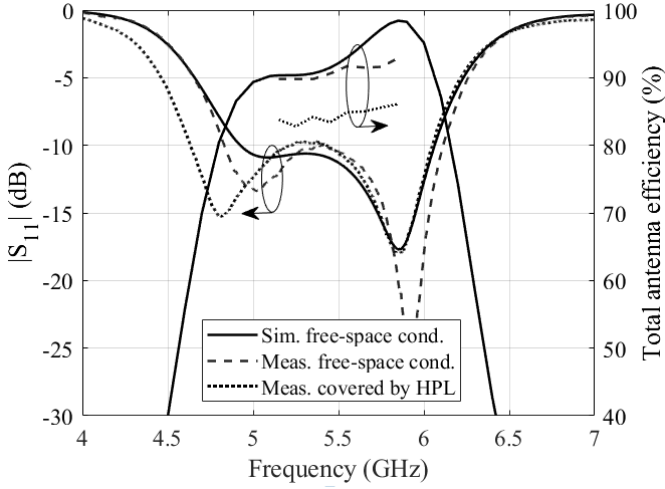


Fig. 4. Measured and simulated $|S_{11}|$ w.r.t. 50Ω and total antenna efficiency.

simulated and measured free-space stand-alone reflection coefficients are depicted in Fig. 4. We obtain a very good agreement between simulation and measurement results. Two resonance peaks can be observed because of the annular rings and cavity. The antenna is matched from 4.9 GHz to 6.1 GHz. Fig. 5 shows the antenna's radiation performance, with a total efficiency higher than 90%. The maximum gain is higher than 5.1 dBi, occurring at $(\theta, \phi) = (33^\circ, 0^\circ)$ in free-space conditions.

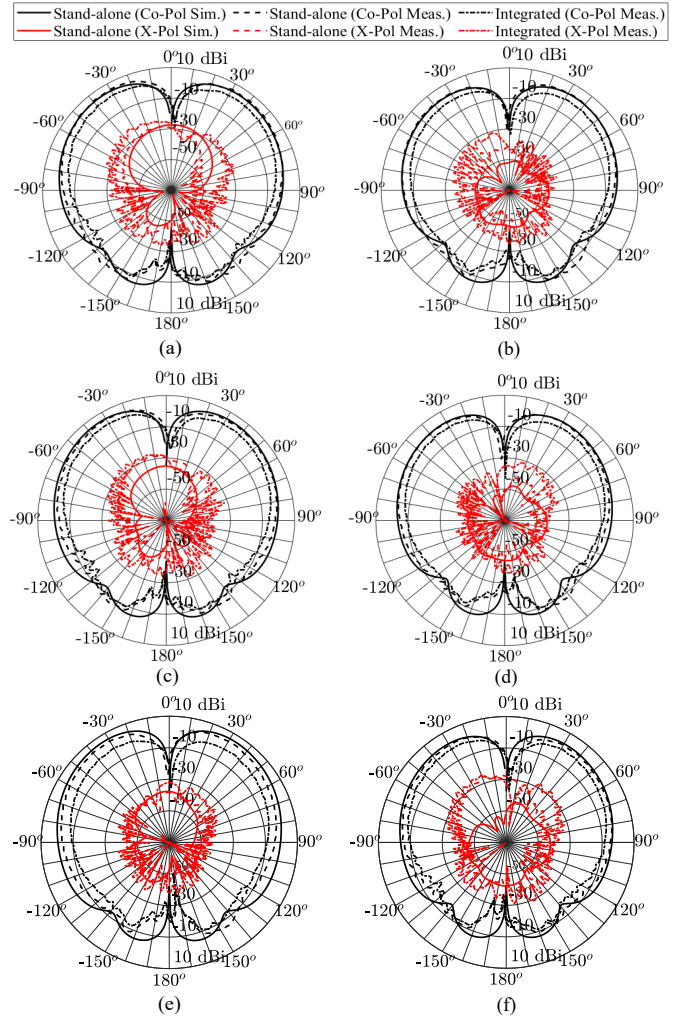


Fig. 5. Measured and simulated radiation pattern [dBi] at 5.15 GHz in (a) the XZ-plane and (b) the YZ-plane, at 5.50 GHz in (c) the XZ-plane and (d) the YZ-plane, at 5.85 GHz in (e) the XZ-plane and (f) the YZ-plane.

To confirm the stable performance after invisible integration, the antenna's characteristics were also measured in the presence of the particle board and both HPL layers. When supporting the antenna by 1-mm-thick HPL on the top, the impedance bandwidth enlarges from 4.6 GHz to 6.05 GHz [Fig. 4]. On the other hand, additional losses in the HPL layer slightly reduce the measured antenna efficiency to 82%. A reduced maximum gain of 3.8 dBi and nearly identical radiation pattern behavior are measured.

IV. CONCLUSION

A highly-efficient circular cavity-backed slot antenna in AFSIW technology is proposed. By relying on a dedicated design procedure, an ultra-wideband substrate-independent AFSIW cavity-backed slot antenna topology that enables straightforward integration into common surfaces is realized for high-performance smart surface applications.

ACKNOWLEDGMENT

The authors would like to thank the ERC for the advanced grant 695495 "ATTO: A new concept for ultra-high capacity wireless networks".

REFERENCES

- [1] A. Karaagac, P. Suanet, W. Joseph, I. Moerman, and J. Hoebeke, "Light-weight integration and interoperation localization systems in IoT," *Sensors*, vol. 18, no. 7, p. 2142, 2018.
- [2] O. L. A. L. et. al, "Massive wireless energy transfer: Enabling sustainable IoT toward 6G era," *IEEE J. of Internet of Things*, vol. 8, no. 11, pp. 8816–8835, 2021.
- [3] P. Mezzanotte, V. Palazzi, F. Alimenti, and L. Roselli, "Innovative RFID sensors for Internet of Things applications," *IEEE J. of Microw.*, vol. 1, no. 1, pp. 55–65, 2021.
- [4] A. Costanzo and D. Masotti, "Energizing 5G: Near- and far-field wireless energy and data transfer as an enabling technology for the 5G IoT," *IEEE Microw. Magazine*, vol. 18, no. 3, pp. 125–136, 2017.
- [5] F. A. et. al, "Smart hardware for smart objects: Microwave electronic circuits to make objects smart," *IEEE Microw. Magazine*, vol. 19, no. 6, pp. 48–68, 2018.
- [6] S. L. et. al, "Threefold rotationally symmetric SIW antenna array for ultra-short-range MIMO communication," *IEEE Trans. Antennas Propag.*, vol. 64, no. 5, pp. 1689–1699, 2016.
- [7] S. Lemey, S. Agneessens, and H. Rogier, "Wearable smart objects," *IEEE Microw. Mag.*, vol. 19, pp. 83–100, 2018.
- [8] L. R. et. al, "Smart surfaces: Large area electronics systems for Internet of Things enabled by energy harvesting," *Proc. IEEE*, vol. 102, pp. 1723–1746, 2014.
- [9] S. L. et. al, "Siw cavity-backed slot (multi-)antenna systems for the next generation IoT applications," in *IEEE Topical Conf. on Wireless Sensors and Sensor Netw.*, Austin, USA, 24-27 2016, pp. 75–77.
- [10] —, "Wearable flexible lightweight modular RFID tag with integrated energy harvester," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 7, pp. 2304–2314, 2016.
- [11] H. F. K. et. al, "Biodegradable dual semicircular patch antenna tile for smart floors," *IEEE Antennas and Wireless Propag. Lett.*, vol. 18, no. 2, pp. 368–372, 2019.
- [12] K. Kapusuz, S. Lemey, and H. Rogier, "Substrate-independent microwave components in substrate integrated waveguide technology for high-performance smart surfaces," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 6, pp. 3036–3047, 2018.
- [13] K. Kapusuz, S. Lemey, A. Petrocchi, P. Demeester, D. Schreurs, and H. Rogier, "Polarization reconfigurable air-filled substrate integrated waveguide cavity-backed slot antenna," *IEEE Access*, vol. 7, pp. 102 628–102 643, 2019.
- [14] K. Kapusuz, S. Lemey, and H. Rogier, "Multipolarization reconfigurable air-filled substrate integrated waveguide cavity-backed slot antenna," *IEEE Antennas and Wireless Propag. Lett.*, vol. 20, no. 4, pp. 622–626, 2021.