Coupled Half-Mode Cavity-Backed Slot Antenna for IR-UWB in Air-Filled SIW Technology

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***Abstract*—A coupled half-mode cavity-backed slot antenna for high-precision impulse-radio ultra-wideband (IR-UWB) localization applications in the $[3.7740; 4.7424]$ GHz frequency band of the IEEE 802.15.4a-2011 standard is designed and implemented in air-filled substrate-integrated-waveguide (AFSIW) technology. The antenna is matched to 50Ω in the $[3.6400; 4.8300]$ GHz frequency band, yielding a bandwidth of 1.19 GHz or 28.1%. Furthermore, a total antenna efficiency higher than 91.0% and a system fidelity factor (SFF) higher than 98% is achieved within the 3dB-beamwidth of the antenna, making it suitable for high-precision IR-UWB localization.**

I. Introduction

High-precision localization systems are imperative in the context of Industry 4.0 and the Internet of Things (IoT). Although adverse propagation characteristics are typically encountered in these dense and heterogeneous indoor environments, impulse-radio ultra-wideband (IR-UWB) localization systems provides optimal performance [1], [2]. However, because of the application of sub-nanosecond pulses in IR-UWB technology, different antenna radiation characteristics are needed compared to narrowband systems. Therefore, substantially different antenna topologies need to be considered, exhibiting both excellent frequency- and time-domain characteristics.

A plethora of suitable IR-UWB antennas can be found in current literature [3]. However, because these antennas were validated in stand-alone free-space conditions, they can easily detune after integration into their deployment platform. UWB cavity-backed slot antennas, proposed in [4], [5], provide robust performance in the frequency domain, even in challenging IoT or Industry 4.0 environments. As a result, the cavity-backed slot antenna topology is a suitable foundation to achieve the desired antenna performance characteristics. Furthermore, by implementing the cavity-backed slot antenna in air-filled substrate-integrated-waveguide (AFSIW) technology, we can enhance the antenna performance quite significantly. As a result, this article introduces a coupled half-mode cavity-backed slot antenna, implemented in a stacked AFSIW technology and optimized for IR-UWB localization.

II. Proposed antenna and operation principle

The proposed antenna, depicted in Fig. 1, is designed in compliance with the IEEE 802.15.4a-2011 standard [6]. The antenna design is optimized both in the frequency and time domain, requiring the antenna to be matched to 50Ω (min. 10 dB return loss) in the $[3.7740; 4.7424]$ GHz frequency band and to exhibit a system fidelity factor (SFF) [7] higher than 98% for all orientations of interest. Furthermore, a total antenna efficiency of more than 85% is required in this band. These requirements guarantee reliable and energy-efficient operation in both IEEE 802.15.4a-2011 channels 2 and 3.

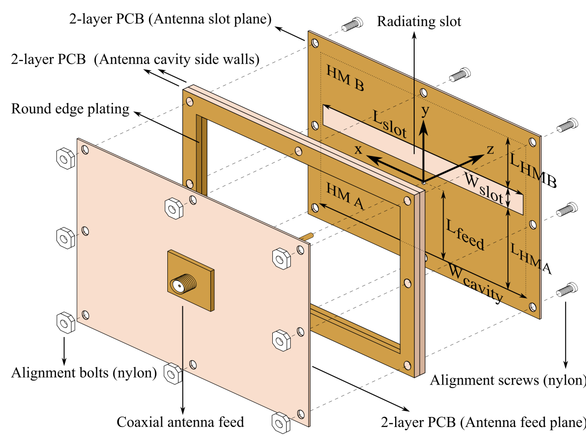

Fig. 1: Implementation and dimensions of the coupled half-mode cavity-backed slot antenna in AFSIW technology. The copper plated surfaces of each layer are colored in dark yellow.

The proposed antenna is composed of two AFSIW half-mode rectangular cavities A and B, brought together to form a cavity-backed slot antenna. The width of the slot defines the distance (and the coupling) between the half-mode cavities. By levering both the coupled half-mode technique [7], [8], inducing mode bifurcation, and AFSIW technology, a highly efficient UWB antenna design is obtained. The final antenna dimensions after optimization are $L_{HMA} = 25.80$ mm, $L_{HMB} = 15.86$ mm, $W_{cavity} = 72.90$ mm, $W_{slot} = 5.90$ mm, $L_{slot} = 70.90$ mm and $L_{feed} = 21.61$ mm. The cavity height, $H_{cavity} = 3.20$ mm, is realized by stacking two milled out and round-edge plated two-layer FR-4 substrates on top of each other, thereby creating an air substrate, as indicated on Fig. 1. Finally, the antenna slot and feed plane, both realized on a 0.250 mm RO4350b ($\epsilon_r = 3.66$) high-frequency laminate, are placed on the top and bottom side of the air substrate. A coaxial probe is then used to feed the antenna.

III. Measurement results

A. Frequency-domain results

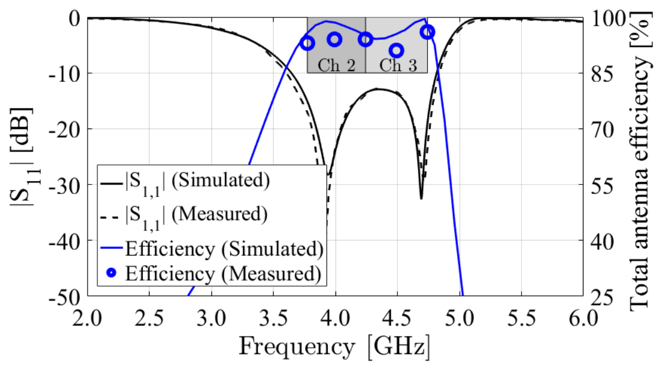

Fig. 2: Measured and simulated $|S_{1,1}|$ w.r.t. 50 Ω and total antenna efficiency.

The antenna was measured both stand-alone and integrated on a 35x35 cm copper plate in an anechoic chamber. Fig. 2 shows a good agreement between the simulated and measured reflection coefficients. Impedance matching with respect to $Z_0 = 50\Omega$ is obtained from 3.64 GHz to 4.83 GHz, yielding a -10 dB impedance bandwidth of 1.19 GHz or 28.1%. Fig. 2 also shows that the measured total antenna efficiency is always higher than 91.0%. Hence, the proposed antenna fulfills the frequency domain requirements. Fig. 3 shows the simulated and measured co- and cross-polarization radiation patterns in the azimuth and elevation plane of the antenna, at the center frequency of both UWB channels 2 and 3. The minimal measured gain in broadside in channels 2 and 3 equals 7.4 dBi and 7.4 dBi, with a front-to-back ratio of 14.8 dB and 12.8 dB, respectively.

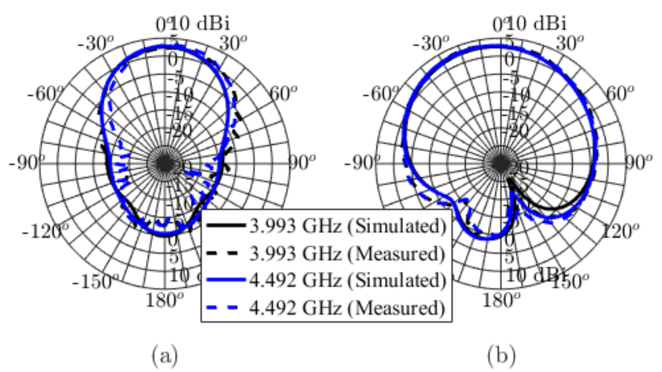

Fig. 3: Measured and simulated radiation pattern [dBi] in UWB channels 2 and 3 in the azimuth (a) and elevation plane (b).

B. Time-domain results

To characterize the antenna's time-domain performance, an UWB link was set up in the anechoic chamber with the proposed antenna serving as both the transmit and receive antenna. The receive antenna is then rotated in azimuth (xz-plane) and elevation (yz-plane) in the positive hemisphere of the antenna, while the transmit antenna remains fixed. In Fig. 4, a SFF higher than 98% is seen for both channels 2 and 3 within the 3dB-beamwidth of the antenna.

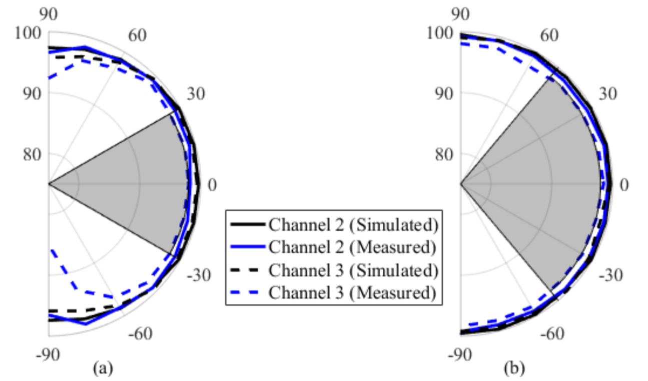

Fig. 4: SFF for channels 2 and 3 in azimuth (a) and elevation (b).

IV. Conclusion

A highly-efficient IR-UWB coupled half-mode cavity-backed slot antenna in AFSIW technology was proposed. By relying on extensive frequency- and time-domain analysis and optimization, the design was optimized for localization applications operating within the IEEE 802.15.4a-2011 standard, more specifically for the channels 2 and 3. The antenna is matched from 3.64 GHz to 4.83 GHz, with a radiation efficiency higher than 91.0%. Furthermore, a SFF higher than 98% is obtained within the antenna's 3dB-beamwidth. As a result, the proposed antenna is well suited for IR-UWB localization applications.

References

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