Compact, Broadband, and Highly Efficient Leaky-Wave Antenna in Air-Filled Substrate Integrated Waveguide Technology

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***Abstract*— A highly-efficient multilayer half-mode air-filled substrate integrated waveguide (HM-AFSIW) leaky-wave antenna (LWA) is demonstrated for millimeter-wave automotive radar systems. The antenna consists of two main parts: the antenna feed and a leaky-wave-based radiating part. The antenna feed is implemented in a single layer high-performance 0.5-mm-thick Rogers 4350B substrate. In the radiating part, two 1-mm-thick FR4 substrates sandwich a Rogers 4350B substrate, realizing an air-filled region. The antenna concept has been validated by measurements in the [22-26] GHz band, exhibiting a scanning capability over 9^o in the elevation plane thanks to the frequency scanning behavior of the leaky-wave radiating part. The developed antenna is well-suited for fabrication by single-layer low-cost printed circuit board processes, and its low profile and compactness can be considered as a promising solution for automotive radar applications. The yz-plane radiation patterns measured in the [22-26]-GHz band show an average half-power beamwidth of about 12^o and sidelobe levels better than 18 dB. The measured peak gain at 24 GHz equals 15 dBi, resulting in a total efficiency higher than 80%.**

***Keywords*— Air filled, automotive radar, frequency scanning antenna, leaky-wave antenna (LWA), substrate integrated waveguide (SIW).**

I. Introduction

Autonomous driving is changing the way we view vehicles and mobility, enabled by the help of the fifth generation (5G) wireless network, implementing a fast connection and ensuring reliable communication between transport systems and the surrounding infrastructure [1]. In addition, there is a need for low-cost, yet high-performance antenna systems that also support automotive radar [2]. Therefore, antenna systems for autonomous vehicles must satisfy ever-increasing performance requirements, such as multi-function support, wideband/multi-band coverage, and fast adaptive beamsteering [3]. Moreover, to fit antenna systems under the hood of a car, automotive-grade miniaturized and highly integrated connectivity solutions need to be developed [4].

Half-mode substrate integrated waveguide (HM-SIW) leaky-wave antenna (LWA) topologies have already shown a great potential to address these challenges, including significant size reduction through the longitudinal size of the substrate integrated waveguide (SIW), wide scanning beams and high directivity with a simple structure without the need for a costly and complicated feeding networks [5], [6]. In addition, these topologies can be fabricated in a reliable and cost-effective way by adopting standard printed-circuit board (PCB) technology [7]. Furthermore, by locally removing the substrate material in the waveguide and creating an air-filled substrate integrated waveguide (AFSIW), the substrate losses [8] and the leakage rate can be significantly improved.

This contribution proposes a half-mode air-filled SIW (HM-AFSIW) LWA, operating in the [22-26] GHz band. This novel design yields (i) low fabrication and beam steering costs, (ii) efficiency enhancement and a small form factor, and (iii) an excellent isolation from the integration platform. In contrast to [8], [9], where partially-filled SIW LWAs are presented, this antenna features a considerable efficiency enhancement in a small form factor and a constant half-power beamwidth when the beam is scanned over a frequency range of [22-26] GHz.

II. Realization of HM-AFSIW Technology

To construct a cost-effective, broadband, and modular solution, standard single-layer PCB laminates are exploited in the realization of the HM-AFSIW technology [Fig. 1(a)]. In particular, Layers 1 and 3, realized by low-cost 1.0-mm-thick-FR4 substrates, implement the top and bottom conducting boundaries. They sandwich Layer 2, consisting of a low-loss 0.5-mm-thick-Rogers RO4350B substrate, containing an air-filled region and arrays of metallic vias. On the one hand, the air-filled part in Layer 2 is implemented by locally milling out the dielectric substrate after which plated via holes are inserted next to this air-filled region. Remark that because of manufacturing issues and mechanical integrity, next to the via row a dielectric region of width W_s is preserved. Yet, the resulting narrow dielectric slab has little dielectric losses as the E-field of the fundamental mode is confined at the center of the waveguide. Based on the guidelines outlined in [10], the diameter of the vias d = 0.4 mm and the via spacing s are fixed such that the relative via spacing s/d remains smaller than 2. On the other hand, to avoid parasitic substrate mode excitation in the top and bottom layers (Layer 1 and Layer 3), their vertical edges are metalized as shown in Fig. 1(c). Subsequently, all layers are held together using 1-mm diameter alignment pins and fixations, to guarantee sufficient electrical contact and to provide correct alignment between layers.

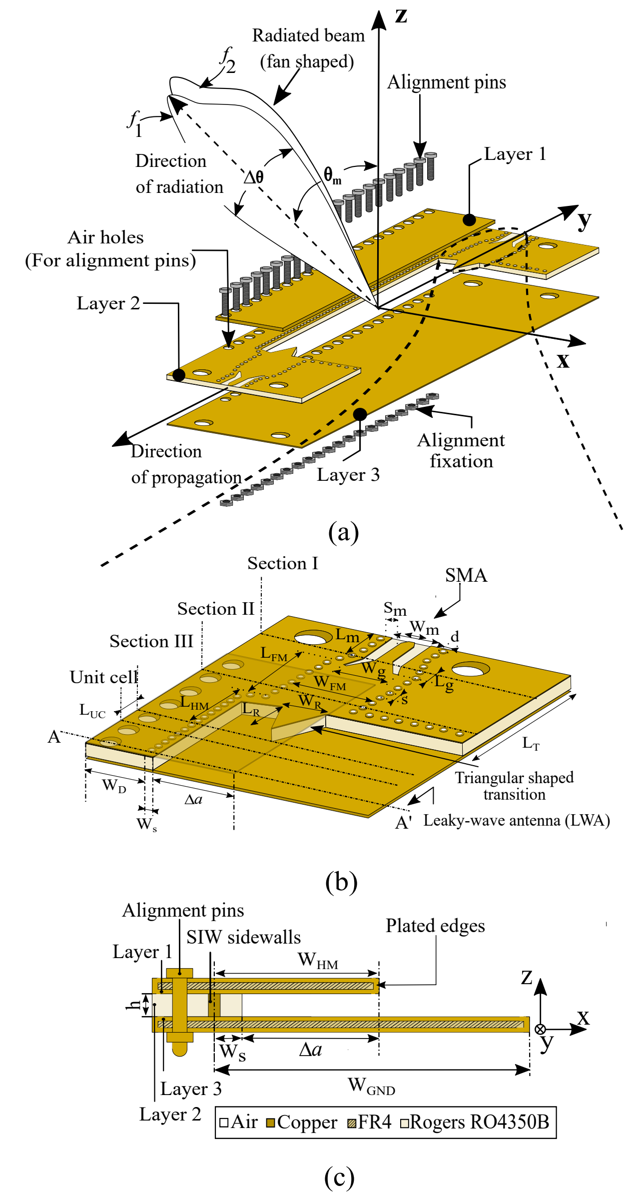

Fig. 1. Concept and architecture of the HM-AFSIW LWA. (a) Exploded view. (b) Three-sections' transition from HM-AFSIW LWA to SMA probe. (c) Cross-sectional view at AA'. Optimized dimensions: W_m = 1 mm, S_m = 0.4 mm, L_m = 3.34 mm, W_g = 3.22 mm, L_g = 1.2 mm, W_{FM} = 4.42 mm, L_{FM} = 5.6 mm, W_s = 0.39 mm, W_{HM} = 3.83 mm, L_{HM} = 3.2 mm, W_R = 1.32 mm, L_R= 2.83 mm, L_{UC} = 1.3 mm, Δa = 3.44 mm, W_D = 10.68 mm, W_{GND} = 11.33 mm, h = 0.5 mm, d = 0.4 mm, s = 0.8 mm.

III. Antenna Topology and Operation Principle

Consider an AFSIW with width w, heigth h and the effective thickness of the via-supporting dielectric slab inside the waveguide W_s (with $W_s << w$). The guided wave is completely bounded by perfect electrically conducting (PEC) walls so that only longitudinal-section modes (LSE_{n0}) can propagate within the AFSIW [11]. Moreover, the center symmetry plane of an AFSIW can be equivalently regarded as a magnetic wall when it operates with its dominant mode (LSE_{10} mode). Therefore, an HM-AFSIW, supporting a quasi-LSE_{10} mode, is obtained by cutting the conventional AFSIW in half along its longitudinal symmetry plane and extending Layer 3 from the open aperture side [Fig. 1(c)]. This desired unbounded structure exhibits strong radiation, especially when operating near its quasi-cut-off frequency.

The dispersion relation of the HM-AFSIW satisfies $k_y(\omega)$ = $\beta_y(\omega)$-$\alpha_y(\omega)$ where $\beta_y(\omega)$ and $\alpha_y(\omega)$ are the phase and leakage constant of the mode, respectively. The mode of the HM-AFSIW's operation is determined by the unit cell parameters in Fig. 1(b). To obtain the desired $\beta_y(\omega)$ and $\alpha_y(\omega)$, CST Microwave Studio full-wave simulation and Bloch theory are exploited by varying the geometrical parameters of the unit cell [Fig. 1(b)]. Then, $\beta_y(\omega)$ and $\alpha_y(\omega)$ are optimized for the 45^o beam direction (θ_m) and 12^o beamwidth ($\Delta\theta$), achieving an 80% radiation efficiency at 24 GHz. Note that the proposed LWA topology exhibits a broad radiation bandwidth since the normalized phase constant in the fast-wave region ($\beta/k_0 < 1$) cannot approach the surface wave zone [8]. Finally, the ground plane width, W_{GND}, is enlarged to provide a front-to-back ratio larger than 18 dB.

To effectively interconnect to the HM-AFSIW LWA, both sides of the HM-AFSIW LWA section are connected to a three-section broadband transition from the LWA to an SMA probe [12]. One of the transitions is terminated by a matched load to avoid reflections that would generate unwanted radiation.

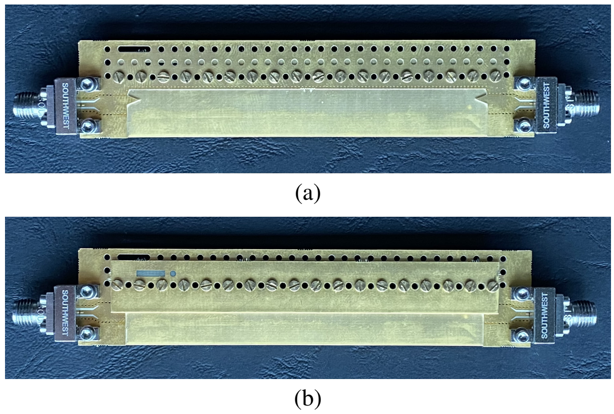

Fig. 2. Fabricated prototype with end-launch connectors. (a) Layer 2 assembled with Layer 3 before adding Layer 1. (b) Top view after final assembly. (electrical length without transitions approximately $6.45\lambda_0$ at 24 GHz).

IV. Experimental Results

To evaluate the performance, a prototype of a 102-mm-long HM-AFSIW LWA (with three-section transitions) has been fabricated [Fig. 2]. In the fabrication process, a 0.508-mm-thick low-loss Rogers 4350B substrate (ϵ_r = 3.66, tanδ = 0.0037) is being exploited as dielectric substrate, whereas FR4 slabs are applied as top and bottom layers of the antenna structure to increase mechanical stability and easy integration. All the layers are assembled by copper

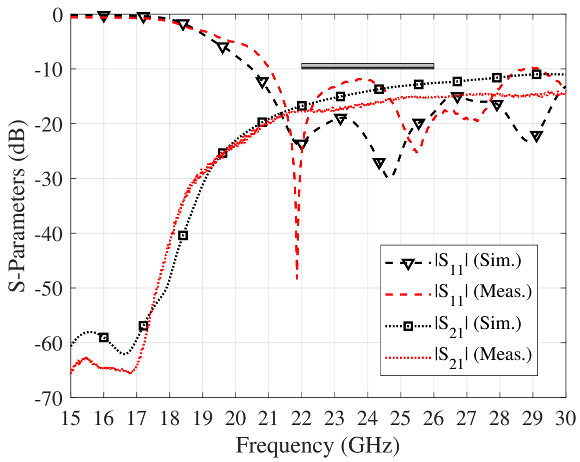

Fig. 3. Measured and simulated S-parameters of the HM-AFSIW LWA.

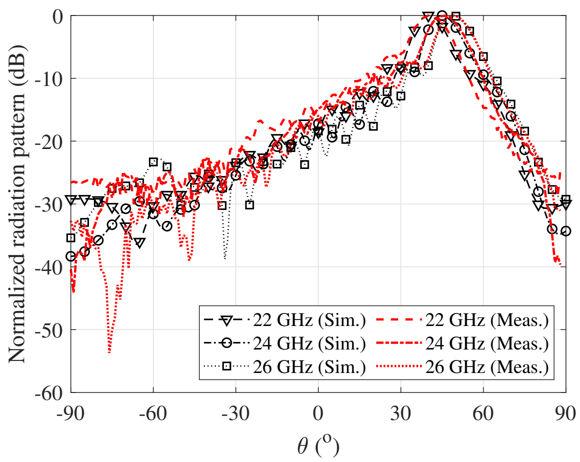

Fig. 4. Normalized simulated and measured radiation patterns in yz-plane at different frequencies.

screws through dedicated unplated vias in all layers. The measured and simulated S-parameters are presented in Fig. 3. The measured $|S_{11}|$ antenna impedance bandwidth extends from 21 GHz to 30 GHz (34%), in which the $|S_{21}|$ also stays below -10 dB. Both simulated and measured normalized yz-plane radiation patterns are shown in Fig. 4 for a set of frequencies within the antenna impedance bandwidth. It is shown that the main beam shifts about 9^o from 22 GHz to 26 GHz. The measured gain at 22 GHz is 12.6 dBi, whereas the gain at 26 GHz equals 13.2 dBi. Above all, the beamwidth remains constant when the beam is scanned over the targeted frequency range [13].

V. Conclusion

An LWA based on the HM-AFSIW topology is proposed. The antenna features compact size, easy fabrication, low cost, low loss, wide bandwidth, and direct integration with planar circuits. Measurements also reveal that the antenna shows a total antenna efficiency over 80%, a minimal boresight gain of 12.6 dBi, and sufficient bandwidth to cover the [22-26] GHz band.

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