ABSTRACT An innovative millimeter-wave (mm-wave) microstrip edge-fed antenna (EFA) for 77 GHz automotive radars is proposed. The radiator is designed under the main requirements of having (i) an horizontally-polarized pattern and (ii) a single-layer layout. Its contour is modeled with a sinusoidal spline-shaped (SS) profile characterized by a reduced number of geometrical descriptors, but still able to guarantee, thanks to a continuously non-uniform width, a high flexibility in the modeling for fulfilling challenging user-defined requirements. The SS-EFA descriptors are effectively and efficiently optimized with a customized implementation of the System-by-Design (SbD) paradigm. The synthesized EFA layout, integrated within a linear arrangement of identical replicas to account for the integration into the real radar system, exhibits suitable impedance matching, isolation, polarization purity, and stability of the beam shaping/pointing within the target band \( f_{\text{min}} = 76 \text{ [GHz]} \leq f \leq f_{\text{max}} = 78 \text{ [GHz]} \). The experimental assessment, carried out with a Compact Antenna Test Range (CATR) system on a printed circuit board (PCB)-manufactured prototype, assesses the reliability of the outcomes from the full-wave (FW) simulations as well as the suitability of the synthesized SS-EFA for automotive radars.

INDEX TERMS Automotive Radar, mm-Waves, 77 [GHz] Bandwidth, Antenna Design, Spline, System-by-Design (SbD).
NOMENCLATURE
ACC Adaptive Cruise Control.
AUT Antenna Under Test.
BDD Beam Direction Deviation.
CATR Compact Antenna Test Range.
CFA CenterFed Antenna.
DoA Direction of Arrival.
DoF Degree-of-Freedom.
DT Digital Twin.
EFA EdgeFed Antenna.
FBW Fractional Bandwidth.
FF Far-Field.
FMCW Frequency Modulated Continuous Wave.
FW Full-Wave.
LBE Learning-by-Examples.
LHS Latin Hypercube Sampling.
MC Mutual Coupling.
MIMO Multiple-Input Multiple-Output.
OK Ordinary Kriging.
PCB Printed Circuit Board.
PR Polarization Ratio.
PSO Particle Swarm Optimizer.
RS Resonant.
SbD System-by-Design.
SS Spline-Shaped.
SSE Solution Space Exploration.
SW Standing Wave.
TW Travelling-Wave.

I. INTRODUCTION

Millimeter-wave (mm-wave) radars play an important role in many modern automotive applications ranging from active safety driver assistance systems to autonomous driving vehicles [1]-[3]. Thanks to the capability to measure the distance, the speed, and the direction of arrival (DoA) of multiple targets with low delays, they are frequently used for blind-spot detection, collision avoidance, and emergency brake assistance [4],[5]. Moreover, automotive radars are a key technology for implementing active comfort systems featuring a high robustness against environmental conditions including high temperature, darkness, and bad weather. For instance, let us consider adaptive cruise control (ACC) systems that allow the vehicle to autonomously accelerate or brake or stop in case of traffic jam to relieve the driver of monotonous tasks.

In order to continuously sense and monitor the surrounding environment [1], multiple receive and transmit antennas/channels are used to implement frequency modulated continuous wave (FMCW) multiple-input multiple-output (MIMO) radars and 77 [GHz] solutions are particularly attractive because of the many advantages over systems operating at lower frequencies (e.g., 24 [GHz] band [1][6][7]). As a matter of fact, the exploitation of the 77 [GHz] band allows one to design smaller antennas with lower volume and weight-related costs as well as to reach a higher spatial

resolution (thanks to the larger absolute bandwidth of the antenna system) and more precise DoA estimations [1].

As for the antenna implementation, different technological solutions have been explored in the last few years including Franklin antennas [6], series-fed microstrip arrays [8][9], comb-line arrays [10][13], lens antennas [14], dielectric resonator antennas [15], planar grid arrays [16][17], leaky-wave antennas [18], ceramic-filled cavity resonators [19], patch arrays [20][21], and substrate integrated waveguides (SIWs) [22]-[26]. Series-fed architectures are nowadays a mainstream choice because of the limited cost, the low profile, the light weight, and the simple manufacturing/integration in automotive systems. However, the feeding mechanism is more complex than that of traditional corporate feeding networks since all the (series-connected) radiating points must be excited in-phase to afford a well-shaped broadside radiation pattern. To address such an issue, both center-fed (CFAs) [27][28] and edge-fed (EFAs) [8] antennas have been studied. The former mitigate the beam tilting (or squint) due to the change of the electrical lengths between consecutive radiating locations at different frequencies within the working band, but they may be unsuitable for a compact integration/connection to the driving pins of a FMCW radar micro-chip. Otherwise, EFAs can be more easily closely-packed in linear array arrangements by means of simpler routing connections [8]. However, the design of EFAs, which can be in turn implemented both as resonant (RS) and travelling-wave (TW) structures depending on the absence or presence of a matched load placed at the termination edge on the opposite of the feeding point [29], turns out to be more challenging because of the more difficult control of each excitation phase from a single feeding point located on one edge. Generally speaking, while TW-EFAs usually enable a more flexible beam shaping of the far-field (FF) pattern, they are also characterized by a larger beam direction deviation (BDD) with frequency and a lower radiation efficiency because of the energy dissipated in the terminating load [29].

Concerning the polarization, several designs radiating a vertically-polarized FF pattern have been reported in the recent scientific literature [6][8][16][29]. However, many automotive applications (including the one considered here) require an horizontal polarization because of the lower backscattering from road pavements, resulting in a reduced amount of clutter and thus allowing a more robust target detection [7][10][22][23][26][52].

Finally, another challenging requirement addressed in this work is the need for a single-layer layout. As a matter of fact, having a manufacturing process where both the radiating elements and the routing connections from/towards the controlling radar chipset can be simultaneously etched on the same face of a single dielectric substrate is highly desirable in terms of fabrication simplicity/costs and mechanical robustness to vibrations [6][13][16][20]. Therefore, although providing remarkable radiation/bandwidth features, available multi-layer solutions are not a viable option since
they are not compliant with such a requirement [17] [21].

Following this line of reasoning, this paper presents an innovative single-layer RS microstrip EFA radiator with horizontal polarization for automotive radars in the 77 [GHz] band. Unlike state-of-art solutions, the contour of the radiating element is modeled as a spline-shaped (SS) profile [33]-[36]. Accordingly, arbitrarily-complex shapes can be yielded by acting on a limited set of geometric degrees-of-freedom (DoFs) to fulfill several challenging requirements on both bandwidth and radiation features. As a matter of fact, the flexibility of the proposed modeling approach enables an accurate control of the feeding phases within the operative band. Moreover, the continuous non-uniformity of the radiator width allows one to optimize the elevation FF features including a lowering of the sidelobe level (SLL), which is beneficial for reducing both near range clutter from the road surface and the multi-path interferences. Furthermore, to yield a robust/reliable design for a fruitful integration within FMCW automotive radars, the non-negligible material losses occurring in the mm-wave regime as well as the mutual coupling (MC) effects when integrating the antenna in the radar system composed by a linear arrangement of identical elements are taken into account by recurring to a full-wave (FW) modelling of the structure at hand.

Owing to the complexity of the synthesis problem at hand, the System-by-Design (SbD) [36]-[38] paradigm has been applied to solve the arising global optimization problem with a high computational efficiency. More in detail, the design of the SS RS-EFA (shortly in the following SS-EFA) has been carried out by means of a customized version of the PSO-OK/C method [37] based on a “low dimension” representation of the solution space and relying on the “collaboration” between a Solution Space Exploration (SSE) functional block based on evolutionary operators [39]-[41] and a Learning-By-Examples (LBE)-based digital twin (DT) of the FW simulator aimed at outputting fast predictions of the electromagnetic (EM) performance of each trial guess solution generated by the SSE [42]. It should be noticed that, although other SS-based antennas can be found in the literature [33]-[35], the present work deals with a completely new design in terms of radiator architecture, requirements, addressed application, and adopted synthesis methodology. More in details, SS layouts have been previously solely investigated to model aperture-stacked patches [33], coaxial probe-fed microstrip monopoles [34], or cavity-backed patch antennas [35] with completely different feeding mechanisms, EM behaviors, and operation bands. Moreover, the proposed antenna outperforms previous SS-based designs [33]-[35] in terms of beam shaping capabilities and polarization purity, since it enables a more effective control/tuning of the current density flowing from the edge feeding point. Furthermore, from the methodological point of view this is the first time, to the authors’ best knowledge, that the design of a SS-based mm-wave radiator is addressed within the SbD framework to speed up the optimization process while considering all non-idealities of the employed materials and the presence of MC. The paper is organized as follows. Section II describes the SS-EFA geometry and it provides some theoretical insights on its EM working principle. The design requirements and the SbD procedure for the optimization of the antenna layout are detailed in Sect. III. Section IV presents selected results from the FW-based numerical assessment of the performance of the optimized radiator along with the experimental validation of a SS-EFA prototype realized on a printed circuit board (PCB) and measured on a custom mm-wave Compact Antenna Test Range (CATR) system. Finally, some conclusions are drawn (Sect. V).

II. SS-EFA LAYOUT AND EM WORKING PRINCIPLE

The layout of the SS-EFA is shown in Fig. 1. The antenna lies on the (x, y) plane and it is printed on a single-layer ground-backed Rogers RO3003TM high frequency ceramic-filled composite substrate with relative permittivity and loss tangent equal to $\varepsilon_r = 3.0$ and $\tan \delta = 1.0 \times 10^{-3}$, respectively, of thickness $h = 0.127$ [mm] (i.e., $h = 5$ [mil]). To take into account all non-idealities/losses occurring in the mm-wave band, both metallizations on the top (i.e., the radiator) and the bottom (i.e., the ground plane) layers are modeled as copper with conductivity $\sigma = 2.5 \times 10^7$ [S/m], thickness $\tau = 25 \times 10^{-6}$ [m], and roughness $\rho = 1.3 \times 10^{-6}$ [m].
The antenna is fed from the bottom edge with a tapered microstrip feeding line of length $l_1$, having controllable starting, $w_1$, and ending, $w_2$, widths to yield a proper 50 [Ω] impedance matching over the complete working band. As for the shape of the radiator, which is connected to the feeding line, an innovative non-uniform SS profile is adopted \cite{33}\-\cite{36} since (i) there is the possibility to model complex geometries for fitting multiple and sometimes contrasting requirements on both bandwidth and far-field (FF) features with a reduced set of properly-tuned DoFs; (ii) the absence of sharp edges is a recipe to mitigate the fringing effects that enhance the MC between the adjacent elements of the final radar layout \cite{33}. More in detail, Bézier spline basis functions \cite{33}, with $C = 37$ control points, $P = \{P_c = (x_c, y_c) : c = 1, ..., C\}$ (Fig. 1), are adopted to shape the contour of the SS-EFA.

The spline radiator is terminated on the opposite side of the feeding point with an open circuit (i.e., no matched load) so that a resonant behavior is yielded by exciting a standing wave (SW) within the microstrip structure (Fig. 2). As a matter of fact, the maxima of the electric field occur in correspondence of the bending corners of the SS-EFA that, in turn, correspond to the positions of the SW maxima (Fig. 2). To afford the desired resonating behavior, the surface current in each spline branch must be tuned in-phase so that the FF radiated contributions constructively add in the antenna broadside direction [i.e., $(\theta_0, \varphi_0) = (0, 0)$ [deg] - Fig. 1]. Towards this end, the electrical length of each $o$-th ($o = 1, ..., O$; $O \equiv \frac{C - 1}{3} \to O = 12$) intermediate spline segment, $\alpha_o$, must be properly designed so that the current, injected from the feeding point and flowing up to the open circuit, is equally-phased at each radiating location (Fig. 2) despite the single-point edge-feeding mechanism.

It is also worth pointing out that thanks to the continuously non-uniform width of the SS metallization (e.g., $\gamma_1 \neq \gamma_2$ - Fig. 3), it is possible to excite a tapered current distribution within the EFA to perform beam shaping and obtain a lower SLL with respect to a uniform-width profile. Such a FF feature is highly desirable in automotive applications since it reduces the interferences from both the asphalt and the sky, thus leading to a more robust and reliable target detection/location and DoA estimation. Clearly, the non-uniform width of the spline profile cannot be arbitrarily set, and its local tuning must be optimized to define a suitable trade-off between the SLL and other important performance indexes (e.g., impedance matching).

As for the FF half-power beamwidth (HPBW), which affects the angular resolution of the automotive radar along the elevation plane, it is controlled by the overall length of the SS radiator. Indeed, longer structures exhibit narrower HPBWs (e.g., $\beta_2 > \beta_1 \to HPBW|_{\beta_2} < HPBW|_{\beta_1}$ - Fig. 3) and vice-versa, because of the different aperture size of the equivalent linear array.

In order to guarantee geometric/electric symmetry by also keeping low the number of problem descriptors, only one half of the spline curve (i.e., $\{P_c : c = 1, ..., 19\}$ - Fig. 1) is optimized, while the coordinates of the second half of the control points (i.e., $\{P_c : c = 20, ..., C\}$ - Fig. 1)
are automatically derived with a mirroring operation with respect to the horizontal axis (i.e., \(x\)-axis - Fig. 1). Enforcing such a symmetry allows one to also yield a lower BDD and a higher similarity of the left/right side-lobes on the vertical plane (i.e., \(\varphi = 90\) [deg] - Fig. 1).

Finally, it is important to point out that despite the unconventional and non-uniform shaping of the radiating element, the SS-EFA radiates, as required, a linearly polarized field along the horizontal direction with a high polarization purity. As a matter of fact, the surface current density distributions excited within each pair of adjacent spline branches (e.g., \(J_1 = J_{1,x} \hat{x} + J_{1,y} \hat{y}\) and \(J_2 = J_{2,x} \hat{x} + J_{2,y} \hat{y}\) - Fig. 4) exhibit in-phase \(x\)-components (e.g., \(J_{1,x}\) and \(J_{2,x}\) - Fig. 4) and out-of-phase \(y\)-components (e.g., \(J_{1,y}\) and \(J_{2,y}\) - Fig. 4) so that, while the \(x\)-components constructively sum, the \(y\) ones cancel out and the EM source turns out to be \(x\)-polarized.

### III. DESIGN PROCESS

The SS-EFA has been synthesized to provide a suitable matching so that \(|S_{11}(f)| \leq S_{11}^{\text{th}}\) \((S_{11}^{\text{th}} = -10\) [dB]) within the frequency range \(\Delta f = [f_{\text{min}}, f_{\text{max}}]\) \([24]\), \(f_{\text{min}}\) and \(f_{\text{max}}\) being the minimum \((f_{\text{min}} = 76\) [GHz]) and the maximum \((f_{\text{max}} = 78\) [GHz]) working frequency, respectively. Concerning the radiation features, the SLL, the HPBW, and the BDD on the vertical plane have been required to comply with the following requirements: \(\text{SLL}(f) \leq S_{\text{LL}}^{\text{th}}\) \((S_{\text{LL}}^{\text{th}} = -15\) [dB]), \(\text{HPBW}(f) \leq \text{HPBW}^{\text{th}}\) \((\text{HPBW}^{\text{th}} = 18\) [deg]), and \(\text{BDD}(f) \leq \text{BDD}^{\text{th}}\) \((\text{BDD}^{\text{th}} = 2\) [deg]).\(^2\)

Furthermore, the polarization ratio (PR) is required to be \(PR(f) \geq \text{PR}^{\text{th}}\) \((\text{PR}^{\text{th}} = 20\) [dB]).\(^3\)

For the sake of clarity, all design objectives/targets are reported in Tab. 1.

To yield a robust design and to enable a reliable prediction of the EM behavior of the elementary radiator when integrated in an automotive radar system\(^4\), it has been synthesized not alone, but within a linear arrangement of \(N = 5\) identical half-wavelength \((W = \frac{\lambda_0}{2} = 1.95 \times 10^{-3}\) [m], \(\lambda_0\) being the free-space wavelength at the central frequency \(f_0 = 77\) [GHz]) spaced SS-EFAs \((W_s = 15\) [mm] - Fig. 5), which has been modeled with a FW finite model. More specifically, the synthesis has been aimed at optimizing all performance indexes for the central embedded element, while the surrounding \((N - 1)\) replicas have been terminated on 50 \([\Omega]\) matched loads (Fig. 5).

Owing to the computational complexity of the synthesis problem at hand, the design has been efficiently carried out within the SbD framework\(^5\)\(^6\)\(^7\). As a matter of fact, the SbD has recently emerged as an innovative paradigm enabling an effective and computationally-efficient use of global optimizers for the solution of complex EM synthesis problems. Accordingly, the computational burden (resulting from the need for iterated accurate FW-assessments of the finite structure in Fig. 5) is addressed by suitably selecting and integrating functional blocks comprising problem-dependent, efficient, and reliable prediction and optimization strategies\(^8\). More specifically, the customization of the SbD to the synthesis problem at hand starts from a “smart” representation of the SS-EFA solution space in the so-called “Problem Formulation” functional block\(^9\). Towards this end, the following \(K = 20\) descriptors \(\chi = \{\chi_k; k = 1, \ldots, K\}\) \(\{\chi_k; k = 1, \ldots, T; T = 11\}\) and \(\chi_k = w_{x-y} (k = T + 1, \ldots, T + U; U = 9)\) (Fig. 1) have been considered instead of using the coordinates of the control points of the spline contour (i.e., \(K = 2 \times C \rightarrow \))

\(^2\)The BDD is defined as \(\text{BDD}(f) = [\theta_{\text{max}}(f)]\), where \(\theta_{\text{max}}(f) = \arg\left\{\max_{\theta} [G(f, \theta, \varphi)|_{\varphi = 90\text{[deg]}}]\right\}\), \(G(f, \theta, \varphi)|_{\varphi = 90\text{[deg]}}\) being the gain pattern function in the vertical (elevation) plane of the antenna (Fig. 1).

\(^3\)The PR is defined as \(PR(f) = \frac{|E_{x}(f, \theta = 0)|}{|E_{y}(f, \theta = 0)|}\), \(E_{x/y}\) being the \(x/y\)-components of the FF electric field, respectively.

\(^4\)FMWC multiple-input multiple-output (MIMO) automotive radars are generally implemented as properly-spaced arrangements of both transmitting and receiving elementary radiators connected to a single driving chip\(^1\)\(^4\)\(^12\).

---

**TABLE 1: Radar antenna requirements.**

| Feature                  | Requirement               |
|--------------------------|---------------------------|
| Operating Band           | \(f \in [f_{\text{min}}, f_{\text{max}}] = [76, 78]\) [GHz] |
| Reflection Coefficient   | \(S_{11} \leq S_{11}^{\text{th}} = -10\) [dB] |
| Sidelobe Level           | \(\text{SLL} \leq \text{SLL}^{\text{th}} = -15\) [dB] |
| Half-Power Beamwidth     | \(\text{HPBW} \leq \text{HPBW}^{\text{th}} = 18\) [deg] |
| Beam Direction Deviation | \(\text{BDD} \leq \text{BDD}^{\text{th}} = 2\) [deg] |
| Polarization Ratio       | \(\text{PR} \geq \text{PR}^{\text{th}} = 20\) [dB] |

---

**FIGURE 4: SS-EFA Working Principle - Pictorial representation of the behavior of the surface current density.**
The synthesis problem has been then reformulated as a minimization one by defining the following customized cost function

\[
\Phi(\chi) = \alpha_{S_{11}} \Phi_{S_{11}}(\chi) + \alpha_{SLL} \Phi_{SLL}(\chi) + \alpha_{HPBW} \times \Phi_{HPBW}(\chi) + \alpha_{BDD} \Phi_{BDD}(\chi) + \alpha_{PR} \Phi_{PR}(\chi),
\]

where

\[
\Phi_{S_{11}}(\chi) = \frac{1}{Q} \sum_{q=1}^{Q} \mathcal{H}\left\{ \frac{S_{11}(f_q, \chi) - S_{11}^{th}}{|S_{11}^{th}|} \right\},
\]

\[
\Phi_{SLL}(\chi) = \frac{1}{Q} \sum_{q=1}^{Q} \mathcal{H}\left\{ \frac{SLL(f_q, \chi) - SLL^{th}}{|SLL^{th}|} \right\},
\]

\[
\Phi_{HPBW}(\chi) = \frac{1}{Q} \sum_{q=1}^{Q} \mathcal{H}\left\{ \frac{HPBW(f_q, \chi) - HPBW^{th}}{HPBW^{th}} \right\},
\]

\[
\Phi_{BDD}(\chi) = \frac{1}{Q} \sum_{q=1}^{Q} \mathcal{H}\left\{ \frac{BDD(f_q, \chi) - BDD^{th}}{BDD^{th}} \right\},
\]

\[
\Phi_{PR}(\chi) = \frac{1}{Q} \sum_{q=1}^{Q} \mathcal{H}\left\{ \frac{PR^{th} - PR(f_q, \chi)}{PR^{th}} \right\},
\]

are the impedance matching, the SLL, the HPBW, the BDD, and the PR cost terms quantifying the mismatch with respect to the corresponding user-defined thresholds.

Moreover, \(\alpha = \{\alpha_{S_{11}}; \alpha_{SLL}; \alpha_{HPBW}; \alpha_{BDD}; \alpha_{PR}\} \geq 0\) are real valued weights, while \(\mathcal{H}\{\xi\} = \xi\) if \(\xi \geq 0\) and \(\mathcal{H}\{\xi\} = 0\), otherwise, is the ramp function. Finally, the frequency band \(\Delta f\) has been uniformly sampled into \(Q = 41\) points, \(f_q = f_{\text{min}} + (q - 1) \frac{(f_{\text{max}} - f_{\text{min}})}{(Q - 1)}\), for constraining the fulfillment of the requirements in the whole bandwidth.

The multi-modal nature of the cost function (1) as well as the impossibility to derive closed-forms expressions of its derivatives prohibit the exploitation of fast local-search gradient-descent algorithms. On the other hand, a global optimization using standard evolutionary algorithms, although guaranteeing an effective exploration of the solution space without being trapped into local minima, would result in a very high computational load. Owing to such considerations, the minimization of (1) has been carried out with a properly customized version of the PSO-OK/C sbd method leveraging on the “collaboration” between the SSE functional block relying on the Particle Swarm Optimization (PSO) operators and a fast DT based on the Ordinary Kriging (OK) LBE technique. The meta-level control parameters of the PSO have been set according to the literature guidelines: \(V = 10\) \((V\) being the swarm size), \(I = 200\) \((I\) being the maximum number of iterations), \(\omega = 0.4\) \((\omega\) being the inertial weight), and \(C_1 = C_2 = 2.0\) \((C_1\) and \(C_2\) being the social and the cognitive acceleration coefficient, respectively).

As for the OK prediction model, the fast surrogate of the FW simulator has been trained with \(S_0 = 100\) training samples generated off-line according to the Latin Hypercube Sampling (LHS) strategy, while \(S_{\text{upd}} = 200\) “reinforcement training” FW simulations have been performed on-line by the PSO-OK/C to adaptively enhance the DT accuracy during the iterative minimization of (1).

The solution, \(\chi_{\text{opt}}\), outputted by the sbd at the convergence \([i.e., \Phi(\chi_{\text{opt}}) = 0]\) that fulfills all the user-defined requirements (letting \(\alpha = 1.0\), as it can be inferred in Sect. IV-A, is reported in Tab. II, while the CAD
model of the corresponding SS-EFA layout (surrounded by four identical replicas) is shown in Fig. 5, the total length of the radiator being equal to \( L = l_1 + 2 \times \left( b + l_2 + l_3 + l_5 + l_6 + l_8 + l_9 + l_{11} \right) \rightarrow L = 18.9 \times 10^{-3} \) [m] since \( b = 3 \times 10^{-3} \) [m] is a fixed offset from the bottom and the top edges of the substrate (Fig. 1).

It is worthwhile to point out that the time saving \( \Delta t_{\text{sav}} \) enabled here by the SbD strategy \([37]\) with respect to a standard optimization that exclusively relies on iterated FW calls (i.e., \( V \times I \)) \([40]\) amounts to \( \Delta t_{\text{sav}} = 85\% \). As a matter of fact, the PSO-O\(K/C\) method only requires to simulate the initial \( S_0 \) training designs and the \( S_{\text{upd}} \) configurations adaptively selected during the optimization, while relying on almost real-time predictions of \( I \) for all the remaining trial particles generated throughout the iterative minimization procedure \([37]\).

Quantitatively, the synthesis has been completed in \( \Delta t_{\text{CPU}} \approx 2.25 \times 10^3 \) [hours], while \( \Delta t_{\text{PSO}} = 1.5 \times 10^3 \) [hours] would be the overall time expense for a standard (non-SbD) PSO-based optimization \([37]\).

IV. PERFORMANCE ASSESSMENT

The goal of this section is twofold. On one hand, to present the results of a careful assessment of the FW-simulated EM features of the synthesized SS-EFA (Sect. 5).
A. NUMERICAL ASSESSMENT

Figure 6 shows the behavior of the reflection coefficient of the central \( n = 1 \) embedded element within the linear arrangement of \( N = 5 \) identical SS-EFAs simulated by means of the Ansys HFSS FW solver [45] (Fig. 5). As it can be inferred, the antenna correctly resonates within the operative band being \(|S_{11}(f)| \leq -11.6 \, \text{dB}\) for \( f \in \Delta f \). Moreover, the optimized SS-EFA provides a suitable inter-element isolation as indicated by the magnitude of the scattering coefficients [i.e., \(|S_{n1}(f)| \leq -22.6 \, \text{dB}\) (\( n = 2, \ldots, N \))].

As for the FF features of the SbD-layout, the curves in Fig. 7(a) show that \( \text{SLL}(f) \leq -15.3 \, \text{dB}\) and \( \text{HPBW}(f) \leq 17.5 \, \text{deg}\) for \( f \in \Delta f \) (i.e., both SLL and HPBW comply with the requirement). Moreover, the synthesized radiator turns out to be fully-compliant in terms of beam pointing stability regardless of the adopted edge feeding mechanism as confirmed by the BDD values (i.e., \( BDD \leq 1.5 \, \text{[deg]} \)) in Fig. 7(b).

On the other hand, it should be very interesting for the readers to observe that the arising SS-EFA structure radiates a linearly (horizontal) polarized field with high polarization purity despite its smooth/non-uniform profile (Fig. 1). Indeed, it turns out that \( PR(f) \geq 21 \, \text{[dB]} \) for \( f \in \Delta f \) [Fig. 7(b)] as a consequence of the distribution of the surface current (Fig. 8) that follows the theoretically-expected configuration sketched in Fig. 4. An overall \( x \)-polarized source is excited in correspondence with each radiating location of the resonant structure shown in Fig. 9 where the near-field (NF) distribution of the magnitude of the electric field, \(|E(x, y; f_0)|\), computed on a \((5W \times L)\)-sized plane at height \( z = \frac{h_0}{20}\) from the SS-EFA, is reported. This latter plot highlights the resonant behavior of the synthesized structure, the field being maximum at fixed and equally-spaced positions. As expected, such maxima, which correspond to those of the SW excited within the structure, arise on the bends of the spline contour and they generate in-phase radiation contributions that result in a suitable beam shaping and a pointing stability within the working band \( \Delta f \) as confirmed by the simulated FF pattern at \( f = f_{\text{min}}, f = f_0, \) and \( f = f_{\text{max}} \) in Fig. 10. Moreover, the magnitude of the coupling field in the adjacent radiators \((n = 2 \) and \( n = 4)\) is always 14.8 \, dB lower than in the driven element \((n = 1)\), the arising MC being always acceptable as

![FIGURE 9: Numerical Assessment (N = 5, n = 1) - Screenshot of the magnitude of the total electric field, |E(x, y; f_0)|, computed over a plane parallel to the (x, y) plane far z = \( \frac{h_0}{20}\) from the SS-EFA surface, at f = f_0.](image)

![FIGURE 10: Numerical Assessment (N = 5, n = 1, \( \phi = 90 \, \text{[deg]} \)) - Embedded gain pattern at f = \( f_{\text{min}} \), f = f_0, and f = \( f_{\text{max}} \).](image)
in principle represent the best trade-off for a given application (i.e., project requirements/constraints). However, it turns out that there are several positive and supporting aspects motivating the proposal of the antenna at hand. By neglecting the HPBW since (i) it is inversely proportional to the length of the radiating structure (Tab. III) and (ii) it is an application-dependent feature, it appears that the proposed design overcomes state-of-the-art EFA alternatives in several fundamental KPIs. For instance, the performance comparison with the solution in \cite{31} shows that the proposed design exhibits higher gain (+23\%) and PR (+23\%) with the same SLL. It also outperforms the design in \cite{32} in terms of gain (+33\%) and BDD (−32\%). Moreover, when compared to the solution in \cite{32}, it shows a remarkably higher gain (+112\%) with a simpler manufacturing process not involving vias (as in slotted SIWs \cite{22}). Otherwise, higher gain (+7\%) and lower SLL (−19\%) are observed with respect to the leaky-wave antenna (LWA) in \cite{30}, which is meant for performing beam scanning with frequency and therefore providing an unsuitable BDD performance for the targeted automotive application of this work. For

![FIGURE 12: Numerical Assessment (N = 5, n = 1, φ = 90 [deg], f = f₀) - Comparison of the embedded gain pattern when enabling (α_{SLL} = α_{HPBW} = 1.0) or disabling (α_{SLL} = α_{HPBW} = 0.0) the optimization of the SLL and the HPBW.](image)

- Picture of (a) the SS-EFA prototype and (b) a zoom on the radiating part.

![FIGURE 13: Experimental Assessment](image)
TABLE 3: Comparison between the proposed antenna and other designs with single-layer structure and horizontal polarization in the recent literature. Gain, SLL, HPBW, PR, and radiation efficiency are reported at $f = f_0$.

| Ref. | Radiator Type | Feeding | $f_0$ [GHz] | FBW [%] | BDD [deg] | Gain [dBi] | SLL [dB] | HPBW [deg] | PR [dB] | Length [$\lambda_0$] |
|------|---------------|---------|-------------|---------|------------|------------|---------|-------------|---------|-------------------|
| This Work | Spline-Shaped | EFA | 77.0 | 2.6 | $\leq 1.5$ | 13.8 | $-15.8$ | 16.5 | 22.7 | 4.9 |
| [13] | Microstrip Line | EFA | 28.0 | 4.6 | N.A. | 10.7 | $-15.8$ | 16 | 18.4 | 6.0 |
| [22] | Asymmetric Trapezoidal Microstrip | EFA | 78.0 | 13.0 | $\leq 2.2$ | 10.4 | $-16.1$ | 22.7 | N.A. | 3.4 |
| [22] | Slotted SIW | EFA | 79.0 | 5.4 | N.A. | 6.5 | $-24.0$ | 34.0 | 30.1 | 2.7 |
| [30] | Periodic Microstrip LWA | EFA | 22.5 | 69.6 | $\leq 55.0$ | 12.9 | $-13.3$ | 10.5 | N.A. | 5.3 |
| [13] | Linear Grid Array | CFA | 24.2 | 1.2 | N.A. | 19.0 | $-20.0$ | 5.0 | 40.0 | 11.6 |
| [26] | Slotted SIW | CFA | 24.0 | 1.7 | 0.0 | 24.0 | $-24.5$ | 4.6 | N.A. | 15.6 |
| [2] | Microstrip Array | CFA | 27.0 | 50.6 | N.A. | 12.5 | $-28.4$ | 25.0 | 22 | 2.7 |

![Image](image1.png)

**FIGURE 14:** Experimental Assessment - Picture of (a) the AUT, (b) the CATR positioner, and (c) the whole measurement setup.

![Image](image2.png)

**FIGURE 15:** Experimental Assessment - Sketch of the measurement scenario.

**B. EXPERIMENTAL VALIDATION**

A prototype of the SS-EFA has been fabricated through PCB manufacturing on a substrate of size $70 \times 70$ [mm] (Fig. 13). The bottom ground plane has been stacked on a 1 [mm]-thick FR-4 layer to enhance the mechanical robustness and rigidity of the antenna under test (AUT). Moreover, four holes, 3.5 [mm] in diameter, have been drilled at the corners of a square of side 48.5 [mm] to fix the AUT on the measurement support by means of plastic screws [Fig. 13(a) and Fig. 14(a)]. The central radiator ($n = 1$) has been fed by using a Rosemberger 01K80A-40ML5 connector installed without soldering at the bottom edge of the AUT substrate [Fig. 14(a)]. The neighboring SS elements (i.e., $n = 2, \ldots, N$) have been terminated on MCR1 compact thick film chip resistors (series 0402) acting as matched loads. Moreover, the active and the dummy radiators as well as the feeding line have been surrounded by a double set of interleaved vias to suppress the insurgence of undesired surface currents due to the electrically-large dimension of the PCB [Fig. 13(b)].

The measurement set-up [Figs. 14(b)-14(c)] has been composed by a mm-wave CATR system within an Asysol anechoic chamber (Fig. 15) suitable for antenna measurements up to 170 [GHz].

Figure 16(a) shows the simulated layout in Ansys HFSS (modeling the prototype of Fig. 13), while a comparison

for the sake of completeness, some CFA solutions have been reported as well (Tab. III). With respect to [13] and [26], the proposed SS-EFA provides a larger bandwidth (+117% vs. [13] and +53% vs. [26]), while it yields a higher gain (+10%) when compared to [9]. Moreover, it is worth remarking that edge-feeding is a highly desirable feature in radar applications where the radiators must be arranged into closely-packed/single-layer layouts in which simple routing connections to the controlling chipset are mandatory. Therefore, the proposed antenna may be a better (if not the only “physically admissible”) technological choice with respect to such center-fed designs.
between the simulated and the measured input reflection coefficient of the central element ($n = 1$) is shown in Fig. 16(b). As it can be observed, the antenna properly resonates in the entire operation band, being $|S_{11}(f)|_{\text{meas}} \leq -11.4$ [dB], $f \in \Delta f$. Figure 17 shows the SS-EFA co-polar (CO) and cross-polar (CX) gain patterns measured along the $\varphi = 90$ [deg]-cut at the minimum [$f = f_{\text{min}}$ - Fig. 17(a)], the central [$f = f_0$ - Fig. 17(b)], and the maximum [$f = f_{\text{max}}$ - Fig. 17(c)] operating frequencies. As it can be observed, the FF patterns of the prototype well match the simulated ones. More specifically, there is a very good agreement in both the co-polar main lobe region and the first left/right sidelobes. Some slight deviations, occurring especially in the lateral sidelobes, are probably due to both prototype manufacturing inaccuracies and measurement tolerances whose impact is certainly significant in the mm-wave regime. Moreover, these experimental results confirm the FW-predicted SLL performance since $SLL_{\text{meas}} \leq -14.5$ [dB], for $f \in \Delta f$ (Fig. 17). Similarly, the measured CX patterns assess the high polarization purity of the proposed SS-EFA radiating element. As a matter of fact, the normalized CX pattern is always lower than $-18$ [dB] for $\theta \in [-90, 90]$ [deg] and lower than $-25$ [dB] along the broadside, for $f \in \Delta f$ (Fig. 17). Finally, the measured realized gain is equal to $RG_{\text{meas}}(f_{\text{min}}) = 11.8$ [dB], $RG_{\text{meas}}(f_0) = 13.2$ [dB], and $RG_{\text{meas}}(f_{\text{max}}) = 14.0$ [dB], at the minimum, central, and maximum frequencies, respectively.

V. CONCLUSIONS

A novel radiating element for 77 GHz automotive radars has been proposed that relies on a spline-based modeling to yield a high geometric flexibility with a reduced number of DoFs, while enabling the fitting of the several con-
REFERENCES

[1] J. Hasch, E. Topak, R. Schnabel, T. Zwick, R. Weigel, and C. Waldschmidt, “Millimeter-wave technology for automotive radar sensors in the 77 GHz frequency band,” IEEE Trans. Microw. Theory Techn., vol. 60, no. 3, pp. 945-960, Mar. 2012.

[2] D. Kissing, Millimeter-Wave Receiver Concepts for 77 GHz Automotive Radar in Silicon-Germanium Technology. New York: Springer-Verlag, 2012.

[3] M. Kim and S. Kim, “Design and fabrication of 77-GHz radar absorbing materials using frequency-selective surfaces for autonomous vehicles application,” IEEE Microw. Wireless Compon. Lett., vol. 29, no. 12, pp. 779-782, Dec. 2019.

[4] J. Overdevest, F. Jansen, F. Uysal, and A. Yarovoy, “Doppler influence on waveform orthogonality in 79 GHz MIMO phase-coded automotive radar,” IEEE Trans. Veh. Technol., vol. 69, no. 1, pp. 16-25, Jan. 2020.

[5] E. Klinefelter and J. A. Nanzer, “Automotive velocity sensing using millimeter-wave interferometric radar,” IEEE Trans Microw. Theory Techn., vol. 69, no. 1, pp. 1096-1104, Jan. 2021.

[6] C. Kuo, C. Lin, and J. Sun, “Modified microstrip Franklin array antenna for automotive short-range radar application in blind spot information system,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 1731-1734, 2017.

[7] C.-A. Yu, E. S. Li, H. Jin, Y. Cao, G.-R. Su, W. Che, and K.-S. Chinet, “24 GHz horizontally polarized automotive antenna arrays with wide fan beam and high gain,” IEEE Antennas Propag., vol. 67, no. 2, pp. 892-904, Feb. 2019.

[8] J. Xu, W. Hong, H. Zhang, G. Wang, Y. Yu, and Z. H. Jiang, “An array antenna for both long and medium-range 77 GHz automotive radar applications,” IEEE Trans. Antennas Propag., vol. 65, no. 12, pp. 7207-7216, Dec. 2017.

[9] Y. Q. Guo, Y. M. Pan, and S. Y. Zheng, “Design of series-fed, single-layer, and wideband millimeter-wave microstrip arrays,” IEEE Trans. Antennas Propag., vol. 68, no. 10, pp. 7017-7026, Oct. 2020.

[10] M. Mosalanejad, I. Ocket, C. Soens, and G. A. E. Vandenbosch, “Wideband compact comb-line antenna array for 79 GHz automotive radar applications,” IEEE Antennas Wireless Propag. Lett., vol. 17, no. 9, pp. 1580-1583, Sep. 2018.

[11] A. Massa and M. Salucci, “On the design of complex EM devices and systems,” IEEE Trans. Antennas Propag., vol. 65, no. 12, pp. 6752-6767, Dec. 2017.

[12] X. Wang and A. Stelzer, “A 79-GHz LTCC patch array antenna using a laminated waveguide-based vertical parallel feed,” IEEE Antennas Wire-

[13] REFERENCES

ACKNOWLEDGEMENTS

A. Massa wishes to thank E. Vico for her never-ending inspiration, support, guidance, and help.
with the computational complexity,” IEEE Trans. Antennas Propag., vol. 70, no. 2, pp. 1328-1343, Feb. 2022.

[38] P. Rosatti, M. Salucci, L. Poli, and A. Massa, “Multiobjective system-by-design for mm-wave automotive radar antennas,” IEEE Trans. Antennas Propag., vol. 71, no. 4, pp. 2958-2973, Apr. 2023.

[39] S. Goudos, Emerging Evolutionary Algorithms for Antennas and Wireless Communications. Stevenage: SciTech Publishing Inc., 2021.

[40] S. K. Goudos, C. Kaliafakis, and R. Mittra, “Evolutionary algorithms applied to antennas and propagation: A review of state of the art,” Int. J. Antennas Propag., vol. 2016, pp. 1-12, Jan. 2016.

[41] P. Rocca, M. Benedetti, M. Donelli, D. Franceschini, and A. Massa, “Evolutionary optimization as applied to inverse scattering problems,” Inverse Problems, vol. 24, no. 12, pp. 1-41, 2009.

[42] A. Massa, G. Oliveri, M. Salucci, N. Anselmi, and P. Rocca, “Learning-by-examples techniques as applied to electromagnetics,” J. Electromagn. Waves Appl., vol. 32, no. 4, pp. 516-541, 2018.

[43] K. Tan, T. Yin, H. Ruan, S. Balon, and X. Chen, “Learning approach to FMCW radar target classification with feature extraction from wave physics,” IEEE Trans. Antennas Propag., vol. 70, no. 8, pp. 6287-6299, Aug. 2022.

[44] W. A. Ahmad et al., “A planar differential wide fan-beam antenna array architecture: Modular high-gain array for 79-GHz multiple-input, multiple-output radar applications,” IEEE Antennas Propag. Mag., vol. 63, no. 4, pp. 21-32, Aug. 2021.

[45] ANSYS Electromagnetics Suite - HFSS (2021). ANSYS, Inc.
CLAUDIO MASSAGRANDE received the master’s degree in electronic engineering (Telecommunications) from Politecnico di Milano, Milan, Italy, in 1996. He is a Principal Antenna Engineer with the Huawei Milan Research Center (MIRC), Milan, Italy. He has almost 25 years of experience in the telecom industry as a microwave and antenna designer for Andrew (now CommScope), Siemens (then Nokia Siemens Networks), and Huawei Technologies. During his carrier, he designed, developed, and tested front ends of several families of microwave radios gaining considerable experience in microwave assembly technologies, such as chip and wire and die attach. His expertise ranges from radio frequency design for microwave PTP radio links for the mobile network backhaul to radio link integration to advanced antenna systems design. His current research activity is focused on advanced antenna systems for mm-wave 5G access.

PIETRO ROSATTI received the B.Sc. degree in electronics and telecommunications engineering and the M.Sc. degree in information and communication engineering from the University of Trento, Trento, Italy, in 2017 and 2020, respectively, where he is currently pursuing the Ph.D. degree in information and communication technology with the International Doctoral School. He is also a Senior Researcher with the ELE-DIA Research Center, University of Trento. His research interests include the design and analysis of wide-angle phased array antennas for modern applications, such as automotive radars and 5G communications.

MOHAMMAD ABDUL HANNAN received the B.Sc. in Electronics and Telecommunication Engineering (ETE) from Daffodil International University, Bangladesh in 2010, the Master Degree in Telecommunication Engineering from University of Trento, Italy, in 2015, and the Ph.D. degree from the International Doctoral School in Information and Communication Technology, Trento, Italy, in 2020. He is currently Assistant Professor at the Department of Electrical and Computer Engineering at the University of Catania, Italy, and a Senior Researcher of the ELEDIA Research Center. His research work is mainly focused on electromagnetic direct and inverse scattering and antenna system synthesis for sensing and communications.

MIRKO FACCHINELLI received the B.Sc. degree in communication and information engineering and the M.Sc. degree in information and communication engineering from the University of Trento, Trento, Italy, in 2021 and 2023. He is an ETRP-Advanced at the ELEDIA Research Center. His research activity is focused on the optimization techniques for the design of simplified antenna arrays.

ANDREA MASSA (IEEE Fellow, IET Fellow, Electromagnetic Academy Fellow) received the Laurea (M.S.) degree in Electronic Engineering from the University of Genoa, Genoa, Italy, in 1992 and the Ph.D. degree in EEECS from the same university in 1996. He is currently a Full Professor of Electromagnetic Fields at the University of Trento, where he currently teaches electromagnetic fields, inverse scattering techniques, antennas and wireless communications, wireless services and devices, and optimization techniques. At present, Prof. Massa is the director of the network of federated laboratories “ELEDIA Research Center” (www.eledia.org) located in Brunei, China, Czech, France, Greece, Italy, Japan, Peru, Tunisia with more than 150 researchers. Moreover, he is holder of a Chang-Jiang Chair Professorship @ UESTC (Chengdu - China), Visiting Research Professor @ University of Illinois at Chicago (Chicago - USA), Visiting Professor @ Tsinghua (Beijing - China), Visiting Professor @ Tel Aviv University (Tel Aviv - Israel), and Professor @ CentraleSupélec (Paris - France). He has been holder of a Senior DIGITEO Chair at L2S-CentraleSupélec and CEA LIST in Saclay (France), UC3M-Santander Chair of Excellence @ Universidad Carlos III de Madrid (Spain), Adjunct Professor at Penn State University (USA), Guest Professor @ UESTC (China), and Visiting Professor at the Missouri University of Science and Technology (USA), the Nagasaki University (Japan), the University of Paris Sud (France), the Kumamoto University (Japan), and the National University of Singapore (Singapore). He has been appointed IEEE APS Distinguished Lecturer (2016-2018) and served as Associate Editor of the “IEEE Transaction on Antennas and Propagation” (2011-2014). Prof. Massa serves as Associate Editor of the “International Journal of Microwave and Wireless Technologies” and he is member of the Editorial Board of the “Journal of Electromagnetic Waves and Applons”, a permanent member of the “PIERS Technical Committee” and of the “EuMW Technical Committee”, and a ESoA member. He has been appointed in the Scientific Board of the “Società Italiana di Elettromagnetismo (SIEm)” and elected in the Scientific Board of the Interuniversity National Center for Telecommunication (CNIT). He has been appointed in 2011 by the National Agency for the Evaluation of the University System and National Research (ANVUR) as a member of the Recognized Expert Evaluation Group (Area 09, "Industrial and Information Engineering") for the evaluation of the researches at the Italian University and Research Center for the period 2004-2010. Furthermore, he has been elected as the Italian Member of the Management Committee of the COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar". His research activities are mainly concerned with inverse problems, analysis/synthesis of antenna systems and large arrays, radar systems synthesis and signal processing, cross-layer optimization and planning of wirelessRF systems, semantic wireless technologies, system-by-design and material-by-design (metamaterials and reconfigurable-materials), and theory/applications of optimization techniques to engineering problems (tele-communications, medicine, and biology). Prof. Massa published more than 900 scientific publications among which more than 350 on international journals (> 15.000 citations h-index = 65 [Scopus]; > 12.000 citations h-index = 59 [ISI-Web of Science]; > 23.000 citations h-index = 89 [Google Scholar]) and more than 550 in international conferences where he presented more than 200 invited contributions (> 40 invited keynote speakers) (www.eledia.org/publications). He has organized more than 100 scientific sessions in international conferences and has participated to several technological projects in the national and international framework with both national agencies and companies (18 international projects, > 5 MEU; 8 national projects, > 5 MEU; 10 local projects, > 2 MEU; 63 industrial projects, > 10 MEU; 6 university projects, > 300 KEU).

***