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A NOVEL STRUCTURE AND DESIGN OPTIMIZATION OF COMPACT SPLINE-PARAMETERIZED UWB SLOT ANTENNA

Slawomir Koziel, Adrian Bekasiewicz

Reykjavík University, School of Science and Engineering, Menntavegur 1, 101 Reykjavík, Iceland
(✉ koziel@ru.is, +354 599 6376, bekasiewicz@ru.is)

Abstract

In this paper, a novel structure of a compact UWB slot antenna and its design optimization procedure has been presented. In order to achieve a sufficient number of degrees of freedom necessary to obtain a considerable size reduction rate, the slot is parameterized using spline curves. All antenna dimensions are simultaneously adjusted using numerical optimization procedures. The fundamental bottleneck here is a high cost of the *electromagnetic* (EM) simulation model of the structure that includes (for reliability) an SMA connector. Another problem is a large number of geometry parameters (nineteen). For the sake of computational efficiency, the optimization process is therefore performed using variable-fidelity EM simulations and surrogate-assisted algorithms. The optimization process is oriented towards explicit reduction of the antenna size and leads to a compact footprint of 199 mm^2 as well as acceptable matching within the entire UWB band. The simulation results are validated using physical measurements of the fabricated antenna prototype.

Keywords: compact antennas, computer-aided design (CAD), EM-driven design, UWB antennas, slot antennas, surrogate-based optimization.

1. Introduction

Size reduction is one of the important criteria in the design of contemporary antennas [1]. It is especially important for wireless communication systems [2], wearable devices [3], as well as internet of things applications [4, 5]. Unfortunately, achieving a compact geometry and maintaining acceptable electrical performance are conflicting goals and, in practice, a compromise solution has to be sought. In the case of UWB antennas, reduction of size (and, consequently, a ground plane) leads to shortening the current path and matching problems at lower frequencies [2]. A number of techniques have been developed to alleviate this difficulty, such as various ground plane modifications (*e.g.*, I-shaped [6] and L-shaped stubs [7], protruded ground plane structures [8], slits below the feed line [7], stripline-fed designs [9], *etc.*) but also slot and quasi-slot structures [10].

Topological modifications leading to a reduced antenna size also result in an increased number of geometry parameters that need to be adjusted but also increase complexity of the structure. This means a higher computational cost of *evaluating the electromagnetic* (EM) simulation model of the antenna, also because the latter has to include – for the sake of reliability – additional components, such as a connector [7]. Taken together, the above factors make the process of adjusting structure dimensions very challenging. In particular, traditional design methods largely based on experience-driven parameters' sweeps are unable to yield truly optimum designs. This is not only because of the fact that multiple parameters cannot be effectively handled this way but, most importantly, because a typical design flow aims at obtaining an acceptable level of the in-band reflection (and, perhaps, other important

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characteristics). A small size is normally a byproduct of the geometrical modifications introduced into the design, but not the effect of explicit minimization of the antenna dimensions through numerical optimization [10].

Cost-efficient simulation-driven design of antenna structures can be realized either through gradient-based optimization using adjoint sensitivities [11, 12] or by means of surrogate-assisted algorithms [13, 14]. The latter approach is more generic and accessible because the majority of surrogate-based techniques are derivative-free [13]. Efficient optimization methods enable to simultaneously handle the antenna size and its electrical performance parameters, see, *e.g.* [15].

In this paper, a novel structure of a compact UWB slot antenna is proposed. In order to increase the number of degrees of freedom the slot is parameterized using splines. The antenna dimensions are adjusted through automated numerical optimization involving variable-fidelity EM simulation models. The optimization process is oriented towards explicit size reduction of the structure. The final design features a very small footprint of 199 mm^2 and acceptable matching below –10 dB in the 3.1 GHz to 10.6 GHz frequency range. Experimental validation of the fabricated antenna prototype is provided.

2. Proposed spline-parameterized UWB slot antenna structure

The structure of proposed slot antenna is shown in Fig. 1. The geometry is based on a design of [16]. The reference structure consists of a microstrip line feed and a stepped impedance ground plane slot. The antenna proposed here has been modified to preserve the compact geometry and simultaneously ensure its acceptable electrical performance. The introduced changes include redesign of the geometry using splines, loading the driven element by the low-impedance stub, as well as introduction of additional degrees of freedom.

The structure is implemented on a Taconic RF-35 substrate (ε_r = 3.5, tanδ = 0.0018, h = 0.762 mm). The design parameters are: $\boldsymbol{x} = [l_0\ l_{g1r}\ l_{g2}\ l_{s1}\ l_{s2}\ l_{s3}\ l_{s4}\ l_{s5}\ l_{f1r}\ l_{f2r}\ w_{s1}\ w_{s2}\ w_{s3}\ w_{s4}\ w_{f2}\ o_{f1r}\ o_{s2r}\ o_{s3r}\ o_{s4r}]^T$. Dependent dimensions (see Fig. 1) are: $l_{g1} = l_{g1r}(l_0 - w_{s1})$, $l_{f1} = l_{f1r}\cdot l_0(1 - l_{f2r})$, $l_{f2} = l_0\cdot l_{f1r}\cdot l_{f2r}$, $o_{f1} = o_{f1r}(l_{s1} + l_{s2} + l_{s3} + l_{s4} + w_{s4} + l_{g2} - w_{f1})$, $o_{s2} = 0.5(o_{s2r}(w_{s1} - w_{s2}) - w_{s2})$, $o_{s3} = 0.5(o_{s3r}(w_{s2} - w_{s3}) - w_{s3})$ and $o_{s4} = 0.5(o_{s4r}(w_{s3} - w_{s4}) - w_{s4})$, whereas w_{f1} = 1.7 remains fixed to ensure 50 Ohm input impedance (the unit of non-relative dimensions is mm). It should be noted that the structure is geometrically small. Therefore, its EM model is supplemented with an SMA connector to improve reliability of the simulation results.

3. Design optimization methodology

In this section, we briefly explain the design optimization technique utilized to adjust the geometry dimensions of the antenna. The optimization process is oriented towards explicit size reduction of the structure. The acceptable level of in-band reflection is ensured by means of a penalty function approach.

3.1. Computational models

The primary EM antenna model $\boldsymbol{R}$ (referred to as the high-fidelity model) is implemented in CST Microwave Studio [17] and simulated using its time-domain solver. It contains about 5,500,000 mesh cells, and its evaluation time on a dual Intel E5540 machine with 6 GB of RAM is about 44 minutes. In the design process, we also exploit a coarse-discretization version of $\boldsymbol{R}$, referred to as the low-fidelity model $\boldsymbol{R}_c$, that is also implemented in CST (~475,000 mesh cells, simulation time 152 s).

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3.2. Problem formulation

There are two design goals to be attained, specifically (i) minimization of the antenna footprint $S(\boldsymbol{x})$, and (ii) maintaining the antenna reflection in the UWB band below –10 dB. The design problem is formulated as:

$$\boldsymbol{x}^* = \operatorname{argmin}\{\boldsymbol{x} : U(\boldsymbol{R}(\boldsymbol{x}))\}, \tag{1}$$

where U is the objective function defined as:

$$U(\boldsymbol{R}(\boldsymbol{x})) = S(\boldsymbol{x}) + \beta \cdot g(\boldsymbol{R}(\boldsymbol{x}))^2 . \tag{2}$$

The second term in (2) is a penalty function defined as:

$$g(\boldsymbol{R}(\boldsymbol{x})) = \max\left\{\frac{\max\{|S_{11}|_{3.1\,\text{GHz to }10.6\,\text{GHz}}\}+10}{10}, 0\right\}. \tag{3}$$

It should be noted that the penalty function $g(\boldsymbol{R}(\boldsymbol{x})) = 0$ if $|S_{11}| \le -10$ dB in the entire UWB band, and it is positive otherwise. In other words, the penalty term contributes to the objective function if and only if the reflection requirement is violated. Here, β is a penalty factor (we use $\beta = 1000$). Its value has to be adjusted so as to make the contribution of the penalty term considerable in the case of a substantial violation of the maximum reflection threshold.

3.3. Optimization algorithm

Due to a considerable computational cost of $\boldsymbol{R}$, a surrogate-assisted design procedure is used [7] to speed up the process of geometry parameter adjustment. In particular, the optimum design $\boldsymbol{x}^*$ is approximated by a series of designs $\boldsymbol{x}^{(i)}$, $i = 0, 1, \ldots$, obtained as:

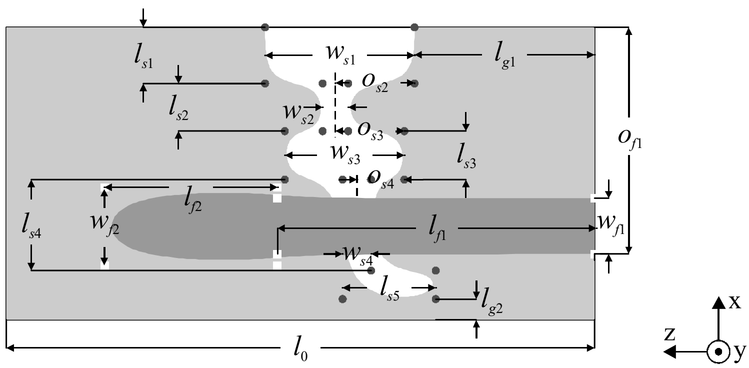

Fig. 1. The geometry of the proposed compact UWB slot antenna. Black dots and white squares represent the spline nodes.

$$\boldsymbol{x}^{(i+1)} = \arg\min_{\boldsymbol{x}} U(\boldsymbol{R}_s^{(i)}(\boldsymbol{x})), \tag{4}$$

where the surrogate model $\boldsymbol{R}_s^{(i)}$ at iteration i is constructed from the low-fidelity model $\boldsymbol{R}_c$ using frequency scaling and output space mapping [13]. Due to a good correlation between the low- and high-fidelity models, the algorithm converges in a few iterations despite the large number of geometry parameters of the antenna.

4. Numerical results

The initial antenna design $\boldsymbol{x}^0$ = [22 0.52 1.4 2.3 2.1 1.6 0.7 2.7 0.68 0.5 4.6 0.8 3.2 0.9 1.7 0.7 0 0 0]^T has been estimated based on dimensions of the reference structure of [16]. The final design $\boldsymbol{x}^*$ = [19.52 0.39 1.57 3.8 1.74 1.49 0.68 2.61 0.64 0.46 4.48 0.69 3.31 0.93 2.35 0.72 0.07 –0.99 0.87]^T has been obtained after five iterations of the procedure described in Section 3.

Comparison of the antenna reflection responses at the initial and the final design is shown in Fig. 2. It should be noted that dimensions of the optimized structure are 10.2 mm × 19.5 mm and it features an overall footprint of 199 mm^2. Moreover, the final antenna design meets the imposed requirements concerning reflection: it is below the acceptable level of –10 dB within the 3.1 GHz to 10.6 GHz band, which is not the case for the reference design of [16].

The proposed structure has been compared regarding the occupied area with other state-of-the-art structures including a miniaturized slot antenna [16], compact monopoles [4, 7, 18] and strip-line-fed structures [9]. The mentioned designs are implemented on substrates with varied electrical properties. For the sake of reliable comparison dimensions of the considered structures have been expressed as the guided wavelength λ_g (defined for the 50 Ohm line operating at the 6.85 GHz center frequency). The results gathered in Table 1 indicate that the proposed antenna structure, although not the smallest in respect of the absolute size, features the lowest λ_g^2 footprint. It should be noted that, in metric units, the presented spline-parameterized antenna is slightly larger than the reference design of [16]. However, the reference antenna violates the specification upon the minimal acceptable in-band reflection below –10 dB.

Table 1 Comparison of UWB antennas' geometry.

Antenna	Dimensions mm × mm	Size mm^2	Effective $\lambda_g \times \lambda_g$	Footprint# λ_g^2
Design [18]	10.0 × 32.5	325	0.42 × 1.38	0.89
Design [9]	7.00 × 25.0	175	0.43 × 1.07	0.46
Design [4]	10.0 × 25.0	250	0.39 × 0.97	0.38
Design [7]	15.8 × 22.0	348	0.50 × 0.69	0.35
Design* [16]	8.50 × 22.0	187	0.35 × 0.92	0.32
This work	10.2 × 19.5	199	0.39 × 0.74	0.28

For fair comparison, the antenna size is expressed in terms of the guided wavelength corresponding to the substrate properties the design is implemented on.

* Design violates the imposed requirement upon the acceptable in-band reflection level below –10 dB. The structure exhibits reflection below –8 dB.

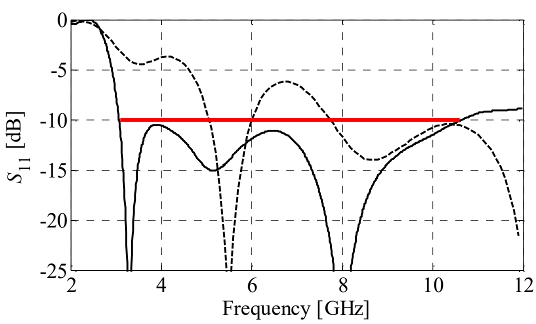

Fig. 2. The reflection response of the proposed UWB slot antenna at the initial (– –) and the optimized (—) design.

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5. Experiment

The proposed compact UWB antenna has been fabricated and measured. Photographs of the manufactured prototype are shown in Fig. 3. Fig. 4 presents a comparison of its simulated and measured reflection characteristics. The results are in a good agreement. The measured response slightly (below 0.3 dB) violates the design specification at its upper edge, which is considered acceptable for a structure with such small dimensions.

Figure 5 shows a comparison of the simulated and measured gain characteristics of the structure at the direction perpendicular to its surface (here, direction y; *cf.* Fig. 1). The characteristics are in close resemblance. The average in-band gains are –0.8 db and –0.5 for simulation and measurements, respectively.

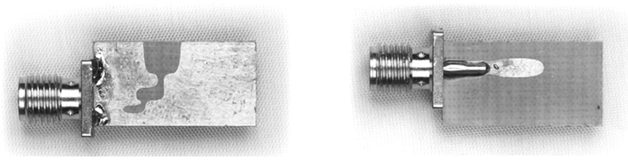

Fig. 3. Photographs of the fabricated compact UWB slot antenna.

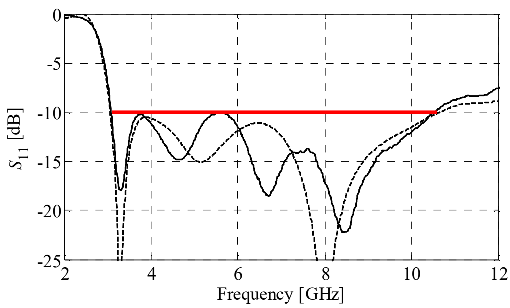

Fig. 4. The simulated (– –) and measured (—) reflection characteristics of the proposed UWB antenna.

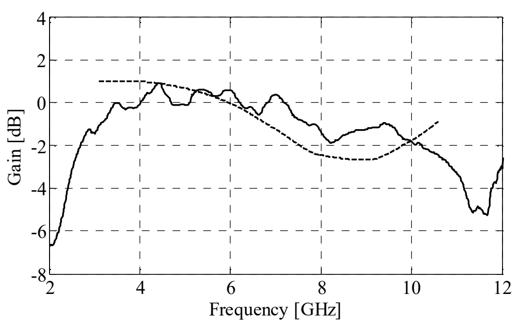

Fig. 5. The simulated (– –) and measured (—) gain characteristics of the compact UWB slot antenna.

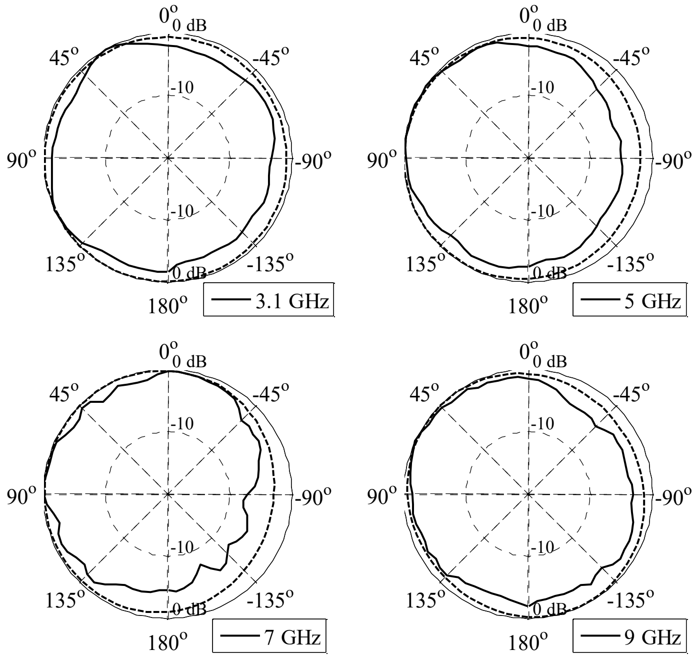

Fig. 6. Comparison of the simulated (– –) and measured (—) H-plane radiation patterns of the proposed UWB slot antenna at selected frequency points.

A comparison of antenna E-field radiation patterns obtained for its H-plane (x–y plane; *cf.* Fig. 1) is provided in Fig. 6. The agreement level between simulations and measurements is acceptable. It should be noted that the peak radiation pattern shifts clockwise with the frequency increase (from about 135° at 3.1 GHz to ~45° at 9 GHz), however its change at 90° remains below 1.5 dB at selected frequencies and, from this perspective, it can be considered stable. Moreover, the H-plane front-to-back ratio remains below 3 dB and 7 dB for simulations and measurements, respectively. The discrepancies between simulated and measured field characteristics are mostly the result of electrically large measurement setup, which was not accounted for in the antenna EM model. To some extent, the observed discrepancies are also introduced by fabrication and assembly imperfections (allocation of the SMA connector, the influence of solder, *etc.*).

6. Conclusion

In the paper, a novel structure of a miniaturized UWB slot antenna with the spline-parameterized geometry has been proposed along with a computationally-efficient procedure for size-reduction-oriented optimization of its dimensions. Simultaneous adjustment of all relevant parameters led to a very compact size of only 199 mm^2 while maintaining good electrical performance. Design correctness has been verified experimentally.

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