# A Structure and Design of Novel Compact UWB Slot Antenna

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***Abstract*—A structure and design optimization procedure of a compact UWB slot antenna is presented. Small size of the antenna and its good electrical performance is achieved by introducing sufficiently large number of geometry degrees of freedom, including a stepped-impedance feed line and a meandered slot with parameterized dimensions. All dimensions are simultaneously adjusted using automated EM-simulation-driven optimization algorithm. Exploitation of variable-fidelity models allows us to maintain low computational cost of the design process. The footprint of the optimized antenna is only 8.93 mm × 17.9 mm (160 mm$^2$) while maintaining low reflection in the entire UWB frequency range.**

***Index Terms*—UWB Antennas, compact antennas, computer-aided design, EM-driven design, surrogate-based optimization.**

## I. INTRODUCTION

Size minimization has become an important consideration in the design of contemporary UWB antennas. It is especially critical for certain applications, e.g., in handheld or wearable devices [1]. Unfortunately, achieving compact geometry and maintaining acceptable electrical performance are generally conflicting objectives. A major difficulty is that reduction of the ground plane typically leads to degradation of the antenna matching at lower frequencies due to shortening of the current path [2].

A number of techniques have been developed to handle this issue, including ground plane modifications (I-shaped slots [3], protruded ground plane structures [4], L-shaped stubs [5], slits below the feed line [5], etc.), slot and quasi-slot antenna structures [6], [7], or uniplanar monopole designs [8] (also useful for broadband impedance matching due to coplanar waveguide feed [6]). All of the aforementioned approaches lead to increased complexity of the antenna structure which makes the design process more challenging. One of the issues is a large number of geometry parameters that need to be simultaneously adjusted. Also, reliable performance evaluation of the antenna can only be realized using full-wave EM analysis which is computationally expensive. Moreover—due to a small antenna size—environmental components such as connectors considerably affect the structure operation and their inclusion into the computational model is mandatory which increases the simulation cost even further.

Traditional design approaches based on parameter sweeps, while still widely used, become problematic and extremely laborious given the challenges mentioned in the previous paragraph, i.e., expensive simulation models and large number of parameters. On the other hand, design automation is difficult because conventional optimization routines are prone to failure and require large number of simulations to converge [9], [10]. Design speedup can be achieved by exploiting adjoint sensitivity techniques [11], [12] available through some commercial EM solvers [13], [14]. Also, surrogate-based optimization (SBO) techniques [15] have been recently applied for compact UWB antenna design [16], [17], which seems to be a quite promising approach in handling this type of design tasks.

In this paper, we propose a very compact UWB slot antenna and describe its efficient design procedure. The antenna structure is based on the design proposed in [7]. In order to allow its further miniaturization, additional degrees of freedom have been introduced, both in terms of parameterization of the slot but also introduction of the stepped-impedance feed line. Surrogate-assisted design procedure is applied in order to achieve the smallest possible footprint while ensuring return loss below –10 dB within the UWB frequency range. The final design features a small size of 160 mm$^2$. Simulation results confirm validity of the design process.

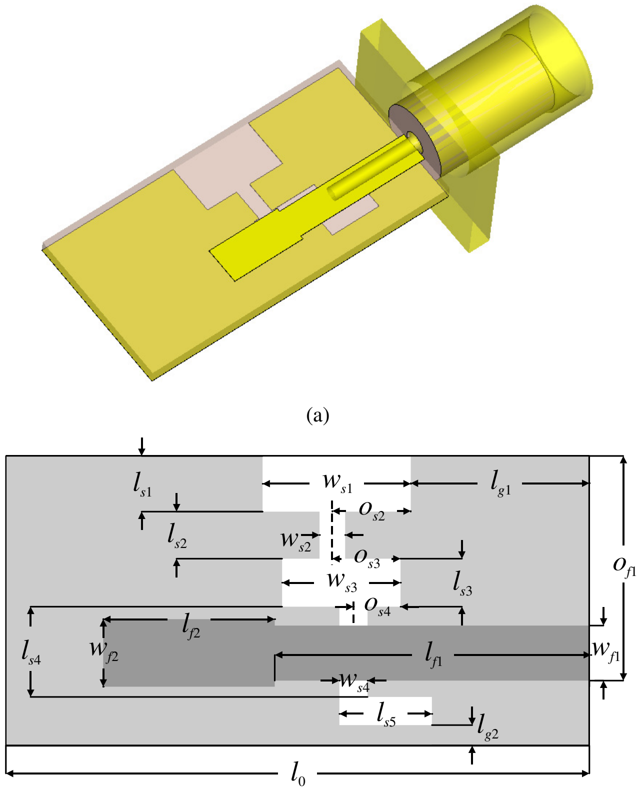
## II. PROPOSED UWB SLOT ANTENNA STRUCTURE

Consider a structure of a compact UWB slot antenna which consists of a driven element in the form of a 50 Ohm microstrip transmission line and a bended stepped impedance slot within a ground plane utilized to realize multiple matching points [7]. The structure is characterized by a compact geometry of 8.5 × 22 mm$^2$, however, it is achieved at a expense of electric performance degradation. The in-band reflection response of the structure is just below –8 dB. In this work, the design has been modified by introducing a stepped stub at the end of the feed line to improve impedance matching. Moreover, a number of degrees of freedom in the structure have been increased by parameterizing sections of the slot so that they can be shifted relative to each other. The geometry of the introduced structure is shown in Fig. 1.

The antenna is implemented on a 0.762 mm thick Taconic RF-35 dielectric substrate ($\varepsilon_r = 3.5$, $\tan\delta = 0.0018$). It is described by 19 parameters $\boldsymbol{x} = [l_0\ l_{g1r}\ l_{g2}\ l_{s1}\ l_{s2}\ l_{s3}\ l_{s4}\ l_{s5}\ l_{f1r}\ l_{f2r}\ w_{s1}\ w_{s2}\ w_{s3}\ w_{s4}\ w_{f2}\ o_{f1r}\ o_{s2r}\ o_{s3r}\ o_{s4r}]^T$. The parameter $w_{f1} = 1.7$ is fixed to ensure 50 Ohm input impedance. Moreover, the dimensions $l_{g1} = l_{g1r}(l_0 - w_{s1})$, $l_{f1} = l_{f1r}{\cdot}l_0(1 - l_{f2r})$, $l_{f2} = l_0{\cdot}l_{f1r}{\cdot}l_{f2r}$, $o_{f1} = o_{f1r}(l_{s1} + l_{s2} + l_{s3} + l_{s4} + w_{s4} + l_{g2} - w_{f1})$, $o_{s2} = 0.5(o_{s2r}(w_{s1} - w_{s2}) - w_{s2})$, $o_{s3} = 0.5(o_{s3r}(w_{s2} - w_{s3}) - w_{s3})$ and $o_{s4} = 0.5(o_{s4r}(w_{s3} - w_{s4}) - w_{s4})$ are set as relative to ensure geometrical consistency of the design during the optimization process. The unit for all geometric parameters is mm.

The simulation model of the antenna is implemented in CST Microwave Studio and simulated using its time domain solver [17]. It should be noted that the considered structure is electrically small. Therefore, for the sake of improved simulation reliability, the EM model of the antenna is supplemented with the SMA connector. The high-fidelity model $\boldsymbol{R}_f$ of the structure consists of ~3,800,000 mesh cells and its average simulation time on a dual Xeon E5540 with 6GB RAM is 22 min. In the design process, we also utilize the relaxed-accuracy low-fidelity model $\boldsymbol{R}_c$ (~420,000 cells and simulation time of 2 min).

The design objective is to minimize the antenna footprint while ensuring reflection below –10 dB within the frequency range from 3.1 GHz to 10.6 GHz.




(a)

(b)

Fig. 1. Compact UWB slot antenna: (a) visualization of the design with SMA connector; (b) geometrical details of the structure with highlighted design variables. The structure is based on a design of [7].

The initial design $\boldsymbol{x}^0 = [22\ 0.52\ 1.4\ 2.3\ 2.1\ 1.6\ 0.7\ 2.7\ 0.68\ 0.35\ 4.6\ 0.8\ 3.2\ 0.4\ 1.7\ 0.72\ 0\ 0\ 0]^T$ is based on dimensions of the reference structure of [7]. The design space bounds are: $\boldsymbol{l} = [15\ 0.3\ 0.2\ 1\ 1\ 0.5\ 0.2\ 1\ 0.3\ 0.1\ 3\ 0.2\ 1.5\ 0.2\ 0.5\ 0.3\ {-0.99}\ {-0.99}\ {-0.99}]^T$ and $\boldsymbol{u} = [30\ 0.99\ 3\ 4\ 3\ 2.5\ 1.5\ 5\ 1\ 0.6\ 6\ 2\ 4.5\ 1\ 2.5\ 1\ 0.99\ 0.99\ 0.99]^T$.

## III. Design Optimization Procedure

The design process aims at adjusting the geometry parameters of the antenna structure in order to minimize its footprint and, at the same time, maintain acceptable electrical performance. More specifically, we want to achieve $|S_{11}| \le -10$ dB for 3.1 GHz to 10.6 GHz.

The above design task can be formulated as a minimization problem of the form

$$\boldsymbol{x}^* = \arg\min_{\boldsymbol{x}} U(\boldsymbol{R}_f(\boldsymbol{x})) \tag{1}$$

where $\boldsymbol{R}_f$ represents a response of the high-fidelity EM antenna model, $\boldsymbol{x}$ is a vector of designable parameters, $U$ is an objective function, whereas $\boldsymbol{x}^*$ is the optimum design to be found. For simplicity, the aforementioned design goals are aggregated into a single objective so that the function $U$ is defined as

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

where $S(\boldsymbol{x})$ is the antenna footprint. The reflection response is controlled by means of a penalty function defined as

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

According to this definition, $g(\boldsymbol{R}_f(\boldsymbol{x})) = 0$ if $|S_{11}| \le -10$ dB in the UWB band so that, effectively, the antenna footprint is minimized if the reflection level is acceptable. Otherwise, the penalty function represents a relative violation of the –10dB threshold. Here, $\beta$ is a penalty factor (in our experiments, we use $\beta = 1000$). We use $g(.)^2$ in (2) so as to ensure that the objective function is smooth with respect to $\boldsymbol{x}$. In other words, the objective function (2) penalizes designs that violate reflection requirements.

Because of high computational cost of evaluating the high-fidelity model, direct optimization of $\boldsymbol{R}_f$ as in (1) is not practical. In this work, we utilize a surrogate-based optimization (SBO) approach [15], which is an iterative process defined as follows

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

where a series $\boldsymbol{x}^{(i)}$, $i = 0, 1, \ldots$, of approximations to the optimum design $\boldsymbol{x}^*$, whereas $\boldsymbol{R}_s^{(i)}$ is a surrogate model at iteration $i$, i.e., a cheaper representation of the high-fidelity model. The surrogate model is constructed as a local response surface approximation of the low-fidelity model $\boldsymbol{R}_c$ sampled in the vicinity of the current design $\boldsymbol{x}^{(i)}$, and corrected using output space mapping [18]. The details concerning the low-fidelity model setup have been provided in Section II. The local approximation model is implemented as a second-order polynomial without mixed terms [19].

### IV. SIMULATION RESULTS

The antenna of Section II has been optimized using the technique of Section III. The optimized design $\boldsymbol{x}^* = [17.92\ 0.41\ 1.5\ 2.8\ 1.82\ 1.48\ 0.45\ 2.85\ 0.65\ 0.35\ 4.57\ 0.78\ 3.66\ 0.87\ 2.08\ 0.72\ -0.07\ -0.78\ 0.91]^T$ has been obtained in five iterations of the algorithm (4). The external dimensions of the compact structure are 8.93 × 17.92 mm$^2$ with overall footprint of 160 mm$^2$. Moreover, the optimized design response (see Fig. 2) fulfills specification with respect to acceptable in-band reflection (i.e., $|S_{11}| \leq -10$dB for 3.1 GHz to 10.6 GHz). The obtained results indicate that the introduced design modifications are essential for obtaining compact design while ensuring acceptable electrical performance.

The E-field radiation patterns of the structure have been obtained in the E-plane and H-plane for frequencies of 4 GHz, 6 GHz, 8 GHz and 10 GHz. The characteristics are shown in Fig. 3. In the H-plane, the results indicate omnidirectional behavior of the antenna in wide frequency range with front to back (F/B) ratios varying from 1.2 dB to 2.9 dB. For higher frequencies the E-plane patterns also became omnidirectional to some extent with F/B at the level of 10.8 dB and 9.6 dB for 8 GHz and 10 GHz, respectively.

The proposed antenna has been compared in terms of the occupied area with other state-of-the-art structures including compact monopole [2], [5], [8] stripline-fed [21] and slot antennas [7]. It should be noted that compared antennas are designed on substrates with different electric parameters. To account for these differences the dimensions of considered structures have been expressed in terms of the guided wavelength $\lambda_g$ (defined for the 50 Ohm line operating at 6.85 GHz center frequency). The obtained results are gathered in Table I. The proposed compact antenna structure outperforms competitive designs in terms of size. At the same time, it fulfills the condition concerning the acceptable in-band reflection below –10 dB which is not the case for the reference design of [7].

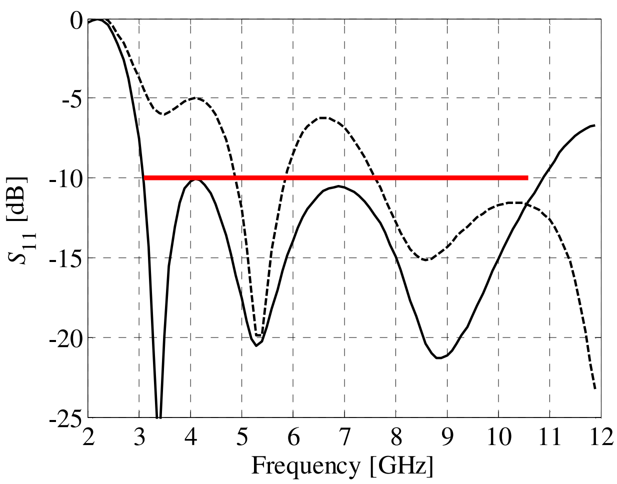



Fig. 2. Reflection responses of the compact UWB slot antenna structure at the initial (– – –) and the final design (——).

TABLE I. A COMPARISON OF UWB ANTENNAS GEOMETRY

| Antenna | Dimensions mm × mm | Size mm$^2$ | Effective $\lambda_g \times \lambda_g$ | Footprint# $\lambda_g^2$ |
|---|---|---|---|---|
| Design [8] | 10.0 × 32.5 | 325 | 0.42 × 1.38 | 0.89 |
| Design [20] | 7.00 × 25.0 | 175 | 0.43 × 1.07 | 0.46 |
| Design [2] | 10.0 × 25.0 | 250 | 0.39 × 0.97 | 0.38 |
| Design [5] | 15.8 × 22.0 | 348 | 0.50 × 0.69 | 0.35 |
| Design* [7] | 8.50 × 22.0 | 187 | 0.35 × 0.92 | 0.32 |
| This work | 8.93 × 17.9 | 160 | 0.34 × 0.68 | 0.23 |

# 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 acceptable in-band reflection below –10 dB. The structure exhibits reflection below –8 dB.

### V. CONCLUSION

In this work, a structure and design of novel compact UWB slot antenna has been presented. The antenna is characterized by a very small footprint of only 160 mm$^2$. The compact geometry has been obtained by means of numerical optimization. The desired electrical performance of the structure has been ensured during optimization process using suitable penalty function. The antenna exhibits omnidirectional radiation pattern in H-plane for wide frequency range, whereas E-plane characteristics are fairly omnidirectional for higher frequencies. Comprehensive comparisons indicate that the proposed compact UWB slot antenna outperforms other state-of-the-art designs reported in literature with respect to size while maintaining acceptable levels of electrical performance parameters. Our further work will focus on fabrication and measurements of the proposed structure.

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### REFERENCES


[1] M. Bod, H.R. Hassani, and M.M.S Taheri, "Compact UWB printed slot antenna with extra Bluetooth, GSM, and GPS Bands," *IEEE Ant. Wireless Prop. Lett.*, vol. 11, pp. 531-534, 2012.

[2] N. Chahat, M. Zhadobov, R. Sauleau, and K. Ito, "A compact UWB antenna for on-body applications," *IEEE Trans. Ant. Prop.,* vol. 59, no. 4, pp. 1123-1131, Apr. 2011.

[3] L. Li, S.W. Cheung, and T.I. Yuk, "Compact MIMO antenna for portable devices in UWB applications," *IEEE Trans. Antennas Prop.*, vol. 61, no. 8, pp. 4257–4264, 2013.

[4] J.-F. Li, Q.-X. Chu, Z.-H. Li, and X.-X. Xia, "Compact dual band-notched UWB MIMO antenna with high isolation," *IEEE Trans. Ant. Prop.*, vol. 61, no. 9, pp. 4759-4766, 2013.

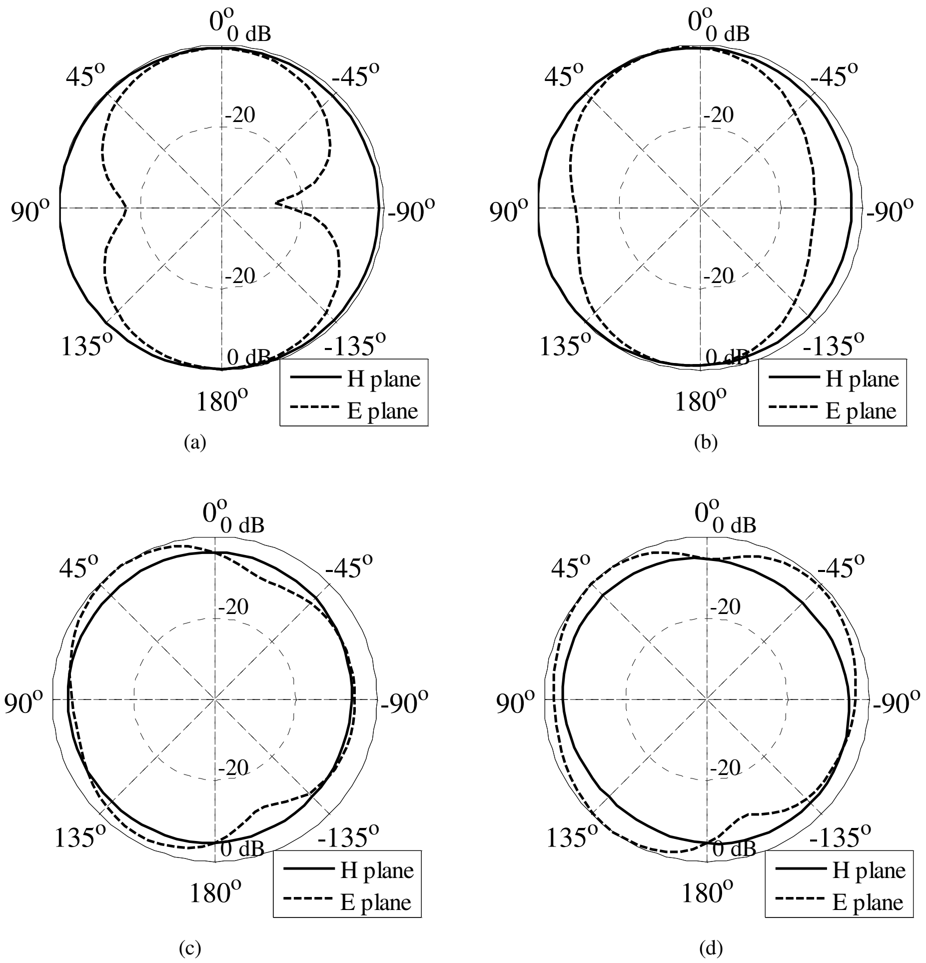


Fig. 3. E-field radiation patterns of the compact UWB slot antenna obtained in H-plane and E-plane: (a) 4 GHz; (b) 6 GHz; (c) 8 GHz; and (d) 10 GHz.


[5] A. Bekasiewicz, and S. Koziel, "Structure and computationally-efficient simulation-driven design of compact UWB monopole antenna," *IEEE Ant. Wireless Prop. Lett.*, vol. 14, pp. 1282-1285, 2015.

[6] A.K. Gautam, S. Yadav, B.K. Kanaujia, "A CPW-fed compact UWB microstrip antenna," *IEEE Ant. Wireless Prop. Lett.*, vol. 12, pp. 151-154, 2013.

[7] Q.-X. Chu, C.-X. Mao, H. Zhu, "A compact notched band UWB slot antenna with sharp selectivity and controllable bandwidth," *IEEE Trans Ant. Prop.*, vol. 61, no. 8, pp. 3961-3966, 2013.

[8] Y.-F. Liu, P. Wang, and H. Qin, "Compact ACS-fed UWB monopole antenna with extra Bluetooth band," *Electronics Lett*. vol. 50, no. 18, pp. 1263-1264, 2014.

[9] M.B. Yelten, T. Zhu, S. Koziel, P.D. Franzon, and M.B. Steer, "Demystifying surrogate modeling for circuits and systems," *IEEE Circuits and Systems Magazine*, vol. 12, no. 1, pp. 45-63, 2012.

[10] S. Koziel, D. Echeverría-Ciaurri, and L. Leifsson, "Surrogate-based methods," in S. Koziel and X.S. Yang (Eds.) *Computational optimization, methods and algorithms*, Series: Studies in Computational Intelligence, Springer-Verlag, pp. 33-60, 2011.

[11] D. Nair and J. P. Webb, "Optimization of microwave devices using 3-D finite elements and the design sensitivity of the frequency response," *IEEE Trans. Magn.*, vol. 39, no. 3, pp. 1325-1328, May 2003.

[12] Y. Song and N.K. Nikolova, "Memory efficient method for wideband self-adjoint sensitivity analysis," *IEEE Trans. Microwave Theory Tech.*, vol. 56, no. 8, pp. 1917-1927, Aug. 2008.

[13] CST Microwave Studio, ver. 2015, CST AG, Bad Nauheimer Str. 19, D-64289 Darmstadt, Germany, http://www.cst.com, 2015.

[14] Ansys HFSS, ver. 14.0 (2012), ANSYS, Inc., Southpointe 275 Technology Drive, Canonsburg, PA 15317.

[15] S. Koziel and S. Ogurtsov, "Antenna design by simulation-driven optimization. Surrogate-based approach," Springer, 2014.

[16] A. Bekasiewicz, and S. Koziel, "Structure and computationally-efficient simulation-driven design of compact UWB monopole antenna," *IEEE Antennas and Wireless Prop. Lett.*, 2015, vol. 14, pp. 1282-1285.

[17] S. Koziel, and A. Bekasiewicz, "A structure and simulation-driven design of compact CPW-fed UWB antenna," *IEEE Antennas Wireless Prop. Lett.*, 2015.

[18] S. Koziel, J.W. Bandler and K. Madsen, "Towards a rigorous formulation of the space mapping technique for engineering design," *Proc. Int. Symp. Circuits, Syst., ISCAS*, vol. 1, pp. 5605-5608, 2005.

[19] S. Koziel, "Computationally efficient multi-fidelity multi-grid design optimization of microwave structures," *Applied Computational Electromagnetics Society Journal*, vol. 25, no. 7, pp. 578-586, 2010.

[20] T.K. Roshna, U. Deepak, V.R. Sajitha, P. Mohanan, "Coplanar stripline-fed compact UWB antenna," *Electronics Lett.*, vol. 50, no. 17, pp. 1181-1182, 2014.