

Structure and design optimisation of compact UWB slot antenna

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A structure and computationally efficient design optimisation procedure of a novel miniaturised UWB slot antenna has been proposed. Upon geometry parameter adjustment, the structure exhibits a very small footprint of just 161 mm². This has been achieved by introducing sufficient number of degrees of freedom, including the parameterised multi-section slot and a multi-section load of the feed line as well as efficient numerical optimisation of all relevant geometry dimensions of the structure. The design process has been formulated as explicit size reduction problem. The electrical performance parameters (here, a maximum in-band reflection) are controlled by suitably defined constraints. The final design has been verified through full-wave electromagnetic simulation as well as physical measurements of the fabricated antenna prototype.

Introduction: In many applications, such as mobile or wearable devices [1, 2] it is essential to maintain small size of the antenna structures being parts of the respective systems. Unfortunately, antenna miniaturisation is a challenging task because it usually stays in conflict with achieving superb electrical performance. In practice, design trade-offs have to be considered that represent acceptable compromises between various objectives [3].

In case of UWB antennas, structure miniaturisation is especially difficult due to a rather straightforward relation between the ground plane dimensions and the current path: shortening of the latter results in degraded antenna matching at lower frequencies. There have been several techniques proposed in the literature to address this issue, such as various ground plane modifications, e.g. introduction of I-shaped [4], or L-shaped stubs [2], as well as slits below the feed line [2]. Other noteworthy methods include uniplanar monopole designs [5], as well as slot structures [6].

In this Letter, a novel structure of a miniaturised UWB slot antenna is proposed. In our approach – in order to ensure sufficient number of degrees of freedom necessary for size reduction – a multi-step slot and a stepped-impedance feeding line are utilised. The flexibility of the antenna geometry is fully exploited by simultaneous adjustment of all its dimensions. For computational efficiency, surrogate-based optimisation (SBO) [7] methods are employed. This is particularly important because the electromagnetic (EM) simulation model of the antenna incorporates the SubMiniature version A (SMA) connector (required for evaluation reliability), which makes it computationally very expensive. Furthermore, the geometry optimisation process is formulated to explicitly reduce the antenna size with the reflection response controlled through suitably defined penalty terms. The final design features a small footprint of only 161 mm² and reflection level below –10 dB for the entire UWB band.

Proposed UWB slot antenna geometry: Fig. 1 shows the geometry of the proposed miniaturised UWB antenna. Although the structure is based on a reference design of [6], it has been considerably modified to improve its electric properties while ensuring compact geometry. More specifically, the antenna consists of a driven element in the form of microstrip line loaded by a three-section stepped-impedance stub and a bended asymmetrical stepped slot. The geometry is parameterised in such a way that sections of the slot can be shifted relative to each other. The increased number of degrees of freedom is essential for obtaining acceptable antenna response while ensuring compact dimensions.

The antenna is implemented on a 0.762 mm thick Taconic RF-35 dielectric substrate ($\epsilon_r = 3.5$, $\tan\delta = 0.0018$). It is described by 23 variables $\mathbf{x} = [l_0, l_{g1}, l_{g2}, l_{s1}, l_{s2}, l_{s3}, l_{s4}, l_{s5}, l_{f1}, l_{f2}, l_{f3}, l_{f4}, w_{s1}, w_{s2}, w_{s3}, w_{s4}, w_{f2}, w_{f3}, w_{f4}, o_{f1}, o_{s2}, o_{s3}, o_{s4}]^T$. The parameter $w_{f1} = 1.7$ is fixed to ensure 50 Ω input impedance. Moreover, the dimensions $l_{g1} = l_{g1r}(l_0 - w_{s1})$, $l_{f1} = l_{f1r}l_0 - l_{f2} - l_{f3} - l_{f4}$, $l_{f2} = l_{f1r}l_0l_{f2r}$, $l_{f3} = l_{f1r}l_0l_{f3r}$, $l_{f4} = l_{f1r}l_0l_{f4r}$, $o_{f1} = o_{f1r}(l_{s1} + l_{s2} + l_{s3} + l_{s4} + w_{s4} + l_{g2} - w_{f1})$, $o_{s2} = 0.5(o_{s2r}(w_{s1} - w_{s2}) - w_{s2})$, $o_{s3} = 0.5(o_{s3r}(w_{s2} - w_{s3}) - w_{s3})$ and $o_{s4} = 0.5(o_{s4r}(w_{s3} - w_{s4}) - w_{s4})$ are set as relative in order to ensure consistency of the design. All geometry parameters (except the relative ones) are in millimetre. Note that the number of antenna dimensions is large so that the design process cannot be conducted using traditional method such as parameter sweeps.

The EM simulation model of the structure is implemented in CST Microwave Studio [8]. In order to ensure reliable evaluation of the antenna performance, the SMA connector is included in the EM analysis. Two models are utilised: a high-fidelity model $\mathbf{R}_f$ (~7,300,000 mesh cells, simulation time 57 min on a dual Xeon E5540 with 6 GB RAM), and a low-fidelity $\mathbf{R}_c$ (~430,000 cells, simulation time 110 s). The low-fidelity model is used by the design optimisation procedure as described in the next section.

Design optimisation procedure: There are two objectives of the design process: (i) minimisation of the antenna footprint, and (ii) maintaining the reflection level below –10 dB within the frequency range from 3.1 to 10.6 GHz. The design problem is handled here as a nonlinear minimisation task of the form

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

where $\mathbf{x}^*$ is the optimum geometry parameter vector to be found, whereas U is an objective function. Here, the primary objective is size reduction. Having this in mind, the function U has been defined as

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

where $S(\mathbf{x})$ is the antenna footprint. The reflection response is controlled by a penalty function defined as $g(\mathbf{R}_f(\mathbf{x})) = \max\{(\max\{|S_{11}|_{3.1-10.6 \text{ GHz}}\} + 10)/10, 0\}$. According to this definition, $g(\mathbf{R}_f(\mathbf{x})) = 0$ if $|S_{11}| \leq -10$ dB in the UWB band; and it is positive (and represents a relative violation of –10 dB threshold) otherwise. The penalty factor is set to $\beta = 1000$ to ensure that the penalty function brings a considerable contribution to the overall objective function if the relative violation of the maximum reflection threshold is larger than a few per cent.

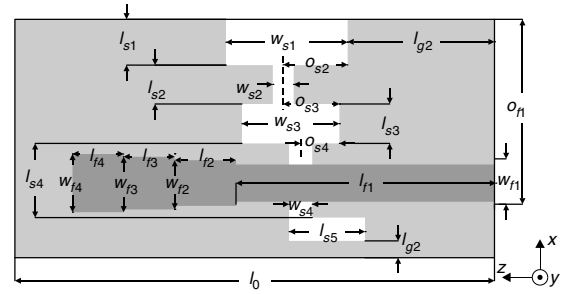


Fig. 1 Proposed compact UWB slot antenna: geometry parameters with highlighted design variables



Fig. 2 Photograph of fabricated UWB slot antenna prototype

There are two practical problems while solving (1): (i) large number of geometry parameters, and (ii) high computational cost of the model $\mathbf{R}_f$. In order to carry out the optimisation process in a realistic timeframe, a SBO procedure is applied [7] that yields a series of approximations $\mathbf{x}^{(i)}$, $i = 0, 1, \dots$, to $\mathbf{x}^*$ as

$$\mathbf{x}^{(i+1)} = \arg \min_{\mathbf{x}} U(\mathbf{R}_s^{(i)}(\mathbf{x})) \quad (3)$$

The surrogate model at iteration i , $\mathbf{R}_s^{(i)}$, is constructed as a local response surface approximation (RSA) of the low-fidelity model $\mathbf{R}_c$. The training data for RSA model identification is acquired by sampling $\mathbf{R}_c$ in the vicinity of the current design $\mathbf{x}^{(i)}$. The RSA surrogate is further corrected using output space mapping [3] in order to align it with the high-fidelity model at the design $\mathbf{x}^{(i)}$, which is a starting point for the i th iteration of (3). The RSA model is implemented as a second-order polynomial without mixed terms [9].

Numerical results and experimental verification: The proposed antenna structure has been optimised using the above described technique. The initial design $\mathbf{x}^0 = [22 \ 0.52 \ 1.4 \ 2.3 \ 2.1 \ 1.6 \ 0.7 \ 2.7 \ 0.68 \ 0.12 \ 0.11 \ 0.11$

4.6 0.8 3.2 0.4 1.7 1.7 1.7 0.72 0 0 0]^T has been estimated based on the dimensions of the reference structure of [6]. The vector of optimised parameters is $\mathbf{x}^* = [17.92 \ 0.41 \ 1.5 \ 2.8 \ 1.82 \ 1.48 \ 0.45 \ 2.85 \ 0.63 \ 0.22 \ 0.17 \ 0.14 \ 4.57 \ 0.78 \ 3.66 \ 0.95 \ 1.7 \ 2 \ 2.7 \ 0.72 \ -0.07 \ -0.78 \ 0.96]^T$. The external dimensions of the structure are $9 \times 17.9 \text{ mm}^2$ with the overall footprint of only 161 mm^2 . The design satisfies the condition $|S_{11}| \leq -10 \text{ dB}$ for 3.1 GHz–10.6 GHz.

The optimised structure has been fabricated and measured. The photograph of the manufactured antenna is shown in Fig. 2. The obtained reflection characteristics (see Fig. 3a) indicate that the introduced structural modifications allow obtaining compact design while ensuring acceptable electrical performance. The measurements are in good agreement with simulation at the edges of operational bandwidth. The fabricated antenna violates the specification by 0.5 dB near 5 GHz frequency; however this is considered acceptable for a structure with such a small footprint. It should be emphasised that the reference antenna design (cf. [6]) not only fails at fulfilling the requirements w.r.t. in-band reflection below -10 dB , but also exhibits larger dimensions (see Table 1).

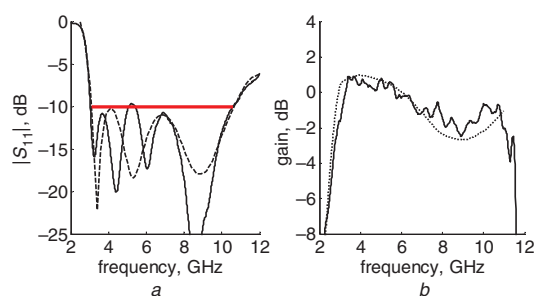


Fig. 3 Simulated (—) and measured (—) responses of proposed compact UWB slot antenna

a Reflection
b Gain measured in y direction

Table 1: Comparison of competitive UWB antenna geometries

Antenna	Dimensions (mm × mm)	Size (mm ²)	Effective $\lambda_g \times \lambda_g$	Footprint λ_g^2
Design [5]	10.0 × 32.5	325	0.42 × 1.38	0.89
Design [10]	7.00 × 25.0	175	0.43 × 1.07	0.46
Design [1]	10.0 × 25.0	250	0.39 × 0.97	0.38
Design [2]	15.8 × 22.0	348	0.50 × 0.69	0.35
Design ^a [6]	8.50 × 22.0	187	0.35 × 0.92	0.32
This work	9.01 × 17.9	161	0.34 × 0.68	0.23

^aDesign violates imposed requirement upon acceptable in-band reflection below -10 dB . Maximum in-band reflection is around -8 dB .

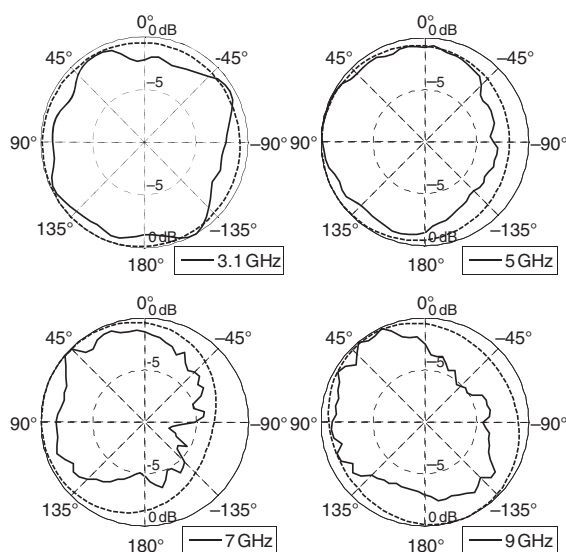


Fig. 4 Radiation patterns of proposed compact UWB slot antenna in H -plane (x - y) at selected frequencies

Comparison of the simulated and measured antenna gain in the direction perpendicular to antenna surface (here, direction y ; cf. Fig. 1) is shown in Fig. 3b. The results are in good agreement. Both the simulated and measured responses are relatively stable along the operational bandwidth. The average simulated and measured in-band gains are -0.9 and -0.7 dB , respectively.

Fig. 4 shows comparison of E -field radiation patterns of the proposed antenna structure obtained for its H -plane (x - y direction; cf. Fig. 1) at 3.1, 5, 7 and 9 GHz frequencies. The agreement between the obtained responses is acceptable. It should be noted that peak radiation pattern shifts clockwise for larger frequency from about 135° at 3.1 GHz to 45° at 9 GHz. The differences between the maximum and the minimum strength of field for the listed frequencies are below 7.5 and 3.5 dB for measurements and simulations, respectively.

The proposed antenna has been compared with other state-of-the-art designs [1, 2, 5, 6, 10] in terms of the size. It should be noted that the benchmark antennas are implemented on various substrates and thus their dimensions have been expressed in terms of the guided wavelength λ_g (defined for $50 \ \Omega$ line operating at 6.85 GHz centre frequency). The results presented in Table 1 indicate that the proposed structure is the smallest among the compared ones.

Conclusion: In this Letter, a structure and a simulation-driven procedure for geometry parameter adjustment of a novel compact UWB slot antenna has been proposed. Upon optimisation, the structure exhibits a small footprint of 161 mm^2 . An important factor that allowed for achieving considerable size reduction was introduction of additional degrees of freedom (including fully parameterised multi-section slot and stepped-impedance feeding line) as well as their efficient numerical optimisation. The simulation results are in good agreement with measurements. A comparative study shows that the proposed structure offers better miniaturisation rate than state-of-the-art designs from the literature while maintaining acceptable electrical performance.

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One or more of the Figures in this Letter are available in colour online.

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