Metallic Antenna Design Based on Topology Optimization Techniques

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Licentiate thesis, May 2013

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List of papers

This thesis consists of an introductory chapter and the following papers:

1. Emadeldeen Hassan, Eddie Wadbro, and Martin Berggren, *Topology optimization of UWB monopole antennas*, In 7^{th} European Conference on Antennas and Propagation (EuCAP2013), 1429–1433, Gothenburg, Sweden, Apr. 2013.

2. Emadeldeen Hassan, Eddie Wadbro, and Martin Berggren, *Topology optimization of metallic antennas*. Submitted to IEEE Transactions on Antennas and Propagation.

3. Emadeldeen Hassan, Eddie Wadbro, and Martin Berggren, *Sensitivity Analysis for Conductive Material Distribution Using the Time-Domain Maxwell's Equations*. Technical report to be published.

Cover picture: Courtesy of NASA/JPL-Caltech

Acknowledgements

First and foremost, I am thankful to **Allah**, the most gracious most merciful. I am grateful to my scientific advisor Martin Berggren for his great guidance, support, and invaluable comments. I wish to extend my sincere thanks to Eddie Wadbro for the fruitful discussions not only on research but on many areas in life as well. I also thank Daniel Noreland for his valuable discussions in the early stage of this work. I would like to thank all my colleagues for the friendly working environment. Finally, I appreciate my wife, my family, and all my friends.

1 Introduction

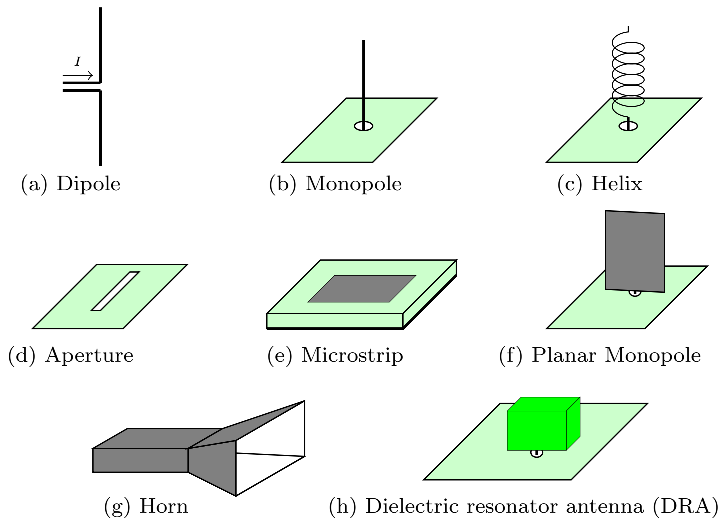
1.1 Background

Recent years have seen an increased use of electromagnetic fields in many applications in society. Common examples include wireless communication systems, radio frequency identification (RFID), non-destructive evaluation and testing, microwave imaging, radar applications, radio telescopes, etc. Each of these applications benefits from the use of electromagnetic fields in a different manner. As a result, antenna technologies have received much attention in order to satisfy the needs of those systems. From an operational point of view, antennas are devices that convert guided electrical waves, for instance the voltage and current in a coaxial cable, to unguided electromagnetic waves in free space and vice versa. Antennas can take on a variety of physical forms. They can be as simple as a single radiating dipole, or far more complicated structures consisting of two-dimensional or three-dimensional geometric shapes [1–3]. The characteristics of the radiated waves depend on the antenna configuration and on the operating frequency band. Generally, Maxwell's equations are used to accurately analyze the antenna response and to predict the propagation and the interaction of the electromagnetic waves in different media.

Currently, there are many accurate numerical methods that allow Maxwell's equations to be solved effectively, such as the method of moments (MoM), the finite element method (FEM), and the finite-difference time-domain (FDTD) method [4]. Further, the rapid increase in computing capabilities reduces the time required to solve Maxwell's equations by these methods. Numerical methods can often replace expensive and very time consuming measurements especially in the design and construction phase. When antennas are analyzed by Maxwell's equations, the configuration of the antenna is described by a set of parameters in Maxwell's equations known as the constitutive parameters that comprise the permeability, the permittivity, and the conductivity [5]. Typically, antennas are named based on their configuration and the constitutive parameters used in their fabrications. Figure 1 shows some standard antenna configurations that can be found in the literature. The performance of the antennas need to be optimized to satisfy the requirements of the evolving new applications [1]. Some of these requirements could be small size, wideband operation, multiband operation, directivity (the relative distribution of the radiated energy in the surrounding space), field polarization (field orientation), or the near field distribution.

1.2 Antenna design

The antenna design problem is to find an appropriate antenna configuration that satisfies one or more of the performance requirements (objectives). Classical design methods start with an existing configuration that is found in the literature or inspired



(a) Dipole (b) Monopole (c) Helix (d) Aperture (e) Microstrip (f) Planar Monopole (g) Horn (h) Dielectric resonator antenna (DRA)

Figure 1: Some antenna configurations.

by prior knowledge. Then the configuration is parameterized by using a set of design variables, and various parameter studies are carried out to find the design variables that better fulfill the required objectives. The quality of the optimized design depends on how the design domain is parameterized and the number of design variables used in the parameterization. The use of a large number of design variables results in a large set of potential solutions and increases the possibility of obtaining a high-performance design.

One approach to design antennas in a systematic way is to use optimization algorithms. In this case the design problem is formulated as an optimization problem that has an objective function and a set of constraints that need to be satisfied. A numerical solution of the optimization problem starts from an initial set of design variables and proceeds through a number of iterations. For each iteration the optimization algorithm computes new updates of the design variables in order to improve the objective function.

In the literature, a large number of antenna design problems has been considered by using different optimization algorithms. Further, most of the current commercial software packages that are used to analyze the antenna performance are provided with one or more of those optimization algorithms. But, most of the currently used optimization algorithms are generally inefficient to handle antenna design problems with a large number of design variables.

1.3 Optimization algorithms

Optimization algorithms can be classified, based on how they update the design variables, into two categories; evolutionary and gradient-based algorithms. In evolutionary algorithms, the design variables are updated in a heuristic manner, which typically includes some stochastic parts. The stochastic parts in these algorithms enable them to avoid being trapped into local optimum while searching for a solution. Evolutionary algorithms require only the value of the objective function, which make them simple to use as black-box software. Typical examples of evolutionary algorithms are genetic algorithms, particle swarm optimization, and simulated annealing [6, 7]. These algorithms either mimic biological systems, individual and collective behavior, or physical processes. Because of their simplicity, they are frequently used in the electromagnetic community for many design problems that are generally characterized by a small number of design variables [8–10]. However, the small amount of information contained in only a sampling of objective function values, together with the random strategies employed to update the design variables, make evolutionary algorithms inefficient for optimization problems with a large number of design variables [11].

On the other hand, gradient-based optimization algorithms can efficiently handle optimization problems that have a large number of design variables. In gradient-based optimization algorithms, the design variables are updated in a deterministic manner. Information about the objective function and its derivatives with respect to the design variables are used to find the new updates. If the Hessian of the objective function (second-order derivatives) is available to a low computational cost, optimization algorithms based on second-order methods, such as Newton methods, are preferred because of their fast local convergence. However, computing the Hessian of the objective function is often expensive, which is why optimization problems are typically solved by first-order methods, such as quasi-Newton methods. First-order methods, besides requiring the objective function value, require the gradient vector (the derivatives of the objective function with respect to the design variables). Basic versions of the optimization algorithms are usually only locally convergent; that is, the algorithm will converge to a local optimum if it is initialized sufficiently close to that optimum. By adding a globalization strategy to a locally convergent algorithm, the algorithm can be made to converge to a local optimum irrespectively of the initial starting point [12].

Unlike evolutionary algorithms, only little work has been done in the literature to use gradient-based optimization algorithms in antenna design [13–15]. One reason for this lack of progress is the difficulty in formulating the design problem as an optimization problem for which the gradient information can be computed in an efficient way. Another reason is the tendency of gradient-based methods to converge to local optima, and it may well happen that the optimization algorithm is trapped in a poor local optimum. Nevertheless, once the optimization problem is formulated, a well-designed gradient-based optimization algorithm will typically find at least a local optimum, which cannot be easily reached if evolutionary algorithms are used instead. Moreover, there are some strategies to avoid poor local optima as will be discussed in Paper I and Paper II in this thesis.

2 Topology optimization

Optimization methods can be classified, depending on how the design domain is parameterized, into three groups: sizing, shape and topology optimization. In sizing optimization, a structure is parameterized by a set of design variables that could express, for instance, height, width, or thickness in that structure. In shape optimization, the design variables characterize the shape of the boundary of a reference domain [9, 16, 17].

The term *topology optimization* is often used to label the most general type of design optimization methods, in which the shapes as well as the connectivity of individual parts of the device are subject to design. The most common way of carrying out topology optimization, which will be used in this thesis, is through the *material distribution approach*. In the material distribution approach, the design domain is divided into small elements, which together represent an image of the device. A design variable $p \in \{0, 1\}$ is assigned to each element to indicate presence or absence of a material, and the various designs are represented as varying coefficients in the governing equations. The material distribution approach to topology optimization was originally developed to design load-carrying elastic structures [18], but the method has been successfully extended also to other areas of engineering such as the design of acoustics and optics devices [19–21]. Instead of optimizing directly over design variables associated with small elements, an alternative topology optimization technique relies on a representation of the geometry through *level sets*: the device boundary is defined as the zero-level contour of a higher-dimensional scalar function [22].

For topology optimization problems, the number of design variables can easily reach thousands and even millions for 2D and 3D design problems [23]. The large number of design variables means that gradient-based optimization techniques will generally be preferred to solve such problems. A main reason for this choice is that the gradient of the objective function contains massive amount of information, and gradients can in many cases be very efficiently computed using solutions of associated adjoint field problem as will be discussed in Paper III. To use gradient-based optimization techniques, the design variables are required to vary continuously between the extreme values (i.e. requires $p \in [0, 1]$). However, the appearance of intermediate values (values that are neither 0 nor 1, also called "gray values") in the final design could lead to ambiguous representation of the obtained design.

Techniques such as solid isotropic material with penalization (SIMP) [18] or artificial damping [24] can be used to suppress these intermediate values in the final design.

In the electromagnetics community, topology optimization techniques have been introduced for the design of magnetic devices by Dyck et al. [25,26] and for the design of dielectric substrates for bandwidth improvement of patch antennas by Kiziltas et al. [13]. Further, Nomura et al. [14] proposed to use topology optimization for the design of dielectric resonator antennas to operate with enhanced bandwidth. Topology optimization methods for the design of metallic antennas have been reported by Erentok and Sigmund [15], who used the material distribution approach, and by Zhou et al. [27] who used a method based on level sets. Both those studies used frequency domain methods and designed antennas for single frequency operation.

3 Finite-difference time-domain method (FDTD)

In 1966, Yee first described a space-grid time-domain numerical technique for the solution of Maxwell's curl equations in his seminal paper [28]. The algorithm was based on a central-difference solution of Maxwell's curl equations with spatially staggered electric and magnetic fields solved alternatively at each time step in a leap-frog algorithm. All implementations of the FDTD method at that time suffered from limitations with respect to the termination of the simulation domain. Mur [29] was the first to present a stable second-order accurate absorbing boundary condition (ABC) for the FDTD method. Then, the perfectly matched layer (PML) was introduced by Brenger [30] to solve many of the previously problematic issues with domain termination.

Currently, the FDTD method has firmly established itself as one of the most popular methods in computational electromagnetics. Its popularity is mainly due to the ease of implementation, the increasing interest of modeling inhomogeneous materials, the wideband data that are potentially available from one simulation, the efficiency in terms of low memory footprint for multiple-frequency analysis, and the wide availability of cheap and powerful computing resources.

The FDTD method discretizes the computational domain into small cubical cells, and for each cell, the six field components are located to match the curl operator. Figure 2 shows Yee's cell for a cube (i, j, k) with dimension Δx, Δy, and Δz. The electric field components are located centered and parallel to the cell edges, while the magnetic field components are located centered and normal to the cell faces. Objects are directly represented in the Yee grid by their constitutive parameters. The conductivity and the permittivity have the same spatial distribution as the discretized electric field, and the permeability has the spatial distribution of the discretized magnetic field. More details about the FDTD method can be found in [31–33].

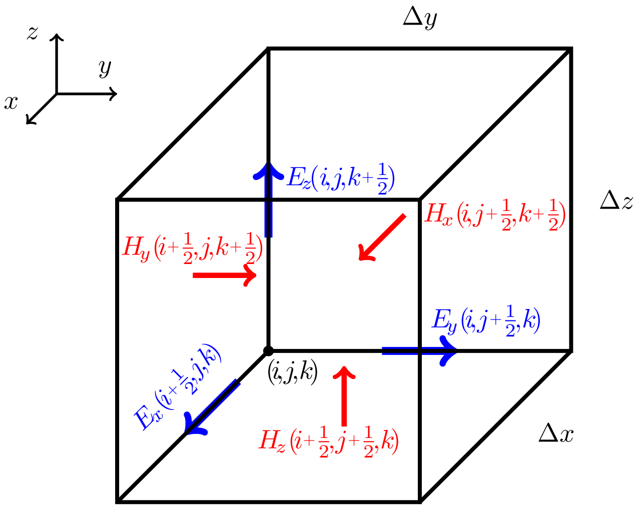


Figure 2: The distribution of the electric and magnetic fields in the basic Yee cell.

Besides being only a second-order-accurate method, a main drawback with the FDTD method is the requirement of using fine grids to accurately model curved objects and small geometrical features. This is due to the Cartesian grid, which leads to a staircase approximation of any geometry inside the analysis domain. There are several suggested remedies to circumvent the effects of the errors introduced by the staircase approximations, but all generally imply more complex arithmetic operations per cell and sometimes instability. Generally, topology optimization techniques require the design domain to be discretized using fine uniform grids to describe the details of the geometry. This requirement turns the main drawback of the FDTD method into an advantage when it is used with topology optimization techniques.

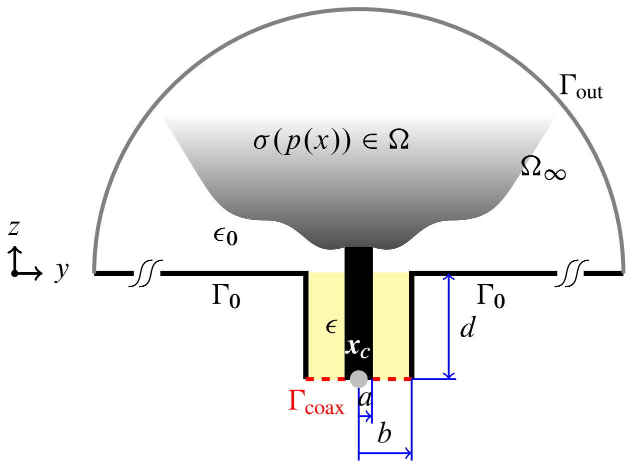


Figure 3: An illustration of the antenna design problem.

4 Summary of Papers

This thesis proposes an approach to carry out gradient-based topology optimization for the design of metallic antennas.

The problem setup is shown in Figure 3, where a design domain $\Omega \subset \Omega_\infty$ holds a conductivity distribution $\sigma(p(\boldsymbol{x}))$ that constitutes an antenna of unknown topology with $\boldsymbol{x}$ representing a point in the design domain. The antenna is connected, through a ground plane located at the xy plane, to a coaxial transmission line that can send (receive) signals to (from) the antenna. The coaxial cable has an inner core with radius a, a metallic shield with radius b, and is filled with a material with dielectric constant ϵ. The boundary Γ_{coax} can be used to introduce incoming signals (signals transmitted to the antenna) or to estimate outgoing signals (signals received from the antenna) inside the coaxial cable. The boundary Γ_{out} represents an outer boundary to the analysis domain.

The governing equations for the design problem are the 3D Maxwell's equations in the upper-half space $z > 0$,

$$\frac{\partial}{\partial t}\mu \boldsymbol{H} + \nabla \times \boldsymbol{E} = \boldsymbol{0}, \tag{1a}$$

$$\frac{\partial}{\partial t}\epsilon \boldsymbol{E} + \sigma \boldsymbol{E} - \nabla \times \boldsymbol{H} = \boldsymbol{0}, \tag{1b}$$

and the 1D transport equation inside the coaxial cable,

$$\frac{\partial}{\partial t}(V \pm Z_c I) \pm c\frac{\partial}{\partial z}(V \pm Z_c I) = 0, \tag{2}$$

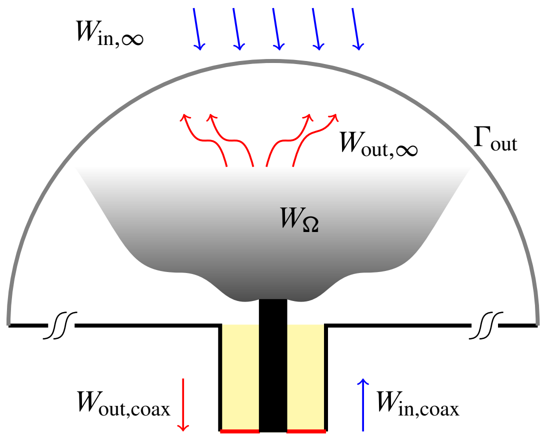


Figure 4: An illustration of the system energy balance.

where μ, ϵ, and σ are the permeability, the permittivity, and the conductivity of the medium, respectively, $c = 1/\sqrt{\mu\epsilon}$, and Z_c is the intrinsic impedance of the coaxial cable. By using appropriate initial and boundary conditions (details are given in Paper II), equations (1a), (1b), and (2) can be solved for the electric field $\boldsymbol{E}$, the magnetic field $\boldsymbol{H}$, the current I, and the potential difference V.

By using the system governing equation, the following energy balance is derived in Paper II,

$$W_{\text{in,coax}} + W_{\text{in},\infty} = W_\Omega + W_{\text{out,coax}} + W_{\text{out},\infty}, \tag{3}$$

in which, as illustrated in Figure 4, the incoming energy $W_{\text{in,coax}} + W_{\text{in},\infty}$ from the coaxial cable and exterior waves equals the ohmic losses in the antenna W_Ω plus the outgoing energy $W_{\text{out,coax}}$ through the coaxial cable and the wave energy $W_{\text{out},\infty}$ exiting the domain.

The signal towards the negative z axis (the signal $V - Z_c I$ in equation (2)) is used to estimate the outgoing energy in the coaxial cable as

$$W_{\text{out,coax}} = \frac{1}{4Z_c} \int_0^T (V - Z_c I)^2 \, dt, \tag{4a}$$

where T denotes the length of the observation time interval. The outgoing energy in the coaxial cable is used as the objective function, and the optimization problem is formulated conceptually as

$$\underset{\sigma(p(\boldsymbol{x}))\in[0,\sigma_{\max}]}{\text{maximize}} \quad W_{\text{out,coax}}(\sigma(p(\boldsymbol{x}))), \tag{5}$$

where the incoming energy to the analysis domain $W_{\text{in},\infty}$ is imposed by a set of prescribed far-field sources and the incoming signal inside the coaxial cable $W_{\text{in,coax}}$

is set to zero; that is, the antenna will be designed based on its receiving mode. By the reciprocity theorem [3], maximizing the energy received by the antenna is equivalent to minimizing the antenna reflection coefficient. Any antenna configuration (dipoles, microstrips, horns, ...) can be designed by solving problem (5).

To solve problem (5) by gradient-based optimization algorithms, the material indicator function $p(\boldsymbol{x})$ must be allowed to take intermediate values between 0 and 1. The corresponding intermediate conductivity $\sigma(p(\boldsymbol{x}))$ introduces energy losses in the design domain. To handle these energy losses, a filtering approach is proposed in Paper I. The gradient of the objective function is obtained by using the adjoint field method [14, 34, 35]. Paper III gives details about the derivation of the gradient of the objective function.

To numerically solve the formulated design problem, the FDTD method is employed. A discrete version of optimization problem (5), based on the FDTD discretization, is given in Paper II. The gradient of the discrete optimization problem is derived in the fully discrete case based on the FDTD discretization of the system of governing equations; details are given in Paper III. The optimization problem is solved by the globally convergent method of moving asymptotes (GCMMA) [36], developed by Svanberg.

4.1 Selected results

4.1.1 Ultrawideband (UWB) monopole design

Recently, UWB antennas has received great attention in applications such as wireless communication and high resolution radar [37, 38]. A key candidate for UWB antennas is the planar monopole. In Paper I, optimization problem (5) is used for complete layout optimization of the radiating element of a planar monopole antenna. The radiating element (design domain) has a size of 75×75 mm^2, is located 0.75 mm above an infinite simulated ground plane, and is connected at the center of its bottom side to a 50 Ω coaxial cable. The radiating element is discretized into 100×100 Yee cell faces, yielding a design domain of 20200 design variables (one conductivity component for each Yee edge). The objective is to maximize the energy received by the planar monopole over the frequency band 1–10 GHz.

To excite the analysis domain, a set of external sources that surround the design domain and radiate vertically polarized plane waves is used. The optimization algorithm requires 132 iterations to converge to the design shown in Figure 5. As a reference for comparison, the reflection coefficient of the planar monopole antenna when the whole radiating area is filled with a perfect conductor, is included in the same figure. The reflection coefficient $|S_{11}|$ of the optimized monopole is below -10 dB over the frequency band $1.2 - 8.5$ GHz and the final design uses only around 50×45 mm^2 out of the available design area.

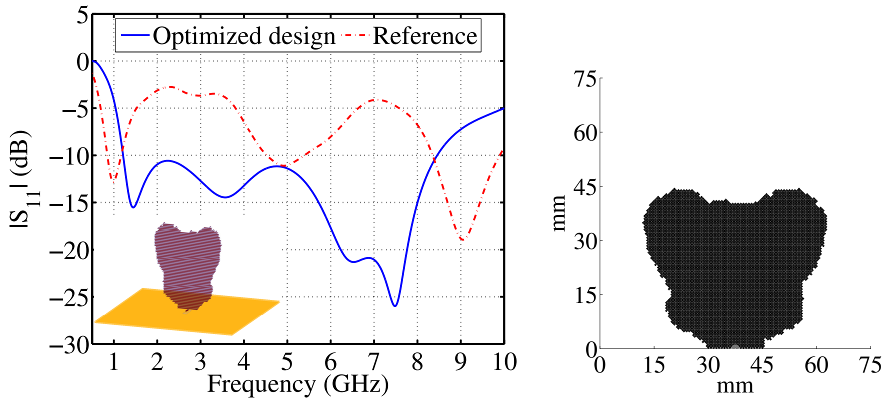


Figure 5: Left: the reflection coefficient of the UWB planar monopole designed based on vertical polarized plane wave excitation, using 20200 design variables. Right: the final conductivity distribution, the coaxial cable connection point is marked gray color.

When the excitation sources are set to radiate circular polarized plane waves, the design shown in Figure 6 is obtained after 126 iterations. In this case, the monopole reflection coefficient $|S_{11}|$ is below -10 dB over the frequency band $1.23-9.75$ GHz.

4.1.2 Microstrip antenna design

Microstrip antennas have been one of the most attractive antennas to use in many wireless systems because of their many unique and attractive properties: low profile, compact and conformable structure, and ease of fabrication and integration with microwave devices [3].

By using design problem (5), the radiating patch of a microstrip antenna is designed to radiate at 1.5 GHz with 0.2 GHz bandwidth. The design domain has the same area and discretization as the UWB monopole case; however, here it is used as the radiating patch of the microstrip antenna. The radiating patch is located 6 mm above an infinite simulated ground plane, and a substrate with 2.62 dielectric constant and 0.001 loss tangent at 2 GHz is used. Figure 7 shows the geometry and the reflection coefficient of the optimized design, obtained by the optimization algorithm after 118 iterations. The inner probe of a 50 Ω coaxial cable is connected to the radiating patch at $18.75, 37.5$ mm and is marked by a gray circle. Included also in the same

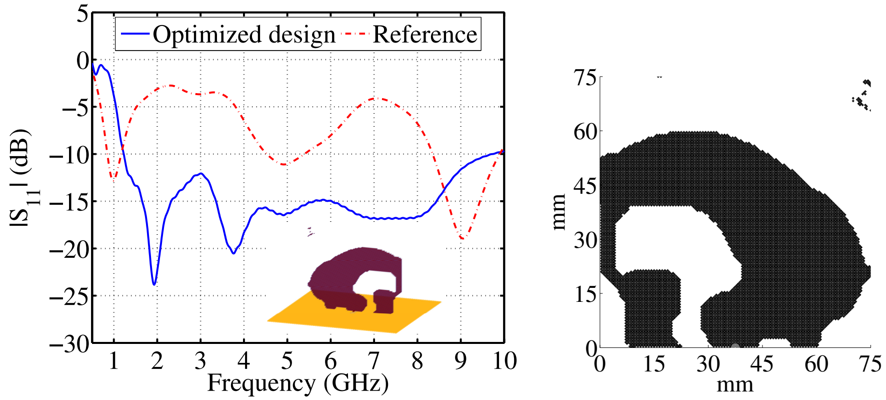


Figure 6: Left: the reflection coefficient of the UWB planar monopole designed based on circular polarized plane wave excitation, using 20200 design variables. Right: the final conductivity distribution, the coaxial cable connection point is marked gray color.

figure as a reference, is the reflection coefficient of the antenna when the whole design domain is filled with a perfect conductor.

The same design domain is used to design a microstrip antenna that has a dual-band operation, with the frequency bands centered around 1.5 and 2.0 GHz. The design problem (5) is slightly modified, to account for the energy received from the two bands, as

$$\underset{\sigma(p(x))\in[0,\sigma_{\max}]}{\text{maximize}} \quad \sum_{i=1}^{2} |W^{(i)}_{\text{out,coax}}(\sigma(p(x)))|^{\frac{1}{2}}. \tag{6}$$

Figure 8 shows the geometry and the reflection coefficient of the optimized design, obtained by the optimization algorithm after 120 iterations. The reflection coefficient of the reference antenna is also included in the same figure for comparison.

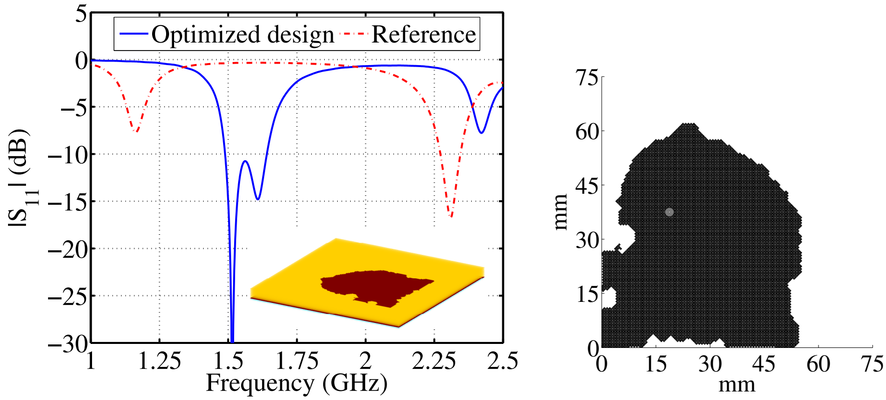


Figure 7: Left: the reflection coefficient of the microstrip antenna optimized to radiate at 1.5 GHz. Right: the final conductivity distribution over the patch area (the probe connection point is marked by a gray circle).

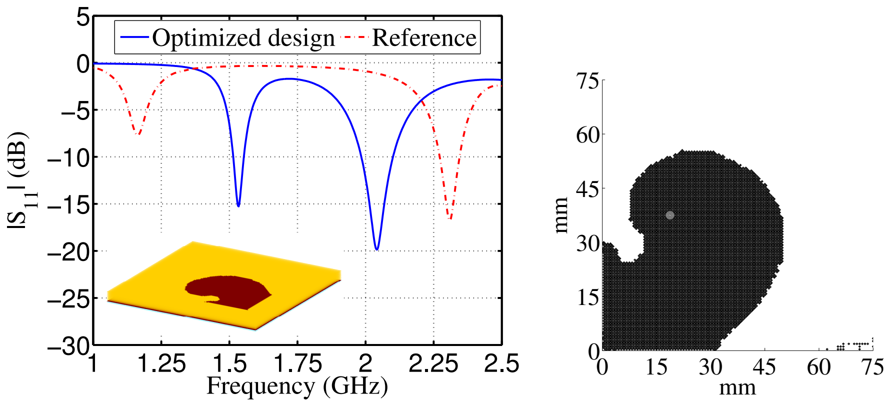


Figure 8: Left: the reflection coefficient of the microstrip antenna that radiates over two frequency band centered around 1.5 GHz and 2 GHz. Right: the final conductivity distribution over the patch area (the probe connection point is marked by a gray circle).

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