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RESEARCH PAPER

A shape optimization library for the design of microwave components

NAJIB MAHDI[1], STEPHANE BILA[1], SERGE VERDEYME[1], MICHEL AUBOURG[1], KHALED KHODER[1], ANNIE BESSAUDOU[1], FRANÇOISE COSSET[1], CHRISTOPHE DUROUSSEAU[1], JÉRÔME PUECH[2], LAETITIA ESTAGERIE[2], DAMIEN PACAUD[3] AND HERVÉ LEBLOND[3]

This paper outlines an original shape optimization library backed by a three dimensional (3D) full-wave electromagnetic (EM) simulator, combining several efficient structural optimization techniques and suitable for viable computer-aided design (CAD) of complex microwave components. The microwave components are modeled by finite element method (FEM) and their dimensions and shape are optimized using four techniques: design of experiments (DOE), level-set method (LS), topology gradient (TG) method, and genetic algorithm (GA). The various methods allow determining the optimal geometry, shape or topology of 2D or 3D objects within the microwave device, by minimizing iteratively a cost function related to the desired specifications. Typical demonstration illustrates the versatility of the proposed library based on the design of a dual mode dielectric resonator filter in order to improve its unloaded quality factor by keeping the same frequency isolation, their accuracy and efficiency are verified by the available measured results.

Keywords: EM field theory and numerical techniques, Filters

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I. INTRODUCTION

Technological revolutions in the field of microwave and communication systems are pushing requirements for the exploitation of electromagnetics-based computer-aided design (CAD) [1–4]. Further innovative designs may be achieved using powerful three dimensional (3D) full-wave electromagnetic (EM) simulators in conjunction with sophisticated optimization algorithms. Conventional optimization techniques incorporated into EM simulators, will not realize their full potential for the designer since they consist in trying dimensional variations on an initial design and using the information gained to improve on the design.

To overcome these restrictions, more generalist optimization techniques have been invented (shape and topology), that let engineers obtain the optimal configuration during the object design phase, as they are implementing the design of the geometry, shape, and the topology of the structure.

This work presents a CAD library including efficient global and local techniques for solving structural optimization problems. The novelty of this work is to couple several structural techniques, which apply to the geometry, the boundary, and the topology of the structure, with the possibility to exchange a solution from an algorithm to another one, by keeping the same discretization, in order to form a general CAD tool for shape optimization. As shown in Fig. 1, an initial design may be optimized regarding its geometry first, followed by its boundary and its topology gaining more and more in generality for the solution. Indeed, by exchanging a solution obtained, for example, from a technique dealing with the geometry of the structure to a technique dealing with its boundary allows us to extend the domain, thanks to a new parameterization and to find by this way the best solution. By changing the parameterization, from geometry to boundary or from boundary to topology, a global method may be employed with the developed CAD library for exploring the solutions before refining with a local method.

The aim of this research is to apply the CAD library to the design of microwave devices. The rest of this paper is organized as follows. We describe the finite element method (FEM), which is used to model the microwave components, and the structural optimization techniques in Section II. Section III illustrates the capability of the developed CAD library to design microwave components. A demonstration was given based on the design of a dielectric resonator embedded in a metallic cavity in order to improve its electrical performances (insertion loss and out-of-band rejection). Finally, a conclusion is made in Section IV.

[1]XLIM UMR 7252, Université de Limoges/CNRS, 123 Avenue Albert Thomas, 87060 Limoges Cedex, France
[2]CNES, 18 Avenue Edouard Belin, 31401 Toulouse Cedex, France
[3]THALES ALENIA SPACE, 26 Avenue J.F.Champollion, 31100 Toulouse Cedex, France
Corresponding author:
S. Bila
Email: stephane.bila@xlim.fr

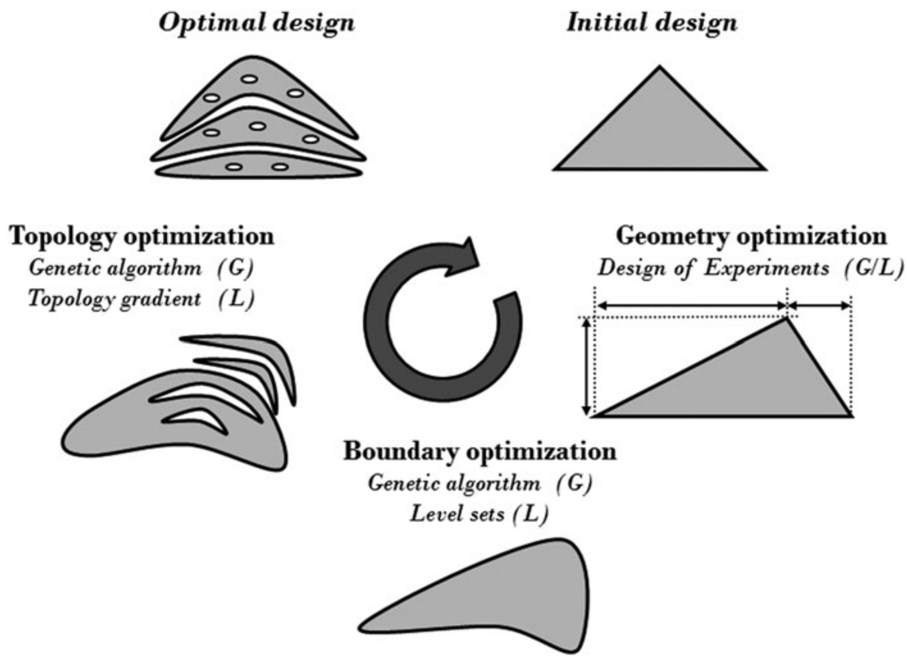

Fig. 1. Techniques developed for the CAD library: *G* stands for global optimization methods and *L* for local optimization methods.

II. SHAPE OPTIMIZATION LIBRARY

The shape optimization library combines an FEM for the analysis of the component and four coupled structural optimization techniques.

A) Finite element method

For analysing a microwave component, the FEM is a popular technique [3, 4] since both planar or waveguide structures (including antennas) can be treated. Modeling a microwave component with FEM requires discretizing the structure into small mesh elements before solving Maxwell's equations. The system to be solved for its EM analysis is:

$$A(\eta)E(\eta) = B \quad (1)$$

Here, *A* is a square symmetric matrix (Maxwell's operator) representing the structural and material properties of the discretized model, *B* is the column vector of the imposed sources, and *E* is the unknown field vector.

In (1), both *A* and *E* depend on η, a parameter defined by assembling small mesh elements, which can be a geometrical dimension or more generally a variable describing a boundary or a topological perturbation and can be optimized with various techniques. In 2D, a metallic distribution can be optimized on top of a substrate, switching between metallic ($\eta = 1$) or non-metallic ($\eta = 0$) conditions for individual mesh elements. In 3D, the shape of a dielectric component can be optimized, switching between two permittivity values for each mesh element.

B) Design of experiments (DOE)

DOE is a simple technique for optimizing the geometrical dimensions of a structure. Also, in combination with response surface modeling (RSM), DOE is an efficient optimization technique. Previous work has demonstrated the advantages of DOE in the modeling and optimization of RF/microwave circuits [5].

In this framework, a DOE technique is adopted with FEM in order to optimize the geometrical dimensions of microwave components (length, diameter, thickness, etc). The DOE approach steps are as follows: first, EM analysis of the system helps identify the important variables to be considered. Then, these variables are included in a factorial experiment and the responses are recorded using an FEM simulator. Explicit statistical models are developed for each of the responses as a function of the input variables. Optimization constraints are afterwards applied to these models and the values of the input variables that best satisfy all of them are calculated by applying a local or a global method.

C) Level-set (LS)

The LS method is used for solving optimization problems with evolving geometries [6]. The basic idea of the LS is that the domains and their boundaries are represented with the so-called LS function of a continuous function rather than a boundary parameterization. The function is expressed in an implicit form of a high dimensional function. The boundary changes are traced by the deformation of this function (estimating a gradient based on the shape derivative). The design boundaries are changed in order to minimize an objective function of a shape optimization problem.

Over the years, the method has proven to be a robust numerical device for designing of microwave devices [7]. In this paper, an LS method coupled with FEM is applied to optimize the boundaries of a microwave component captured on a fixed mesh by minimizing iteratively the cost function related to the model specifications. The latter mesh is supported by FEM discretization and the boundary is then moved during optimization along with the gradient direction by modifying

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the physical property of the mesh elements considering their inclusion or exclusion of the structure.

D) Topology gradient (TG)

This technique has been successfully applied for designing microwave components and antennas [8]. The TG method evaluates the gradient of a cost function related to the model behavior with respect to the characteristics modification of small topological elements, very locally ($\eta = 0 \rightarrow 1$ or $\eta = 1 \rightarrow 0$). One can note that the topological elements are directly the mesh (finite) elements, or a collection of them, and are characterized by an individual value for η.

The optimization procedure starts from an initial configuration of the domain and converges iteratively to the optimum using the gradient calculation for each topological element. All of the elements with a negative gradient can be modified (physical properties are modified) to minimize the cost function, and the procedure is repeated iteratively until a local minimum is attained.

E) Genetic algorithm (GA)

GA was applied for the optimization of several microwave structures and antennas [9]. It is an evolutionary optimizer (EO) that takes a sample of possible solutions (individuals) and employs genetic operators for optimization. In this work, a GA coupled with FEM aims to optimize the shape or the topology of microwave components, by applying an on/off strategy. Chromosomes are characterized by binary genes ($\eta = 0$ or 1) supported by the discretized FEM structure. GA begins an optimization process starting with a large population of randomly generated or predetermined solutions characterized by a fitness function. These solutions undergo a mutation or recombination process to produce better solutions until the population converges to a final unique solution or some other criteria are met.

III. APPLICATION TO THE DESIGN OF DUAL MODE DIELECTRIC RESONATOR FILTER

In order to show the validity of the developed library in 3D, a demonstration aiming to improve the electrical performances (quality factor and stopband) of dual mode dielectric resonator filter was given.

A) Initial design

Dielectric resonators provide all of the advantages of compactness and lightness and offer higher Q's as well as better temperature stability over conventional waveguide resonators. Moreover, dual-mode dielectric resonator filters have been widely used in transmission and satellite communication systems due to their high selectivity, small size, and mass [10].

The investigated structure, presented in Fig. 2, consists of a dual mode dielectric resonator truncated at the 4 corners and embedded in a metallic cylindrical cavity. It has four contacts with the metal walls, which ensure its maintenance. The resonator is weakly excited by a rectangular window connected to standard rectangular waveguides. The dielectric material is characterized by a relative permittivity (ε_r) of 12.6 and a loss tangent ($\tan\delta$) of 5.5×10^{-5}. The metal is characterized by a conductivity (σ) of 4.7×10^7 S/m.

The resonator is designed for working on its fundamental TE1 mode. As shown in Fig. 2, the resonant frequency (F_0) is equal to 4 GHz and its unloaded quality factor (Q_0) is around 10^4. The frequency of the first higher-order mode (F_1) is around 6.4 GHz, which defines a frequency isolation (FI) of 2.4 GHz.

B) Optimization of individual resonators

1) Improvement of insertion loss

The goal of the design is to improve the unloaded quality factor by optimizing the distribution of dielectric material in the resonator region. The cost function (J_{Q_0}) is minimized in order to reduce the distance between the scattering parameter (S_{21} in dB) of the current model and the ideal (lossless) resonator model.

$$J_{Q_0}(S) = \sum_{i=1}^{N} \left| -20\log_{10}(|S_{21}^{l}(f_i)|) + 20\log_{10}(|S_{21}^{c}(f_i)|) \right|^2 \quad (2)$$

Where f_i is the frequency among the N frequencies used for error computation and S_{21}^{c} and S_{21}^{l} are respectively the computed and ideal scattering parameter S_{21}.

Initially, LS, TG, and GA are applied individually. DOE cannot be applied with the initial shape since no more parameters can be tuned for optimizing the structure considering a fixed cavity. The final solutions, shown in Fig. 3, are introduced as initial solutions for each other technique in order to improve the unloaded quality factor. The optimal solution is attained by applying the LS and the TG successively. This

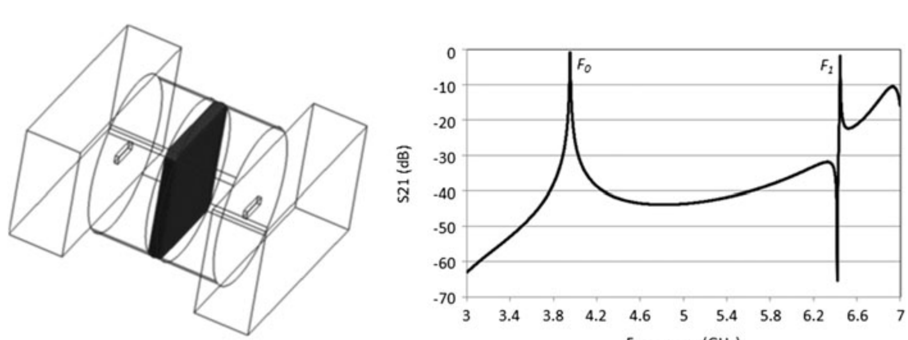

Fig. 2. Initial design and simulated response (S_{21} scattering parameter).

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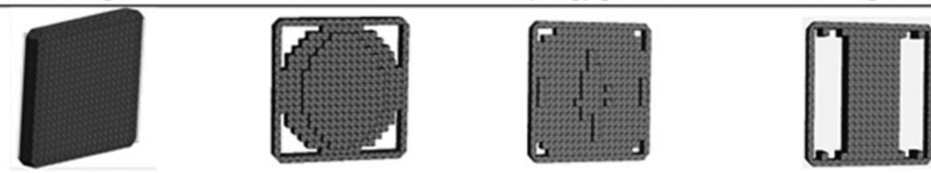
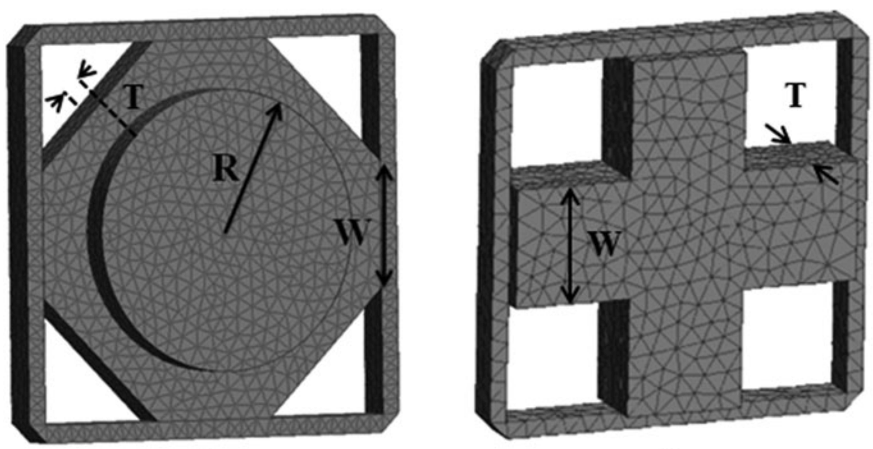
Initial design	Level-sets	Topology gradient	Genetic algorithm



-	82 iterations	61 iterations	> 1000 iterations
$Q_0 = 10100$	$Q_0 = 12325$	$Q_0 = 10970$	$Q_0 = 12420$

Fig. 3. Solutions attained by individual techniques.



(a) (b)

Fig. 4. Optimized dielectric resonators.

solution is smoothed in order to obtain a simple and original resonator form and approximated by the dielectric object shown in Fig. 4(a). Since this approximation modifies the optimal solution slightly, the resonator is parameterized with three geometrical parameters, R and W described in Fig. 4(a), and the thickness of the resonator. The latter are finally optimized using DOE. The unloaded quality factor is improved by 30% ($Q_0 = 12\,970$) compared to the initial one due to the concentration of dielectric material in the middle of the cavity and the FI (2 GHz) remains sufficient considering standard needs.

2) Improvement of spurious performance

The second section of this demonstration carries on improving together the unloaded quality factor (Q_0) and the FI. The new cost function (J) is formulated to recover the bandwidth at F_0 with similar characteristics and attenuate (above α dB) or shift upward the second resonance at F_1

$$J(S) = J_{Q_0}(S) + J_{FI}(S) \tag{3}$$

$$\text{With } J_{FI}(S) = \sum_{i=1}^{N} \mathrm{Re}\left(\sqrt{20\log_{10}\left(|S_{21}^{c}(f_i)|\right) + \alpha}\right)^4 \tag{4}$$

where α is a positive real, which controls the maximum level of scattering parameter S_{21} at frequency f_i.

Figure 4(b) illustrates the final shape resulting from the application of the previous cost function with the GA and

	Q_0	FI (GHz)		Q_0	FI (GHz)		Q_0	FI (GHz)
Simul.	5455	2.9	**Simul.**	6690	2.53	**Simul.**	6650	3.3
Meas.	4600	2.95	**Meas.**	6710	2.58	**Meas.**	6400	3.23

Fig. 5. Simulations and measurements of initial and optimized resonators.

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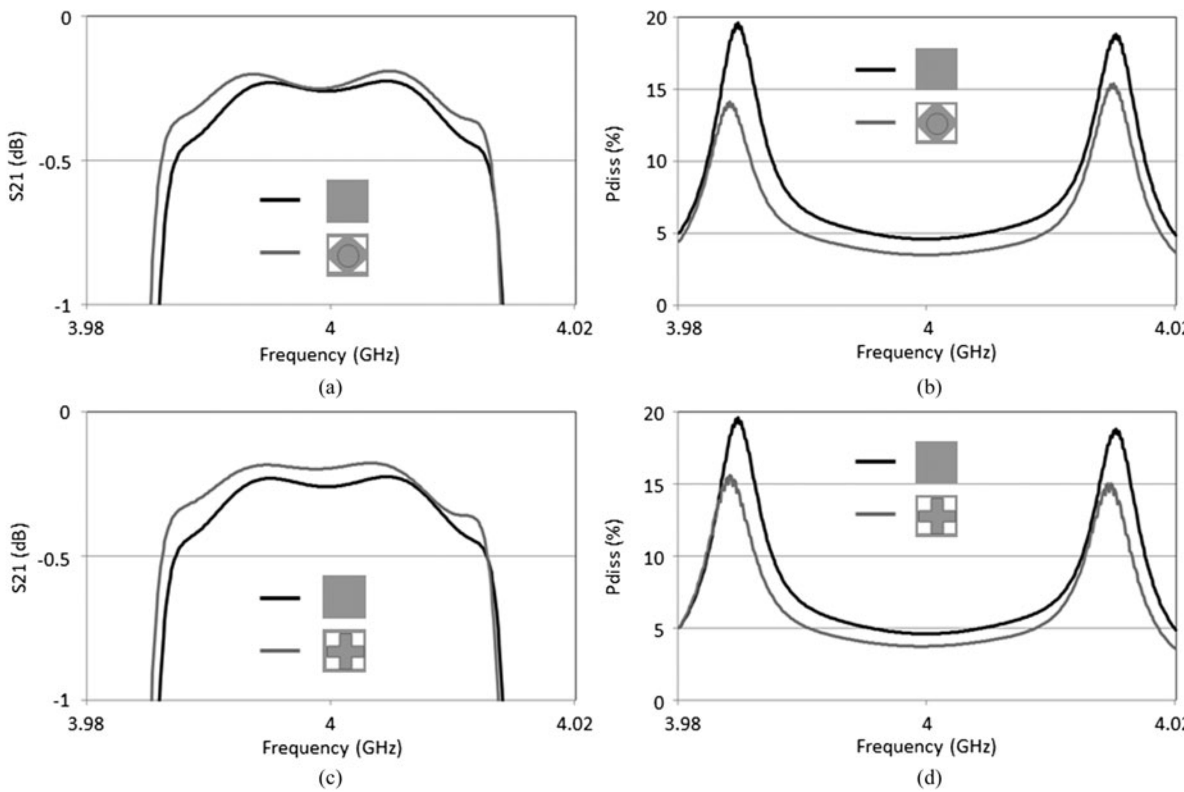

Fig. 6. Simulated response obtained with reference and optimized filters: (a) and (c) are transmissions in the passbands, (b) and (d) are percentages of dissipated power.

the TG. The unloaded quality factor is improved by 29% ($Q_o = 12\,900$) compared to the initial one and the FI is extended to 2.8 GHz.

3) EXPERIMENTAL VALIDATION

For validating the optimization techniques, the initial and optimized resonators have been fabricated using a stereolithography process [11]. Figure 5 presents the comparison between the simulated and the measured performances. It can be observed that the agreement between the measured and the simulated results is very good.

C) Design of a dual-mode dielectric resonator filter

A four-pole filter can be constructed using two dual-mode dielectric resonators assembled together with a metallic cross-iris. A four-pole dielectric resonator filter centered at 4 GHz with 27.5 MHz bandwidth is designed using previous resonators by applying a coupling matrix identification procedure [12]. Figure 6 shows a comparison between the initial and the optimized filter responses in terms of transmission (S_{21}) and dissipation. It is obvious from these comparisons that optimized filters offer higher performances than standard one.

IV. CONCLUSION

In this paper, a CAD library combining four structural optimization techniques coupled with FEM is developed for the design of microwave components. These techniques are described and applied to the design of a dual mode dielectric resonator filter for improving its electrical performances. The results show the potential of such a CAD library for the design of advanced microwave components. The main advantages are the rapid convergence and the versatility and the generality of the procedure, which can be applied in two or three dimensions.

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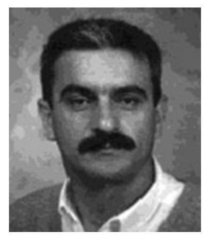
Najib Mahdi was born in Kousaibeh, Lebanon, on December 12, 1985. He received the Ph.D. degree in microwave and optical communications from the university of Limoges, France, in 2012. His thesis work focused on the development of a library of structural optimization techniques for advanced computer aided design (CAD) of microwave components and circuits. In November 2012, he joined the Information and Communication Science and Technology Laboratory, Brest, France, where he is currently working on high frequencies modelling of microvias interconnects for high density printed circuit board (PCB) and wireless interconnects for interchip data transmission.

Stéphane Bila was born in Paris, France, in September 1973. In 1999, he received the PhD degree from the University of Limoges, Limoges, France. He then held a post-doctoral position during one year with the French Space Agency (CNES), Toulouse, France. In 2000, he became a researcher at the National Centre for Scientific Research (CNRS) and joined IRCOM (now XLIM), Limoges, France. His research interests include numerical modelling, optimisation and computer aided techniques for the advanced synthesis of microwave components and circuits.

Serge Verdeyme was born in Meilhards, France, in June 1963. He received the Doctorat degree from the University of Limoges, Limoges, France, in 1989. He is currently Professor at XLIM (formerly IRCOM) and Vice-President of the University of Limoges, in charge of the Scientific Council. His main area of interest concerns the design and the optimization of microwave devices. He is a member of IEEE.



Michel Aubourg was born in Neuvy Saint-Sepulcre, France, in April 1950. He received the Maitrise of Mathematics, the Doctorat de troisième cycle and the Doctorat d'état degrees from the University of Limoges, Limoges, France, in 1975, 1978, and 1985, respectively. Since 1979, he has been Chargé de Recherche at the CNRS, working at XLIM (formerly IRCOM), University of Limoges. His main area of interest is the application of the FEM in the design microwave transmission components.

Annie Bessaudou was born in France, in june 1958. She received the Habilitation degree from the University of Limoges, Limoges, France in 2001. She is currently a Professor at the University of Limoges, and is leading research into XLIM research institute. Her current research activity is focused on innovating materials elaboration and more especially metal-insulator transition oxides.

Françoise Cosset was born in Speyer, Germany, in August 1966. In 1994, she received the PhD degree from the University of Limoges, Limoges, France. She then held a post-doctoral position during five years. In 1999, she became an Associate Professor in physics at the Faculty of Science, Limoges, France and joined C2M team then IRCOM (now XLIM), Limoges, France. Her research interests include optimisation and computer aided techniques for the advanced synthesis of microwave components and circuits, and new technologies for micro fabrication of components like: RF MEMS-NEMS and MOEMS, circuit integration of innovative materials for microwave and optical applications.

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Christophe Durousseau was born in Limoges, France, in July 1970. He received the Ph.D degree in mathematics from the University of Limoges (Limoges, France) in 1999. He teaches mathematics since 1999 in the 3iL engineering school (Limoges, France) and he joined the Research Institute XLIM in 2006. His research activities are mainly focused on shape optimization in microwaves domain based on gradient methods and design of experiments.

Jérôme Puech was born in Rodez, France, in 1974. He received Dipl-Ing. degree from the Institut National des Télécommunications, Evry, France, in 1998. In January 2000, he joined the Centre National d'Etudes Spatiales (CNES) (French Space Agency) in Toulouse, France, where he is involved in Microwave Research activities mainly oriented toward microwave breakdown within space components, microwave filters, and traveling wave tubes.

Laetitia Estagerie was born in Limoges, France, in April 1981. She received the Master's degree in high frequency and optical telecommunications from the University of Limoges, France, and obtained the PhD degree at the Research Institute XLIM, in 2007. Her research interests were dedicated to millimeter-wave filters based on LTCC technology. In 2008, she joined the Centre National d'Etudes Spatiales, Toulouse, France, where she has been involved in microwave research activities mainly oriented toward microwave filters and microwave passive equipments. Since 2013, she is in charge of telecommunications payload activities.

Damien Pacaud was born in France, in December 1971. He received the Ph.D. degree in Applied Mathematics and Scientific Computing from the University of Bordeaux 1, France, in 2001. In 1996, he joined the CEG Center to develop powerful numerical techniques in electromagnetism. In 2000, he joined IEEA (Paris) to develop RF numerical software. Since 2001, he is in charge of Filters and Multiplexers studies and developments for spatial applications at Thales Alenia Space, Toulouse, France.

Hervé Leblond was born in 1979. He received his master's degree and the PhD degree in high-frequency and optical telecommunications from the University of Limoges, France in 2002 and 2006 respectively. He joined Thales Alenia Space in 2006 and worked as microwave design engineer. He was in charge of the development of the new generation of RF equipments.