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Fast Design Optimization of Waveguide Filters Applying Shape Deformation Techniques

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***Abstract*—This paper presents an efficient design of microwave filters by means of geometry optimization using shape deformation techniques. This design procedure allows for modelling complex 3D geometries which can be fabricated by additive manufacturing (AM). Shape deforming operations are based on radial basis function (RBF) interpolation and are integrated into an electromagnetic field simulator based on the 3D finite-element method (FEM). The optimization controls two sets of design variables, i.e. the geometrical parameters of the structure and the parameters that determine the shape deformation. This approach provides great design flexibility at marginal additional cost since shape deformations require very little computational effort. A complete design procedure of a Ku-band RX waveguide bandpass filter is shown to verify this approach. The designed filter is fabricated with selective laser melting (SLM) technology. Measurements are presented in comparison with simulation.**

***Index Terms*—waveguide filters, computer-aided design, design optimization, shape deformation, radial basis functions.**

I. Introduction

Recent advances in microwave components design, among others, indicate a strong interest in new fabrication technologies such as additive manufacturing, also known as 3D printing [1]–[4]. AM enables the fabrication of complex 3D structures of almost arbitrary shapes, thus opening up new design possibilities for RF and microwave engineers. The introduction of more complex, smooth geometries enables new designs with enhanced electromagnetic (EM) performance, such as e.g. higher quality factor Q and low loss, wider higher-order mode separation in microwave filter design, or higher power handling. However, most of the widely used CAD software for high-frequency EM design does not offer sufficient tools to meet these new design opportunities. This is because the currently prevailing paradigm for geometry manipulation in EM CAD tools is constructive solid geometry (CSG), which is based on performing operations on simple building blocks such as boxes, cylinders, and cones. Structures which cannot be constructed from these geometrical primitives are not allowed, which can be a major limitation in the design procedure. In order to overcome these design restrictions and make greater use of the advantages offered by 3D printing technology, the solution is to give RF designers more degrees of freedom in the modelling of microwave components. One of the ways to achieve this goal is to extend the conventional CAD based on CSG with shape deformation techniques [5].

Shape deformation of 3D geometries can be performed utilizing several techniques. This concept was first brought into use in computer graphics applications with the introduction of the free-form deformation (FFD) method in 1986 [6]. This approach, along with several other techniques which have been developed afterwards [7], [8], has then been applied to multiple areas of engineering [9]–[11]. Recently, shape deformations based on RBF interpolation have been introduced for RF and microwave components design [12].

The aim of this paper is to present fast and efficient optimization of waveguide filters using shape deformations in the design process. The new functionality of InventSim software combines RBF-based geometry modification with fast EM simulation with 3D FEM, as a result offering an all-in-one integrated optimization tool [13]. The design can be modified with two sets of optimization variables, namely the geometrical parameters of the structure and the variables controlling the deformation. The optimization procedure uses the zero-pole method, which has proven to be very efficient for microwave filter design [14], [15]. This strategy estimates the error using the location of zeros and poles of the filter's transfer and reflection functions. The proposed optimization procedure is applied to the design of a waveguide bandpass filter for satellite communications. The complete optimization process is described in Section IV-A. A prototype filter is fabricated using SLM process from aluminum alloy AlSi10Mg. The simulated model is verified by measurements in Section IV-B.

II. Shape deformation with RBFs

The shape deformation method used in this study is based on RBF interpolation, as shown in [9]. The principle of this operation is based on the definition and modification of some arbitrarily chosen control points. The deformation is performed by mapping the structure (defined by a surface or volume mesh) according to the displacements of the control points. The mapping operation is represented in general by a mapping function $\mathcal{D}$:

$$\mathcal{D}(\boldsymbol{x}) : \mathbb{R}^3 \to \mathbb{R}^3$$
$$\boldsymbol{x} \mapsto \mathcal{D}(\boldsymbol{x}) = \boldsymbol{x} + \boldsymbol{d}(\boldsymbol{x}) \tag{1}$$

In this notation, $\boldsymbol{d}(\boldsymbol{x})$ is a vector displacement field which is applied to the 3D model. If radial basis functions are used in the process, the deformation field takes the following form:

$$\boldsymbol{d}(\boldsymbol{x}) = \sum_{i=1}^{N} \boldsymbol{\gamma_i} \varphi(\|\boldsymbol{x} - \boldsymbol{x_i}\|) + p(\boldsymbol{x}) \tag{2}$$

where N is the number of control points defining the deformation, $\boldsymbol{\gamma_i}$ are the weights of radial basis functions φ, defined in the positions of the control points $\boldsymbol{x}_i$, and $p(\boldsymbol{x})$ is a low-order polynomial (optional). To define the mapping, one needs to define a set of N control points and their displacements, i.e., their initial and new (shifted) coordinates. Next, the linear system is solved to calculate the unknown weights $\boldsymbol{\gamma_i}$. The constructed deformation field is then applied to smoothly deform the object.

III. General Framework for Design Optimization with RBF Interpolation

The proposed framework for the design optimization is shown in Fig. 1. The optimization loop consists of two design stages, each controlling separate design variables. The first stage involves managing the conventional geometrical parameters which are used to alter the basic shape of the structure that is constructed using CSG. The second stage is performed after mesh generation and comprises the shape deformation, which is controlled by dedicated parameters, i.e. the positions and displacements of the control points. Then, the deformed structure (volumetric mesh) is analyzed by an EM simulator to calculate its response in the frequency domain (S-parameters). Based on the frequency response of the filter, the optimizer evaluates the goal function, which is defined by the designer. We can use either the zero-pole based optimization scheme developed for filter design, or a general approach based on allowed and forbidden areas (masks) defined for transfer function. The optimization of the structure continues until certain termination conditions are met (e.g. error value below a preset threshold or maximum number of iterations reached). The proposed scheme is empowered with fast sensitivity analysis to evaluate the gradient of the cost function defined in the optimization, which also takes into account the design variables that define shape deformation. Such a low level integration significantly speeds up the optimization process.

IV. Example of Filter Design

The verification of the developed optimization procedure is carried out on an exemplary design of a Ku-band RX bandpass filter in waveguide technology. The specifications to be met by the filter are a wide passband of $13 - 14.8$ GHz (center frequency $f_0 = 13.9$ GHz, fractional bandwidth FBW = 13%) and an in-band return loss (RL) over 20 dB. The topology chosen for this design is a simple inline sixth order structure. To present the versatility of this design procedure, the initial structure constructed with CSG is a short section of a WR-75 waveguide with rounded corners, as shown in the upper left of Fig. 2.

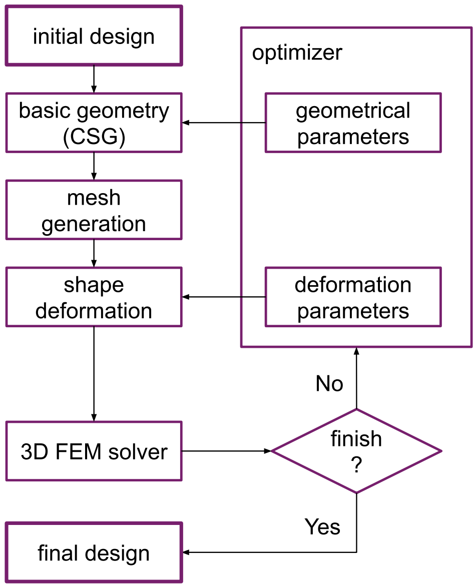

Fig. 1. A flowchart representing the general design optimization workflow.

A. Design Optimization

In this filter design, the inductive couplings between the cavities are realized by squeezing a straight waveguide section from both sides. The design is controlled by a total of 13 parameters: $L_1 - L_6$ describing the lengths of the cavities and $a_1 - a_7$ standing for the deformation depth of each iris section.

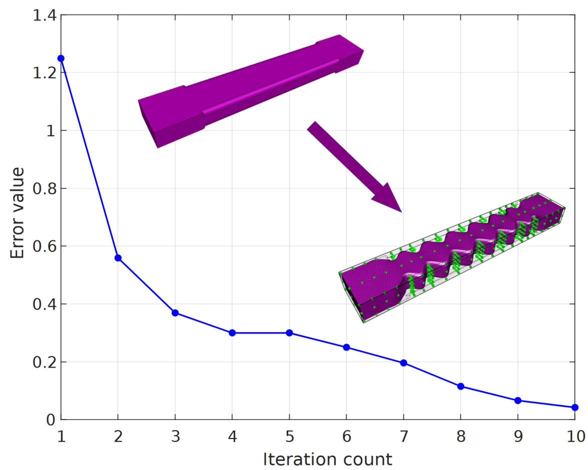

Fig. 2. Optimization error per iteration step. The basic (non-deformed) and deformed structure of the filter is also provided.

The length of each inductive iris section separating the cavities was set to a constant value of $d = 4$ mm. The positions of the control points were parameterized in a way the points are always placed in the middle of each iris section, following the changes of the resonators' lengths.

As mentioned previously, in this study the goal function compares the locations of zeros and poles extracted from the filter's transfer and reflection functions with reference values of the prototype filter [14]. Here, the starting point for the optimization task gave an error value of 1.25, whereas the goal was to reduce the error value below 0.05. The optimization was performed on Intel Core i9-10900X workstation with 64 GB RAM. The task took only 10 iterations and was completed in 47 minutes, resulting in a final error value of 0.042, as shown in Fig. 2. The S-parameters response of the initial and the optimized design is provided in Fig. 3. It can be seen that the framework is exceptionally efficient, leading to an optimized design even from a poor starting point in a very short time.

B. Fabrication and Measurement

The optimized design was prepared for fabrication and 3D-printed in one piece with AlSi10Mg alloy using SLM technology, as shown in Fig. 4. The fabricated component was measured and the results were compared with the simulations. Based on several previous prototypes manufactured using SLM, the effective conductivity of the metal, due to surface roughness, was estimated as $\sigma_{eff} = 4.2 \cdot 10^6$ S/m [12]. As shown in Fig. 5, the measurements show a very good agreement with the simulated model. This is a very successful result since no tuning was applied to obtain such a response. The passband is shifted ca. 50 MHz above the specified band, which is less than 3% of the bandwidth and could be corrected by tuning screws. The in-band RL of the filter is over 20 dB, and the insertion loss is 0.17 dB at f_0 and varies from 0.1 to 0.3 dB over the passband, which corresponds to a Q-factor of 1800. When compared to a classic sixth-order inductive waveguide filter design with the same effective conductivity σ_{eff}, the proposed design would provide a 20% higher Q-factor over the reference with only ca. 1.2% increase of total volume (17221 mm^3 vs. 17011 mm^3). To achieve a better effective conductivity and obtain a high Q-factor, the model could undertake surface polishing or silver plating. Nonetheless, this design shows the possibility of obtaining an improved EM performance by design based on smooth geometry deformations.

Fig. 4. A 3D-printed prototype of the filter.

V. Conclusion

A fast design optimization of waveguide filters using shape deformations was presented. The proposed all-in-one integrated CAD tool gives RF and microwave engineers an easy and efficient way to design novel microwave filters with enhanced electromagnetic performance. This design framework can be used to exploit the full potential of additive manufacturing techniques. In the future, geometry deformation

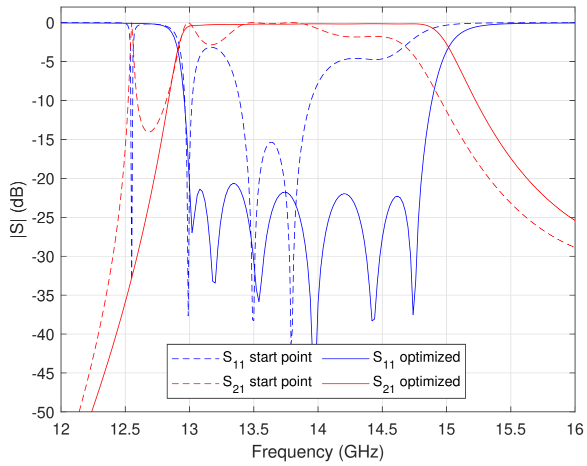

Fig. 3. S-parameter response of the filter. Dashed lines - initial design, solid lines - optimized design.

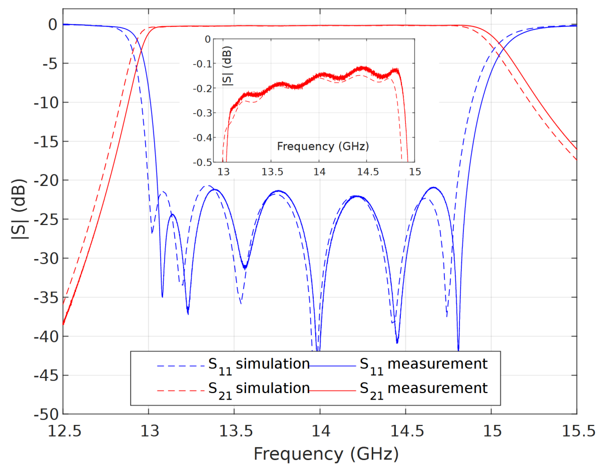

Fig. 5. Comparison of simulation and measurement results. Dashed lines - simulation, solid lines - measurement.

will be applied to design more complex passive components, such as waveguide filters with more stringent specifications, complex topologies, additional transmission zeros, or couplers and multiplexers.

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