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Improvement of the Electromagnetic Performances through Surrogate Modeling and Particle Swarm Optimization of a Frequency Selective Surface

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Abstract Frequency Selective Surfaces (FSSs) consist of the repetition of unit cells for controlling reflection, transmission/absorption of electromagnetic (EM) fields. They are typically employed at radio and optical frequencies. Simulation of such large (in terms of wavelength) structures based on the traditional EM simulations is time consuming and requires significant computational resources. Hence, this paper devotes to present an optimization-oriented methodology for designing and optimizing FSS in an automated fashion. The FSS structure is optimized using the artificial neural network paradigm, where the particle swarm optimization is applied for sizing the design parameters. The optimization process is an automatic one where electronic design automation tool with numerical analyzer are working together, leading to effectively optimize the FSS design. To verify the effectiveness of the proposed method, an FSS structure exhibiting a wide transmission band for normal incidence in the 7.0 GHz to 11.2 GHz range is considered.

Keywords Artificial Neural Network (ANN) · Frequency Selective Surface (FSS) · optimization methodology · Particle Swarm Optimization (PSO).

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1 Introduction

In the radio frequency (RF) range FSSs are employed for various applications as partially reflecting surface in Fabry-Perot antenna, radomes, and others [1,2,3]. Recently they have been also analysed as metamaterials, even if the propagation for these last group happens along the surface and not across as for the FSSs. The typical structure of the FSS is based on periodic arrangement, and consists of a two-dimensional array that is supported by a dielectric substrate. FSS configurations are also named as metasurfaces that are constituted by different metallic patterns; patches [4] are the simplest. The general structure of the FSS is presented in Fig. 1, and Fig. 2 lists different applications of FSS in various domains.

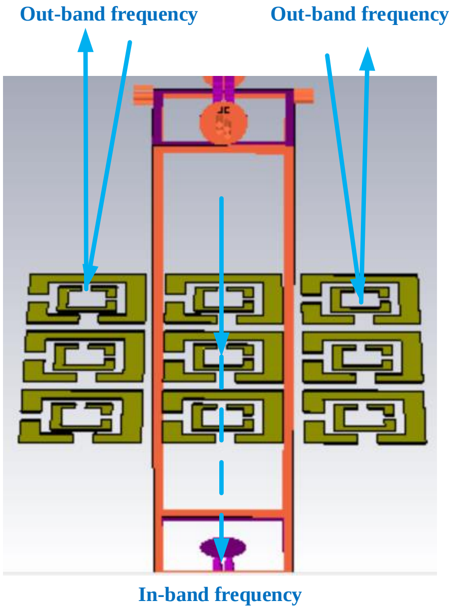

Figure 1: The behaviour of the incident signal on the FSS structure [5]: reflection (out-band) and transmission (in-band), (incidence from top left).

In the recent years, diverse methods have been employed for designing and optimizing FSS structures [?,?,?,?,?,?,?,?]. Additionally, functional surrogate modelling and artificial neural network (ANN) methods [6,7] are increasingly used due to their ability in accurately optimizing RF designs [8,9,10]. In simple words, these methods can be used for high-level designs through electronic design automation (EDA) tools. The ANN paves the way of designers, since this approach can more effectively model the input-output relationships [11, 12,13]. Additionally, the ANN environment is an intelligent one where diverse optimization methods can be employed for dealing with large amount of data.

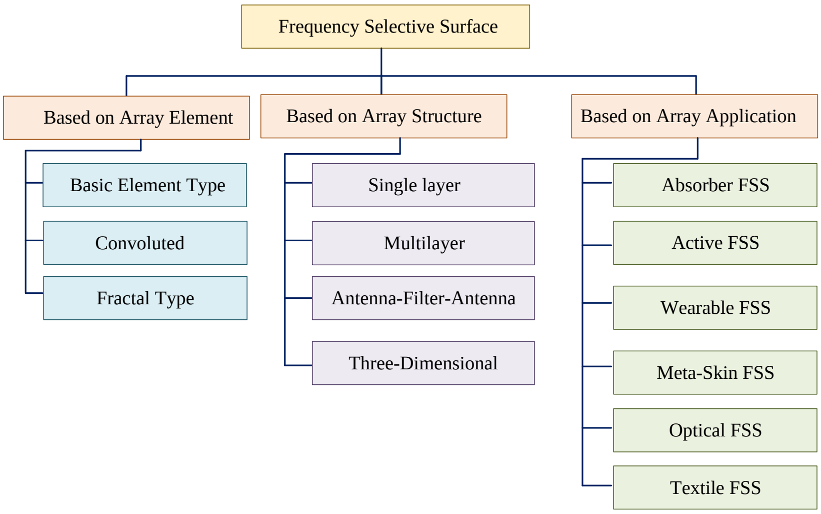

Figure 2: Various applications of FSS.

In this paper, we present an intelligent-based optimization method aiming to design and optimize FSS. For this case, we firstly design the initial structure of the FSS, and then train the ANN with one hidden layer, namely as shallow neural network (SNN), which includes the optimization method. In this work the particle swarm optimization (PSO) is employed. This PSO algorithm is used at the output layer of the SNN leading to optimize the FSS's output specification in terms of S-parameters. In order to verify the proposed method, one FSS structure at the X-band is designed and optimized.

The reminding part of this paper is structured as follows: Section 2 presents the proposed optimization method and Sec. 3 describes the simulation outcomes achieved from the surrogate modelling based optimization method. Finally, Sec. 4 concludes this manuscript.

2 Proposed Optimization-oriented Process

This section presents in detail the proposed optimization method that is based on the surrogate modelling and targets to optimize the FSS structure. The basic concept of the ANN is using the Gaussian Process (GP) model, and afterwards an acquisition function is used for making a decision for the samples [14]. The acquisition function involves the Expected Improvement (EI) and the Probability of Improvement (PI) factors where EI is an efficient global optimization and PI describes the most possible points in the search space. The input and output sampling points are described as $\underline{x} = [x_1,\ldots,x_k]$, and $[f(x_1),\ldots,f(x_k)]$, respectively where k is the dimension of the search space. Considering these data, the ANN is trained and the new points are predicted by the definition as: $\underline{x} = \text{argmax}_{\underline{x}\in R^k}[\text{EI}(\underline{x}) \cdot \text{PI}(\underline{x})]$.

After designing the initial structure, the suitable amount of sampling data is obtained by iterating the design parameters of the initial configuration considering a variation boundary of ±10%. Afterwards, by applying the random iteration the number of neurons is achieved for the SNN, that includes one hidden layer. Finally, the neural network is constructed using expression (1). It must be noted that all the optimization process is done by the combination of EDA tool as Microwave Studio (Dassault Systèmes) and numerical analyzer as Matlab.

$$\text{net} = \text{trainNetwork}(x_k, f(x_k)) \tag{1}$$

The general configuration of the proposed surrogate modelling is presented in Fig. 3. As it can be noticed, it consists of three layers as input layer, hidden layer, and output layer. The input layer consists of design parameters presented in the FSS structure. And in this work, the output layer is presenting the S_{11} specification for various frequencies in the considered frequency band. In the output layer, the PSO algorithm is employed leading to optimize the bandwidth.

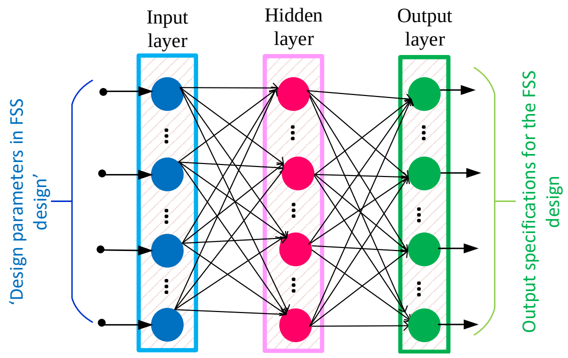

Figure 3: Proposed SNN for optimizing the FSS structure.

3 Simulation Results

This section devotes to present the achieved optimal structure and outcomes from the proposed method. For this case, firstly the initial structure of the FSS is constructed by using two nested rings. Then the random iteration on the defined design parameters is performed for collecting various sampling data. This gathering data is done by the collaboration of Microwave Studio and Matlab tools where the later is working in the background and is collecting output specifications generated from CST side [15].

After achieving a suitable amount of data, the presented SNN structure in Fig. 3 is constructed by using defined equation in (1). Sequentially, Fig. 5

describes the overall structure of the FSS design with the explanation of two ports. The used dielectric is foam with ε_r=1.06 and thickness of 1 mm. In this study, the input layer of SNN includes the design parameters depicted in Fig. 4 (i.e., W_{1-5}, L_{1-3}). Also the output layer feature, devotes to S-parameter specification in the FSS design where the PSO algorithm is employed. The number of neurons is achieved by using the 'rule of thumb'. In total 550 sampling data are generated and the achieved optimal neuron number is 230. The achieved design parameters before and after the optimization are presented in Tab. 1.

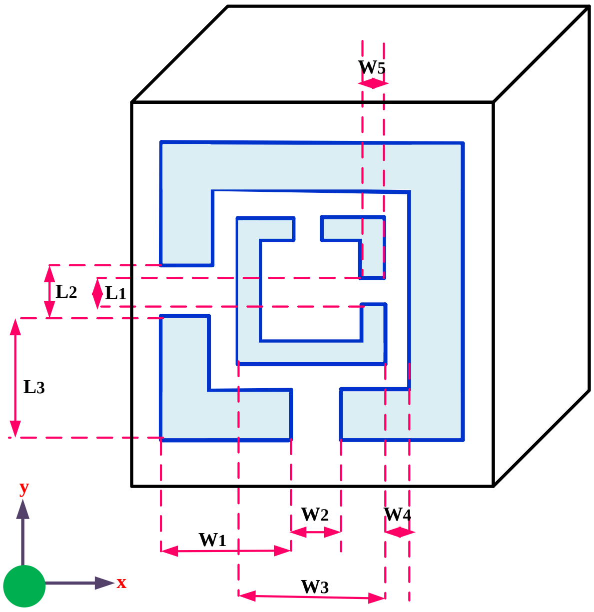

Figure 4: Proposed FSS structure: the reported dimensions represent the design parameters, i.e., the input for the ANN.

To validate the proposed approach, Fig. 6 presents the S-parameter outcomes achieved before and after the optimization. The simulation results demonstrate that after employing the proposed approach the overall performance of the FSS structure is improved significantly and it operates in a wide range of the X-band, namely from 7.0 GHz to 11.2 GHz. The overall generated power from port 1 and port 2 are presented sequentially in Fig. 7 and Fig. 8.

Table 1: Values of FSS structure presented in Fig.4 for before and after optimization

Design parameters	**Before optimization (mm)**	**After optimization (mm)**
W_1	2	2.63
W_2	0.6	1.0
W_3	2.0	3.01
W_4	0.5	0.5
W_5	0.5	0.5
L_1	0.5	0.5
L_2	0.6	1.01
L_3	2.0	2.51

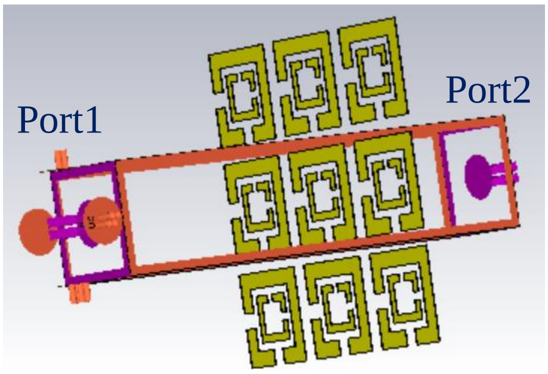

Figure 5: Excitation of the FSS structure; Linearly polarized filed with E field parallel to X axis.

4 Conclusion

Microwave designs are usually complex, and project of innovative challenging circuits needs significant computational effort. Hence, accurate modelling and techniques are required for efficient design. This work devotes to present design and optimization method based on the surrogate modelling where the PSO algorithm is employed for sizing the design parameters. For this purpose, a SNN network is considered, and the optimization method is employed with the combination of EDA tool and numerical analyzer. Validation of the efficiency of the proposed optimization process is performed by designing the FSS structure consisting of two nested square-ring configuration. The simulation results demonstrate that it is suitable for wide-band operation in the X-band (i.e., 7.0 GHz to 11.2 GHz). The significant increases of the bandwidth of the final configuration (after optimization) with respect to the initial structure (before optimization) proves the validity of the proposed method. This work reports some preliminary results on investigation for partially reflective surface to be used in Fabry-Perot type antennas at X-band frequencies. In

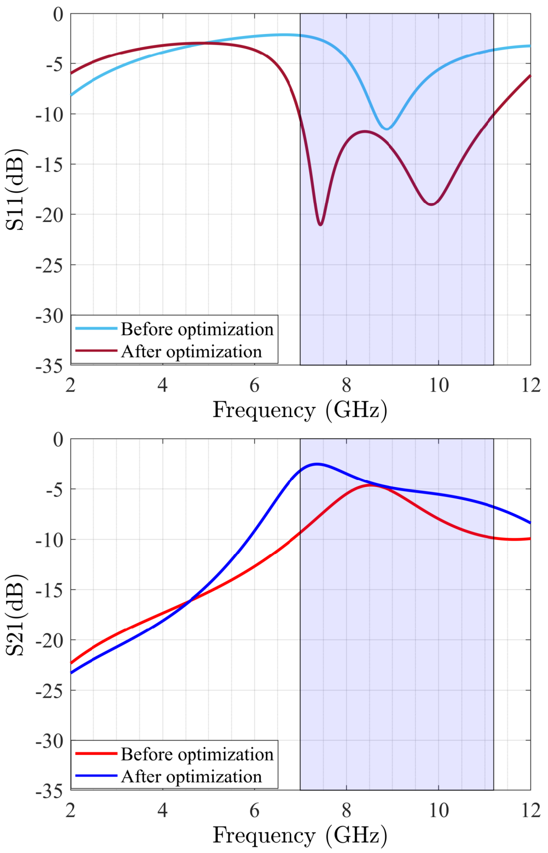

Figure 6: S-parameter specifications of the FSS structure presented in Fig. 5, before and after the optimization.

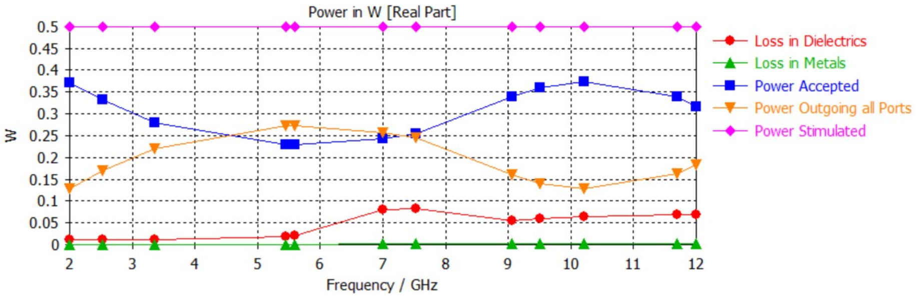

Figure 7: Generated power from port 1 of Fig. 5 after optimization.

the future, intelligent-based multi-objective optimization methods for various complex Fabry-Perot type antennas will be considered.

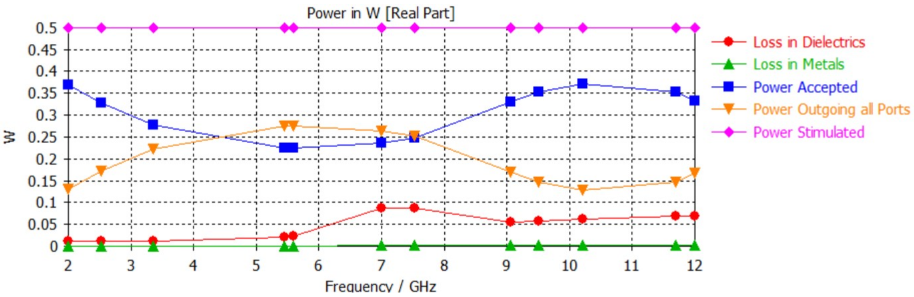

Figure 8: Generated power from port 2 of Fig. 5 after optimization.

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Since 1995, he has been with the Department of Electronics and Telecommunications, Politecnico di Torino, first with a post-doctoral fellowship, then as a Research Assistant. He joined the same Department as Assistant Professor in 2002 and was appointed as Senior Assistant Professor in 2005 and as Associate Professor in 2014 respectively. In February 2017 he obtained the Full Professor qualification (Italy). In late 2005, he was Visiting Scientist at the Antennas and Scattering Department, FGAN-FHR (now Fraunhofer Institute), Wachtberg, Germany. Beginning July 1, 2009, for two years he has been a Marie Curie Fellow at Macquarie University, Sydney, NSW, Australia, where in 2013 he also held a Visiting Academic position and in 2014 has been appointed as Honorary Fellow. Since 2020 he is Honorary Professor at Polytechnic University of Timisoara, Romania and Associate of the Italian National Research Council. He has been appointed as Member of the National Council for the Attestation of University Degrees, Diplomas and Certificates (CNATDCU), Romania, for the term 2020-2024.

His main research activities concern numerical analysis of printed antennas and in particular development of new, numerically efficient full-wave techniques to analyze large arrays, optimization techniques and active and passive metamaterials for cloaking applications. Material parameter retrieval of these structures by inverse methods and different optimization techniques have also been considered. In the last years, bio-electromagnetic aspects have also been contemplated, as for example design of implantable antennas or development of nano-antennas for example for drug delivery applications.

He has published 375+ papers, including 90+ journal contributions, and delivered seminars on these topics all around the world: Europe, USA (AFRL/MIT-Boston), Australia, China, Russia, etc.. Prof. Matekovits has been invited to serve as Research Grant Assessor for government funding calls (Romania, Italy, Croatia and Kazakhstan) and as International Expert in PhD thesis evaluation by several Universities from Australia, India, Pakistan, Spain, etc.

Prof. Matekovits has been a recipient of various awards in international conferences, including the 1998 URSI Young Scientist Award (Thessaloniki, Greece), the Barzilai Award 1998 (young Scientist Award, granted every two years by the Italian National Electromagnetic Group), and the Best AP2000 Oral Paper on Antennas, ESA-EUREL Millennium Conference on Antennas and Propagation (Davos, Switzerland). He is recipient of the Motohisa Kanda Award 2018, for the most cited paper of the IEEE Transactions on EMC in the past five years, and more recently he has been awarded with the 2019 American Romanian Academy of Arts and Sciences (ARA) Medal of Excellence in Science and by the Ad Astra Award 2020, Senior researcher, for Excellence in Research.

He has been Assistant Chairman and Publication Chairman of the European Microwave Week 2002 (Milan, Italy), and General Chair of the 11th International Conference on Body Area Networks (BodyNets) 2016. Since 2010 he is member of the organizing committee of the International Conference on Electromagnetics in Advanced Applications (ICEAA) and he is member of the technical program committees of several conferences. He serves as Associated Editor of the IEEE ACCESS, IEEE Antennas and Wireless Propagation Letters and IET MAP and reviewer for different journals.