Optimal Design of PCS Ceramic Microwave Filters using the Differential Evolution Algorithm

Theodoros I. Kosmanis [1], Ioannis T. Rekanos [2], and Stelios P. Tsitsos [3]

[1] Department of Vehicles Engineering
Alexandrion Technological and Educational Institute, Thessaloniki, PO Box 141, GR-57400, Greece
kosmanis@vt.teithe.gr

[2] School of Electrical and Computer Engineering
Aristotle University, Thessaloniki, GR-54124, Greece
rekanos@auth.gr

[3] Department of Computer Engineering
Technological and Educational Institute of Central Macedonia, Serres, GR-62124, Greece
s.tsitsos@teicm.gr

Abstract **─** The optimal geometrical design of a ceramic microwave filter according to the specifications of the downlink band of the PCS-1900 mobile communications protocol is investigated in this paper. An efficient combination of the Differential Evolution Algorithm and the Finite Element Method leads to the optimal values of four design parameters.

Index Terms **─** Evolutionary algorithm, microwave filter design, PCS.

I. INTRODUCTION

A major issue in the design of modern microwave structures is the compliance with strict communication specifications, obtained mainly through optimal geometry characteristics [1]. The evident complexity of microwave structures connects the fulfilment of their specifications with a significant number of design parameters, mainly geometrical ones. The design is usually formulated as an optimization problem where the objective is to minimize an appropriately defined cost function. The cost function is nonlinear with respect to the design parameters with many local or even global minima. As a result, traditional deterministic optimisation techniques based on the use of the optimization function gradients (gradient-based techniques) do not guarantee a successful approach. They may easily be trapped in local minima, while the final optimal solution directly depends on the selection of the initial values of design parameters. Moreover, the gradient-based techniques may not be implemented in minimization problems due to the lack of convexity of the minimization function.

A more successful alternative to this problem may be attained by the so-called global optimization algorithms. Evolutionary algorithms such as the Particle Swarm Optimization (PSO) method [2] and the Differential Evolution Algorithm (DEA) [3] are very promising in achieving global optimization because they offer ease of implementation and faster convergence than the conventional gradient-based optimization methods. Furthermore, they have been successfully used in design and optimization problems of various scientific fields as well as computational electromagnetics [4-9]. The counterpart to their efficiency is the significant time consumption they require since the original simulation is multiply executed.

In this paper, the DEA is combined with the Finite Element Method (FEM) towards the optimal shape design of ceramic microwave filters in order to meet specific requirements. This type of filter is widely used in cellular telephony and operates under the Personal Communication System (PCS-1900) protocol, one of the three versions of the Global System for Mobile Communications (GSM). The optimal design of microwave filters, which satisfies the PCS-1900 downlink specifications, is investigated through a multi-parametric DEA-FEM analysis, where precision is of great importance.

II. THE PCS-1900 MICROWAVE FILTER

The ceramic microwave filter under design is meant to be used in one of the three versions of the GSM cellular communications and particularly the GSM-1900 or PCS-1900 as it is well known [1]. It is used mainly in the U.S.A. and characterized by two bands; the uplink frequency band (1825-1885 MHz), and the downlink frequency band (1930-1990 MHz). The interest of the present work is focused on the downlink band, which is

Submitted On: November 14, 2015
Accepted On: March 18, 2016

characterized by the specifications given in Table 1.

Table 1: Filter specifications in the downlink band

Specification	Desired Value
Lower cut-off frequency	1930 MHz
Upper cut-off frequency	1990 MHz
Central frequency	1960 MHz
Bandwidth	60 MHz
Band pass insertion loss	< -3 dB
Band pass return loss	> -10 dB
Band stop attenuation	-7 dB at 1910 MHz, -17 dB at 2090 MHz

Figure 1 presents a 3D view of a PCS ceramic microwave band-pass filter used in mobile handsets [10]. Figures 2 (a) and 2 (b) illustrate its facial and top cut respectively. The filter consists of three metalized coupled $\lambda/4$ resonators, where λ is the wavelength corresponding to the central frequency of the pass-band. Each resonator employs a metallic cup that defines the coupling capacitances between the resonators and the loading capacitances between the resonators and the metallic case of the filter. The air part appearing at the top of the filter was used to prevent the electromagnetic energy radiation. The surrounding ceramic material has a relative dielectric constant, ε_r=92 and dielectric losses, tanδ=0.0007, while the material of the resonators, the metallic cups and the filter case is a silver paste with a conductivity of 5.219×10^7 S/m.

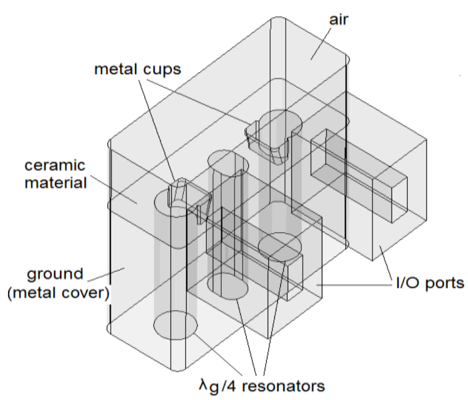
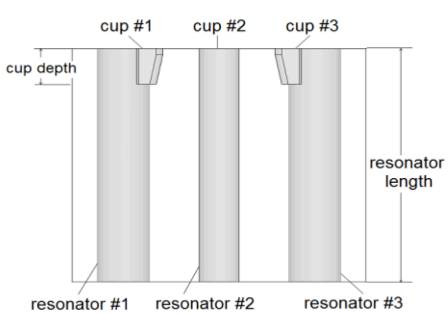
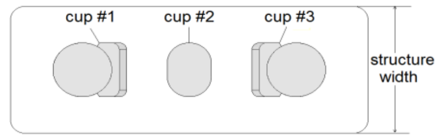


Fig. 1. 3D view of the PCS ceramic filter.



(a)



(b)

Fig. 2. PCS ceramic filter: (a) side view and (b) top view.

III. DESIGN TECHNIQUE

The overall design technique aimed at the compliance of the ceramic filter (described in the previous section) with the PCS-1900 downlink band specifications of Table 1. Particularly, the values of four geometrical characteristics of the microwave filter that allow this compliance are investigated. These are the resonator length, the structure width, the central resonator width and the cup depth of the side resonators.

The optimization scheme used for this purpose was an efficient combination of the DEA and the FEM. The overall algorithm is implemented by a two-step procedure, which is repeated iteratively. In the first step, for a given set of the design parameters values, the electromagnetic analysis problem is solved using the Ansoft HFSS [11] computational package, which is based on FEM [12]. In the second step, the DEA updates the values of the design parameters based on their performance in meeting the design specifications.

A. Differential Evolution Algorithm (DEA)

The common characteristic of all optimization algorithms that are based on the principles of evolutionary optimization algorithms is the mimic of natural phenomena and mechanisms for the quest of an optimal solution [3]. They are based on a population of possible solutions and not on a unique one, unlike standard optimization algorithms.

For the design of the PCS-1900 microwave filter, the initial population of DEA was selected to consist of 100 members (candidate solutions). Each member was characterized by a different set of values of the four design parameters, thus providing a different FEM solution of the microwave filter analysis problem.

The initial population of the algorithm was randomly generated where each design parameter is uniformly distributed within specific value ranges whose lower and upper limits are given in Table 2. Each new generation was produced iteratively after three operators, namely mutation, crossover and selection were applied on each candidate solution, assuring that the best candidate solution (the one with the lowest cost function) of the new generation performs at least as good as the best candidate of the previous generation. This procedure is repeated iteratively until the cost function of the candidate solution is lower than a predefined threshold, or until a predefined total number of generations have been generated. The DEA algorithm was implemented in the MATLAB environment. The heart of the overall procedure is a MATLAB code that, first, updates the design parameters of the filter and, second, it calls the HFSS for the evaluation of the filter performance. The MATLAB/HFSS interface can be easily created. The time required for the algorithm to complete one optimization depends on the initial solutions that are randomly produced and the discretization required by HFSS. However, the average execution time was found to be around 3 hours.

The choice of the cost function is of crucial importance for the convergence of the algorithm. For the case of the PCS-1900 microwave filter the cost function was selected to be the following:

$$C = \begin{cases} 160 - 4\left|S_{11}^{dB}(f_c)\right| + 20\sum_{k=1}^{2}\left|3 + S_{12}^{dB}(f_k)\right| & if\ S_{11}^{dB}(f_c) > -40\,dB \\ 20\sum_{k=1}^{2}\left|3 + S_{12}^{dB}(f_k)\right| & if\ S_{11}^{dB}(f_c) \le -40\,dB, \end{cases} \quad (1)$$

where f_1 = 1.93 GHz, f_2 = 1.99 GHz and f_c = 1.96 GHz. S_{11} and S_{12} stand for the S-parameters of the microwave filter. In (1), coefficient 3 corresponds to the -3dB of the reflection coefficient (parameter S_{11}) that is the goal in the upper and lower cut-off frequencies of the filter. Coefficients 160, 4 and 20 are produced via a trial and error procedure. However, coefficients 160 and 4 are connected via the maximum 40 dB which was set as a goal for the filter's central frequency reflection coefficient (parameter S_{11}). The maximum number of iterations of the DEA-FEM design technique was 250. The value of the cost function, corresponding to the best candidate solution in each generation versus the number of iterations is depicted in Fig. 3. The specific figure was chosen to prove the convergence of the algorithm to a specific solution following a convergence stopping criterion.

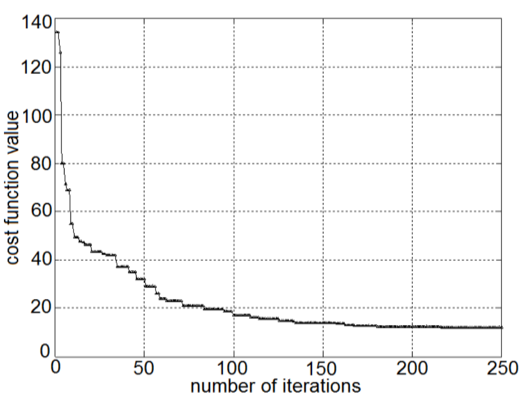


Fig. 3. Cost function vs. number of iterations.

B. Results and discussion

The final optimal solution resulted from the optimization algorithm was found to meet the specifications of Table 1. This is clearly illustrated in Fig. 4 where the S-parameter values are presented. In this figure the scattering parameters S_{11} and S_{21} of the filter's response are compared in two cases. The best initial solution corresponds to the solution which results in a minimum value of the cost function, among all candidate solutions produced at the very first step of the simulation. The optimal solution corresponds to the solution which results in a minimum value of the cost function as a result of the overall simulation. The extracted results are compared well with the results obtained by the HFSS and an equivalent circuit frequency response as presented in [13]. The ceramic filter under investigation was manufactured by TDK Corporation, Japan. Some technical details were made available to the authors; however, measured results were not made available. Measured results are available for a similar technology GSM filter in the 900 MHz frequency band [14].

In particular, the scattering parameters S_{11} and S_{12} of the best candidate solution in the initial population are compared with those of the final optimal solution. It is evident that the optimal solution completely meets the bandwidth requirements of the PCS-1900 protocol. The values of the design parameters that led to the optimal solution are given in Table 2. The upper and lower dimension bounds were determined according to the manufacturing process and the dimensional tolerances information given by the manufacturer (TDK Corporation, Japan).

The variation in the design parameter values during simulation is not presented, since any effort to plot the design parameters would lead to rather abstract figures. Having 100 candidate solutions and a maximum of 250 iterations would give four sets of almost 2000 values. Moreover, the optimal solution per iteration is a function of all four design parameters which means that they should all be treated as one. The ideal representation would be in a four-dimensional space.

Table 2: Design parameter values

Design Parameter	Lower Limit (mm)	Upper Limit (mm)	Final Value (mm)
Resonator length	3.60	4.30	3.9709
Structure width	0.75	1.50	0.6704
Cup depth	0.15	0.70	0.4552
Resonator radius	0.01	0.32	0.2988

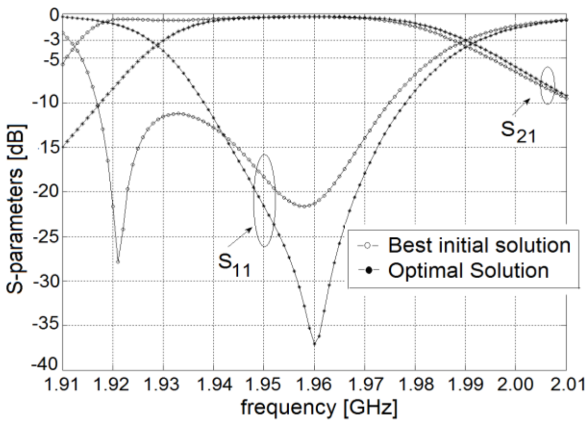


Fig. 4. S-parameters of the microwave PCS filter before and after optimization.

ACKNOWLEDGMENT

The authors wish to acknowledge the financial support provided by the Research Committee of the Technological and Educational Institute (T.E.I.) of Central Macedonia, Serres, Greece, under grant SAT/IC/020316-34P/6.

REFERENCES

[1] A. F. Molisch, *Wireless Communications*, J. Wiley & Sons Ltd., 2005.

[2] J. Kennedy and R. C. Eberhart, *Swarm Intelligence*, Morgan Kaufmann, 2001.

[3] R. Storn and K. Price, "Differential evolution – A simple and efficient heuristic for global optimization over continuous space," *J. Global Optimization*, vol. 11, pp. 341-359, 1997.

[4] J. Robinson and Y. Rahmat-Samii, "Particle swarm optimization in electromagnetic," *IEEE Trans. Antennas Propagat.*, vol. AP-52, pp. 397-407, 2004.

[5] S. Caorsi, M. Donelli, A. Lommi, and A. Massa, "Location and imaging of two-dimensional scatterers by using a particle swarm algorithm," *J. Electromagn. Waves Applicat*., vol. 18, pp. 481-494, 2004.

[6] A. Qing, "Electromagnetic inverse scattering of multiple two-dimensional perfectly conducting objects by a differential evolution strategy," *IEEE Trans. Antennas Propagat*., vol. AP-51, pp. 1251-1262, 2003.

[7] I. T. Rekanos and T. V. Yioultsis, "Convergence enhancement for the vector finite element modeling of microwaves and antennas via differential evolution," *AEÜ Int. J. Electron. Commun.*, vol. 60, pp. 428-434, 2006.

[8] I. T. Rekanos, "Shape reconstruction of a perfectly conducting scatterer using differential evolution and particle swarm optimization," *IEEE Trans. Geosci. Remote Sens*., vol. 46, pp. 1967-1974, 2008.

[9] K. E. Parsopoulos and M. N. Vrahatis, "Recent approaches to global optimization problems through particle swarm optimization," *Natural Comput.*, vol. 1, pp. 235-306, 2002.

[10] S. Tsitsos, A. A. P. Gibson, L. E. Davis, and I. T. Rekanos, "Design of a 3-pole PCS-type monoblock filter using an equivalent circuit approach," *AEÜ Int. J. Electron. Commun.*, vol. 60, pp. 638-646, 2006.

[11] Ansoft High Frequency Structure Simulation (HFSS), ver. 10, Ansoft Corporation, Pittsburgh, PA, 2005.

[12] S. R. H. Hoole, *Computer-Aided Analysis and Design of Electromagnetic Devices*, Elsevier, 1989.

[13] P. Kyriazidis, S. Tsitsos, A. Kouiroukidis, and A. A. P. Gibson, "Equivalent circuit parameter extraction techniques for a PCS ceramic filter, using commercial electromagnetic software," *Proc. of the* 36^{th} *European Microwave Conf.*, pp. 1159-1162, Manchester, UK, 2006.

[14] S. Tsitsos, A. A. P. Gibson, and L. E. Davis, "A new technique for the extraction of equivalent circuit parameters from 3-D monoblock filters," *Int. Journal of RF and Microwave Computer-Aided Engineering*, vol. 15, no. 2, pp. 210-217, 2005.

Theodoros I. Kosmanis was born in Thessaloniki, Greece in 1974. He was awarded the Diploma in Electrical Engineering and the Ph.D. in Electrical and Computer Engineering from the Aristotle University of Thessaloniki, in 1997 and 2002, respectively. From 2003 until 2007, he was an Associate Lecturer in the Department of Mechanical Engineers of the University of Thessaly, Greece and the Departments of Mechanical Engineering and Computer Engineering of the Technological and Educational Institute of Central Macedonia, Serres, Greece. Since 2008, he is with the Department of Automotive Engineering of the Alexander Technological and Educational Institute of Thessaloniki, Greece, where he is now an Associate Professor. His research interests include electrical drive-trains, power signal management algorithms and computational electromagnetics. Kosmanis is a Member of the TCG (Technical Chamber of Greece), SAE (Society of Automotive Engineers), IEEE (Institute of Electrical and Electronics Engineers) and Hel.E.V. (Hellenic Institute of Electric Vehicles).

Ioannis T. Rekanos was born in Thessaloniki, Greece, in 1970. He was awarded the Diploma in Electrical Engineering and the Ph.D. in Electrical and Computer Engineering from the Aristotle University of Thessaloniki, in 1993 and 1998, respectively. From 2000 to 2002 he was a Post-doctoral Researcher in the Department of Radio Science and Engineering of the Aalto University (former Helsinki University of Technology), Finland. His research was funded by the European Commission through the Marie Curie Individual Fellowships program. In 2006 he joined the Aristotle University of Thessaloniki, Greece, where he is now a Professor in the School of Electrical and Computer Engineering. His research interests include wave propagation, inverse scattering, microwave tomography, computational electromagnetics, optimization techniques and signal processing. Rekanos is a Member of the TCG (Technical Chamber of Greece), and Senior Member of the IEEE (Institute of Electrical and Electronics Engineers).

Stelios P. Tsitsos was born in Giannitsa, Greece in 1966. He was awarded the Diploma in Electrical and Computer Engineering from the Democritus University of Thrace, Greece, in 1989. In 1991 he was awarded the Master's degree in Telecommunications Engineering and Digital Electronics from the University of Manchester Institute of Science and Technology (UMIST), UK. In 1994 he was awarded his Ph.D. degree in Microwave Engineering from the same University. From 1996 to 1999, he worked as a Research Associate at UMIST, UK, where he conducted research on the design and optimization of ceramic filters for mobile phones, for TDK Corporation, Japan. From 1999 to 2002, he worked for the Greek Telecommunications Company (OTE) as a Senior Engineer. In 2002 he joined the Department of Computer Engineering of the Technological and Educational Institute of Central Macedonia, Serres, Greece, where he is now an Associate Professor. His research interests include passive and active microwave components and devices for wireless communications and computational electromagnetics. Tsitsos is a Member of the TCB (Technical Chamber of Greece), IEEE (Institute of Electrical and Electronics Engineers) and ARMMS (Automated RF and Microwave Measurement Society), UK.