Optimization of Frequency Selective Surface with Simple Configuration Based on Comprehensive Formation Method

N. Fallah Amini [1], M. Karimipour [1], K. Paran [1], and S. Chamani [2]

[1] Faculty of Electrical and Computer Engineering
Shahid Beheshti University G.C. (SBU), Tehran, +98, Iran
majid.karimipour2000@gmail.com, n.falahamini@gmail.com, k_paran@sbu.ac.ir

[2] Faculty of Electrical and Computer Engineering
K. N. Toosi University of Technology, Tehran, +98, Iran
Chamaani@eetd.kntu.ac.ir

Abstract **─** A new approach to design a frequency selective surface (FSS) is presented based on optimizing the shape of its unit cell geometry. A method based on spline concept has been adopted to specify geometrical features of the elements. In the design process, a hybrid optimization process including genetic algorithm and pattern search method has been used for this purpose. The shape of the structure is improved in each iteration based on specific fitness function. The commercial software CST is used for accurate analysis of structures along the optimization process. A VBA code is developed in order to link Matlab code, which includes optimization tools, and analyzer software CST. This method is used to develop band-pass and band-stop FSSs. Our simulated results show that the transmission and reflection characteristics of the designed FSS are very good in specified frequency band.

Index Terms **─** Frequency Selective Surface (FSS), genetic algorithm, spline.

I. INTRODUCTION

Frequency selective surfaces are periodic structures in either one or two dimensions (i.e., singly or doubly periodic structures), which, as the name suggests, perform a filter operation. Thus, depending on their physical construction, material and geometry, they are divided into low-pass, high-pass, band-pass, and band-stop filters [1,2]. FSSs are also used as a high-impedance surface, radome, absorber, and so on [3-5]. Nowadays, FSSs find many applications from the microwave to the THz region, for both scientific and commercial purposes, which span from antenna systems for radio astronomy research to the screen doors of the microwave ovens. To meet the requirements of those application purposes, many things should be considered at the design stage of FSSs such as selection of the appropriate unit cell geometry, spacing between unit cells, thickness and electrical properties of substrate [5], etc. Several approaches have been proposed to obtain multiple resonance properties, which include FSSs consisting of unit cells with same geometrical shape but different sizes [6] or unit cells with fractal geometry [7,8].

There are two frequency sensitive processes which are commonly exploited in the design of these surfaces. One is the interference of waves reflected from cascaded partially transmitting, and the other is the resonant interaction of waves with segments of conductor - normally periodic arrays of conducting elements or slots in conducting screens. The cascaded boundaries could simply be the interfaces between stacked dielectric sheets, where the number of boundaries, their spacing and the dielectric permittivity are the quantities influencing the transmission response. Double or multiple layers of the metallic grids described later in these notes or cascaded arrays of elements can be employed, or more often in practice a combination of dielectric interfaces and arrays of elements.

The performance and behavior of the FSS filters depend on the following factors: (I) the conductivity and thickness of the FSS conductor, (II) the geometry of the FSS element, (III) the permittivity and thickness of the FSS substrate, and

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(IV) the periodic arrangement of FSS elements [1]. Many numerical methods have been proposed in the last decades for the simulation of FSSs, both in the hypothesis of infinitely thin metal screens and by considering metal screens with finite thickness. Among those, the most popular methods are Finite Difference Time Domain (FDTD) technique [9,10], Finite Element Method (FEM) [11], and Method of the Moments (MoM) technique [12,13].

In this paper, at first a new optimization process will be introduced to design a FSS with desired radiation properties. Secondly, some examples including band-pass filter and band-stop filter are presented to verify the proposed method. The proposed design procedure searches for the optimal shape of the FSS elements. The outline of each FSS element is formed symmetrically by 8 splines. The optimal shape of the FSS element can be obtained by tuning the parameters of the main spline through an optimization process. During the optimization process the analysis of structures is carried out by CST software. A VBA code is developed in order to link Matlab code, which includes optimization tools, and analyzer software.

II. THE PROPOSED METHOD FOR DESIGNING A FREQUENCY SELECTIVE SURFACE

A. Spline interpolation method

In the mathematical field of numerical analysis, spline interpolation is a form of interpolation where the interpolant is a special type of piecewise polynomial called a spline. Spline interpolation is preferred over polynomial interpolation because the interpolation error can be made small even when low degree polynomials is used for the spline. Moreover, spline interpolation avoids the problem of Rung's phenomenon which occurs when interpolating using high degree polynomials. Splines can be considered as a mathematical model that associates a continuous representation (curve or surface) with a discrete set of points of an affine space. The resulting curve may either approximate the control points or interpolate them [14].

A spline can be generated in several procedures such as interpolation and approximation method. We used the approximated spline to derive the final shape of FSS unit cell. In this method, several points are obtained instead of calculating the formulation of the polygon curves. This leads to simplify the definition of the shape unit cell in the design softwares. As shown in Fig. 1 (a), a spline replaces each edge of a given polygon by a curve with specified expansion and sharpness which are determined respectively by expansion (e_n) and sharpness (s_n) factors assigned to that edge. Expansion factor represents a part of curve length at a corner which can be replaced with spline. The amount of expansion factor is considered between 0 and 0.5 (when it is equal to 0.5, spline is obtained in form of a straight line from middle of one side to middle of another side of corner). The value of sharpness factor is also considered between 0 and 1 (when it is equal to 1, the sharpness of spline shape is the same as sharpness of corner).

After assigning the values of expansion and sharpness factors, the points A, B, C_1, C_2 and U_1 (middle point of $\overline{C_1C_2}$ segment) are determined (Fig. 1 (b)). Shaping process of spline is done by an iterative method. This method is done by connecting the middle of each adjacent segment to the others which leads to generate the new segment. For example in the first step, the middle of AC_1 and BC_2 segments are connected to middle of C_1U_1 and U_1C_2 segments, respectively. This method is repeated to generate a smooth shape from corner.

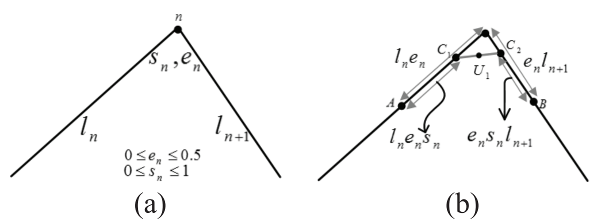

Fig. 1. Expansion and sharpness factors at a corner.

B. Design of FSS element

To create the shape of the unit cell, we used a spline interpolation method. The proposed method has been recently used for optimization of UWB antennas [15]. One of the main advantages of this method is applying some limitations to the boundaries in order to decrease the complexity of the element shape. It results in less manufacturing difficulties. With the spline concept, discontinuity problem is eliminated at the boundaries of the structures and elements can also be described with low number of parameters without limiting the variety of possible geometries. Figure 2 shows the primitive sketch with its main parameters of the proposed element based on spline interpolation procedure.

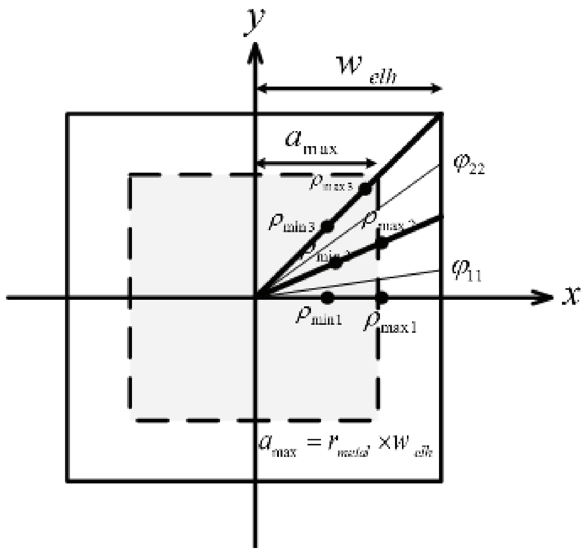

Fig. 2. Primitive design and geometrical parameters of element.

As shown in Fig. 2, desired structure has been considered within the square with dimensions $w_{elh} \times w_{elh} \left(cm^2\right)$. In order to have sensible margin with other neighboring elements, boundaries are embedded in the region with dimensions $a_{max} \times a_{max}$ where $a_{max} = r_{metal} \times w_{elh}$ and $r_{metal} \le 1$. For simplifying purposes and having the element least sensitivity with respect to the wave polarization, the elements have been considered with one of eighth (1/8) symmetry in the φ plane. Therefore we will require to design only 1/8 of element shape in the optimization process. In the first step, three primitive points of the element boundaries is considered at $\varphi_1 = 0°$, φ_2, and $\varphi_3 = 45°$ planes, where φ_2 is a polar angle between the specified φ_{11} and φ_{22} planes according to Fig. 2. For each point a certain boundary is considered for the variation of its polar radius. Parameters ρ_1, ρ_2 and ρ_3 are the polar radius of the points where $\rho_{min1} < \rho_1 < \rho_{max1}$, $\rho_{min2} < \rho_2 < \rho_{max2}$ and $\rho_{min3} < \rho_3 < \rho_{max3}$. Amounts of ρ_{min1}, ρ_{max1}, ρ_{min2}, ρ_{max2}, ρ_{min3} and ρ_{max3} parameters are constant and will be determined at the beginning of the optimization process. Altogether, 10 parameters including the expansion and the sharpness factors corresponding to each point (s_i and e_i $i = 1, 2, 3$) also ρ_1, ρ_2, ρ_3 and φ_2 are the optimization variables that must be changed during the optimization process. These parameters are tuned according to the desired fitness function to minimize the cost function defined in the optimization algorithm.

The variety of possible geometries raise the possibility of having different optimum designs. On the other hands, the objective function may have multiple local minima in the search domain. Consequently, global optimization methods should be used in order to search for the best design. Moreover, the process of calculating the objective function for each FSS structure is relatively complex and time consuming, including the electromagnetic simulation of antenna and the computation of characteristics which are involved in the definition of objective function. Therefore, the implementation of heuristic strategies is necessary in order to reduce the overall time needed for the completion of the optimization process. On the other hand, the final stages of optimization with heuristic strategies are subjected to stagnation, so it is better to complete the global optimization by implementing a local optimization method. Accordingly, the optimization process includes a combination of local and global optimization algorithm. The traditional electromagnetic software CST is used during the optimization process to calculate the desired characteristic of the FSS (including the reflection and transmission coefficients). It will raise the accuracy of the designed structure. This optimization procedure is much better than CST's inner code optimization. More degree of freedom for designed parameters, capability to determine arbitrary genetic algorithm options, possibility to combine local and global optimization procedures, are some advantages of the proposed method.

While the optimization process was completed, the optimum position of each point is determined. A spline is fitted to these points and the element shape will be constructed by repeating the spline in the whole φ plane according to the 1/8 symmetry. Finally, obtained element is simulated with frequency solver CST microwave studio considering periodic boundaries and excitation. This is important to point that substrate thickness $\left(t_{sub}\right)$ and dielectric constant (ε_r) will be remained fix during the optimization process.

C. Determining the fitness function of the optimization method

Figure 3 shows a sample shape for desired transmission coefficient (S_{21}) of a band-pass FSS. Desired reflection coefficient (S_{11}) of a band-stop FSS can be determined in a similar manner.

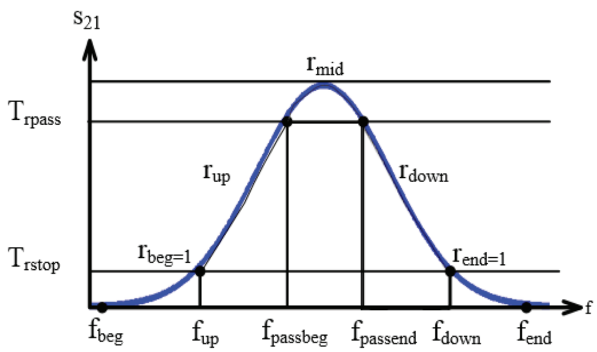

Fig. 3. Desired S_{21} with relative parameters to determine the fitness function.

As shown in Fig. 3, there are many parameters to clarify the fitness function. These parameters have been determined based on desired frequency band and maximum acceptable amount of S_{21} or S_{11} coefficients. It would be desired that S_{21} coefficient should be more than T_{rpass} in the pass-band region and less than T_{rstop} in the stop-band region and behaves as a linear function in the transient bands from T_{rpass} to T_{rstop} and vice versa. Given the importance of different regions in the frequency band, different weights such as r_{beg}, r_{mid}, r_{up}, and r_{end} have been assigned to different regions of S_{21} curve. The fitness function has been considered as follows:

$$F = F_{beg} + F_{up} + F_{mid} + F_{down} + F_{end}, \tag{1}$$

where F_{beg}, F_{up}, F_{mid}, F_{down} and F_{end} are assigned in different frequency regions as follows:

For $f_{beg} < f < f_{up}$:

$$F_{beg} = \left(r_{beg} / n_{beg}\right)\sum_{n=1}^{n_{beg}}\begin{bmatrix}\left|S_{21}(n)\right| - \\ \min\left(\left|S_{21}\right|, T_{rstop}\right)\end{bmatrix}, \tag{2}$$

where f_{beg} and f_{up} are the beginning frequency of the channel and transient region, respectively. Parameter n_{beg} is the number of sample frequency in the first region.

For $f_{up} < f < f_{passbeg}$:

$$F_{up} = \left(r_{up} / n_{up}\right)\sum_{n=1}^{n_{up}}\begin{bmatrix}\left|S_{21}(n)\right| - \\ \min\left(\left|S_{21}, T_{rm1}\right|\right)\end{bmatrix}, \tag{3}$$

where $f_{passbeg}$ is the beginning frequency of the pass band region with high reflection or transmission coefficient. Parameter n_{up} is the number of sample frequency in the transient region and parameter T_{rm1} is obtained as follows:

$$\begin{aligned} T_{rm1} = T_{rpass} + \left(T_{rpass} - T_{rstop}\right) \times \\ \left(f - f_{up}\right) / f_{passbeg} - f_{up}. \end{aligned} \tag{4}$$

For $f_{passbeg} < f < f_{passend}$:

$$F_{mid} = \left(r_{mid} / n_{mid}\right)\sum_{n=1}^{n_{mid}}\begin{bmatrix}\min\left(\left|S_{21}(n)\right|, T_{rpass}\right) \\ -\left|S_{21}(n)\right|\end{bmatrix}, \tag{5}$$

where $f_{passend}$ is the ending frequency of the pass band region with high reflection or transmission coefficient. Parameter n_{mid} is the number of sample frequency in the pass band region.

For $f_{passend} < f < f_{down}$:

$$\begin{aligned} F_{down} = \left(r_{down} / n_{down}\right) \times \\ \sum_{n=1}^{n_{down}}\begin{bmatrix}\left|S_{21}(n)\right| - \\ \min\left(\left|S_{21}(n)\right|, T_{rm2}\right)\end{bmatrix}, \end{aligned} \tag{6}$$

where f_{down} is the ending frequency of the second transient region. Parameter n_{down} is the number of sample frequency in the second transient region and parameter T_{rm2} is obtained as follows:

$$\begin{aligned} T_{rm2} = T_{rpass} + \left(T_{rpass} - T_{rstop}\right) \times \\ \left(f_{down} - f\right) / f_{down} - f_{passend} \end{aligned}. \tag{7}$$

And finally for $f_{down} < f < f_{end}$:

$$F_{end} = \left(r_{end} / n_{end} \right) \times \sum_{n=1}^{n_{end}} \left[\left| S_{21}(n) \right| - \min\left(\left| S_{21}(n) \right|, T_{rstop} \right) \right], \tag{8}$$

where f_{end} is the ending frequency of the channel. Parameter n_{end} is the number of sample frequency in this region.

III. SIMULATION RESULTS

In this section, two examples are provided to verify the proposed method. At first, we designed a band-pass FSS. It is desired that the designed FSS has a high transmission coefficient and low reflection coefficient around at 1.2 THz. Important parameters of the band-pass FSS and fitness function associated with transmission coefficient (S_{21}), are shown in Table 1. Optimization process has been done for normal incidence and both TE and TM polarizations. Schematic of the designed FSS has been shown in Fig. 4. The population size and number of generations of the optimization process have been considered 50 and 6, respectively, which are appropriate to reach good results. There is a tradeoff between the accuracy and the optimization time. Accordingly, the population size and the generation numbers values are selected based on the optimization time and the accuracy of the results. The number of frequency samples are considered 1000 in the whole band. For simplifying, these frequency samples are considered with equal distances. Parameters r_{beg}, r_{mid}, and r_{end} are valued relative to each other. It means, they represent the importance of different regions in the fitness function, accordingly the final results don't merely depend on their exact values. Almost, the value of parameter r_{mid} is assigned greater than the others. The optimization time takes about 8 hours by a computer with 8 core CPU and 16 GHz of RAM. The transmission coefficient of TE and TM mode of the designed FSS as a function of frequency is shown in Fig. 5.

As shown in Fig. 5, the 3-dB bandwidth of the designed FSS is from 0.72 THz to 1.7 THz which has a good agreement with input parameters $f_{passbeg}$ and $f_{passend}$.

Table 1: Unit cell, substrate, frequency band, and fitness function parameters for band-pass FSS design

Unit Cell Parameters	
w_{elh} (μm)	102
r_{metal}	0.95
Substrate Parameters	
ε_r (F/m)	2.89
$tan(\delta)$	0.002
T(μm) (thickness)	12
Frequency Band Parameters	
f_{beg} (THz)	0.2
f_{end} (THz)	2.3
$f_{passbeg}$ (THz)	0.7
$f_{passend}$ (THz)	1.8
Coefficients of Fitness Function	
r_{beg}	20
r_{mid}	40
r_{end}	20

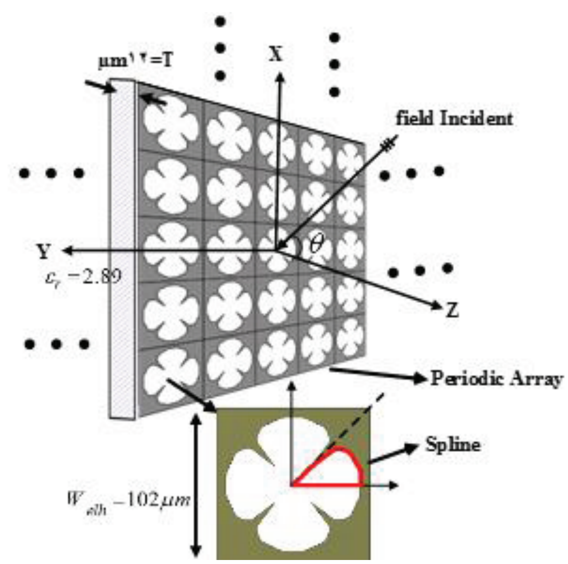

Fig. 4. Designed band-pass FSS with the proposed method around at 1.2 THz.

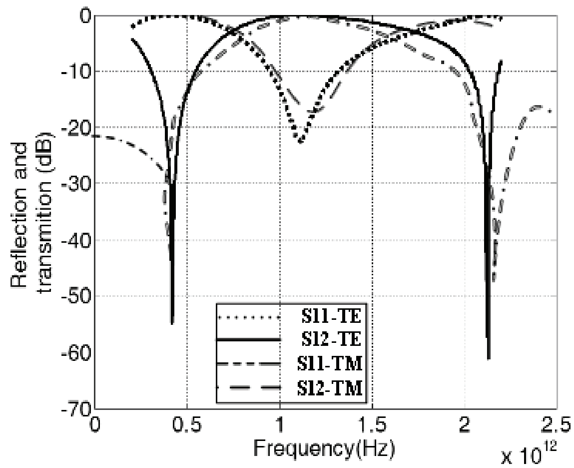

Fig. 5. Reflection and transmission of the designed band-pass FSS obtained by CST software for TE and TM waves.

The deviation of resonance frequency is less than 3% for TE polarization and less than 2% for TM case. The most important feature of the proposed structure is nearly same reflection-transmission behavior under different incident angles. Due to the 1/8 symmetry of the structure, which is applied to reduce optimization parameters and decrease the optimization time, FSS has less sensitivity to the incident angle. In order to investigate this fact, we considered the optimized configuration and calculated reflection and transmission coefficients for $\theta = 30°$. Figure 6 shows that a $30°$ inclination of incident wave has a little effect on reflection-transmission characteristics.

As a second example, we designed an FSS configuration to behave as a band-stop filter around at 9.2 GHz. Therefore, the fitness function has been changed to realize this configuration. Table 2 shows important data associated to FSS and its fitness function. Figure 7 shows the optimized structure. The population size and number of generations in the optimization process have been considered 54 and 6, respectively. These values are selected by testing the algorithm several times to get better results. Other parameters have been considered similar to the previous example. Reflection and transmission of the designed FSS is shown in Fig. 8. As shown in Fig. 8, a band-stop FSS around at 9.2 GHz is realized. There is more than 20 dB difference between amounts of S_{11} and S_{21} coefficients. Furthermore, this structure has low sensitivity with respect to the impinging wave polarization, especially near the central frequency.

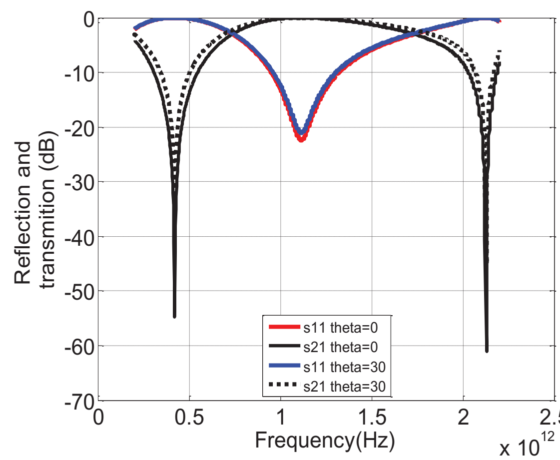

Fig. 6. Reflection and transmission of band-pass FSS for two different incident angles obtained by CST software.

Table 2: Unit cell, substrate, frequency band, and fitness function parameters for band-stop FSS design

Unit Cell Parameters	
w_{elh} (mm)	15
r_{metal}	0.95
Substrate Parameters	
ε_r (F/m)	2.89
$tan(\delta)$	0.02
T(μm) (thickness)	12
Frequency Band Parameters	
f_{beg} (GHz)	7.5
f_{end} (GHz)	11.4
$f_{passbeg}$ (GHz)	8.6
$f_{passend}$ (GHz)	9.8
Coefficients of Fitness Function	
r_{beg}	5
r_{mid}	10
r_{end}	5

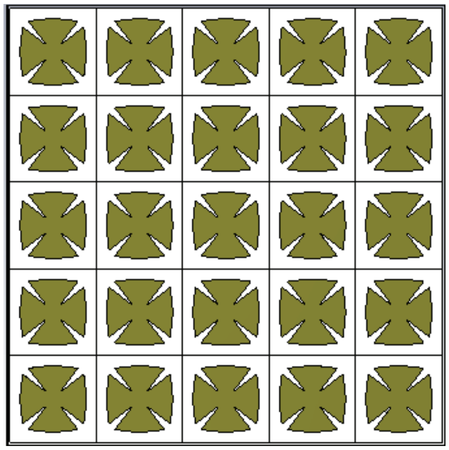

Fig. 7. A part of periodic array designed with the proposed method to have band-stop behavior around at 9.2 GHz.

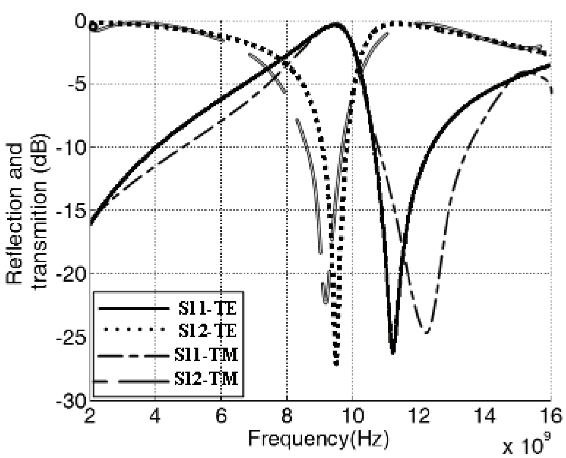

Fig. 8. Reflection and transmission of the resulted band-stop FSS for TE and TM waves obtained by CST software.

Figure 9 and Fig. 10 show the output results of genetic and pattern search algorithm for this example.

In the previous works, the binary parameters were used to describe the shape of the unit cell [16-18]. For example, in the case of the genetic algorithm, all the parameters which require optimization, namely, the kind and the thickness of each dielectric layer, the periodicity of the surface and the shape of the unit cell element are encoded into a binary-encoded chromosome. Disadvantage of the proposed design procedures is high sensitivity of structures to fabrication tolerance.

The advantage of the designed structure in this present is low sensitivity of the designed FSS with respect to the manufacturing tolerance. The use of spline concept in the design procedure is the main reason of this fact. Splice concept cause to generate unit cell with continuous borders and prevents to generate complex unit cell shape. In order to show this advantage, a FSS with +5% variation at the input variables of the optimization algorithm is generated, simulated and compared with original case. Figure 11 shows the result of new structure with 5% tolerance in its shape. As shown in Fig. 11, there is no sensible difference between modified structure and original one. This is an acceptable criterion for designing a FSS.

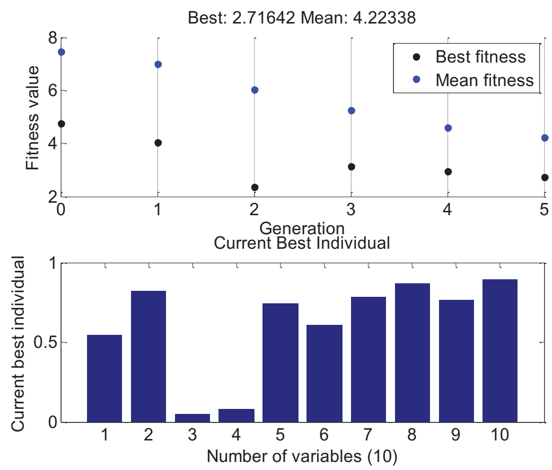

Fig. 9. Fitness value and current best individual in the genetic algorithm.

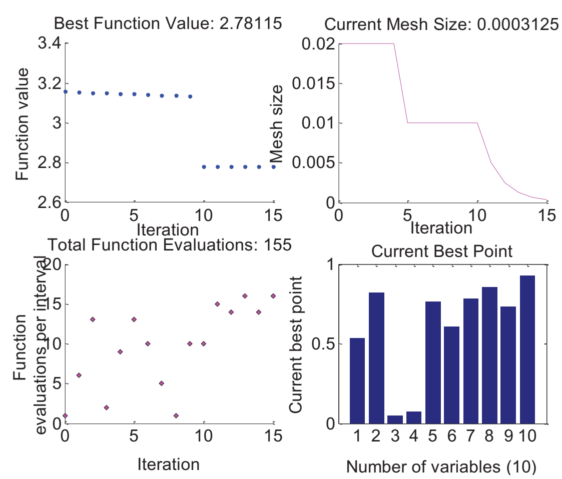

Fig. 10. Results of pattern search method.

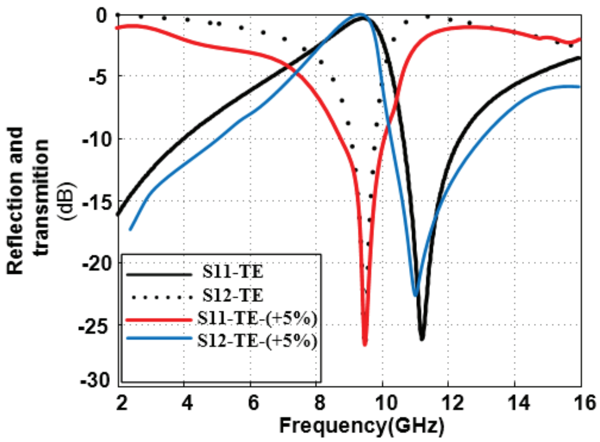

Fig. 11. Comparison between designed FSS and modified case.

IV. CONCLUSION

A novel method for the optimization of FSS with simple configuration is proposed. The main idea is formation the boundaries of each element symmetrically with 8 splines and then finding the parameters of the main spline through an optimization process to have a desired reflection or transmission characteristics. For the accurate analysis of periodic structure, we used CST software to simulate FSSs during the optimization process. The optimization process is a hybrid procedure including genetic algorithm and pattern search method. A VBA code is developed to link CST software and optimization code. The process resulted in structures with low sensitivity to the polarization and incident angle.

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Majid Karimipour received his B.S. and M.S. degrees in Electrical Engineering in 2008 and 2011 from Shahrekord University, Shahrekord, Iran and Shahid Beheshti University (SBU), Tehran, Iran, respectively. He is currently working towards the Ph.D. degree in Communication Engineering at Iran University of Science and Technology (ISUT), Tehran, Iran. His major research interests are the development and design of reflectarray antennas, complex EM media, design antennas in THz bands such as reflectarray, numerical methods in EM, and design of microwave devices.