Multi-objective Particle Swarm Optimization for the Realization of a Low Profile Bandpass Frequency Selective Surface

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***Abstract*—This paper presents a new application of evolutionary optimization algorithm to design an extremely low profile bandpass frequency selective surface (FSS). A particle swarm optimization algorithm is interfaced with a commercial time-domain solver to design and optimize a second-order bandpass FSS at 10 GHz with 20% fractional bandwidth. Four structure variables are defined in the algorithm to be optimized for realization of a grid of capacitive patches and inductive strips, which constitute the bandpass FSS. Optimization led to a FSS with a total thickness of $\lambda_o/65$.**

I. Introduction

In the new era the demand for optimization in terms of various requirements such as cost, space and time has significantly increased. Nowadays, there are several optimization methods available and evolutionary algorithms (EAs) are the youngest among them. EAs are inspired by evolution and natural selection. More precisely, evolutionary algorithms refer to a class of iterative search methods that imitate evolutionary processes in nature. There are many forms of EAs such as genetic algorithm [1], ant colony optimization [2] and particle swarm optimization (PSO) [3]-[4].

PSO was initially proposed by Kennedy and Eberhart in 1995 [3], and employed in antenna design from 2002 [5]. PSO is based on the movement and intelligence of swarms and in some instances outperforms its other counterparts like genetic algorithms [6]. PSO is characterized by having simplified coding and good convergence, making the algorithm suitable for various electromagnetic applications. Several antenna designs have been optimized using PSO [4]-[7].

In this study, a PSO algorithm is implemented in Matlab and interfaced with CST Microwave Studio (CST MWS), to design an extremely low-profile frequency selective surface with second-order bandpass response. The implemented algorithm provides more adaptability in terms of fitness function definition and boundary conditions compared to embedded optimization methods in commercial EM software packages. This paper is organized in five sections. Section II discusses frequency selective surfaces. The implementation of the PSO algorithm and results are presented in section III. Finally, a brief conclusion is given in section IV.

II. Frequency Selective Surface Design

Frequency selective surfaces (FSSs) have been extensively investigated due to their wide applications from antennas and microwave systems to satellite communications and radar [8]-[9]. Generally, FSSs are periodic structures, composed of identical elements arranged in a one or two-dimensional grid. These elements can be metallic patches with a certain pattern or apertures of complimentary geometries on a substrate. The FSSs exhibit total reflection or transmission for certain frequency ranges, and like microwave filters [10]-[12] they can provide lowpass, highpass, bandpass, or bandstop frequency responses. These responses do not only depend on frequency, as in the microwave filters, but also on the angle of arrival and polarization of the incident electromagnetic waves.

Several techniques have been used to design FSSs. Traditionally, periodic arrays of resonant elements are employed to achieve bandpass or bandstop characteristics [13]. This approach can lead to a periodic array of slot elements that provide a first order bandpass response. To achieve a filtering behavior with high out-of-band rejection, multiple first-order FSS panels with a quarter-wavelength spacing are stacked together, resulting in bulky structures especially at low microwave frequencies. On the other hand, this spacing between panels increases the response sensitivity to the angle of the incidence.

To address the aforementioned issues, a PSO algorithm is presented in the next section to realize a super low profile FSS. To design a FSS with the center frequency of 10 GHz and 20% fractional bandwidth, a structure composed of two dielectric substrates with three metal layers on top, middle and bottom is suggested. The two substrates are bonded together. The layout of the proposed structure is shown in Fig. 1. As it is observed, the structure in Fig. 1 maintains its original shape as it is rotated by 90 degree. Therefore, the frequency response of the structure is polarization insensitive.

To save time in the optimization process, unit cell model of the proposed structure, shown in Fig. 2, is considered. The unit-cell size is 5.6 mm corresponding to $\lambda_o/5$, where λ_o is the free-space wavelength at the operating frequency.

To theoretically justify the filtering mechanism of the used structure in Fig. 1, an equivalent circuit is extracted from the structure. The top and bottom capacitive patches are modeled

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with two parallel capacitors (C1 and C3), while the inductive strip is modeled with a parallel inductor ($L1$), as depicted in Fig. 3. The two substrates are considered as two short lossless transmission lines with the impedance of $Z = Z_0/\sqrt{\varepsilon_r}$ and the length of h, where Z_0 is the free-space wave impedance ($Z_0 = 377\ \Omega$) and ε_r is the relative dielectric constant of the substrate ($\varepsilon_r = 3.27$). By substituting the transmission lines with their equivalent circuits and converting the produced inductive T-network to a π-network, as illustrated in Fig. 3 , the typical topology of a second-order bandpass filter is achieved and shown in Fig. 3(c). More details about lumped-equivalent circuit extraction are explained in [14].

III. Particle Swarm Optimization Algorithm

A. PSO Parameters

There are four parameters to be optimized by the PSO algorithm. They are the sizes of capacitive patches ($p1$ and $p2$), the width of strip (s) in the middle layer and the thickness of the substrates (h), while the objective of the algorithm is to design a FSS with the predetermined center frequency and bandwidth. Hence, it becomes a multi-dimensional multi-objectives optimization problem. The solution space for the parameters are as following (unit: mm)

$$p1,\ p2 \in [0.05,\ 5.60]; s \in [0.05,\ 2.75]\,; h \in [0.20,\ 0.80] \quad (1)$$

Table I shows the pseudo code of this algorithm. The optimization is initialized with a random swarm of six particles. Each particle flies through the search space with velocity updated by 3 factors:

1) Inertia factor (ω): This factor prevents particles from drastically changing in one direction.

2) Cognitive factor (C_1): This factor makes the particles draw back to their personal best position (Pbest).

3) Social factor (C_2): This factor makes the particles draw toward the global best position (Gbest) found by the swarm.

The personal best position (Pbest) and the global best position (Gbest) refer to the best position fittest to the "fitness function" found by each individual and by the whole swarm of particles, respectively. At each iteration the particle's velocity and particle positions are calculated by

$$\begin{aligned} V_t = \omega V_{t-1} + C_1\alpha_1\left(Pbest_{t-1} - P_{t-1}\right)\triangle t \\ +C_2\alpha_2\left(Gbest_{t-1} - P_{t-1}\right)\triangle t \end{aligned} \quad (2)$$

$$P_t = P_{t-1} + V_t \triangle t \quad (3)$$

In the above equations, t denotes the current iteration, while α_1 and α_2 are the random variables. $\triangle t$ is the time interval between two successive iterations that is set to unity. The inertia factor (ω) has an initial value of 1 and decreases in each iteration by the factor of 0.99, while $C_1$and C_2 are set to 2. The position of each particle at iteration t, is denoted by P_t.

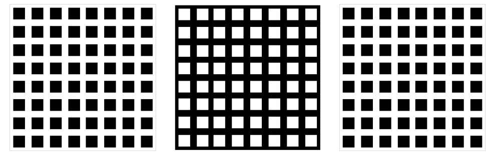

Fig. 1. The layout of the proposed second order bandpass FSS. (a) Capacitive patches on the top. (b) Inductive wire grid in the middle. (c) Capacitive patches on the bottom. Black color represents the metal and white color shows the dielectric.

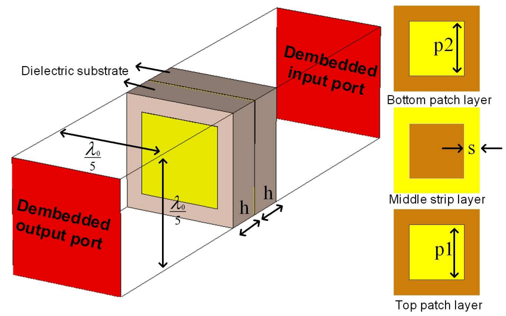

Fig. 2. Unit cell optimization model. Yellow indicates metalized area.

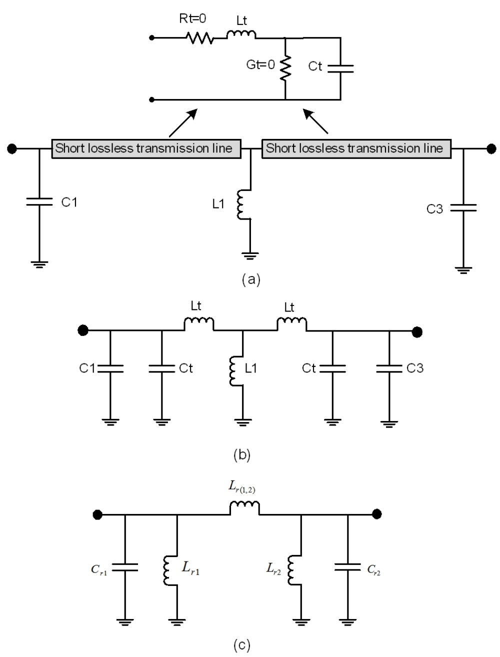

Fig. 3. Equivalent circuit model for the proposed FSS in Fig. 1 . (a) Transmission line model. (b) Lumped element equivalent circuit. (c) Lumped elements of the second-order bandpass filter.

B. Velocity Considerations

In a PSO optimization, the particles that pass the solution space, must be handled in a proper way. The out of boundary particles result in physically invalid designs. To tackle this problem, in the proposed algorithm when a particle hits the boundary in one dimension, the velocity sign in that dimension is changed. As a result the particle is reflected back into the solution space. This boundary condition is known as reflecting walls [15]. In addition to confining particle's position in the

TABLE I. PSO ALGORITHM PSEUDO CODE

```
Initialize the swarm
Evaluate the fitness for the initialized swarm by interfacing Matlab with CST
For each iteration do
For each particle do
Compute velocity
Compute new position
Evaluate the fitness for new position by interfacing Matlab with CST
Update the Pbest and Gbest
End for
End for
```

solution space, the particles velocity should also be restricted in a reasonable range, otherwise particles with very high speed may miss some high fitness positions. So, the maximum allowed movement for each particle at each iteration is set to 25% of its solutions space.

C. Fitness Function and Results

To evaluate fitness function, the produced particle's position in each iteration are physically realized in the form of unit cell and analyzed by transient solver of CST MWS. Visual basic for application (VBA) is employed to invoke CST MWS and the file containing the unit cell variables. Then the computed S-parameters from CST MWS are used in the fitness evaluation. In order to control the band width and out-of-band rejection, the transmission coefficient at some particular frequencies are recorded and used in fitness evaluations. Fig. 4 illustrates those frequencies. In this PSO algorithm, a better design is defined to have a higher fitness value, therefore the fitness function is defined as

$$f = -28\mathrm{A} + 0.35\mathrm{B} - 2.5\mathrm{C} - 1.5\mathrm{D} - \mathrm{E} - 10\mathrm{BW} \quad (4)$$

Where,

$$A = |S21\,(f_0)| \quad (5a)$$

$$B = |S11\,(f_0)| \quad (5b)$$

$$\mathrm{C} = \left|\mathrm{S21}\,(\mathrm{f}_2) + \mathrm{S21}\left(\mathrm{f}_2^{'}\right)\right| \quad (5c)$$

$$\mathrm{D} = \left|\mathrm{S21}\,(\mathrm{f}_3) + \mathrm{S21}\left(\mathrm{f}_3^{'}\right)\right| \quad (5d)$$

$$\mathrm{E} = \left|\mathrm{S21}\,(\mathrm{f}_4) + \mathrm{S21}\left(\mathrm{f}_4^{'}\right)\right| \quad (5e)$$

$$\mathrm{BW} = |\mathrm{S21}\,(\mathrm{f}_1) - 3\mathrm{dB}| + \left|\mathrm{S21}\left(\mathrm{f}_1^{'}\right) - 3\mathrm{dB}\right| \quad (5f)$$

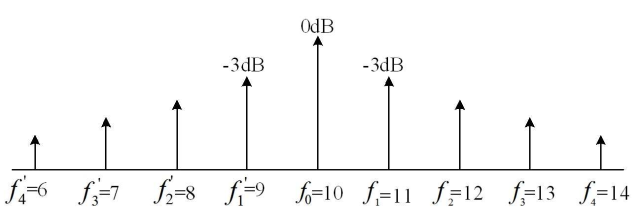

Fig. 4. Frequency selection in the fitness function. Vertical axis represents transmission coefficient (dB), horizontal axis shows frequency (GHz).

The weights of factors in the fitness function are selected based on tracking the behavior of the algorithm in the early iterations.

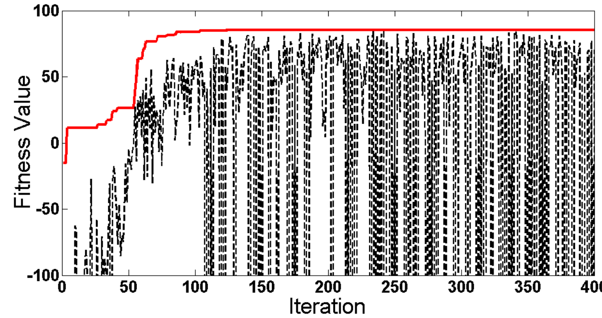

Fig. 5. Convergence results for the low profile FSS. Solid red line represents global best and dotted black line shows the average fitness at each iteration.

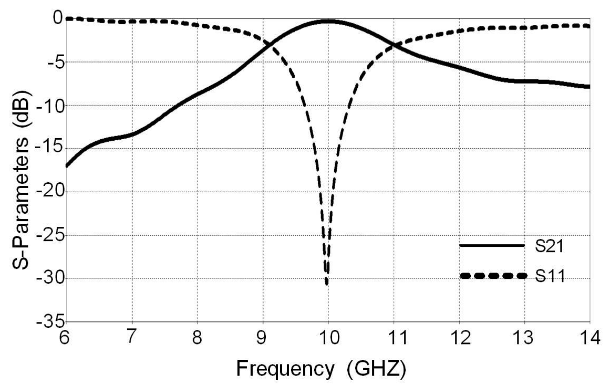

Fig. 6. Computed S-parameters of the proposed bandpass FSS by the PSO algorithm.

The highest fitness value of 85.33 was found at the 125^{th} iteration. Fig. 5 shows the convergence of PSO algorithm over 400 iterations. The geometrical parameters of the optimized bandpass FSS are as following:

$$p1 = 4.68\;mm;\; p2 = 4.67\;mm;\; s = 1.4\;mm;\; h = 0.23\;mm$$

The optimized thickness of each substrate is only 0.23 mm, corresponding to $\lambda_0/130$, whereas in the classical FSS this thickness is around $\lambda_0/4$. This presents a profile reduction by a factor of 32.

The computed S-parameters of the optimized structure are depicted in Fig. 6. It can be seen that the return loss at the center frequency is higher than 30 dB, while the insertion loss is less than 0.35 dB, showing very good passband characteristics. The computed fractional bandwidth is around 19% at the center frequency of 10 GHz.

IV. CONCLUSION

A multi-objective, multi-dimensional particle swarm optimization algorithm is implemented to design an extremely low-profile bandpass frequency selective surface (FSS). The overall profile (thickness) of the designed FSS is only $\lambda_0/65$.

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