PARTICLE SWARM OPTIMIZATION FOR A METAMATERIAL SPIRAL RESONATOR

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Abstract— Soft computing techniques are emerging as highly efficient global optimization techniques in the field of electromagnetics and communication systems. These techniques have proved their efficiency in antenna engineering, wireless communication, absorber design and a few in the field of metamaterial structural analysis. Particle swarm optimization, although has been used recently in controls, is still new to the field of metamaterial science and technology. In this paper, particle swarm optimization (PSO) is used for design optimization of a spiral resonator (SR). Equivalent circuit analysis is used for the analytical model of the SR. The aim of particle swarm optimization is the estimation of structural parameters of the SR at a desired frequency range. A comparative study with other soft computing techniques w.r.t. accuracy and computational time is provided.

Index Terms— PSO; material; spiral resonator; ECA

I. INTRODUCTION

The emerging trends of soft computing techniques reveal that genetic algorithm has been employed extensively for diverse metamaterial applications [1]. In contrast, although particle swarm optimization (PSO) and bacteria foraging algorithm (BFA) are extensively used in control and filter applications [2-3] but are new to the design and optimization of metamaterial applications. The author of this paper have implemented PSO for design and optimization of a few metamaterial applications [4]. In this paper an effort has been made to study the feasibility of PSO in metamaterial design and optimization.

Split ring resonators, spiral resonators, nano-rods are the building blocks of metamaterial design, which gives the negative refractive index at a particular resonant frequency. The resonant frequency of these structures depends on the structural parameters of the design such as width, length and separation of the ring and dielectric constant of the substrate as well. In this paper equivalent circuit analysis is used in conjunction with PSO for estimation of the design parameters of SR at a desired resonant frequency.

II. DESIGN AND OPTIMIZATION OF SPIRAL RESONATOR USING PSO

Particle Swarm Optimization (PSO) is an evolutionary computational technique based on the intelligence of swarms proposed by James Kennedy and Russell Eberhart in 1995. This algorithm is simple and more efficient global search method [4]. The key terms used by PSO are given below:

1) Swarm: Entire collection of particles.
2) Particle or Agent: Each individual in the swarm is referred as particle.
3) Position or Location: Position is referred to as particle’s place in the field.
4) Fitness: Fitness is defined as a single number representing the goodness of a given solution. The fitness function must take the position in the solution space and return a single number representing the value of that position. The fitness function provides the interface between the physical problem and optimization algorithm.
5) pbest (personal best): It is defined as the best position found by the particle. Each particle has its own personal best. It will be updated whenever the particle reaches a position with better fitness value than the fitness value of the previous personal best. Personal best position of a particle expresses the cognitive behavior of particle.
6) gbest (global best): It is defined as the best position found by all the particles in the swarm. For entire swarm there is only one global best. It will be updated whenever a particle reaches a position with better fitness value than the fitness value of the previous
global best. Global best position expresses the social behavior.

PSO is implemented here to optimize the structural parameters of the SR at a desired frequency of operation. The solution approach with the cost function is given in the subsequent Section.

A. PSO Algorithm:
The algorithm of PSO starts with defining solution space i.e the no of parameters to be optimized and follows the definition of fitness function.

1) Define the solution space: Solution space is a place where it will take the parameters which have to be optimized and give them a reasonable range to search for optimal solution. It is referred to Xmin\_n and Xmax\_n respectively, where n ranges from 1 to N.

2) Define a fitness function: The fitness function and solution space must be specifically developed for each optimization.

3) Initialize Random Swarm Location and Velocities: Each particle begins by its own random location with random velocity. Initial position encountered by each particle becomes each particle’s respective pbest. Among these initial positions one value is chosen as gbest.

4) Systematically fly the particle’s through the solution space: Each particle must then move through the solution space. The algorithm acts on each particle one by one, moving it by small amount and cycling through the entire swarm. The following steps are enacted on each particle individually,

a) Evaluate the Particle’s Fitness, compare to gbest, pbest: The fitness function returns a fitness value assigned to the current location. If that value is greater than the value at the respective pbest for that particle, or the global best gbest, then the appropriate locations are replaced with current location otherwise the previous value will be remain same.

b) Update Particle’s Velocity: The velocity of the particle is changed according to the relative location of pbest and gbest. The following equation is used to update the particle velocity.

\[ v_n = w * v_n + c1 * \text{rand}() * (p_{best,n} - x_n) + c2 * \text{rand}() * (g_{best,n} - x_n) \]

\( v_n \) is the velocity of a particle in the n\textsuperscript{th} dimension. \( x_n \) is the particle’s coordinate in the n\textsuperscript{th} dimension. \( w \) is known as inertial weight (range is between 0 and 1) \( c1 \) and \( c2 \) are two scaling factor which determine the relative pull of pbest and gbest \( \text{rand}() \) is random function in the range [0,1]

c) Move the Particle: Once the particle velocity has been updated the particle has to move to its next location. The velocity is applied for time-step t and new coordinate \( x_n \) is computed for each of the N dimensions according the following equation.

\[ x_n = x_n + \Delta t * v_n \]

5) Repeat: For each particle in the swarm the process is repeated starting at Step 4. Every second the snapshot is taken for the entire swarm so at that time the positions of all particles are evaluated and correction made to pbest and gbest values if required. Repetition is continued until the termination conditions are met.

The flowchart of PSO algorithm is given below:

B. Spiral resonator
Spiral resonator is widely used in the design of metamaterials for various applications including biomedical sensors. The schematic of a square SR with
the dimensions is shown in Figure 1a where a is the length, w denotes the width of rings, and d is the gap present between the rings. In this method, the distributed network is converted to lumped network (Figure 1) and analysis is carried out. The metallic inclusions in the shape of spiral forms the inductance and capacitance which in turn resonate at desired frequency depends on the geometrical values of a, w and d.

Fig. 1: Schematic of the square SR and its equivalent circuit

The resonant frequency for square SR is given by [4]

\[ f_0 = \frac{1}{2\pi \sqrt{LC_s}} \]  

(1)

where, L and C are the inductance and capacitance of the SRR respectively [6].

C. Problem Formulation

The efficiency and accuracy of implementation of PSO depends on the formulation of the cost function. The cost function used for this optimization is

\[ f_{err} = \left| \frac{f_d - f_c}{f_d} \right| \]  

(2)

where, \( f_d \) is the desired frequency and \( f_c \) is the calculated frequency obtained by equivalent circuit analysis.

The steps of PSO are followed for optimization of the cost function and the design parameters such as length of the SR, gap between the rings and width of the rings for a desired resonant frequency are obtained. These design parameters become input for the design of metamaterials for various applications.

As PSO is new to the metamaterial science, a comparative study of the other techniques under this umbrella has been provided in Table 1.

Comparison of Soft Computing Techniques for Optimization of a SR at 1.6 THz (Intel Core, 4 GB RAM)

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Accuracy (( f_{err} ) in THz)</th>
<th>CPU Time (in Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSO</td>
<td>0.0184</td>
<td>0.059739</td>
</tr>
<tr>
<td>BFA</td>
<td>0.0298</td>
<td>0.213547</td>
</tr>
<tr>
<td>Genetic Algorithm</td>
<td>1.5630</td>
<td>0.246406</td>
</tr>
</tbody>
</table>

The feasibility study shows that PSO is more efficient in terms of accuracy and CPU time. It is important to mention here that the accuracy and CPU time of all these above mentioned soft computing techniques depends on the parameter selection and depends on type and complexity of the problem.

III. CONCLUSION

In this work, particle swarm optimization algorithm is implemented for design and optimization of metamaterial structures. PSO in conjunction with equivalent circuit analysis method is used for estimation of the design parameters of a spiral resonator. The estimated design parameters can be used as input for design and simulation of metamaterial spiral resonator structure. This work will be a module for design optimization and fullwave simulation of metamaterial sensors for biosensing applications.

REFERENCES


