 CMC, vol.37, no.3, pp.135-146, 2013

Soft Computing for Terahertz Metamaterial Absorber Design for Biomedical Application

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Abstract: The terahertz region of the electromagnetic spectrum plays a vital role in biomedical imaging because of its sensitivity to vibrational modes of biomolecules. Advances in broadband terahertz imaging have been emerging in the field of biomedical spectroscopy. Biomedical imaging is used to distinguish between the infected (cancer) and the non-infected tissue, which requires broad band and highly efficient radar absorbing material (RAM) designs (to obtain high resolution image of the tissue). In this paper, a metamaterial broadband RAM design is proposed towards biomedical spectroscopy applications in the THz region. The particle swarm optimization (PSO) algorithm is used for the design and optimization of the RAM, which enhances the absorption to nearly 99.32% at the required operational frequency.

Keywords: Terahertz, Metamaterial absorber, Biomedical Spectroscopy, Soft computing, PSO.

1 Introduction

Terahertz region of the electromagnetic spectrum has potential application in biomedical spectroscopy because of its sensitivity to liberational and vibrational modes of bio-molecules [Wallace, Arnone, Woodward and Pye (2002)]. The properties of terahertz radiation such as low scattering in biological tissue, high resolution, non-ionization, and low power level (which does not effect in dividing keratinocytes), makes it feasible to use for biomedical spectroscopy. The wavelength of THz is short enough to achieve submillimiter lateral resolution, which makes the system to operate successfully to characterize DNA [Fitzgerald *et al.* (2006)].

Terahertz spectroscopy is a dominant histological examination technique used to study microscopic biological tissues such as carcinogenic cells. THz spectroscopy has grabbed the attention of scientists to exploit the electromagnetic (EM) behavior of materials designed in this region. There is a difference in the properties

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like reflection, absorption of an infected cancer tissue to that of a normal tissue. An infected cancer tissue absorbs more electromagnetic radiation compared to a non-infected tissue [Fitzgerald *et al.* (2006)]. This leads to the role of radar absorbing materials (RAM) in Terahertz imaging. The concept behind RAM is to minimize transmission and increase absorption thereby differentiating the infected tissue from the normal tissue. Terahertz imaging is difficult to achieve by making use of naturally occurring materials due to their inefficient EM response. In order to overcome this, electromagnetic metamaterials [Narayan, Joshi, Nair, and Jha (2012)] may be used to obtain devices that operate in terahertz imaging. RAM has several applications including those of biomedical spectroscopy. Several RAM designs have been proposed over a few decades and the performance enhancement *w.r.t.* material parameters are continuing including the recent trend of metamaterial application. Biomedical spectroscopy requires broad band [Fitzgerald *et al.* (2006)] and highly efficient RAM designs. The RAM structures designed so far have efficiency about 70% to 90% [Wen *et al.* (2009); Landy *et al.* (2008); Landy *et al.* (2009); Narayan *et al.* (2013)] which is not sufficient for biomedical application (to obtain high resolution image of the tissue).

In this paper, a novel RAM design with high efficiency over the required wideband is presented. The performance is enhanced considerably by introducing an optimized metamaterial split ring resonator (SRR). Such an application requires design of metamaterial structures for a desired frequency range (equivalent to the operational frequency of the RAM design). A particle swarm optimization (PSO) algorithm is developed here, which optimizes the resonant frequency and provides the structural parameters. This optimized design is further used as one of the layers of RAM design. The resulting optimized structure provides a near unity absorption within the required frequency range (1.6 THz).

2 Radar Absorbing Materials

Apart from stealth technology, electromagnetic shielding of high reflection surfaces and metal surfaces, radar absorbing materials (RAM) can also be used in biomedical spectroscopy. The common radar absorbing materials are made up of several layers of dielectric, magnetic materials. According to the arrangement of the layers *w.r.t.* thickness and material the RAM designs are named as Dallenbach, Salisbury screen, and Jaumann surfaces [Vinoy and Jha (1996)], which are narrow band resonant absorbers. However, the performance of the RAM designed using natural materials does not yield satisfactory results in the terahertz regime for biomedical imaging due to its demanding requirement on absorption. Another constraint in the above mentioned RAM designs is of the required ultra wide bandwidth. To overcome these limitations, a metamaterial RAM design is proposed here for biomedical applications.

2.1 Principle of RAM Design

The idea behind RAM design is to minimize the transmission and to simultaneously minimize the reflectivity through impedance matching. By manipulating resonances in ε and μ independently, it is possible to absorb both the incident electric and magnetic field. Additionally, by matching ε and μ, a metamaterial can be impedance-matched to free space, thereby minimizing reflectivity. The absorption is defined as

$$A = 1 - |S_{11}|^2 - |S_{21}|^2 \tag{1}$$

where, A is the absorption, S_{11} and $S_{21}$are the scattering parameters.

To minimize the reflection, one can tune the intrinsic parameters of the metamaterial to get the effective ε and μ matched so that the impedance of the metamaterials $z = \sqrt{\mu/\varepsilon}$ is equal to one, and matched to the free space, so that the reflection is in principle, be eliminated completely. To minimize the transmission, the metamaterial needs to be designed such that the imaginary parts of ε and μ are as large as possible, since they correspond to the loss in the metamaterial. Although it is difficult to get the transmission eliminated by one single layer of the metamaterial, there are ways to achieve unit absorption.

The RAM design outlined in this paper consists of 4 layers. The layers are composed of a metal layer adjacent to a dielectric spacer layer. The top layer, which is made of gold is a split ring resonator (SRR) structure (metamaterial). The SRR structure designed here contains inductances and capacitances. The linear bars act as inductive elements whereas the gaps act as capacitive elements which contribute to permittivity and permeability of the structure. Soft computing technique has been used towards optimization of metamaterial structure. Particle swarm optimization (PSO) algorithm is used for design and optimization of the top SRR layer. The implementation of PSO algorithm, for achieving the structural parameters of SRR is discussed below.

3 PSO for Square SRR Design

The performance enhancement of a metamaterial RAM design at a desired frequency can be achieved by placing a metamaterial structure of the same resonant frequency. To get the structural parameters of a metamaterial structure at a desired frequency of operation is *a priori* requirement for analyzing its effect on the performance of RAM design. Hence, a soft computing optimization algorithm is implemented here to get the structural parameters of square SRR.

Soft computing techniques are a collection of computational techniques in computer science, artificial intelligence and machine learning. These techniques includes artificial neural network (ANN), genetic algorithm (GA), fuzzy logic (FL), particle swarm optimization (PSO) algorithm, bacteria foraging optimization (BFO), etc. [Jang *et al.* (1997); Holland (1975); Kennedy *et al.* (1995); Passino (2002)].

Among soft computing techniques available, the PSO is one of the global optimization methods based on the movement and intelligence of swarms, which optimizes difficult multidimensional discontinuous problems [Choudhury, Bisoyi and Jha (2012)]. It is an evolutionary computational technique proposed by Kennedy and Eberhart in 1995 [Kennedy and Eberhart (1995)]. The PSO is a promising, simple, yet effective and robust method, used for search and optimization in various EM problems. The development of PSO can be illustrated through an analogy similar to a swarm of bees in a field. The goal of a swarm of bees in a field is to find the location with the highest density of flowers. This motivates the engineers to use PSO as an optimization technique. The implementation procedure along with the algorithm [Robinson and Rahmat-Samii (2004)] and the parameters used are given below.

3.1 PSO Algorithm:

The PSO algorithm is given here for better understanding of the implementation for optimization of the resonant frequency (and hence to extract the structural parameters) of a metamaterial square SRR described in the following section. The step by step procedure is given below.

*Step*1: Define the solution space: A meaningful range with a minimum $x_{min(n)}$, and a maximum $x_{max(n)}$, is defined for the parameters that are selected to be optimized, where n ranges from 1 to N is defined.

Step 2: Define a fitness function: The fitness function is formulated in such a way that it has a functional dependence relative to the importance of each parameter to be optimized.

Step 3: Initialize random swarm location and velocities: Each particle initializes at its own random location with a random velocity. Using this initial position, *pbest* is found for each particle and the best of these is selected as *gbest*.

Step 4: Systematically fly the particles through the solution space: The algorithm is designed to act on each particle one by one, moving it by a small amount by cycling through the entire swarm. The following steps are encountered on each particle.

- Evaluate the particle's fitness, compare to *gbest*, *pbest*.

- Update the particle's velocity. The following equation is used to update the particle velocity.

$$v_n = w^* v_n + c1^* rand()^* (p_{best,n} - x_n) + c2^* rand()^* (g_{best,n} - x_n) \tag{2}$$

where, v_n is the velocity of a particle in the n^{th} dimension; x_n is the particle's coordinate in the n^{th} dimension; w is known as inertial weight (range is between 0.0 and 1.0); $c1$ and $c2$ are two scaling factors, which determine the relative pull of *pbest* and *gbest*, and *rand* () is random function in the range [0,1]

Move the particle to next location: The particle has to move to its next location, once its velocity is updated. The velocity is applied for time-step t and new coordinate x_n is computed for each of the N dimensions according to the following equation.

$$x_n = x_n + \Delta t * v_n \tag{3}$$

Step 5: For each particle in the swarm *Step* 4 is repeated. Every second the snapshot is taken for the entire swarm so at that time the positions of all particles are evaluated and correction is made to *pbest* and *gbest* values if required.

3.2 Square SRR Design using PSO Algorithm:

Square split ring resonator is a metamaterial structure which consists of two square shaped rings with gap [Billoti, Toscano and Vegni (2007)]. This structure is printed on a dielectric substrate of thickness 8 μm and permittivity 2.8814. The schematic of a square SRR with the dimensions is shown in Figure 1 where a, is the side length of the square, w is the width of conductor, d is the space between the inner and outer square, and g is the gap present in the rings. The equivalent circuit of the square SRR is a parallel LC tank circuit, given in the Figure 2. The resonant frequency of the square SRR is obtained by equivalent circuit analysis method. In this method, the distributed network is converted to lumped network (Figure 2) and analysis is carried out [Fan, Liang and Dai (2007)].

The resonant frequency of the split ring resonator is given by

$$f_r = \frac{1}{2\pi\sqrt{LC_s}} \tag{4}$$

where, C_s is the equivalent capacitance, and L is the effective inductance due to both the rings.

The effective inductance of the square SRR is given by [Billoti *et al.* (2007)]

$$L = \frac{4.86\,\mu_0}{2}(a - w - d)\left[\ln\left(\frac{0.98}{\rho}\right) + 1.84\rho\right] \tag{5}$$

ρ is the filling factor of the inductance and is given by

$$\rho = \frac{w+d}{a-w-d} \tag{6}$$

The equivalent capacitance, C_s is given by

$$C_s = \left(a - \frac{3}{2}(w+d)\right) C_{pul} \tag{7}$$

where, C_{pul} is the per-unit-length capacitance between the rings.

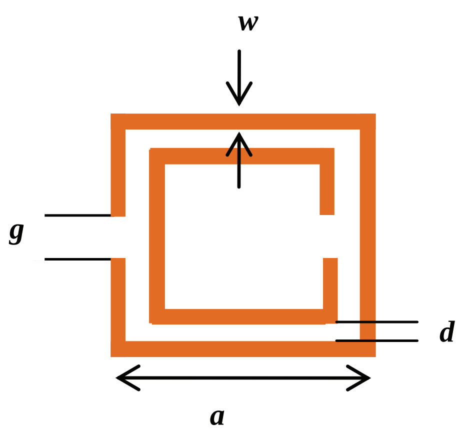

Figure 1: Schematic of a square split ring resonator.

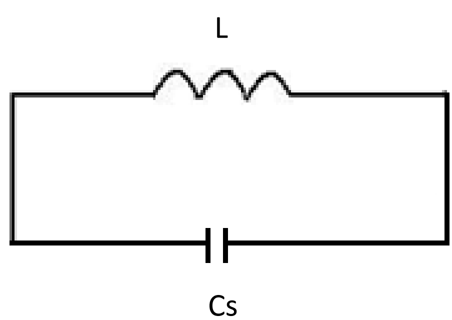

Figure 2: Equivalent circuit of the square SRR

The PSO optimizer acts here as a CAD package, which yields the structural parameters such as the length, width, and spacing for a desired resonant frequency.

The fitness function used for this optimization is

$$f_{err} = \frac{|f_d - f_c|}{f_d} \tag{8}$$

where, f_d is the desired frequency and f_c is the frequency arrived at by the equivalent circuit analysis. As per the algorithm mentioned, the different parameters are assigned with respect to the problem. The parameters of the PSO program are given in Table 1.

Table 1: List of parameters along with their values considered in PSO

PSO Parameters	**Value**	**Use**
w	0.25	Inertial weight
$c1$	2.05	Constant1, to determine *pbest*
$c2$	2.05	Constant 2, to determine *gbest*
Np	10	Number of particles
Nd	5	Number of dimensions
Nt	20	Number of time steps
X_{min}	0	Scalar, min. for particle position
X_{max}	10	Scalar, max. for particle position
V_{min}	-1.5	Scalar, min. for particle velocity
V_{max}	1.5	Scalar, max. for particle velocity

The PSO optimizes the fitness function and extracts the structural parameters. The extracted length a, width w, and the space between the inner and outer ring d, are 25.90 μm, 3 μm and 3 μm, respectively. These optimized values are used for design of the square SRR and the permittivity and permeability values are extracted [Smith, Schultz, Markos, Soukoulis (2002)] using equations (11) and (12).

The simulated scattering parameters (S_{11} and S_{21}), and the corresponding extracted permittivity and permeability are given in Figure 3 and Figure 4. The metamaterial characteristics of the proposed structure are readily inferred in Figure 5, from 0.5 to 2 THz.

$$n = \frac{1}{kd}\cos^{-1}\left[\frac{1}{2S_{21}}\left(1 - S_{11}^2 + S_{21}^2\right)\right] \tag{9}$$

$$z = \sqrt{\frac{\left(1 + S_{11}^2\right)^2 - S_{21}^2}{\left(1 - S_{11}^2\right)^2 - S_{21}^2}} \tag{10}$$

$$\varepsilon = \frac{n}{z} \tag{11}$$

$$\mu = nz \tag{12}$$

The PSO algorithm is implemented to optimize the structural square SRR parameters such as width, length and gap between the slits, for a desired frequency of operation with the overall objective to increase the absorptivity of the RAM structure.

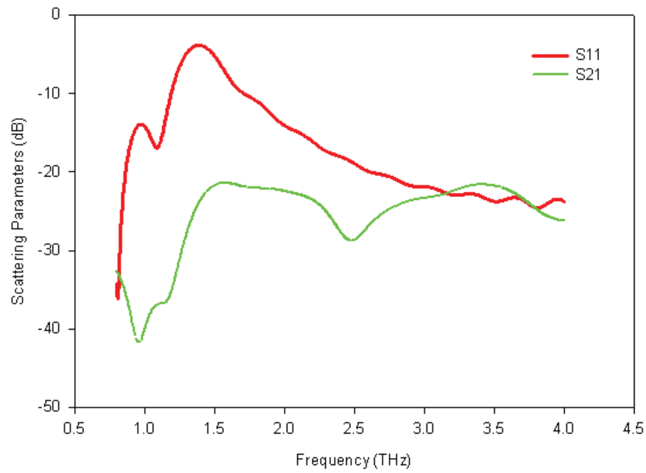

Figure 3: Scattering parameters S_{11} and S_{21} parameters of the designed square SRR optimized using PSO algorithm.

4 RAM Design

The RAM designed here consists of 4 layers as shown in Figure 6. The layers are composed of a metal (gold) layer adjacent to a dielectric spacer layer. The thickness of the gold layer is 0.4 μm and the thickness of dielectric spacer is 8 μm. The top layer made of gold is an array of SRR structure (metamaterial). The SRR structure designed here contains inductances and capacitances. The linear bars act as inductive elements whereas the gaps act as capacitive elements which contribute to permittivity and permeability of the structure. The conductivity of the gold layer is 4.09×10^7s/m. The permittivity of the polyimide layer is 2.8814, and permeability is unity.

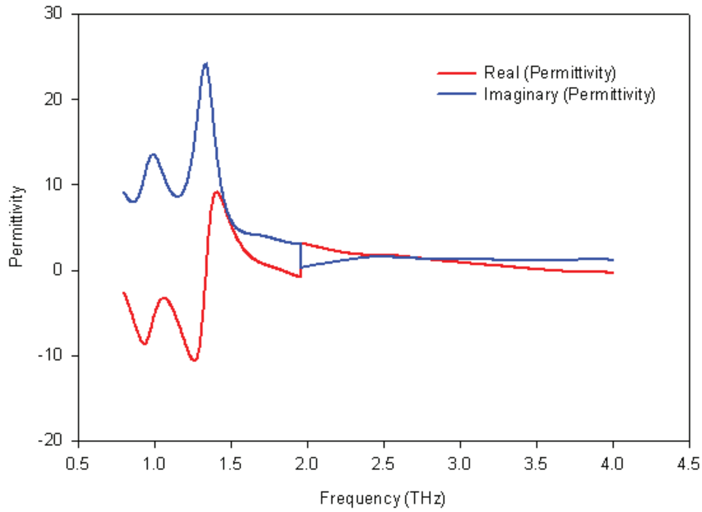

Figure 4: Extracted permittivity of the designed square SRR.

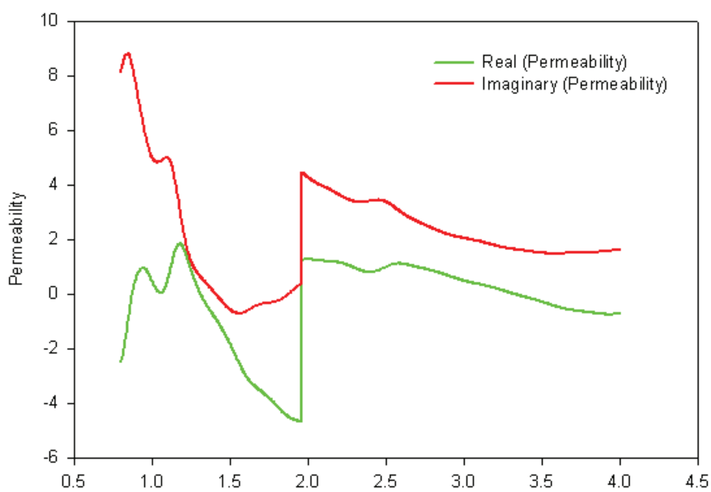

Figure 5: Extracted permeability of the designed square SRR.

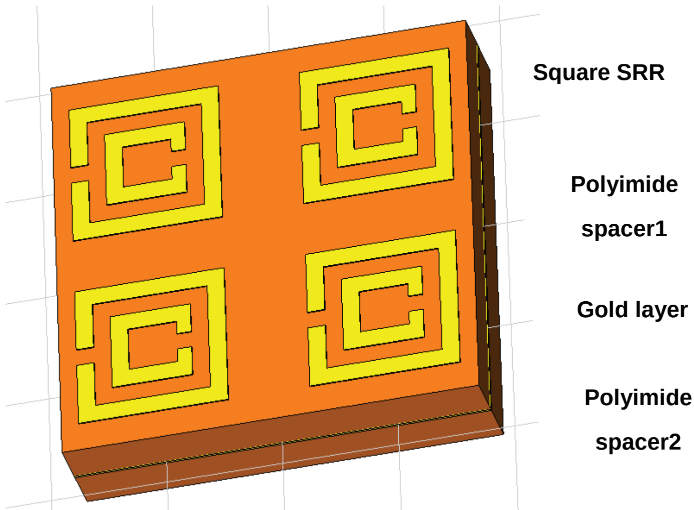

Figure 6: The four layer Metamaterial RAM design. The top layer consists of four optimized square SRR structures

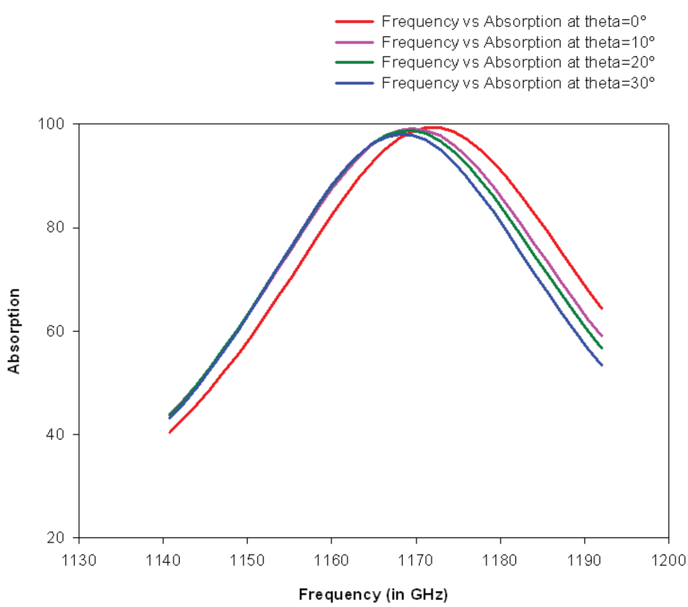

Figure 7: Absorption characteristics of the RAM (absorber) designed by soft computing PSO algorithm.

5 Results and Discussions

The optimized square SRR is introduced as the top layer of the RAM design. The scattering parameters of the designed structure are extracted and used for calculation of absorption. The calculated absorption is given in Figure 7. It is observed from the figure that the absorption (in %) is nearly 99.32 % over the required range of frequency, which is sufficient enough for biomedical spectroscopy applications.

6 Conclusions

An optimized novel metamaterial RAM (absorber) design with high efficiency as high as 99.32% over the required bandwidth is presented for biomedical terahertz application. The performance is enhanced by significant amount by introducing an optimized metamaterial SRR layer. The particle swarm optimization (PSO) algorithm is developed here, which optimizes the resonant frequency and provides the structural parameters of the square SRR structure at the desired resonant frequency. This optimized design is further used as one of the layers of absorber design. It is observed that the absorption is 99.32 % at 1.16 THz, which is sufficient for biomedical spectroscopy applications.

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