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Emerging Trends in Soft Computing Techniques for Metamaterial Design and Optimization

Balamati Choudhury[1], Sanjana Bisoyi[1] and R M Jha[1]

Abstract: Soft computing methods play an important role in the design and optimization in diverse engineering disciplines including those in the electromagnetic applications. The aim of these soft computing methods is to tolerate imprecision, uncertainties, and approximations to achieve a quick solution, which is both robust and economically viable. Soft computing methods such as genetic algorithm, neural network and fuzzy logic have been widely used by researchers for microwave design since the last decade. The metamaterial multilayer concept in conjunction with transformation optics leads to exciting applications in the microwave regime with such examples as invisible cloak, frequency selective surfaces (FSS), radomes, etc. An important aspect of these metamaterial applications is the design and optimization towards actual hardware realization. This paper identifies the emerging trends and suitability of different soft computing techniques for various metamaterial design and optimization applications.

Keywords: Soft Computing, Metamaterial, ANN, GA, PSO, BFO

1 Introduction

Soft computing techniques are gaining momentum in the field of electromagnetic (EM) applications. The exciting features of metamaterials adds to the efficiency of these EM applications, which has encouraged the researchers to move forward in the direction of using the soft computing techniques for design and optimization of metamaterial structures.

The term soft computing was coined by Zadeh (1992). Soft computing is a multidisciplinary system which includes neural network (NN), fuzzy logic and evolutionary computing techniques such as genetic algorithm (GA), genetic programming (GP), simulated annealing (SA), particle swarm optimization (PSO), bacteria foraging optimization (BFO), etc. The aim of these soft computing methods is to achieve quick solutions resembling human like decisions.

[1] CSIR-NAL, Bangalore, India

Applications of these soft computing techniques can be found in every branch of engineering. In this work, an extensive literature survey of the soft computing techniques for metamaterial applications has been carried out. It is observed that genetic algorithm has been employed extensively for diverse metamaterial applications. In contrast, the emerging soft computing techniques like the PSO and the BFO have not been explored comprehensively for these applications. Hence, soft computing techniques for various metamaterial applications are systematically reviewed in this paper. The implemented soft computing techniques for several EM applications in metamaterial design such as FSS, metamaterial absorber, AMC surface, cloaking, etc., are also included. This paper also implements some of the emerging soft computing techniques (e.g. PSO, BFO) for metamaterial design along with the comments on their suitability for such applications.

2 Soft Computing Techniques

Soft computing may be defined as a collection of computational techniques in computer science, artificial intelligence and machine learning, which attempt to study, model, and analyze very complex phenomena for which more conventional computing methods have not yielded low cost, analytic, and complete solutions. Much of the soft computing techniques are inspired from biological phenomena and the social behavior of biological populations. Earlier in most literature, the term soft computing was confined to neural network (NN), genetic algorithm (GA), and fuzzy logic (FL) (Jang *et al.,* 1997). The recently developed methods based on swarm intelligence, and foraging behavior of natural and biological populations such as birds, fishes, ants, and bacteria are also considered to be part of the growing array of soft computing techniques (Holland, 1975; Kennedy *et al.,* 1995; Passino, 2002). A brief description about the soft computing techniques used for metamaterial applications are given below.

2.1 Neural Network

The artificial neural networks (ANN) have been motivated from the inception by the recognition that the brain computes (capability to recognize and perceive) in a different manner than the computer. These features of the brain were studied and the concept has been incorporated in the neural network (NN).

The neural network was first developed by McCulloch in 1943. Some of the inherent capabilities of NN are:

- Suitable for solving hard problems, as processing takes place in parallel instead of in serial mode.

- Can learn in both supervised and unsupervised mode. In supervised mode, the network is provided with the correct response, and in unsupervised mode, the network self-organizes and extracts patterns from the data presented to it (Wasserman, 1993).
- For solving pattern matching problems (Haykins, 1994).
- Hardware implementations of these systems are possible using the VLSI technology (Zebulum *et al.,* 2002).

2.2 Genetic Algorithm (GA)

Genetic algorithm (GA) was developed by John Holland in 1975. The goals of GA are to understand the adaptive processes of natural systems and to design artificial systems software that retains the robustness of natural systems. It uses the concept of natural selection and genetic inheritance. Genetic algorithm is a robust optimization procedure and the search algorithm is based on natural selection process. The basic concept of this optimization is based on evolution, and the concept of the survival of the fittest.

Genetic algorithms are different from normal search algorithms in the following way:

- Coding of parameters (binary or real) is used instead of parameters themselves.
- Searches through a population of points, instead of single point.
- Uses objective function instead of derivatives.
- Uses probabilistic rules instead of the deterministic ones

The most important parameters in genetic algorithm are population size, evolution function (fitness function), cross-over and the mutation rate.

2.3 Particle Swarm Optimization (PSO)

The strategy used by the swarm of bees in locating the highest density of flowers inside a field (garden), is the inspiration for the particle swarm optimization (PSO) algorithm. The bees start at a random location with a random velocity, and optimize the path to reach their goal without any prior knowledge of the field. This behavior was modeled by Kennedy and Eberhart (1995) as an optimizer. The key terms used by PSO are Swarm, Particle, Position or Location, Fitness, personal best (pbest), global best (gbest), etc.

2.4 Bacterial Foraging Optimization (BFO)

As compared to PSO, the bacterial foraging optimization (BFO) is relatively new in the field of electromagnetics. This technique was introduced by K.M. Passino in 2002. The algorithm is inspired by the imitation of food-ingesting (foraging) *E-Coli* bacteria, which are present in our intestines. Here, a group of bacteria moves in search of rich nutrient concentration and away from noxious elements.

The BFO proceeds by selecting or eliminating bacteria based on their foraging strategies. The natural selection tends to eliminate animals with poor foraging strategies and favor those having the successful ones. After many generations, the poor foraging strategies are either eliminated altogether or reshaped into the good ones. The foraging strategy is governed by four different steps which include chemo-taxis, swarming, reproduction and elimination-dispersion.

3 Soft Computing in Metamaterial Design Application

Each one of the soft computing technique mentioned above has their own capabilities, advantages and drawbacks. It is observed that genetic algorithm has been used extensively for various metamaterial applications. The emerging soft computing techniques like the PSO and the BFO however have not been sufficiently explored for metamaterial applications. Hence, in this work an extensive literature survey on implementation of soft computing techniques for metamaterials has been carried out.

3.1 Metamaterial Absorber

An electromagnetic absorber is a structure that ideally absorbs all the incident electromagnetic radiation, without any transmission or reflection. The performance of such an absorber depends on its material properties (effective permittivity and permeability), thickness, and morphology. The exciting properties of metamaterials (negative permittivity and permeability) lead to design of high performance electromagnetic absorber through implementation of various soft computing techniques.

3.1.1 Genetic algorithm(GA) for metamaterial absorber design

The recent trends in the metamaterial absorber design and analysis is to use high-impedance FSS surfaces (Kern and Werner, 2003*a*), artificial magnetic conductor (AMC) surfaces, and the electromagnetic band gap (EBG) structures (Liang *et al.*, 2005). As these are complex structures, soft computing provides an efficient mechanism for design and optimization of the same.

Genetic algorithm was implemented by Kern and Werner (2003*a*) to optimize high impedance frequency selective surfaces (HZ-FSS) for the design of metamaterial absorber. An ultra-thin electromagnetic bandgap absorber was designed at 6 GHz. The fitness function used for the optimization of the HZ-FSS was

$$FF = \frac{1}{0.2\,|\phi_{\max}/180| + 0.8\,|\Gamma_{\max}|} \tag{1}$$

where, $\phi_{\max}$ and $\Gamma_{\max}$ are the maximum reflection coefficient magnitude and phase respectively.

The parameters optimized using GA were the thickness, dielectric permittivity and unit cell size of the HZ-FSS structure. The overall thickness of the metamaterial absorber was reduced without placing a separate resistive sheet in close proximity to the FSS.

Another ultra-thin electromagnetic band gap (EBG) absorber proposed by Liang *et al.* (2005), was made up of FSS screen placed above a conventional metallic ground plane separated by a relatively thin dielectric layer and a lossy conducting polymer. The structure was optimized using genetic algorithm at 4 GHz with a maximum absorption at a conductivity of 40S/cm.

Wang *et al.* (2008) modeled a wave-absorber, made up of two layers over the metal substrate whose structural parameters were optimized using genetic algorithm. The first layer was made up of left-handed material (LHM), while the second layer consisted of regular absorbing material with high absorptivity in the microwave region. By using LHM as the absorber, absorbing bandwidth was widened to a range of 0.4 to 10GHz, with a reflectance of -12dB.

The genetic optimizer was also used by Wang and Werner (2009) for analysis of resistive FSS screens embedded in a stratified medium. An efficient spectral domain periodic method of moments (PMM) formulation was presented. The optimal parameters for enhanced wideband absorption for both the polarizations over a wide range of incident angles were derived. Using this formulation, double-sided wideband absorbers, that employ resistive FSS screens and multi-band ultra-thin EBG absorbers operating over a wide range of incidence angles, were designed.

A thin multilayered metallo-dielectric metamaterial absorber was proposed by Bayraktar *et al.* (2010). The absorber was made up of a periodic array of electrically small metallic FSS screen sandwiched between two different dielectric materials. Satisfactory reflection was obtained at the desired frequency with an attenuation of more than 45dB. The genetic algorithm was used for optimization of the sandwiched FSS screen.

Jiang *et al.* (2010*b*), proposed a similar kind of metamaterial absorber for single band and dual band applications. The absorber design consisted of two metallic layers separated by a thin dielectric spacer, with a top layer having an array of patterned metallic screens and a bottom layer, which had continuous metallic sheets. The design parameters were optimized using a genetic algorithm for the mid-infrared band. The geometrical parameters of the metamaterial absorber were optimized to provide absorptivity greater than 0.94 by the cost function

$$Cost = \sum_{freq} \cdot \sum_{\theta_i} [|A_{i,TE} - A_{tar}| + |A_{i,TM} - A_{tar}|] \tag{2}$$

where, $A = 1 - |S_{11}|^2 - |S_{21}|^2$ and the desired absorption i.e. $A_{tar} = 1$. $A_{i,TE}$ and $A_{i,TM}$ are the absorption for corresponding TE and TM polarization, respectively.

Kollatou *et al.* (2011) presented the design and simulation of an ultra-thin, resonant metamaterial absorber for the operation at microwave frequencies having an improved bandwidth and wide-angle, with near unity absorbance. Genetic algorithm was used to optimize the unit cell parameters. The simulated design reached a peak absorbance of 99.2% at 12.8 GHz, which was used to implement electromagnetic absorber with nearly perfect absorption in the microwave and terahertz regions.

A nano-structured multilayer absorber was designed by Micheli *et al.* (2011) using genetic algorithm for radar-absorbing material (RAM) and shielding structures. They proposed a GA code, which was flexible in selecting algorithm parameters such as frequency band, range of angle of incidence, overall maximum multilayer thickness and that could decide whether the design optimization procedure must privilege the thickness minimization and/or loss maximization.

Liu *et al.* (2011) presented a metamaterial absorber to maximize the absorption and the operational bandwidth. This was made up of electromagnetic smart screen (ESS) of square patch array loaded with pin diodes and the structure was optimized using genetic algorithm. Reflectivity of small screen was measured with free space method and determined through finite element simulation. The relative dynamic bandwidth was observed to be as large as 40%.

Jiang *et al.* (2011) simulated and fabricated a conformal dual band optical metamaterial absorber consisting of a doubly periodic array of stub-loaded H-shaped nano-patches. This structure was optimized using genetic algorithm for the mid-infrared region, with absorption bands at 3.3μm and 3.9μm with absorption larger than 90%.

3.1.2 Particle swarm optimization (PSO) for metamaterial absorber design

Guodos and Sahalos (2006) used an extended version of PSO viz., the multi-objective particle swarm optimization (MOPSO) for the design of planar multilayer coatings with high absorption for a desired range of frequencies and angles. A comparison of multi-objective genetic algorithm with the multi-objective PSO (MOPSO) led to the conclusion that the MOPSO algorithm was faster and more efficient.

3.2 Metamaterial FSS

Frequency selective surface (FSS) is an alternative to the fixed frequency metamaterial where static geometries and spacing of unit cells determine the frequency response of a given metamaterial. Because arrayed unit cells maintain static positions throughout the operation, a new set of geometrical shapes and spacing have to be embedded in a newly fabricated material for each distinct radiated frequency and response. The FSS based metamaterials instead allow for the optional changes of frequencies within a single medium (metamaterial) itself rather than restricting the fixed frequency response. A typical unit cell of metamaterial FSS structure as adapted from Mumcu *et al.*, (2007) is shown in Figure 1.

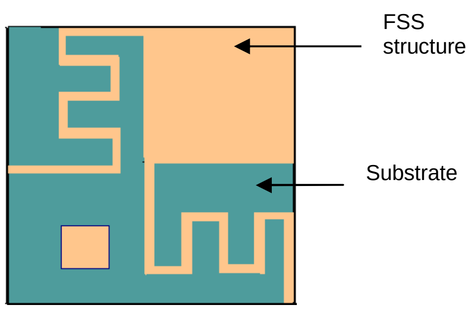

Figure 1: Metamaterial FSS unit cell (schematic)

3.2.1 Genetic algorithm (GA) for metamaterial FSS design

The FSS have wide range of applications those as including aerospace structures, e.g. radome, conformal antennas, etc. As these are essentially multilayered structures and require multiple parameter optimizations, soft computing is an excellent choice for design and analysis.

Kern and Werner (2003*b*) proposed genetic algorithm for design of the meta-ferrite structure that has desirable magnetic properties at frequencies above 2 GHz. Genetic algorithm was used for design of a meta-ferrite with nearly any desired real and imaginary values of permeability by optimizing the surface impedance of the HZ-FSS.

Another thin multi-frequency artificial magnetic conductor (AMC) was realized by Kern *et al.* (2003*c*) by placing a FSS above a perfect electric conductor, which was separated by a thin dielectric layer and optimized using a micro-genetic algorithm to operate at multiple, narrow frequency bands. The operational frequency ranges in dual band FSS were 8 and 23 GHz and in triple band FSS were reported as 3.5, 11 and 18 GHz, respectively.

Gingrich and Werner (2005*b*) realized a thin, planar, low-loss zero index metamaterial (ZIM) using FSS. The design of FSS, superstrate/substrate combination was optimized using genetic algorithm. The optimization was implemented for design constraints such as center frequency, the desired index of refraction and the amount of loss.

Ge and Esselle (2006) designed both the single and multi-band AMC surfaces consisting of FSS screens. The optimization was done by combining the micro-genetic algorithm (MGA) along with finite-difference time-domain (FDTD) method, which was used to determine the fitness function. By using MGA, the optimization time was reduced significantly.

Yet another genetic optimization algorithm was used by Mumcu *et al.* (2007) to design fairly complex composite material textures exhibiting unique field characteristics and dispersion by optimizing the transmission response of FSS. A comparison study of transmission response of the ideal and the optimized loaded fan FSS was reported to have an excellent agreement. The computation time required for this complex structure optimization was 11 Hours using 24 distributed computers.

Bossard *et al.* (2008) used aligned nematic liquid crystal (LC) cells to design micron-scale metallodielectric FSS, all-dielectric tunable FSS and metamaterial whose index of refraction was tunable from negative, through zero, to positive values at the operational frequency. The FSS with a liquid crystal superstrate was designed using conventional and genetic algorithm, which had broadband tunable filter characteristics at the mid-IR wavelengths. The corresponding cost function, C used to optimize the superstrate structure is

$$C = \sum_{Pass} R^2 + \frac{3}{2} \sum_{Stop} T^2 \tag{3}$$

where R is reflectance at each specified pass-band frequency and T is transmittance at each specified stop-band frequency. This structure can be used as IR/optical switches for THz applications.

Jiang *et al.* (2009*a*) used genetic algorithm for optimization of two FSS based multilayer ZIM for cloaking application. Dielectric layers were included and fabrication constraints were incorporated in the design. The refractive index and impedance were optimized using the cost function given below:

$$C = \left|n_{eff} - n_{target}\right|^2 + \left|z_{eff} - z_{target}\right|^2 \quad (4)$$

where n_{target} and z_{target} are the desired refractive index and impedance (normalized to free-space) for the metamaterial. The operational frequency of the optimized structure was 11 GHz with a transmission loss of -0.08 dB.

3.3 Metamaterial Antenna

Metamaterial antennas (Lafmajani and Rezaei, 2011) are widely used in wireless communication in various platforms including aerospace structures due to their features like compactness, compatibility with MMIC (conformal) design, and high performance. The exciting features of metamaterials are used in antenna applications towards performance enhancement. These include gain enhancement, mutual coupling reduction, multi-band applications etc. A typical metamaterial loaded microstrip antenna is shown in Figure 2.

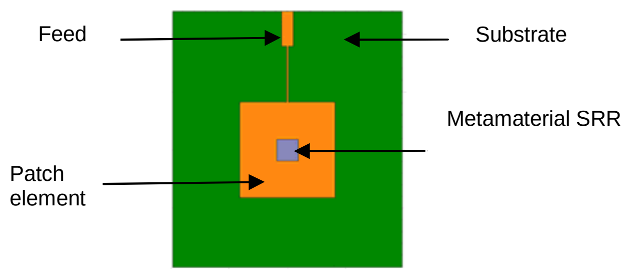

Figure 2: Schematic of a metamaterial loaded antenna

3.3.1 Genetic algorithm (GA) for metamaterial antennas

Kim and Yeo (2007) designed and fabricated a dual band passive RFID tag antenna using an artificial magnetic conductor (AMC) ground plane, whose lumped element in the equivalent circuit was optimized using a hybrid genetic algorithm. This antenna exhibit a dual band operation at European (869.5∼869.7 MHz) and Korean (910∼914 MHz) UHF frequency bands.

Kossiavas and Dubard (2007) designed an AMC named Fabry-Perrot based cavity antenna, which was made up of partially reflecting surface (PRS), perfect electric conductor (PEC) and a patch antenna source to simultaneously enhance the gain and reduce the thickness of planar antennas. Micro-genetic algorithm was used for optimization of the antenna for the operational frequency in the UMTS-WLAN frequency band (1.95 GHz; 2.5 GHz).

An artificial magnetic metamaterial was designed and optimized by Chen *et al.* (2008) using genetic algorithm in which the metamaterial structure was automatically generated by computer via filling element methodology and a fitness function was employed to produce negative magnetic permeability.

$$fitness = \min\left(\left|\left(\mu'_{eff} + R_a\right)\right| + \left|\left(\mu''_{eff} + R_b\right)\right|\right)\Big|_{4GHz<f<10GHz} \quad (5)$$

where, μ'_{eff} and μ''_{eff} represents the real and imaginary part of effective permeability, μ_{eff}. As the desired permeability is -1, R_a =1 and R_b=0.

Tonn and Bansal (2009) designed a linear insulated antenna with a metamaterial coating in the HF band (3 - 30 MHz), whose performance was examined using genetic algorithm based on maximum antenna bandwidth, gain and gain-bandwidth product. The metamaterial coating was explained by a dispersion model, and shown to be equivalent to a capacitively loaded antenna.

A novel stacked-patch antenna was designed by Werner *et al.* (2009), which was made up of matched magneto-dielectric materials as substrates. Genetic algorithm along with periodic moment-method (PMM) code was used to select the optimal material thicknesses, dielectric constant, FSS screen geometry and the unit cell size to reduce the total thickness of the antenna. The targeted center frequency of the antenna was 1.2 GHz and 20% bandwidth, with VSWR less than 2:1.

A new method was proposed by Jafargholi and Kamyab (2010) to obtain an ultra wide band (UWB) radiation from an array of elements placed on a spiral curve and to improve the array performance such as the radiation pattern, array bandwidth, array directivity and front-to-back ratio, using genetic algorithm (GA). The GA was used to shape the radiation pattern through array frequency realization of highly directive UWB spiral array antennas. It was observed that metamaterial covering improved directivity by 5-7 dB. Similarly, a 2×2 circularly polarized antenna array was designed, fabricated and measured by Kossiavas *et al.* (2011), which was optimized using micro-genetic algorithm. Further, to improve its performances, a metamaterial type partially reflective surface (PRS) was placed above the array, which operated in a frequency band from 9 to 9.8 GHz.

A low-cost square dual-polarization horn antenna with a thin metamaterial lining was designed by Scarborough *et al.* (2011) using genetic algorithm to provide low sidelobes, low cross-polarized radiation and radiation patterns that was almost independent of polarization.

Using a computational FEM-based eigenvalue analysis, the uni-planar compact cross-like EBG structure was used by Assimonis *et al.* (2012) for the design of

MIMO (multiple-input and multiple-output) antennas with reduced coupling using genetic algorithm to maximize the bandgap zone.

3.3.2 Particle swarm optimization (PSO) for metamaterial antennas

Jin and Samii (2005) implemented PSO technique to determine the quadrature reflection phase structure (QRPS) topology. In this paper the optimizer was integrated with FDTD technique and the miniaturization effect was observed at 5.7 GHz and 8.8 GHz.

It is pointed out here that although genetic algorithm is implemented for most of the applications, the novel efficient global optimization techniques are not sufficiently explored in the literature. Hence in this paper, the PSO is implemented for mutual coupling reduction of antenna arrays.

Towards this, a single ring split ring resonator (SSRR) is designed and optimized using PSO for the desired resonant frequency. Further, an array of the optimized SSRR was loaded in between the antenna elements (Figure 3). The mutual coupling of the antenna array with and without SSRR is shown in Figure 4. It is observed that the mutual coupling can be reduced significantly when the SSRR is placed in between the array elements.

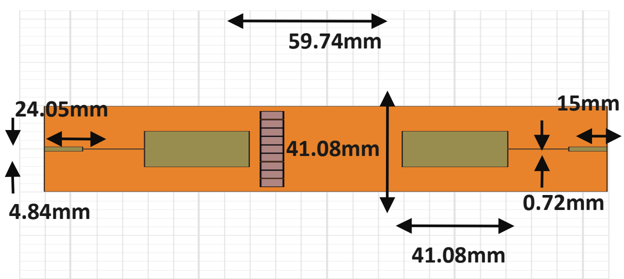

Figure 3: An array of optimized SSRR placed in between the designed antenna array

3.4 Metamaterial Structure

Metamaterials may classified as single negative metamaterials (SNG) and double negative metamaterials (DNG). These properties can be achieved using a number of structures such as the split ring resonators (SRR), artificial magnetic conductor (AMC), high impedance surfaces, frequency selective surfaces (FSS), etc. Some of the typical metamaterial structures are shown in Figure 5.

For various applications, it is invariably required to design the metamaterial structure for a given frequency of interest. Soft computing techniques prove to be an excellent choice for achieving an optimized structure.

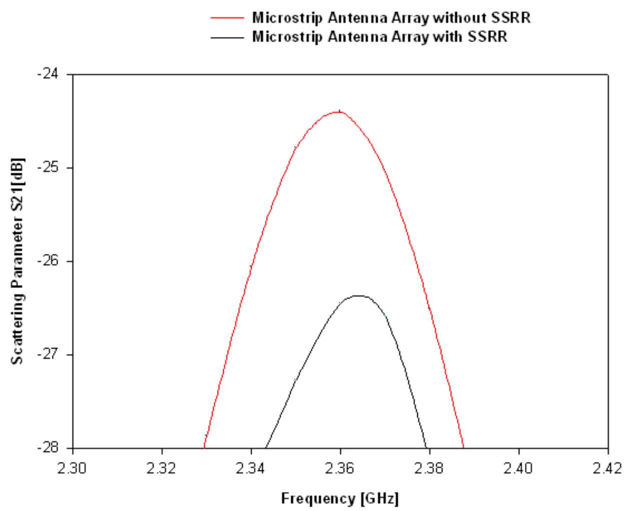

Figure 4: Mutual coupling of antenna array with and without SSRR

3.4.1 Genetic algorithm (GA) for metamaterial structure

Towards metamaterial structure design, Kern *et al.* (2005) used genetic algorithm for synthesis of meta-ferrites which has desirable magnetic properties at frequencies above 1 GHz. Genetic algorithm was used for HZ-FSS optimization to achieve the desired effective permeability. Three different FSS structures were presented and the final design was optimized using the fitness function:

$$FF = -\sum_{n=1}^{N_f} (\mu_r'(f_n) - 4)^2 + (\mu_r''(f_n) - 3)^2 \tag{6}$$

where, N_f is the number of frequencies for optimization.

A new method was presented by Gingrich and Werner (2005a) based on FSS for the synthesis of thin, planar, light weight, low-loss and easily fabricated low/ zero refractive index metamaterial (LIM/ZIM) using GA optimization with operational goals including frequency, bandwidth, effective refractive index, surface impedance and transmission. It was observed that, the real part of the inverted effective index of refraction of the optimized structure was very low (0.005) over 8 – 10 GHz.

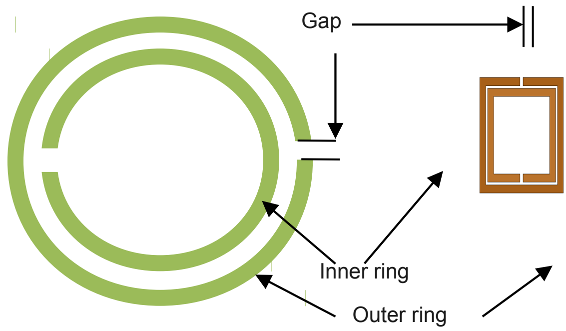

Figure 5: Schematic of typical metamaterial structures (a) Circular split ring resonator (b) Square split ring resonator

Similarly, another design methodology for LIM/ZIM was proposed by Kwon *et al.* (2007*c*) by optimizing the parameters of the low/ zero refractive index metamaterial (LIM/ZIM) using genetic algorithm. It combined a conventional non-dispersive dielectric material with a Drude type material arranged in a checkerboard pattern, which yields an effective permittivity that approaches zero. The metamaterial was formed by stacking several layers of the checkerboard structure rotationally, and the design parameters of the metamaterial were optimized using genetic algorithm.

ZIM structures were also achieved by employing FSS screens for infrared operation at a wavelength of around 20μm (Bossard *et al.,* 2007). Genetic algorithm was used to set the range of target frequency from 15 THz to 20 THz. As a result, a low transmission loss of -1.4 dB was obtained at 18.3 THz.

Zhao *et al.* (2011) presented a negative index metamaterial (NIM) with desired electromagnetic characteristics using metamaterial microstructure design methodology, which uses a FDTD solver optimized by genetic algorithm. The structure was designed to operate up to 20 GHz. From GA optimization, it was also proved that SRR was a fundamental negative refractive index metamaterial for microstructure design.

To design different types of EBG metamaterials, Werner *et al.* (2005) optimized a dual-band GPS/cellular EBG AMC FSS ground plane using genetic algorithm. The optimized structure was simulated and fabricated. The reflection phase plot illustrated that the targeted resonant frequencies were achieved, with a percent bandwidth of 4.43% at 1.575 GHz and 2.2% at 1.96 GHz.

Hybridization of genetic algorithm along with multilayer finite-difference method (M-FDM) was used by Kim *et al.* (2009) for the design and fabrication of EBG structure. The shape of the structure was obtained using a binary sequence generated by genetic algorithm. The suggested method was verified using MATLAB.

Further bandwidth improvement of planar periodic EBG structure was carried out by Deias *et al.* (2009) using genetic algorithm. The optimization was used to find the best structure for a resonant frequency of 14.25GHz.

Bayraktar *et al.* (2007, 2009*b*) proposed a technique to synthesize an artificial magnetic conductor (AMC) metamaterial structure made of FSS screens, separated by a dielectric material, in which the top and bottom surfaces were optimized by a genetic algorithm. The structure showed dual band behavior from 2.14 GHz to 2.23 GHz, and from 5.17 GHz to 5.32 GHz, with gains of 9 dB and 7 dB, respectively.

Ge and Esselle (2007) also used genetic algorithm to design and optimize single band and dual band AMC surfaces consisting of grounded FSS structures by integrating FDTD method. The parameters such as thickness of substrate, permittivity, metallic pattern of the single band AMC structure were optimized to operate at 4.5 GHz to 5.5 GHz. Similar parameters were optimized for dual band AMC to operate at 5.0 GHz to 6.0GHz and 11.5 GHz to 12.5 GHz.

Kwon and Werner (2007*a*) designed a low-index metamaterial in the visible spectrum in which the genetic algorithm was used for optimization of the structure to achieve desirable bulk electrical properties. These structures were used as building blocks for an invisibility cloak in the visible spectrum. A transmittance of 68% was achieved at a wavelength of 0.71μm, and a transmittance of 88% was achieved at a wavelength of 0.69μm.

Chiral metamaterials were also designed and optimized using genetic algorithm (Kwon *et al.*, 2008). The unit cell of the double-periodic metamaterial design was optimized for maximum circular dichroism (CD) and for maximum optical cavity. Circular dichroism value of 56% was obtained at a wavelength of 1.087μm.

A flexible low loss negative index metamaterial designed by Bossard *et al.* (2009) consisting of stacked metal (gold) and dielectric screens perforated with periodic array of air holes. The structure was optimized by genetic algorithm for the given refractive index (-1) with minimum absorption and impedance values in the mid-IR spectrum (85THz to 90THz).

Kahlout and Kiziltas (2009) proposed a technique to design and fabricate the unit cell topology of the heterogeneous periodic material, which was a combination of material simulation model and genetic algorithm.

To achieve desired electromagnetic material properties, a GA-based frame work was designed with material compositions of a periodically repeated unit cell. The low-loss planar multilayer NIM-ZIM-UIM consisted of cascaded modified fishnet metal screens sandwiched dielectric slabs with drilled air holes designed by Jiang *et al.* (2009*b*) whose parameters were optimized using genetic algorithm to obtain the desired effective refractive index and an impedance match to free space at each specified frequency. Further improvement on similar applications was reported by Jiang *et al.* (2010a) using genetic algorithm combined with a generalized inversion method. The designed ZIM showed better impedance match and a lower absorption loss.

Genetic algorithm was also combined with standard transmission/reflection (TR) techniques to determine an automated retrieval procedure of the effective parameters such as effective permittivity and permeability of a metamaterial sample for a given frequency range (Weikai *et al.*, 2010).

A genetic algorithm based CAD package was designed by Pradeep *et al.* (2011) for design and synthesis of SRR, which exhibited negative magnetic permeability. The resonant frequency was in the range of 1GHz to 8GHz.

An optimization procedure based on the genetic algorithm was presented by Radovanovic *et al.* (2011) to develop a model of carrier transport in quantum cascade lasers placed in a strong magnetic field. They also explained the applications of quantum cascade laser-type structures, the design of metamaterials with tunable complex permittivity, based on amplification via inter sub-band transitions.

Similarly, Ni *et al.* (2011) used the dyadic Green's function technique for the design and fabrication of spontaneous emission patterns of electric and magnetic dipoles on different metallic surfaces and a hyperbolic metamaterial (HMM) surface using a genetic algorithm and a pattern search algorithm.

3.4.2 Particle swarm optimization (PSO) for metamaterial structure

Kwon *et al.* (2007) implemented genetic algorithm (GA) and particle swarm optimization (PSO) to design two-dimensional IR-Visible metamaterial using realistic bulk silver parameters. This was done by maximizing a properly defined figure of merit. For this design example, PSO converged more quickly than the GA.

Tavallaee and Samii (2007) used a multi-conductor transmission line based code integrated with the particle swarm optimization (MTL-PSO) algorithm, which was a fast and efficient tool for electromagnetic bandgap power distribution network (EBG-PDN) design optimization. In this paper, a shielded mushroom-like EBG structure was optimized using MTL-PSO. Using simple circuit models, the optimization time was reduced and the accuracy was maintained comparable to full-wave simulators. The MTL-PSO integrated a 1-D MTL-PSO algorithm that reduced the EBG-PDN optimization time greatly with accuracy comparable to FE-based optimizer.

Another novel soft computing technique based on foraging behavior of bacteria (BFO) was also used by several researchers for antenna engineering, and electronic control applications. But the BFO is yet to be explored for metamaterial applications. In this paper the authors have implemented BFO for design and optimization of metamaterial structures. BFO is implemented here to optimize the structural parameters of the SSRR at a desired frequency of operation. The BFO optimizer acts here as a CAD package, which yields the structural parameters like length (a), width (w), and spacing (d) at a desired resonant frequency. The cost function used for this optimization is

$$f_{err} = \frac{|f_d - f_c|}{f_d} \tag{7}$$

where f_d is the desired frequency and f_c is the frequency calculated by equivalent circuit analysis. The BFO-optimized value, along with the equivalent circuit analysis method, is compared and the error is shown, which is within the tolerable limits (Table 1).

Table 1: Optimized structural parameter for desired frequency

Desired frequency (GHz) f_d	f_{err}	*Design optimization output*		
		Length (mm)a	Width (mm)w	Gap (mm) d
0.649	0.000074	15.4	0.7	0.5
0.879	0.000001	9.0	0.4	0.1
1.430	0.000007	6.4	0.6	0.1
3.362	0.000140	3.0	0.1	0.1

3.4.3 Artificial Neural Network (ANN) for metamaterial structure

The capability of artificial neural network (ANN) for design and analysis of metamaterial structures was reported by Subramanian *et al.* (2012). ANN was used for design optimization of dual log-spiral resonator (DLSR), which was an optimal design in the X band. The equivalent circuit model was used for the data generation and network training. Although ANN takes significant computational time, it becomes effective once this training period is over.

Another metamaterial structure, SSRR is optimized using genetic algorithm (GA), artificial neural network (ANN) and hybrid GA-ANN by Vidyalakshmi and Raghavan (2010). In this paper, the structural parameter is achieved by optimizing the resonant frequency. A comparative study of these three techniques were implemented and it was observed that GA provides a better search space and accuracy, the neural network provides quick solutions and hence the combination i.e., hybrid GA-ANN produced an effective structure.

3.5 Metamaterial Cloak

Hiding an object from detection by radar or any other detecting device is the key to invisibility cloaking. This can be achieved when an electromagnetic wave incident on an object, which is to be concealed, comes out of the cloak without being scattered or reflected by that object i.e. electromagnetic field bends around the object (Figure 6).

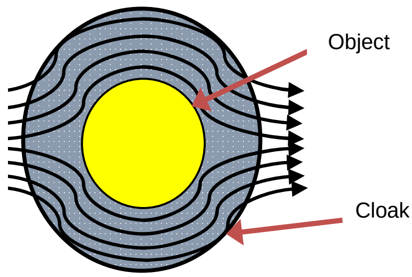

Figure 6: Schematic of an invisibility cloak

The basic concept of cloaking is transformation optics (Ivsic *et al*., 2011) in which a conformal coordinate transformation is applied to Maxwell's equations to obtain a spatially distributed set of constitutive parameters that defines the cloak.

The permeability and permittivity tensors of the cloak material is derived in such a way that the material become spatially invariant, anisotropic and inhomogeneous, which is the property required to achieve cloaking. As the cloak is a multilayer structure, soft computing can be efficiently used for design of the cloak.

3.5.1 Genetic algorithm (GA) for metamaterial cloak

Qiu *et al.* (2008) used genetic algorithm for design and optimization of a cylindrical cloak. A study on the effect of EM and material properties in arbitrary shaped cloaks, effect of concentrators on cylindrical cloak along with improved models were carried out. It was observed that by placing an extra layer of material (or even air gap) at the inner surface of a simplified cloak, the zeroth–order scattering canceled out completely at a certain wavelength.

Feng *et al.* (2011), used genetic algorithm for design of an invisibility cloak having layered structures of isotropic homogeneous media.

With minimum layers of non-magnetic isotropic materials, Yu *et al.* (2011) designed a cylindrical invisibility cloak using genetic algorithm for acceptable cloak performance and a 20 dB reduction in the scattering width for all directions.

Xu *et al.* (2011) designed and fabricated a broadband cylindrical cloak in free-space. Genetic algorithm based optimization procedure was used to minimize the radar cross section (RCS) and optimize the finite positive constitutive parameters of an invisibility cloak at 2.12 GHz via different azimuth angles along with the experimental results.

Oraizi and Abdolali (2008) presented the optimization based on the method of least squares (MLS), which combines the genetic algorithm (GA) and conjugate gradient method (CG) to control the RCS in an ultra wideband width from the study of electromagnetic wave scattering over multilayered cylindrical structures.

Further Oraizi *et al.* (2010) used genetic algorithm and conjugate gradient (GA-CG) to optimize the double-zero metamaterials (DZR) coatings to minimize the reflected power in the radar absorbing applications.

3.5.2 Particle swarm optimization (PSO) for metamaterial cloak

Ivsic et al. (2010) used PSO for metamaterial cloak design and optimization. The developed PSO algorithm was implemented to optimize the relevant constitutive parameters of each layer to achieve minimum possible total scattering width. Although practically invisible cloak can be realized with 10 layers, a comparable level of invisibility can be achieved with 3 layers.

Further the analysis of cylindrical and spherical structures were presented by Ivsic *et al.* (2011), in terms of bi-static RCS. The PSO and CLPSO (Comprehensive learning particle swarm optimization) algorithms were employed to find the constitutive parameters of the cloak that reduced both the backscattering and the forward scattering. It was observed that the number of particles was 300 in case of PSO whereas it reduced to 40 for CLPSO.

3.6 Metamaterial Transmission Line

Metamaterials can be represented by distributed L-C circuit by spatially discretizing Maxwell's equation, thereby arriving at Kirchhoff's voltage and current laws. The lumped element model of the transmission line can be determined by applying quasi-static field conditions to Maxwell's equations and obtaining the circuit equations, leading to the analogy between permeability, inductance, permittivity, and capacitance (Iyer and Eleftheriades, 2002). Soft computing techniques are also used for optimization of transmission line stub.

Gunel (2009) designed a numerical model for composite right/left-handed (CRHL) nonreciprocal and non-symmetric transmission line radial stub using continuous parameter genetic algorithm (CPGA), which requires less storage and less computing time than the binary genetic algorithm (BGA).

Genetic algorithm based procedure was also used by Gunel (2011) for the synthesis of dual-frequency transmission line impedance matching sections. This was implemented for both uniform and nonuniform transmission line impedance matching sections. It was observed that CPGA was faster than the BGA for nonuniform transmission line impedance matching sections.

3.7 Meta-Surface

Meta-surface is a mapping interface supporting interactive design of two-to-many mappings through the placement and interpolation of parameter snapshots on a plane. The schematic of a fundamental meta-surface (Wu *et al.,* 2010*a*) is given in Figure 7.

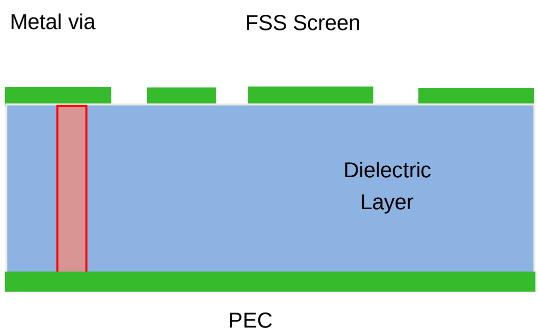

Figure 7: Schematic of a meta-surface

A new design technique for creating matched magneto-dielectric metamaterial slabs was presented by Bayraktar *et al.* (2009*a*). Genetic algorithm was implemented for optimization of thin metallo-dielectric meta-surfaces, consisting of a periodic array of electrically small unit cells, backed by a perfectly conducting ground plane.

A meta-surface with customized electromagnetic properties characterized by their surface impedances was designed by Wu *et al.* (2010*a*) using genetic algorithm, which was used to evaluate the performance in antennas applications.

A broadband meta-surface was designed by Wu *et al.* (2010*b*) using the combination of an optimization technique and an efficient full-wave electromagnetic solver, which satisfied the balanced hybrid condition. The target frequency of soft surface was set at 10 GHz and the unit cell parameters were optimized. Another hybrid metasurface over 11-14 GHz was also designed, which could be used in hybrid-mode horn, conical horn, etc.

4 Conclusions

An extensive literature survey has been carried out in this paper for design and optimization of metamaterials using soft computing techniques. The implementation of the soft computing techniques are systematically described through several EM applications in metamaterial design such as FSS, metamaterial absorber, AMC surface, metamaterial antennas, cloaking, meta-surfaces, etc.

It is observed that genetic algorithm is implemented in most of the cases. The computational time and resources increase with the complexity of structure, which can be reduced by implementing some of the hybridized soft computing techniques such as GA-ANN, MOPSO etc.

In contrast the advanced optimization techniques like PSO, BFO are yet to be explored to its full potential. This paper also includes implementation of some of these emerging soft computing techniques (e.g. PSO, BFO) for metamaterial design along with the comments on suitability of soft computing techniques for specific metamaterial applications.

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