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Optimum topological design of negative permeability dielectric metamaterial using a new binary particle swarm algorithm

N. Di Cesare*, D. Chamoret, M. Domaszewski

Université Bourgogne Franche-Comté, UTBM, IRTES-M3M, EA 7274, Belfort Cedex 90010, France

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ABSTRACT

This paper presents a Particle Swarm Optimization-based topology optimization method for the design of negative permeability dielectric metamaterials.

As the electromagnetic metamaterials have some physical properties not available in nature, they have attracted a huge scientific research interest for decades. In fact, electromagnetic metamaterials can exhibit simultaneously negative permeability and negative permittivity. The aim of this work is to find an optimal topology of a dielectric metamaterial that achieves negative permeability at a given frequency. A binary Particle Swarm Optimization is developed and applied to a negative permeability dielectric metamaterial topology design problem. The optimization process is achieved using a developed numerical model of the studied metamaterial, which is solved by the Finite Element Method.

First, the governing equations and the weak formulation of the electromagnetic problem are presented. Then, the optimization problem to be solved is formulated. The developed binary Particle Swarm Optimization method, and the developed interfacing method are explained. Some numerical examples are presented to demonstrate that the binary Particle Swarm Optimization is adapted to the topology optimization of negative permeability dielectric metamaterials, at given frequencies, to demonstrate the utility and validity of the presented method.

1. Introduction

As the metamaterials have some physical properties not available in nature, they have attracted huge scientific research interest for decades. In fact, many studies have proved that the metamaterials can exhibit some extraordinary electromagnetic properties, like the negative permittivity and permeability, both due to the possibility to obtain the negative refractive index and impedance [1]. In mechanics, some research works [2] have shown the possibility to obtain negative Poisson's coefficient with metamaterials.

In general, the metamaterials have a periodic form [3]. Each unit cell is composed of a background material, along with another material which is included in the background. Even if the two materials are not extraordinary, the inclusion of the second one in the background material exhibits the physical properties of the metamaterial [4] when it is impacted by a periodic wave. The possibility to obtain these extraordinary electromagnetic properties was first proposed by Veselago [5] in 1968. He demonstrated that an original arrangement of the materials in a periodic sequence could exhibit the negative permeability and permittivity. Later, Pendry et al. [6] and Smith et al. [7,8] showed that arrangements of split-ring resonators and metalic wires can exhibit a negative refraction index at a certain frequency. They have also stated that the permeability and the permittivity can be determined knowing the scattering parameters. Furthermore, the possibility to obtain simultaneously negative permittivity and permeability by new types of metamaterials that utilize the magnetic and electric resonance phenomena of dielectric materials, rather than effects primarily derived from metallic inclusions has been shown in [9–12]. As they are isotropic, and made of dielectric materials, these new types of metamaterials could be very effective, and could be used easily in engineering systems. Holloway et al. [10] showed theoretically that designed dielectric spheres embedded in a host material can achieved negative effective permeability and negative effective permittivity simultaneously. Therefore, more practical structures have been proposed, such as spheres with different radii [11] , structures using spheres with the same radii, but with different dielectric parameters [12], and structures using cylindrical dielectric materials embedded in a host material [13]. Experimental results proposed in Zhao et al. [14], Peng et al. [15] and Shibuya et al. [16] have confirmed the obtaining of the negative effective permeability and

* Corresponding author. Tel.: +33 3 84 58 39 17.
E-mail address: noelie.di-cesare@utbm.fr (N. Di Cesare).

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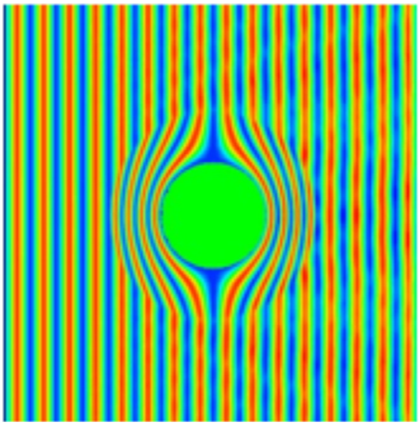

Fig. 1. The field lines deviated from their original path by an electromagnetic metamaterial.

permittivity. Therefore, Chen et al. [17], Cotuk [18], Smith et al. [7], Feng [19] and Hasar et al. [20] developed the efficient matrix methods to retrieve the effective parameters of the complete metamaterial from the scattering parameters, which can be easily be implemented.

In the field of electromagnetic applications, the metamaterials are generally impacted by an electromagnetic field, and react modifying the field lines path. In fact, with a negative refraction index, and a negative impedance, the impacting field lines are able to get around the metamaterial, as can be seen in Fig. 1. Kanellopoulos et al. [21] and N'Guessan [22] demonstrated that the finite element method can be adapted and used for the electromagnetic problems at high frequencies. The aim of their work was to determine an adapted numerical modeling, a method to discretize the Maxwell laws in two and three dimensions, and the precise definition of the boundary conditions to be used. In fact, three typical techniques for the truncation of the finite element computational domain [23] have been developed and used:

- First, the absorbing boundary conditions (ABC) [21] have been proposed to truncate the computational domain in the nonperiodic directions of electromagnetic structures [24]. This formulation is efficient and applicable both for scattering and radiation analysis, and can be used for the numerical implementations of infinitely periodic structures models.
- Secondly, a perfectly matched layer has been developed to absorb without reflection the electromagnetic waves in a structure modeled with the finite-difference time-domain method [25–28]. The perfectly matched layers have been used as some absorbing boundary conditions in the finite-element method [29] to solve the three-dimensional electromagnetic scattering problems.
- And thirdly, the boundary integral equations which can provide a truly perfect reflectionless boundary condition for mesh truncation at higher computational cost have been developed [24]. This method was originally implemented to truncate the computational domain [30–33] and provided exact results, although the computational cost was significantly increased. A preconditioner was also presented to accelerate the convergence to solve the equations obtained from the application of the hybrid finite-element boundary-integral (FE-BI) method to three-dimensional electromagnetic scattering problems [34]. In the developed model, the Perfectly Matched Layers (PML) elements have been used to decrease the computational cost, and obtain some the approximative results of the scattering parameters. In this way, many applications have been proposed to benefit from the extraordinary physical properties of metamaterials, such as cloaking devices [35], waveguides [36], leaky wave antennas [37], acoustic cloaking devices [38], and mechanical applications [39].

Then, the research focused on the possibility to optimize the metamaterials in order to obtain the best physical properties. First, Zhou et al. [40] used a level set method for the design of electromagnetic metamaterials, by a topology optimization. The objective of the work was to obtain some double negative metamaterials, with both negative permeability and permittivity, finding an optimized layout of metallic inclusions. In this case, the objective function was formulated using current flow. Subsequently, Zhou et al. [41] proposed a second level-set-based method to optimize the electromagnetic properties of metamaterials. The aim was to express the permeability of the studied metamaterial in function of the scattering parameters, and then be able to use the permeability as the objective function in the optimization process.

Therefore, Otomori et al. [42] applied the level-set method to the topology optimization of a metamaterial, in order to obtain the best electromagnetic properties. The aim of their research was to optimize especially the negative permeability of dielectric metamaterials. They used the scattering parameters to determine the effective permeability and then, the imaginary part of the effective permeability was minimized. Secondly, using the obtained results during the first optimization process, the real part of the effective permeability was minimized.

Moreover, in the work of Boltasseva et al. [43], some fabrication methods of optical negative-index metamaterials were developed. Combining the works concerning the optimization of metamaterials, and the work of Boltasseva et al. [43], one can think about the possibility to use the metaheuristic methods to optimize the physical properties of electromagnetic metamaterials, such as the effective permeability. In fact, for many optimization problems, there are no deterministic methods reliable enough to obtain the satisfying results. Indeed, these optimization methods can converge to local optima, calculating the sensibilities. So, even if there is no mathematical proof of the global convergence of the metaheuristic methods, they can be used to very efficiently solve the difficult optimization problems [44].

The population-based metaheuristic methods (such as PSO and the genetic algorithms) have the ability to converge to the global optimum, because they consider a population of potential solutions, instead of just one solution. As they use some stochastic parameters, these methods can avoid the combinatorial explosion of the number of solutions. These methods are inspired by physical or biological phenomena. For example, the Ant Colony Optimization [45] draws its inspiration from the foraging behavior of some ant species. The genetic algorithms mimic the process of natural evolution, using processes such as inheritance, mutation, selection and crossover. In this work, the Particle Swarm Optimization (PSO) is considered to optimize a metamaterial model. This method is due to the observation of some flocks of birds by Reynolds [46] in 1987, and has been developed by Keneddy and Eberhart in 1995 [47]. Understanding how the birds can achieve their complex and optimal motion, a new optimization method which could use a swarm of potential solutions has been proposed. Due to stochastic parameters, these solutions can follow the best particles and converge together to the global optimum. To optimize the metamaterials, a modified binary PSO algorithm is developed, that adapts the concept of genotype-phenotype representation [48] presented by Luh et al. in 2011. In the developed method used to solve the optimization problem, the governing equations are solved by the Finite Element Method (FEM) with the software ANSYS® which calculates also the scattering parameters. The optimization problem is solved by the developed PSO algorithm using MATLAB®. The software programs have been interfaced to efficiently solve the problem.

In this paper, a binary particle swarm optimization algorithm is developed for negative permeability dielectric metamaterials topology optimization. Section 2 gives the governing equations of the electromagnetic problem, as well as the statement of the problem. In Section 3, the optimization problem to solve is formulated. Section 4

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