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CONCEPTUAL DESIGN OF MULTIFUNCTIONAL RECONFIGURED ARCHITECTURES FOR ELECTROMAGNETIC NONDESTRUCTIVE EVALUATION

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Abstract: *Multifunctional architectures have gained interest in different research fields. Many innovative designs have implied new components from advanced materials. This paper will approach multifunctional architectures made on the basis of identical and periodic unit cells where the repetitive unit cell approach is used both in the structure [2x2] and in [4x4] UC for which the electromagnetic interaction will be simulated and optimized. Green dyadic functions as well as FDTD (Finite Difference Time Domain) method were used for numerical codes in order to simulate the reconfigurable architecture to validate its electromagnetic (EM) field focusing ability in the nondestructive evaluation (NDE) of materials.*

Key words: *multifunctional reconfigurable concept, EM NDE, simulations, nanostructured materials.*

1. INTRODUCTION

The artificial materials are products of human ingenuity and allow us to design atom-like units and create materials with special properties [1]. These distinctive characteristics of materials are derived from their microstructural geometry, instead of being derived from the materials composition. A material with a special distinctive quality based on its structure is referred to as a structured material. The development of these artificial structures with unconventional signals, due to appropriate geometric or topological concept, is a new challenge for materials research [2].

New trends in research and technology are multifunctional devices being possible for materials that change their properties depending on the application. For example, the emerging use of electromagnetic/optical transformation requires spatial gradients that natural materials do not possess [3]. One of the solutions to this problem is artificially designed materials and has been explored by researchers in various fields for multiple applications [4]. Developing these artificial designs gain more interest in the developing new and advanced materials based on reconfigurable architecture [5]. Multifunctional materials are essential in the development of industries based on advanced technology [6]. These materials couple the interaction between shape and mechanical deformation with electromagnetic waves (EM) and are of interest because they have a high potential in communications applications, waveguides, signal processing and detection.

Signal processing is done starting with the direction of wave propagation up to the location point of the sensor area. Using EM field in the nondestructive testing method, in a C-scan given by an eddy current sensor array, the detection of the flaw boundary is difficult to determine. In NDE of materials, an EM wave propagate through sample and detected after interaction with it. Materials characteristics as density, damping velocity, boundary conditions, loadings, inhomogeneities influence the EM wave propagation. Testing conditions given by work frequencies, sensor accuracy, signal acquisition and processing device also play an important role. Features such spatial location (in the EM signals, the location signal can be extracted from the position of the sensor with respect to the target) are used in addition to classical EM testing using time domain. The sensor array reduces the time of testing. With periodic space between elements in the sub-wavelength domain, reconfigurable architectures are developed with dielectric and magnetic materials.

Multifunctional architecture is made of structures with intuitive properties that originate in unit cell geometry (UC) instead of the properties of each component. The interest in periodic multifunctional structures derives from the connection between elastic and EM features [7].

These architectures can be manufactured by 3D printing [8] or [9], lithography [10], metals or ceramics. In order to meet some design requirements, a specific shape of the cell geometry can be chosen, instead of mixing various materials. Micro and nanoarchitectures that are particularly engineered to provide certain qualities are frequently used to create multifunctional materials. The design of multifunctional materials minimizes the rational geometry of the structure that determine the required features, because the EM properties of materials depend on their structure. Multifunctional materials overall homogenized behavior, nonetheless, mimics that of materials. Additionally, the structure ability to be created in a way that produces materials with exotic variety of physical and mechanical qualities has a significant impact on the properties [11, 12].

New classes of materials including shape-morphing, topological and nonlinear metamaterials exhibit special functionalities, such as layout and shape changes in response to mechanical stress, stiffness, waves propagation or dissipation [13]. Since the properties of architectural materials are governed mainly by their geometry, another interesting way is to embed inner mechanisms able to change the volume of materials, architecture allowing the creation of materials that have reconfigurable functionality. An engineered material with unusual qualities produces a multifunctional design, based on reconfigurable components or UC. According to the diverse features scales of physical fields interacting with them, such as acoustic waves, high frequency EM waves, these components or UC range in size from 10^{-2}m to 10^{-9}m.

New research shows that the multifunctionality of materials with the possibility of reconfiguring architecture can trigger homogeneous and reversible transformations. For artificial materials, the geometric reorganization is both reversible and repeatable and takes place in a narrow range of applied load [14] or [15]. Therefore, reconfiguring architecture offers new opportunities to design structures with controlled changing characteristics. Electronics devices frequently employ multifunctional reconfigurable EM architectures, which can be modified to take advantage of a material special features, particularly EM characteristics that are not typically found in nature. The fundamental requirements for designing multifunctional structures or devices are weight, loading stress, strength, adaptability to environmental conditions, as well as different specific functionalities. Therefore, whether the specific tasks are mechanical or not, design is important in the construction of complex structures [16] or [17].

In this work, a new concept of multifunctional architecture made of identical and periodic unit cells is addressed where the repetitive unit cell approach is used in reconfigurable UC structure for which the EM interaction is simulated and optimized. The ability of a structure to change its shape to achieve a desired deformation or change in function is essential, especially for smart multifunctional reconfigurable architectures (MRA). Green dyadic functions as well as the FDTD method were used for the numerical codes to simulate the reconfigurable architecture to validate its EM field focusing capability in NDE of materials.

2. ARCHITECTURE SENSOR; THEORETICAL PRINCIPLES AND CONSTRUCTION

The network structures considered contain more than one node in a UC (Figure 1). The new planar features of networks are given by cell shape and bond stiffness constants.

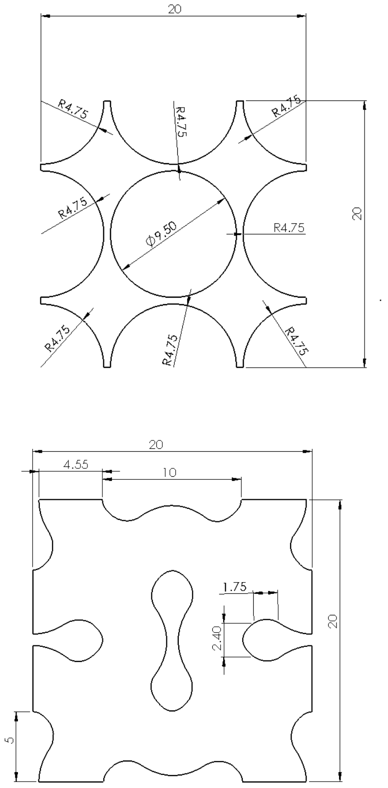
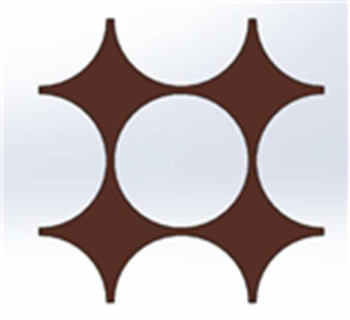
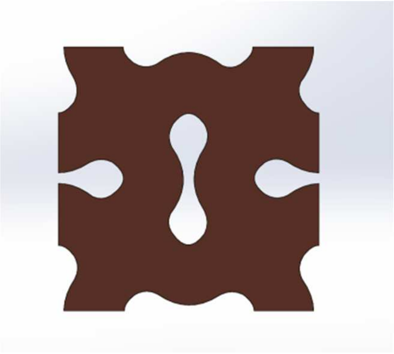


Fig.1. Unit cell: (a) nondeformed and (b) reconfigured

In architecture, nodes connection is considered elastic and isotropic connecting the elements. Under these conditions the constants taken into account are no longer independent and can be found by the shape and dimensions of the connections. In design, two types of architectures were studied: one based on two nodes in the elementary cell nondeformed (Figure 2a) and another based on four nodes in the UC reconfigured (Figure 2b).



(a)



(b)

Fig.2. UC concept: (a) non-deformed and (b) reconfigured

Unit vectors $n^{\gamma}_{\alpha\beta}$ were taken into consideration for nodes ligatures with its closest neighbors, so γ marks the belonging to the specified node, and β corresponds to the neighboring node, respective α to cell. For the cell taken in the analysis, the indexing is *"0"* and for the other cells it is chosen so that

$$\bar{a}^{\gamma}_{\alpha\beta} = a^{\beta}_{-\alpha\gamma}\bar{n}^{\gamma}_{\alpha\beta} = -\bar{a}^{\beta}_{-\alpha\gamma}\,. \qquad (1)$$

The overlapping grid of grids with constant geometric dimensions, arranged at predetermined distances, leads to the formation of UC whose shape is conventionally rhomboidal. After deformation, the geometric parameters of the new structure were determined. Note the unit vectors of the connections:

$$\bar{n}^{1}_{12} = \bar{n}_1;\quad \bar{n}^{1}_{02} = \bar{n}_2;\quad \bar{n}^{1}_{22} = \bar{n}_3\,. \qquad (2)$$

In the case of a conventional cell, the angle, ψ at which it can deform, is positive. Therefore, the network of the deformed structure is negative $(\sin\psi)$. For UC the area is given by the relationship

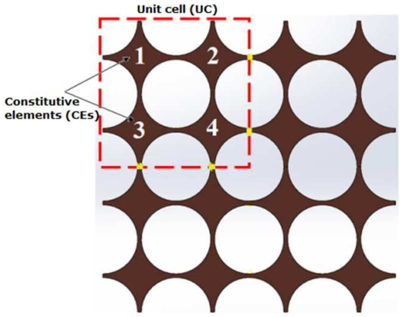
$$S = 2a\cos\psi\left(b + a\sin\psi\right). \qquad (3)$$

Because the structure is similar to the honeycomb network, it can be approximated

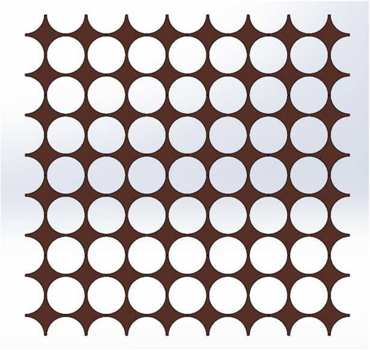
$$S_* = h\left(2a+b\right) \text{ and } \rho = \frac{\left(b/a+2\right)}{2\cos\psi\left(b/a+\sin\psi\right)}\beta\,. \quad (4)$$

where $\rho = S_*/S$ is density, h is thickness of the cell structure and S_* is the material area located in the UC area [18].

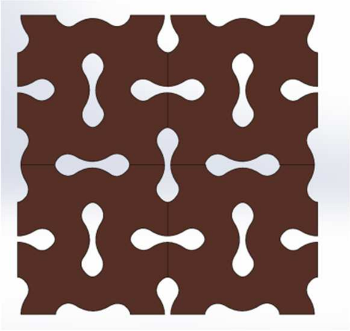
Since the studied multifunctional architectures are made based on identical and periodic unit cells, the repetitive unit cell (RUC) approach can be used in the simulations. By multiplying periodic RUCs, the structure [2x2] UCs was designed for which the electromagnetic interaction is to be simulated and optimized. This represents a 2D model of EC, then by multiplication develops an even number periodic RUCs and respectively UCs, corresponding to the column and line to which the EC belongs. For the accuracy of the system in simulation the network will be refined, the design being concentrated for a multifunctional material. Figure 3 shows a [2x2] UCs structure before and after deformation.



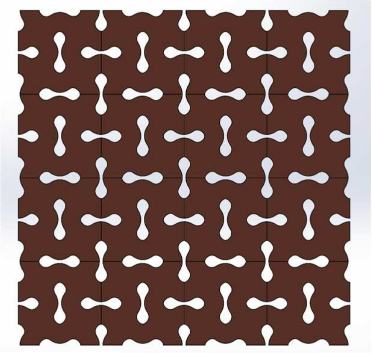
(a) ([2x2] UCs) nondeformed



(b) ([4x4] UCs) nondeformed



(c) ([2x2] UCs) reconfigured



(d) ([4x4] UCs) reconfigured

Fig.3. (a), (b) Periodic multiple UCs structure before and (c), (d) MRA after deformation

By evaluating and optimizing the 2D, then 3D topological configuration, a MRA with a given permittivity was achieved. In the analysis of structure performance, density plays an important role [19] $\rho = S_*/S$, where S_* is the material area located in the UC area. Because the structure is similar to the honeycomb network, it can be approximated

$$S_* = h(2a+b) \text{ and } \rho = \frac{(b/a+2)}{2\cos\psi(b/a+\sin\psi)}\beta . \quad (5)$$

The β parameter is given by the report of the cell structure thickness h and nodes distance a, $\beta = h/a$, being limited by $|\sin\psi| < |\sin\psi_{\max}| = b/2a$ due to network geometry (Figure 4). In particular, the density cannot be infinite because $(b/a + \sin\psi)$ it is always positive. If the Poisson's ratio has the values $-1/3 < \nu < 1$, the angle condition can be obtained from the network geometry $\sin(-\psi) < b/2a$.

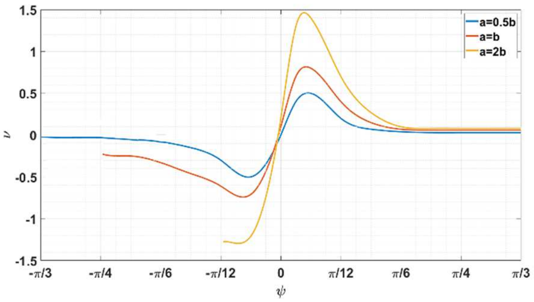


Fig.4. Poisson coefficient vs ψ

Based on the obtained ratios, the graphical representation of the Poisson's ratio by angle ψ for $\beta = 0.1$, depending on the ratio a/b, shows the same curve both for a single UC and for deformed architecture, allowing to configure the optimal layout. One can observe a shift of the curves to the negative half-space for $\psi = 0$ when ratio a/b increases.

3. EXPERIMENTAL SET-UP, SIMULATIONS AND RESULTS

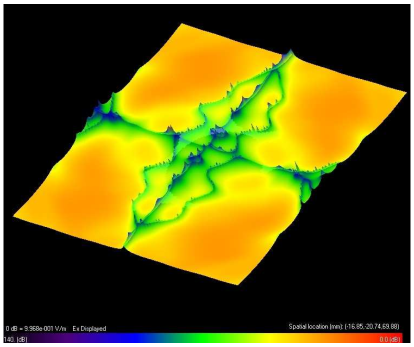
Starting from the UC integral evaluation, the reconfigurable architecture for sensor modeling is taken into study. The metamaterials focus the EM field, and further promote the developed sensor for testing new and advanced materials.

Green dyadic function method and the volume integral method [20] were implied for functional modeling of a rhombohedral UC. Given the geometry presented in Figure 1, the field is created by a complex current source.

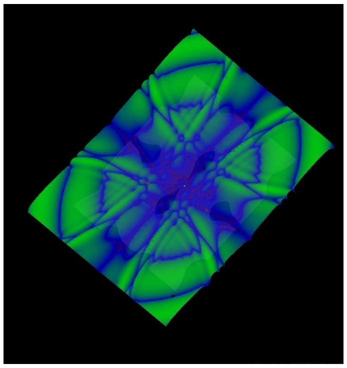
The structure behavior was simulated in FDTD at the 498MHz frequency, without deformation. Placing the UC after the source leads to EM waves focusing. Figures 5a, b presents the signals of multiple periodic UCs at excitation with 498MHz frequency EM wave UC based ECs have been designed in SolidWorks in CAD-*STL format. The simulation was carried out in XFDTD 6.3, REMCOM.

The maximum sensibility of an architecture is seen in the middle of each periodic UCs, and minimum on the border.

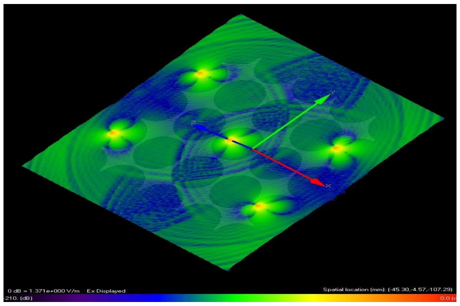
The amplitude and phase of the excitation current in a region free of discontinuities determine the sensitivity in the MRA center. When MRA is placed in XY plane, the EM wave will be radial propagated and normal to the MRA plane, hence only the EM_z wave component is taken into account [21].



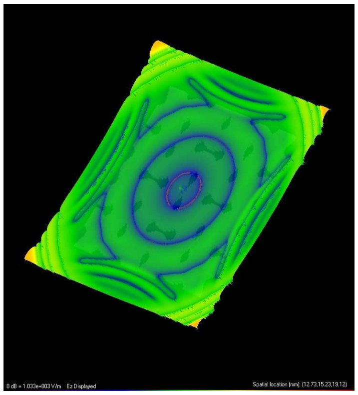
(a) nondeformed UC



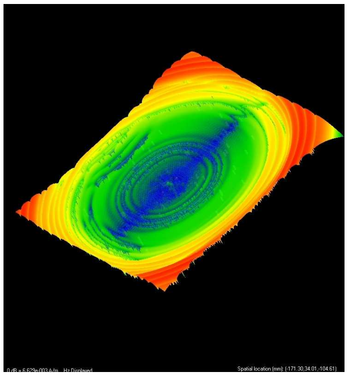
(b) reconfigured UC



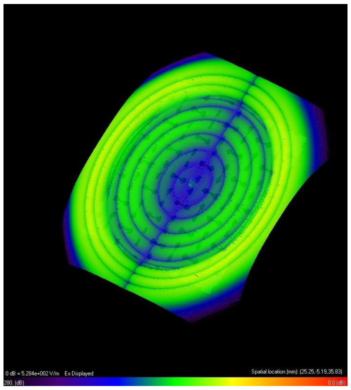
(c) nondeformed [2x2]UCs



(d) reconfigured [2x2]UCs



(e) nondeformed [4x4]UCs



(f) reconfigured [4x4]UCs

Fig.5. FDTD simulations results to UC based on repetitive unit cell approach

4. CONCLUSIONS

The studied multifunctional architectures are made on the basis of identically and periodic unit cells using the repeating unit cells approach. By multiplying periodic RUC, the both structure [2x2] and [4x4] UCs was designed for which the electromagnetic interaction was simulated and optimized. For the accuracy of the system in simulation the network was refined, the design being concentrated on a multifunctional material. Evanescent waves appears on slits between UC when the architecture is excited with a discrete sinusoidal EM wave. The Poisson's ratio was determined by the plane, kinematics and length of the reconfigurable architecture made from an even number of UC. Green dyadic function method and FDTD method, are used into numerical codes to simulate the behavior of the reconfigurable architecture, demonstrating the capability to focus the EM field response of the materials non-destructive tested.

These structures can be used in the field of ISM radio frequencies (industrial, scientific, medical) in the monitoring and evaluation of special purpose materials to highlight discontinuities, the evaluation of inhomogeneity in micro and nanostructured materials, the uniformity of the deposition of different materials with special destinations used in intelligent applications. In the future works, the frequency range will be extended up to 10GHz to monitor the influence of the constraints on the model parameters.

5. ACKNOWLEDGMENTS

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Evaluarea electromagnetica nedestructiva bazata pe conceptul de arhitectura reconfigurabila multifuncțională

Arhitecturile multifuncționale au devenit intens studiate încă de la începutul acestui secol, iar cercetătorii din domeniile electromagnetic, acustic, mecanica si fizica au propus o multitudine de designuri complexe la nivel de material sau componente. In aceasta lucrare sunt abordate arhitecturi multifuncționale realizate pe baza celulelor unitare (CU) identice si periodice in care abordarea celulelor unitare repetitive este utilizata atât in structura [2x2] cat si in [4x4] CU pentru care interacțiunea electromagnetica va fi simulata si optimizata. Va fi simulat comportamentul arhitecturii reconfigurabile folosind un cod numeric bazat pe metoda funcției diadice Green si integrarea volumului FDTD, demonstrând capacitatea de a focaliza răspunsul câmpului electromagnetic al materialelor testate.

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