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RECONFIGURABLE ELECTROMAGNETIC SENSOR USED TO DETECT DISLOCATIONS OF CONDUCTIVE MATERIALS

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Abstract: *The models designed CAD/CAM were loaded into the simulator to analyze the characteristics of the experimental devices attached. The array of sensors with unconventional architecture with reconfigurable unit cells (UCs) was topologically optimized, establishing the opening angle of the cell, the active surface, the geometry of the structure of the areas starting from the idea that the resonance frequency should be within the range of ISM frequencies. The simulations and determinations of test parameters of UC geometry are used for realization of arrays with reconfigurable shapes having the same aperture angle that can be used as noncontact sensors for dislocations detection nanostructured materials.*

Keywords: *reconfigurable electromagnetic sensor, design and simulations, dislocations detect, nanostructures materials*

1. INTRODUCTION

Metasurfaces [1] and planar electromagnetic devices with sub-wavelength unit cells [2,3] have recently attracted attention for their ability to control of electromagnetic waves [4], from microwave to visible range [5]. With tenability added to the unit cells, the reconfigurable metasurfaces [6] enable us to benefit from multiple unique functionalities controlled by external stimuli. In the early stages of metasurfaces research, once the UC is designed, its function is fixed, for example, an absorber works at a certain frequency where the input impedance is matched to the free space. Thus, if change the working frequency or even the functionality, reconfigurable architectures are made due to the structural nature of the UC. In fact, the properties of the metasurfaces can be adjusted by adding tuning capability in the UCs [6]. Such metasurfaces are reconfigurable and they provide more opportunities in achieving as multilayer structures applications [7]. A variety of electromagnetic sensors have been developed, such as: linear array [8], rotating magnetic fields [9], pulsed eddy current [10], waveguides and gratings [11], sensors with metamaterials [12,13]. They show some advantages, but at the same time, they possess some limitations and drawbacks [14] such as: spatial resolution, depth of penetration, conductivity of the material, positioning with respect to the tested material.

Based on these it is expected to exceed the limits in the realization of a multifunctional material with properties and performances based on electromagnetic and mechanical microstructures of the metal-dielectric-metal (MDM) and metasurfaces. The mechanical properties of interest include low density, high rigidity, breaking resistance vs. rigidity or even a specific stress/strain curve. For this, the performance of the material is based on the close interaction between the electromagnetic and mechanical microstructures that can have special effects in the design of the communication and radar systems, the miniaturization of the devices and the design of new sensors with special properties.

Due to the realize mode their inclusions (geometry, material) and arrangements, metasurfaces exhibit distinctive properties not easily found in traditional materials and/or existing technology [15]. Recently, there has a growing interest in metasurfaces, based on the combination of two basic UC with out-of-phase responses [16].The literature presents theoretical study of the relevant scaling-laws, which sheds light on the physical mechanism underlying the scattering-signature reduction [4]. Moreover, was analytically derived some absolute and realistic bounds, and introduced a simple, deterministic sub-optimal design strategy based on the theory of flat polynomials [17].

This paper presents a new type of sensor, whose construction and simulation are based on a reconfigurable architecture using an MDM type material. The realization of the model was conceived in SolidWorks in CAD-*STL format and imported in XFDTD 6.3 produced by REMCOM was simulated the model being then imported into FDTD. The CAD/CAM models of reconfigurable architecture were designed in the multiple UC structure considering that the kinematics of a structure with CEs is function of the angle in the XY horizontal plane. The simulation of the operation of the wavelength excitation process, first realized theoretically using the Finite Difference Time Domain (FDTD) method, was performed using specialized XFDTD software. The modification of the architecture and the size of the structure are imposed by the response of unconventional reconfigurable architecture to the interaction with the electromagnetic field in order to obtain a higher resolution to can be used as noncontact sensors for dislocations detection nanostructured materials.

2. RECONFIGURABLE ARCHITECTURE SENSOR. PRINCIPLE AND DESIGN

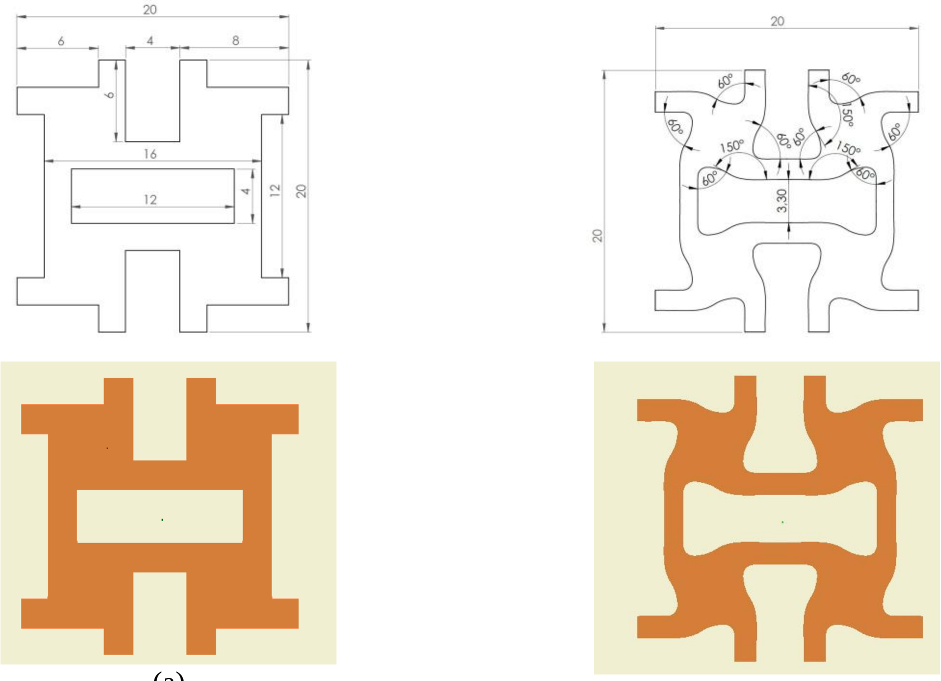
It has been shown that in semiregular architecture 1D, evanescence waves can occur in the zones between the unit cells constituents (voids) when the structure is excised with discrete sinusoidal electromagnetic wave. Using a numerical code based on the Green dyadic function method and the FDTD volume integration, the semiregular architecture behavior was simulated demonstrating the capability to focus the electromagnetic field response of materials involved in non-destructive testing [18]. The geometry of the UC taken in the analysis is shown in Figure 1, having the lattice constant a. The resonant layer, in UC is by definition normal to the unit vector $\hat{u}_i, (i = x, y, z)$ and is centered in the point $x_{0,i} = -(a/2)\hat{u}_i$. The assembly of CEs based on periodic UC is based on an anisotropic response, but within the range of the wavelength used, the material response is approximately isotropic due to the spatial arrangement. It is assumed that a structure can be characterized by the impedance obtained from the model circuit, $Z_0 = j\omega L + 1/(\omega C)$ (for simplicity the effect of metal losses is neglected). A structure that behaves as metasurfaces is an arrangement from identical UC, in 2D layout [19,20].

The design variables $\xi \in [0,1]$ interpolate the material properties for each CE used for the discretization of the structure. If the design variable has a value of 0, we should have material from phase 1, and if the design variable has a value of 1, we should have material from phase 2. We chose a linear interpolation between the phases, since

$$\begin{aligned} \rho(\xi) &= (1-\xi)\rho_1 + \xi\rho_2 \\ \mu(\xi) &= (1-\xi)\mu_1 + \xi\mu_2 \\ \lambda(\xi) &= (1-\xi)\lambda_1 + \xi\lambda_2 \end{aligned} \tag{1}$$

where indices 1 and 2 represent the properties in materials 1 and 2 respectively, λ and μ are the Lame coefficients, ρ is material density.

The conceptual model was simulated based on the structure parameters that determine the ECs dimensions considering a weak deformable elastic behavior. In modelling, the dimensions of a CEs based on the UC were set at 20x20mm (Figure 1), with the possibility of being reconfigured to be integrated into an unconventional multilayer structure. The support for modelling and simulation has a Cu layer with a thickness of 18μm deposited on a 12μm polyimide film without adhesive between them. Figure 1a shows the structure of a CE based on a configured UC and Figure 1b shows the structure of the derived unit using the field phase method.



(a)

(b)

Figure 1: Single unit cell of a unconventional architecture (a) configurable and (b) reconfigurable

Figure 2a shows the architecture realized from (4x4) CUs and Figure 2b shows details of the center of the layout (2x2) CUs. The structural dimensions were determined by scalable changes for pre-established frequency, the design reconfigured having dimensions in functions of the wavelength so that the excited frequency in the CE to be in the radio frequency range. The connections in establishing the design were followed to maintaining configuration during the reconfiguration. It is important to maintain the materials properties after making changes to the structures. The defect-free surface can still be as surfaces for the design and construction of CE based on reconfigurable UCs with the role of belonging to an evanescent in the gaps between them.

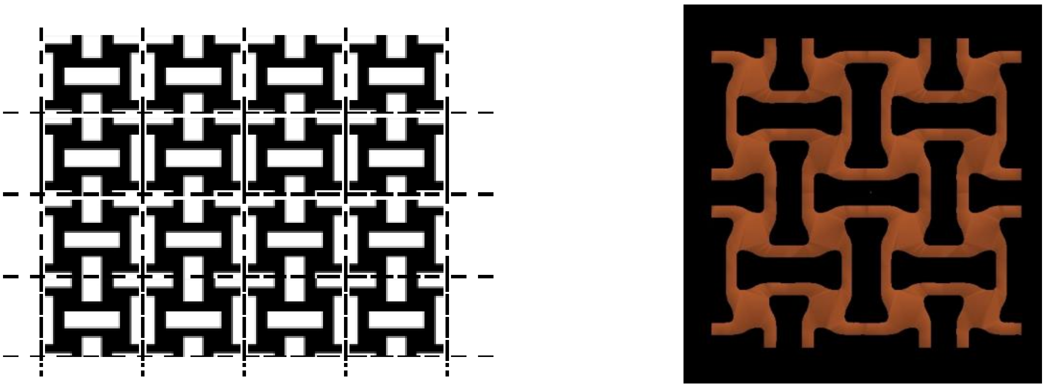

(a) (b)

Figure 2: Unconventional periodic architecture base on UCs: (a) configurable; (b) reconfigurable

The proposed approach yields to results that are comparable with those typically obtained by numerical optimization, in terms of radar cross section reduction, but with a substantially reduced computational burden. Therefore, it renders the design of structures with arbitrarily large electrical size computationally affordable. The linearized problem for a small surface (boundary Ω_A, volume V_A), specified by the displacement limits is solved using linear programming. Physical modelling then identifies the main phenomena that appear in operation and the source of the EM field being followed by mathematical modelling. Using the Maxwell equations and considering the component of the electric field in the z direction, the reduced form is written

$$\int_{\Omega_A}\left[\left(\frac{\partial\tilde{E}_z}{\partial x}\frac{\partial E_z}{\partial x}+\frac{\partial\tilde{E}_z}{\partial y}\frac{\partial E_z}{\partial y}\right)-\varepsilon_r k_0^2\tilde{E}_z E_z\right]\mathrm{d}\Omega=\int_\Gamma \tilde{E}_z\frac{\partial E_z}{\partial n}d\Gamma \quad \text{for } E_z\in V_A, \forall\tilde{E}_z\in V_A \tag{2}$$

where

$$V_A=\left\{E_z\in H^1(\Omega_A) \text{ with } \begin{matrix} E_{z|\Gamma}=\xi E_{z|\Gamma} \\ \left.\frac{\partial E_z}{\partial x}\right|_\Gamma=\xi\left.\frac{\partial E_z}{\partial x}\right|_\Gamma \end{matrix}\right\} \tag{3}$$

$$\xi=\exp\left(-j\sqrt{\varepsilon_r}k_0\sin\theta\right)$$

Equations (2) and (3) describe the physical phenomena at boundary, looking for the solution and identifying the results. Validation is done by comparing at boundary, looking for the solutions (obtained by solving the EM field problem using the discretized model) with the experimental data. As the amplitude of a coupled evanescent wave measures the energy stored in the material, their increase is realized by the EM oscillations at the resonance of the sample. To excite the weak waves, the incident field must be in phase with these waves, so the extraction field must be an evanescent wave.

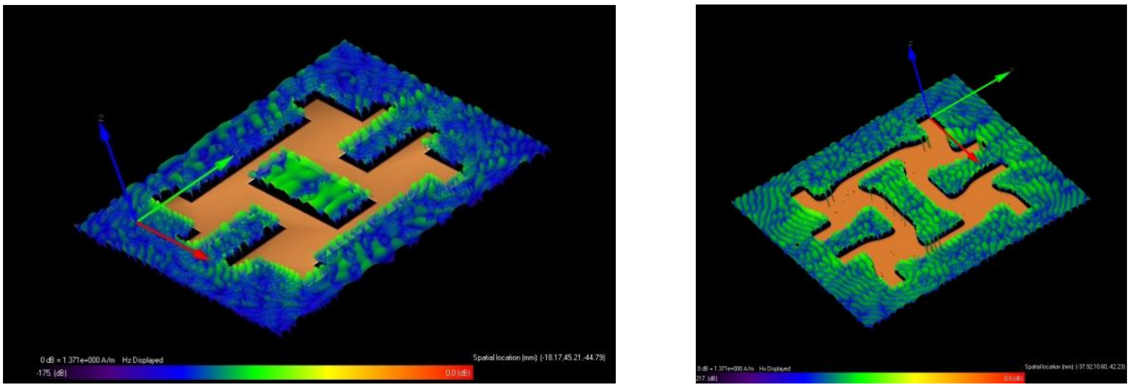
3. SIMULATION AND RESULTS

In nondestructive evaluation of materials, an electromagnetic wave is generated and directed to the interrogated structure and detected after it has propagated into the structure. Propagation is affected by material properties (attenuation and propagation speed, density), environmental conditions (residual stress, dislocations, mechanical loading and border conditions,) and measurement conditions (sensitivity, size and sensor location, interrogation frequency and control electronics). The modelling the sensors have started from the UC analysis, taking into account the reconfigurable architecture.

The presence of the metasurfaces aims at focusing the field, taking into account the technical aspects related to the use of the metasurfaces structure, namely the masking, the selection of materials (the behavior was simulated taking into an account the existing tensions and the expansion that may occur). Functional modelling was performed using the Green dyadic function and volume integration method for a UC having rectangular shapes. The current source that creates the field has a complex structure due to the geometry presented in Figure 1. As such, we can assume that a Hertz dipole placed at a distance equal to the focal distance of the metasurfaces will generate for longer distances than the focal distance, the same type of field, so a spherical wave front.

The design parameters showed that for CE studied, having the length as a defining element fixed at 20mm, made from LONGLITE^{TM} 200, the optimal working frequency is around 320MHz. In order to validate the model, the behavior of a UC based CEs designed in SolidWorks in CAD-*STL format and imported in XFDTD 6.3 produced by REMCOM was simulated. For this reason, a development in 256x256 spatial harmonics was used. It is observed of the UC in front of the source, excitation being electromagnetic wave, at the frequency of 498MHz, without being subjected to mechanical stretching, has the ability to focus the field after crossing it (Figure 3a). After reconfiguration, this ability of the architecture is observed also without modification of the parameters (Figure 3b).

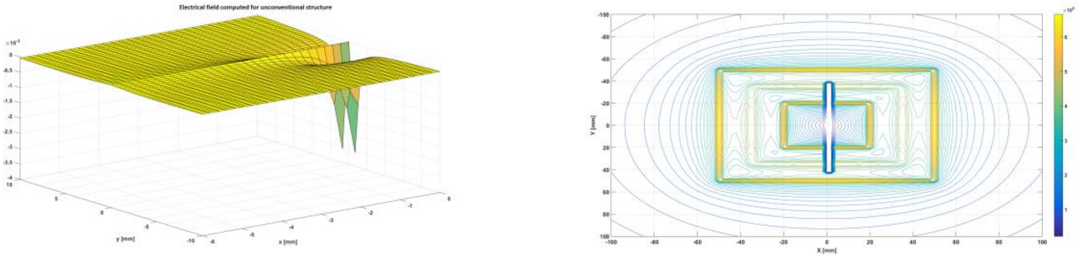
Figure 3 shows the field distribution on the surface of a UC based on CEs for frequencies in the near field and away from the resonant frequency. Figure 3a shows a reduced focusing of the electric field intensity in the central area considered empty; indicating a low electromagnetic resonance, in Figure 3b it is observed the formation of loops sustaining the electromagnetic resonance and the confinement of the electric field to the central narrowed zone EC.



(a) (b)

Figure 3: FDTD simulations results to CE based on UC: (a) configurable and (b) reconfigurable

Examination of the results in Figure 4 shows that reconfigurable architecture as a waveguide improves the image of the scattering surface and might function as perfect lens. The evanescent waves can be coupled efficiently in surface modes and can be strengthened by their resonance nature, when their wave vectors are adapted. As the amplitude of the control evanescent wave measures the energy stored in the material, their increase is realized by the EM oscillations at the resonance of the sample. To excite the weak waves, the incident field must be in phase with these waves, so the extraction field must be an evanescent wave (which quickly dampens). The resonance occurs when the propagation factor of the incident field corresponds of the propagation factor of the surface waves. In this case the surface waves are excited more efficiently.



(a) (b)

Figure 4: (a) Real component of the electric field for the unconventional multilayer structure; (b) distribution of currents in the layer

4. CONCLUSIONS

It is known that in 1D semiregular structure, when the reconfigurable architecture is excited with discrete sinusoidal electromagnetic wave, evanescence waves appear in the areas between the constituent elements of the unit cells. Thus, the behavior of 2D multilayer architecture was simulated and demonstrated the ability to focus the electromagnetic field response of materials involved in non-destructive testing based on a numerical code using the Green dyadic function method and FDTD volume integration. The field focuses in the presence of metasurfaces taking into account the characteristic aspects related to the use of the reconfigurable architecture of metasurfaces, in terms of material properties in order to use as noncontact sensors for dislocations detection nanostructured materials. To validate the model, the behavior of a UC-based CE was simulated and the optimal working frequency was found to be around 498 MHz. The unconventional structures based on metasurfaces (constituent elements based on unit cells) are systems made up of multilayer type configurable component elements in different 2D arrangements. They are able to reconfigured, with significant properties, from the point of view practically, noting the strong concentration of a magnetic flux of radio frequency.

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