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NONDESTRUCTIVE ASSESSEMENT OF NANOSTRUCTURED MATERIALS BASED ON RECONFIGURABLE DESIGN

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Abstract: *A reconfigurable sensors design (RSD) has been studied in order to be used as sensors array in electromagnetic nondestructive evaluation. A set of constituent elements (CE) based on periodic unit cells (UCs) is based on an anisotropic response, but in the used wavelength range, the response of the material is approximately isotropic due to the spatial arrangement. The electromagnetic sensors array, whose construction and simulation are based on an RSD, is using Metal-Dielectric-Metal type material. The CAD/CAM models of RSD 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 performed theoretically using the finite difference time domain (FDTD) method, was carry out using specialized XFDTD software.*

Keywords: *reconfigurable sensors design, electromagnetic nondestructive evaluation, design and simulations, nanostructures materials*

1. INTRODUCTION

According to [1] a sensor array is a group of sensors, usually deployed in a certain pattern used for collecting and processing electromagnetic (EM) or acoustic signals. To determine the direction of wave field travel, a set of sensors are deployed in space to monitor the radiating energy. The localization of the object in a given image frame can be derived from knowledge of the sensor position in relation to the target pursued. The technique using eddy current sensors array to recognize the inspected zone has been intensively studied [2, 3]. The signals processing starts from classical direction of arrival [4] which indicate the direction from where the wave is propagating arriving in the localization point of the sensors set. In nondestructive testing method using electromagnetic (EM) field, at a C-scan obtained from an eddy current sensors array, the identification of the flaw boundary is difficult to estimate. To overcome the problem, using conventional eddy current techniques (which extract only temporal characteristics), the characteristics are complemented by spatial location (the location of the area in the electromagnetic image can be derived from knowing the position of the sensor relative to the target). Along with all these benefits, the advantage of these sensor arrays also includes the simplified procedure of reducing the inspection time of complex parts. Reconfigurable periodic structures are constructed using areas of dielectric and magnetic materials, with periodic spacing close to the operational wavelength of radiation, intended to cause the target element. The periodic microstructures incorporating EM materials use the concept of propagation behavior to generate EM structures that have the desired functions. Reconfigurable EM structures are widely used in electrical devices and can be adapted to exploit the specific properties of materials, especially EM properties that are not usually observed in nature, through the appropriate reconfiguration of metastructures. This paper presents a new reconfigurable sensor design (RSD), whose construction and simulation are based on unit cells (UCs) made an MDM type material.

2. PRINCIPLE AND RECONFIGURABLE SENSORS DESIGN

In modelling, the dimensions of a constituent elements (CE) based on the periodic UC were set at 20x20mm, made from LONGLITE TM 200 with the possibility of being reconfigured to be integrated into a multilayer structure. The support for modelling and simulation has a Cu layer deposited on a polyimide film without adhesive between them in order to not increase the dielectric losses. The resonant layer, in UC is by definition normal to the unit vector

$$\hat{u}_i, \left(i = x, y, z\right) \tag{1}$$

where $x_{0,i} = -\left(a/2\right)\hat{u}_i$ is centered in the point. The electromagnetic sensors array is constituted by the emission part Em and reception part Re, thus, we denoted with X_i the amplitude of in phase component and Y_i, in phase quadrature, measured at the output, the electromotive force is

$$a_i = \sqrt{X_i^{\ 2} + Y_i^2} \tag{2}$$

$$\psi_i = a\tan\left(\frac{Y_i}{X_i}\right) \tag{3}$$

In the field of radar application [5] the resolution of eddy current array can be significantly improved by detecting the direction of propagation. The signals received from the sensor array can be written as a vector $x_i = a_i e^{j\Psi_i}$ where M is the number of receivers, a_1 ... a_M the amplitude and respectively ψ_1 ... ψ_M the phase of the induced electromotive force for each element and j is the unit imaginary number.

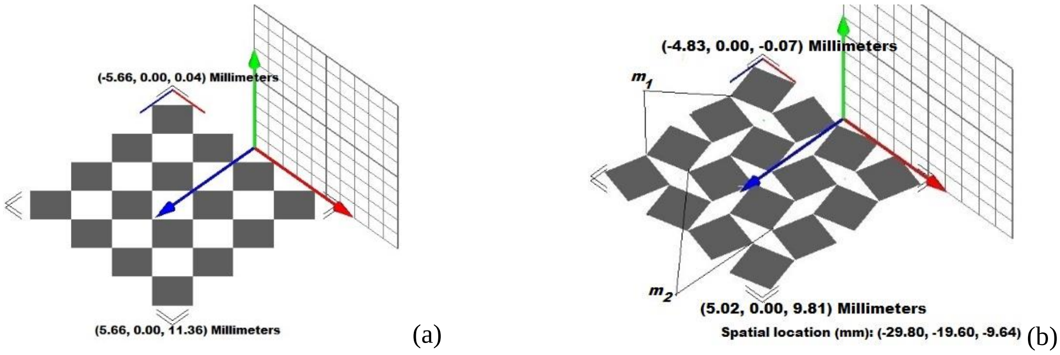


Figure 1: (a) periodic multiple UCs and (b) RSD

3. SIMULATION AND RESULTS

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, RSD 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. The real challenge in order to apply the eddy current sensors array method appears when two discontinuities are closer than the spatial resolution of the UC. When the distance between discontinuities is large enough, the position of the local maximum of the normalized response as a function of position is distinct [6], so two maxima of the discontinuity location curves appear. If the distance between the discontinuities is small, the corresponding peaks will overlap, the signal increases in intensity and a single peak will appear [7-9]. The modification of the design could vary this distance so that the spatial resolution between two flaws shall be acceptable. In order to be able to locate multiple closer flaws, the solution is applying the super resolution method based on maximum likelihood and performing multiple simulations [10]. In order to validate the model, the behavior of a UC based ECs designed in SolidWorks in CAD-*STL format and imported in XFDTD 6.3 produced by REMCOM was simulated, Figure 2.

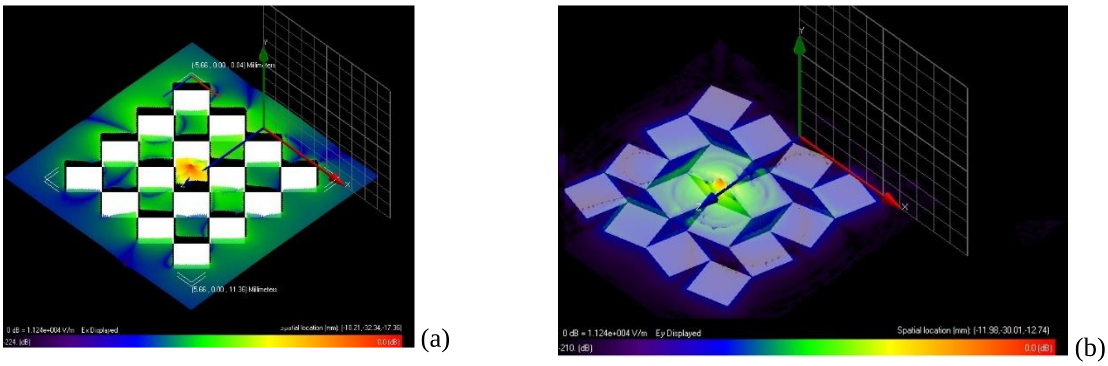


Figure 2: FDTD simulations results: (a) multiple periodic UCs and (b) RSD

The maximum sensitivity of a sensor array appears in the center of the array, meanwhile on the border is minimum. The sensitivity in the center of the RSD depends on the amplitude and phase of the excitation current in a region without discontinuities. For placing the RSD in the XY plane, the EM wave will propagate in the radial direction and perpendicular to the plane of the RSD, so that only the EM wave component in the direction of the Oz axis is considered [11].

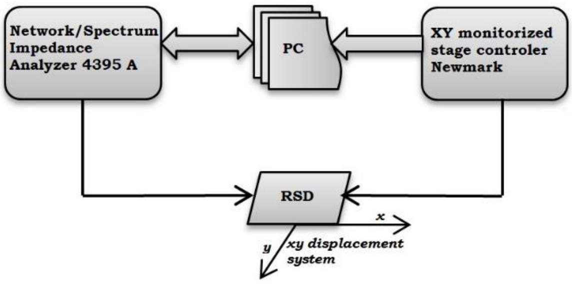
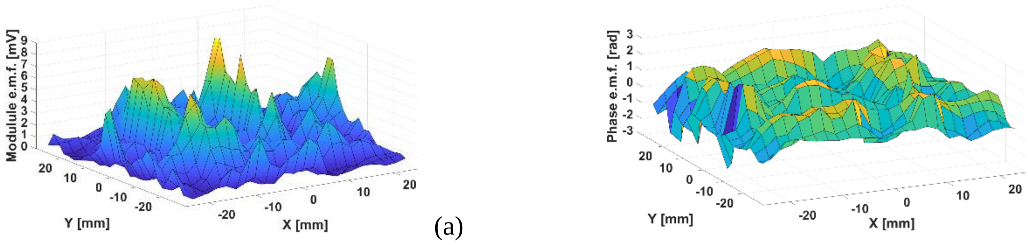


Figure 3: Experimental set-up

In Figures 4(a) is represented the response of a periodic UC when are excited with an EM wave at the frequency of 495MHz and Figure 4(b) is given the CU answer consisting of 4x4 elements. It is observed that due to the small dimensions considered of the periodic UCs and the fact that the maximum physically achievable scanning step was considered to be 10μm, the signals obtained correspond to the periodic UC shape. In order to obtain the focused image, a holographic procedure is proposed.



(a) (b)

Figure 4: Response of scatter for: (a) periodic UC and (b) RSD

Figure 5 shows that due to the small dimensions considered of the CU and the fact that the maximum physically achievable scanning step, the signals obtained correspond to the CU shape. Let $\mathrm{U}(x,y,z_0)$ the signal provided by CU and $\tilde{U}(u,v,f_0)$ the 2D Fourier transform of the signal recorded in the CU virtual focus plane, f_0, u and v be the Fourier variables. The expression of the backpropagator used in image reconstruction [12] with $m=1,2,...$, phase multiplier is given in

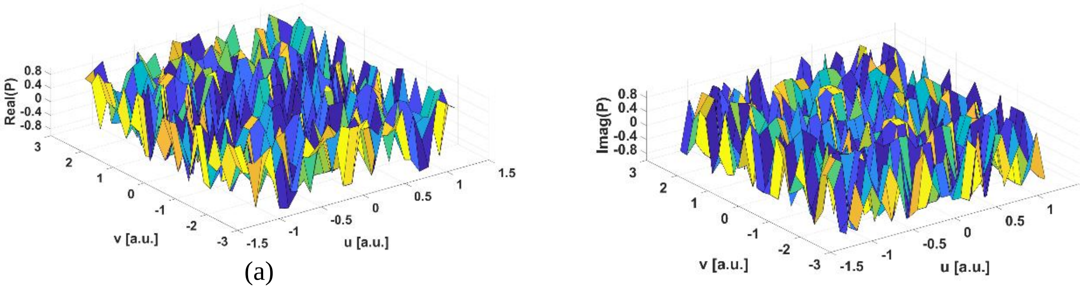
$$P(u,v,f_0)=\exp\left[-\frac{4\pi}{\lambda}f_0\sqrt{1-\left(\frac{\lambda u}{2m}\right)^2-\left(\frac{\lambda v}{2m}\right)^2}\right] \tag{4}$$

In figures 5 (a) and (b), the real and the imaginary component of the backpropagator given by the eq. (4) for m =16 are presented. The filtered and focused signal is given by the 2D Fourier transform of the convolution product $\tilde{U}(u,v,f_0)$ with the kernel $P(u,v,f_0)$

$$U(x,y,f_0)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\tilde{U}(u,v,f_0)P(u,v,f_0)\exp\left[2\pi j(ux+vy)\right]dudv \tag{5}$$

The image processed is obtained with the relationship

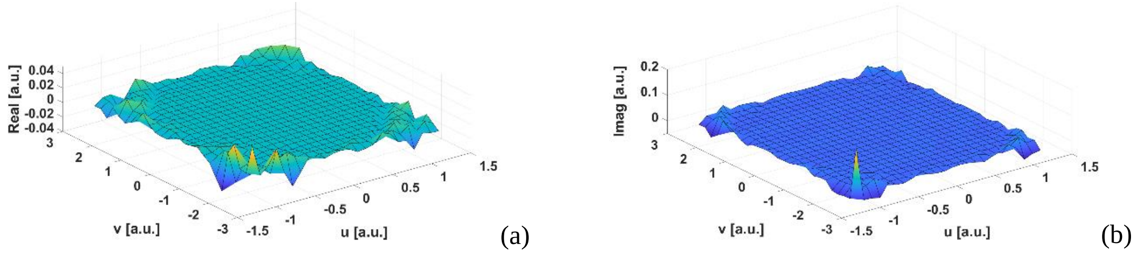
$$I(x,y,f_0)=\left|U(x,y,f_0)\right|^2 \tag{6}$$



(a) (b)

Figure 5: The electric field for the RSD (a) real component;
(b) imaginary component

Reconfigurable sensors design 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. In Figures 6 gives the real and imaginary component of the 2D Fourier transform of the response signal of the RSD with 4x4 elements.



(a) (b)

Figure 6: 2D Fourier transform of the response signal of the RSD (a) real component and (b) imaginary component

From eq. (6) it is observed that an increase of *m* is equivalent to an artificial decrease of m times the wavelength. From the holographic reconstruction experiments it resulted that in the conditions in which formally the artificial wavelength decreases by increasing the value of the phase multiplier, for values higher than 16; the holographic reconstruction becomes difficult to achieve.

4. CONCLUSIONS

The behavior of 2D RSD was simulated and demonstrated the ability to focus the EM field response of materials involved in nondestructive testing based on a numerical code using the Green dyadic function method and FDTD volume integration. The field focuses in the presence of MDM material taking into account the characteristic aspects related to the use of the RSD, in terms of material properties. 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. To validate the model, the behavior of a UC-based CE was simulated and the optimal working frequency was found to be around 495 MHz.

ACKNOWLEDGMENTS

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