METAMATERIALS – A CHALLENGE FOR ELECTROMAGNETIC NONDESTRUCTIVE EVALUATION

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Abstract:
In this paper are presented a new type of metamaterial named conical Swiss roll and few theoretical equations required for tailored specific constitutive parameters.
This metamaterial was used for the realization of an electromagnetic transducer which, together with the afferent measurement equipment, plays the role of an eddy current microscope with a very good spatial resolution and which can be utilized in most diverse applications.

Introduction

It has been known for a long time that the electrical properties of a host material can be changed by the periodic inclusion of small, variously shaped pieces of metals. The subject has been known as artificial dielectrics, microstructures materials or metamaterials [1], [2]. The metamaterials can have novel properties such as negative values of ε (electrical permittivity) and μ (magnetic permeability) at electromagnetic frequencies that are achieved by virtue of their physical arrangement rather than their constituents. The metamaterials with both ε and μ negative represent a medium with negative refractive index and the theory has been developed by Professor Veselago [3].
Theoretical approach to metamaterials often uses an effective medium approximation, which relies on the averaging of microscope fields [1]. The theory has been able to predict the reflection and transmission of a transverse electromagnetic wave incident on a slab of metamaterials and measured results have been reasonably close to the predicted ones.
Application of the metamaterials have been reported for delay lines [4], parametric amplification [5], splitters [6], filters [7], lenses for sub-wavelength imaging [8], guide for radio frequency flux in magnetic resonance imaging [9].
The capability of metamaterials to be used as lens and as magnetic flux concentrator, recommends them as having a huge potential in the developing of the electromagnetic procedures for nondestructive testing [10].
This paper proposes that, starting from the advantages of a new type of metamaterial, conical Swiss rolls, to develop a new electromagnetic transducer intended, among others, to the eddy current microscopy.

Swiss rolls metamaterials

A Swiss roll is made of a thin conducting foil and an insulating sheet rolled on a mandrel of radius r (see Figure 1).

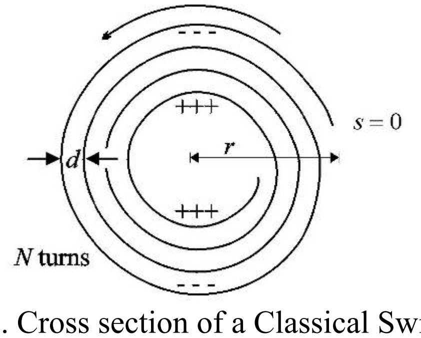


Figure 1. Cross section of a Classical Swiss roll

The conducting foil can support a current in the roll cross section; this current is expressed per unit length of roll, and is denoted j_S. Such a current generates a longitudinal magnetic field inside the roll; thus, the roll has an inductance L_S, inversely proportional to its length. When a current circulates around the roll, charge q_S accumulates on the first and last turns of conducting foil – the roll also has a capacitance per unit length C_S. Therefore, the roll is an effect a resonant RLC circuit which can be described by its resonant frequency ω_0 and quality factor Q.
The resistance is a combination of a series resistance due to the finite conductance of the foil and a parallel resistance due to the finite resistance of the dielectric. We assume that all losses come from the parallel resistance R_P [1]. The properties of the rolls are then [1], [11].

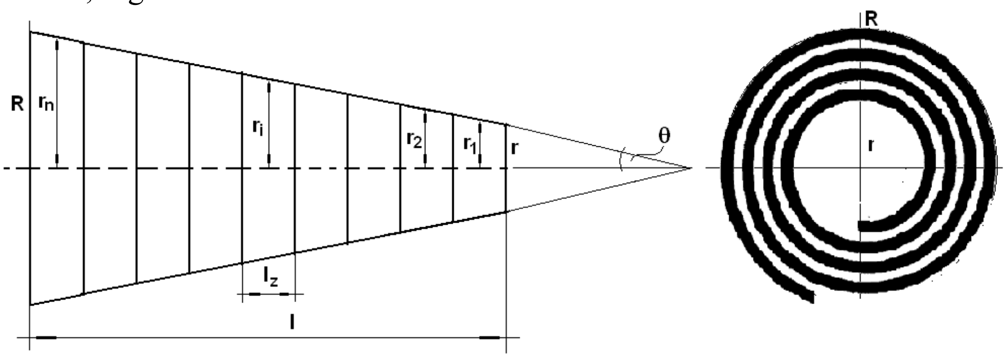
$$L_s = \mu_0 \pi r^2 \left(N-1\right)^2$$
$$C_s = \frac{\varepsilon_0 \varepsilon_r 2\pi r}{d\left(N-1\right)}$$
$$R_p = \frac{d\left(N-1\right)}{2\pi r}\rho_{diel} \tag{1}$$
$$\omega_0 = \frac{1}{\sqrt{L_s C_s}}$$
$$Q = \frac{\omega_0}{\Delta\omega} = \frac{R_p}{\omega_0 L_s}$$

where d is the thickness of the insulating sheet, N is the number of turns in the roll, r is the radius of the mandrel, ρ_{diel} is the resistivity of the dielectric, μ_0 magnetic permeability of the vacuum and ε_r is the relative electrical permittivity of insulating foil.
The magnetic fields inside and outside of roll are related by [11]

$$H^{in} - H^{out} = \left(N-1\right) j_S \tag{2}$$

Conical Swiss rolls

A pronounced effect of focusing the electromagnetic field can be obtained with a Swiss roll realized as truncated cone, Figure 2.



a b

Figure 2. Conical Swiss roll: a) cross section; b) transversal view

Due to the shape, the truncated cone will be partitioned into n segments of equal length, enough numerous so that the radius r_1, r_2, ….,r_i, …,r_n can be considered mean radius of the segments. In this way the truncated cone will be modeled by a succession of cylinder with radius more and more bigger.
The length of a segment from the height of truncated cone will be

$$l_z = \frac{l}{n} \tag{3}$$

and the radius is calculated as

$$r_i = r + i\frac{l}{2}\tan\theta, \qquad i = 1, 2, ..., n \tag{4}$$

where θ represents the angle of truncated cone.
Using these observations, the electrical properties of Swiss roll

$$L_s = \frac{\mu_0 \pi (N-1)^2 n}{l} \sum_{i=1}^{n} \left(r + i\frac{l}{2n}\tan\theta \right)^2$$
$$C_s = \frac{\varepsilon_0 \varepsilon_r 2\pi}{d(N-1)} \frac{n}{l} \sum_{i=1}^{n} \left(r + i\frac{l}{2n}\tan\theta \right) \tag{5}$$
$$R_p = \frac{d(N-1)}{2\pi} \rho_{diel} \sum_{i=1}^{n} \frac{1}{r + i\frac{l}{2n}\tan\theta}$$

With the calculated values L_s, C_s and R_p, taking into account that these circuit's elements are parallel, using a program developed in Matlab 2009a, the parameters S can be calculated, also, they can be easily measured using a Network Analyzer.

Method to retrieve the constitutive parameters of metamaterials

In order to retrieve the effective permittivity and permeability of a slab of metamaterials, we need to characterize it as an effective homogeneous slab. In this case, we can retrieve the permittivity and permeability from the S parameters data. For a plane wave incident normally on a homogeneous slab of thickness d with the origin coinciding with the first face of the slab, the S parameters are related to refractive index n and impedance Z by [12]

$$S_{11} = \frac{R_{0_1}\left(1 - e^{j2nk_0 d}\right)}{1 - R_{0_1}^2 e^{j2nk_0 d}} \tag{6a}$$

$$S_{21} = \frac{\left(1 - R_{0_1}^2\right) e^{j2nk_0 d}}{1 - R_{0_1}^2 e^{j2nk_0 d}} \tag{6b}$$

where $R_{0_1} = \frac{Z-1}{Z+1}$.

The refractive index n and the impedance Z are obtained by inverting Eqs.(6a) and (6b), yielding

$$Z = \pm\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}} \tag{7a}$$

$$e^{jnk_0 d} = X \pm j\sqrt{1 - X^2} \tag{7b}$$

where $X = \frac{1}{2S_{21}\left(1 - S_{11}^2 + S_{21}^2\right)}$

Since the metamaterial under consideration is a passive medium, the signs in Eqs. (7a) and (7b) are determined by the requirement

$$Z' \geq 0 \tag{8a}$$
$$n'' \geq 0 \tag{8b}$$

where □ '□ and □ "□ denote the real and respective imaginary part operators.
The value of refractive index n can be determined from Eq (7b) as

$$n = \frac{1}{k_0 d}\left\{ \left[\left[\ln\left(e^{jnk_0 d}\right) \right]'' + 2m\pi \right] - j\left[\ln\left(e^{jnk_0 d}\right) \right]' \right\} \tag{9}$$

where m is an integer related to the branch index of n'.

Electromagnetic transducer realized with metamaterials, conical Swiss roll type

The electromagnetic transducer used in the eddy current microscopy must be an absolute send-receiver type. The field generated by the emission part of the transducer must be as focused as possible and this for frequencies in the range of tens of MHz, where the ferrites have the relative permeability diminished and great losses. The scattered field must be also focused to can be detected by the reception part of the transducer. The focusing of the electromagnetic field is made with conical Swiss rolls.

For the realization of conical Swiss roll, a laminated material made from Copper foil with 18μm thickness and a layer of polyamide with 12μm thickness, having the commercial name LONGLITE™200 produced by ROGERS CORPORATION USA.

The dielectric layer presents a relative dielectric permittivity of 3.2 and tanδ=0.0099.

The volume resistance of the dielectric is $1.3\text{x}10^{16}\Omega\cdot\text{cm}$, and the surface one is $1.4\text{x}10^{15}\Omega$.

For the realization of conical Swiss roll, a conical mandrel with 20^0 aperture at the pick was used.

The geometrical parameters of the Swiss roll are:

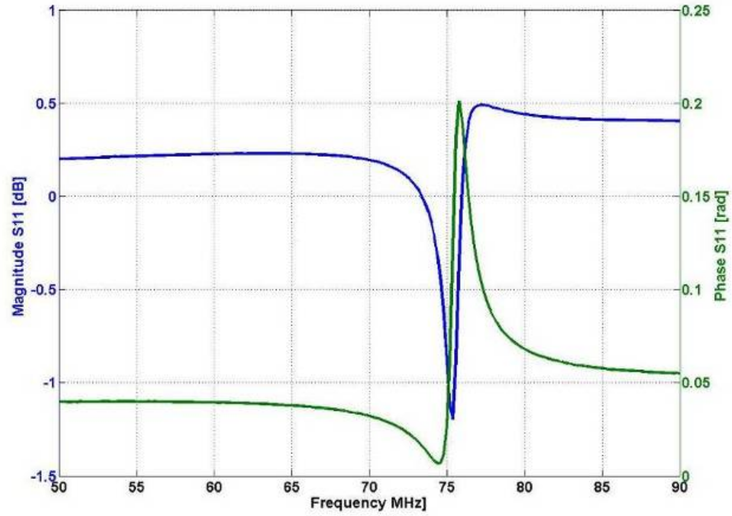
- diameter of the base 20mm
- diameter of the top 3.2mm
- angle of the top 20^0
- height 55mm
- number of turns 5

The physical realization of a conical Swiss roll is presented in Figure 3.

Figure 3. Conical Swiss roll made from LONGLITETM200

For determination of the constitutive parameters of Swiss roll, the S_{11} and S_{21} have been measured using an Network/Spectrum/Impedance Analyzer 4395A, Agilent USA coupled with S Parameter Test Kit 87511A, Agilent, USA.

In Figure 4a are presented the measured values of S_{11} parameter, amplitude and phase, for one of Swiss roll and in Figure 4b, the values obtained for S_{21} parameter.



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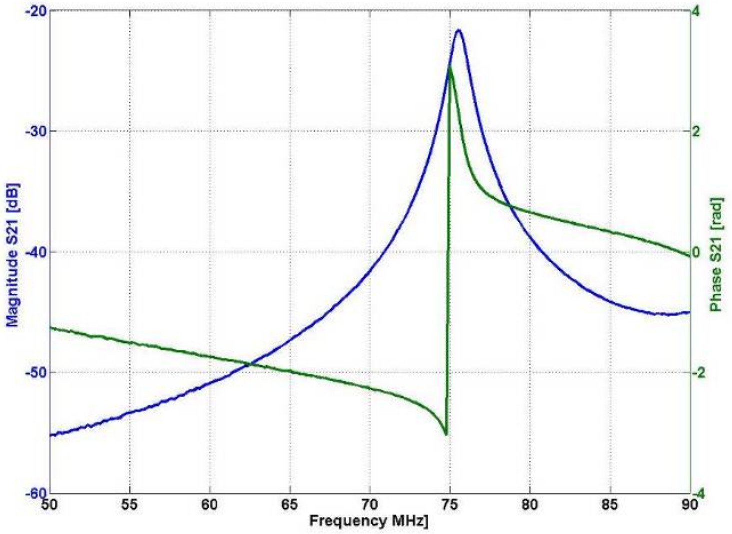


b

Figure 4. S_{11} and S_{21} parameters for a conical Swiss roll
a) S_{11}-amplitude and phase; b) S_{21}-amplitude and phase

In the basis of eq.(7a), the dependence of impedance by frequency for a slab from conical Swiss roll has been determined, being presented in Figure5, while, in Figure 6a and b are presented the dependence of the magnetic permeability and respective relative dielectric permittivity by frequency for the same Swiss roll.

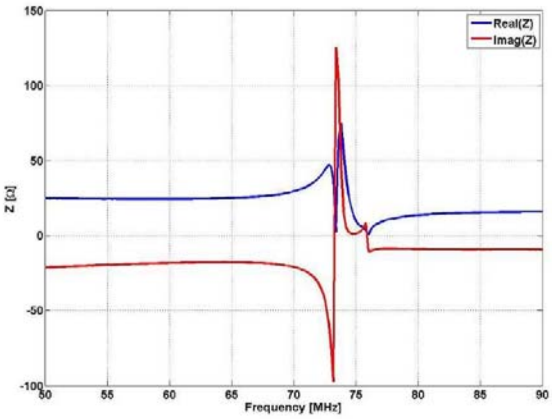
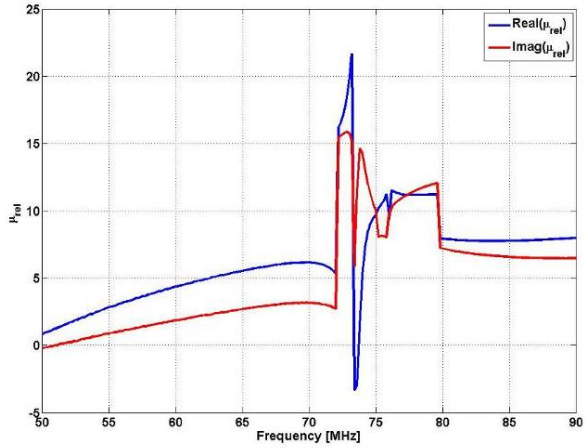


Figure 5. The dependency of impedance of a slab from conical Swiss roll by frequency



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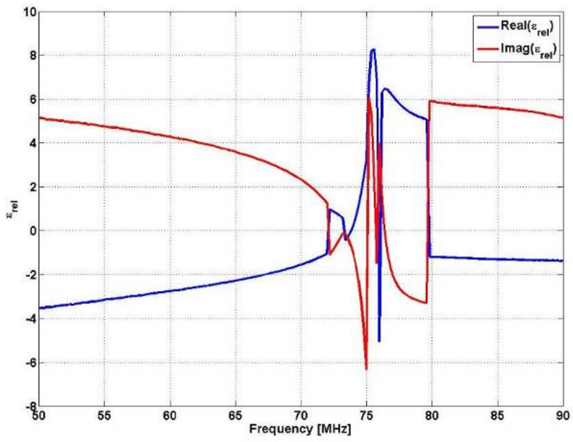

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Figure 6. The dependency of electromagnetic parameters of a conical Swiss roll by frequency: a) relative magnetic permeability; b) relative dielectric permittivity

Examining the data from Figure 6, it can be observed that the conical Swiss roll presents, in a certain frequency range, a relative magnetic permeability of 22 and for another zone, negative magnetic permeability. Similarly phenomena are observed for the relative dielectric permittivity.

The realization of the transducer using metamaterials, conical Swiss roll type is presented in Figure 7.

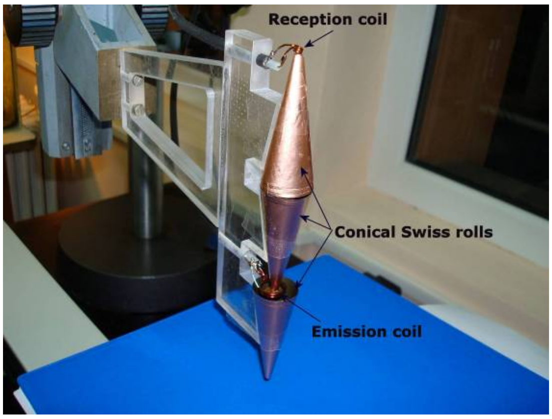


Figure 7. Electromagnetic transducer using conical Swiss roll

The emission coil of the transducer has 2 turns, 16mm diameter, from copper wire 1.2mm diameter. The reception coil has also 2 turns with 3mm diameter, from the same wire type.
The field generated by the emission coil is concentrated by the conical Swiss roll on the examined piece. Its resonance frequency is 77.6MHz and the relative magnetic permeability at this frequency being 24.
To concentrate the field scattered by inhomogeneities from the examined material, a lens formed by 3 Swiss rolls (Fig.7). The first Swiss roll has resonance frequency of 75.7MHz and at the frequency of 77.6MHz has both magnetic permeability and dielectric permittivity negative. The second Swiss roll has 77MHz resonance frequency and positive permeability and permittivity.

The experimental set-up.
The electromagnetic transducer presented above is connected to a Network/Spectrum/Impedance Analyzer 4395A –Agilent USA. It is fixed on a support. The examined piece is mounted on a X-Y displacing system, type Newmark. Both equipments are commanded by PC through a program developed in Matlab 2009a.
The performances of the system were verified on two test blocks made form Plexiglas, having thickness 8mm. the first block has practiced in center a borehole with 1mm diameter in which a copper cylinder was inserted. The second block has 2 central holes with the same diameter, having inserted copper cylinders, the distance between their centers being 2mm.
In Figure 8 is presented the experimental set-up and in Figure 9 the test blocks.
The Cu cylinder can be considered as punctiform scatter so that the response of eddy current equipment at the scanning of the region which contains the scatter will represent the point spreading function for the eddy current microscope [13].
In Figur e10 is presented the response of the measurement system and the eddy current transducer with metamaterials for the case of the scatters quasi punctiform. It is observed that the signal/noise ratio is very good and the spatial resolution is better than 1mm due the fact that the response of the two scatters appears absolutely distinctive.

Figure 8. The experimental set-up

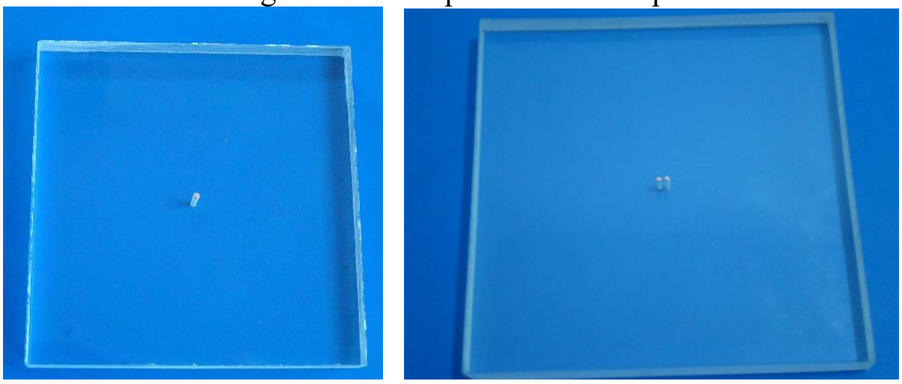


Figure 9. The test blocks

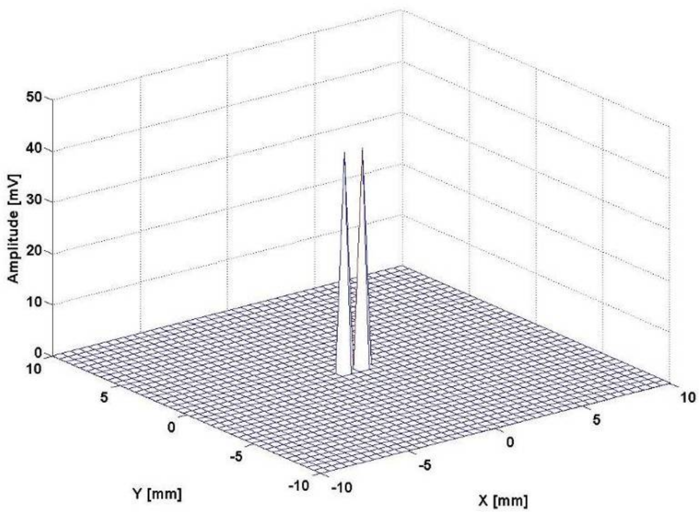
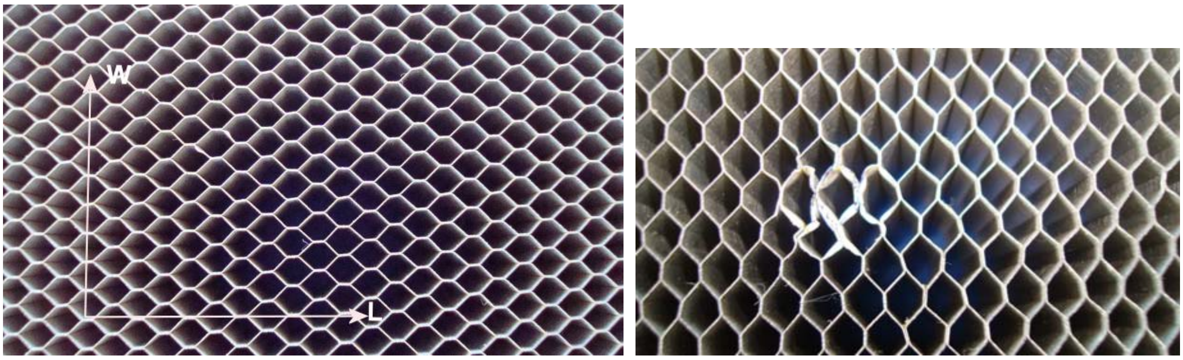


Figure 10. The response of the equipment at the scanning of region with two scatters

The studied samples and results

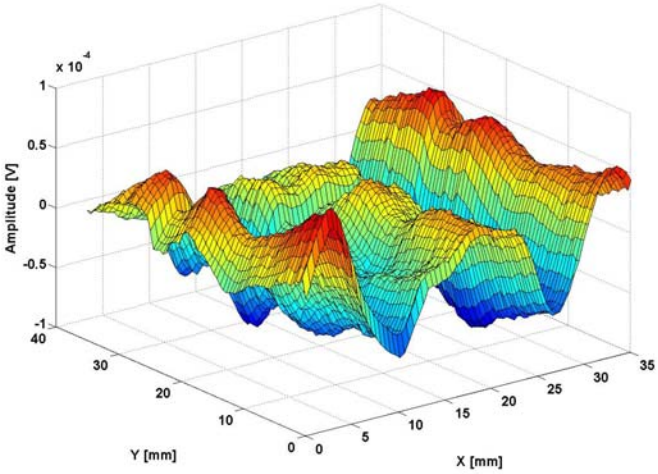
With the eddy current microscope, honeycomb cores made form AlMg with cells of 1/6” dimension have been examined. On some samples, the cells were deformed by impact. The images of the studied samples are presented in Figure 11.



a b

Figure 11. Honeycomb core AlMg with 1/6" cell's dimension
a) reference sample; b) sample with cells deformed by impact

In Figure 12 a and b are presented the amplitude and the phase of the signal delivered by the control equipment at the scanning of the sample with intact cells. Especially, on the phase information, the cell's shapes are perfectly visible.



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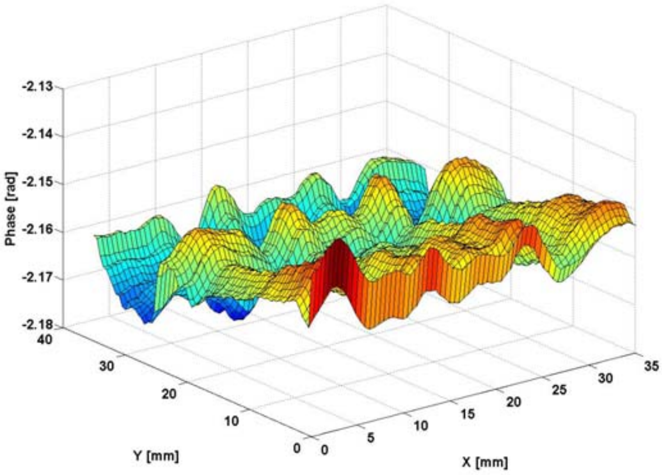

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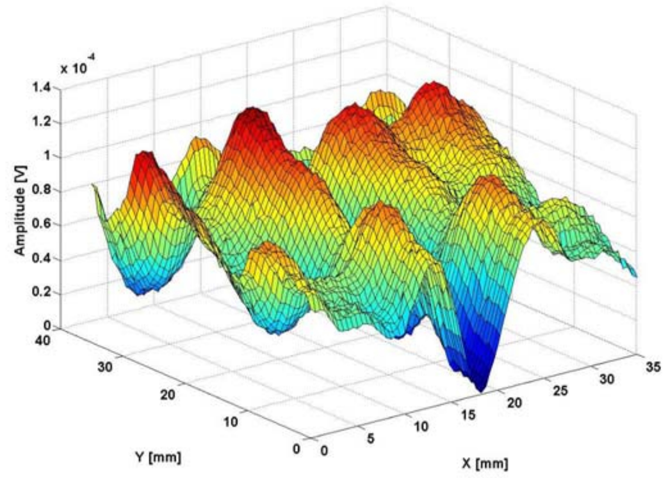
Figure 12. Signal delivered at the scanning of the sample with intact cells: a) amplitude; b) phase

In the case in which the honeycomb cells are deformed, the amplitude and the phase radically modify its aspects (Figure 13).



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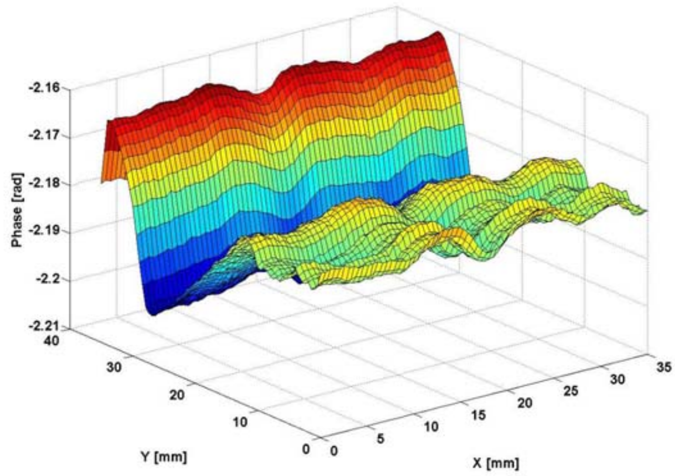

b

Figure 13. Signal delivered at the scanning of the sample with deformed cells by impact
a) amplitude; b) phase

Conclusions

The constitutive measures of metamaterials can be designed function of application. These measures can be evaluated by inversion of data obtained through S parameters measurement. A new type of metamaterials has been realized, named conical Swiss roll that present great capacity of radio frequency flux concentration and which, in function of the utilized frequency, can present μ and ε positive with high values or respectively negative. This fact allows the realization of l=the lens for the range of radio frequency and thus, it can be used in nondestructive evaluation as eddy current microscope. The electromagnetic transducer made with conical Swiss rolls has a good spatial resolution, better than 1mm and were tested with good results at the examination of AlMg alloy honeycomb core structures.

Acknowledgments

This paper is partially supported by the Romanian Ministry of Education, Research and Innovation under Nucleus Program – 09 43 01 04 and National Plan II - Contract no. 71-016/2007- MODIS and Contract no. 32-134/2008- SYSARR.

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