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Waveguide sensor with metamaterial structure for determination of dielectric properties

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Abstract. Microwave sensor (MWS) compared with classical sensor, offers many advantage such as rapid and nondestructive measurement. At microwave (MW) frequencies, dielectric properties of materials depend on frequency, moisture content, bulk density and temperature. MW waveguide sensors can measure properties of materials based on MW interaction with matter, and provide information about dielectric properties of investigated dielectric material, characterized with complex permittivity. The paper presents a new approach for determination of the dielectric properties of dielectric material by embedding a metamaterial (MM) structure over the aperture of waveguide sensor in order to increase the sensing properties of classical waveguide sensor. The optimal design of MM structure for waveguide sensor tuning in MW X-band is obtained. In this new approach the MM function in two ways: like a tool for increasing the sensibility of classical waveguide sensor and the tool sensitive to the dielectric properties of investigated material through the adjusted resonance frequency of designed MM units. The numerical simulation of 2D MM structure properties and experimental results for dielectric properties of dielectric materials are carried out.

1. Introduction

Dielectric properties of dielectric materials are important to known, especially when they are involved in interaction with MW. At MW frequencies, the dielectric properties are dependent of frequency [1]. The study of the dielectric properties of biological tissues become interesting since the middle of last century, from the heat transfers mechanisms point of view. Knowing the dielectric properties of biological tissues is essential to the understanding of the interaction of electromagnetic (EM) radiation within human body. Biological tissues are complex heterogeneous materials. Their dielectric properties have major roles in biomedical applications [2]. EM radiation in the RF less than 400 kHz to MW frequencies, or exceeding 10 GHz is currently under review for its use in therapeutic applications in the fields of cardiology, urology, surgery, ophthalmology, cancer therapy and other and diagnostic applications for the detection of tumours or unknown entities inside the body [3, 4].

The dielectric properties of materials can be determined by measuring the modifications in resonant circuits [5], by electronic bridge [6], by transient methods in DC [7]. MW measurements can be carried out by velocity modulated tubes, cavities, waveguide technologies and free space configurations [8]. MW waveguide sensors [9] measure dielectric properties of materials due to MW interactions with them.

MM are structures which behave unusual under specific EM excitation [10] and allow the gathering of evanescent waves [11] and their enhancement, leading to the improvement of near field sensors. Recently, the MM structures have been employed in improvement of MW waveguide sensor sensitivity by embedding them at the opening of classical MW guides [12].

This paper present the improvement of MW guide sensor using MM's in order to determine dielectric properties of dielectric materials with application to biological tissues. The next aim of our paper was to optimise arrangement of patch anttenas and their tunning with metamaterial structures in order to find maximum energy contrentation in interested area of bilogical structure phantom. For this reaserch firstly the numerical simulation were used for optimisation of position and number of MMS and than the results were experimntally verified.

2. EM field for human body

During interaction of EM field on biological tissue different phenomens tacke place such as absorbtion, scattering, reflection according with structures of tissue. Biological tissues are lossy materials and losses changes the way the EM wave interacts with the material and its propagation behavior. The material is heated up if the EM energy is cumulated. For a lossy material, Ampere's law for harmonic waves is

$$\nabla \times H = \left(\sigma + \omega\varepsilon''\right)E + j\omega\varepsilon' E \tag{1}$$

where ε' and ε'' is real respectively imaginary components of complex permitivity; H(Am^{-1}), E (Vm^{-1}) magnetic and respective electric field intesity; σ (Sm^{-1}) conductivity of material and ω angular frequency. The equation bind the current that produces a loss (heat) in the material through movement of free charges and bound charges with the displacement current which represents the losses portion of the oscillation of the bound charges [13]. The loss properties of material are usually

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\varepsilon_r''\varepsilon_0} \tag{2}$$

During the interaction between MW and biological tissues, the characteristics cellular structures and intracellular fluid too are determinative. The permitivity of biological tissues is determind by the dispersion phenomena. Dispersion characteristics for biological materials [14] is represented by Cole Cole equation

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \left(j\omega\tau\right)^{1-\alpha}} \tag{3}$$

where ε_∞ and ε_s represent relative permitivity of material at infinite and zero frequencies respectively, (1-α) is distribution of relaxation in material, with α distribution parameter (0≤α<1) [15]. To determine the dielectric properties of biological tissues, the S parameters have been determined. For two-port network viewed as a transmission line , the independent variable a_1 and a_2 wich represent the amplitudes of incident waves at port 1 and 2 allows to defines S parameters, figure 1.

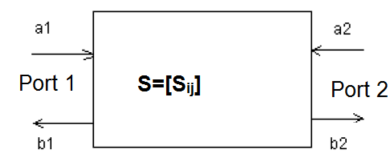

Figure 1. Definition of S parameters.

In the schematic view of this, shown in figure 1, the scattering parametres have the form

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$S_{11} = \left.\frac{b_1}{a_1}\right|_{a2=0}$ input reflection coefficient with the output port terminated by a matched load;

$S_{21} = \left.\frac{b_2}{a_1}\right|_{a2=0}$ forward transmission gain with the output port terminated by a matched load;

$S_{12} = \left.\frac{b_1}{a_2}\right|_{a1=0}$ output reflection coefficient with the input port terminated by a matched load;;

$S_{22} = \left.\frac{b_2}{a_2}\right|_{a1=0}$ reverse transmission gain

and they are dimensionless.

3. MM's structure and antenna

MM structure with negative permeability values can be implemented as an array of split ring resonators (SRR) [16]. The resonant frequency of such a field can be corrected by changing the parameters of the SRR [17], the complex permittivity and the magnetic permeability of MM structure can be determined by scattering-parameters, which are based on reflection and transmission of EM wave through a MM structure [18]. The SRR array behave as a LC resonant circuit that can be excited by a time variable EM field (figure 2). The placement of the structure in front of a patch antenna at a distance d, has been simulated, in order to determine the optimal value of *d*.

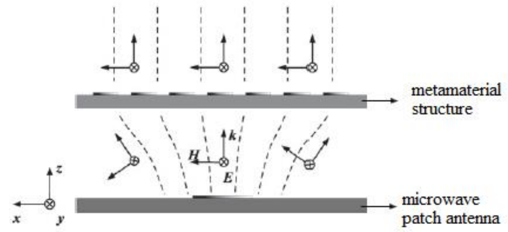

Figure 2. Interaction of the MM structures with the radiation of microstrip patch antenna.

Such a structure has anisotropic and dispersive; therefore, to determine the permeability tensor at different frequencies, several numerical methods can be used. Based on the Lorentz model, the magnetic permeability tensor of structure is determined [19]

$$\overset{=}{\mu} = \begin{bmatrix} \dot{\mu}_{xx} & 0 & 0 \\ 0 & \dot{\mu}_{yy} & 0 \\ 0 & 0 & \dot{\mu}_{zz} \end{bmatrix} \quad (4)$$

with $\mu_{xx} = 1$, $\mu_{yy} = 1$ and $\mu_{zz} = 1 - \frac{F\omega^2}{\omega^2 - \omega_m^2 + j\gamma\omega}$**;** where ω is the angular frequency, γ is the loss factor, ω_m is magnetic plasma angular frequency and F is the filling factor determined by the dimensions of SRR structures [20]. Value of F depends on geometrical parameters of resonant unit cell of MM.

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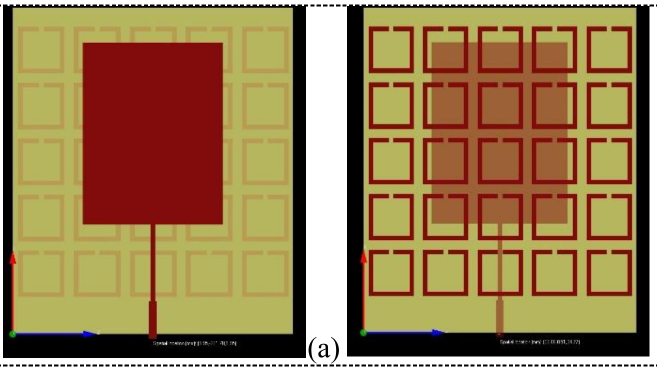

Figure 3. Configuration used for simulation: (a) face 1- patch antenna.; (b) face 2 - SRR structure.

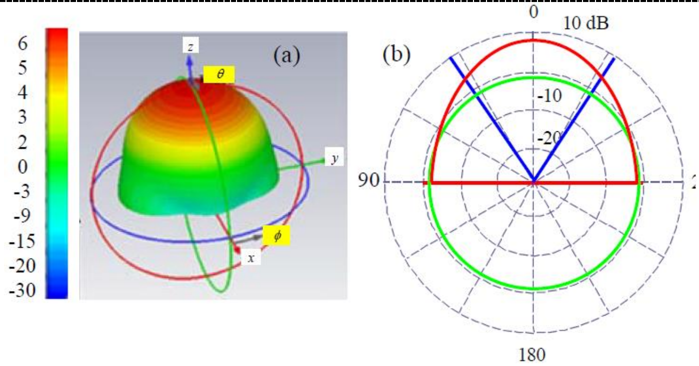

Figure 4. Simulation radiation pattern of patched antenna with SRR structure: (a) 3D image; (b) polar coordinates.

The MM structure and microstrip patch antenna were realized from high frequency laminate Roger RT /Duroid 5870 with a thickness of the dielectric substrate h = 0.508 mm, suitable for applications in the MW frequency band and its parameters match the criteria of microstrip of patch antennas design [21]. The characteristics of the antenna with a resonance frequency of 2.5 GHz, which is commonly used in the hyperthermia treatment of tumours, allow the depth of heating from 2.5 to 3 cm [22]. The relative permittivity of the laminate at a frequency of 2.5 GHz is ε '= 2.33 [23].

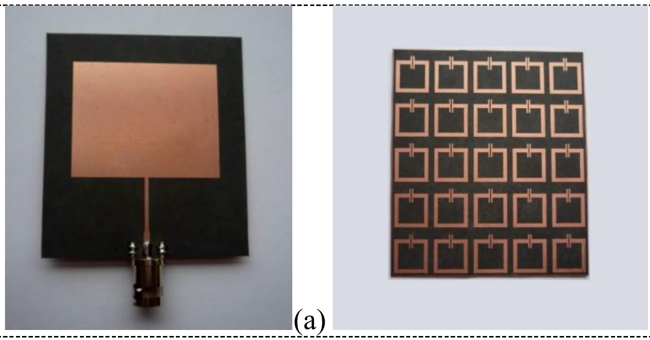

Figure 5. Configuration used for measurements: (a) face 1- patch antenna.; (b) face 2 - SRR structure.

Figure 6 presents the measured S_{11} parameter of the realized configuration showing its agreement with the calculations.

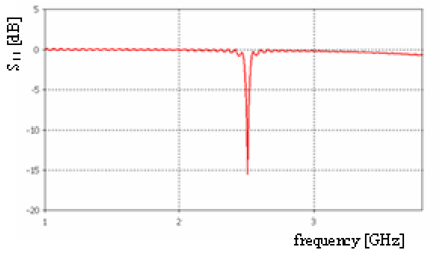

Figure 6. Frequency dependence of scattering parameter S11 amplitude for conventional patch antenna with MM structure.

4. Simulation of dielectric materials behavior in free space and inside the waveguide

The most important dosimetric parameter to assess human exposure to high frequency EM field is SAR (Specific Absorption Rate). Dosimetric studies quantify the interaction of EM fields with biological tissue. Usually SAR value can be evaluated from energy absorbed per unit mass of biological tissue

$$SAR = \frac{\left(\sigma + \omega\varepsilon_0\varepsilon_r^{"}\right)E^2}{\rho} \tag{5}$$

in (W/kg), where ρ is density of tissue. SAR depends by induced electric field and electric properties of biological tissues. This situation has been simulated using CST Microwave Studio. A model of homogeneous soft tissue with ε '= 36 and σ = 1.2 S / m [24] was created. The soft tissue in the form of a cylinder with a radius of 6 cm was irradiated by four microstrip array antenna at a distance of 2 cm, figure 7, in order to detect the focussing points of the maximum EM radiation in different conditions of irradiation. The simulations were performed at 2.5 GHz for the dominant TE_{10} mode [19], each antenna was fed with pulsed signal (pulse width of 1 ns) with a Gaussian power density to 1 W / m^2. The model is placed in air, which was also taken into account when the boundary conditions have been set.

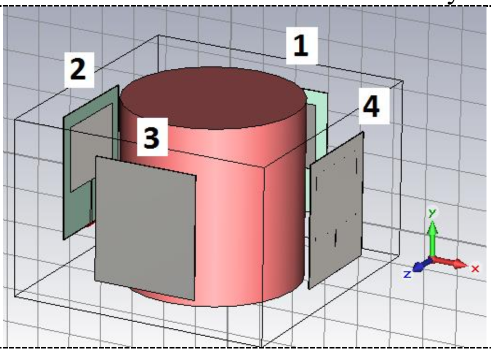

Figure 7. The simulation model for monitoring parameter SAR in biological tissue.

The simulation in figure 8 shows the results of irradiation of a homogeneous soft tissue model for changing the number of antennas 1-4, wherein the antennas are in phase with each other and the radiating surface of the slices are oriented perpendicular or parallel to the plane XZ. Figure 8 shows that for the homogeneous model, one radiation antenna with a resonance frequency of 2.5 GHz, there is the EM radiation focussing in particular on the periphery of the irradiated object with a high SAR parameter, therefore, the irradiation with a single antenna particularly is suitable for the surface of biological tissue.

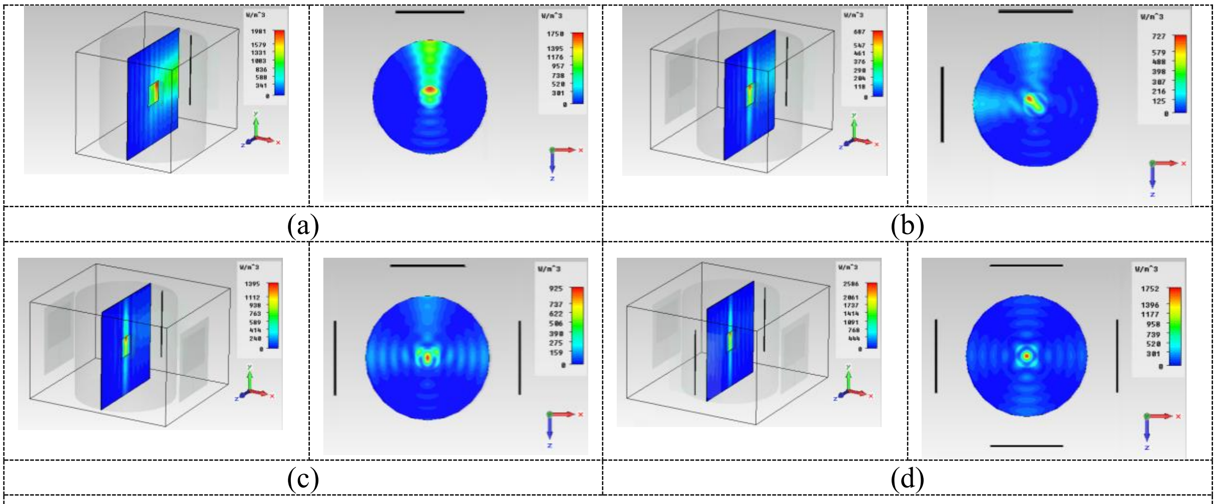

Figure 8. Distribution of power loss density in a model of soft tissue. The number of antennas and irradiation: (a) 1st; (b) 2nd; (c) 3rd; (d) 4th.

When using multiple antennas, figure 8b, figure 8c, figure 8d, there is a higher concentration of EM field to some specific points within tissues, their position depends on the arrangement of the antennas and the properties of the irradiated object. The model of a homogeneous soft tissue give the optimal solution as using the four antennas, the EM field being concentrated in one narrow area where SAR is relatively high, also, obtaining a significant SAR arround the biological sample.

5. Experimental set-up and results

Experimental measurements were conducted to study the proposed emission of patched microstrip antennas without and with MM structure and to monitor the absorption of EM radiation excited in a soft biological tissue. The measurement was carried out at standard room temperature. The MM antenna structure was positioned in a polystyrene support, the sample is placed in the middle of square shape with dimensions of 9.3 cm side and 7cm depth. The set-up has been partitioned into four sectors A, B, C and D, parallel slots cut in support allow the placement of microstrip antenna and the MM structures at 1, 2, 3, 4, and 5 cm from the edge of the sample (figure 9).

Patch microstrip antenna is powered through the Vector Analyzer Anritsu VNA Master MS2024C in the frequency range 2-3 GHz. On the second port of VNA, the probes were connected in order to determine the size of the tranmission coefficient of EM radiation in one of the four sample points (S1 - S4), figure 9b.

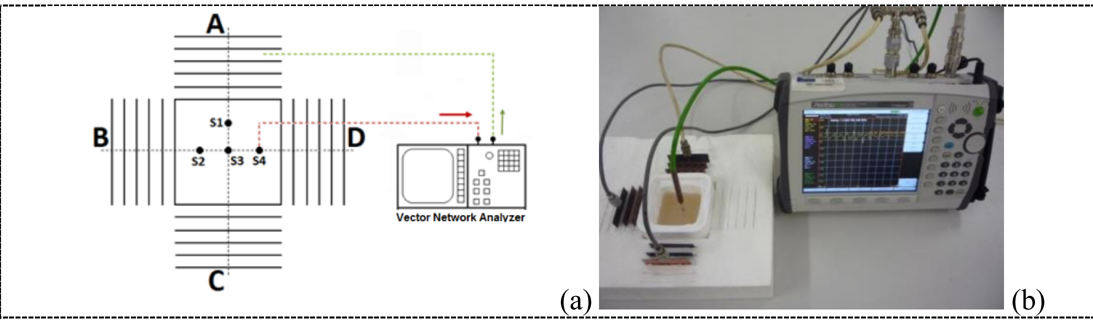

Figure 9. The measuring system for monitoring the intensity of EM radiation in the sample, with proposed microstrip antenna and MM structures in the radiating antenna field: (a) scheme; (b) the experimental set-up.

In the first step, the intensity of EM field in the selected measurement points were determined for one patched antenna placed succesively in all sectors and in each slots without metamaterial structures. The next step was carried up replacing the simple microstrip antenna with the realized configurations containing SRR array on the back side of the antennas and measuring the EM field in the selected points for all combinaiton of the arrangements that can be created within the sector (31 combinations). A configuration in which the intensity of EM field in a selected point of maximum, was left in the sector, and the same measurement was repeated by adding another radiating antennas and metamaterial structures in Sector B, where they were again adjusted all feasible combinations. The same procedure was also applied by the addition of a metamaterial antenna structure into sectors C and D. The results of the measurements are processed to show the strength of the EM field in Arbitrary Units (a.u.), the field being normalized to the field measured without SRR structures (figure 10).

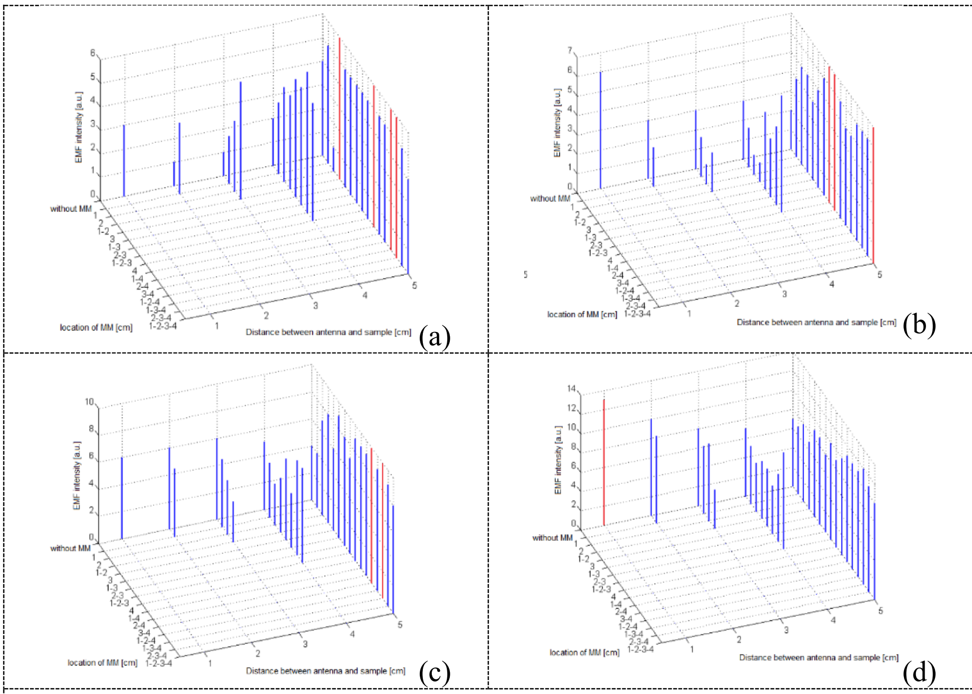

Figure 10. Experimental field strength measurements of soft biological tissues in point S3 for realized configuration in region: (a) A; (b) B; (c) C); (d) D.

The results of measurements in point S3 for a soft biological tissue, the use of metamaterial structures on the four antennas reached maximum intensity of the EMF of 13 a.u., which, compared to the exposure without the MM, increases with 85%. Knowing the field intensity and measuring SAR, the dielectric properties of samples can be determined according eq. (5).

6. Conclusions

The paper further demonstrated basic knowledge of measuring the dielectric properties of biological tissues in the frequency range of microwave frequencies and above are some experimental results for which examines the effect of temperature change on change dielectric properties of selected biological tissue. For monitoring the dielectric properties of biological tissues in the solid state sensors composed by patched strip antennas and split ring resonators array that create a metamaterial structure with negative permeability values. The proposed sensors are used to experimentally determine the relative permittivity of soft biological tissues that exhibit significantly different dielectric parameters. Numerical simulations also demonstrate the possibility of use of the metamaterial sensor for the detection of tumors located in the healthy tissue that is characterized by significantly different dielectric properties.

Metamaterial sensor may therefore represent a future minimally invasive and cost-saving method of diagnosing cancer, as well as the sensor back reaction of tumor tissue to an applied EM field in the hyperthermic treatment. The advantage of metamaterials is the reducing of their implementation to millimeter dimensions, which offers the possibility of inserting into the human body through endoscopy.

7. Acknowledgements

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