DESIGN AND SIMULATIONS OF IDC SENSOR USING COMSOL MULTYPHYSICS AND DIELECTRIC SPECTROSCOPY OF LTCC MATERIALS

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Rezumat- În această lucrare sunt prezentate permitivitatea relativă εr şi pierderea tangentă tanδ a ceramicilor LTCC fabricate de Heraeus Circuit Materials Division, care au fost testate în gama de frecvenţe de la 10 MHz la 1 GHz la temperatura camerei. Sistemul de măsurători a spectroscopiei dielectrice şi caracterizarea materialelor LTCC au fost efectuate pe analizorul de impedanţă Agilent 4191. Rezultatele obţinute ca urmare la caracterizarea dielectrică au fost utilizate în modelări 3D şi simulări de senzori de tip IDC pentru monitorizarea mediului.

Cuvinte cheie- Proprietăți dielectrice; Spectroscopie dielectrică, LTCC, Senzori, IDC, Permitivitate, Comsol, Simulări.

Abstract — In this paper are shown relative permittivity εr and loss tangent tan δ, of LTCC ceramics manufactured by Heraeus Circuit Materials Division, which are tested for frequencies at range 10 MHz to 1 GHz at room temperature. The measurements system for dielectric spectroscopy and characterization of LTCC materials were conducted on the impedance analyzer Agilent 4191. Obtained results due dielectric characterization were used in 3D modeling and simulations of IDC sensor for environmental monitoring.

Index Terms — Dielectric Properties; Dielectric spectroscopy; LTCC; Sensors; IDC; Permittivity; COMSOL; Simulations;

1.INTRODUCTION

Interdigital capacitors (IDC) have been involved in many sensing applications over the past five decades. Interdigitated sensors are well known to be combined with isotropic dielectric materials. In these cases, the sensing mechanism is based on the dielectric properties of these materials which include physical, chemical, or structural properties of these materials.

The powerful software tools, today in modern engineering, are replacing most of the laboratory work and processes of fabrication of device's prototype, and they are largely saving a precious time and expensive materials. The COMSOL multiphysics is a commercial PDE (partial differential equations) solver and enables simultaneous computation of multiple physics. The advantage of COMSOL multiphysics includes its user friendly modeling interface and versatility to be extended to electromagnetic field, or electrostatic field. The main approach of design capacitive sensor is that sensing layer has possibility to change its permittivity, or permeability depending on changes of particular pollution.

Accurate knowledge of dielectric properties of LTCC materials is very important for efficient design and simulations of LTCC systems, especially for design of capacitive sensors and communication filters at different frequency. Therefore, in this paper are shown relative permittivity ε_r and loss tangent tan δ of a variety of LTCC ceramics manufactured by Heraeus Circuit Materials Division. The dielectric properties of two kind LTCC tapes were measured in the frequency range from 10 MHz up to 1 GHz at room temperature. Characterization of material at frequency variation was done using a system for automated dielectric spectroscopy, given by Novocontrol GmbH Germany, precisely the impedance analyzer for high frequency, Agilent 4191. Obtained results due dielectric characterization were used in 3D modeling and simulations of IDC sensor in COMSOL Multiphysics software.

2. DIELECTRIC SPECTROSCOPY OF LTCC MATERIAL

Every material has a unique set of electrical characteristics that are dependent on its dielectric properties. Accurate measurements of these properties can provide scientists and engineers with valuable information to properly incorporate the material into its intended application for more solid designs or to monitor a manufacturing process for improved quality control. A material is classified as “dielectric” if it has the ability to store energy when an external electric field is applied. The dielectric material increases the storage capacity of the parallel plate capacitor by neutralizing charges at the electrodes, which ordinarily would contribute to the external field. If an AC sinusoidal voltage source V is placed across the same capacitor (Fig. 1), the resulting current I (1) will be made up of a charging current I_c and a loss current I_l that is related to the dielectric constant. The losses in the material can be represented as a conductance (G) in parallel with a capacitor (C).

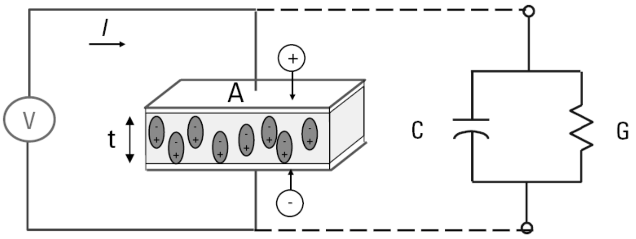


Figure 1. Principles of parallel plate capacitor.

$$\begin{aligned} & I = I_c + I_l = V(j\omega C_0 \kappa' + G) \\ & \text{If} \quad G = \omega C_0 \kappa'', \text{ then} \\ & I = V(j\omega C_0)(\kappa' - j\kappa'') = V(j\omega C_0)\kappa \\ & \omega = 2\pi f \end{aligned} \qquad (1)$$

The complex dielectric constant k (2) consists of a real part k' which represents the storage and an imaginary part k" which represents the loss

$$k = k^* = \varepsilon_r = \varepsilon_r{}^* \qquad (2)$$

From the point of view of electromagnetic theory, the definition of electric displacement (electric flux density) *Df* (3) is:

$$Df = \varepsilon E \qquad (3)$$

where $\varepsilon = \varepsilon^* = \varepsilon_0\varepsilon_r$ is the absolute permittivity (or permittivity), ε_r is the relative permittivity, $\varepsilon_0 \approx 136\pi$ x 10^{-9} *F/m* is the free space permittivity and *E* is the electric field. Permittivity describes the interaction of a material with an electric field *E* and is a complex quantity.

$$k = \varepsilon\ \varepsilon_0 = \varepsilon_r = \varepsilon_r{}' - j\ \varepsilon_r{}'' \qquad (4)$$

Dielectric constant (k) is equivalent (4) to relative permittivity (ε_r) or the absolute permittivity (ε) relative to the permittivity of free space (ε_0). The real part of permittivity (ε_r ') is a measure of how much energy from an external electric field is stored in a material. The imaginary part of permittivity (ε_r ") is called the loss factor and is a measure of how dissipative or loss a material is to an external electric field. For the spectroscopy at high frequency Impedance analyzer Agilent E4991A has been used [8], (Fig. 2) which is a part of Turnkey system for automated dielectric spectroscopy (with special extension and electrodes of dielectric cell BDS 2200).

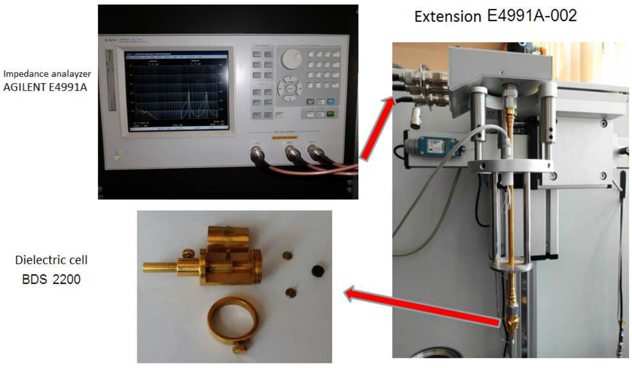


Figure 2. Impedance analyzer E4991A with dielectric cell.

The disk samples were fabricated in LTCC technology using tapes of producer Heraeus, which are used for fabricating LTCC components. Investigations were conducted on disk samples of two kinds of tapes, which are laminated and prepared in sizes which are needed for cell BDS 2200 (Fig.2). The disk samples were fabricated in LTCC technology using tapes of producer Heraeus, which

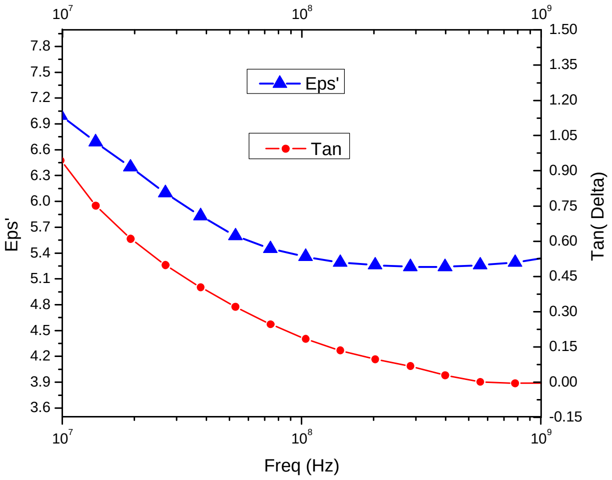


Figure 3. Real permittivity and dielectric losses of LTCC sample CT 707 tape Heareus

are used for fabricating LTCC components. Investigations were conducted on disk samples of two kinds of tapes, which are laminated and prepared in sizes which are needed for cell BDS 2200 (Fig.2). The measurements at high frequency were performed in the frequency band 10 MHz ÷ 1 GHz, on the disk sample of Heareus tape CT 707, with three laminated layers, thickness 0.31 mm, diameter 5 mm (Fig. 3), and same the measurements were done in a same frequency band on disk sample of Heareus tape GC (glass ceramic), four laminated layers, thickness 0.28 mm, diameter 5 mm (Fig. 4).

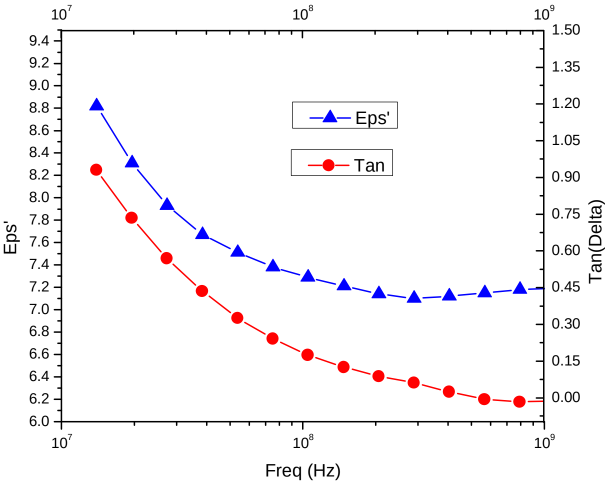


Figure 4. Real permittivity and dielectric losses of LTCC sample ceramtape GC Heareus

The obtained results for real permittivity and tan delta, during dielectric spectroscopy of samples, are with small variations in the measured values of capacitance with changing frequency. It can be seen from 2D graphs, which are drawn in Origin 8 software, that due increasing frequency, the permittivity value decline and loss tangent decreases also. During sintering of LTCC sample, the changes appear in density and the microstructure of material, changing the electrical characteristics, consequent increase of permittivity. [1] Considering these changes at a microstructure, obtained values permittivity of investigated tapes coincides in satisfied percents with the value specified by the manufacturer for tapes before the fabrication of samples.

3. PRINCIPLES AND PARAMETERS OF IDC SENSOR

Capacitive interdigital structures are very common in new micro strip and planar electronics technology. Interdigital capacitors (IDC) have been involved in many sensing applications over the past five decades.

Interdigitated sensors are well known to be combined with isotropic dielectric materials. In these cases, the sensing mechanism is based on the dielectric properties of these materials which include physical, chemical, or structural properties of these materials.

Interdigital capacitor (Fig. 5) is a finger like or comb like periodic pattern of electrodes deposited on a broad selection of substrates which could be opaque, porous or transparent, e.g., silicon or glass, where dielectric film coats these electrodes. Interdigital capacitor (IDC) is a widely used component to build a few picofarads capacitance in microstrip technology [2].

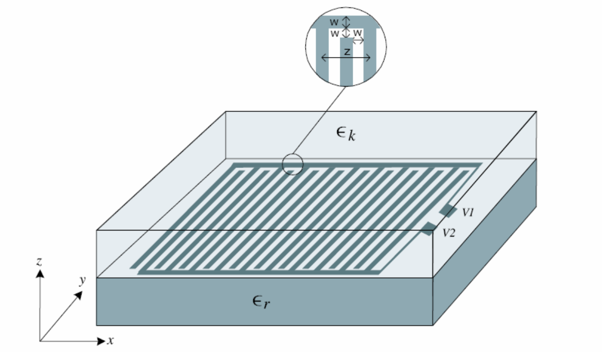


Figure 5. Structure of interdigital capacitor

The capacitance measured between the electrodes depends on the dielectric constants of the substrate and the dielectric film which is applied on the layer above IDC fingers, in capacitive sensors. Therefore it is necessary to know characteristics of material, and its own properties (permittivity, conductivity).

Fringing capacitance between the interdigitated electrodes depends on electrode’s width, *w*, where transverse capacitance depends on the electrode’s thickness, *t* and the distance between the adjacent electrodes. When the dielectric film is an isotropic material, the unit cell capacitance per length is given by the closed form

$$C_{uc} = \epsilon_o(\epsilon_r + \epsilon_k)\frac{K\left(\sqrt{1-(\mathrm{w}/\mathrm{z})^2}\right)}{K(\mathrm{w}/\mathrm{z})} + 2\epsilon_o\epsilon_k\frac{t}{\mathrm{w}} \qquad (5)$$

where □*o* is the dielectric constant (5) in the free space, □*o* = 8.8542 x 10^{-12} F/m. □*r* and □*k* are the dielectric constants of the substrate and the dielectric film, respectively. *K*(•) is the complete elliptic integral of the first kind. By making full use of symmetry and neglecting the capacitances of the edges, the total capacitance (6) of the IDC is calculated by

$$C_{TOTAL} = C_{uc}(N-1)L \tag{6}$$

where *N* is the number of unit cells in the capacitor and *L* is the length of the electrode fingers. This capacitance model is valid in the presence of an isotropic dielectric film. In the case of anisotropic film, the dielectric permittivity is a tensor rather that a single constant.

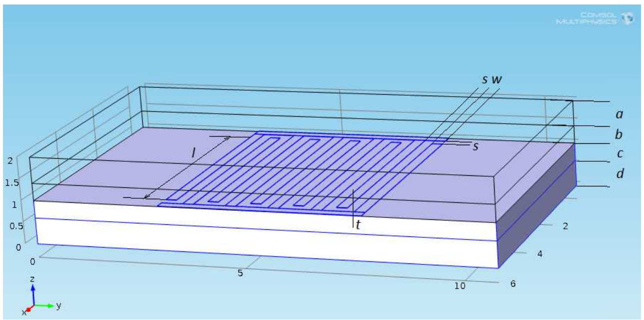


Figure 6. IDC structure and changeable parameters

Therefore, simulations of IDC structures were performed with different geometrical and technological parameters (Table 1.). The parameters were changed independently to observe dependence between the capacitance of structure and each parameter (Fig. 6).

TABLE I. IDC PARAMETERS AND THEIR DESCRIPTION

Symbol	Parameter description
N	Number of IDC fingers
w	Width of IDC fingers
s	Space between IDC fingers
l	Length of IDC fingers
t	Thickness of conductors
a	Thickness and permittivity of the layer above the sensor structure (water, air)
b	Thickness and permittivity of the sensitive layer
c	Thickness and permittivity of the ceramic substrate
d	Thickness and permittivity of the layer below the sensor structure (water, air)

4. DESIGNING AND SIMULATIONS OF IDC SENSOR

COMSOL Multiphysics is a software package which is widely used for modeling. This software not only helps to define the geometry, meshing, defining physics but also helps to visualize the end results. All performed simulations are needed to evaluate influence of the geometrical parameters of IDC and variation of sensitive layer permittivity at the IDC capacitance.

Modern sensor requirements can be fulfilled by Micro Electro Mechanical Systems (MEMS) technology, which was coined in the USA in the late 1980s. MEMS are made up of components between 1 to 100 micrometers in size (i.e. 0.001 to 0.1 mm) and MEMS devices generally range in size from 20 micrometers (20 millionths of a meter) to a millimeter. [3] MEMS with its batch fabrication techniques enables components and devices to be manufactured with increased performance and reliability, combined with the obvious advantages of reduced physical size, volume, weight and cost.

The results of simulations can help us to design IDC sensor structure with optimal dimensions and range of changeable capacitance due to interaction with the pollutants. To perform simulations we used software Comsol Multiphysics, and his MEMS module, Electrostatics, which allow us to make 3D design of sensors structure and to obtain value of capacitance of the simulated structure.

Investigating dependency between length of fingers and value of capacitance, in order to find optimal sizes and outputs, were designed different IDC structures (Fig 7.) with 5, 7.5, 10 and 15 mm length of fingers. A structures have 10 fingers with 20 µm thickness of conductors, and two layers of ceramics of 200 µm thickness with theoretic relative permittivity 1 ($\varepsilon_r = 1$).

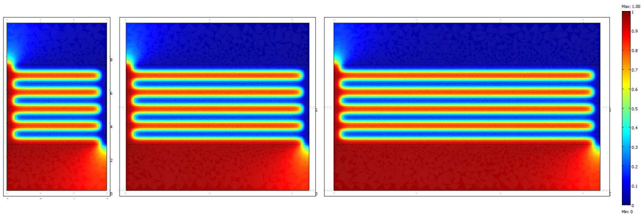


Figure 7. IDC structures with 5, 10 and 15 mm length of fingers

TABLE II. CAPACITANCE OF SIMULATED IDC WITH DIFFERENT LENGTH OF FINGERS

Permittivity of all layers	**Length of fingers, mm**	**Capacitance value, [pF]**
1	5	0.429065
1	7.5	0.622793
1	10	0.816585
1	15	1.203819

The results of the simulations on different length of IDC fingers are represented in Table 2. It is obviously linear dependence of capacitance by the length of fingers.

The length of the fingers cannot grow an indefinitely, it has to be shorter than a quarter guided wavelength. On the other hand, the increment in the number of fingers results in lower frequencies of the undesired resonances.[4]

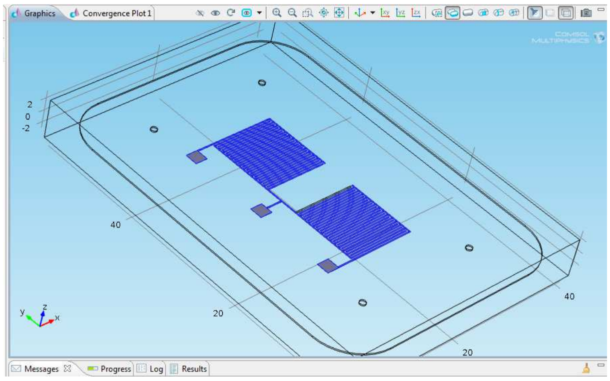


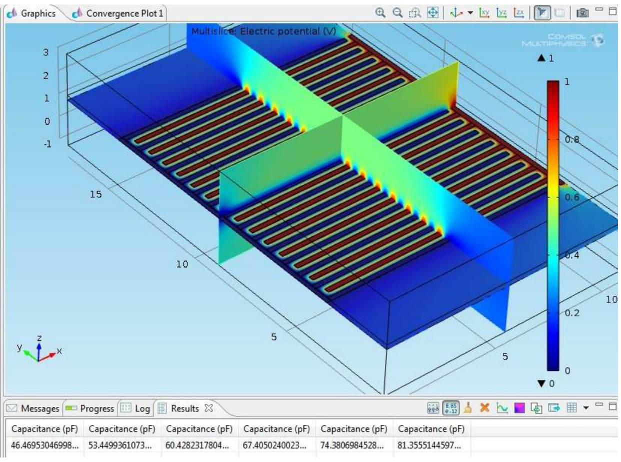
Figure 8. Designed coupled IDC sensor

In aim to design and fabricate a sensor platform based on interdigital capacitors, which will be used in testing of new sensitive materials as well as in monitoring of environment and the pollutants, were designed two (coupled) IDC sensor (Fig. 8) with next parameters of identical capacitors:

- Finger width, w - 0.2 mm
- Space between fingers, s - 0.2 mm
- Number of fingers, N - 29
- Length of fingers, l - 10 mm
- Thickness of ceramic layer, c - 2 mm
- Thickness of sensing layer, b - 0.2 mm

Both capacitors can be coated with sensing material, but one of them can be referent capacitor, with fixed value without sensing layer, in order to compare the obtained values in better precision. The simulations were done separately at one of the capacitors of IDC sensor (Fig. 9), using the theoretical assumptions about sensing material ZnO-WO3 [5] [6] [7], which has possibility of permittivity reductions exceeding 50% for NO exposure.

Obtained permittivity 8.2 using dielectric spectroscopy of glass ceramic at 16.9 MHz (Fig. 4) was utilized in the simulations of capacitance of IDC sensor.



Capacitance (pF)	Capacitance (pF)	Capacitance (pF)	Capacitance (pF)	Capacitance (pF)	Capacitance (pF)
46.46953046998...	53.4499361073...	60.4282317804...	67.4050240023...	74.3806984528...	81.3555144597...

Figure 9. Simulations of designed IDC sensor

In Table 3 are shown obtained results of simulations on an influence of assumed NO on overall capacitance of IDC. It is possible to see very satisfied response of the capacitance on the output of simulated IDC structure according on sensing layer. Capacitance value of simulated IDC sensor increases due the increasing of permittivity of sensing layer, almost in linear dependency.

TABLE III. CAPACITANCE OF SIMULATED IDC WITH DIFFERENT PERMITTIVITY OF SENSING LAYER

Permittivity of LTCC glass ceramic	**Permittivity of sensing layer**	**Capacitance value, [pF]**
8.2	25	46.4695
8.2	30	53.4499
8.2	35	60.4282
8.2	40	67.405
8.2	45	74.3806
8.2	50	81.3555

5. CONCLUSION

This article shows very real and obvious connection between applied materials and design of novel IDC sensors for environmental monitoring. Dielectric spectroscopy of LTCC material was explained and conducted on the disk samples of LTCC tapes. The principles of design IDC sensor are explained and IDC sensor was designed and simulated, using COMSOL Multiphysics with satisfied response according sensing layer.

The intent is to fabricate designed IDC sensor, to connect simulations data with real data of fabricated sensor, as well to conduct more simulations with another data inputs from different sensitive and ceramics materials

The sensing layer assumed for this sensor can be readily adapted to sense a variety of other gases and other phenomena by incorporating a dielectric that produces an electrical response to the property of interest.

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BIBLIOGRAPHY

[1] **V. Radonic, G. Radosavljevic, N. Blaz, Lj. Zivanov, W. Smetana**, Characterization of dielectric tapes for LTCC technology using capacitive method in the frequency range between 1kHz and 1MHz, *Hem. ind*. 63 (3) 209–216 (2009)

[2] **A. S. Abu-Abed, R. G. Lindquist**, Capacitive Interdigital Sensor with Inhomogeneous Nematic Liquid Crystal Film, Progress In Electromagnetics Research B, Vol. 7, 75–87, 2008

[3] **R.Karthick, Dr.SPK.Babu,** AR.Abirami, S.Kalainila, Design of High Sensitivity and Fast Response MEMS Capacitive Humidity Sensor using COMSOL Multiphysics, Proceedings of the 2011 Comsol conference in Bangalor

[4] **F. P. Casares-Miranda, P. Otero, E. Márquez-Segura, C. Camacho-Peñalosa**, Wire Bonded Interdigital Capacitor, IEEE Microwave and Wireless Components Letters, VOL. 15, no.10. October 2005

[5] **E. Birdsell and M. G. Allen,** Wireless Chemical Sensor for High Temperature Environments, Solid-State Sensors, Actuators, and Microsystems Workshop Hilton Head Island, South Carolina, June 4-8, 2006

[6] **T. Ishihara, S. Sato, Y. Takita**, Capacitive-Type Sensors for the Selective Detection of Nitrogen Oxides, *Sensors and Actuators B*, Vol. 24-25, pp. 392-395, 1995

[7] **K. Omar, M. D. Johan Ooi, M. M. Hassin**, Investigation on Dielectric Constant of Zinc Oxide, Modern Applied Science, http://ccsenet.org/journal

[8] **AGILENT TECHNOLOGIES**, Agilent 16451B dielectric material test fixture Operation Manual.

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