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Wireless LTCC sensors for monitoring of pressure, temperature and moisture

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Abstract: In this paper five different wireless sensors operating in the MHz range are presented. Embedded pressure sensors, temperature sensor and sensor for moisture detection all based on a passive wireless inductor-capacitor resonant circuit are realized, following specifications of the LTCC technology design and fabrication process. Considered resonant sensor principle is based on the passive resonant circuit (LC circuit), where changes are detected by variation of sensor capacitance, while inductor inductance remains invariable.

Key words: pressure sensors, temperature sensor, sensor for moisture detection, LTCC.

Brezžični LTCC senzorji za merjenje pritiska, temperature in vlage

Povzetek: V članku je predstavljenih pet različnih brezžičnih senzorjev, ki delujejo v MHz področju. Vgrajeni senzorji pritiska, temperature in vlage temeljijo na brezžičnem induktivno-kapacitivnem resonančnem vezju in so izvedeni po specifikacijah LTCC tehnologije in proizvodnega procesa. Način pasivnega LC resonančnega vezja deluje na spremembo kapacitivnosti, pri čemer induktivnost ostaja nespremenjena.

Ključne besede: senzorji tlaka, senzorji temperature, senzorji vlage, LTCC.

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1. Introduction

Monitoring of physical parameters, such as a pressure, temperature, moisture etc. and its measurement are widely employed in different areas of everyday life [1-5]. Precise detection of pressure or temperature variations is important in many applications e.g. automotive or aerospace industry, internal combustion or turbine engines etc. Control of moisture in products can be a vital part of the process of the product. The measurement of moisture has been of interest to building professionals for many years. Development of innovative methods for monitoring and measuring physical parameters in the civil engineering is therefore both commercially and scientifically important.

Sensors should have high sensitivity for the measured parameters and they should be insensitive to the other parameters of environment. Sensitivity should be followed with linearity of measured values in order to simplify the sensing element configuration. Small dimension of the sensors, low cost and non-contact measurement system for data retrieval are very often required.

Choice of the adequate technology and properties of materials involved in the sensor realizations can ensure its application in chemically aggressive environments and in environments with extreme operating conditions. Since devices fabricated in the Low Temperature Co-fired Ceramic technology (LTCC) are based on glass ceramics they are very well suited for harsh environments. LTCC has been proven as a valuable tool for the realization of three dimensional microsystem structures [4-9]. The variety of available LTCC tapes, as well as a number of methods for substrate pattering, possibility of integration in one LTCC module fluidic channels, heaters, sensors, electronics put LTCC technology in the high-ranking place among technologies suitable for the fabrication of compact sensors devices.

This paper proposes a realization concept of a five resonant sensors configurations. Embedded pressure sensors, temperature sensor and sensor for moisture detection all based on a passive wireless inductor-capacitor resonant circuit are realized.

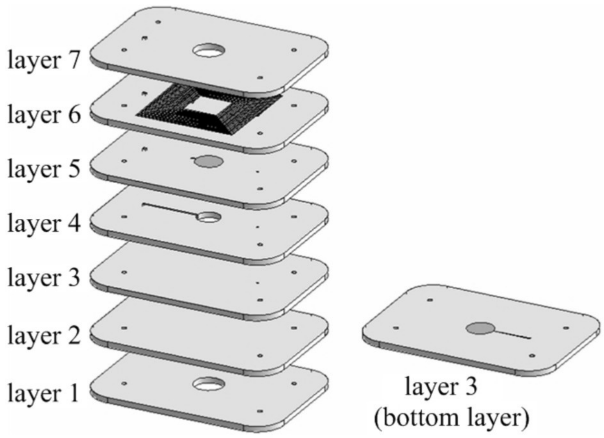
In section 2 are presented design, detection principle, fabrication and measured results for pressure sensors. Temperature sensor and sensor for detection of moisture in building materials are presented in Section 3 and Section 4, while in section 5 conclusions are made.

2. Pressure sensors

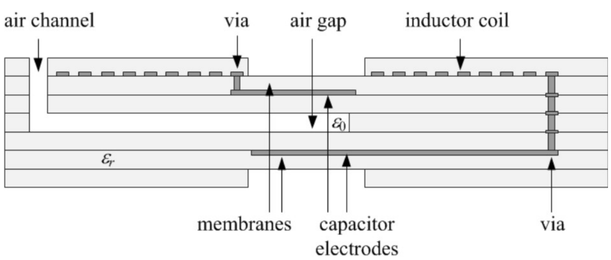
Three pressure sensors are designed and fabricated in the LTCC technology. The sensors are realized as a parallel resonant circuit where pressures changing are detected by variation of capacitance, while inductor remains constant.

2.1 Design, geometrical parameters and theoretical model of the pressure sensors

The first sensor can be found suitable for applications in chemically aggressive environments, since sensor membranes are formed as a sandwich composition comprising electrode layers placed between two dielectric tapes and connected in parallel with inductor windings, Fig. 1. The sensor is built up by seven laser



a) Exploded 3D view



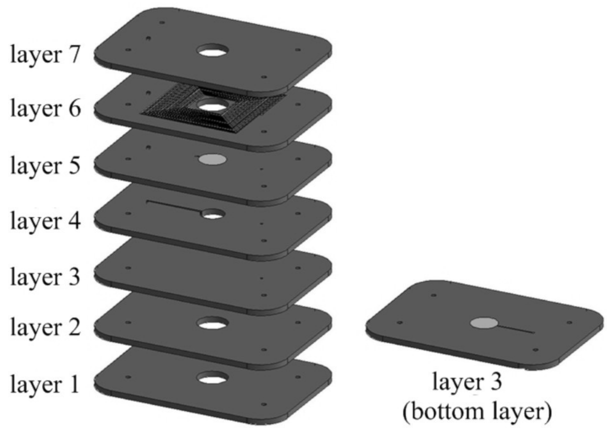
b) Cross section

Figure 1: Pressure sensor type 1.

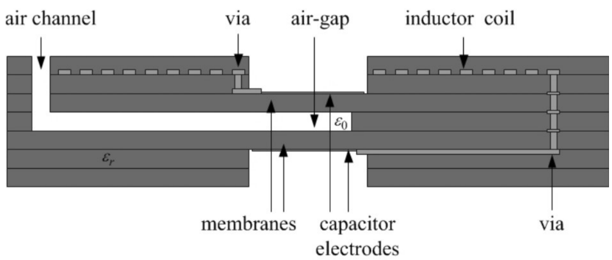
micromachining tapes carrying out vias and holes. Capacitor plates are printed on the top of layer 5 and to the bottom of layer 3, while inductor is placed on the layer 6. Capacitor electrodes are embedded in an each of membranes, which are separated by the cavity. Membranes exposed to the pressure to be measured are formed by the tape layer 2, 3, 5 and 6.

The second design of the pressure sensor incorporates capacitor electrodes that are placed on the outer side of membranes enabling direct application of the pressure to be measured, Fig. 2. Formation of the outer electrodes is attained by implementation of the thin film metallization deposited in the post firing process. This procedure for sensor realization differs from the firstly presented sensor configuration with buried electrodes, resulting in increased sensitivity.

The last sensor design of the pressure sensor was realized with intention to minimize overall sensor dimension. The inductor coil is realized in two layers resulting in miniaturization of the sensor overall dimension, Fig. 3.



a) Exploded 3D view



b) Cross section

Figure 2: Pressure sensor type 2.

Measured relevant electrical and mechanical characteristic of used LTCC tapes are presented in the Table 1 and Table 2, while geometrical parameters of all sensors are presented in the Table 3 and Table 4.

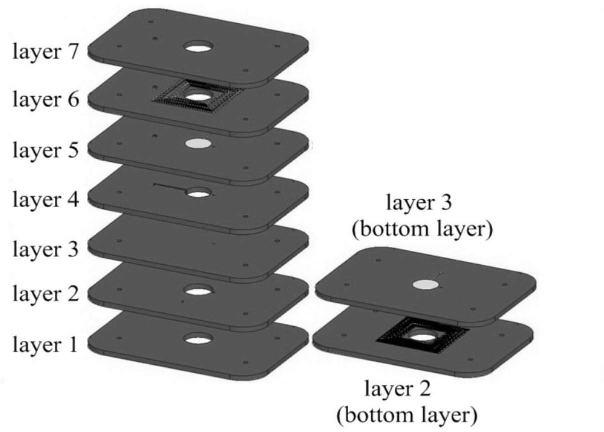


Figure 3: Explode view of sensor type 3.

Table 1: Physical properties of LTCC tapes.

Material	Thickness in green state	Thickness after firing
CeramTec GC	100 [μm]	80 [μm]
Heraeus CT707	125 [μm]	95 [μm]

Table 2: Measured parameters of LTCC tapes.

Material	Relative permittivity @ 1 kHz	Young's modulus @ 25 °C
CeramTec GC	7.8	61.36 [GPa]
Heraeus CT707	6.39	53.49 [GPa]

Table 3: Geometrical parameters of inductors design.

Parameters	Dimension		
	Type 1	Type 2	Type 3
din	10 [mm]	10 [mm]	10 [mm]
s	200 [μm]	270 [μm]	270 [μm]
w	350 [μm]	285 [μm]	285 [μm]
N	17.5	17.5	9.75 (x2)

d_{in} - minimal distance between opposite segments of inner winding, s - spacing between adjacent segments, w - width of conductor line, N - number of windings.

Table 4: Geometrical parameters of capacitors design.

Parameters	Dimension	
	Type 1	Type 2 and Type 3
av	3.3 [mm]	3.5 [mm]
a	4 [mm]	4.35 [mm]
tcond	12 [μm]	12 [μm]
tm	80 [μm]	95 [μm]
tg	80 [μm]	95 [μm]

a_v - hole radius, a - electrode radius, t_{cond} - conductor thickness, t_m - tape thickness, t_g - cavity thickness.

Overall dimensions of the fabricated sensors are presented in Table 5.

Table 5: Overall sensors dimension.

Sensor	Dimension
Type 1	35 x 29 x 0.56 [mm]
Type 2	35 x 29 x 0.665 [mm]
Type 3	24.5 x 20.5 x 0.665 [mm]

Theoretical model and wireless detection will be explained for the sensor type 2. Pressure variations are detected by changes in the sensors capacitance during deflection. The sensor capacitance is a complex structure composed from four capacitances - two directly under/above the air-gap (C_1 and C_3), the air-gap capacitance (C_2) and the annulus capacitance (C_4), Fig. 4.

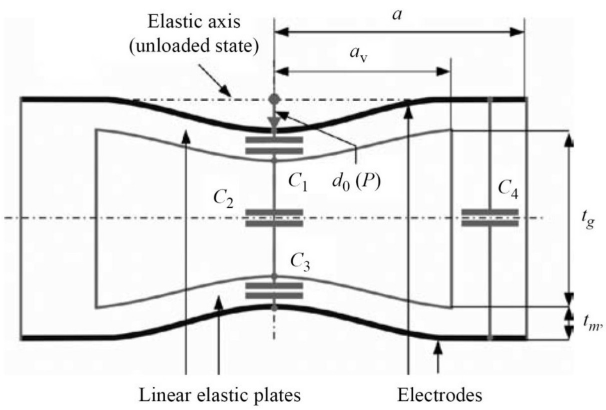


Figure 4: Sensor capacitance corresponding to attribution of individual capacitances.

Deflection of membranes occurs when pressure is induced, resulting in the change of the sensor overall capacitance, $C_S(P)$. Value of $C_S(P)$ has been derived in [8, 9] and can be obtained as

$$C_s(P) = C_s(0)\frac{ar\tanh\left(\sqrt{\dfrac{2d_0(P)}{t_g+\dfrac{2t_m}{\varepsilon_r}}}\right)}{\dfrac{2d_0(P)}{t_g+\dfrac{2t_m}{\varepsilon_r}}} + \frac{\varepsilon_0\varepsilon_r\pi\left(a^2-a_v^2\right)}{2t_m+t_g}, \quad (1)$$

where $C_s(0)$ is the equivalent capacitance for the sensors at zero pressure can be determined as,

$$C_s(0) == \frac{\varepsilon_0\varepsilon_r a_v^2\pi}{2t_m+\varepsilon_r\cdot t_g} + \frac{\varepsilon_0\varepsilon_r\pi\cdot\left(a^2-a_v^2\right)}{2t_m+t_g}. \quad (2)$$

and d_0(P) represent the central deflection of membranes.

Values of the membranes central deflection increase under load consequently leading to increase the overall capacitance of the sensor as can been seen from the Fig 5.

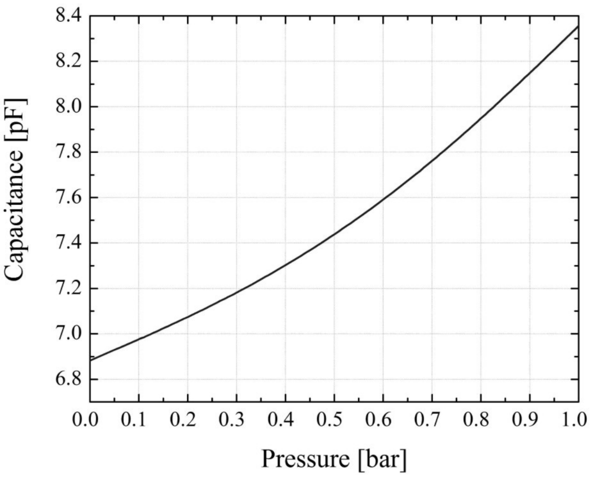


Figure 5: Sensor capacitance versus applied pressure.

For the determination of the inductance values monomial expression present in [10] is used.

Sensor resonant nature enables a wireless system for data retrieval using antenna coil, which is present on the Fig 6.

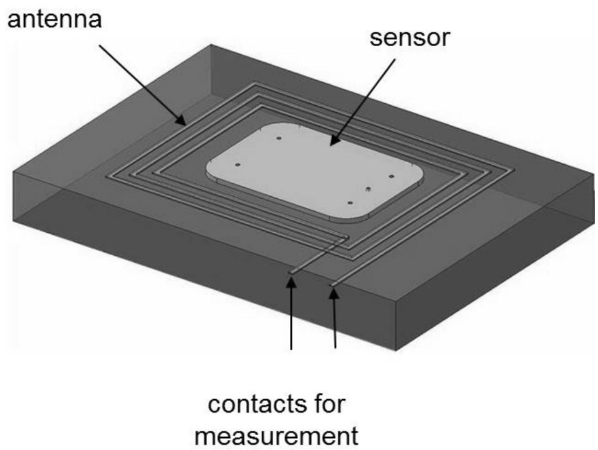


Figure 6: Wireless measurement setup scheme.

Resonant frequency of the sensor antenna system is a pressure dependent value and can be determinate from the system input impedance when the imaginary part of that value becomes zero, Fig 7. Dependence of the resonant frequency of the sensor antenna system versus pressure are presented on the Fig. 8 and Fig. 9.

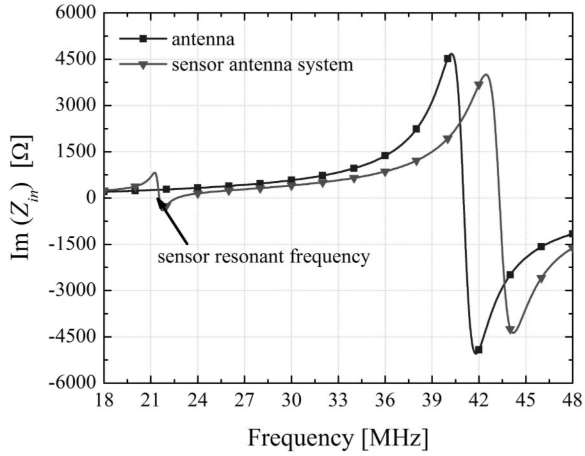


Figure 7: Imaginary part of the input system impedance versus frequency for zero pressure.

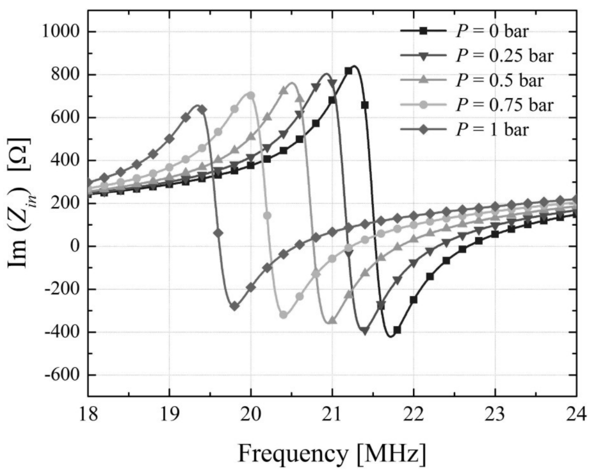


Figure 8: Imaginary part of input impedance versus frequency for different pressure values.

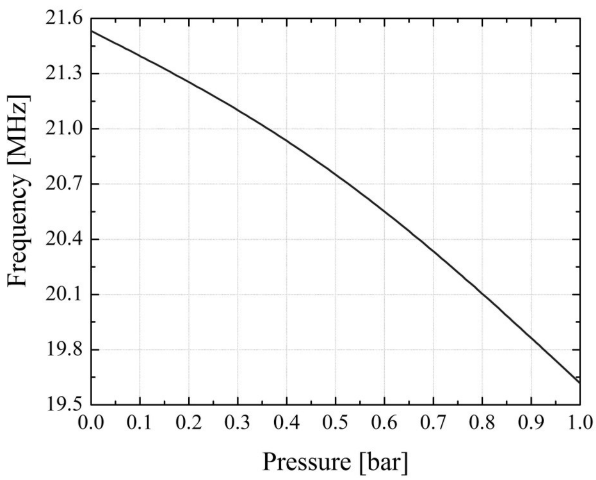


Figure 9: Resonant frequency versus pressure

As can been seen from the Fig. 8 and Fig. 9 that pressure variations influence on the capacitance value, resulting in a shift of the sensors resonant frequency.

Increase of the pressure induced onto sensor membranes leads to an increase of the sensor capacitance and consequently results in a decrease of the system resonant frequency value.

2.2 Fabrication and measured results

Sensor type 1 is fabricated by application of the standard LTCC technology which covers structuring of tapes using laser micromachining, metalizing, laminating, and finally co-firing the stack of LTCC tape layers. CeramTec GC tapes and compatible silver pastes (Heraeus TC 7303 for line printing and Heraeus TC 7304 for via filling) [11, 12] have been used for the sensor fabrication. Isostatic lamination of the collated LTCC layers has been performed at pressure of 50 bar, temperature of 75 °C, and exposure time of 5 min. Firing of the laminated LTCC stack has been conducted in a six zone belt furnace at peak temperature of 900 °C and total firing cycle time of 210 min.

Sensors type 2 and type 3 is also realized implementing the conventional LTCC technology. Heraeus CT 707 tapes are combined with compatible silver pastes (Heraeus TC 7303A for line printing and Heraeus TC 7304 for via filling) [12] are used for sensor fabrication. Collated tape layers are isostatically laminated at pressure of 70 bar and temperature of 75 °C for 5 minutes. The laminated stack is fired in a six zones belt furnace at peak temperature of 880 °C and total firing cycle time of two hours. This is followed by thin film deposition of silver electrodes onto sensor membranes using the sputtering method.

Resonant operating principle of the sensor allows the possibility for the usage of wireless measurement system for the data retrieval. The measurement setup comprises an antenna and a device for the resonance detection. During the measurement procedure, the sensor is placed in the center of the antenna. The test setup for wireless recording of sensor characteristics is built up by a clamping system where two plates made from acrylic glass, are carrying ducts for the supply of pressurized air, Fig. 10. The exhaust holes for the air in the center of the plates are positioned exactly above the sensor membranes exerting the pressure to be measured. The test setup is additionally equipped with a rectangular antenna coil required for the wireless measurement which is connected to the spectrum analyzer (Anritsu MS620J).

The measured results, compared with the theoretical results for the sensor type 2 are presented in the Fig. 11, while compared measurement results of all sensors are presented in the Fig. 12.

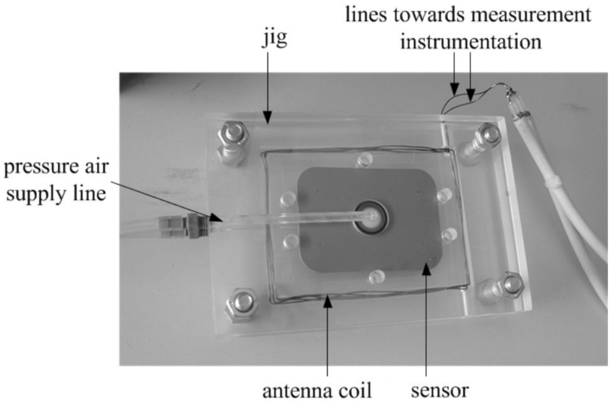


Figure 10: Test setup for the measurement.

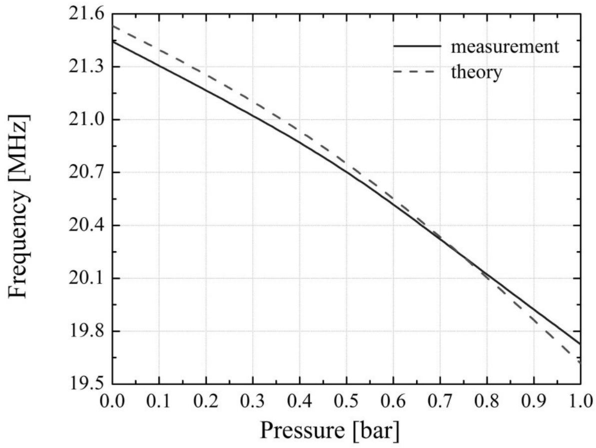


Figure 11: The theoretically and measured results for the pressure sensor type 2.

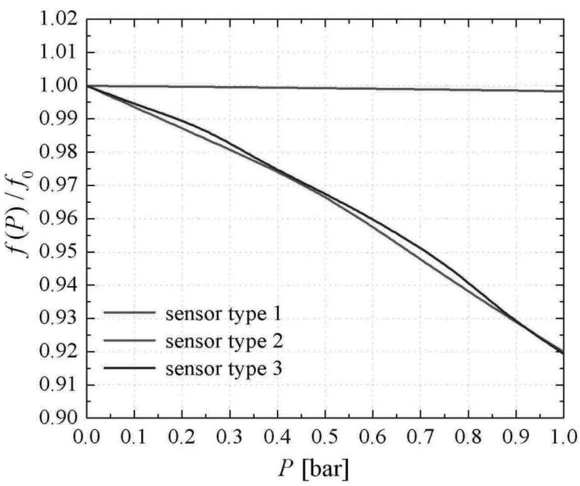


Figure 12: Relative change of sensors resonant frequency versus pressure (measured results).

As can been seen from the Fig. 11 there is a good agreement between theorethical and measured results. It is proved that theorethical model describe sensor antenna system very well.

From the Fig. 12 can be seen that formation of the sputtered thin film electrodes and usage of tapes with higher elasticity significantly contributes to the increase of sensor sensitivity compared to designs for sensor type 1. In addition, 3D realization of inductor coil does not decrease the sensor sensitivity, while the overall dimension of sensor can be significantly reduced.

3. Temperature sensor

Temperature measurement is state of the art using many different techniques reaching from thermocouples over resistors (PTC, NTC, Pt100) to fully digital wireless silicon systems. The approach to use a temperature dependent capacitor along a coil to form a resonating structure leads to a wireless temperature sensor that is embedded in a rugged ceramic body and resistant to corrosive environments and can be read by means of an antenna coil.

The sensor introduced in this paper permits temperature measurement in a high pressure, high temperature and even corrosive environment due to its realization in LTCC technology. Design of the temperature sensor is presented on the Fig. 13.

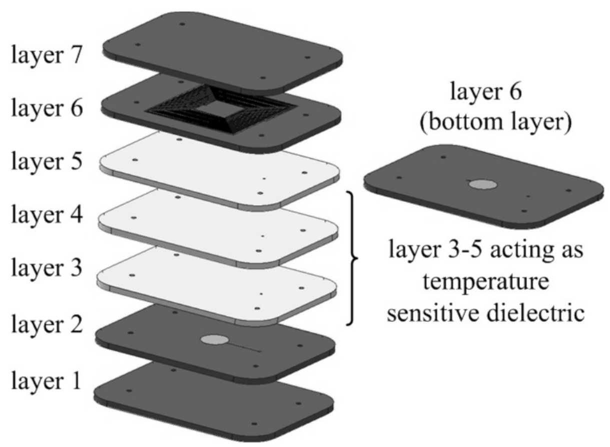


Figure 13: Temperature sensor exploded 3D view.

The sensor consists of several layers of LTCC tapes where the inner layers carry the actual sensor components (inductor and capacitor) and additional outer layers increase the mechanical stability of the device. Electrodes of the capacitor are screen-printed on the top of layer 2 and bottom of layer 6, while the square spiral shaped inductor is place on top of layer 6. For the realization of the sensors, Heraeus CT707 in combination with Heraeus CT765 (sensitive dielectric - ferroelectric) are used. The electrode radius is 4 mm, while geometrical parameters of inductor are presented in the Table 6.

Table 6: Geometrical parameters of inductors design.

Parameters	Dimension
din	10 [mm]
s	270 [μm]
w	285 [μm]
N	17.5

d_{in} minimal distance between opposite segments of inner winding, *s* - spacing between adjacent segments, *w* - width of conductor line (*w*), *N* number of windings.

The working principle of the sensor is based on a resonant circuit (inductor and capacitor) and changes its resonant frequency due to thermal expansion of the bulk material and change in permittivity of a special dielectric layer. The capacitance of sensor can be calculate using the following equation [13].

$$C_s == \frac{\varepsilon_0 \cdot \varepsilon_r(T) \cdot A(T)}{d(T)} \tag{3}$$

where $A(T)$ is temperature dependent plate area $d(T)$ temperature dependent plate distance and $\varepsilon_{re}(T)$ temperature dependent relative permittivity.

The biggest influence on changing the sensor capacitance with the temperature has relative permittivity of the material. Relative permittivity increases if ambient temperature raises leading to increasing the capacitance of the sensor, while value of inductance remains constant, as a resulting that sensor resonant frequency decrease.

The sensor is fabricated using the standard LTCC fabrication process. Tape layers were first structured with a Nd:YAG laser. After the following screen-printing step using Heraeus TC7304 as via-filler and TC7303 as conductor paste, the layers are dried, stacked in a lamination fixture and laminated for 3 minutes at a temperature of 70 °C and a pressure 60 bar in an isostatic press. Firing of the tapes has been performed in a conventional six zones thick film furnace with a cycle time of 2 h and 880 °C peak temperature. Fabricated sensor element is presented on the Fig. 14.

The measurement set-up shown in Fig. 15 consists of a heat resistant alumina plate that is held 2 cm above a jig that contains a rectangular antenna coil Cu-wire. A hot air stream heats the sensor that is located on the top of the alumina plate and is surrounded by heat resistant insulating bricks (the bricks have been removed for clarity in Fig. 15) to prevent excessive heat loss. Temperature measurement via thermocouples on top and bottom side of the sensor provided defined thermal conditions during measurement.

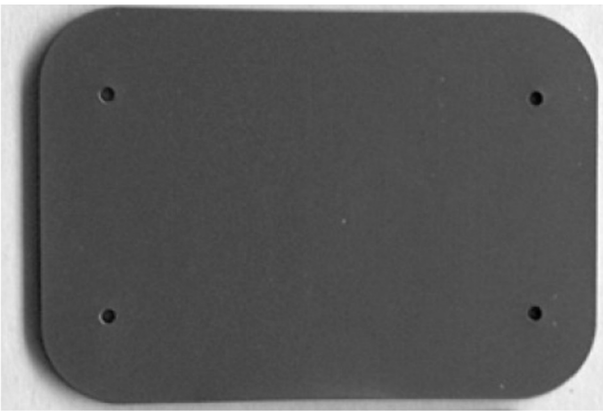


Figure 14: Fabricated temperature sensor (top view).

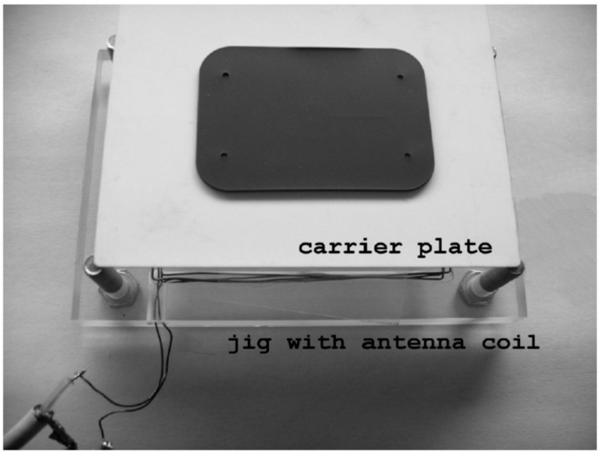


Figure 15: Measurement set-up.

For the measurement, a network spectrum analyzer is connected to the antenna coil via two BNC-terminated coax cables (RG58). Measurements are taken as linear magnitude plots in the relevant range. The measured results for the temperature sensor is presented in the Fig. 16.

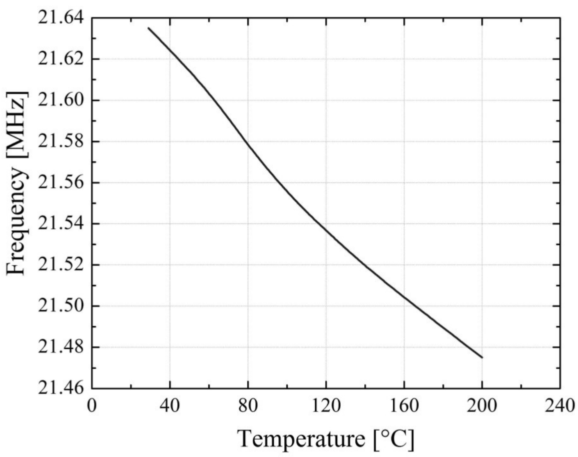


Figure 16: Resonant frequency versus temperature.

As can been seen from the measured results that the resonant frequency of the sensor decreasing when ambient temperature increase. Reason for that is the capacitance of the sensor which increases due to the increasing of the relative permittivity of material over the temperature.

4. sensor for detection of moisture in building materials

In order to know the condition of buildings and other construction structures in the construction industry, there is a need to monitor moisture content. In this way, small (and cheap) repairs at the right time, to extend the life time of a building, are ensured. This is especially important for objects which are sensitive to environmental influences.

In this section it will be presents a LTCC sensor for measuring moisture content of building material (clay brick). The proposed sensor consists of two dielectric layers [14], Fig. 17. The LC structure was screen-printed on the first dielectric layer (as a substrate) and the second layer has a window over capacitor's electrodes. Through this window the sensor is exposed to moisture (thanks to the hydrophilic behaviour), which will then cause change of its relative permittivity and total capacitance, and consequently the resonant frequency of the LC sensor.

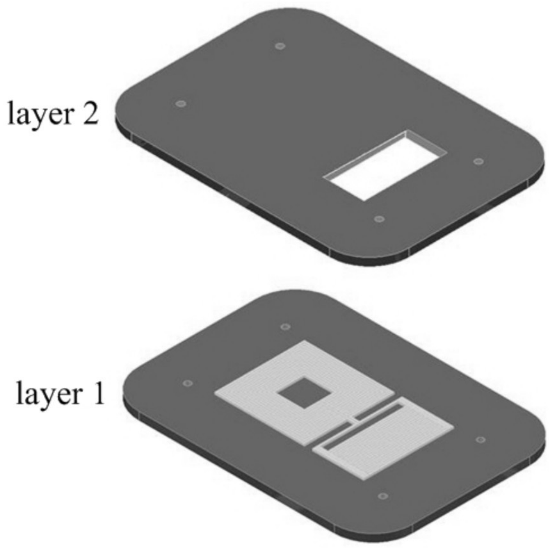


Figure 17: Exploded view of the sensor for moisture detection.

This LC sensor is realized that the inductance of the sensor remains constant. The inductive part was covered with dielectric layer. Contrary to this, the capacitance of the interdigitated electrode system is changed with the variation of the permittivity of the medium (exposed through the small window from the top side of the sensor). This will cause the shift of sensor's resonant frequency. The capacitance of the interdigitated can be calculate using equation proposed in [15, 16],

$$C_s = \frac{\varepsilon_{re} \cdot 10^{-2}}{18\pi} \cdot \frac{K(k)}{K^{'}(k)} \qquad (4)$$

where l is length of the fingers expressed in micrometers and N is number of fingers. The ratio of complete elliptic integral of first kind $K(k)$ and its complement $K'(k)$ is given by [4,5]. ε_{re} is the effective dielectric constant of the microstrip line width w, and define by following equation,

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot F\left(\frac{w}{h}\right) - M \qquad (5)$$

F and M are given explain in [15, 16].

As can been seen from equation (4) and (5) if relative permittivity is higher capacitance of the sensor will be bigger, while inductor remains constant, resulting in a decreasing the resonant frequency of the sensor.

Dimensions of the sensor elements are presented in the Table 7 and Table 8.

Table 7: Geometrical parameters of inductors design.

Parameters	Sensor
din	7.6 [mm]
s	100 [μm]
w	500 [μm]
N	13

d_{in} - minimal distance between opposite segments of inner winding, *s*- spacing between adjacent segments, *w*- width of conductor line, *N* - number of windings.

Table 8: Geometrical parameters of capacitor design.

Parameter	Dimension
w	500 [μm]
s	100 [μm]
l	13.2 [mm]
N	18
dx	13.2 [mm]
dy	21 [mm]

w - finger width, *s* - spacing, *l* - length of fingers, *N* - number of fingers, d_x - total length, d_y - total width

Total dimension of the sensor are (38.2 x 24 x 0.4) mm.

The sensor was fabricated using the LTCC technology, comprising the processing steps of structuring tapes by means of laser micro-machining, metallizing, laminating and co-firing the stack of two LTCC tape layers. For the sensor fabrication Heraeus CT700 [12] dielectric tapes were combined with compatible silver paste Heraeus TC 7303A for conductive line printing. Collated tape layers were isostaticaly laminated at pressure of 70 bars and temperature of 75 °C for 3 minutes. The laminated stack was fired in a six zones belt furnace at a temperature peak of 880 °C and a total firing cycle time of 2 hours. Fig. 18 illustrates the fabricated sensor. In the Fig. 19 is presented measurement setup and measured results (for the clay brick) are presented in the Fig. 20.

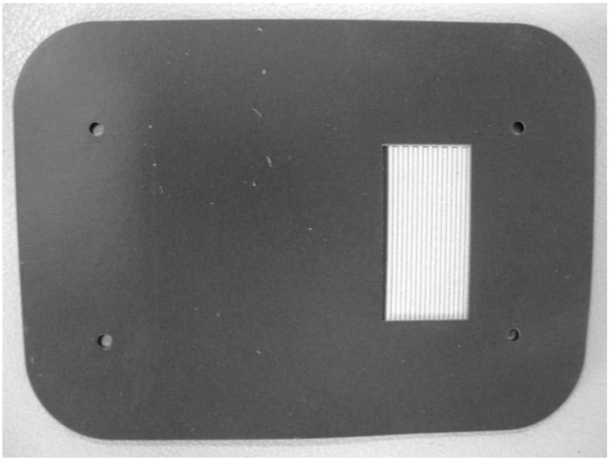


Figure 18: Fabricated sensor for moisture detection (top view).

Figure 19: Experimental setup for measuring the resonant frequency of the sensor embedded into building material.

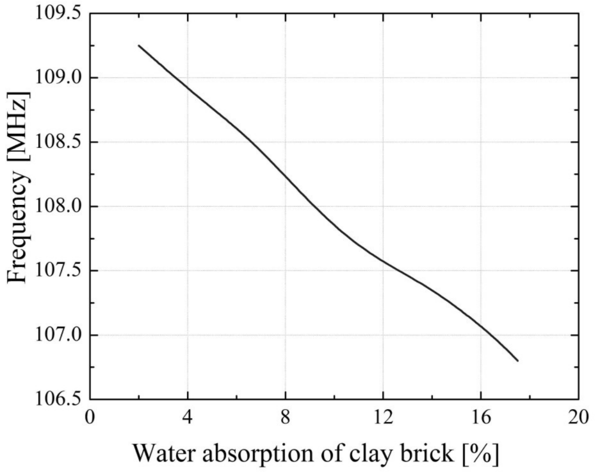


Figure 20: Resonant frequency versus percent of water absorption.

The measure results shows that the resonant frequency changes from 109.2 MHz to 106.9 MHz while the percentage of water ranging from 2% to 17.5%. The variation of resonant frequency changes is 2.3 MHz while the change in moisture content is 15.5%. It can also be seen that the deviation of measured values from the ideal linear dependence is very small. The sensitivity of the sensor in this case is 169 kHz/percentage of water content.

5. Conclusion

The sensor modules presented in this paper are a passive LC resonant type sensor designed for the operation in MHz range and are fabricated using the conventional LTCC technological process. Three pressure sensors, one temperature and one sensor for the moisture detection are designed and fabricated in the LTCC technology. For all sensors a wireless measurement set-up is used for non-contact retrieval of the measured data.

It is shown that formation of the sputtered thin film electrodes and usage of tapes with higher elasticity significantly contributes to the increase of sensitivity of the pressure sensor. While 3D realization of inductor coil does not decrease the sensor sensitivity, it contributes to the significant reduction of sensor overall dimensions.

The experiments have shown, that LTCC technology offers the possibility to realize different wireless readout sensors with nearly linear characteristics.

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