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A wireless double planar coil sensor arrangement for monitoring capacitance changes due to water uptake embedded in a thin fiber-reinforced composite

S.Sauer[a]*, W.-J. Fischer[b]

[a]TU Dresden, Institute for Semiconductors and Microsystems, 01062 Dresden, Germany
[b]Fraunhofer IPMS, Wireless Microsystems, 01109 Dresden, Germany

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Abstract

A wireless, near-field coupled sensor based on two planar spiral coils embedded in a thin fiber-reinforced composite material is presented. The measurement effect exploits the fact that penetrating water changes the effective dielectric permittivity in the volume surrounding the planar coils. This leads to an increase of the sensor self-capacitance and to a decrease of the sensor self-resonant frequency. The sensor targets applications in which non tactile, in-situ monitoring of water uptake, within a confined volume of material, is of interest. In order to describe the general electric behavior a circuit model, considering the sensor and an inductively coupled detection coil, has been developed and verified. An analytic expression for the resonance frequency was deduced. Sensor prototypes were integrated in a glass fiber polypropylene composite. Applied measurements demonstrate the resonance frequency change due to water entering and leaving the material during immersion and drying tests.

Keywords: Wireless passive sensor; ICR sensor; composite material; water uptake; resonant sensor; embedded sensor;

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1. Introduction

There is a strong interest in monitoring material properties in situ [1,2,3]. A targeted quantity is the water content in composite materials. Especially in the case of natural fiber composites, mechanical

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* Corresponding author. Tel.: +49-351-463-34939; fax: +49-351-463-37021.
E-mail address: sebastian.sauer@tu-dresden.de.

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properties are affected by the water content [2]. Inductively coupled resonant sensors (ICR) are easy to manufacture, integrate and allow passive, short distance, wireless sensing. Water entering or leaving a material by fluid diffusion processes causes a change of the electric properties of the affected material volume. A possible sensing approach is the observation of capacitance changes of a conductor assembly caused by electric permittivity variations [4]. In order to monitor the water uptake within a composite, without breaching the outer material boundaries, an electric resonator circuit is embedded into the material. The change of the water content of the material surrounding the sensor alters its intrinsic coil capacitance which also leads to a change of the self-resonant frequency f_0. By using an external detection coil the resonance frequency of the sensor can be monitored wirelessly. In the presented approach (Fig.1) two planar coils are connected by a single wire. This provides an increased sensitivity to capacitance changes in the inner measurement volume.

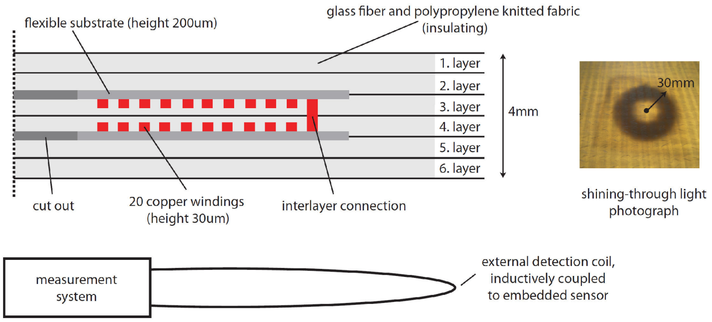


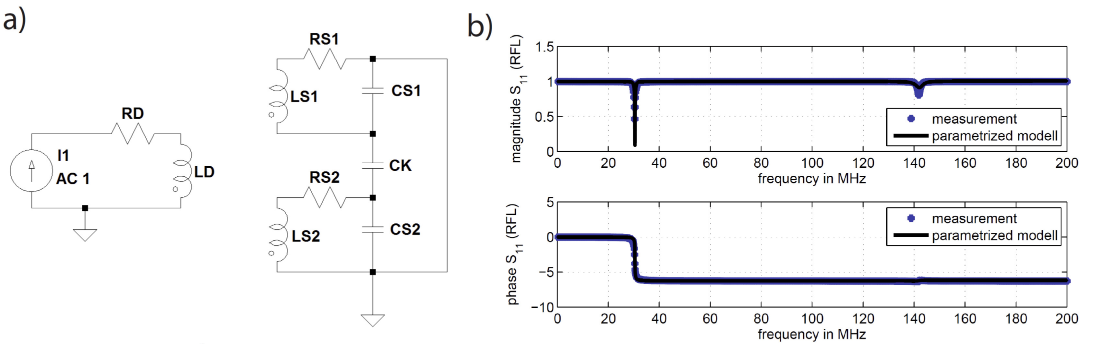
Fig 1: Wireless sensor concept based on a double planar coil sensor arrangement embedded in a thin fiber-reinforced composite, which inner capacitance and resonance frequency varies due to a water uptake or loss of the surrounding material. A single coil has 20 turns with a winding width and gap of 0.2mm, the outer coil diameter is 30mm. The substrate area is 35mm x 35mm with a thickness of 0.2mm. The overall dimensions of the GRP sample are 110mm x 80mm x 3mm.

2. Sensor fabrication and composite integration

To demonstrate the feasibility of the measurement approach the double planar coil sensor arrangement has been placed within six plies of glass fiber polypropylene knitted fabrics. The planar coils are located between the 2nd and 3rd as well as the 4th and 5th layer, connected through an additional single wire. Demonstrators were cured by thermoforming at a temperature of approximately 200°C and a pressure of 500kPa and have final dimensions of 110mm x 80mm x 3mm. Coils were manufactured using a standard subtractive printed circuit board process on a 200µm thick substrate with an average conductor width and gap of 200µm and a height of 20µm.

3. System model and measurement procedure

The developed model (Fig. 2a) consists of two connected technical coils (R_{SX}, L_{SX}, C_{SX}) with internal electric (C_K) and magnetic coupling (M), which are inductively coupled (M_1, M_2) to an external detection coil (R_D, L_D). A frequency response measurement of the overall system shows good agreement with the parameterized, model predicted frequency response (Fig. 2b). In dependence of the internal sensor parameters a second resonance at higher frequencies can be observed. An analytic expression for the phase or imaginary resonance frequency (Fig. 2c) has been obtained for a simplified case (equal internal sensor parameters $R_{S1}=R_{S2}$, $C_{S1}=C_{S2}$, $L_{S1}=L_{S2}$ and detection coil coupling $M_1=M_2$) which can be used to relate the resonance frequency to a capacitance change. The additional coupling capacitance C_K provides an increase in sensitivity compared to a single planar coil concept, which would only possess capacitance changes C_S.



c)

$$Z_{C1} = \frac{1}{sC_{S1}}$$
$$Z_{C2} = \frac{1}{sC_{S2}}$$
$$Z_{11} = R_D + sL_D$$
$$Z_{22} = R_{S1} + sL_{S1} + \frac{1}{sC_{S1}}$$
$$Z_{33} = R_{S2} + sL_{S2} + \frac{1}{sC_{S2}}$$
$$Z_{44} = \frac{1}{sC_K} + \frac{1}{sC_{S1}} + \frac{1}{sC_{S2}}$$

general case:

$$Z_D(s) = Z_{11} - \underbrace{\frac{(sM_1Z_{C2} - sM_2Z_{C1})^2 + Z_{44}(2s^3MM_1M_2 - s^2M_1^2Z_{33} - s^2M_2^2Z_{22})}{s^2M^2Z_{44} - 2sMZ_{C1}Z_{C2} + Z_{33}Z_{C1}^2 + Z_{22}Z_{C2}^2 - Z_{22}Z_{33}Z_{44}}}_{Z_T}$$

simplified case:

$$Z_T = -\frac{2M_1^2s^3(C_S + 2C_K)}{(MC_S + 2MC_K + L_SC_S + 2C_KL_S)s^2 + (R_SC_S + 2C_KR_S)s + 1}$$

resonance frequency expression:

$$f_{0,Phase} = f_{0,Imag} = \frac{1}{2\pi\sqrt{(L_S + M)(2C_K + C_S)}}$$

Fig 2: a) Electric sensor model as SPICE circuit representation consisting of the two planar coils connected through a single wire, a coupling capacitance (displacement currents through the enclosed measurement volume), internal magnetic coupling as well as an inductively coupled detection coil. b) Comparison of a frequency response measurement (S_{11}-magnitude and phase) of a free sensor arrangement and the calculated response of the parameterized electric model (converted to S_{11} parameter representation). c) Deduced analytical expression for the impedance on detection coil side Z_D, transformed sensor impedance Z_T and an expression for the resonance frequency for a simplified case.

4. Measurement procedure and experimental results

The measurement setup consists of a network analyzer (Agilent/HP 8752C) connected to a detection coil and a water tank in which demonstrators were placed. Measurement data was transferred to a measurement PC via the IEEE-488 general purpose interface bus for data storage and further analysis. The calibration routine described in [5] was used to isolate the transformed sensor impedance. During immersion tests composite samples with embedded sensors were placed in the water tank filled with distilled water. For drying tests the same experimental setup without water has been used. Tests were carried out under laboratory conditions. Sensor and detection coil were separated, with a distance of 10mm. Placing sensors in water leads to an initial sensor resonance frequency increase due to the surrounding water and the thin geometry. An examined composite sample with an embedded sensor showed a weight variation due to water uptake/loss of 0.25g and an associated resonance frequency shift of 660kHz from an initial frequency of 10.43MHz. For the presented sensor arrangement the water uptake process follows an inverse hyperbolical tangent function whereas the drying process follows an exponential function.

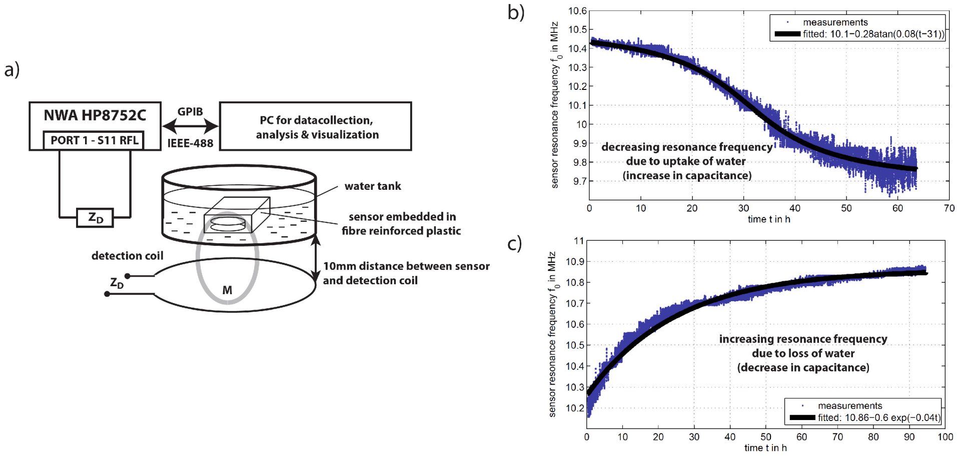


Fig 3: a) Measurement setup used to wirelessly monitor the resonance frequency shift due to water uptake of the proposed sensor arrangement. b) During water uptake the resonance frequency decreases, showing a time dependence which can be described by an inverse tangent function, whereas during drying c) the resonance frequency increases, with a time dependence following an exponential function.

5. Conclusion

A wireless, passive sensor based on a double planar coil arrangement for monitoring water uptake of composite materials has been presented. Experimental results prove the time dependent change of the sensor resonance frequency due to water uptake and loss of the composite. The approach is feasible for applications which require in-situ monitoring of the water content of a composite material.

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