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Registration	November 5, 2010
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Contactless Quality Monitoring Sensor Based on Electrical Conductivity Measurements

[1]Armin SATZ, [1]W. GRANIG, [2]D. TUMPOLD and [1]F. REININGER
[1] Infineon Technologies Austria AG, Siemensstrasse 2, 9500 Villach, Austria
[2] KAI GmbH, Europastarße 8, 9524 Villach, Austria
E-mail: Armin.Satz@infineon.com

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Abstract: A first prototype of a contactless conductivity sensor for AdBlue® quality monitoring is presented. Based on a detailed sensor mode analysis it is shown that capacitive sensors can be designed to sense electrical liquid conductivity. The sensor design process is based on a sensor model, which allows simulating capacitive senor responses for arbitrary electrode and liquid tank geometries. Finally, temperature induced errors are estimated. *Copyright © 2010 IFSA.*

Keywords: AdBlue® quality monitoring, Contactless conductivity sensor, Sensor modeling

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1. Introduction

In addition to the liquid level, liquid quality monitoring becomes more and more important for automotive sensor applications. Concerning the Selective Catalytic Reduction (SCR) principal, which reduces emissions of oxides of nitrogen from the exhaust of diesel-engined motor vehicles, a quality monitoring of AdBlue® is needed. AdBlue® [$(NH_2)_2CO + H_2O$] is the registered trademark for an aqueous urea solution (32.5 %). It is reported in [1] that quality monitoring of AdBlue® can be achieved by sensing optical properties of the liquid. In contrast to the optical sensing principal also ultrasonic methods are applicable, see [2]. A major disadvantage of these sensor principals is given by the fact that they need direct contact with the fluid or at least a flow-through sensor setup.

In contrast to the mentioned methods above, capacitive sensors can operate outside the liquid tank. They do not need direct contact to the liquid, or any construction parts inside the liquid tank. As a consequence, the lifetime of capacitive sensors is not limited by liquid induced contamination or corrosion. Furthermore, capacitive sensing technology offers the possibility to combine liquid level and liquid quality monitoring within the same sensor technology. The remainder of this paper is structured as follows:

Section 2 explains the measurement principle, which is used to sense the urea concentration. It is shown that the urea concentration can be related to the electrical conductivity and the dielectric permittivity of the liquid. Furthermore, a sensor model is introduced, which allows to identify three different kind of capacitive sensor modes. Finally, the first quality monitoring prototype, which is designed to operate in conductive coupling mode, is described. Measurement and simulation results are presented in section 3. Based on the fact that a temperature dependency of the sensor signal is expected, also an estimation of the needed temperature resolution is given. Finally, the conclusion sums up the documented results and gives an outlook on further development activities.

2. Measurement Principle

Electrical properties of a solid or liquid are given by the electrical conductivity σ [S m^{-1}] and the relative dielectric permittivity ε_R. Like depicted in Fig. 1, these two properties can be sensed by analyzing the amplitude and the phase of an idealized parallel plate capacitor.

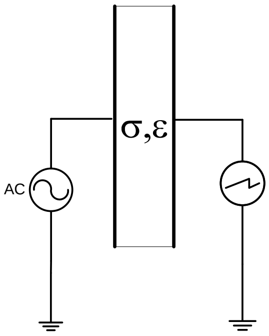


Fig. 1. Parallel plate capacitor.

A test fixture (Agilent 16452A Liquid Test Fixture), which is constructed to behave like an idealized parallel plate capacitor, together with the impedance analyzer (Agilent 4294A) is used to measure electrical properties of AdBlue® for different concentrations and temperatures. The measurement results clearly show that the electrical conductivity shows a much higher sensitivity on urea concentration variations than the permittivity. As can be seen in Fig. 2, the aqueous urea solution shows a relative change in the electrical permittivity ε_R, which is given by ε_R (100 %)/ε_R (0%) = 1.33, whereas the relative change in the electrical conductivity is given by σ (100 %) / σ (0%) = 126.

Following the arguments mentioned above, one must conclude that electrical conductivity sensing is a much more preferable method in comparison to permittivity sensing, because the sensitivity is much higher. At this point it must be stated that according to the knowledge of the authors, a fundamental understanding of the curvatures presented in Fig. 2 cannot be found in literature. In [3] it is assumed that the influence of urea on water structure and/or a urea self-aggregation takes place and therefore the electrical conductivity increases with increasing urea concentration. Nevertheless, the conductivity dependency on the concentration and the temperature can be measured easily and therefore be used as a sensor principle.

A major disadvantage of a conductivity sensor is given by its temperature dependency σ (%, T). Details about the temperature dependency and a compensation method are given in section 3.1.

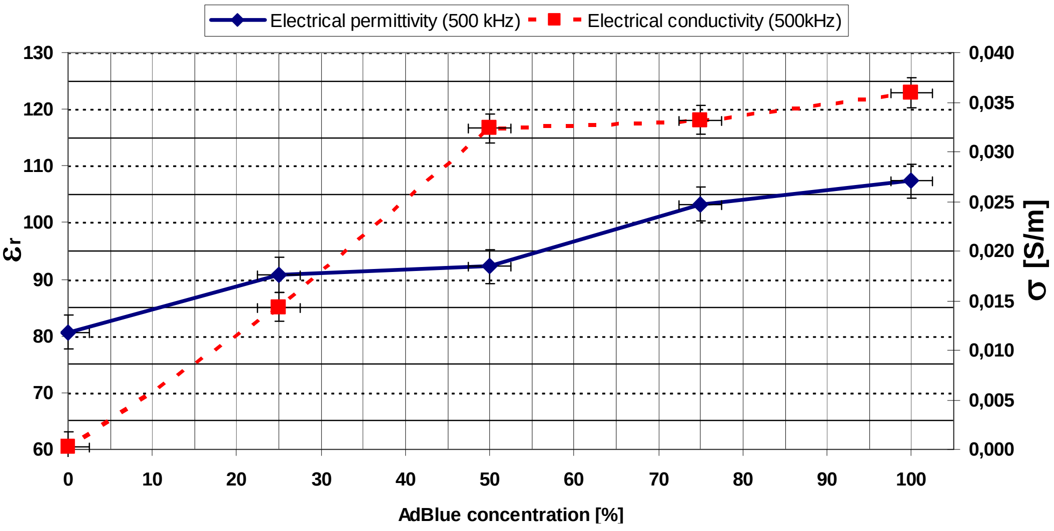


Fig. 2. Relative dielectric permittivity ε_R and electrical conductivity σ as a function of urea concentration (%) for room temperature and 500 kHz.

2.1. Sensor Model & Sensor Modes

Now, that it is shown how the electrical conductivity is related to the AdBlue concentration, it will be demonstrated how this sensor principal can be utilized for AdBlue quality monitoring.

Basically, capacitive sensors are sensitive not only to the conductivity of the liquid to be sensed. Moreover, they are sensitive to the liquid permittivity, to the geometric structure of the electrodes, to the liquid level, to the electric properties and geometric design of the sensor materials, which are used to separate the electrodes from the liquid (liquid tank materials). In order to understand and to quantify the contributions of these different parameters to the measured sensor signal, a sensor model (see Fig. 3) is needed.

This model serves as a tool for mapping the previously mentioned parameters to lumped circuit elements. The equivalent circuit, which is depicted in Fig. 3, defines the transfer characteristic between transmitter and receiver electrodes. The calculation of the corresponding electrical network parameters is based on the Finite Element Method (FEM).

The application of FEM models for the simulation of the circuit parameters is necessary because of the fact that analytic approximations of the electric field are available for only very specific electrode structures, see [4]. To meet the requirements of the sensor application, the electrode design cannot be restricted to these specific cases. Like shown in Fig. 3 we focus on open electrode structures. This means that the sensor is forced to work under electric stray field conditions. A basic guide to simulate these open electrode structures is given in [5].

At this point it has to be mentioned that the FEM simulations are electrostatic simulations, which means that electromagnetic radiation is not considered in the calculation. Temperature or frequency is assumed to change electrical material parameters and therefore the simulation input parameters, not the type of simulation.

Before designing an electrode structure for a capacitive quality monitoring application, a detailed analysis and understanding of the described sensor transfer characteristic must be gained. In order to design an optimized electrode structure, the transfer network in Fig. 4 must be interpreted as a superposition of at least three different sensing modes.

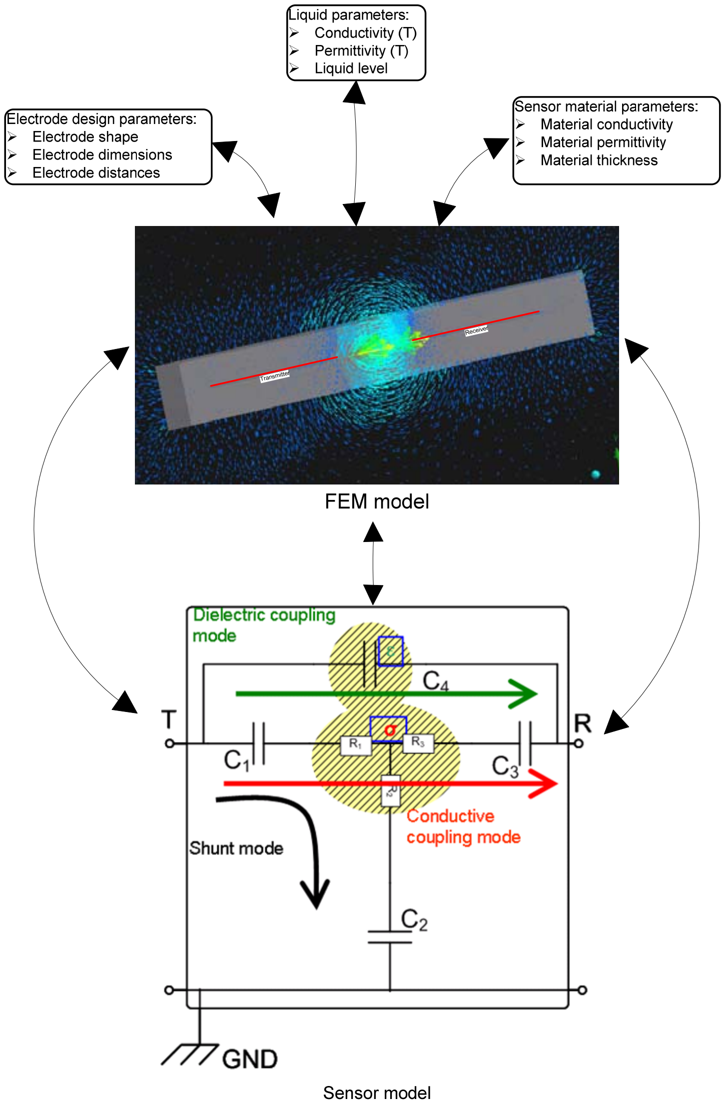


Fig. 3. FEM model and capacitive sensor model describing the transfer function between transmitter (T) and receiver (R) electrode.

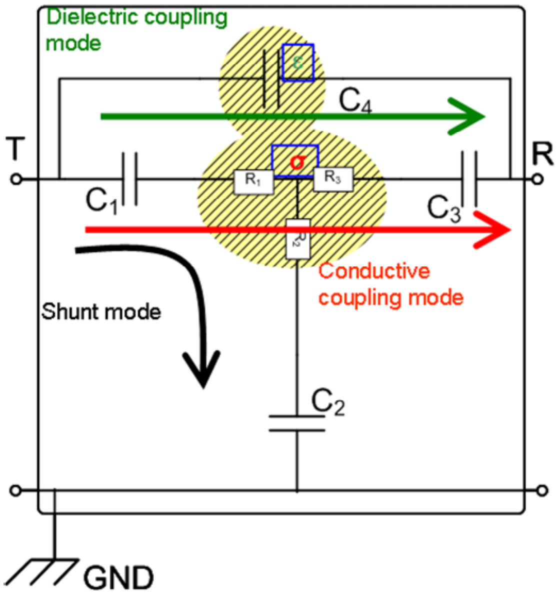


Fig. 4. Visualization of three different sensor modes.

Basically, these modes are not limited to the application of liquid quality monitoring, they are also reported in [6-8] for the application of capacitive occupant detectors. The three modes of operation are the dielectric coupling mode, the conductive coupling mode and the shunt mode. A basic description of these modes is given in the next paragraphs.

2.1.1. Dielectric Coupling Mode

Dielectric coupling mode is based on a direct capacitive coupling (given by the capacitor C_4 in Fig. 4) between transmitter and receiver electrode. A sensor operating in this mode must fulfill the following design criteria:

1. $C_4 >> C_1$ and C_3;
2. ΔC_4 must be sensitive to the property to be sensed.

In order to fulfill these criteria the electrodes should be placed only in small distances to one another and the object/property to be sensed should change its permittivity (ε_R) value.

A change in the liquid permittivity can also be interpreted as a liquid level. Consequentially for AdBlue®, a dielectric coupling mode would be a preferable mode for a liquid level sensor, because of the high permittivity values of this aqueous solution. Quality monitoring for AdBlue® in the frequency range between 500 kHz and 10 MHz cannot be realized in dielectric coupling mode because the permittivity change over AdBlue® concentration is by far too small for the investigated stray field geometries.

2.1.2. Conductive Coupling Mode

A capacitive sensor operating in conductive coupling mode means that the signal current flows from the transmitter electrode to the object (over C_1), and from the object (over R_{liq}) back to the receive electrode (over C_3). This signal path (see Fig. 5) is possible for conductive objects and for electrode arrangements which guarantee that $C_4 << C_1$, C_3. AdBlue® is a liquid with a conductivity of 0.035 [S/m], which is a quite large conductivity compared to distilled water 0.00028 [S/m.]. If AdBlue® is diluted by distilled water the conductivity of the solution is decreased and this fact can be sensed in the conductive coupling mode.

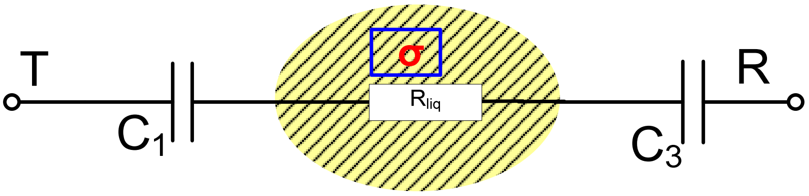


Fig. 5. Signal path for conductive coupling mode.

In Fig. 5 the sensing principle of the conductive coupling mode is given. C_1 and C_3 are considered to be constant, because they mainly depend on the sensor material permittivity and the distance between the electrodes and the conductive liquid. The liquid resistor R_{liq} is assumed to change over liquid concentration R_{liq} (%). As a consequence the phase relation between the transmitted and received signal should change over concentration, and therefore capacitive sensors operating in conductive coupling mode must be able to sense phase relations between transmitted and received signals.

2.1.3. Shunt Mode

A capacitive sensor operating in shunt mode measures signal losses. The signal is shunt away from the receiver (over C_2) by the object. Shunt mode measurements need conductive objects. They are mainly used for capacitive proximity detectors.

2.2. First Prototype

The prototype dimensions and a photo are depicted in Fig. 6. It is designed to be operated in conductive coupling mode.

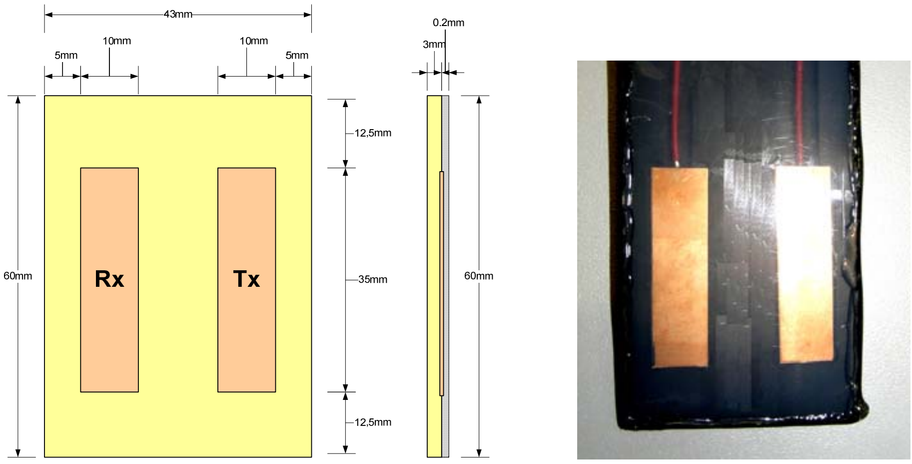


Fig. 6. First prototype for a capacitive conductivity sensor for liquids.

In the application the sensor must be totally covered by the liquid. This means that there must be a lower limit for the liquid level, because the possibility of a signal variation due to liquid level variations must be excluded. In the side view of the quality sensor in Fig. 6, it can be clearly seen that it exists a front and a backside of the sensor. The front side is the sensitive side, because the sensor material is very thin (200 µm). This quite small thickness is necessary in order to maximize the capacitances C_1 and C_3, see also Fig. 4.

3. Results

In the next paragraphs, measurement results are described and compared to the simulation results.

3.1. Measurement Results

For analyzing the sensor characteristics an impedance analyzer (Agilent 42 94A) is used. This analyzer is based on the auto-balancing bridge method [9]. The high-potential and the high-current terminals are attached to the transmitter electrode (T_x) and the low-potential and low-current terminals to the receiver electrode (R_x). The guard terminals (shield potential of the four measurement terminals) and the ground terminal (chassis) are not connected to the sensor.

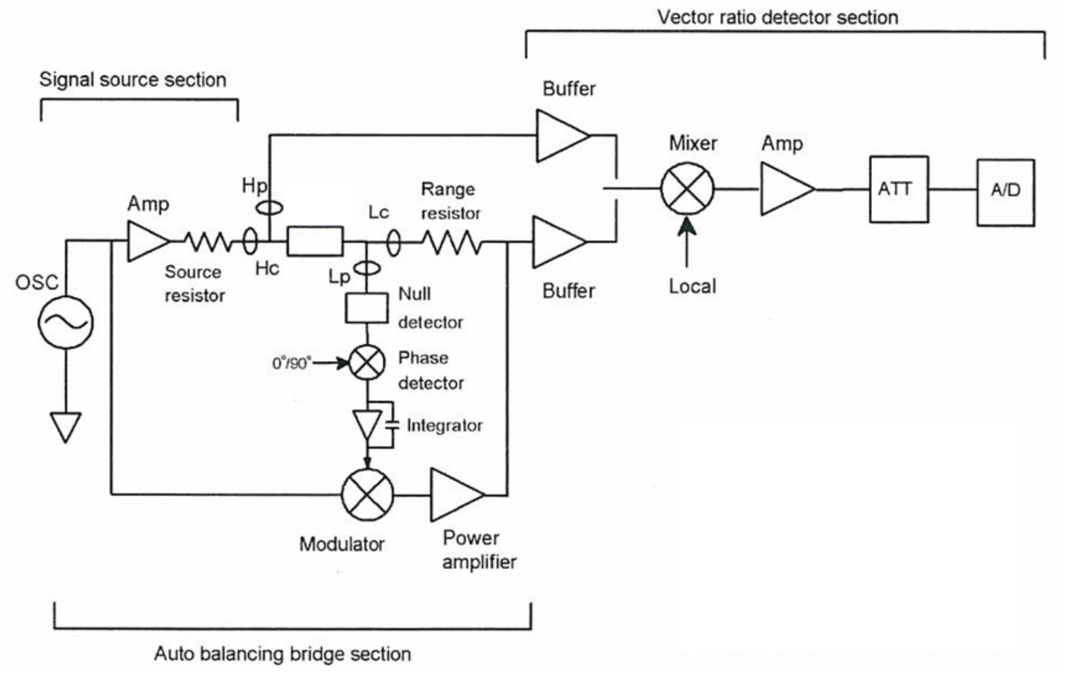


Fig. 7. Schematic of the auto-balancing bridge method [8].

The measurement circuit is decoupled from the chassis potential and therefore also independent from the liquid to ground/chassis coupling parasitic capacitor C_2, which is depicted in Fig. 4. At this point it has to be mentioned that this is a specific measurement boundary condition, which is useful for the applied auto-balancing bridge method. This assumption cannot be automatically assigned to other measurement principles.

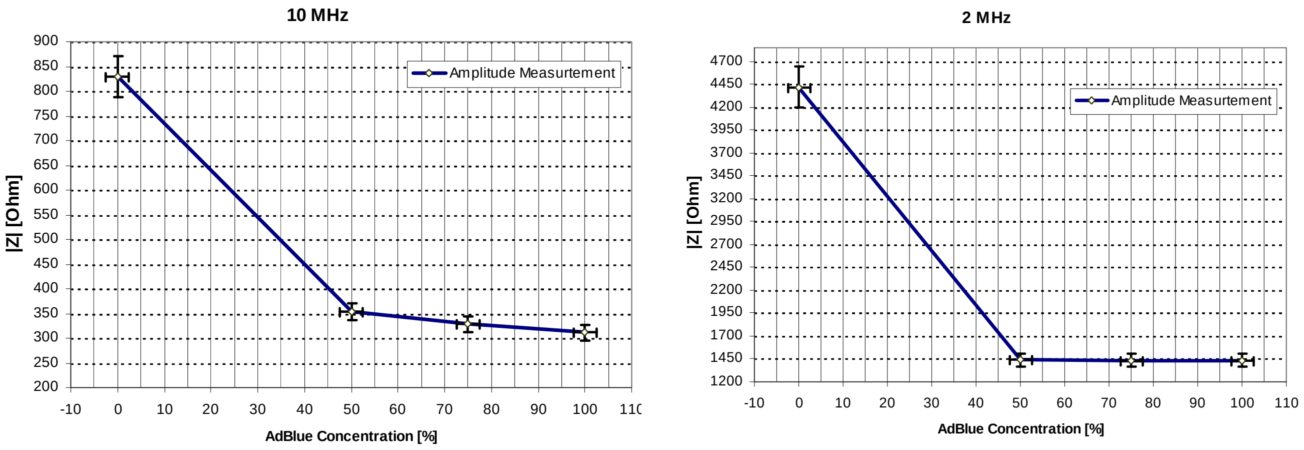
The measured impedances are given by the amplitude |Z| [Ohm] and the phase [°]. In order to investigate the frequency dependence of the quality sensor, measurements for 2 MHz and 10 MHz were taken.

The measurement results, which are given in Fig. 8, show conductivity dependence. Between distilled water (0% AdBlue concentration) and a solution of 50 % AdBlue the conductivity changes with 6.4 10^{-4} [S m-1 %-1]. For concentrations from 50 % to 100 % AdBlue the conductivity changes with 7.2 10^{-5} [S m-1 %-1], see Fig. 8 e.). This sensitivity change is also observed in the measured amplitudes and phases for 2 MHz as well as for 10 MHz.

It must be concluded that the measured sensor signals (amplitude and phase) show a qualitative relation to the conductivity of the liquid. In order to verify this qualitative relation the sensor model described above is utilized. In the next section, sensor modeling and simulation results are presented, which enables also a quantitative analysis of the discussed measurement results.

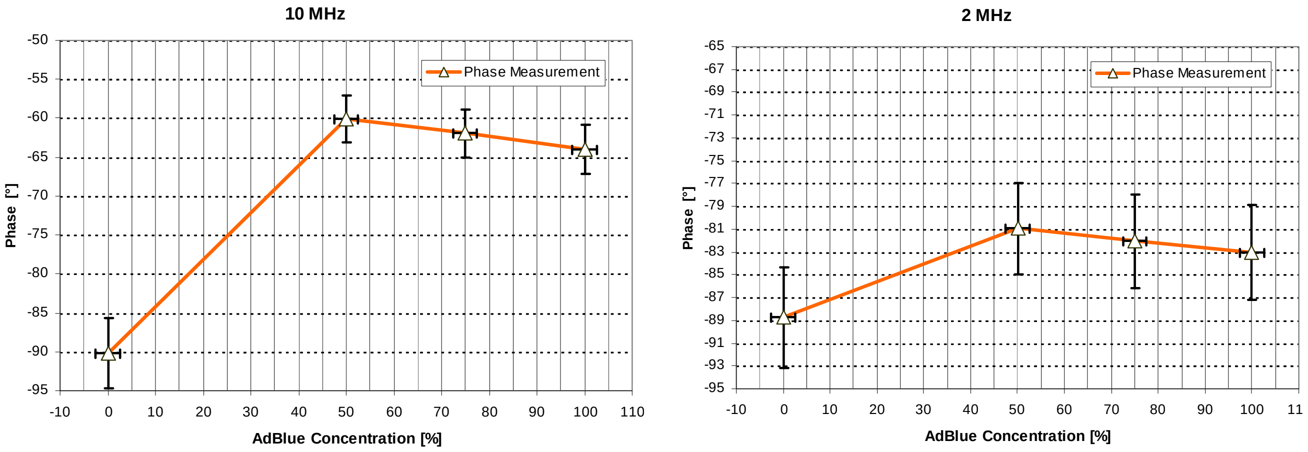
3.2. Modeling Results

The modeling and simulation method used for the verification of the measurement results is described in section 2.1. The resulting circuit parameters and their concentration dependency are listed in Table 1.



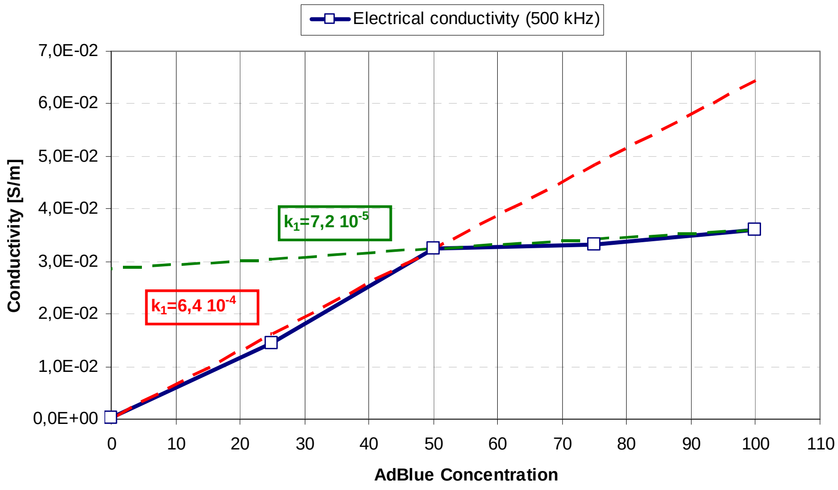
(a) Measured amplitude for 10 MHz.

(b) Measured amplitude for 2 MHz.



(c) Measured phase for 10 MHz.

(d) Measured phase for 2 MHz.



(e) AdBlue® conductivity as a function of urea concentration.

Fig. 8. Summary of prototype measurements.

Table 1. FEM simulated electric circuit parameters describing the transfer function of the prototype sensor.

AdBlue %	C1 [F]	C2 [F]	C3 [F]	C4 [F]	R1 [Ohm]	R2 [Ohm]	R3 [Ohm]
100	5,32E-11	1,00E-15	5,32E-11	9,01E-12	2,85E+02	1,47E+02	2,85E+02
75	5,32E-11	1,00E-15	5,32E-11	9,01E-12	3,79E+02	1,96E+02	3,79E+02
50	5,32E-11	1,00E-15	5,32E-11	9,01E-12	5,64E+02	2,91E+02	5,64E+02
0	5,32E-11	1,00E-15	5,32E-11	9,01E-12	2,85E+04	1,47E+04	2,85E+04

After extracting the circuit parameters out of the FEM simulation environment they serve as an input for an electric circuit simulation. The two port network transmission impedance change over liquid concentration change is calculated for 10 MHz and 2 MHz.

A comparison of the simulated and measured amplitude/phase for 2 MHz and 10 MHz is given in Fig. 9.

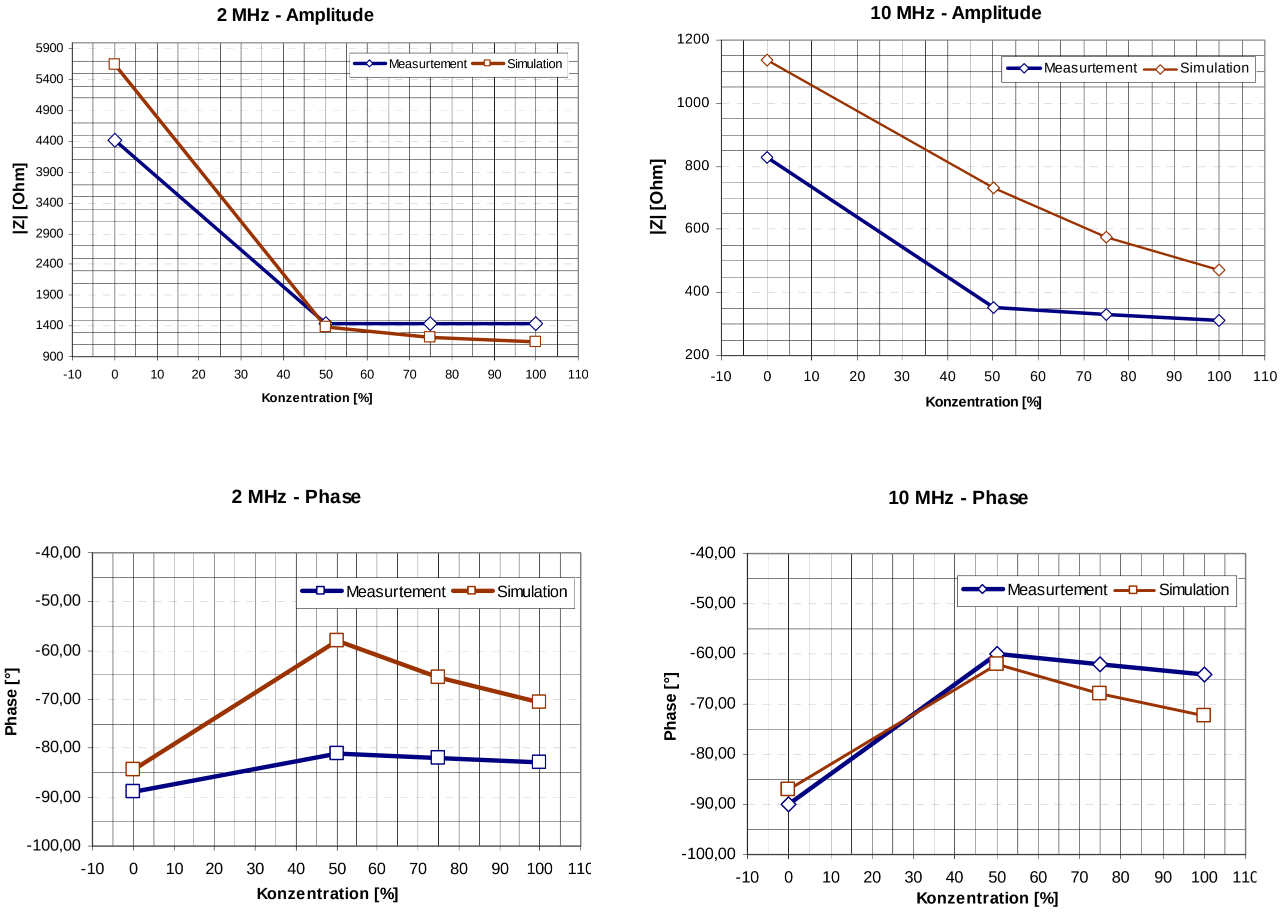


Fig. 9. Comparison between simulated and measured impedances.

Obviously, there are some mismatches between the measured and simulated data. The reachable modeling accuracy is limited by the input parameter accuracy. Tolerances in the design parameters lead to tolerances in the sensor output.

In principal, two different design parameters turn out to be critical for the model verification, namely d_S and ε_S. The first parameter is the distance between the electrodes and the liquid (d_S). This parameter directly influences the capacitances C_1 and C_3. For the construction of the first prototype we expect design tolerances of more than 50 %. In contrast to the distance between the electrodes and the liquid

(d_s), the dielectric permittivity of the sensor material (ε_s) also influences C_1 and C_3. For the first prototype, it was not possible to find suited materials with well defined permittivity (ε_s). Typical parameter values and their specification range, which were used for the prototype are listed in Table 2.

Table 2. Most important material parameters and their specification range.

Min.	**Typ.**	**Max.**
d_s= 150 µm	d_s= 200 µm	d_s= 250 µm
ε_s= 3	ε_s= 5	ε_s= 7

These input variations are the main reason for the observed mismatch. The effect of different liquid to electrode distances and different sensor material permittivity on simulated amplitudes and phases is shown in Fig. 10.

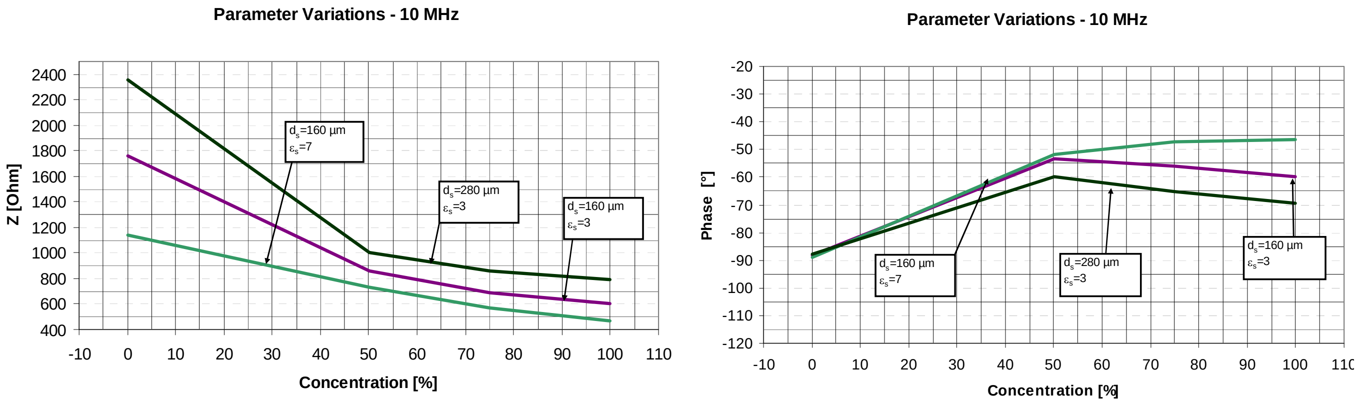


Fig. 10. Material parameter variations and their influence on quality sensor signals.

In the next step, the parameter range of the materials used for the prototypes must be reduced. Nevertheless, the comparison between simulated and measured sensor characteristics allows a direct verification of the sensor model.

4.1. Temperature Considerations

The electrical conductivity of AdBlue® depends not only on the urea concentration, but also on the temperature. According to the measurements presented in Fig. 11 the electrical conductivity is direct proportional to the temperature. This behavior is confirmed for the temperature range from 2° up to 40°. For 500 kHz signals the temperature coefficient of AdBlue conductivity is approximately $10.3\ 10^{-4}$ S m^{-1} T^{-1} (see Fig. 11).

The temperature coefficient must be compared to the concentration coefficients for low concentrations ($k_1=6.4\ 10^{-4}$ S m^{-1} $\%^{-1}$) and high concentrations ($k_2=7.2\ 10^{-5}$ S m^{-1} $\%^{-1}$), which are illustrated in Fig. 8 (e). In a first order approximation it is assumed that these concentration coefficients do not depend on temperature. According to the previously mentioned arguments, a temperature variation of 1° is equivalent to a concentration variation of approximately 10 % for the high concentration region.

It must be concluded that a quality monitoring sensor based on conductivity sensing must be combined with a temperature sensor, which measures the temperature of the liquid. The sensor performance directly depends on the accuracy of the temperature sensor and must be considered in the sensor system design.

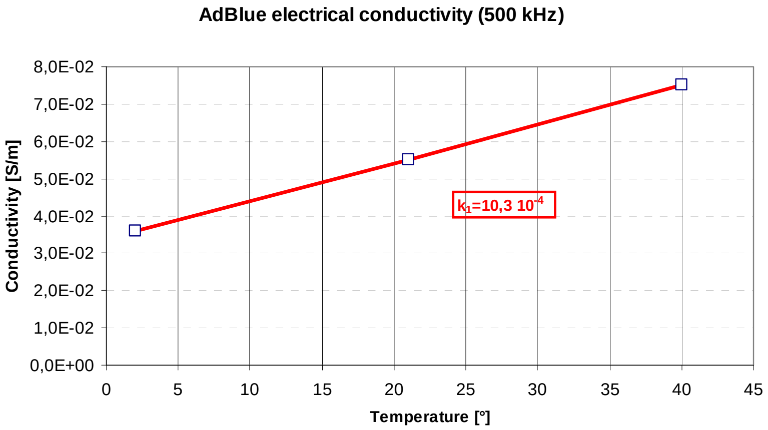


Fig. 11. Virtual prototyping procedure.

4. Conclusions

A contactless conductivity sensor is presented. The sensor performance is demonstrated for a first prototype. Measurements and simulations are carried out to show the feasibility of the introduced sensor principle. A major drawback is the large temperature dependency of AdBlue conductivity. Only a capacitive sensor combined with a temperature sensor can be used for AdBlue quality monitoring. Nevertheless, further electrode geometry and sensor material optimization cycles must be performed. The optimization target must be a larger conductivity sensitivity of the sensor. In the final application the sensor signals must be handled by some interface electronic and a microcontroller in order to compensate the temperature induced errors and run calibration algorithms.

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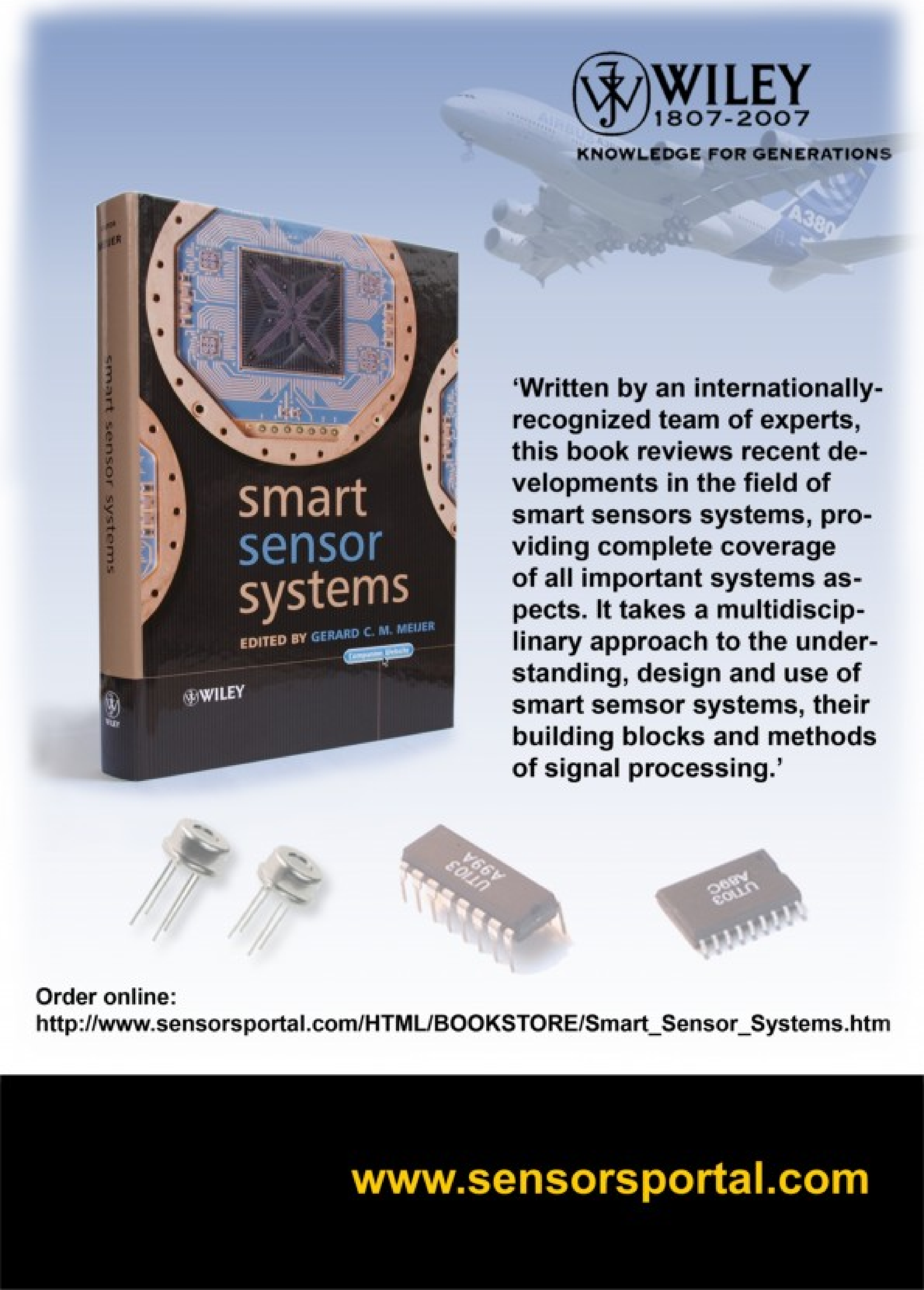
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