Radio-Requestable Passive SAW Water-Content Sensor

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***Abstract*—A new passive sensor for remote measurement of water content in sandy soil was designed, using a surface acoustic wave (SAW) reflective delay line. Information from this sensor can be obtained by an interrogation device via a radio link operating in the European 434-MHz industrial–scientific–medical band. The SAW device, manufactured on the YZ cut of $LiNbO_3$, is mounted and sealed in a standard dual inline 16 package and contains four electroacoustic transducers. One transducer is connected to an external antenna to pick up an RF request signal from the interrogation device and to send back an RF response. The second transducer operates as a reflector. The bus bars of this transducer are connected with two measuring rods through an electrical transmission line. These rods can be inserted into sandy soil. The final two transducers operate as reflectors and are included for reference purposes. The transmission line and the two rods spanning the sand–water mixture have a characteristic impedance $Z_{\rm load}$, which loads the second transducer. Changes in the soil water content are observed as a change of the total permittivity due to the high permittivity of free water, which, in turn, affects $Z_{\rm load}$ as well. The amplitude and phase of the acoustic reflection at the second transducer changes due to a variation of the terminating $Z_{\rm load}$. This then results in a difference in attenuation and phase of the corresponding peak in the time domain. Thus, the RF response of the sensor carries information about the water content between the rods, which, therefore, can be detected by and evaluated in the interrogation unit.**

***Index Terms*—Dielectric sensor, electrically loaded acoustic reflector, passive radio sensor, remote measurements, SAW reflective delay line, soil water content, transmission-line model.**

I. Introduction

Artificial irrigation is used in many agricultural and horticultural growing systems (e.g., greenhouses), especially in semiarid and arid regions. Also, water is sometimes scarce and, therefore, expensive. It is, therefore, often advantageous to irrigate only when necessary and to use only the minimal amount of water needed. This helps ensure a sustainable use of resources and lowers costs. Improper watering will result in lower crop yield. Therefore, automatic irrigation systems can benefit from water-content sensors for improved control of water usage. Cabled sensors may be suitable in greenhouses; however, in open fields, they would interfere with the conduct of many agricultural operations. Using batteries is not desirable for ecological and economic reasons. Therefore, utilizing passive water-content sensors, which can be monitored by radio link (see Fig. 1) for irrigation systems, can be quite advantageous. Moreover, such sensors can be applied in many other technical applications where moisture control is important, e.g., in medical sterilizers.

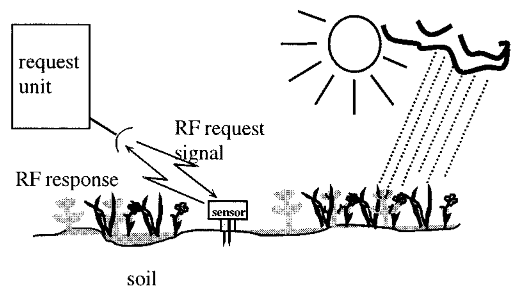

Fig. 1. Schematic drawing of a radio-link system for sensing the water content of the soil consisting of a request unit, a sensor device, an incoming pulse, and the corresponding outgoing signal, which has been coded by the sensor.

In recent years, surface acoustic wave (SAW) devices have gained increasing attraction for industrial measuring. When designed as a one-port device connected to an electromagnetic antenna, it can be monitored by means of a wireless radio link [1]. With such a SAW transponder, which typically has delay times in the order of some microseconds, data signals can easily be separated from the very high frequency (VHF)/ultrahigh frequency (UHF) multipath radio echoes. In addition, such sensors require neither wiring, nor batteries.

In Europe, the industrial–scientific–medical (ISM) band at 433.92 MHz has a bandwidth of 1.74 MHz. With 25-mW effective isotropical radiated power (EIRP) and 10-dB SNR, we get transceiver–SAW transponder inter-distances of up to 10 m, which is sufficient for applications for irrigation purposes.

In [1] and [2], it has been shown that classical sensors with a varying impedance can be read out by a wireless radio link when combined with SAW transponders. For the application discussed here, an interdigital transducer (IDT) is loaded by the external sensor. In the SAW transponder arrangement, this transducer is used as a reflector. Variations in the load impedance change the acoustic transmission and reflection properties of

Manuscript received October 16, 2000; revised January 17, 2001.

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Publisher Item Identifier S 0018-9480(01)02906-4.

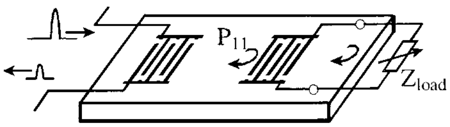

Fig. 2. Schematic drawing of a passive SAW device connected to an external classical sensor.

the IDT [3], as outlined in Fig. 2. In the P-matrix notation, the short-circuit reflection is denoted by P_{11SC}, the electroacoustic transfer coefficient by P_{13}, and the input admittance of the transducer by P_{33}. The acoustic reflection P_{11} of a transducer, which is loaded by the complex termination impedance $Z_{\rm load}$, is given by

$$P_{11}(Z_{\rm load}) = P_{11SC} + \frac{P_{13}^2}{P_{33} + \dfrac{1}{Z_{\rm load}}}. \tag{1}$$

References [4]–[6] show that the water content of soil can be measured with the help of some rods that are placed into the soil. The complex impedance between the rods depends strongly on the free water content of the soil due to the high dielectric constant ε. The conductivity σ of the water is determined upon the dissolved amount of salts. The resulting permittivity of the soil is in the order of $\varepsilon \approx 5$ for dry sand. It raises up to $\varepsilon \approx 30$ for sand, which is fully saturated with water and reaches $\varepsilon \approx 80$ for free water. These values hold for frequencies up to the gigahertz range.

The load impedance of such sensors can be controlled by selective spacing of the rods. This approach leads to the possibility of combining the working principles of [2] and [4], resulting in a radio-requestable device for the measurement of water content based on a reflective SAW device with an impedance-loaded reflector.

Section II discusses the design of a SAW device with one adjustable reflector. Section III discusses the changing impedance of the rod configuration with varying water-content levels of the soil. Section IV presents an overview on the completed sensor configuration, and Section V discusses the results of the radio measurements of the soil water content.

II. SAW Device Structure with Adjustable Reflector

Fig. 3 presents a schematic drawing of the investigated structure, which was fabricated using the YZ cut of an $LiNbO_3$ substrate. The tested SAW device contains one acoustic track and incorporates one electrode-width-controlled single-phase unidirectional transducer (SPUDT) [7], which is connected to the external antenna and three reflectors. The center frequency of the transducers is 433.92 MHz. We chose an aperture of 75λ to avoid diffraction effects. In order to minimize ohmic losses, a metallization height of 150 nm was chosen.

The reflectors consist of split-finger transducers. Reflectors #1–#3 incorporate 14, 16, and 14 overlaps, respectively. The distances between the coupling SPUDT and reflectors are 660λ, 880λ, and 1100λ, respectively (see Fig. 4), resulting in time-domain signals of 3, 4, and 5 μs. Reflector #2 is connected via a pin from the housing to the variable impedance; the other two reflectors remain unconnected and are used to estimate time delay

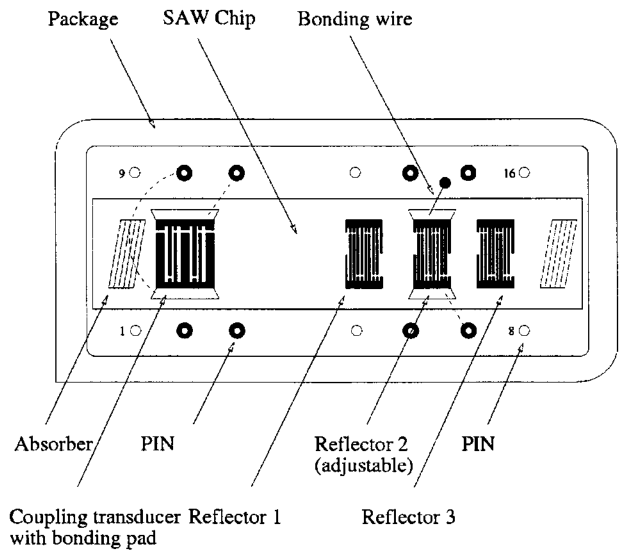

Fig. 3. Schematic drawing of the realized SAW chip mounted in a standard DIL 16 package.

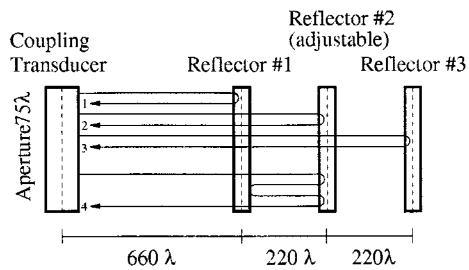

Fig. 4. Reflections of the SAW due to the reflector arrangement. Depicted is also the path of a signal (4) due to multireflections.

between the request unit and sensor, and also the time delay in the SAW device to reflector #2 caused by shifts in temperature.

Fig. 5 shows the electrical reflection coefficient S_{11} of the device in the Smith chart. The reference impedance of all shown Smith charts is 50 Ω. The SPUDT transducer is matched to 50 Ω at 434 MHz. Due to multiple echoes with long time delays, a ripple occurs in the frequency domain, as can be seen in Figs. 5 and 6.

Fig. 6 presents the measured electrical reflection coefficient S_{11} of the structure when reflector #2 is used as transducer. The dashed line gives the calculated reflection coefficient of the transducer without any surrounding reflectors. The phase shift between measurement and calculation is caused by the pads, bonding wires, and pins of the housing, which were not taken into account in the calculations.

Fig. 7 shows the reflection coefficient of the device in time domain. A prompt electrical reflection of the SPUDT appears at $t = 0$ μs. At $t = 3$, 4, and 5 μs, the reflections of reflectors #1–#3 can be seen, respectively. Some additional, small reflection signals created by reflections from the chip edges and from multireflections are also visible in Fig. 7. With the help of the echo signals from reflectors #1 and #3, a reference amplitude and phase can be calculated, which is both independent from the signal propagation delay between the interrogation device and the SAW transponder and the temperature of the SAW substrate. The sensor information is then extracted from the relative

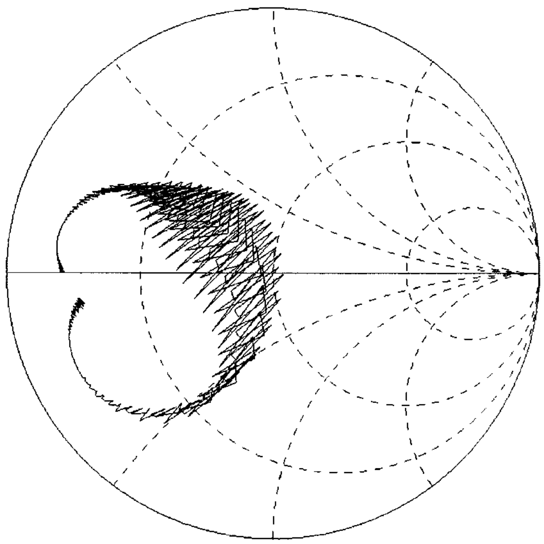

Fig. 5. Measured reflection coefficient S_{11} of the in and out coupling transducer shown in the Smith chart. Center frequency is 434 MHz, with a span of 50 MHz. The reference impedance is 50 Ω.

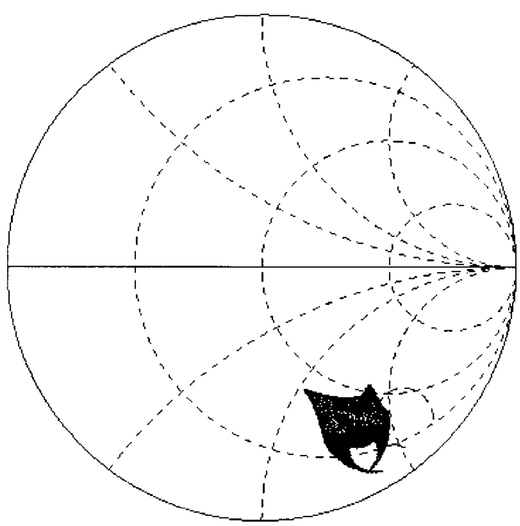

Fig. 6. Measured reflection coefficient S_{11} of the structure when reflector #2 is used as a transducer, as shown in the Smith chart. The dashed line gives the calculated reflection coefficient of the transducer. The reference impedance is 50 Ω.

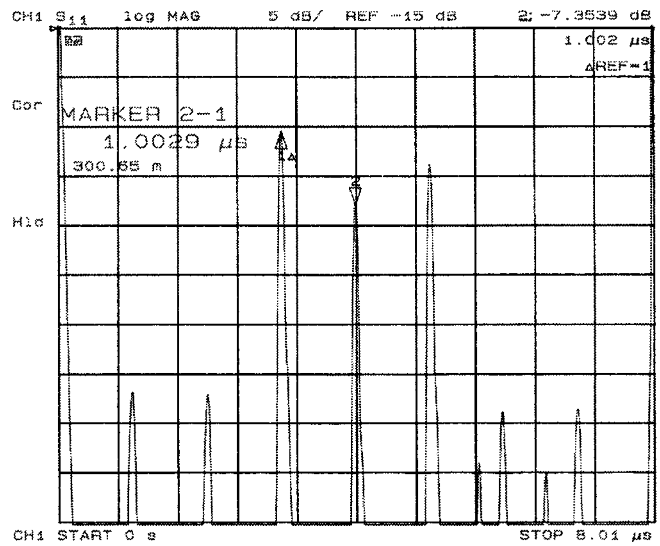

Fig. 7. Absolute value of the Fourier transform of Fig. 5 shown in the time domain.

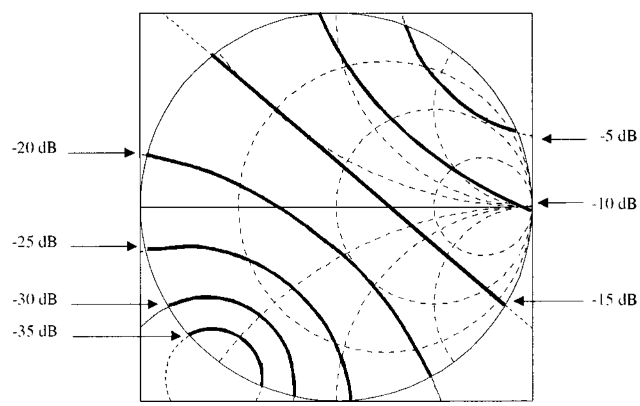

Fig. 8. Calculated contour lines (thick lines) of the acoustic reflection of reflector #2 as a function of the loading impedance $Z_{\rm load}$. The loading impedances are transformed to their corresponding electrical reflection coefficient and shown in the Smith chart. The normal impedance is 50 Ω.

echo amplitude and phase between reflector #2 and this reference.

Using (1), we calculated the amplitude and phase of the acoustic reflection from reflector #2 due to the terminating impedances $Z_{\rm load}$. Fig. 8 illustrates the result as contour lines depicted over the terminating impedances, which are shown in the Smith chart. The thick lines show loads that result in constant acoustic reflection. Reflector #2 is realized with a split-finger transducer with $P_{11SC} = 0$. The maximum of the acoustic reflection P_{11} occurs if the denominator of (1) is at its minimum. This is achieved with a termination impedance $Z_{\rm load}$, where $R = 0$ and X compensates for the imaginary part of P_{33}. On the other hand, minimal reflection occurs if the denominator is at its maximum, which is obtained if the impedance of the transducer and the loading impedance together comprise a short circuit.

III. Impedance of the Rod Configuration

Fig. 9 shows the used sensing-rod configuration together with the corresponding electrical circuit diagram. The rods are made of stainless steel. The dimensions of the rods, especially their length $l_{\rm rod}$, thickness, and distance, can be selected in such a way that the RF impedance level during operation is advantageous for controlling the reflection from reflector #2. The rods have a length of 50 mm and can be affixed to the printed circuit board with $M2$ threads. The distance between the two rods is 20 mm. The rods were placed into sandy soil. At the operating frequency (f) of 434 MHz, the rod configuration has to be simulated with the help of an open-ended transmission-line model, as shown in Fig. 9. The effects of the use of fertilizers and water content on soil conductivity are discussed in detail in [4]–[6]. In our simulation, we set the conductivity of the soil proportional to its water content.

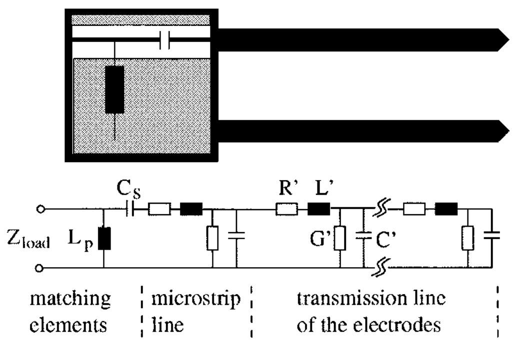

Fig. 9. Schematic drawing of the rod configuration to sense the water content of the soil and corresponding electrical circuit diagram.

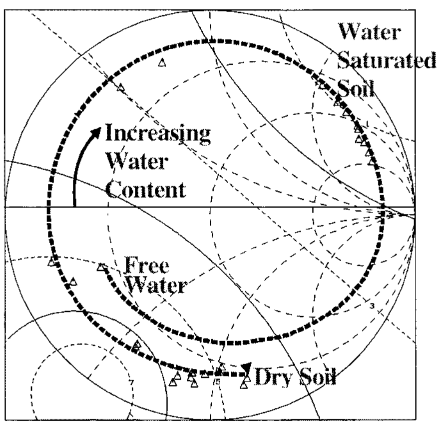

Fig. 10. Electrical reflection coefficient of the rod configuration (Fig. 9) at 434 MHz with changing water content of the soil, as shown in the Smith chart. The normal impedance is again 50 Ω. Starting from dry soil, the water content (with respect to weight) was increased by 1% up to 21%. The Δ marks show these measurement points of two experiments. The dashed line gives the calculated line according to (2). Also shown are the lines of constant acoustic reflection according to Fig. 8 in 5-dB intervals.

The phase φ of the electrical reflection coefficient mainly depends on the ratio of the geometrical length $l_{\rm rod}$ to the electrical wavelength $\lambda(\varepsilon)$, which is strongly influenced by the relative permittivity ε_r and permeability μ_r of the medium

$$\varphi = -2 \cdot 2\pi \cdot \frac{l_{\rm rod}}{\lambda(\varepsilon_r \cdot \mu_r)} = -\sqrt{\varepsilon_r \cdot \mu_r} \cdot \frac{4\pi \cdot l_{\rm rod} \cdot f}{c_0}. \quad (2)$$

In (2), c_0 denotes the velocity of light. With help of two matching elements, the variation of the impedance of the rods, which results between dry and water-saturated soil, was matched to that impedance level to which reflector #2 is most sensitive. In order to protect the electrodes of the SAW transducer from static charges and direct currents, we chose a matching configuration consisting of a series capacitor ($C_s = 100$ nF) and an inductivity ($L_p = 105$ nH) in shunt.

We measured the resulting impedance at 434 MHz as a function of the water content of sandy soil with this rod configuration. The water content Φ of the soil is given by the ratio of the weight of the water to the total weight of the soil. The soil was water saturated at a value of $\Phi = 0.21$.

Fig. 10 presents the resulting changes of the electrical reflection coefficient of the rod configuration, as related to the changing water content of the soil. Starting from dry soil, the water content was increased by 1% up to 21%. The Δ marks show these measurement points from two experiments. The dashed line denotes the calculated graph according to the electrical circuit diagram shown in Fig. 9. The phase shift follows the simple model given in (2).

Reflector #2 is electrically loaded by this matched rod configuration. Hence, any change of the electrical reflection coefficient of the rod configuration changes the acoustic reflection properties of reflector #2 according (1).

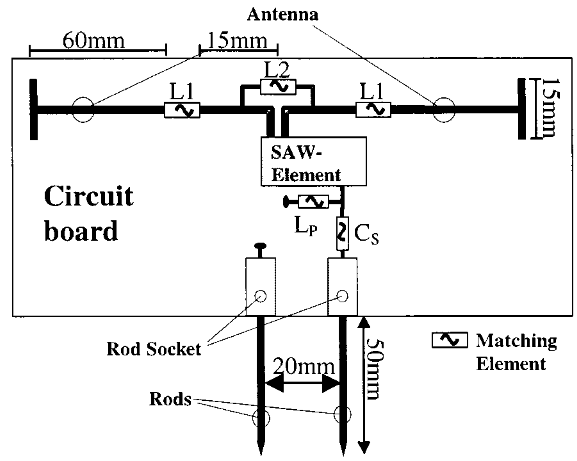

Fig. 11. Schematic drawing of the overall water-content sensor configuration.

IV. Realized Water-Content Sensor

Fig. 11 shows the overall sensor configuration fabricated on FR4 copper clad. For the electromagnetic receiver and transmitter antenna of the passive sensor, we selected a shortened dipole realized in a microstrip technique. The antenna feeds the SPUDT of the SAW device symmetrically. Antenna length was shortened by the use of a capacitive load at the end of the strip lines and by using center-load inductors ($L1$). To better match the antenna to the impedance of the SPUDT, we chose a matching configuration, which also protects the SAW transducer from static discharge. This is accomplished by the inductor $L2$. The connection of reflector #2 to the sensing rods was discussed in the previous section.

V. Measurement Results

We made remote water-content measurements with this sensor device, as illustrated in Fig. 1, using a network analyzer for the request unit. The ports were connected to electromagnetic antennas operating in the 434-MHz range. The read-out distance with an EIRP of 10 mW was between 0.5–5 m, depending on the size and orientation of the antenna. The response signal of the sensor was Fourier transformed and analyzed in the time domain. Due to relaxation phenomena, the water absorption of the soil changed after the first experiment; we, therefore, analyzed the later experiments.

Fig. 12 shows two typical measurement results of the sensor. Fig. 12(a) depicts recordings made in dry soil (7% water content) and Fig. 12(b) depicts the lower graph measurements made in moist soil (12% water content), respectively. The rods, which

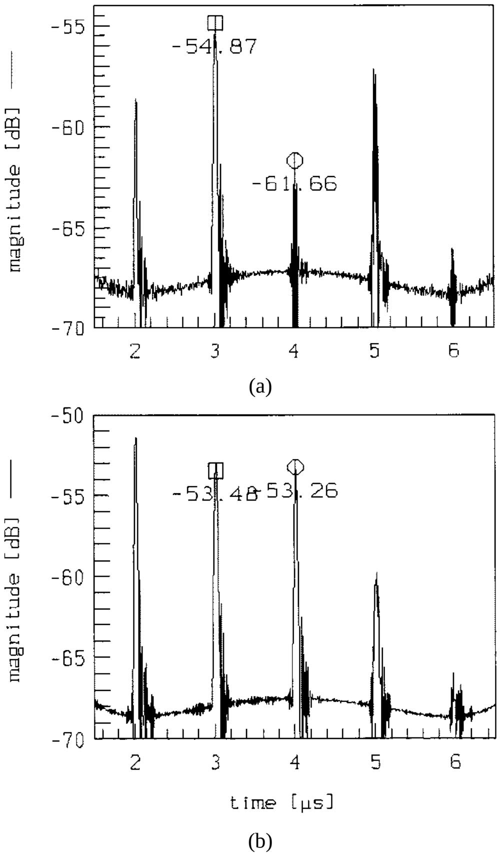

Fig. 12. Measurement results of the sensor requested by a radio signal in the time domain. (a) Recorded at a dry soil with 7% water content. (b) Recorded at a moist soil with 12% water content.

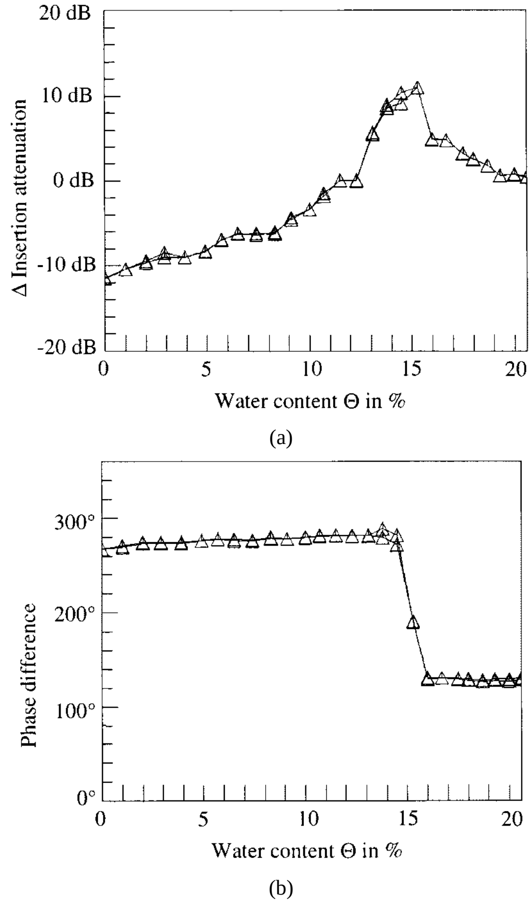

Fig. 13. Difference of the: (a) amplitude and (b) phase difference between reflectors #2 and #1 as a function of the water content of the soil. The Δs mark the values at two measurements.

were immersed in the soil, also function as electromagnetic antennas. Therefore, an additional signal arises at 2 μs, which corresponds to the acoustic distance between the SPUDT and reflector #2. As shown in Fig. 4, there is also a multireflection signal, which interferes with the intended signal at 5 μs and, therefore, affects the temperature compensation of the signal.

Fig. 13 plots the results of two different measurements. In the upper graph, the relative echo amplitude between reflectors #2 and #1 is shown as a function of the water content of the soil. The result is in fairly good agreement to the prediction shown in Fig. 10. According to the calculation shown in Fig. 10, the expected change in the electrical impedance of the rods should lead to a change of the acoustic reflection of between -30 and -5 dB, resulting in a dynamic range of 25 dB. A dynamic range of only 20 dB was achieved in our measurements. This may be due to parasitic ohmic losses between the acoustic reflector #2 and the measurement rods. Furthermore, the calculations predict that the minimum of the acoustic reflection is realized with a 5% water content of the soil. In our measurements, this minimum already occurred at a water content of 0%. This may be due to an additional electrical delay between the acoustic reflector #2 and the measurement rods, which was not taken into account in our calculations.

If the amplitude and phase information shown in Fig. 13 is evaluated, the water content of the soil can be estimated without any ambiguity. The precision of the radio measurements depends on the SNR of the detected response signal and on the reproducibility of the electrical properties of the sensor rods, matching networks, and SAW device. The read-out distance can be enhanced by using a $\lambda/2$ vertical antenna. Further, it seems feasible to measure the range of the water content of the soil with a resolution consisting of 10–20 subdivisions. Of course, the behavior of the sensor will change contingent upon different soil types. Thus, the sensor will have to be calibrated for the type of soil being recorded. The aging and resultant degradation of accuracy for sensors will need to be the subject of further research.

VI. Conclusion

In this paper, we have demonstrated the feasibility of a passive radio sensor, which makes possible the wireless monitoring of the water content of sandy soil. The proposed sensor incorporates an antenna and a reflective SAW device where one reflector is electrically loaded by the impedance of a pair of rods inserted into the soil. We reached a read-out distance of up to 5 m and a measurement accuracy of 5%–10% in our investigations.

Acknowledgment

The authors would like to thank W. Gawlik, EPCOS AG, Munich, Germany, S. Berek, EPCOS AG, Munich, Germany, V. Dordevic, EPCOS AG, Munich, Germany, and B. Bienert, EPCOS AG, Munich, Germany, for preparing the devices, W.-E. Bulst, Corporate Technology, Siemens AG, Munich, Germany, and W. Ruile, EPCOS AG, Munich, Germany, for helpful discussions, and J. M. Reindl, for the proofreading of this paper's manuscript.

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