Measurement 45 (2012) 1723–1728

Contents lists available at SciVerse ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

A new 1.4-GHz soil moisture sensor

Masoud Rezaei [a], Emad Ebrahimi [a,*], Sasan Naseh [a], Mehdi Mohajerpour [b]

[a] Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
[b] Department of Agriculture, Ferdowsi University of Mashhad, Mashhad, Iran

ARTICLE INFO

Article history:
Received 6 October 2011
Received in revised form 10 February 2012
Accepted 21 April 2012
Available online 1 May 2012

Keywords:
Aquametry
Phase detector
Soil moisture
Time domain reflectometry (TDR)

ABSTRACT

Moisture content determination in agriculture and civil engineering is a common process which needs special sensors with high accuracy, durability and compatibility with the measurement environment. A new 1.4-GHz soil moisture sensor using microstrip transmission line is presented. The proposed sensor consists of two separate parts: (1) A sensor head, which is a microstrip transmission line to be placed in the soil, and (2) an electronic transceiver which sends a sinusoidal wave into the sensor head at one end of the transmission line, and receives the traveled wave from the other end. Transmitter is basically a Colpitts oscillator, and the receiver is a phase detector that measures the phase shift due to velocity variation caused by the moisture content of soil. At a certain frequency, the velocity of a microwave traveling through a media depends on the permittivity of that media. The proposed sensor is implemented and tested on one sample of typical soil. The main advantages of the proposed sensor are its high accuracy, quickness of measurement, its low cost and ease of implementation. Since the sensor has low power consumption, it can be recommended for low-power applications such as wireless sensor network.

1. Introduction

On-line moisture content measurement in various solids, liquids and gases is required in many industrial applications. Electromagnetic aquametry is widely used for determining the level of water content in solids using different methods such as time domain, frequency domain, and nuclear magnetic resonance [1,2]. Measurement of the moisture content of the soil and concrete [3] are the subject of interest in agriculture and civil engineering, respectively. For example, modern automatic irrigation systems need several moisture sensors which can measure the water content of the soil at several places in a farm field. The cost of these sensors must be as low as possible while they can measure the moist content precisely and accurately.

The moisture content of a medium may be defined as ratio of the mass of the water in a unit volume of the medium m_w, to the mass of the dry material in the unit volume of the medium m_d, and expressed in percent as follows [1,4]:

$$\eta = \frac{m_w}{m_d} \times 100 = \frac{m_m - m_d}{m_d} \times 100 \tag{1}$$

in which m_m is the total mass of the unit volume of the medium (i.e. $m_m = m_d + m_w$).

The standard and precise methods of moisture content determination performed in laboratories are *direct* methods based on definition of Eq. (1). The most often used *direct* method involves weighing a sample of wet material, drying the material by evaporating its water content using an oven at appropriate temperature, and reweighing the remained dry material. Although the *direct* methods have a good accuracy, they are time-consuming, invasive and in vitro. For rapid and in vivo moisture content determination and monitoring, *indirect* methods calibrated against the standards methods can be utilized. Typical

* Corresponding author. Tel./fax: +98 912 773 8762.
E-mail addresses: rezaei@ieee.org (M. Rezaei), ebrahimi_em@yahoo.com (E. Ebrahimi), naseh@um.ac.ir (S. Naseh).

0263-2241/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.measurement.2012.04.014

non-destructive techniques for determining moisture content of the materials consist of measuring the electrical properties of the material and relating these properties to the moisture content [1].

Many different *indirect* techniques in time and frequency domain have been presented [2]. Time domain reflectometery (TDR) [5–8] was the first method applied for moisture determination in soil. In TDR, parallel-wire lines in a two- or three-line fork structures are used as sensors. This method is based on the detection of the travel time of a pulse at the end of an open line which is surrounded by the moist material (Fig. 1a). Obviously, the measured travel time must be translated into the moisture content of the medium (i.e. calibrated). In order to have accurate results, a precise and complex electronics is needed. Therefore, due to the complexity, cost, and high power required by the TDR measuring systems, the existing systems are not economical and are not easy to use in practical applications [1].

Frequency domain (FD) methods [1,9–12], e.g. resonator-based humidity sensors [9–11], are based on the dependency of frequency characteristics of these sensor on the moisture/humidity of the medium. Resonator-based sensors include a resonator (coaxial, two-wire, strip line, cavity, etc.) which its resonance frequency and quality factor are changed by the moisture content of the medium interacting with the electromagnetic fields of the resonator [1].

Another technique in frequency domain is based on the dependency of the soil dielectric on its moisture content [13]. The capacitance is directly proportional to the dielectric constant of its insulator material ($C = k\varepsilon_0 A/d$). In order to measure the soil dielectric constant, two conductive plates separated by a known distance with soil inserted between them are used (Fig. 1b) and a high frequency alternating current is applied to one plate and the signal received at the other plate is measured. Capacitance is calculated by (2) and translated to the soil moisture content.

$$C = \frac{I_{rms}}{V_{rms} \cdot 2\pi f} \tag{2}$$

Unfortunately soil capacitance sensors and TDRs are very sensitive to the salt content and are not suitable for high saline soil environments. On the other hand, resonator based sensors need very precise and complicated electronics to measure very small frequency shifts. Some other techniques, like acoustic method [14], have also been presented in literatures which has its advantages and disadvantages.

In this paper, a new indirect soil moisture sensor based on the permittivity variation of the soil due to its water content is presented. The proposed sensor measures the phase shift due to the velocity variation of the electromagnetic waves in a transmission line and translates it into the soil moisture.

In the next section the principle of operation, structure and considerations of the proposed sensor are explained. The experimental results are presented in Section 3 and the last section is the conclusion.

2. The Proposed soil moisture sensor

The best approach to measure the water-content of a medium (e.g. soil) is to sense the specific dielectric constant of the material [15–20]. Dry soil has a relative dielectric constant ε_r between 3 and 5 and that of water is about 80. Thus, the overall relative dielectric constant of the moist soil varies from 3 to higher values below 80 (e.g. 30 for saturated soil) [20], depending on the water and salt content. However, at operating frequencies between 1 GHz and 3 GHz the effect of the salt content on the dielectric of the soil is negligible [1].

The use of sensor with operating frequency in the microwave region has several advantages. Since the penetration depth into a medium is roughly due to absorption condition caused by water molecules, the electric and magnetic fields of the electromagnetic wave (for wavelength about 15 cm) used for the measurements can penetrate deep into the medium under test. In this way, not only the surface moisture but also the moisture in the bulk of the medium under the test can be measured. It is worth noting that the effective penetration depth can be

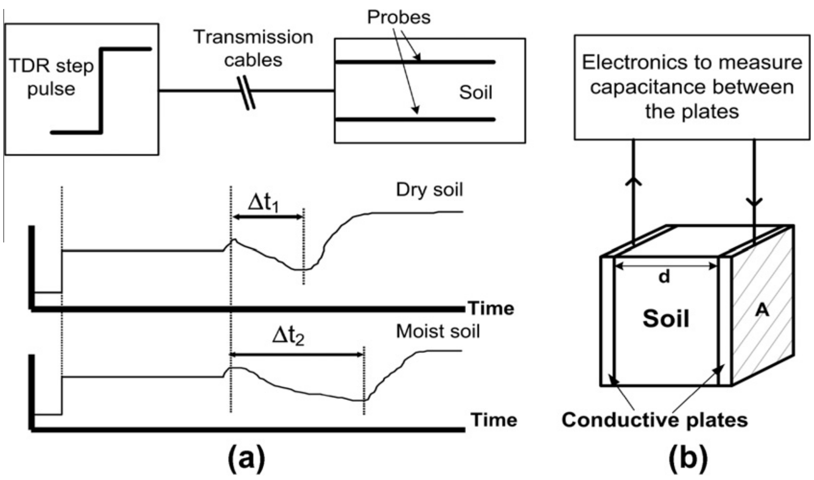

Fig. 1. The concept of the (a) TDR and (b) soil capacitance sensors.

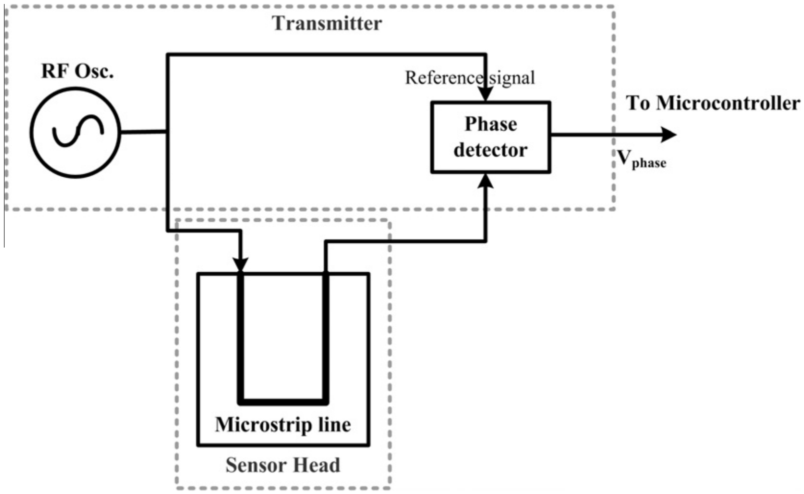

Fig. 2. Building blocks of the proposed soil moisture sensor.

controlled with the power of the transmitted signals as well. In addition, the measurements at such frequencies are independent of salt and mineral concentrations which can vary to a large extent. This is because the ionic conductivity of salts dissolved in water does not have any influence at this frequency range [1]. Also the least frequency dependency of the soil dielectric on salt occurs above 500 MHz [21]. Hence, in order to have a robust and precise soil moisture sensor, using microwave frequencies is mandatory.

The building blocks of the proposed soil moisture sensor are shown in Fig. 2. It is comprised of two main parts: a sensor head and an electronic transceiver. The sensor head is simply a microstrip line implemented on a printed circuit board (PCB), which will be inserted into the soil whose moisture to be measured. The transceiver itself is made of two main blocks: an oscillator and a phase detector both implemented on the same PCB (but different from that of the sensor head). The signal generated by the oscillator is split in two, one of which is directly sent to one of the two inputs of the phase detector via an interconnect as shown in Fig. 2. The other part of the oscillator output is sent into one end of the sensor head and is received from its other end, which is then delivered to the other input of the phase detector. The connections between the electronic transceiver PCB and the sensor head PCB are made via coaxial cables. Both sides of the sensor head PCB is laminated with a thin transparent plastic layer, isolating the microstrip line from the soil.

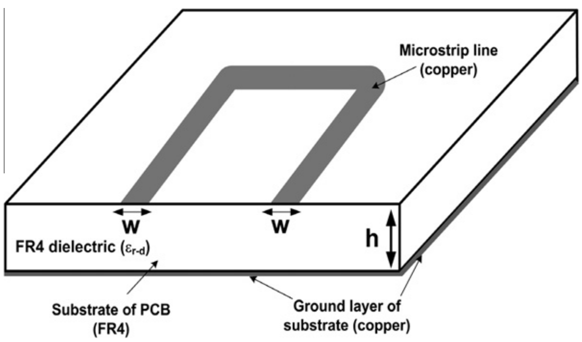

Fig. 3. Sensor head (it is surrounded by moist soil with $\varepsilon_{r\text{-}s}$).

The proposed soil moisture sensor operates based on the principle that for a certain frequency, wave transmitted into a fixed length transmission line, the phase shift depends on the velocity of propagation, which is strongly a function of the soil moisture content [20].

2.1. Principle of the operation

Microstrip transmission lines are increasingly attracting interest [22] due to their flat profile, low weight, ease of fabrication and low cost. In Fig. 3 the sensor head PCB when inserted in the soil is depicted. According to Eq. (3), propagation constant (γ) of an electromagnetic wave in a lossy transmission line includes real (α) and imaginary (β) parts named attenuation and phase constant, respectively [3,23]

$$\gamma = \alpha + j\beta = j\omega\sqrt{\mu_d \varepsilon_d} \tag{3}$$

in which dielectric permeability, μ_d, is equal to μ_0 for nonmagnetic material, and dielectric permittivity, ε_d, is a complex number. Thus, for nonmagnetic materials, like fire resistant (FR4) material (the material of the sensor head PCB) and soil, relation (3) can be simplified as,

$$\gamma = j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_r + j\frac{\sigma}{\omega}} \tag{4}$$

in which ε_r, λ_0 and σ are relative permittivity, free space wavelength and conductivity, respectively. Using (3) and (4), phase constant can be obtained as (5) [23]. Since $tan\delta = \sigma/\omega\varepsilon_r$ (loss tangent) in microwave frequencies is much less than 1, the term $tan^2\delta$ can be neglected.

$$\beta = \frac{2\pi}{\lambda_0}\sqrt{\frac{\varepsilon_r}{2}(\sqrt{1+\tan^2\delta}+1)} \approx \frac{2\pi}{\lambda_0}\sqrt{\varepsilon_r} \tag{5}$$

In situations such as in this work (Fig. 3), where the electromagnetic waves propagate into two medias (i.e. moist soil with $\varepsilon_{r\text{-}s}$ and FR4 substrate (dielectric) with $\varepsilon_{r\text{-}d}$) effective relative permittivity, $\varepsilon_{r\text{-}eff}$, must be used as follow [23]

$$\varepsilon_{r\text{-}eff} = \frac{\varepsilon_{r\text{-}d} + \varepsilon_{r\text{-}s}}{2} + \left(\frac{\varepsilon_{r\text{-}d} - \varepsilon_{r\text{-}s}}{2}\right)\left(\frac{1}{\sqrt{1 + 12\frac{h}{w}}}\right) \tag{6}$$

in which h and w are the height of the substrate (i.e. FR4 layer) and width of the microstrip line, respectively (Fig. 3). Regarding (5) and (6), if an electromagnetic wave is fed to a buried microstrip line with known length of l the phase shift ϕ is proportional to the square root of the effective permittivity of the media,

$$\phi = \beta l = \frac{2\pi}{\lambda_0} l \sqrt{\varepsilon_{r\text{-}eff}} \tag{7}$$

Since the relative permittivity of the soil ($\varepsilon_{r\text{-}s}$) is strongly dependent on its water content, the phase shift variation ϕ is solely related to the moisture of the soil. Therefore it is only needed to place the microstrip line in the soil, measure the phase shift caused by the moisture content and relate it to the moist content.

2.2. Design considerations

Based on the available components and discussion on the suitable frequency region for soil moisture measurement, a colpitts oscillator with 1.4 GHz oscillation frequency and −10 dBm output power was designed as a microwave signal generator. This oscillator has two buffered outputs [24], one is used as a reference and the other is sent into the sensor head which is inserted in the soil. To measure the phase difference between the reference and the propagated wave, AD8302 is utilized as a phase detector. AD8302 is a phase/gain detector which is capable of operating from low-frequency to 2.5 GHz with input power from 0 to −60 dBm [25]. The phase detection accuracy is 10 mV/deg but as can be seen in Fig. 4, lead/lag can not be recognized. Therefore the maximum detectable phase difference is effectively 180°.

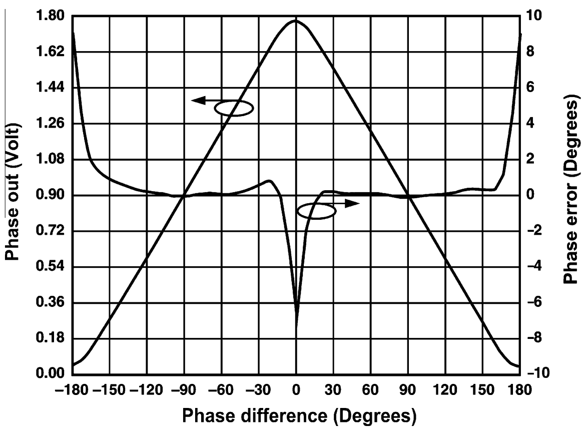

Fig. 4. Output voltage vs. phase difference, and corresponding phase error in AD8302 phase detector [24].

The implemented soil moisture sensor is shown in Fig. 5. There are three main considerations in the design of microstrip line as a soil moisture sensor. First, due to the phase ambiguity of the AD8302, the length of the microstrip line should be chosen such that the initial phase difference of the microstrip (in dry soil) is near $k\pi$ (k = 0, ±1, ±2, etc.) in order to have the maximum dynamic range. As shown in Fig. 4, to avoid the phase error caused by AD8302 a small phase margin should be considered. Second, the sensitivity of the sensor must be controlled. In other words, the overall phase variation between dry and saturated soil must be less than 180° (e.g. to have a good linearity and accuracy the phase shift in dry and saturated soil can be considered near 20° and 160° respectively). And the third, since the output power of the oscillator is −10 dBm and the AD8302 can detect signals with strength power more than −60 dBm, the attenuation of the sensor must not be more than 50 dB. Therefore the length and the width of the microstrip transmission line should be chosen in such a way that the desired phase difference and the best impedance matching can be acquired, respectively (since at this frequency range the dielectric of the moist soil is dominated by it's water content, the same sensor head can be used for different types of soils).

In order to match the microstrip to 50 Ω, the width of the microstrip has been chosen 2 mm on an FR4 printed circuit board (PCB) which has a relative permittivity of ε_r = 4.4 and thickness of 1.6 mm. Taking into account phase delay caused by coaxial cables, the length of the microstrip is selected 70 mm. To have good durability, the microstrip sensor can be coated with gold or nickel plating and also to lessen the sensitivity the whole PCB (sensor) can be covered with green solder mask.

3. Simulation and experimental results

The proposed sensor was simulated with High Frequency Structure Simulator (HFSS) software. To have

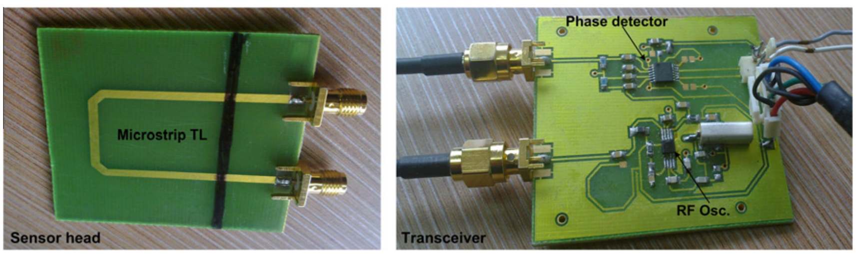

Fig. 5. Implemented soil moisture sensor.

an estimate of the phase shift caused by the water content of the soil, the relative permittivity of the soil ($\varepsilon_{r\text{-}s}$) was swept from 4 to 30 and the phase of the S_{21} was simulated. As shown in Fig. 6, the total phase shift of the propagated RF signal is 150° which falls in the allowable range of the phase detector.

As seen in Fig. 7, the reflection loss (S_{11}) and insertion loss (S_{21}) are less than −22 dB and 0.3 dB, respectively. Therefore the proposed sensor has a good matching over the whole range of soil moist content.

To calibrate the proposed sensor, a suitable amount of a loam soil (from a garden) is mixed with enough amount of water such that a saturated combination is obtained. Then the total weight of the combination is measured using a precise scale. The microstrip transmission line (sensor head) is then inserted into the saturated moist loam soil vertically (in such a way that the SMA connectors do not touch the soil) and let the soil dry gradually. Meanwhile, weight of the evaporated moist is measured regularly (reweighing the moist soil and subtracting it from the initial weight of the moist soil), and at the same time value of output voltage of the phase detector is recorded. Finally, to have the weight of the mass of dry soil (to calculate moisture content η from Eq. (1)), the moist soil is placed in an oven at 105°Centigrade for 24 h. Using the measured data and Eq. (1), the values of moisture content is calculated and is associated with the corresponding output voltage read-out. As shown in Fig. 8, to relate the voltage to the moist content, a second-order polynomial (8) with R^2 = 0.997 (R^2 is regression coefficient) can be fitted for a calibration equation. Assuming that the relative permittivity of the moist soil is approximately linear-proportional to the water content, a slight difference between simulation result in Fig. 6 and the measured data in Fig. 8 can be explained by the effect of green solder mask that was not considered in the simulations.

$$V_{Phase} = -0.001194 \times \eta^2 + 0.07624 \times \eta - 0.03946 \tag{8}$$

where η is the moisture content.

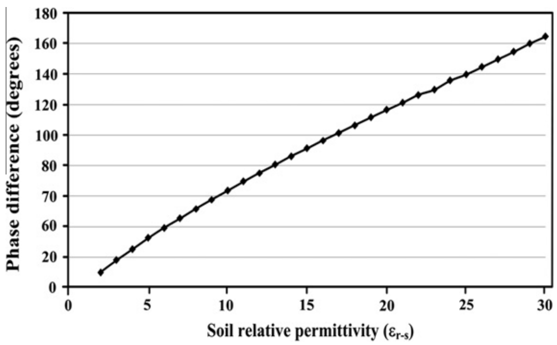

Fig. 6. Simulated phase shift due to dielectric variation in HFSS.

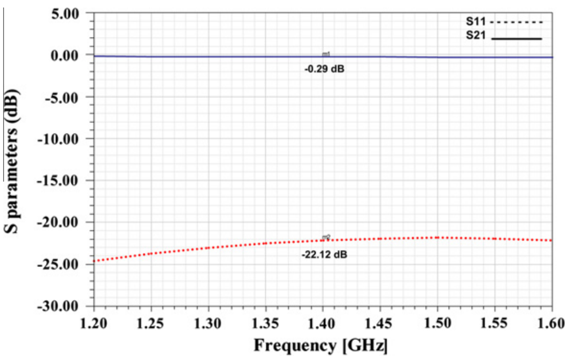

Fig. 7. Scattering parameters of the microstrip sensor.

3.1. Specifications of the sensor

The proposed sensor can measure the moist content with resolution better than 0.5% instantaneously. Each measurement takes less than 100 ns (including response time of phase detector). The operation frequency of the sensor is 1.4 GHz and hence, it is insensitive to the soil type and saline. The total power consumption of the sensor in measurement mode is as low as 140 mW. That is, using a typical 4.8-V Ni–Cd battery, the sensor can operate for several months. Therefore, in wireless sensor network applications where the power consumption is a critical issue the proposed moisture sensor can be utilized.

Since temperature variation causes a slight drift in the soil's dielectric constant, the proposed sensor (similar to other indirect methods) needs to be compensated for temperature. The signal velocity in the microstrip sensor

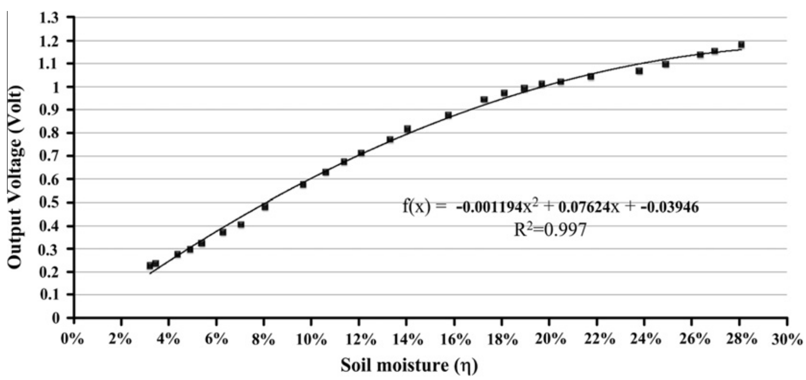

Fig. 8. Experimental results (each 10 mV of the output voltage shows 1 degree of phase shift).

influenced only by the moisture in the soil under test (and not the soil itself) and in this way density fluctuation of the soil can be eliminated [1]. However, for more accurate measurements re-calibration is recommended.

4. Conclusions

In this paper a new soil moisture sensor was simulated, implemented and tested. The proposed soil moisture sensor operates based on the principle that the speed of traveling of a signal in a transmission line is dependent on the dielectric constant of the medium surrounding the conductors of the transmission line.

The sensor head is a microstrip transmission line through which a 1.4-GHz RF signal propagates. The dielectric of the medium surrounding the microstrip, and hence the speed of traveling of a signal is changed due to change in the soil moisture content, which then results in a phase shift in the signal. The phase difference between this signal and a reference signal with a constant phase is detected by a phase detector, which is then translated into soil moisture content. Some of the design considerations and specification of the sensor was explained.

Compared to the TDR method, the proposed technique is accurate, inexpensive, low power, and applicable to situations such as large sensing volume and saline soils, and also is suitable to incorporate into wireless sensor networks.

Acknowledgments

The financial resource for this work was provided by the Microelectronics Headquarters of Iran. The authors gratefully acknowledge the Microelectronics Headquarters financial supports.

References

[1] K. Kupfer, Electromagnetic aquametry: electromagnetic wave interaction with water and moist substances, Springer-Verlag Berlin Heidelberg, Germany, 2005.
[2] U. Kaatze, C. Hubner, Electromagnetic techniques for moisture content determination of materials, Measurement Science and Technology 21 (2010) 082001.
[3] K. Kupfer, RF & microwave instrumentation for moisture measurement in process and civil engineering, Subsurface Sensors and Applications, Proceedings of SPIE 3752 (1999) 39–46.
[4] A. Kraszewski, Microwave aquametry: an effective tool for non-destructive moisture sensing, Subsurface Sensing Technologies and Applications 2 (2001) 347–362.
[5] P. Ferre, G. Topp, Time-domain reflectometry sensor techniques for soil water content measurements and electrical conductivity measurements, vol. 7, Weinheim, Wiley-VCH, 2000 (Sensor update).
[6] M. Stacheder, K. Koehler, R. Fundinger, New time-domain reflectometry sensors for water content determination in porous media, vol. 7, Weinheim, Wiley-VCH, 2000 (Sensor update).
[7] CH. Hübner, A. Brandelik, Distinguished problems and sensors in soil and snow aquametiy, vol. 7, Weinheim, Wiley-VCH, 2000 (Sensor update).
[8] R. Cerny, Time-domain reflectometry method and its application for measuring moisture content in porous materials: a review, Measurement 42 (2009) 329–336.
[9] K. Sarabandi, E.S. Li, A microstrip ring resonator for soil moisture measurements, IEEE Transaction on Geoscience and Remote Sensing 35 (1997) 1223–1231.
[10] M.I. Menzel et al., Non-invasive determination of plant biomass with microwave resonators, Plant, Cell and Environment 32 (2009) 368–379.
[11] A. Kawalec, M. Pasternak, Microwave saw humidity sensor microwaves, IEEE Radar and Wireless Communications (2006) 662–664.
[12] V. Radonic, G. Kitic, V. Crnojevic-Bengin, Novel Hilbert Soil-Moisture sensor based on the phase shift method, IEEE Mediterranean Microwave Symposium (2010) 377–380.
[13] D. Wobschall, D. Lakshmanan, Wireless soil moisture sensor based on fringing capacitance, Proceedings of IEEE Sensors (2005) 8–11.
[14] F. Adamo, G. Andria, F. Attivissimo, N. Giaquinto, An acoustic method for soil moisture measurement, IEEE Transactions on Instrumentation and Measurement 53 (2004) 891–898.
[15] Hilhorst, M.A. Dielectric characterization of soil. PhD thesis, IMAG-DLO Wageningen, The Netherlands, 1998.
[16] M.A. Hilhorst, A broad-bandwidth mixed analog/digital integrated circuit for the measurement of complex impedances, IEEE Journal of Solid-State Circuits 28 (1993) 764–769.
[17] J.F. Posada, An automated data acquisition system for modeling the characteristics of a soil moisture sensor, IEEE Transaction on Instrumentation and Measurement 40 (1991) 836–841.
[18] Y.K. Yeow, Z. Abbas, K. Khalid, Application of microwave moisture sensor for determination of oil palm fruit ripeness, Measurement Science Review 10 (2010) 7–14.
[19] D.H. Gadani, A.D. Vyas, Measurement of complex dielectric constant of soils of Gujarat at X- and C-band microwave frequencies, Indian Journal of Radio & Space Physics 37 (2008) 221–229.
[20] J.O. Curtis, Moisture effects on the dielectric properties of soil, IEEE Transaction on Geoscience and Remote Sensing 39 (2001) 125–128.
[21] W. Skierucha, A. Wilczek, A FDR sensor for measuring complex soil dielectric permittivity in the 10–500 MHz frequency range, Sensors 10 (2010) 3314–3329.
[22] F. Jafari, K. Khalid, W. Yusoff, J. Hassan, The analysis and design of multi-layer microstrip moisture sensor for rice grain, Biosystems Engineering 106 (2010) 324–331.
[23] D.M. Pozar, Microwave Engineering, 2nd ed., Wiley, New York, 1998.
[24] MAX2620 data sheet, 10 MHz–1050 MHz Integrated RF oscillator with buffered outputs. Maxim Integrated Products.
[25] J. Cowles, B. Gilbert, Accurate Gain/Phase measurement at radio frequencies up to 2.5 GHz, Analog Dialogue (2001) 05–35.