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A Comprehensive Review of Portable Microwave Sensors for Grains and Mineral Materials Moisture Content Monitoring

NIMA JAVANBAKHT[1,2], (Member, IEEE), GEORGE XIAO[2], (Fellow, IEEE), AND RONY E. AMAYA[1], (Senior Member, IEEE)
[1]Department of Electronics, Carleton University, Ottawa, ON K1S 5B6, Canada
[2]National Research Council Canada, Ottawa, ON K1A 0R6, Canada

Corresponding author: Nima Javanbakht (nima.javanbakht@carleton.ca)

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ABSTRACT In this paper, a comprehensive review of portable microwave sensors for monitoring moisture content (MC) is presented. MC monitoring is crucial in different industries, particularly food and farming. Microwave-based approaches for measuring the MC of the grains and mineral materials are studied. These approaches are categorized into three groups: S-parameters, dielectric constant, and impedance measurements. While these methods are interrelated, they have differences. The investigated methods use different microwave antenna sensors for MC monitoring, such as coaxial probes, horn antennas, loop antennas, microstrip patch antennas, and frequency selective surface (FSS) antenna. State-of-the-art microwave sensors were investigated thoroughly to clarify the current challenges and possible solutions of MC monitoring. A comparison between the investigated sensors was made to determine their advantages and disadvantages. According to the comparison, sensors operating above 10 GHz suffer from cross-interference. Moreover, microstrip patches can monitor a wide MC range as extensive as 60%. At the same time, the FSS sensor has the highest sensitivity with an error as low as 0.023% at X-band. Microstrip patch and FSS antennas can be printed directly on a flexible, low-loss, and lightweight material to monitor the grain MC. The flexibility, compactness, portability, ease of environment-friendly fabrication, and high sensitivity are among the criteria determining the most suitable microwave sensors for industrial and consumer MC monitoring applications.

INDEX TERMS Antenna, moisture, portable, printed, sensor.

I. INTRODUCTION

Monitoring the moisture content (MC) is crucial in precision farming and the food industry as an indicator of the quality of grains, fruits, and foods [1]–[13]. Monitoring the MC is not limited to agriculture since it plays a vital role in monitoring the body hydration, the moisture level of the skin [14]–[16], microplastic concentration in liquids [17], [18], and the sensitivity of the mineral materials [19], [20] and fabric [21], [22] to the humidity. It is also essential to investigate the response of the communication devices in the presence of humidity.

Due to the correlation between electrical properties of the grain and MC level [4], methods for monitoring MC were proposed, including monitoring variations in the S-parameters (*i.e.,* return loss and insertion loss) [1], [2], [5]–[7], [14], [23]–[33], [20], dielectric constant [8]–[10], [11], [22], [34]–[36], and impedance (i.e., through reflected voltages) [4], [21], [37], [38]. These can be achieved by implementing coaxial probes [31]–[33], [35], [18], ring antennas [1], [21], [26], [37], [17], horn antennas [25], [27], [28], [30], [34], [39], waveguides [27], [28], [31], and microstrip patch antennas [24], [29], [36], [40]–[43], [15], [16], [20]. Using coaxial probe is a destructive method and may damage the sample since the sensor needs to be inserted into the sample. Implementing antennas is a preferable method for MC monitoring because of its contactless nature. It should be noted that variations in the temperature result in the inaccuracy of the

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MC measurement due to the cross-interference [33]. Hence, the frequency bands in which the dielectric constant of the water changes abruptly by varying the temperature should be avoided.

It should be noticed that the investigated methods are primarily applicable for measuring the MC of small samples. However, measuring the MC of the field soil and grains in large areas is often achieved through remote sensing and measuring radar cross-section [43], which is out of the scope of this paper.

A comparison among the state-of-the-art MC monitoring approaches and portable sensors are reported in Tables 1 and 2, respectively. Since the dielectric constant of the water at some frequency bands changes with the temperature variations, sensors with no/minor cross-interference sensitivity are more desirable. The portability and compactness of the sensor are also crucial factors for field applications.

TABLE 1. A summary of different approaches for MC monitoring.

Method	Frequency range	Contactless	Simplicity	Portability
S-parameters	All frequency bands	Yes	Simplest	Yes
Dielectric constant	Below V-band	Yes	Moderately simple	Yes
Impedance	Low frequency band (below S-band)	Yes	Moderately simple	Yes

The organization of this paper is as follows; first, the operation principles of MC monitoring are discussed. Then state-of-the-art microwave sensors for MC measurement based on measuring S-parameters, dielectric constant, and impedance are investigated and compared with each other.

II. OPERATION PRINCIPLES

The MC is calculated by $MC = (W_w - W_d)/(W_w - W_c)$ [3], [5] where W_w, W_d, and W_c are the weight of sample under test (SUT), dried SUT, and container weight without SUT, respectively. The MC indicates the amount of water that exists in the SUT. In other words, the more water be in the sample, the higher the MC will be. As a first approximation, we can assume that the dielectric constant of the SUT is a weighted average of the dielectric constants of the dried sample and water. Hence, variation in the MC is similar to varying the dielectric properties of the SUT, affecting dielectric constant, S-parameters, and input impedance. This is the common foundation of the investigated approaches for MC monitoring. The coloration between MC, dielectric constant, and S-parameters for a few grains are shown in Fig. 1 [11]. According to Fig. 1, increasing the MC leads to the rise of the dielectric constant and reduction of the reflection coefficient's magnitude. This indicates that detecting variations in the dielectric constant and reflection/transmission coefficients is useful for grains' MC monitoring.

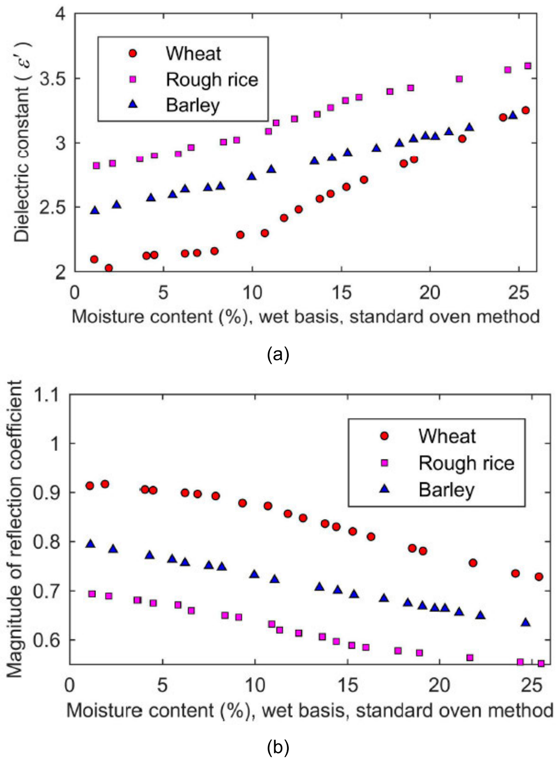

FIGURE 1. The MC of wheat, rough rice, and barley reported in [5] (a) dielectric constant versus MC, (b) reflection coefficient versus MC © 2002 IEEE.

We categorize different MC monitoring methods as follows; S-parameters measurement (i.e., reflection and transmission coefficients measurement), dielectric constant measurement, and impedance measurement. MC monitoring can be achieved efficiently through variation in the amplitude and phase of S-parameters [1], [2], [5]–[7], [14], [23]–[33]. Observing the variations in the dielectric constant is another attractive method for measuring the MC [8]–[10], [11], [22], [34]–[36]. Generally, impedance and voltage measurements are performed accurately in the low frequency band (*i.e.*, below 1 GHz) [32]. Monitoring MC through S-parameters and dielectric constant measurement is typically suitable for all frequency bands.

A. S-PARAMETERS METHOD

MC monitoring can be achieved by measuring variations in the amplitude and the phase of S-parameters. This is because variations in the dielectric properties lead to changes in the reflection and transmission coefficients. Monitoring S-parameters can be carried out by measuring the return and insertion losses (*i.e.*, reflection and transmission coefficients) using a vector network analyzer (VNA). Monitoring MC through return loss measurement is more desirable

TABLE 2. Comparison among different sensors for MC monitoring.

Reference	Center Frequency	SUT	Sensor Type	MC Range (%)	Cross-interference sensitivity	Error
FSS Antenna	2 GHz	Barley	FSS	10–25	No	0.075%
[1]	93 MHz	Red winter wheat	Microstrip patch	15–25	No	Not reported
[3]	250 MHz	Corn	Ring resonator	12.59–36.5	No	Not reported
[4]	152 MHz	Corn	Ring resonator	15.7–31.5	No	3.54%
[5]	10.5 GHz	Rice	Horn	11–27	Yes	Not reported
[6]	2.45 GHz	Rice	Dipole	11–22	No	0.366%
[7]	14 GHz	Red winter wheat	Horn	10.6–19.2	Yes	0.135%
[8]	9.5 GHz	Biomass (alfalfa)	Coaxial probes	11.5–73	Yes	Not reported
[9]	4.5 GHz	Soya	Horn	0–20	No	Not reported
[10]	14.2 GHz	Wheat	Horn	11–18	Yes	0.611%
[11]	4 GHz	Wheat	Probe	1–26	No	Not reported
[12]	2.45 GHz	Granular	Microstrip patch	0–30	No	7.31%
[13]	10 GHz	Barley	FSS	10–25	Yes	0.023%
[24]	2.45 GHz	Sand	Waveguide	0–16	No	0.1%
[25]	1.9 GHz	Soil	Microstrip patch	0–20	No	0.2%
[34]	1.25 GHz	Soil	Ring resonator	0–30	No	Not reported
[35]	500 KHz	Soil	Microstrip line	20–80	No	3%
[36]	900 MHz	Soil	Microstrip tag	30–65	No	Not reported
[20]	5.5 GHz	Soil	Microstrip patch	Not reported	No	Not reported

because it only requires a one-port sensor, simplifying the fabrication and reducing the cost. Monitoring the return loss is similar to monitoring the shift in the resonance frequency, which is easier to detect using a VNA integrated into the sensor. This method was primarily used in [1], [2], [5]–[7], [14], [23]–[33].

B. DIELECTRIC CONSTANT METHOD

Monitoring MC can be performed by measuring variations in the dielectric constant as well. Measuring the dielectric constant can be done by monitoring the S-parameters or the time delay of the reflected signal from the open side of the coaxial probe inserted into the SUT [45]. This is because changing MC corresponds to variations in the amount of water inside SUT, which changes its dielectric properties. It is possible to measure the dielectric constant directly using a programable network analyzer (PNA) or indirectly through S-parameters and post-processing methods, adding to the complexity and cost of the sensor. The operating principle of the reported sensors in [8]–[10], [11], [22], [34]–[36] is based on dielectric constant measurement.

C. IMPEDANCE METHOD

MC monitoring can also be achieved by measuring the input impedance of the sensor in the presence of SUT. This can be done through monitoring variations in the capacitance value of the ring resonators and microstrip patches. Measuring the amplitude and phase of the reflected voltage signal is another technique. The MC monitoring in [3], [4], [21], [37], [38], [42], and [43] was accomplished through measuring the input impedance. It should be noted that measuring impedance is also possible through S-parameters measurement. However, in [3], [4], [21], [37], [38], [42], and [43], MC monitoring was achieved by direct measurement of voltage and impedance. In addition, using VNA is not favorable in some applications due to the relatively high cost.

A summary of different MC monitoring methods is reported in Table 1. Monitoring MC through S-parameter measurements is suitable for all frequency bands. The only restrain is the frequency range of the implemented VNA. Measuring MC through monitoring variations in dielectric constant is applicable mainly for the frequency bands below 100 GHz since the modern approaches for measuring the dielectric constant, using PNAs or post-processing approaches, are only accurate up to the V-band. However, monitoring MC directly through input impedance variations is only valid in the low frequency band (i.e., below S-band) using commercial and in-lab sensors. This is because measuring the capacitance and inductance at high frequency bands is challenging since the transmission line effect needs to be considered. Measuring S-parameters is also simpler and cheaper than measuring the dielectric constant.

All the investigated methods can be used to monitor MC remotely without touching the SUT. However, it is necessary to insert sensors into the SUT in some applications, such as measuring the MC of soil. Moreover, all the investigated sensors are inherently portable and can be integrated into portable reading instruments (e.g., portable VNAs). It should be noted that the reading instrument of the dielectric constant is often more complex than a simple VNA used for measuring the S-parameters. This is among the advantages of the s-parameters method compared to the dielectric constant approach. Overall, measuring the MC by monitoring variations in S-parameters is the most popular approach due to the contactless nature, simplicity, wide frequency bands, and small size of the sensor.

III. MC MONITORING MICROWAVE SENSORS

As stated before, different antenna sensors, such as horn antennas, microstrip antennas, and ring resonators are implemented to monitor the MC by measuring S-parameters, dielectric constant, and impedance. In this section, we investigate the state-of-the-art microwave sensors for MC monitoring of grains and mineral materials. The sensing mechanism of the MC monitoring sensors investigated in this section is based on variations in the dielectric properties. As discussed in section II, these variations can be detected by measuring the S-parameters, dielectric constant, or impedance. It should be noted that the focus of this manuscript is a survey on the microwave sensors for grains and mineral materials' MC monitoring.

A. GRAIN MC MONITORING SENSORS

MC of different types of rice can be measured using two horn antennas at 10.5 GHz, as demonstrated in Fig. 2 [5]. The MC is obtained by monitoring the transmission coefficient. The SUT was located between two horn antennas, connecting to VNA ports. The measured MC ranges from 11% to 27% at 10.5 GHz [5]. Horn antennas can also be implemented to measure the MC of red winter wheat in the frequency band of 10−18 GHz through monitoring the transmission coefficient, as shown in Fig. 3 [7]. The measured MC ranges from 10.6% to 19.2%, with a mean absolute error of 0.135%. Horn antennas can be used to monitor the MC of soya in the range of 0−20% at 4.5 GHz [9]. The proposed method in [9] is based on variations in the phase and the amplitude of the transmission coefficient.

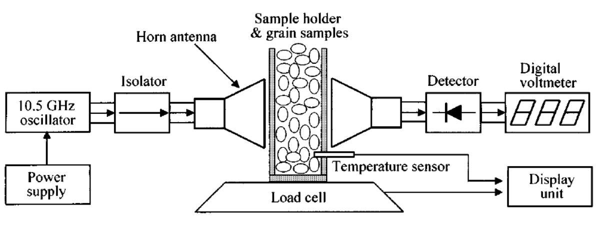

FIGURE 2. The measurement setup for MC monitoring of rice reported in [5] ©2002 IEEE.

The MC monitoring of wheat can also be made by measuring the dielectric constant using the reflection and transmission coefficients [10]. The measurement was carried out using two horn antennas and a VNA in the frequency range of 11.3−18 GHz [10]. The MC ranges from 10.6% to 19.2% with the error ranging from 0.524% to 0.696% at 14.2 GHz [10].

Using a microstrip trapezoid-shape patch mounted in the inner wall of an industrial container, the MC of red

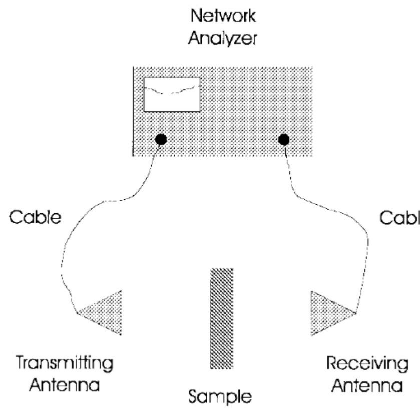

FIGURE 3. The measurement setup for MC monitoring of red winter wheat reported in [7] ©1998 IEEE.

winter wheat in the range of 15−25% can be measured at 93 MHz [1]. The MCs of wheat and rice in the range of 1−26% at 4 GHz can also be measured using the UWB probe inserted into the sample, as shown in Fig. 4 [11]. Coaxial probes can also be implemented to measure the MC of biomass (alfalfa) in the frequency band of 1−18 GHz [8]. The measured MC of [8] ranges from 11.5% to 73%. The invasive methods reported in [8] and [11] are not desirable since inserting the probe can damage the sample.

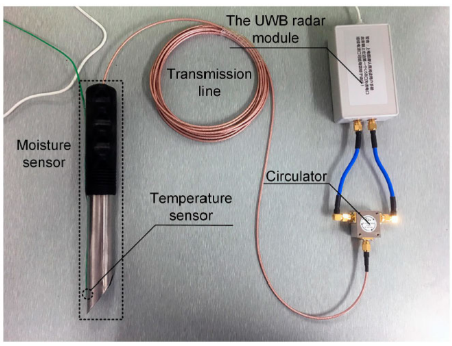

FIGURE 4. The measurement setup for MC monitoring of wheat and rice was reported in [11].

The MC monitoring of corn ear can be carried out nondestructively using a handheld sensor based on a ring resonator antenna, as shown in Fig. 5. [4]. The reported portable sensor operated in the frequency range of 140−165 MHz. The operating principle of the investigated sensor is based on measuring the capacitance variation as a function of MC. The measurement was carried out on 73 samples at 160 MHz covering the MC ranges of 15.7%−31.5% with an error of 3.54%. The proposed sensor includes a double ring antenna based on PTFE substrate, an active reflection bridge, direct digital synthesizer, low pass filter, power splitter, 3dB attenuator, microprocessor control, and detection chip to measure the amplitude and the phase of the reflection coefficient. The MC of the corn was determined using the measured phase of

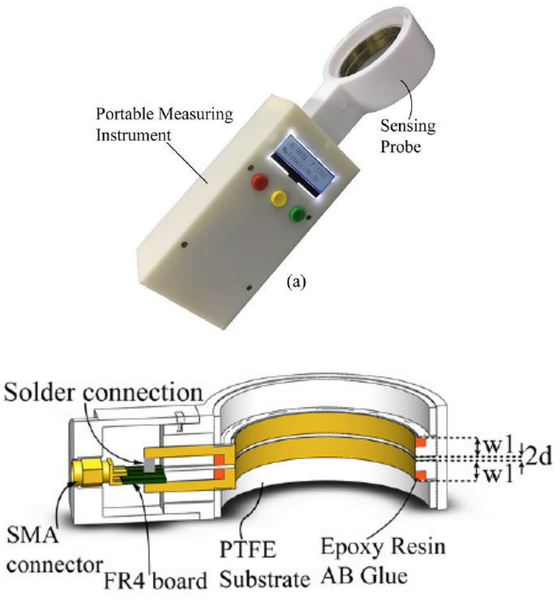

FIGURE 5. The proposed microwave sensor for moisture monitoring of corn ear reported in [4] ©2020 IEEE. (a) fabricated handheld sensor, (b) schematic of the sensor.

the reflection coefficient. The MC in the middle of the corn ear can be considered a suitable indicator for the total MC of the corn [4].

The MC of corn can also be measured through the impedance variations using a ring resonator, VNA, and quarter-wave coaxial line, as presented in Fig. 6 [3]. More precisely, MC was measured through the standing wave ratio and phase angle of the output voltage. In other words, the MC measurement was carried out by transmitting a sinusoidal wave into the systems and measuring the reflected voltage due to the mismatch of the ring impedance and the impedance of the quarter-wave transmission line. Overall, measuring the electrode output impedance in the frequency band of 0.3−500 MHz, the MC in the 12.59−36.5% range was determined.

Another suitable sensor for MC monitoring is the FSS antenna [46]–[50], [13], which can be printed on the inner wall of the container to minimize the container blockage effect, as shown in Fig. 7. The reported sensor is the novel work of the authors presented here for the first time. The investigated FSS antenna is a 30 × 1 array of complementary square-shaped ring resonators (CSRRs) made of conducting ink layer with a thickness of 0.127 mm. The inner square-shaped ring has a side length of 2 mm with a gap of 0.3 mm. The spacing between adjacent CSRR is 2 mm. The container is a cylinder made of PF-4 substrate that is flexible, low-loss, and lightweight. The height, inner radius, and outer radius of the container are 26 mm, 27 mm, and 28.6 mm, respectively. Monitoring the MC of barley in the range of 10−25% is performed by measuring variations in the resonance frequency of the FSS antenna. This sensor can

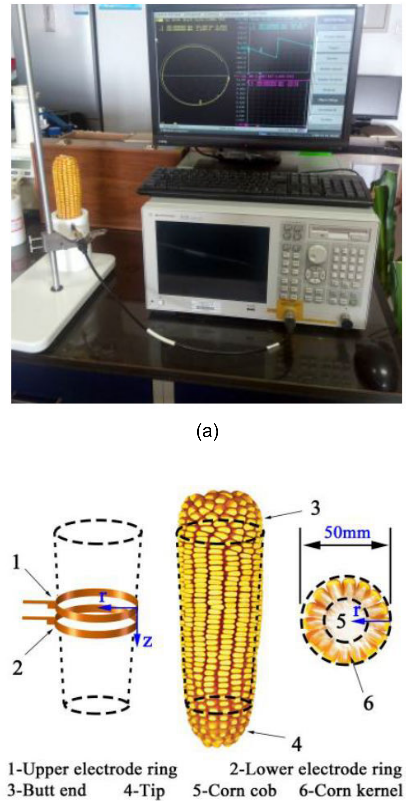

FIGURE 6. The proposed double-ring sensor for moisture monitoring of corn ear [3]. (a) VNA connected to the sensor, (b) double-ring resonator sensor.

be integrated with a mini-VNA, indicating the portability and ease of use in the field. Moreover, the additive manufacturing technique can lead to environment-friendliness fabrication. The S_{11} of the antenna is presented in Fig. 8, indicating a 200 MHz shift in the resonance frequency by varying the MC from 10% to 25%. It should be noted that FSS is suitable for MC monitoring due to the high frequency sensitivity to the MC variations. In other words, small variations in MC lead to relatively large variations in the resonance frequency, which can be easily detected using a VNA.

Another FSS-based sensor for monitoring the MC of barley at X-band, center frequency of 10 GHz, is reported in [13]. The schematic of the investigated FSS sensor is presented in Fig. 9, indicating the compact size of the proposed sensor. According to [13], changing MC from 10 to 25% leads to a 650 MHz shift in the resonance frequency of the CSSRs. This indicates the high sensitivity of the investigated sensor. However, the reported sensor suffers from cross-interference due to the sensitivity of the water dielectric constant to the temperature at high frequency [51]. In other words, the accuracy of the sensor changes by varying the temperature.

The MC of several granular materials such as bean, rice, and peanuts were measured by monitoring transmission coefficient and attenuation [12]. The reported sensor is a

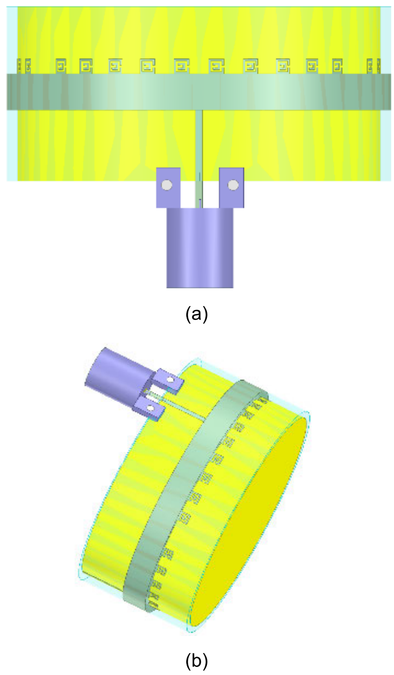

FIGURE 7. The Schematic of the proposed novel FSS antenna by the authors. (a) Top view, (b) 3D view.

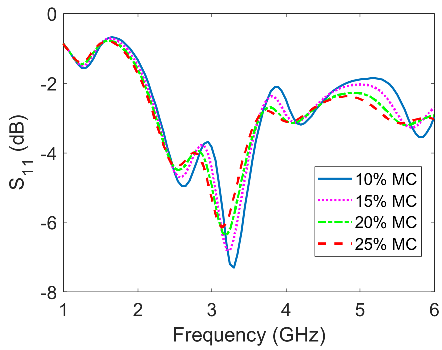

FIGURE 8. The S_{11} of the proposed FSS antenna for different MC values.

2×2 microstrip patch array antenna connected to a VNA, as demonstrated in Fig. 10. The proposed sensor was able to measure MC in the range of 0−30% at 2.45 GHz.

B. MINERAL MATERIALS MC MONITORING SENSORS

The MC of soil in the range of 0−20% can be measured through a low-cost and non-invasive sensor based on monitoring the variations in the return loss and resonance frequency [32]. The proposed sensor is a microstrip patch antenna operating in the frequency band of 1.8−2 GHz, as presented in Fig. 11. The SUT is placed on top of the microstrip patch. Changing the MC leads to variation in the dielectric constant and the resonance frequency of the microstrip patch antenna. It should be noted that the variations in the resonance frequency are mainly due to the variations in the real part of the dielectric constant. It was found that increasing the water content leads to reducing the resonance frequency and minimum value of the S_{11} [32].

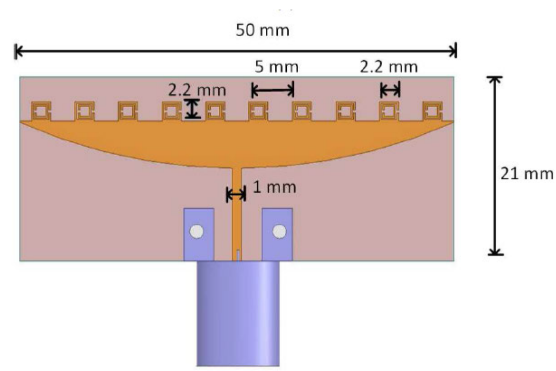

FIGURE 9. The top view of the compact FSS antenna sensor for MC monitoring at *X*-band [13] ©2021 IEEE.

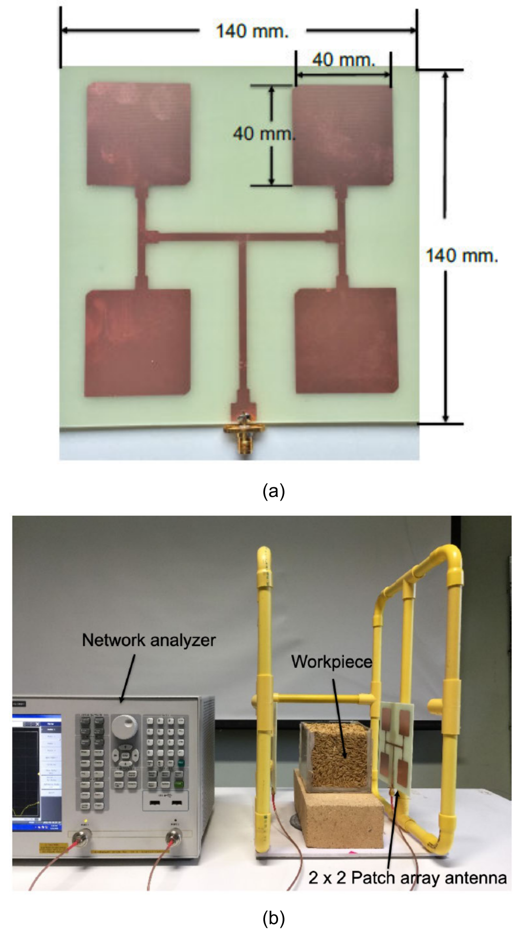

FIGURE 10. The proposed sensor reported in [12] ©2021 IEEE. (a) microstrip patch array antenna, (b) measurement setup.

A microstrip ring resonator antenna can also be implemented as the sensor for the MC monitoring of soil at 1.25 GHz, as illustrated in Fig. 12 [41]. The operational principle of the proposed sensor is based on measuring the dielectric constant using the variations in the resonance frequency and quality factor of the resonator. The SUT is

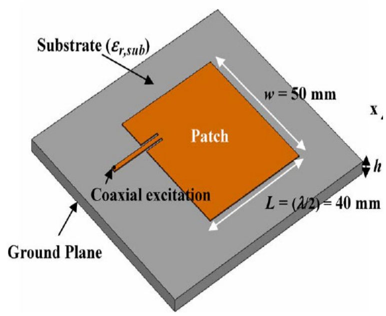

FIGURE 11. Microstrip patch antenna proposed in [32] for the MC monitoring of the soil ©2009 IEEE. The SUT is placed on top of the microstrip patch.

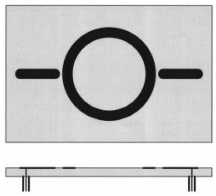

FIGURE 12. The proposed ring resonator antenna for MC monitoring of soil was reported in [41] ©1997 IEEE. The SUT is placed on top of the ring resonator.

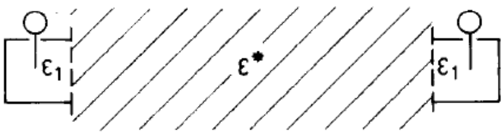

FIGURE 13. The measurement setup for MC monitoring of sand reported in [31] ©1991 IEEE.

placed over the ring resonator. The proposed sensor measured the MC of the soil from 0 to 30%.

The MC of sand can be measured using a waveguide, as shown in Fig. 13 [31]. The proposed sensor measured the MC below 16% with an accuracy of 0.1% at 2.45 GHz. It was found that the MC affects the dielectric constant and transmission coefficients. Increasing the MC leads to the rise of the real part of the dielectric constant, loss, and phase of the transmission coefficient, while the magnitude of the transmission coefficient reduces. A rectangular waveguide was filled with the sample, and the transmission coefficient was measured using two coaxial probes and a network analyzer [31].

The MC of soil can be measured using an interdigital microstrip lines probe at 500 kHz, as shown in Fig. 14 [42]. The MC of soil can also be measured using a microstrip RFID tag on a probe in the frequency band of 0.8−1 GHz, as shown in Fig. 15 [43]. It should be noted that the reported sensors in [35] and [43] can damage the soil since they need to be inserted into it. On the other hand, the reported sensor in [20] measures the soil humidity at 5.5 GHz using a microstrip patch without being inserted into the sample, as shown in Fig. 16. The sensing mechanism in [20] is based on monitoring the shift in the resonance frequency.

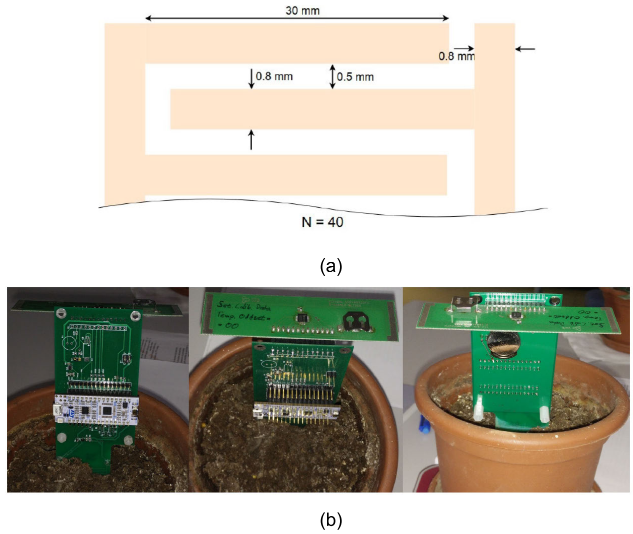

FIGURE 14. The measurement setup for MC monitoring of soil reported in [42]. (a) Interdigital microstrip line, (b) Measurement probe.

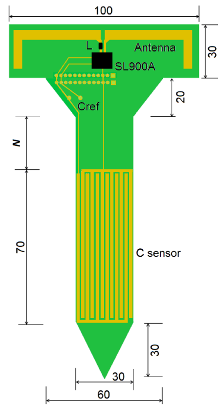

FIGURE 15. The proposed antenna for MC monitoring of soil [43].

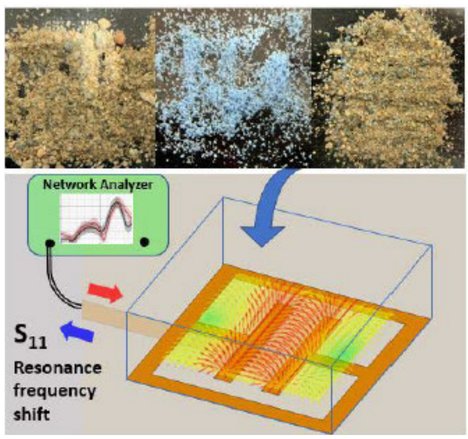

FIGURE 16. The reported sensor for humidity measurement of soil [20] ©2020 IEEE.

IV. COMPARISON BETWEEN MC MONITORING PORTABLE SENSORS

In this section, a comparison between state-of-the-art portable MC monitoring sensors is performed in Table 2. According to Table 2, novel FSS antenna sensors reported here and in [13] by the authors have the highest sensitivity (i.e., smallest error) in MC monitoring with little to no cross-interference (i.e., small/no MC changes due to the temperature variations). The reported sensor in [8] has the broadest MC range, whereas it suffers from cross-interference. Generally, sensors operating below 8 GHz have small to no cross-interference since the dielectric constant of the water changes very slowly by varying the temperature at those frequency bands [51]. Therefore, [5], [7], [8], and [10] suffer from cross-interference. It should be noted that the sensors operating below 1 GHz has large size and not suitable as portable sensors. Some of the investigated sensors in Table 2 are not flexible, which degrades their potential usage in the field. Overall, the compactness, portability, no/small sensitivity to the temperature variations, minor error, ease of environment-friendly fabrication process, and flexibility of the FSS antenna make it suitable for MC measurement applications.

V. CONCLUSION

Monitoring MC is crucial in different fields, including farming and the food industry. A comprehensive survey of the portable sensors for MC monitoring was made in this paper. This comprehensive review paper acts as a starting point for the MC monitoring sensor designers, enlightening the advantages and challenges of different sensors. The fundamental concepts of microwave methods for measuring MC were investigated first. Comparison between different approaches indicates the S-parameters method is the most suitable approach for MC monitoring. Then state-of-the-art portable microwave sensors for MC monitoring were studied with the focus on grains and mineral materials as the SUTs. A comparison between MC monitoring sensors was performed as a guideline for the consumers and designers. According to the comparison, the FSS antenna is the most suitable portable sensor for MC monitoring. This is due to its high accuracy, compactness, portability, flexibility, ease of fabrication, and no/small cross-interference sensitivity.

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NIMA JAVANBAKHT (Member, IEEE) received the B.Sc. and M.Sc. degrees in electrical engineering from Ferdowsi University of Mashhad, Mashhad, Iran, in 2013 and 2016, respectively, and the Ph.D. degree in electrical engineering from Carleton University, Ottawa, ON, Canada, in 2021.

Furthermore, he was a Research Intern with the National Research Council Canada (NRC), in 2020 and 2021. He has been a Postdoctoral Research Fellow with the Department of Electronics, Carleton University, since 2021. He has authored more than 30 technical articles in journals and conference proceedings. His research interests include analysis and design of leaky-wave antennas, sidelobe suppression, reconfigurable antennas, compact microwave sensors, metamaterial structures, scalable phased arrays, silicon on-chip antennas, textile microwave devices, and mm-wave communication devices.

Dr. Javanbakht's awards and honors include Ontario Graduate Scholarship (OGS), the Doctoral Excellence Award, Epstein Foundation Scholarship, Curie Award, and the CUASA Scholarship.

GEORGE XIAO (Fellow, IEEE) received the Ph.D. degree from Loughborough University, U.K., in 1995. He is currently the Principal Research Officer of the National Research Council of Canada. He has brought significant benefits to the society by brining technologies from concepts to products. He has managed large research and development projects in industries, academics, and government labs covering areas, including RFID/NFC, flexible/printable/wearable electronics, fiber optic sensor systems, photonic sensing and measurement, structural health monitoring, indoor air quality monitoring, structural materials, and smart materials. He received the 2014 Technical Award from the IEEE Instrumentation and Measurement Society, and the 2018 Distinguished Service Award from the IEEE Instrumentation and Measurement Society. He is the Editor-in-Chief of the IEEE JOURNAL OF RADIO FREQUENCY IDENTIFICATION and an Associate Editor-in-Chief of IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT.

RONY E. AMAYA (Senior Member, IEEE) received the M.Eng. and Ph.D. degrees in electrical engineering from Carleton University, Ottawa, ON, Canada, in 2001 and 2005, respectively.

He joined the Design Center, Skyworks Solutions, Ottawa, in 2003, as a Senior Engineer, where he was involved in the design RFIC's for wireless transceivers. He also held a Research Scientist position with the Communications Research Centre Canada, from 2006 to 2015, where he was involved in developing integrated RF circuit and system solutions from *S*-band to *E*-band and addressing packaging integration. He is currently an Associate Professor with the Department of Electronics, Carleton University. He has authored or coauthored more than 60 technical articles in journals and conference proceedings and holds several patents. His research interests include intelligent wireless communications systems making use of enabling microwave/RF technologies, such as smart engineered surfaces, gallium nitride and metamaterials, wireless power transfer, contactless communication links, and power harvesting with applications to RFID and the IoT systems, monolithic integrated Si/GaN/GaAs circuits, high-performance microwave circuit packaging, integrated active antennas, low temperature co-fired ceramics, micro-electro-mechanical systems, RF, and millimeter-waves.

Dr. Amaya is a member of the Association of Professional Engineers of Ontario.