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Original Article

Soil moisture sensors based on metamaterials

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Abstract

In this paper novel miniature metamaterial-based soil moisture sensors are presented. The sensors are based on resonant-type metamaterials and employ split-ring resonators (SRR), spiral resonators and fractal SRRs to achieve small dimensions, high sensitivity, and compatibility with standard planar fabrication technologies. All these features make the proposed sensors suitable for deployment in agriculture for precise mapping of soil humidity.

Keywords: soil moisture sensor, metamaterials, split-ring resonators, fractal curves

1. Introduction

One of the factors that determine the optimal plant growth and therefore the agricultural production is the soil moisture content. The yield can be increased for 40% when partial irrigation systems are used during the complete production cycle (Ludlow *et al.*, 1989). Furthermore, the soil moisture plays a very important role in determining the level of acids and pollution in the soil.

Different methods have been developed for the determination of soil moisture, neutron moderation, electromagnetic methods, and methods based on the drying of the sample, etc. (Liu *et al.*, 2004; Muñoz-Carpena, 2009). Sampling and drying relies on the measurement of volume or mass of the sample before and after drying process. However, it requires laboratory equipment, it is very expensive and time consuming, and above all it is destructive. The neutron moderation relies on exposing the soil to the emission of the neutron beam from the radioactive source. Although the beam can penetrate into the ground and construct a 3D profile of soil moisture, the beam radius is very small, totally 30-40 cm. On the other hand, there are very strict limitations concerning application of this method in agricultural production.

Soil moisture can be estimated by measuring certain values, which depend on the soil moisture content. In a great extend, electrical characteristics of the soil are determined by its moisture. This fact leads to the development of the electromagnetic methods, which are based on the measurement of electrical properties, such as conductivity, resistivity, or dielectric constant of the soil. Measurement of the soil moisture via the resistivity is a very simple technique based on application of two electrodes. Although simple, this method has a big disadvantage of the resistivity being a function of an ion concentration and not moisture content exclusively. It can be concluded that the great benefits of the indirect methods are their nondestructive properties and fast response, but on the other hand they demand a very precise calibration.

Some of the techniques mentioned use relatively expensive equipment with high power consumption, others are not accurate enough. These drawbacks make them poor candidates for the mass production or application on a great number of locations. Sensors for state-of-the-art applications in precision agriculture should have several characteristics. First, they should have small dimensions to allow measurements with no or minimal disturbance of the surrounding soil. Also, since monitoring of soil moisture at certain depths (i.e. in the root zone) is of great interest to the end-users, small dimensions of the sensor will facilitate its simple insertion into the ground. Secondly, power consumption of the

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sensors should be low, to facilitate constant maintenance-free monitoring of soil moisture. Furthermore, the sensors should be precise, low-cost, reliable, durable, safe to use, easy for mass production, and perform nondestructive measurements. The type of sensor that meets all listed demands is an electromagnetic sensor that operates on the principle of the permittivity measurement, due to the fact that the soil permittivity strongly depends on the volumetric soil moisture content. Microstrip architecture is suitable for the realization of the sensor because the propagation of the electromagnetic waves along a microstrip depends on the medium that surrounds it. Microstrip circuits are low-cost and easy to fabricate. Typically, they operate at the GHz frequency range and, therefore, can be used to perform non-destructive measurements.

Metamaterials present a new paradigm in microwave engineering and have recently been used to design super-compact high-selectivity resonators, filters, and other passive devices (Pendry, 1999; Baena 2004; Baena, 2005). Metamaterials are artificial structures composed of a number of unit cells with sub-wavelength dimensions. They inherently posses small size and high-selectivity, and in the same time are fully compatible with conventional fabrication technologies such as PCB (printed circuit board). This paper focuses on microstrip soil moisture sensors which use various metamaterial unit cells, split ring resonator (SRR), multiple SRR with six concentric rings (M-SRR), spiral resonator (SR), and Sierpinski split ring resonator (SS-SRR) (Crnojevic-Bengin *et al.*, 2007; 2008). All these sensors operate at the principle of the resonant frequency shift. They are compared in terms of size and the influence of the soil moisture on the resonant frequency shift of the given configuration.

2. Sensor Design

The layout of the proposed metamaterial-based microstirp soil moisture sensors is shown in Figure 1. The sensor consists of a microstrip line loaded on both sides with two metamaterial unit cells. This structure behaves as the notch, (Baena *et al.*, 2005; Crnojevic Bengin *et al.*, 2007) whose resonant frequency and stop-band characteristics depend on the size and type of the metamaterial unit cell. Compared to the case when only one unit cell is used, the proposed sensor topology has slightly lower resonant frequency and increased insertion losses in the stop-band. It should be mentioned that the dimensions of all unit cells used in this paper are smaller than $\lambda_g/16$, which result in very compact sensor dimensions equal to $0.07\lambda_g$ x $0.176\lambda_g$ (4.9 mm x 11.3 mm), where λ_g is the guided wavelength. The sensor is placed in an inhomogeneous medium, as shown in Figure 2, characterized by an effective dielectric constant, ε_s. In general the resonant frequency of the sensor is influenced by the properties of the used dielectric substrate, the medium that surrounds the sensor and sensor geometry. For a fixed dielectric thickness of the substrate, *h*, dielectric constant, ε_d, and a chosen sensor geometry, the resonant frequency of the sensor solely depends on the effective dielectric constant. The effective dielectric constant is given by Equation 1, where ε_s, presents the unknown permittivity of the soil sample and *w* is the width of the microstrip line:

$$\varepsilon_{eff} = \frac{\varepsilon_d + \varepsilon_s}{2} + \left(\frac{\varepsilon_d - \varepsilon_s}{2}\right)\left(\frac{1}{\sqrt{1+12\dfrac{h}{w}}}\right), \quad (1)$$

since the soil moisture strongly influences the soil permittivity and therefore the effective permittivity, it can easily be obtained from the resonant frequency of the sensor.

Metamaterial unit cells used for the sensor design are shown in Figure 3: SRR, M-SRR with 6 rings, SR and SS-SRR. The overall dimensions of all unit cells are 4.9 mm x 4.9 mm, while the ring gap, distance between the rings and the width of the conductive lines are all equal to 100 μm. The cells are placed 100 μm from the microstrip, to increase the coupling. All structures are realized on 1.27 mm thick Taconic CER-10 substrate, characterized by the dielectric constant equal to 9.8 and loss tangent equal to 0.0035. The width of the 50 Ω line on the used substrate is 1.4 mm.

The performances of the proposed sensors are determined for soil moisture varying from 2 to 20 %, as it corresponds to the values encountered in real-life. For typical agricultural soils, variation of soil moisture from 2 to 20% corresponds to the change of dielectric constant from 1 to 20. Since the change of the soil humidity is also followed by

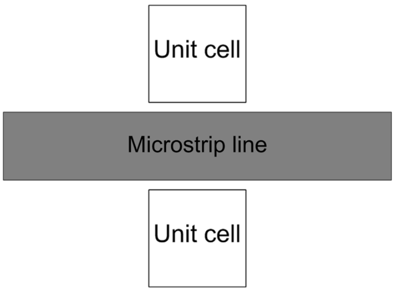


Figure 1. Layout of the metamaterial-based soil moisture microstrip sensors.

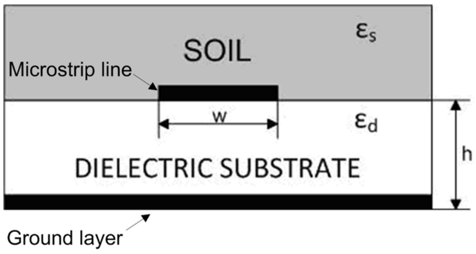
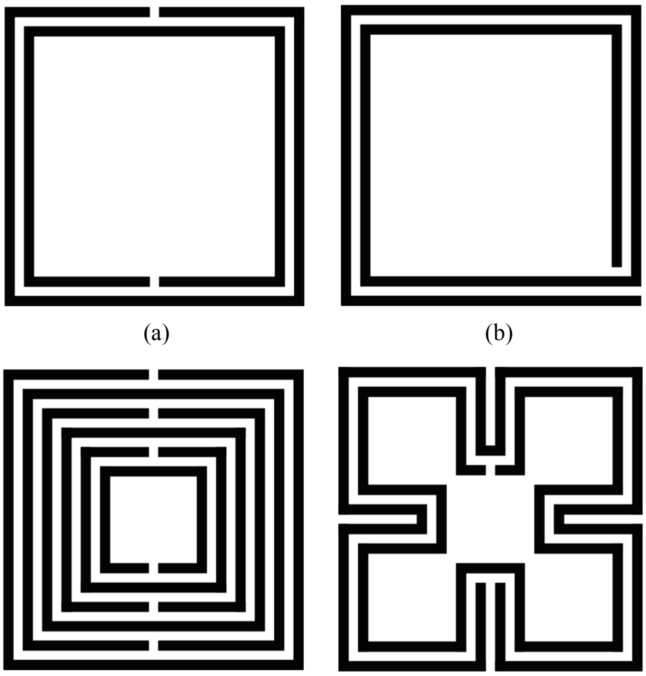


Figure 2. Microstrip sensor placed in an inhomogeneous medium with unknown dielectric constant, ε_s.



(a) (b)

(c) (d)

Figure 3. Metamaterial unit cells that are used for the sensor realization: (a) SRR, (b) SR, (c) M-SRR, and (d) SS-SRR.

the change of loss tangent of the medium, the latter is also considered. The exact values used in the analysis are listed in Table 1.

The resonant frequency of all proposed sensors as the function of the soil permittivity is shown in Figure 4 to 7, for various metamaterial unit cells used. All simulations were performed in EMSight, electromagnetic simulator in *Microwave Office*, ver 4.2. The losses in the conductor are modeled using bulk conductivity for copper.

It can be noticed that higher soil moisture causes an increase of the soil dielectric constant, which leads to a higher effective permittivity. This results in the decrease of the resonant frequency of the sensor. However, at the same time, the losses in the soil are also larger, which leads to a decreased insertion loss and a reduced selectivity of the resonant peak, making it more difficult to detect it. In this case the use of detectors with higher sensitivity to the change of the signal strength is needed.

Table 1. Values of soil moisture and corresponding dielectric constant (ε_s) and loss tangents factor (tg δ).

Soil moisture [%]	ε_s	tg δ
2	2.5	0.06
5	5	0.07
8	7.5	0.09
11	10	0.10
13	12.5	0.11
15	15	0.12
18	17.5	0.14
20	20	0.15

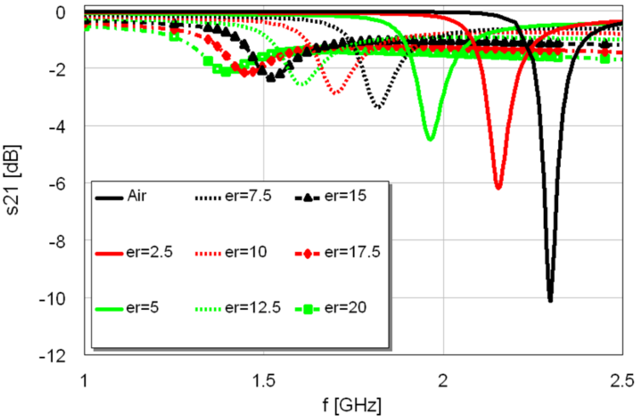


Figure 4. Resonant frequency of the SRR sensor as the function of the soil permittivity.

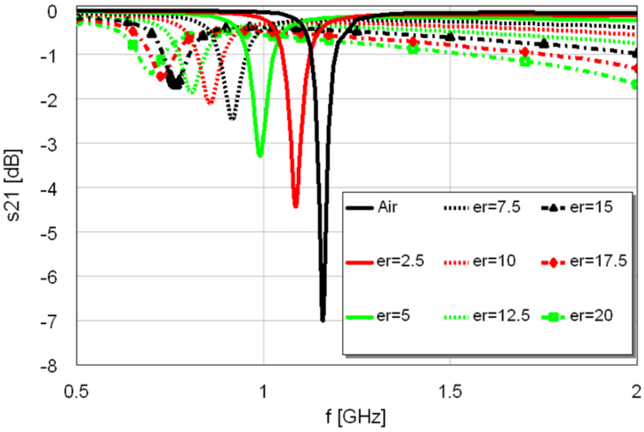


Figure 5. Resonant frequency of the SR sensor as the function of the soil permittivity Figure 6. Resonant frequency of the M-SRR sensor as the function of the soil permittivity

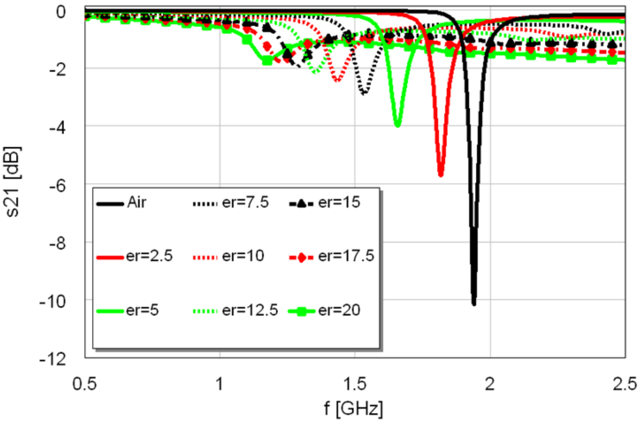


Figure 6. The resonant frequency change with the change of soil dielectric constant for the case of M-SRR sensor.

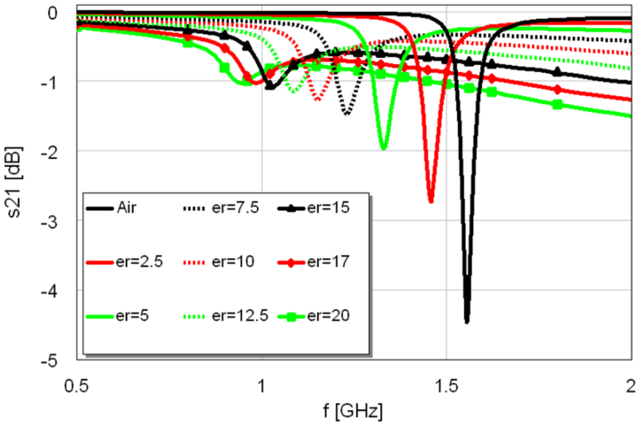


Figure 7. Resonant frequency of the SS-SRR sensor as the function of the soil permittivity.

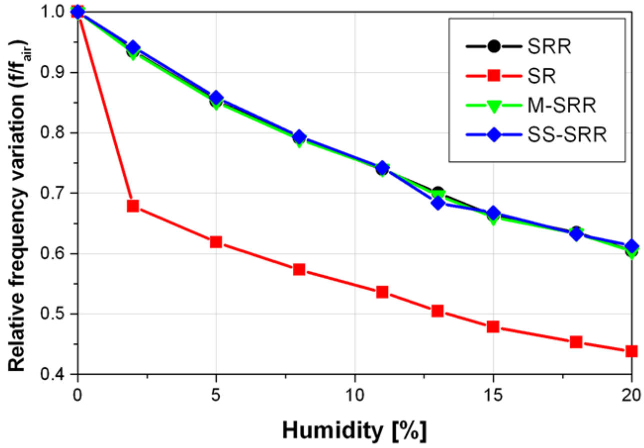


Figure 8. Comparison of the proposed sensors in terms of relative resonant frequency variation with soil moisture content.

The largest resonant frequency shift equal to 910 MHz occurs in the case of SRR-based sensor, while the smallest shift equal to 600 MHz is exhibited by the SR-based sensor. Also, among all proposed geometries, SRR shows the highest insertion losses for high soil moisture content.

All proposed sensors are compared in Figure 8, where the relative frequency shift in respect to the initial resonant frequency obtained for the case when no soil is placed above the unit cells is shown as the function of the soil moisture. It can be noticed that the relative frequency shift is a linear function of the soil moisture, in the case the sensors based on SRR, M-SRR and SS-SRR. However, the SR exhibits nonlinearity for low soil moisture contents, which makes it unsuitable for the sensing applications.

The SRR-based sensor exhibits the largest change of the resonant frequency in the case of varying soil moisture, i.e. it can be used to determine the soil moisture with the highest resolution of all proposed geometries. This sensor also exhibits the highest insertion loss, which facilitates the detection of the resonant peaks. Although SR shows the smallest range of frequency shift and the lowest resonant frequency, it is also characterized with relatively small attenuation for high soil moisture values and nonlinear frequency shift. SS-SRR has a linear change of the resonant frequency, but like SR, it also shows relatively small attenuation for high soil moisture content, which further complicates the detection process. M-SRR represents the solution, which shows linear change of the resonant frequency with small range of change and insertion losses that are similar to the SRR resonator.

3. Conclusion

In this work metamaterial-based soil moisture sensors, which operate on the principle of the resonant frequency shift, were presented. The influence of the soil moisture on the performances of the proposed sensors was considered. The proposed sensors are characterized by extremely small size, linear change of the frequency with the change of the soil moisture, and compatibility with standard low-cost planar fabrication technologies. The drawback of some of the proposed sensors is relatively small insertion loss at the resonant frequency, especially in case of high soil moisture contents. However, this can be overcome by a proper detector design.

Acknowledgments

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