Novel Hilbert Soil-Moisture Sensor Based on the Phase Shift Method

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Abstract — **In this paper, novel soil-moisture sensor based on the Hilbert fractal curve is proposed. The developed sensor is intended to be integrated into wireless sensor network whose goal is the monitoring of the agricultural soils. The operating principle of this sensor is based on the phase shift method which in essence represents the measurement of the soil permittivity. Analytical expressions for the calculation of optimal operating frequency and the absolute moisture content derived from effective permittivity are presented. The influence of the order and the number of fractal curves used to the sensor characteristics are analyzed. The proposed sensor operates at 1.2 GHz and provides phase shift in the range of 70.76° for the extreme cases of the soil moisture content (2 % and 20 %).**

Keywords - soil moisture; microstrip sensor; Hilbert fractal curve

I. INTRODUCTION

Measurement of soil water content is useful to achieve better crops, to maintain the eco-systems (parks, forests and overall vegetation), moreover it is helpful in every type of soil study. Most of physical and chemical properties of soil are determined by its humidity. The proper growth, vegetation process and maintenance of the plants depend on this factor, [1]. For example, on the one hand the decline of soil water content will result in a decrease of photosynthesis and cell expansion of the plant. On the other hand, the result of overflow irrigation is leaching of nutrients and poor utilization of natural rainfall because of high surface run off. Mentioned overflow irrigation provokes progress of plants diseases [2]. The usage of the optimal partial irrigation systems makes it possible to increase yield for 40 %. For these specified reasons, precise partial measurement of the soil water content is very important.

In the past, different methods for measuring soil moisture content were developed, that in general can be divided into direct and indirect methods.

The direct methods are characterized by taking a soil sample at a certain location and measuring its weight or volume before and after drying process. These methods are accurate, precise and relatively cheap, but also very slow, destructive and do not allow repetitions of measurements in the same location [3].

The disadvantages of direct methods paved a way for numerous indirect methods, which estimate soil moisture by a relationship with some other measurable variables, [4]. These methods differ in cost, accuracy, response time, installation, managing and durability. Indirect method that imposes due to its low price, good response time and possibility for large scale sensor integration, is a phase shift method, [5]. This method is based on phase shift measurement of the sinusoidal wave that propagates along transmission line. Phase shift is determined by the velocity and the frequency of the signal, as well as the physical properties of the transmission line.

Among different topologies of transmission lines, the microstrips topology represent optimal and the simplest solution. Microstrips are inevitable components of every printed circuit board, which leads to optimal production of this kind of transmission lines. Also, they are easily integrated with other components, whose task is to control this type of sensors. In the microstrip topology, the permittivity only changes with soil moisture.

One of fundamental advantages of the phase shift method is that all measurements are performed at only one frequency. When choosing the operating frequency, one should consider that insertion loss is greater on higher frequencies, while on lower frequencies the velocity of the signal also depends on conductance of the medium through which signal propagates. The upper limit of the operating frequency is determined for the sensor topology so that attenuation of the signal is not greater than 3 dB and phase shift does not have any nonlinear properties.

In this paper, novel soil moisture sensor based on the Hilbert fractal curve is proposed. The influence of the physical parameters to the sensor characteristics is investigated. In order to increase the sensitivity of the proposed sensor, the square section of the ground plane positioned under microstrip line is removed.

II. PHASE SHIFT METHOD

The influence of the soil moisture on signal propagation is reflected in effective permittivity of the microstrip, which depends on medium placed over miscrostrip, in this case soil, and dielectric substrate, from which microstrip sensor is made, Fig. 1.

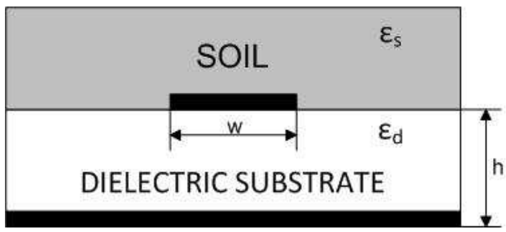


Figure 1. The microstrip sensor placed in the soil.

Effective permittivity of the microstrip presented in Fig. 1 can be defined as:

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

where ε_s is permittivity of soil, ε_d is permittivity of substrate, and h and w are the height and the width of the microstrip substrate, respectively , [6].

Absolute moisture content can be obtained from:

$$\sqrt{\varepsilon_s} = \sqrt{\varepsilon_{ds}} + \rho_{ds}\Psi(\sqrt{\varepsilon_w} - 1), \quad (2)$$

where ε_{ds} is permittivity dry soil, ρ_{ds} is density of dry soil, ε_w is permittivity of water and Ψ is absolute moisture. In practice the change of the relative permittivity is in the range between 2.5 for very dry soil (2 %) and 20 for high moisture content soil (20 %).

Sinusoidal signal $A\sin\omega t$ that propagates along the transmission line is considered in order to determine the impact of the physical parameters of the microstrip on phase shift. At the beginning of line, at the moment t_1, the phase of the signal is ωt_1. Analogous to that, at the end of the line, at the moment t_2, its phase is ωt_2. The phase shift that occurs during this propagation is:

$$\Delta\varphi = \omega(t_2 - t_1) = \omega t_d, \quad (3)$$

where t_d is time delay, and it represents the time needed for signal to propagate from the beginning to the end of transmission line. If the per length capactitance and per length inductance of the microstrip are C' and L', respectively, and if high frequency signal propagates down the line, the velocity of the signal can be defined as:

$$v = \frac{1}{\sqrt{L'C'}}. \quad (4)$$

For the case of straight microstrip line, which length is l_{sm}, the time delay can be obtained as:

$$t_d = \frac{l_{sm}}{v} = l_{sm}\sqrt{L'C'} = \sqrt{LC}, \quad (5)$$

and the phase shift is:

$$\Delta\varphi = \omega\sqrt{LC}, \quad (6)$$

where L is total inductance and C total capacitance of the microstrip. The simulation results for phase shift of the signal propagating down the microstrip as the function of operating frequency is showed in Fig. 2. The phase shifts for the different cases of relative permittivity (humidity) of the soil are represented. These results are obtained using *Microwave Office*. The thickness of the dielectric substrate is 0.508 mm, while its relative permittivity and loss tangent are equal to 2.17 and 0.0009, respectively. The width of the microstrip line is 1.6mm while the length is 6.7mm. The range of soil moisture that is analyzed in the simulation is between 2 % and 20 %.

As can be seen in Fig. 2, the only difference between the phase shift characteristics in the range of 0 – 2 GHz is their slope. The slope is affected by soil moisture via total capacitance C of the microstrip, which is linearly proportional to the ε_{eff}. In that way, it is possible to use phase shift to determine ε_{eff}, and then calculate absolute soil moisture Ψ with using equations (1) and (2).

In order to accomplish the best resolution of measurement, it is necessary to have the widest range of phase shift as possible, but not larger than 90º (to avoid ambiguity). The following derivations are done for the case of the straight microstrip line. The extreme cases of the soil moisture are considered, the dry soil (soil moisture under 2 %, relative permittivity is 2.5 and loss tangent is 0.06) and the wet soil (soil moisture around 20 %, relative permittivity is 20 and loss tangent is 0.15). If the phase shift in the case of the dry soil is

$$\Delta\varphi_1 = \omega\sqrt{L_1C_1}, \quad (7)$$

and in the case of the wet soil is:

$$\Delta\varphi_2 = \omega\sqrt{L_2C_2}, \quad (8)$$

then the range of phase shift can be defined as:

$$\Delta\Phi = \omega(\sqrt{L_1C_1} - \sqrt{L_2C_2}). \quad (9)$$

Total inductance L_1 and total capacitance C_1 refer to the dry soil case, analogous to that, L_2 and C_2 are total inductance and capacitance in the case of the wet soil, respectively. Since soil moisture has no effect on total inductance ($L_1 = L_2 = L$) the expression for the range of phase shift can be reduced to

$$\Delta\Phi = \omega\sqrt{L}(\sqrt{C_1} - \sqrt{C_2}). \quad (10)$$

As can be seen in (10), in order to gain wider range of the phase shift, measurements should be done at higher frequencies; also the total inductance of the sensor should be increased, as well as the difference between total capacitances for the extreme cases of the soil moisture.

Performing the measurement at higher frequencies has two fundamental disadvantages. First of all, the insertion loss at higher frequencies is greater, as the simulation results display in Fig. 4, and the phase shift characteristics show certain nonlinear effects, Fig. 2. At the frequency of 2 GHz the simulation results show that the range of phase shift is 20.67°, and insertion loss is 1.56 dB in the worst case.

III. SENSOR BASED ON HILBERT FRACTAL CURVE

The novel microstrip sensor based on Hilbert fractal curve is proposed in this paper. This space-filling property of fractal offers high potentials for miniaturization of microwave circuits, because, theoretically, the application of fractal curves allows the design of infinite-length lines on a finite substrate area. The realization of microstrip as Hilbert fractal curve increases the range of phase shift by increasing total inductance of the sensor which at the same time remains compact. In Fig. 4 the first six iteration of Hilbert fractal curve are presented. Compact sensor could be realized by meander line too, but as it is proved in [7] on the same area of realization Hilbert fractal curve has larger inductivity.

Proposed sensor consists of two parallel segments, where each segment comprises two Hilbert fractal curves of the fourth order connected in serial, Fig. 5. The Hilbert curve itself is realized with the line width and the spacing between the lines of 100µm. The segments are 6.7 mm long, 3.1 mm wide and the distance between two fractal lines is 1.4 mm. The results of simulations for the proposed sensor are shown in Fig. 6.

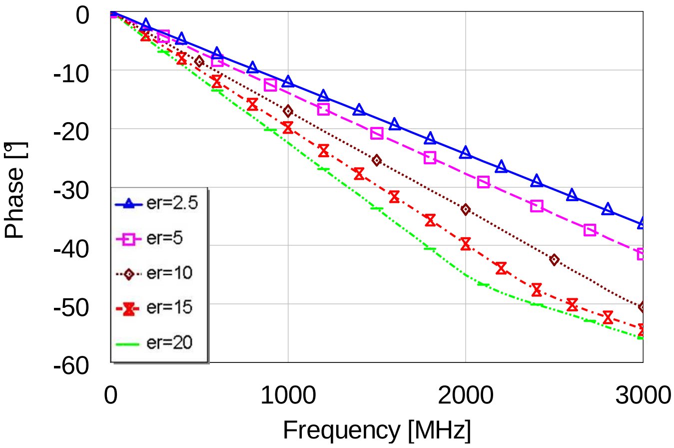


Figure 2. The phase shift as the function of operating frequency.

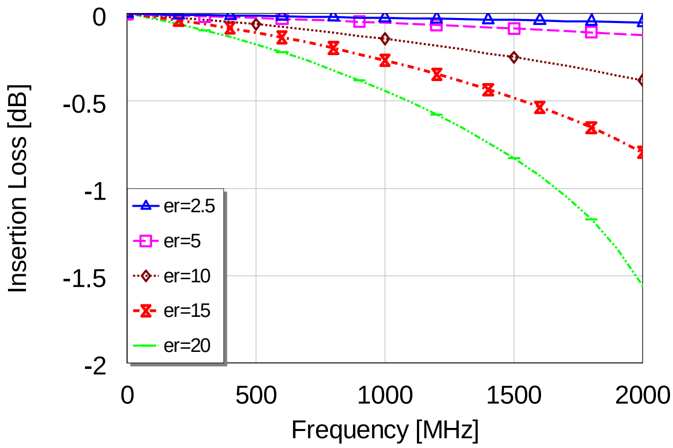


Figure 3. Insertion loss as the function of frequency.

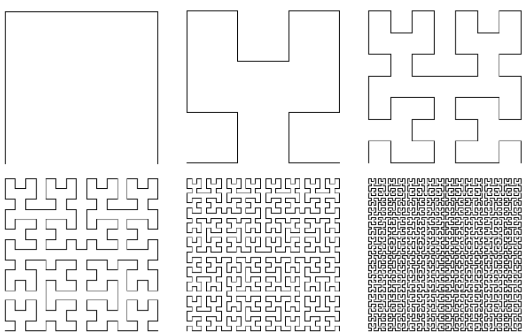


Figure 4. First six iteration of Hilbert fractal curve.

As can be seen the consequences of the line modification are greater insertion loss and size of the sensor. The results of these simulation show that the range of phase shift for this configuration at the frequency of 1.2 GHz is 66.64º, and insertion loss in the worst case is 2.98 dB. Compared to the straight microstrip from the section II, which has the same length, the range of phase shift is increased for more than three times. Although the insertion loss in this case is larger it is still within acceptable range of 3 dB. Stated results show that the usage of Hilbert fractal curve leads to more compact sensor characterized by higher sensitivity than already available soil moisture sensors based on the same method, [5].

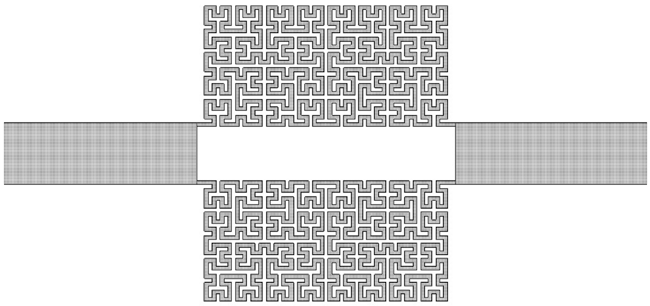


Figure 5. Soil moisture sensor based on Hilbert fractal curve.

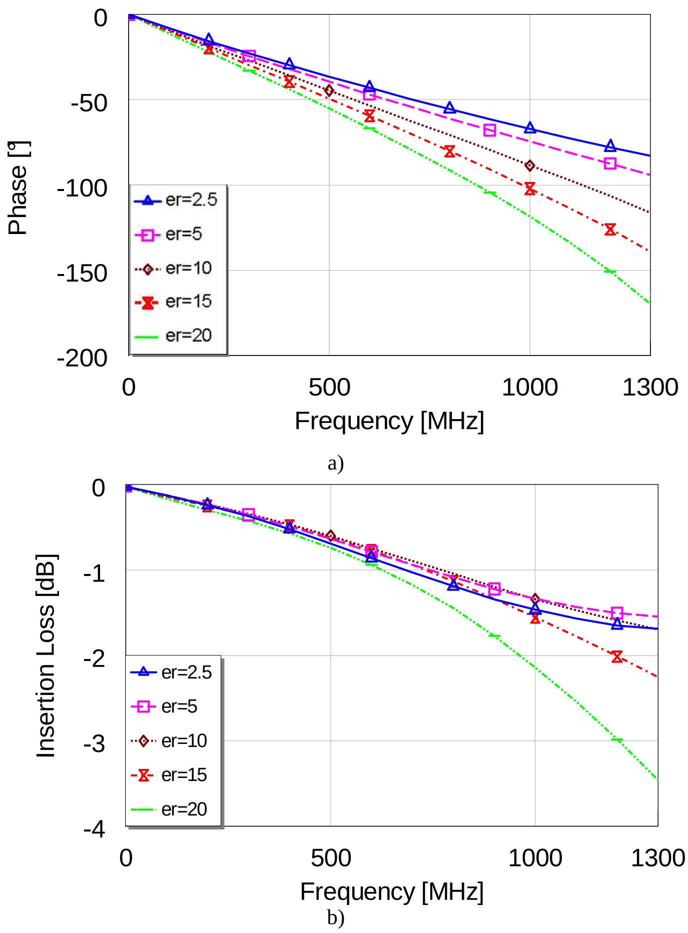


Figure 6. The simulation results of proposed sensor: a) the phase shift, b) the insertion loss.

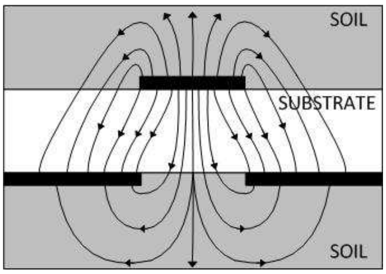
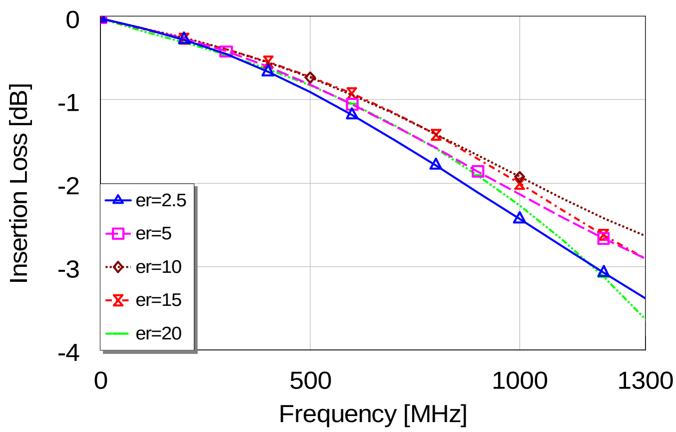
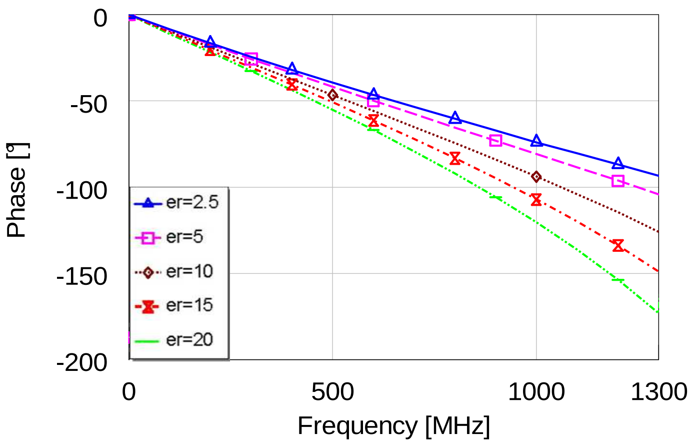


Figure 7. Electric field lines in the proposed sensor with uncovered ground plane.



a)



b)

Figure 8. The simulation results of proposed sensor with uncovered ground plane: a) the phase shift, b) the insertion loss.

The additional analyses that were done in order to investigated the influence of different topology to the range of phase shift. It can be noted that increasing the iteration of the Hilbert fractal curve also increase the range of phase shift, accordingly the insertion loss is greater, too. The same effect can be obtained using several fractal curves connected in series. When Hilbert fractal curves are connected in parallel the range of phase shift is approximately the same, but insertion losses are decreased. However, the proposed configuration of sensor provides the largest range of phase.

In order to increase the sensitivity of the proposed sensor, part of the ground plane that is positioned under Hilbert curve of the sensor was removed. In that way a certain passage for the lines of electric field is made, so they can pass through it in to the soil under the sensor and end up at the bottom side of ground plane, Fig. 7. In that way, soil moisture has larger effect on the sensor characteristics. The simulation results for the sensor with partially uncovered ground plane are presented in Fig. 8.

It can bee seen that the range of phase shift for the sensor with partially uncovered ground plane is 70.76º at the frequency of 1.2 GHz, and the insertion loss is 2.98 dB. Modification in ground plane improved the range of phase shift for more than 6 %, while insertion loss does not change.

IV. Conclusion

In this paper, microstrip sensors based on Hilbert fractal curve were proposed, that operate principle is based on phase shift method. The influence of the soil moisture on the proposed sensors was investigated. In order to increase the sensitivity of the proposed sensor, part of the ground plane that is positioned under the Hilbert curve was removed. The proposed sensor with partially uncovered ground plane operates on the frequency of 1.2 GHz with the range of phase shift of 70.76º. The use of Hilbert fractal curve in realization of the microstrip sensor increases its sensitivity with remaining compact dimensions. Good sensibility, small dimensions and compatibility with planar fabrication technology are making this sensor suitable for application in wireless sensor networks.

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