Design and Implementation of a self-calibrating, compact micro strip sensor for in-situ dielectric spectroscopy and data transmission

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Abstract—A compact, on-board, self-calibrating, micro strip sensor is presented. The sensor can make accurate multi-frequency measurements of complex permittivity in real time and transmit this information wirelessly by using the same sensor as a micro strip patch antenna. Such multi-frequency measurements in a multi-phase mixture like soil are used to estimate the concentration of individual constituents like bulk-soil, water, and various nutrients in soil. The sensor architecture comprises of a programmable phase locked loop (PLL) which sweeps through the frequency band of 3-40 MHz. The signal generated by the PLL is allowed to reflect from the micro strip patch which is surrounded by the dielectric medium under test (such as soil or food). The amplitude and phase of incident and reflected signals are captured and impedance due to the surrounding dielectric mixture is calculated. This impedance value is used to estimate the dielectric constant by mapping the input impedance of the micro strip sensor to different surrounding dielectric constant values. The sensor has an inbuilt self-calibrating mechanism which makes it useful for remote, underground and hand held applications.

I. INTRODUCTION

Microstrip antennas are widely used due to their compact size, low cost and ease of integration with the transceiver system. Such antennas have previously been used as underground sensors [9] in soil-moisture sensing applications. Our previous work on soil-sensing using modified quarter wavelength type sensor electrode [5], [6] has proven that multi-frequency impedance measurement of a soil mixture has the capability to provide information about the concentration of different ions like moisture, nitrates in soil. In [6] we presented a self-calibrating, multi-frequency dielectric sensor for combined moisture and soil ions sensing, while in [5] we showed how dielectric-mixing models can be reasoned to analyze the multi-frequency dielectric measurements to estimate the soil moisture and ion concentrations. We have also shown that the quarter wavelength monopole antenna can simultaneously be used as a sensor and transmitting antenna. This was achieved by separating the low-frequency sensing path from high frequency transmission path using a diplexer. Integration of such sensors with microstrip antenna instead of previously used quarter wavelength monopole can make the sensors more compact and more usable for in-situ operation.

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II. OVERVIEW: MULTI-FREQUENCY IMPEDANCE MEASUREMENT

Figure 1 describes the main idea behind multi-frequency impedance measurement. A signal $V_i$ is generated at the programmable signal source (PLL). The signal is reflected from the soil surface and a reflected signal $V_r$ is generated. Accurate measurements of amplitudes and phases of $V_r$ and $V_i$ can be used to determine the impedance presented by the soil $Z_L$ using the equation:

\[
\Gamma_L = \frac{V_r}{V_i} = \frac{Z_L - Z_0}{Z_L + Z_0}
\]

To make these measurements, incident and reflected signals, which are on the same transmission line, have to be separated. This can be done efficiently using a pair of directional couplers [11]. Two directional couplers are connected to the main line as shown in Figure 1. One coupler couples the incident signal, while the other couples the reflected signal to its output port. Since on-board couplers are not point objects, there always is a finite distance between point at which load is connected to the line and the point where signal coupling takes place. This means that the coupled signals at ports 3 and 4 are gain/phase...
A. Self-Calibration Mechanism using SP6T switch

As seen in previous section, for sensor calibration we need the measurements on a set of minimum 3 known impedances in order to account for the non-colocation of the load impedance and the coupler output ports. In theory, only 3 known impedances are needed for calibration but using more known impedances provides larger data set for calibration. Moreover, using multiple impedances improves accuracy of calibration constants over a large range of known impedances. In order to make the sensor a self-calibrating system, we have designed a self-calibrating mechanism using a Single-Pole-6-Throw (SP6T) switch. An SP6T switch has a 3 bit control signal which controls the connection of input RF port to one of the 6 output ports (see Figure 2). The control signal is programmed by the microprocessor at the beginning of each sensing event to cycle through all the six values. Once the control signal has swept through the values 000 (open-circuit), 001 (short-circuit) and 010, 011, 100 (known-loads), we calculate the calibration constants $a, b$ and $c$. For the measurement of unknown impedance, the control signal is changed to 110. Using the $\Gamma_m$ for this measurement and calculated $a, b, c$ values, we calculate $\Gamma_L$ which is then used to calculate load impedance $Z_L$.

The measurement of unknown load impedances to be $\infty$ (open-circuit), 0 (short-circuit) and $Z_0$ (matched load), with the corresponding load reflection coefficients $\Gamma_L$ being 1, -1 and 0 respectively. The equations in 3 unknowns can be solved to determine the calibration constants $a, b$ and $c$. For ease of calculation we can chose these three known load impedances be $\infty$ (open-circuit), 0 (short-circuit) and $Z_0$ (matched load), with the corresponding load reflection coefficients $\Gamma_L$ being 1, -1 and 0 respectively. The equations in 3 unknowns can be solved to determine the calibration constants $a, b$ and $c$.

Once we know the values $a, b$ and $c$, we can use these values and the measurement of $\Gamma_m$ to infer

$$\Gamma_L = \frac{b - \Gamma_m}{c \Gamma_m - a}, \quad (3)$$

when an unknown impedance is presented as the load. This value of $\Gamma_L$ can then be used to calculate the unknown load $Z_L$, by applying Equation 1.

### III. Sensor Architecture

Our sensor architecture consisting of microprocessor, transceiver, phase-lock-loop (PLL) for sinusoid generation, directional coupler, amplitude and phase detector, SP6T and SP2T switches, power amplifier, low-pass-filter and diplexer as shown in Figure 3.

Upon start, the microprocessor programs the $I^2C$ interface of the programmable PLL to generate a frequency $\omega$. The $\omega$ signal is the probing signal that is chosen in the range of 3-40 MHz. This probing signal is sent through the transmission line to the SP6T switch, which is programmed by microprocessor to select among a set of loads. The incident and reflected signals are captured using directional couplers and are passed on to the phase detector which calculates the amplitude and phase of each signal and passes this information to microprocessor for further processing and transmission via antenna. These values are received by the microprocessor through an in-built 12-bit ADC. In the calibration mode, these values are used...
to calculate calibration parameters. In the measurement mode, these calibration parameters are used to find out the reflection coefficient $\Gamma_L$ for an unknown load from its value measured at the decoupler. The $\Gamma_L$ value is then used to determine the unknown load impedance $Z_L$.

The design also integrates a wireless interface for which a transmission-path boost amplifier is included for enhanced transmission range. Also a diplexer allows the sensor electrodes to dual as antenna (the measurement frequency is 3-40 MHz while transmission frequency is 915 MHz).

IV. MICROWAVE PATCH SENSOR/ANTENNA

Microstrip antennas have been extensively studied in literature [2]. The width and length of microstrip antenna can be derived using the well known transmission line model. Width, $W$ is given by equation:

$$W = \frac{c}{2f_0 \sqrt{\frac{\varepsilon_r}{2} + 1}}$$  \hspace{1cm} (4)

where $f_0$ is the transmission frequency of 915 MHz and $\varepsilon_r$ is the relative permittivity. The length, $L$ of the patch is given by:

$$L = \frac{\lambda}{2} + 2\Delta L.$$  \hspace{1cm} (5)

$\Delta L$ is the length correction factor given by:

$$\Delta L = 0.412h \frac{\varepsilon_{eff}}{\varepsilon_{eff} - 0.268} \frac{W}{h} + 0.8$$  \hspace{1cm} (6)

where $h$ is the height of the dielectric substrate and $\varepsilon_{eff}$ is the effective permittivity due to multiple media (substrate dielectric and air) involved and is given by:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[1 + 12 \frac{h}{W}\right]^{-\frac{1}{2}}.$$  \hspace{1cm} (7)

For the transmission frequency of 915 MHz, the length and width were calculated to be 88 mm and 110 mm respectively. The ground plane size was decided based on the analysis presented in [4] ($(W + 6h)X(L + 6h)$). Coaxial feed was used and lowest return loss feedpoint was determined using 3D simulations in HFSS. Figure 4 shown the patch antenna size at transmission frequency.

Fig. 4. Patch Dimensions for transmission frequency of 915 MHz.

IV. MICROSTRIP PATCH SENSOR/ANTENNA

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V. RESULTS

A. Comparison with Network Analyzer

The soil impedance was measured by the on-board sensor that we designed and for comparison of its accuracy also by a Network Analyzer (HP8714ES). This micro-strip patch sensor that is buried in soil, acts as the unknown load as discussed in Section II. The data recorded by the on-board circuit is transmitted to a receiver which first calculates the a; b and c calibration constants and then calculates the soil impedance. The real and imaginary parts of impedance measured using the on-board sensor showed a good match with those measured using the network analyzer in the range 3-40 MHz (see Figures 5 and 6).
Fig. 7. Conductance variation with varying sodium nitrate solution concentration.

Fig. 8. Susceptance variation with varying sodium nitrate solution concentration.

B. Admittance variation with varying moisture and nitrate conditions

Figures 7 and 8 show the variation in patch admittance with changing values of sodium nitrate solution. A 100 mM sodium nitrate solution was added in steps of 4% by volume to the soil that had the patch sensor buried into it. It was observed that both conductance and susceptance of the patch increased as the concentration of sodium nitrate was increased in soil. This proves that the accurate measurement of soil impedance (hence admittance) using microstrip patch at multiple frequency has the ability to detect change in ionic concentration in soil.

VI. CONCLUSION AND FURTHER WORK

An on-board self-calibrating multi-frequency sensor was designed, fabricated and validated using a network analyzer. The sensor was shown to accurately measure the soil impedance at multiple frequencies. The impedances measured by the sensor can be used to estimate the contents of individual ions in soil. This work has previously been done in our group [5], [7]. It was shown in these papers that if the real and imaginary permittivity is calculated using the impedance values, then the dielectric mixing models [3], [8] can be applied at multiple frequencies to form equations in unknown concentrations of individual ions. These equations can then be solved to derive the individual ionic concentration. Although a closed-form expression that relates microstrip patch impedance with surrounding permittivity does not exist, many models have been developed in literature that relate the impedance of patch to surrounding permittivity [1], [10]. Such models can be applied to data obtained in this work to determine the permittivity of the surrounding soil and permittivity values at multiple frequencies can then be used to estimate individual ionic concentration.

REFERENCES