Wireless Power Transfer Through Soil Over a Range of Moisture Levels for *In-Situ* Soil Health Monitoring

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***Abstract*—This paper presents the design and measurement results of wireless power transfer through soil over a range of soil moisture levels for future low-cost, wireless, battery-less, and *in-situ* soil health monitoring technologies. A pair of packaged 6 cm-diameter coils can wirelessly transfer 0.56 mW from an external RF power source of 37 mW through a soil depth of 15 cm over a typical moisture level ranging from low 30% to 40%. An optimal frequency of 1.4 MHz and 1 MHz was chosen for an efficient operation in loamy soil and sandy soil, respectively. The demonstrated power transfer is sufficient to energize underground soil health monitoring devices. In addition, a pair of packaged 12 cm-diameter coils, taking the loss contributed by the surrounding soil into design consideration, can achieve a 130 µW power delivery with an efficiency of approximately 8% over a 30 cm air gap. It is expected that a similar performance can be achieved through a 30 cm soil depth.**

Keywords—Power transfer through soil, wireless soil sensing, wireless power transfer, inductively-coupled power transfer, coils characterization in soil, soil loss.

I. INTRODUCTION

The world's population is expected to surpass 9 billion by 2050, thus calling for an increased demand for food production, which in turn can adversely degrade soil health and threaten food security [1]. Sustaining high levels of food production depends on healthy soil. Therefore, there is a strong and urgent need to develop low-cost, long-life, wireless, and *in-situ* sensing technologies for monitoring soil health to ensure future sustainable agriculture. In this work, we propose to develop a wireless underground *in-situ* soil sensing network, as depicted in Fig.1, where autonomous vehicles, both ground and aerial, can potentially power or recharge an underground sensor module or network in a wireless manner as well as communicate with the sensor for data telemetry [2, 3]. Sensor data can include soil moisture, salinity, temperature, pH, etc., which are indicative of soil health condition. Autonomous vehicles can transfer radio-frequency (RF) power to the sensor from a power source incorporated as a part of the vehicles as shown in Fig. 1(a) and Fig. 1(b). To access farmland covered by tall crops, an unmanned aerial vehicle (UAV) can communicate and transfer power to an above-ground telemetry post, which is further connected to an underground sensor module as illustrated in Fig. 1(c).

Inductively-coupled RF power transfer techniques have been widely employed for biomedical, industrial, and consumer electronics applications [4-16]. Each application has its own inherent trade-offs based on system operating conditions. Wireless power transfer through soil has not been demonstrated to enable practical soil sensing applications. In this research, we investigate the feasibility and limitation of the inductively-coupled approach for wireless power transfer through soil over a range of moisture levels to enable the proposed wireless *in-situ* soil sensing capability. Previous research reveals that the efficiency of inductively-coupled wireless power transfer is directly proportional to the quality factor (Q) of the coils employed in the system [15-17]. Therefore, it is highly critical to achieve high-Q for coils buried in soil over a typical moisture range. The quality factor is defined as the ratio of the coil's inductive impedance over its loss in the form of serial resistance, which is correlated with the moisture level of surrounding soil.

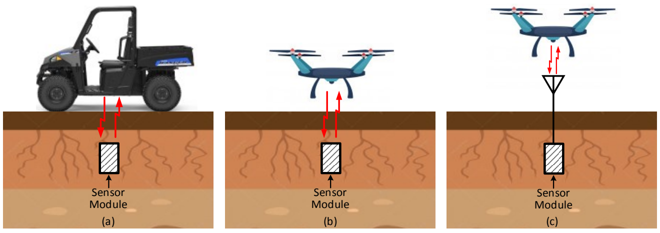


Fig. 1. Wireless underground *in-situ* soil sensing network architecture.

II. RF COILS DESIGN, PACKAGING AND CHARACTERIZATION IN SOIL

Prototype coils are implemented with a diameter of 6 cm and 12 cm, each having 9 turns, to investigate the feasibility of wireless power transfer through a soil depth between 15 cm and 30 cm [18], which represents a typical cultivation layer thickness. Power transfer to a deeper location, for example at a depth of 1 meter, may be required for more demanding applications. Further, the prototype coils are constructed by using litz wire, exhibiting an outer diameter of 1.7 mm, made of 660 strands of 40 µm Cu wires. Litz wire is chosen due to its high conductivity, critical for achieving high quality factor. Previous research indicates that an air gap on the order of 1 cm and 2.5 cm between the soil and the 6 cm-diameter coil and the 12 cm-diameter coil, respectively, is necessary for minimizing loss contributed by the surrounding soil when the coils are buried in the soil [18]. Fig. 2 shows a photo of a packaged 6 cm-diameter coil with a 1 cm lateral and vertical clearance for an illustration purpose. The coil achieves an inductance value of approximately 5 µH with a self-resonant frequency above 20 MHz. It should be noted that a 3D-printed package (with a similar dimension) by using polylactic acid (PLA) plastic was built to achieve an improved package robustness for the in-soil test. The packaged coil was then buried in processed Parleys loam, collected in northern Utah, for quality factor characterization using an impedance analyzer over a controlled soil moisture level.

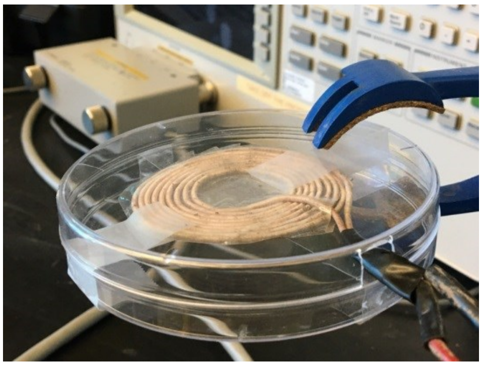
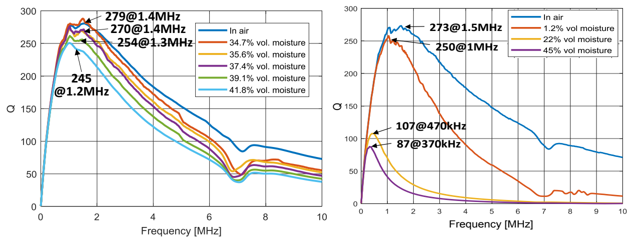


Fig. 2. Packaged 6 cm-diameter coil.

Fig. 3(a) presents the measurement result over a moisture range from approximately 35% to 42%. The measurement data indicates that the buried coil can achieve a high-Q value ranging from 245 at 1.2 MHz under 41.8% moisture level to 279 at 1.4 MHz under 34.7% moisture level, which is close to the in-air performance. The peak Q occurs within a narrow frequency range between 1.2 MHz and 1.4 MHz, which is highly desirable for designing a wireless power transfer system that can operate at a pre-defined fixed frequency over a range of typical moisture level, thus greatly simplifying the system design and operation while maintaining high performance. As a comparison, Fig. 3(b) shows the measurement result of the same coil buried in loamy soil without having a proper air gap between the coil and surrounding soil. The measurement data reveals that the coil suffers from a significant Q degradation as the soil moisture level increases. Furthermore, the frequency at which peak Q occurs varies over a wide range, rendering a system design that can be overly complex or impractical.



(a) (b)

Fig. 3. Measured Q vs. frequency of a 6 cm-diameter coil buried in loamy soil over a range of moisture levels: (a) packaged condition and (b) unpackaged condition.

Subsequently, a similar test was performed in Syracuse loamy fine sand collected in northern Utah, referred to as sandy soil in this work. Fig. 4 presents the measurement result demonstrating a high-Q performance at 1 MHz over a moisture range from 21% to 36%. It should be noted that the frequency at which the peak Q occurs is slightly lower than that obtained in loamy soil, which is likely caused by the difference in dielectric constant attributed to variation in texture, bulk density, and electrical conductivity between the two types of soil [19, 20].

A 12 cm-diameter coil, exhibiting an inductance value of approximately 16 µH with a self-resonant frequency over 10 MHz, was packaged in a 3D-printed case accommodating a 3 cm lateral as well as vertical clearance between the coil and the case. The packaged coil was then buried in both loamy and sandy soil for its quality factor characterization under a controlled moisture level. Fig. 5 presents the measurement results demonstrating that the packaged coil can achieve a high-Q performance over a range of moisture levels in both types of soil. Similar to the 6 cm-diameter coil, the frequency at which the peak Q occurs in sandy soil is slightly lower than that obtained in loamy soil.

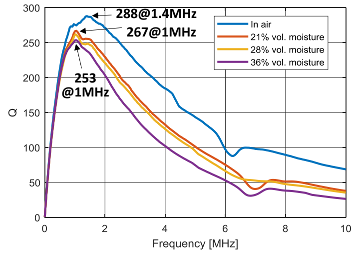
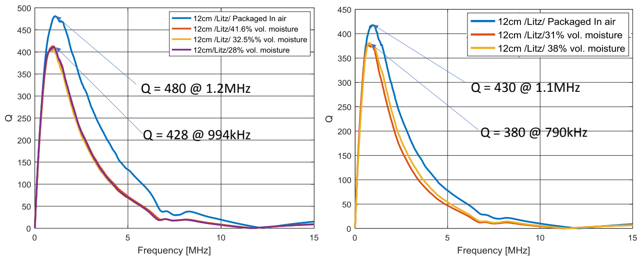


Fig. 4. Measured Q vs. frequency of a packaged 6 cm-diameter coil buried in sandy soil over a range of moisture levels.



(a) (b)

Fig. 5. Measured Q vs. frequency of a packaged 12 cm-diameter coil over a range of soil moisture levels: (a) buried in loamy soil and (b) buried in sandy soil.

III. Wireless Power Transfer Through Soil

Fig. 6 presents an inductively-coupled wireless power transfer system design diagram, where an input RF power is coupled to a secondary coil, L_2, from a primary coil, L_1, tuned to the same frequency through the mutual inductance. The received RF power exhibits an AC voltage swing at V_{out} across a load resistor, R_{load}. The AC voltage swing can be further rectified and filtered to produce a DC voltage to energize the soil sensing system. It should be noted that the secondary coil represents the coil buried under the ground, whereas the primary coil is above the ground. System design guidelines in terms of voltage gain, power transfer efficiency, and optimal load can be found in [17].

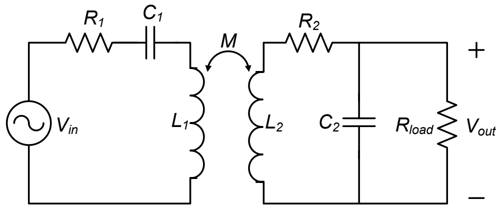


Fig. 6. Inductively-coupled wireless power transfer system.

In addition to the coils' quality factor, the coil-to-coil coupling factor as a function of the coils' geometry and distance between the two coils is another critical parameter in system design, components selection, and performance estimation. Fig. 7 shows a photo of an experimental setup for characterizing the coupling factor between two co-axially aligned 6 cm-diameter coils with an adjustable vertical distance in between. Characterization results show that a coupling factor of 2.5×10^{-3} and 2×10^{-4} can be achieved for the coils with a 15 cm and 30 cm distance, respectively. Further, a pair of 12 cm-diameter coils can achieve a coupling factor of 3×10^{-3} with a distance of 30 cm. It should be noted that the apparatus holding the coil is made of plastic to avoid any undesirable interference.

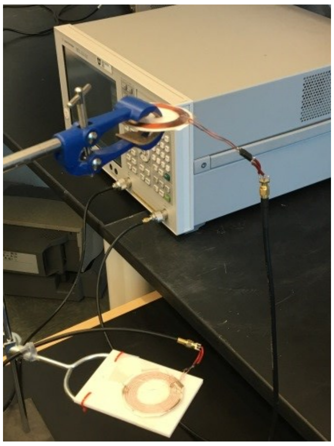
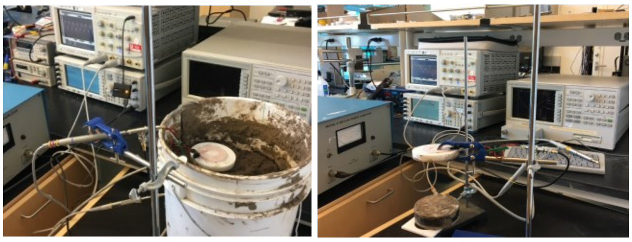


Fig. 7. Experimental setup for characterizing coupling factor between coils.

Based on the characterized coils' Q value and coupling factor, a wireless power transfer system is designed to demonstrate power transfer between a pair of packaged 6 cm-diameter coils with a 15 cm-deep loamy soil in between. The system is designed to operate at approximately 1.4 MHz since the Q of the packaged coil peaks around that frequency when buried in loam as shown in Fig. 3(a). An optimal R_{load} of 7.8 kΩ is determined and used for the system design as a matched load. Further, high-Q capacitors are employed for implementing the LC tank circuits for minimizing loss. Computer simulation reveals an achievable voltage gain of approximately 32 while experimental results indicate a measured gain of 25 due to additional loss incurred in the system. Fig. 8 (a) shows the experimental setup with one packaged coil buried under the loamy soil acting as a power receiving coil while another coil is positioned above the soil serving as a power transmitting coil with a 15 cm distance in between. Fig. 8(b) shows a setup for wireless power transfer in air achieving a nearly identical performance as through the soil. Fig. 9 presents the measured voltage waveforms at both input and output of the system, demonstrating that an output voltage signal with $6V_{pp}$ (corresponding to 0.56 mW developed into the load) can be achieved under an input driving voltage with a peak-to-peak amplitude of 233 mV, corresponding to a voltage gain of 25 and an AC power transfer efficiency of approximately 1.5%. This level of



(a) (b)

Fig. 8. Experimental setup for wireless power transfer: (a) through 15 cm loamy soil and (b) across 15 cm air.

performance can be achieved over a range of soil moisture levels between 34% and 40%. The $6V_{pp}$ output signal is chosen for the prototype design for ultimately producing a DC voltage close to 3V, which can be used to energize a wireless *in-situ* soil health monitoring system. A similar test was conducted in sandy soil with the system tuned to 1 MHz, where the Q of the packaged coil is maximized in sandy soil, as shown in Fig. 3(b). The measurement data reveals a voltage gain of 24 with an AC power transfer efficiency of approximately 1.5% achieved over a moisture range between low 30% and high 30%. Further, coils lateral misalignment between 1-3 cm results in a gain reduction by about 15%.

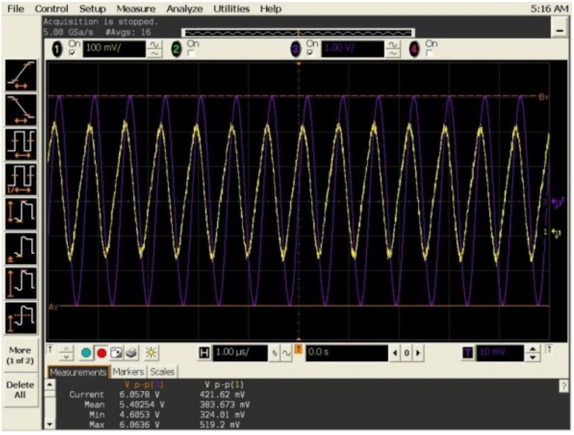


Fig. 9. Measured input and output voltage waveform for a pair of 6 cm-diameter coils with 15 cm loamy soil in between.

Another system demonstration using a pair of packaged 12 cm-diameter coils separated by a distance of 30 cm in air was performed. The prototype system was designed to operate at approximately 1 MHz and achieved a voltage gain of 81, corresponding to a power of 130 µW delivered to an optimal load with an AC power transfer efficiency of approximately 8%. It is expected that a similar performance can be achieved in soil.

IV. CONCLUSION

A pair of packaged 6 cm-diameter coils can achieve a power transfer of 0.56 mW from an external RF power source of 37 mW through a soil depth of 15 cm over a typical moisture level ranging from low 30% to 40%. An optimal frequency of 1.4 MHz and 1 MHz was determined for an efficient operation in loamy soil and sandy soil, respectively. A properly encapsulated coil, accommodating certain clearance from the coil to the surrounding soil, is critical to ensure a coil high-Q performance as well as a small frequency range during which a maximum quality factor occurs when the coil is buried in soil over a typical moisture range. Therefore, a reliable wireless power transfer system through soil can be developed and demonstrated by operating at a pre-defined frequency. The demonstrated power transfer is sufficient to energize underground soil health monitoring devices as well as to provide a design guideline in terms of the power dissipation requirement for *in-situ* soil sensors. Further, based on in-air characterization results it is expected that a pair of packaged 12 cm-diameter coils can achieve a 130 µW power delivery with an efficiency of approximately 8% over a 30 cm depth of soil.

ACKNOWLEDGMENT

The authors would like to acknowledge the research support from the National Science Foundation for this work.

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