Biodegradable On-plant Resonator for Backscatter Communication Based Wireless Growth Monitoring

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***Abstract*— Early growth monitoring plays a crucial role in assessing a plant's health trajectory. In this paper, a biodegradable on-plant passive wireless sensor that can monitor the plant sapling's growth is proposed. The sensor consists of a split-ring resonator and a dielectric load. As the plant grows, the dielectric load ascends, which changes the resonant behavior of the passive sensor. Importantly, the sensor is engineered to mitigate any variations in the electrical properties of the plant that could potentially impact its performance. The proposed sensor can monitor the plant growth up to 4.0 mm with a resonance shift from 3.221 GHz to 3.463 GHz. At 0.5 mm intervals, the average resonance shift is observed to be 30 MHz.**

***Keywords*— biodegradable sensors, passive sensing, plant monitoring.**

I. Introduction

Food production can be improved by the utilization of greenhouses since they provide a more controlled environment which can be optimized for plant health and abundance. Smart greenhouses are becoming more common, which establishes a feedback loop for the greenhouses for further optimization. The number and diversity of sensors used are increasing as the technology matures [1]. Critical parameters such as humidity [2] and temperature [3] of the environment or the water content [4] and elongation of the plant [5] are already being monitored using these sensors.

More recently, scientists have been pushing the technology further by focusing on creating wireless sensors by minimizing the size and energy consumption. One technology that stands out is back-scatter based sensing where the sensor located on the plant is electromagnetically passive and the wireless link is formed by a reader located off the plant. The principle is based on tracking the resonant behaviour of the sensor on the plant as the parameter to be monitored changes. Examples include leaf wetness detection [6], [4], and ripeness monitoring [7]. Although promising, the sustainability aspect of these passive sensors is understudied. In [8], a biodegradable passive sensor has been proposed where the authors monitored subsoil volumetric water. Here, we share the motivation of this work and aim to create a biodegradable sensor. However, we would like to achieve early growth monitoring with the final goal of health estimation.

A biodegradable on-plant sensor is proposed for the growth estimation of pepper saplings. The resonant frequency of the sensor changes with the elongation of the trunk, which is then wirelessly monitored using an off-plant reader. The on-plant sensor is designed such that it is not affected by changes in the average permittivity and the radius of the trunk.

The paper first presents the analysis on the variation of permittivity along pepper saplings in Section II. Section III then proposes the sensor design which mitigates the variation problem. Finally, the paper concludes in Section IV.

II. Permittivity Estimation

The sensors typically placed on the leaves or trunk of the plant are utilized to monitor aspects such as water content and plant elongation. In the case of on-plant wireless sensors, the primary parameter that influences sensor design is the average permittivity of the environment. That's why a measurement setup was designed to estimate the permittivity of the saplings' and the measurements are taken on four different types of saplings, with five samples from each of the sapling types. The sapling samples are illustrated in Fig. 1 as an example. The measurement setup, including a slot antenna and a 3D-printed case, is prepared to estimate the permittivity of the trunk. The slot antenna has dimensions of 25 mm $\times$ 13 mm $\times$ 1.3 mm to ensure compatibility with the size of the trunks and take measurements, while the plant is alive, without damaging the plant. The design of the 3D-printed case includes a cavity to stabilize the positioning of the trunk and the contact between the antenna and the plant. The position of the cavity for placing the trunk on the antenna is chosen to maximize the effect of the permittivity change on the resonance frequency of the antenna. The measurement setup can be seen in Fig. 3.

Fig. 1. Pepper saplings.

The measurements were repeated four times for each plant, and the results are depicted in Fig. 2. As expected, the resonance of the slot antenna without the plant on it

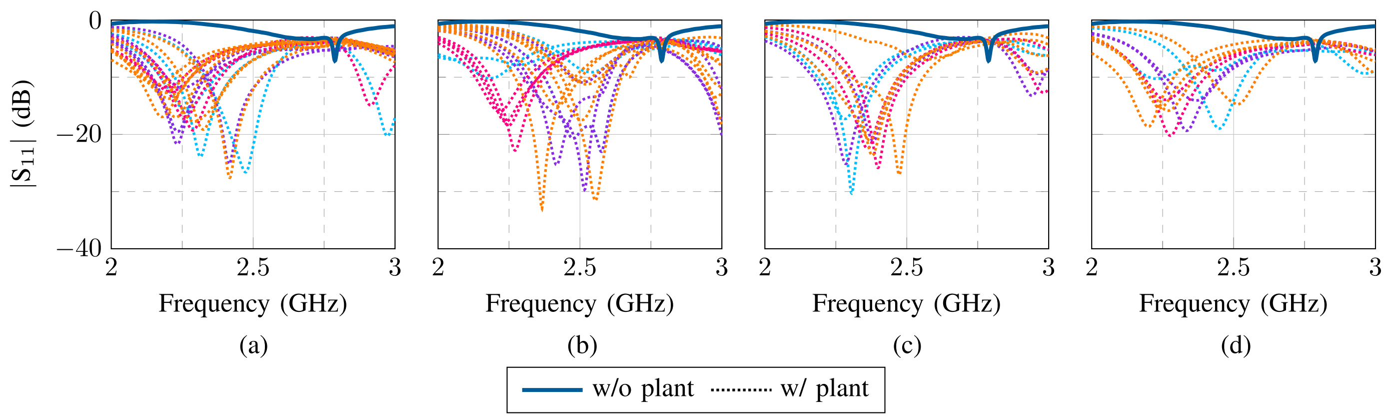


Fig. 2. The effects of the different pepper saplings on the slot antenna's reflection coefficient for four different types of pepper saplings, with five samples per each type. (a) Capsicum annuum 'Bell', (b) Capsicum annuum 'Capia', (c) Capsicum annuum 'Charleston', (d) Capsicum annuum 'Demre'.

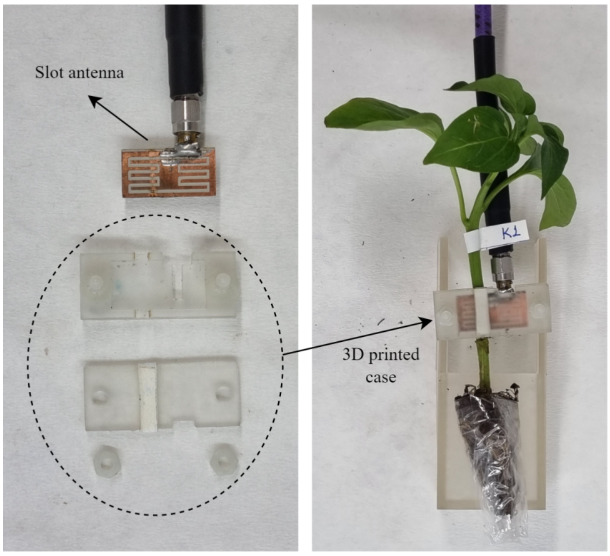


Fig. 3. The measurement setup for the permittivity estimation of pepper saplings.

occurs at a higher frequency, approximately around 2.8 GHz. When the trunk's permittivity loads the antenna, the resonance shifts to lower frequencies. However, the shift in resonance is inconsistent between the different samples. Although the connection between the antenna and the trunks is stabilized as much as possible with the 3D-printed case, possible air gap between the antenna and the trunk may affect the measurement accuracy. Additionally, the radius of the saplings' trunks ranges from 1.2 to 1.8 mm, directly impacting the average permittivity that is seen by the slot antenna. The permittivity values may also vary from one plant to another due to the age of the sapling and the water content of the trunk. These effects will also apply to the on-plant wireless sensor operation. Consequently, the sensor is designed so that the variations in the permittivity of the trunk do not affect the sensor's operation, which is detailed in Section III.

III. Resonator Design

The on-plant sensor consists of a split-ring resonator (SRR) with an adjustable gap capacitance that is controlled by a movable dielectric load. The overall system is depicted in Fig. 4 (a). In order to mitigate the effect of the aforementioned variations in the permittivity of the plant, the SRR is strategically positioned away from direct contact with the sapling. Rather, it remains stationary, and securely fixed to the soil via a biodegradable mechanical support. The dielectric load placed into the gap of the SRR is attached to the sapling. As the plant grows, the dielectric load ascends with the sapling and the effective permittivity of the SRR gap changes, which results in a shift in the resonant frequency of the SRR. This operating principle is shown in Fig. 4 (b). Note that the substrate of the SRR and dielectric load are biodegradable and zinc is utilized as the metal, which ensures the sensor's complete biodegradability. After use, the sensor degrades entirely.

The geometry of the sensor is shown in Fig. 5. Note that the depiction of the mechanical support and the connection between the dielectric load and the plant are excluded for clarity. In order to increase the gap capacitance, parallel strips are introduced between the gap edges. The relative permittivity of the biodegradable substrate is chosen as 3. As the plant grows and the dielectric load ascends, the effective permittivity of the gap decreases. Initially, it closely matches the relative permittivity of the biodegradable substrate. However, as the dielectric load ascends, the presence of air in the gap increases, leading to a reduction in effective permittivity and consequently, an increase in the resonance of the SRR. In order to mitigate the effects of dielectric load movements along the normal vector to the SRR, its dimensions are deliberately increased. This ensures that even if movement occurs in this direction, the effective permittivity of the gap remains relatively stable. The overall dimensions of the resonator are adjusted so that its resonant frequency is in the ultra-wideband frequency range.

In the future, the fabrication process of the sensor will involve the use of two types of custom-made biodegradable

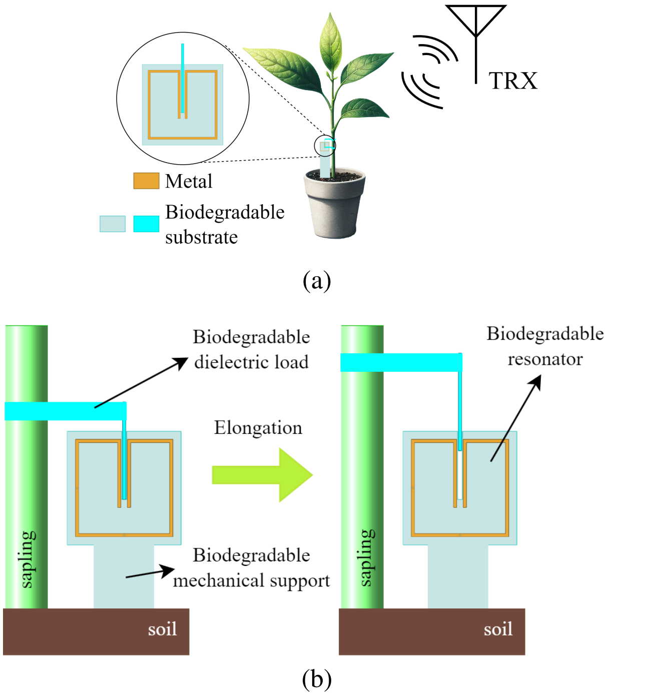


Fig. 4. (a) The depiction of the overall system and (b) the operating principle of the proposed system.

substrates, both composed of polylactic acid (PLA), and utilizing various techniques. PLA has been chosen as the substrate material due to its ability to adjust its mechanical properties. The substrate for the biodegradable resonator, intended to be a thin, rigid film, will be prepared using an encapsulation technique that fully embeds the conductive zinc resonator within two rigid PLA sheets through a spin coating technique. The film is envisaged to have a thickness of 0.3 mm. The movable biodegradable dielectric load as well as the biodegradable mechanical support are to be produced using a drop casting method to obtain high stiffness.

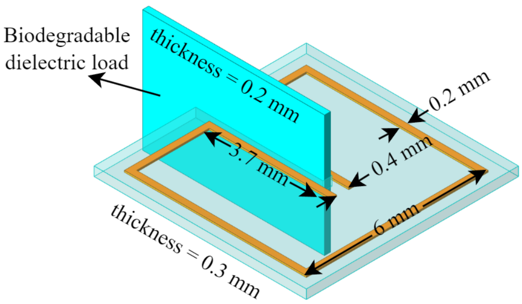


Fig. 5. The geometry of the resonator. The biodegradable mechanical support and the connection between the dielectric load and the sapling is not shown due to visulization purposes.

To characterize the resonance behavior of the sensor as the plant grows, it is simulated within a parallel plate waveguide. As the SRR is not directly positioned on the plant, its resonance is minimally influenced by the plant's presence. Consequently, the simulation model is simplified by omitting the soil, mechanical support, and the plant itself. Only the SRR and the dielectric load are included in the simulation, as depicted in Fig. 6.

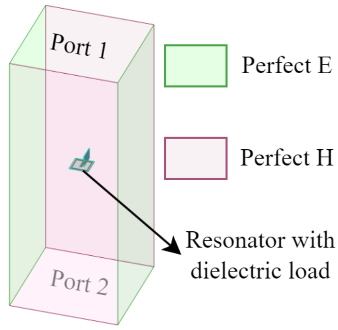
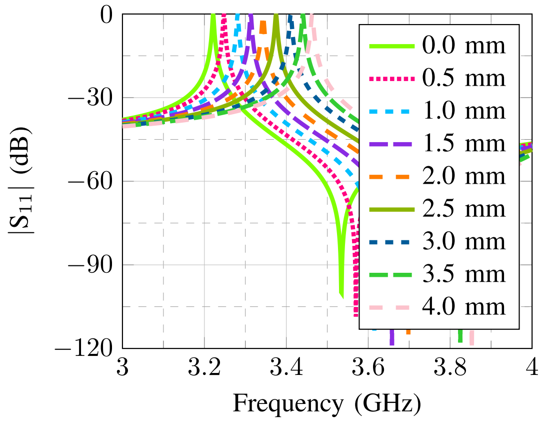


Fig. 6. The simplified EM simulation model.

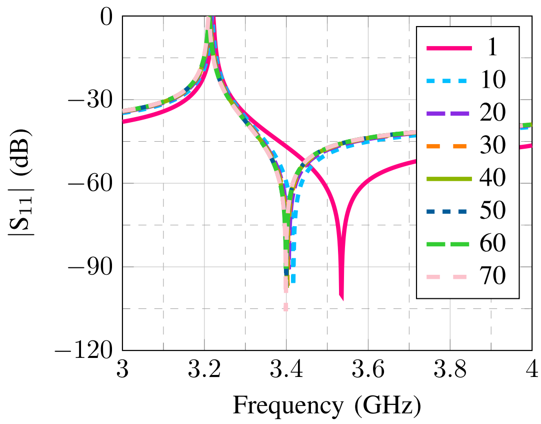
The simulation results depicted in Fig. 7 (a) show the frequency variations as the dielectric load is displaced in increments of 0.5 mm, ranging from 0.0 mm to 4.0 mm. The resonant frequency of the SRR shifts from 3.221 GHz to 3.463 GHz, with a mean frequency change of 30 MHz between consecutive steps. Notably, the minimum shift is observed when the dielectric load exits the gap, moving from 3.5 mm to 4.0 mm, resulting in a resonance change of 23 MHz. Conversely, the maximum resonant frequency shift occurs during the transition from 2.5 mm to 3.0 mm, with a shift of 36 MHz. Additionally, to assess the influence of the plant's presence, simulations are conducted for the initial case, where the elongation is 0.0 mm. The plant's sapling is modelled as a cylinder with a radius of 1.3 mm, positioned at a distance of 1.2 mm from the sensor. The relative permittivity of the sapling is varied from 10 to 70 in increments of 10, as illustrated in Fig. 7 (b). Remarkably, the presence of the plant has a negligible effect on the resonant frequency of the SRR, with a discrepancy of only 10 MHz observed between the cases of relative permittivity at 1 and 70.

IV. Conclusion and Future Work

In this study, we present a biodegradable on-plant sensor designed for monitoring the growth of plant saplings. The sensor utilizes a split-ring resonator with an adjustable gap capacitance, controlled by a dielectric load. Initially, we attempted to estimate the permittivity values for various pepper saplings using a slot antenna. However, significant variations in the slot antenna's resonance across different pepper saplings prompted us to design a sensor that is unaffected by the presence of plants. The resonator remains stationary and fixed in the soil, while the dielectric load ascends with the plant's growth. Consequently, the effective permittivity of the gap capacitance decreases, leading to an increase in the resonance of the SRR. Validation of the sensor's operation is conducted through EM simulations, which indicate a mean resonance shift of 30 MHz with each 0.5mm increment in elongation, ranging from 3.221 GHz to 3.463 GHz, corresponding to a 4.0 mm



(a)



(b)

Fig. 7. (a) The simplified waveguide simulation result for different elongation lengths and (b) the effect of the relative permittivity of the plant on the resonant frequency of the resonator for 0.0 mm elongation.

elongation. Notably, simulations demonstrate that the presence of the plant has a negligible effect on the sensor's performance.

The future work will focus on validating the sensor's operation with a transmitter/receiver antenna pair through EM simulations. Subsequently, the sensor and antennas will be prototyped, and simulation results will be validated through measurements. It's worth noting that the resonance of the sensor can be influenced by the changes in the permittivity of the surrounding air due to variations in humidity and temperature. To address this potential issue, a differential technique will be employed. One sensor will remain completely stationary, with its dielectric load remaining fixed, while the other sensor will operate as described in this paper. This approach aims to mitigate changes in the electrical properties of the air, ensuring the sensor's reliability and accuracy.

Acknowledgment

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