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Enhancing High-Frequency RFID Sensing Through PEDOT-Enabled Technologies

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Abstract—In this study we investigate the integration of Poly(3,4)-ethylenedioxythiophene (PEDOT), a well-known conductive polymer, into high-frequency RFID tags operating at 13.56 MHz to enable real-time sensing applications. By modeling PEDOT as a material with adjustable conductivity, we compare several deposition approaches (including complete coating versus selective deposition using both linear and circular patterns) to examine how the polymer’s molecular ordering and deposition methodology affect sensor performance. Our results demonstrate that the PEDOT-enhanced RFID sensor is not only cost-effective and scalable but also seamlessly compatible with existing RFID infrastructures. Comprehensive experimental evaluations, coupled with robust numerical simulations using CST Microwave Studio, confirm that the PEDOT layer can reliably modulate the tag frequency behaviour in response to environmental stimuli. This work lays the groundwork for innovative applications in logistics, healthcare, IoT systems, and environmental monitoring, offering a new generation of high-sensitivity, passive sensors for advanced tracking and temperature integrity control.

Index Terms—RFID tag, HF frequency band, organic semiconductor-based sensor

I. INTRODUCTION

THE modern landscape of wireless sensing demands compact, efficient, and low-cost chemical sensors for critical applications in environmental monitoring, public health, and industrial safety [1]. Real-time detection of environmental and chemical changes is essential in today’s data-driven society. RFID-based sensing platforms, which operate passively and economically, are uniquely positioned to address these challenges [2]. RFID systems use electromagnetic fields to wirelessly transmit data between a reader and a tag [3]. The tag reflects and modulates the signal from the reader to communicate its ID or sensor data stored in a microchip, which in addition handles signal modulation, allowing interaction with the reader. As a promising alternative, chipless RFIDs can be used to reduce cost, simplify fabrication, and enable sensing by encoding information in the tag geometry or materials, eliminating the need for a silicon chip [4]. However, conventional RFID sensors frequently suffer from limitations, including low selectivity, dependency on expensive ancillary

instrumentation, and complex signal processing requirements that restrict their broader utility [5, 6].

Recent advancements have sought to overcome these obstacles by integrating advanced materials such as flexible polymers and nanocomposites into sensor designs. In particular, the incorporation of organic semiconductors into RFID tags has emerged as a promising route to enhance sensor functionality [7]. These materials, with their tunable electrical properties and inherent mechanical flexibility, offer the prospect of significantly increasing the sensitivity and robustness of RFID sensors. Two main strategies have been pursued: one is the direct deposition of the organic semiconductor on the metallic antenna, constituting a straightforward, one-step process [8]; the other is a more intricate “disrupted-bridge” design, where selective removal of metallic traces precedes the deposition process [9]. While the latter can provide finer control over sensor characteristics, it is more susceptible to variations in processing conditions and mechanical stability.

A central aspect of OS-based sensor performance is the molecular organization of the deposited organic semiconductor. High molecular order promotes efficient charge transport, whereas disordered domains can severely impede conductivity [10]. Consequently, techniques such as spin coating, drop casting, and inkjet printing—which allow control over the molecular packing and uniformity of the film—are critical in optimizing sensor performance [11]. Despite numerous individual studies addressing these techniques, there is a lack of systematic comparative analysis that establishes standardized guidelines for the fabrication of OS-based RFID sensors.

This study builds upon our earlier proof-of-concept [12, 13] for a temperature integrity sensor utilizing an HF RFID tag, by incorporating nanostructured organic semiconductors to achieve improved functionality. Whereas the previous work concentrated on simulated impedance changes using a thiophene-based conductor, the present research moves forward with experimental validation and performance evaluation of an enhanced HF RFID sensor employing Poly(3,4)-ethylenedioxythiophene (PEDOT) as the active conductive material. PEDOT is an organic semiconductor renowned for its balanced, tunable conductivity (ranging from 10 to 1000 S/cm

via doping), mechanical flexibility, and robust environmental stability. In contrast to other materials like Kapton [14], PVA [15], or even graphene [16] (which often comes with integration challenges) PEDOT retains its electrical properties under mechanical stress and deformation. We investigate three distinct deposition configurations: a complete coating of the RFID tag, and two forms of selective deposition employing circular and linear patterns. By analyzing these approaches through both experimental measurements and computational modeling, we aim to elucidate the relationship between deposition technique, molecular order, and the resulting sensor performance. Ultimately, this work paves the way for a new generation of organically semiconductor-based RFID sensors that are scalable, passive, and ideally suited for integration into existing 13.56 MHz RFID systems.

II. PEDOT APPLICATION METHODS AND SENSOR MANUFACTURING PROCESS

Our investigation centers on evaluating three different deposition techniques for applying PEDOT to RFID tags. Each method distinctly affects the polymer molecular alignment, conductivity, and adhesion, which in turn influence the sensor frequency response and overall performance:

1. **Inkjet Printing:** This technique enables precise, localized deposition by ejecting micro-droplets of PEDOT solution onto specific regions of the sensor substrate. The high resolution of inkjet printing minimizes material waste and allows for the creation of intricate patterns. As a result, the sensor selectivity is enhanced, and it becomes possible to fine-tune the electrical properties in targeted areas.
2. **Drop Casting:** In drop casting, a PEDOT solution is applied over a larger, designated area of the RFID tag surface, yielding a broad and uniform film. While this method is simple and cost-effective, its success depends largely on controlled drying conditions; variations in the evaporation rate can lead to inconsistencies in film thickness, adversely impacting the material conductivity and the sensor's performance.
3. **Spin Coating:** Spin coating produces consistently thin films over extensive areas by rapidly rotating the substrate. This process guarantees a uniform distribution of PEDOT, leading to consistent electrical properties across the sensor. However, the inherent uniformity may restrict the ability to achieve localized impedance tuning, which can be critical for optimizing sensor operation in specific frequency bands.

The experimental platform for our study is a commercial high-frequency RFID tag (NXPG1200) operating at 13.56 MHz (Fig.1). We applied each of the deposition techniques, conducting detailed computational simulations using CST Microwave Studio to model how varying conductivity levels (reflective of the "ON" and "OFF" states of PEDOT) impact the sensor impedance matching and frequency response. The experimental phase involved rigorous S11 measurements using a custom-designed loop antenna to validate the simulation results. The interplay between deposition technique, molecular ordering, and sensor performance is discussed in depth based on both

numerical modeling and physical measurements.



Fig. 1. HF RFID tag used for the characterization of the OS-based compound.

III. EXPERIMENTAL ANALYSIS AND MAIN RESULTS

A comprehensive experimental setup was employed to evaluate the performance of PEDOT-integrated RFID sensors. Using reflection coefficient (S11) measurements as a primary metric, we compared the frequency responses of unmodified RFID tags against those modified with PEDOT applied via the three configurations (Fig.2 a-c):

- **Configuration 1: Complete Coating**
The entire RFID tag is uniformly covered with PEDOT through spin coating at 1500 rpm for 60 seconds, followed by annealing at 70 °C for 20 minutes (Fig.2a). Although this method was expected to enhance sensitivity, it led to an overly conductive tag that diminished frequency selectivity and produced a flattened frequency response (Fig.4), undermining sensor performance.
- **Configuration 2: Selective Deposition with Circular Pattern**
Here, PEDOT is selectively deposited in a circular pattern over the antenna critical regions via drop casting, followed by heating at 80 °C for 10 minutes (Fig.2b). This method ensures a controlled modulation of the sensor electrical properties. The selective deposition bridges discrete regions of the conductive network, resulting in an optimized and tunable frequency response, and ultimately yields a sensor whose performance closely mirrors that of the unmodified tag while enhancing specific parameters (Fig.4).
- **Configuration 3: Selective Deposition with Linear Pattern**
In this configuration, PEDOT is deposited on precise areas of the RFID tag using inkjet printing (via a Dimatix Materials Printer 2800). The resulting linear pattern (Fig.2c) intentionally bridges specific areas, inducing localized impedance variations that heighten the sensor responsiveness to environmental changes

(Fig.4). This targeted approach results in significantly improved sensitivity.

The experimental measurement setup (Fig.3) uses a custom loop antenna connected to an Aursinc Nanovna-H4. The loop antenna (comprising three concentric copper loops mounted on a cylindrical PLA structure) is optimized for operation at 13.56 MHz, with the RFID tag positioned centrally on the PLA surface.

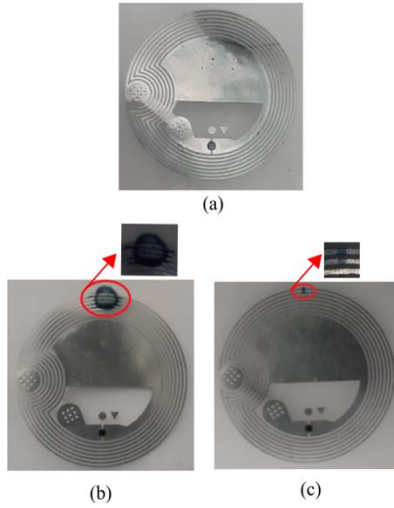


Fig. 2. Explored configurations of the RFID tag used for the characterization of the PEDOT compound. a) Configuration 1: Complete Coating of the Tag; b) Configuration 2: Localized Application of the Compound with circular pattern; c) Configuration 3: Localized Application of the Compound with linear pattern.

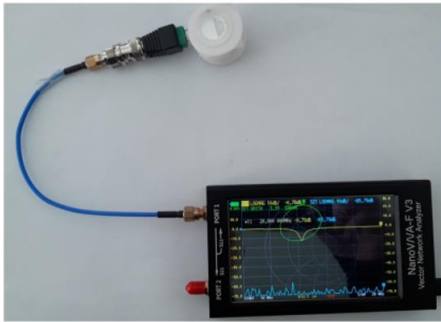


Fig. 3. Measure setup

The experimental outcomes, illustrated in Fig. 4, compare the frequency responses of the three PEDOT deposition strategies against that of the baseline, unmodified RFID tag. Configurations 2 and 3 maintain frequency characteristics closely aligned with the original tag, whereas Configuration 1 results in a markedly flattened response (primarily due to short-circuit effects caused by the continuous PEDOT coating). These observations are further validated through numerical simulations that account for different conductivity levels of the PEDOT material. The simulation results clearly demonstrate a

relationship between the deposition approach, the molecular ordering of the PEDOT layer, and the overall sensor performance. For instance, Fig. 5 presents the simulated behavior of Configuration 2 across a range of conductivity values σ_{COMP} used to model PEDOT, showing strong agreement with the experimental data in Fig. 4. This integrated analysis highlights the critical role of deposition technique in balancing sensor sensitivity, impedance tuning, and long-term operational stability.

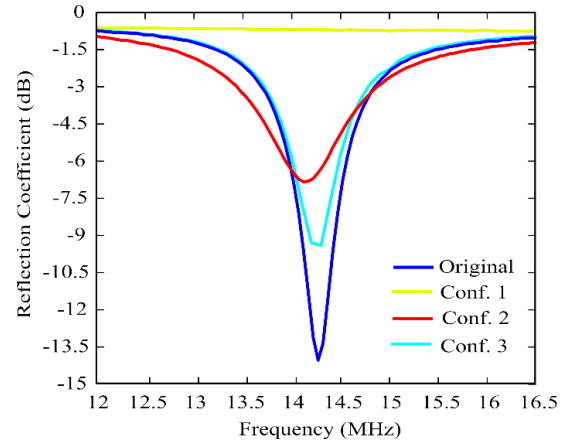


Fig. 4. Measured reflection coefficient of the loop antenna loaded with the original tag and of the three configurations reported in Fig. 2 when the compound is activated (ON state).

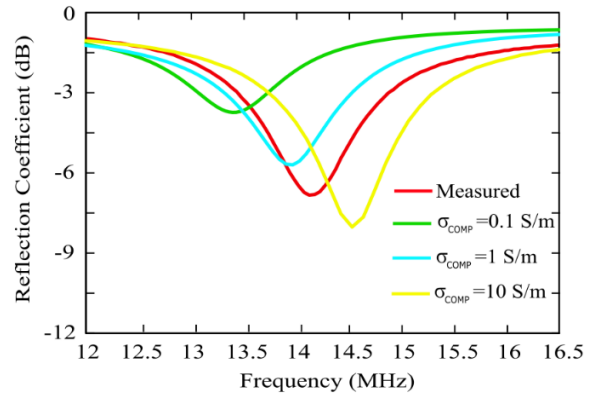


Fig. 5. Measured reflection coefficient of the loop antenna loaded with tag for the “Configuration 2” when the compound is activated (ON state) compared with the simulations for different compound conductivities σ_{COMP} .

Conducting reliability tests is crucial for evaluating the long-term stability and durability of the PEDOT-enhanced RFID sensor under real-world operating conditions. In the upcoming months, we plan to carry out a series of environmental stress tests designed to replicate demanding field scenarios [17, 18]. These tests will subject the sensor to multiple stressors, including mechanical bending, ultraviolet (UV) exposure, temperature variation, and elevated humidity levels. The goal is to assess how well the sensor performs under such challenging

conditions.

During the testing period, we will continuously track the sensor S11 parameters to identify any signs of electrical degradation or performance shifts. This real-time monitoring will help verify whether the sensor maintains consistent impedance characteristics and operational stability throughout the stress exposure.

These rigorous evaluations are intended to yield critical insights into the sensor's durability, confirming its ability to operate reliably without functional decline over time. Ultimately, this testing will validate the sensor robustness and suitability for deployment in demanding environments (such as industrial settings, cold-chain logistics, healthcare monitoring, and IoT-based systems) where uninterrupted, high-reliability performance is essential.

IV. PRACTICAL APPLICATIONS AND INDUSTRIAL SIGNIFICANCE

The optimized PEDOT-based RFID sensor presents transformative potential across a range of applications:

- **Logistics and Cold Chain Monitoring:** With its real-time frequency shift detection capabilities, the sensor is ideal for tracking temperature-sensitive goods such as pharmaceuticals and perishable food items, thereby reducing spoilage and financial losses.
- **IoT and Smart Systems:** When integrated into IoT networks, the sensor facilitates seamless real-time monitoring and predictive maintenance, significantly contributing to the digital transformation of industrial processes.
- **Healthcare and Biomedical Applications:** Its passive, battery-free operation is highly suited to developing wearable biosensors, smart bandages, and drug compliance monitoring systems, thereby improving patient safety and treatment efficiency.
- **Environmental Monitoring:** By detecting subtle changes in impedance, the sensor enables effective monitoring of air and water quality, soil conditions, and other environmental parameters, crucial for sustainable agricultural practices and resource management.

The low-cost, maintenance-free nature of the PEDOT-based sensor positions it as a viable alternative to traditional, more complex sensing systems.

V. CONCLUSION

This study represents a significant advancement in the field of organic semiconductor-based RFID sensors. Through the strategic integration of PEDOT into high-frequency RFID tags, we have demonstrated that deposition method plays a critical role in determining sensor performance. Selective deposition (whether implemented via circular or linear patterns) yields an optimal balance between sensitivity and impedance control, while a full coating approach tends to overcompensate, flattening the sensor's frequency response. Our combined numerical simulations and experimental evaluations confirm that the PEDOT-integrated sensor is passive, cost-effective, scalable, and fully compatible with existing 13.56 MHz RFID systems. These attributes make it especially promising for applications across logistics,

healthcare, IoT, and environmental monitoring. Future work will focus on enhancing long-term stability through rigorous environmental stress testing, refining deposition methods for improved reproducibility, and exploring stretchable PEDOT films to further extend sensor applicability.

Through these efforts, our research lays a solid foundation for next-generation wireless sensing technologies that deliver high sensitivity, robust performance, and versatile integration in industrial and commercial settings.

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