Additively Manufactured Miniaturized RF Sensor for Temperature Sensing

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***Abstract*—This paper presents the development and characterization of a miniaturized RF sensor designed for temperature sensing applications, leveraging advanced additive manufacturing techniques. The sensor utilizes NiTiNOL, a superelastic alloy, as the temperature-sensing material, integrated into a split-box resonator structure. The resonator operates at a frequency of 38.125 GHz, and the design benefits from the flexibility and precision offered by 3D printing technology. This approach allows for a compact form factor and robust performance in harsh environments. The sensor's performance was evaluated through a series of simulations, demonstrating high sensitivity and reliability in temperature measurement. The results highlight the potential of additively manufactured RF sensors in various industrial, medical, and environmental monitoring applications, offering advantages such as reduced size, weight, and power consumption, along with enhanced mechanical robustness and thermal stability. This work underscores the significance of additive manufacturing in advancing next-generation sensor technologies.**

Keywords—additive manufacturing, NiTiNOL, temperature sensing, split-box resonator.

I. Introduction

The advent of additively manufactured (AM) technology has transformed the field of radio frequency (RF) sensors, allowing for the creation of highly miniaturized and efficient sensing devices. This is particularly impactful for temperature sensing applications, where precision, compactness, and integration are crucial. Traditional manufacturing struggles with producing complex geometries and integrating multiple materials, challenges that AM, or 3D printing, successfully overcomes through its design flexibility and material customization. As a result, AM technology enhances sensor functionality and performance. These miniaturized RF sensors represent a cutting-edge advancement, meeting the demand for compact, versatile, and highly accurate temperature monitoring solutions across various industries and applications.

Recent studies highlight the potential of additive manufacturing (AM) technologies in creating miniaturized RF sensors with superior performance, including enhanced sensitivity and accuracy. This improvement is due to the precise control over material properties and structural dimensions provided by AM. Additionally, integrating advanced materials like conductive inks and dielectric polymers has broadened these sensors' capabilities, allowing their use in varied and challenging environments. The development of such sensors is driven by the demand for adaptable and efficient temperature measurement devices in electronics, aerospace, biomedical engineering, and environmental monitoring [1-3]. Traditional temperature sensors often face limitations in size, flexibility, and integration, challenges that AM, or 3D printing, effectively addresses by facilitating the fabrication of complex geometries and the seamless integration of multiple materials [1-3].

Temperature sensing is crucial in industrial, medical, and environmental monitoring for process control, safety, and quality assurance. Additively manufactured (AM) RF sensors offer advantages over conventional sensors, such as reduced size, weight, power consumption, and enhanced mechanical robustness and thermal stability. These features make AM RF sensors ideal for harsh and constrained environments where traditional sensors may fail or be impractical. A significant advantage of AM RF temperature sensors is their wireless operation without an internal power source, achieved through RF backscatter technology, where the sensor modulates and reflects an incoming RF signal based on the detected temperature [4]. This passive operation extends the sensor's lifespan and makes it suitable for environments where powered sensors might be impractical or unsafe [1].

The design of these sensors typically involves a combination of carefully selected materials and precise geometries. For instance, a recent study by scholars from Loughborough University, University of Southampton, and University of Glasgow demonstrated a flexible RF temperature sensor made from a composite made of short strand carbon fiber and polydimethylsiloxane (PDMS) [4]. This composition allows for exceptional flexibility and durability, with the sensor capable of being bent and stretched while maintaining functionality [4].

The manufacturing process for these sensors leverages various additive manufacturing techniques, including aerosol-jet printing (AJP), ink-jet printing (IJP), and micro-dispense printing (MDP) [5]. These methods enable the deposition of functional materials with features as small as 10 μm, facilitating significant miniaturization compared to traditional sensor fabrication methods [5]. This level of precision allows for the creation of sensors that can be seamlessly integrated into a wide range of devices and structures.

The temperature sensing capability of these RF sensors is often based on the principle of resonant frequency shift or change in the amplitude level of the frequency response of the designed sensor. As the temperature changes, it affects the electrical properties of the sensor's materials, causing a shift in its resonant frequency or amplitude level of the frequency response [2]. This shift or change can be detected and measured remotely, providing accurate temperature readings without physical contact or wired connections.

One of the most significant advantages of additively manufactured RF temperature sensors is their wide operating range. For example, some designs have demonstrated the

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ability to measure temperatures from 30°C to over 200°C, surpassing the capabilities of many traditional thermistors [4]. This broad range makes them suitable for diverse applications, from monitoring electronic components to high-temperature industrial processes.

The flexibility in design and fabrication offered by additive manufacturing also allows for the customization of sensor shapes and sizes to fit specific applications [4]. This adaptability is particularly valuable in scenarios where space is limited or where the sensor needs to conform to irregular surfaces. For instance, these sensors could potentially be integrated into the housing of electronic devices, woven into textiles, or embedded within structural materials [4].

As research in this field progresses, we can expect to see further improvements in sensitivity, accuracy, and robustness of additively manufactured RF temperature sensors. The integration of advanced materials, such as nanomaterials or smart polymers, could lead to even greater performance enhancements and expanded functionality [3].

The scalability of additive manufacturing (AM) processes enables the rapid prototyping and production of customized RF sensors tailored to specific applications. This is crucial for advancing next-generation sensing technologies and meeting the growing demand for smart, connected devices in the Internet of Things (IoT) ecosystem. In conclusion, additively manufactured miniaturized RF sensors for temperature sensing represent a major advancement in sensor technology. They combine the benefits of AM with RF sensing principles, offering a unique solution to temperature monitoring challenges across various fields. As this technology evolves, it promises to enable new applications and enhance existing ones, driving progress in areas such as consumer electronics and industrial process control [6-7].

Additively manufactured temperature sensors are particularly valuable for use in polypropylene pipes for several reasons. First, 3D printing allows for the creation of intricate and customized sensor designs that can be seamlessly integrated into the curved surfaces of polypropylene pipes, ensuring precise placement and optimal performance. The flexibility and adaptability of additive manufacturing enable the production of sensors that can easily conform to different sizes and shapes of polypropylene pipes, meeting various application requirements without extensive retooling [8]. Additionally, silver nanoparticle ink and acrylates used in 3D printing ensures compatibility with polypropylene, reducing the risk of chemical reactions or degradation over time. Moreover, additively manufactured sensors can be more cost-effective, especially in low-volume or custom applications, compared to traditional manufacturing methods that require expensive molds and tooling [9]. The enhanced performance of 3D-printed sensors, due to the integration of advanced materials and innovative designs, improves sensitivity, accuracy, and durability in harsh environments. The compact and lightweight nature of these sensors facilitates seamless integration into polypropylene pipes without significantly affecting the pipe's structure or flow characteristics. Overall, additively manufactured temperature sensors offer a versatile, efficient, and effective solution for monitoring temperature in polypropylene pipes, with significant advantages in design flexibility, material compatibility, and production speed [3].

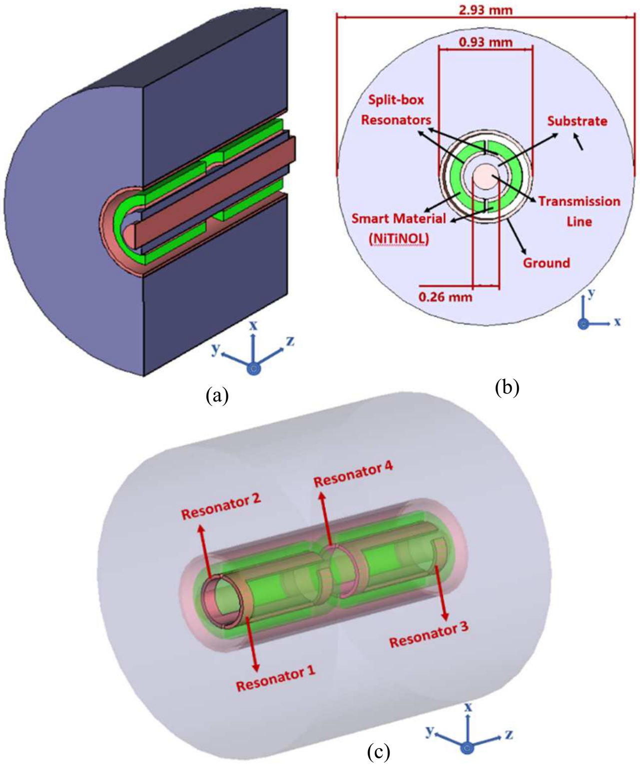

Fig. 1. (a) Cutting plane view, (b) front view with specification, (c) transparent view showing the resonators and inner components of the sensor.

In this paper, we present the design, characterization, and analysis of an additively manufactured miniaturized RF sensor for temperature sensing. We have designed a temperature sensor operating at 38.125 GHz, which falls within the millimeter wave (mmWave) frequency range used in 5G technology. This sensor can be seamlessly integrated into both 5G and future 6G technologies, leveraging the high-frequency capabilities to enhance temperature sensing accuracy and performance in advanced communication systems. The sensor leverages advanced 3D printing techniques to achieve a compact form factor and high performance. We discuss the material selection, structural design, and integration methods employed in the sensor design process. Additionally, we evaluate the sensor's temperature sensing capabilities through a series of simulations and discuss its suitability of usage in other applications other than temperature. The results demonstrate the potential of AM RF sensors to provide accurate and reliable temperature measurements, highlighting their applicability in various real-world scenarios.

II. Design of RF Sensor

A. RF Sensor Design and Working Principle

The RF sensor developed in this study is a split-box resonator, resonating at 38.125 GHz. The resonator is cylindrically bended around a cylindrical transmission line with a diameter of 0.26 mm. There is a thin layer of 0.09 mm of dielectric material separating the transmission line and the resonators. Total four of the resonators were placed around the transmission line where upper (resonator 1 & 2) and lower (resonator 3 & 4) resonators were mirrored. A smart temperature sensing material (NiTiNOL) was placed on top of the resonators. The ground is placed surrounding the resonators and smart materials. Substrate material is covering the ground on the outside. All these are demonstrated in Fig. 1. The resonating frequency of the entire structure enabling its specific temperature sensing capability is defined by:

$$f_r = \frac{c}{\lambda\sqrt{\varepsilon_r}} \quad (1)$$

where, f_r is the resonant frequency, which is set to 38.125 GHz, λ is the corresponding wavelength which has been used to determine the resonator dimension, and ε_r is the substrate dielectric constant.

The proposed sensor, composed of several layers, poses fabrication challenges for traditional PCB methods. However, 3D printing technology makes it easy to construct the sensor and can address a number of PCB manufacturing issues. First off, 3D printing eliminates the need for the bonding procedure, which is frequently employed in PCBs to ensure a strong connection between layers. Second, rather than adhering to the PCBs' normal thickness, the distance between consecutive metal layers can be freely chosen based on the design requirement. More importantly, when the number of layers increases, the cost will not rise appreciably because the layers are formed in an additive manner with strong connections. The 3D printing method will be used to quickly prototype the sensors in order to achieve this goal. The dielectric layer is formed using ultraviolet (UV) curable acrylates ink, which has a dielectric constant of 2.8 and a loss tangent of 0.012. The conductor layers are formed by using nanoparticle ink, which has a conductivity of 2 x 10^7 Sm^{-1}. The miniaturized overall dimension of the sensor is 2.93 mm x 2.88 mm, corresponding to $0.000023\lambda_0$ operating at the resonance frequency of 38.125 GHz. The 3D printing technology used here has a printing limitation of 3 mm in the z-direction, hence the dimension of the sensor is kept under 3 mm. Table I exhibits the properties of materials used in the 3D printing.

Similar in structure and properties to spiral resonators which are frequently employed in chipless RFID are split-box resonators. True to their name, split-box resonators feature a box-like shape with one corner split. They provide a number of benefits over spiral resonators, including a higher quality factor and a greater separation between successive harmonics. A higher quality factor signifies improved energy storage capability, which enhances wireless detection when the resonator is interrogated with a reader [8]. To create the frequency signatures, the dimension of the split-box resonators is formed by using (1). To achieve distinct frequency signatures at 38.125 GHz, the dimension of the split-box resonators is adjusted, and the dimension of all the four resonators are identical. The length of the resonator is set to 1.0855 mm, width is 0.66 mm, and the corner split is maintained at 0.081 mm.

B. Selection of Smart Material

The smart material used in this study for sensing temperature is Nickel Titanium Naval Ordnance Laboratory (NiTiNOL) superelastic foil with a thickness of 0.1 mm. It is an alloy composed of Nickel and Titanium. NiTiNOL superelastic foil is employed due to its remarkable strength, flexibility, chemical resistance, and puncture resistance, making it suitable for a wide range of applications. This foil is exceptionally durable and highly resistant to punctures [9-10]. Due to the superelasticity feature, NiTiNOL can be perfectly placed cylindrically around the resonators. Also, this feature combined with the miniature size of the sensor enable the sensor to be integrated with many small systems and placed inside bended pipes for temperature sensing. Along with that, it opens up new avenue for sensing deformation, strain, and crack. Table II showcases the specification of NiTiNOL superelastic foil of thickness of 0.1 mm:

TABLE I. MATERIAL SPECIFICATION OF 3D PRINTING

Material	Specification		
	Parameter	***Value***	***Unit***
Acrylates Ink	Dielectric constant	2.8	NA
	Dissipation factor	0.012	NA
Silver Nanoparticle Ink	Conductivity	2 x 10^7	Sm^{-1}

TABLE II. SPECIFICATION OF NITINOL SUPERELASTIC FOIL - 0.1 MM

Specification		
Parameter	***Value***	***Unit***
Electric conductivity	7.9	Sm^{-1}
Thermal conductivity	13.3	W/K/m
Material density (Rho)	0.00645	Kgm^{-3}
Specific heat	322	J/K/kg
Thermal diffusivity	6.40377	m^2/s
Young's modulus	79	GPa
Poisson's ratio	0.33	NA
Thermal expansion coefficient	14.3	1e-6/K

III. RESULTS ANALYSIS AND DISCUSSIONS

In the following section, we analyze the performance of the designed sensor for temperature sensing.

Fig. 2 depicts the frequency response (transmission coefficient) of the designed temperature sensor depicted in Fig. 1(c), having around 2.02 dB depth at 38.125 GHz. It actually depicts the frequency response of all the four resonators surrounded in a tubular environment. From simulation, it is evident that the number of resonators increases the depth of the frequency response.

To observe the effect of temperature sensing, a smart temperature sensing material, NiTiNOL, has been used. We placed superelastic foil of 0.1 mm thick NiTiNOL on top of the four resonators, in between the resonators and the ground tube. By varying the electrical conductivity (Sigma) of NiTiNOL, we observed an amplitude variation of the proposed sensor, demonstrated in Fig. 3. From Fig. 3 it can be observed that with increase in electrical conductivity, amplitude of the frequency response is decreasing throughout the frequency range from approximately10 GHz to 100 GHz. With this consistent pattern, it can be inferred that the proposed sensor is not only suitable for use at 38.125 GHz but also for any frequency in the range from 10 GHz to 100 GHz and beyond. As we know, conductivity is inversely related to resistivity, and with increase in temperature of a material, its resistivity decreases.

To make the relationship of electrical resistivity of NiTiNOL with the amplitude of frequency response of the sensor, we derived Fig. 4. Amplitude of frequency response, transmission coefficient (S12), at 38.125 GHz was taken from Fig. 3 for each value of the electrical conductivity (Sigma). Later, we plot each value of the transmission coefficient against their corresponding value of electrical resistivity and derived Fig. 4. From the figure, it is apparent that with decreasing resistivity or increase in temperature, amplitude of transmission coefficient increases. With this ability of the

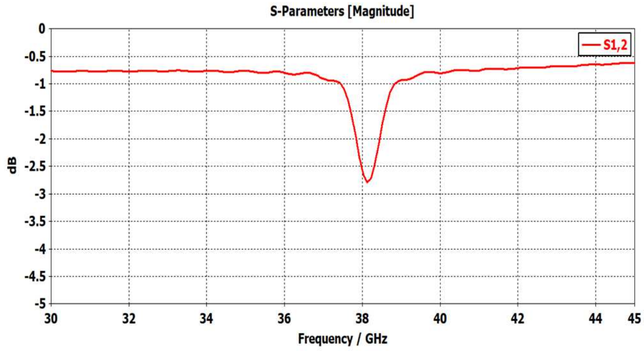

Fig. 2. Frequency response of the designed sensor specified to operate at 38.125 GHz.

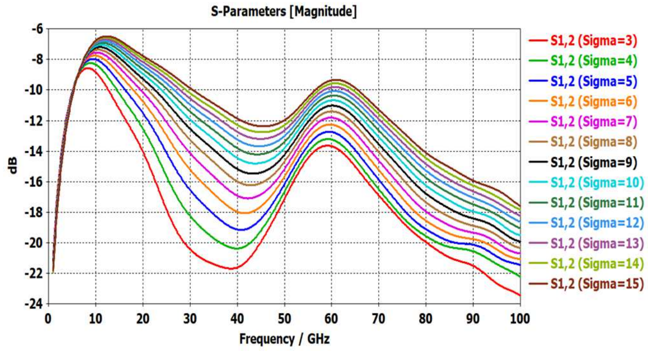

Fig. 3. The variation of amplitude of the frequency response of the designed sensor in relation to electrical conductivity (Sigma).

sensor and its miniaturized size, it is possible to integrate the sensor to sense temperature change in many applications.

IV. Conclusion and Future Works

This study presents the design, analysis, and characterization of an additively manufactured miniaturized RF sensor for temperature sensing. By leveraging advanced 3D printing techniques, the sensor achieves a compact form factor and high performance, making it suitable for various applications. The split-box resonator, which resonates at 38.125 GHz, demonstrates superior energy storage capability and improved wireless detection due to its high-quality factor. The integration of NiTiNOL, a smart temperature sensing material, enhances the sensor's sensitivity and enables it to be used in diverse settings, including industrial, medical, and environmental monitoring. Our experimental results confirm that the sensor provides accurate and reliable temperature measurements, underscoring its potential for real-world deployment in harsh and constrained environments.

Future work will focus on fabricating the sensor and measure experimentally to corelate with simulation results, also enhancing the sensor's performance and expanding its applications. This includes optimizing materials for better sensitivity and durability, further miniaturizing the sensor, and conducting extensive environmental testing. Integrating wireless communication modules and reducing power consumption will facilitate real-time data transmission and improve efficiency. Customizing the sensor for specific applications, studying long-term stability, and extending its capabilities to measure additional parameters like deformation, strain, crack, and humidity will also be explored. These efforts aim to advance the capabilities and adoption of additively manufactured RF sensors in various fields.

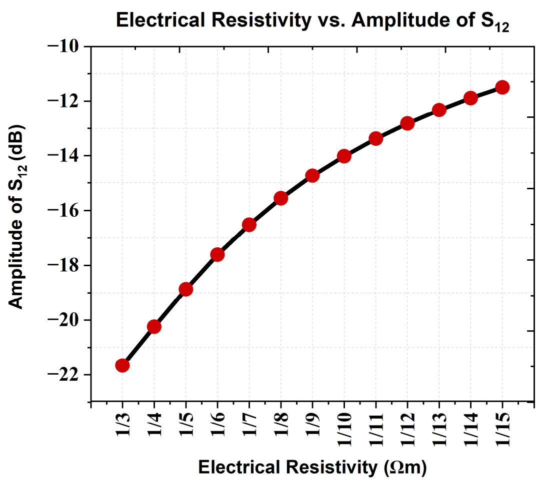

Fig. 4. Relationship of temperature (with respect to electrical resistivity) with corresponding amplitude of transmission coefficient of the designed sensor.

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