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Passive Wireless Temperature Sensing in Extreme Harsh Environments

Michael R. Comparetto

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Passive Wireless Temperature Sensing in Extreme Harsh Environments

Michael R. Comparetto

Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Electrical Engineering

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2017

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Abstract

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Michael R. Comparetto

As the technology in the fields of aerospace and the US power generation industry advances, there is a critical need for new extreme high temperature sensing / monitoring technologies to replace the current out-of-date sensing systems. As the operating temperatures of these jet and turbine engines continue to rise over 1000 C, it is vitally important to monitor the extreme high temperatures in these engines for system health monitoring and to achieve greater engine efficiencies. We propose a new passive wireless temperature sensor capable of sensing these extreme high temperatures. The sensor uses an LC resonance circuit to measure the temperature through passive wireless communications. A new novel method of capturing large quantities of frequency information from the sensor is proposed and allows for advanced signal processing methods from other applications areas like wireless communications, radar, and radio astronomy to be implemented. The passive wireless LC resonance high temperature sensor was successfully able to sense temperatures up to 700 C.

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Chapter 1

Introduction

1.1 Motivation

New generations in technology in the aerospace and electrical power generation industries require materials that can survive in temperatures from cryogenic (below -150 C) to values greater than 1000 C. In addition to requiring materials that can survive these extreme harsh environments, these new technologies require sensors to perform real-time passive wireless monitoring of key physical parameters, namely temperature sensing. The need for wireless temperature sensing technology built to survive these extreme environments and provide real-time monitoring is essential to the new generation of aircraft engines and gas turbine engines. Operating at such extreme high temperatures is critical for gas and aircraft engines to achieve greater engine efficiency [2] . The ability to measure and monitor the temperature inside of these turbine engines is critical for two key reasons: 1) Temperature sensing and monitoring ensures that the engine is running at optimal efficiency providing savings on fuel costs, 2) Temperature sensing and monitoring prevents overheating and thermal damage to engine components increasing the safety and lifespan of the turbine engine. There are four key requirements for extreme high temperature sensors: 1) The sensors must be able to operate in extremely harsh environments where temperatures are greater than 1000 C. 2) The sensors must be wireless to allow them to access any section of the turbine engine. These wireless sensors must also be passive as batteries will not function or become impractical at these temperatures. 3) The sensors need to have a small form factor and have low mass.

4) The fabrication of these passive wireless sensors must be simple and low cost [13]. In the last several years, NASA has reached out to the research community for new innovative sensor technologies for temperature monitoring in the next generation of intelligent aircraft engines. From the ground up to the edge of space NASA has applications that require passive wireless sensor technologies [such as temperature sensors] in extreme aeronautical environments [14]. These sensor technologies will improve the affordability, performance, and safety of the aircraft engines. These new sensor technologies will allow the engines to perform self-diagnostics, be adaptable, and optimize themselves to current conditions. NASA and the U.S. Department of Defense are pursuing revolutionary technology advances to achieve the realization of intelligent aircraft engines, which will be self-diagnostic, self-prognostic, self-optimizing, and mission adaptable. [15]. One of the critical sensing needs, for these intelligent engines, is passive wireless temperature sensing. These temperature sensors will need to be able to survive in temperatures from cryogenic (-150 C) to temperatures greater than 1000 C. These temperature ranges make powering the sensors with batteries infeasible and often the placement of these sensors require them to be wireless [16]. A current method for measuring temperature inside an aircraft engine is to use long massive wires to transmit the gathered data outside of the engine. These heavy wires have to be supported inside the aircraft with even heavier metal infrastructure. This added weight to the aircraft translates into reduced fuel efficiency, increased fuel costs, as well as frequent maintenance [1]. By replacing these heavy wired systems with small passive wireless temperature sensors, which can be placed in areas of the engine that the heavy wires cannot be, the aircraft engines can operate at higher engine efficiency due to weight reduction and the collection of more accurate temperature data. Another critical need of NASA's aeronautical researchers is to significantly reduce the complexity of their ground and flight engine test systems. These test systems require many sensors to be placed in the engine, one of which is the temperature sensor. These sensors are connected with a multitude of wires and cables. This greatly increases the cost and time required to perform these tests [1]. Switching to passive wireless sensors would greatly reduce the complexity of the test systems and reduce the time and cost required to perform the testing. Figure 1.1 shows an engine in a ground test system with massive wires and cables attached to it and supported by a large metal infrastructure.

These wires and cables are used to connect the testing instruments with sensors inside the engine.

Figure 1.1: An aerospace engine in a ground test system with a multitude of wires and cables [1].

Passive wireless temperature sensors fulfill another critical need of NASA's. With NASA's efforts in integrated vehicle health monitoring (IVHM), NASA needs to monitor the health and structural integrity of its vehicles. For hypersonic vehicles (speeds exceeding Mach 5), as shown in Figure 1.2 extreme high temperatures exist on the vehicle's surface due to skin friction heating. These temperatures can reach above 1000 C [16]. The current temperature sensors along the vehicle's structure are wired. This adds weight to the vehicle. These wired sensors also have reliability issues as they are prone to being damaged by structural strain. Passive wireless temperature sensors would reduce the weight of the aircraft and improve the reliability of the temperature monitoring system.

Another critical need for passive wireless temperature sensing can be found in the U.S. electrical power industry. In 2015, the power generation from nuclear, natural gas, and coal consisted of nearly 86% of the total power generated (see Figure 1.3)¹. These power

¹U.S. Energy Information Administration: <https://www.eia.gov/electricity/data.php>

Figure 1.2: The X-51A Waverider Hypersonic Vehicle mounted underneath the wing of a B-52 aircraft (left) and an artist conception of X-43A hypersonic experimental vehicle (right).

generating systems rely on combustion or steam turbine engines to produce electricity (see Figure 1.4) for a gas turbine engine. Extreme harsh environments exist inside of these turbine engines where temperatures can reach over 1000 C. Real-time passive wireless temperature monitoring is needed to increase the engine efficiency, reliability, and safety.

Figure 1.3: U.S. electric power industry net generation in 2015.

Real-time monitoring of the temperature inside the turbine is vital. To improve fuel efficiency, the firing temperatures of turbine engines has increased over time and now is over 1000 C. Figure 1.5 shows roughly a 10% increase in work output for every 55 C increase in temperature [2]. With the increase in the firing temperature, the need for real-time passive wireless temperature monitoring has arisen to keep the temperature inside the turbine stable

Figure 1.4: Gas turbine engine (Courtesy ALSTOM).

and at optimum values [17]. This ensures that the turbine is operating at peak fuel efficiency thus saving on fuel costs. It also ensures that turbine blades are not suffering thermal damage from overheating. This increases the turbine's life span, reliability, and reduces operating costs.

Figure 1.5: Efficiency work output vs pressure ratio at multiple temperatures[2].

1.2 Our Contribution

To answer NASA's call for innovative temperature sensing and monitoring technologies for their next generation of intelligent aircraft engines and to fulfill the U.S. electrical power generation industry's critical need for real-time temperature monitoring, this thesis proposes a novel state of the art passive wireless sensor and sensing methodology. The proposed sensor is able to 1) survive extreme harsh environments with temperatures over 1000 C; 2) have a small form factor and low mass; 3) perform real-time temperature monitoring through passive wireless communication; and 4) keep its fabrication process simple and at a low cost. Thus, the proposed real-time monitoring system fulfills the four requirements established for modern extreme temperature monitoring and has an additional benefit of being easily placed on the desired surface through a peel and stick decal process.

1.3 Overview of Thesis

This thesis presents a novel solution for a passive wireless temperature sensor and sensing methodology for extreme harsh environments where the temperature reaches values that can exceed 1000 C. Chapter 2 discusses current state of the art temperature sensing technologies that attempt to fulfill the four requirements established for modern extreme temperature monitoring. These technologies are briefly explained along with their limitations. Chapter 3 explains our system engineering approach to this critical problem. An explanation is given of the process used to design and test the sensors as well as the digital signal processing used to infer temperature readings from passive wireless communications. Chapter 4 lists the results of the passive wireless temperature sensing experiments and discusses the challenges that were encountered. Chapter 5 summarizes the thesis and gives suggestions for future work.

Chapter 2

Current State of the Art Passive Wireless Temperature Sensing Technologies for Extreme Harsh Environments

2.1 Introduction

As stated previously in this thesis, being able to measure physical parameters, like the temperature inside turbine and jet engines, is critically important for enabling the engine to operate at higher efficiencies as well as increase the safety and lifetime of the engine. Currently there are no commercial technologies available that provide a passive wireless communication method for real-time monitoring of the temperature in a turbine engine. Wireless communication is very desirable as it allows sensors to be placed at critical sensing locations that are currently not possible like turbine blades. The passive feature of the sensors is critically important as the extreme harsh environment renders the use of batteries for power to be impractical or infeasible. In this chapter, several state of the art passive wireless temperature sensing technologies for extreme harsh environments are briefly summarized. The methodologies used in these technologies, their success, and their weaknesses are discussed in this chapter.

2.2 Integrated Resonator / Antenna Sensors

One of the emerging technologies for passive wireless temperature sensing in extreme harsh environments where the temperatures can exceed 1000 C, is integrated resonator / antenna sensors. The sensors are made up of an resonator cavity with an integrated antenna as shown in Figure 2.1 [3]. These wireless temperature sensors are constructed using microwave cavity resonators with an integrated slot antenna [4] [18] [19]. An interrogator antenna transmits a radio frequency (RF) signal toward the resonator sensor. The sensor captures some of the energy of the RF signal. The captured RF signal oscillates in the sensor and the frequency components of the RF signal that are close to the sensor's resonant frequency have the strongest oscillations. The sensor then reradiates the received RF signal. The interrogator antenna receives this reflected signal from the sensor and the strongest reflections are at the sensor's resonant frequency. In [4] the resonator sensor is made by etching a cavity out of the substrate. The cavity is then lined with platinum. The sensor presented in [3] improves upon the sensor presented in [4]. A cylindrical substrate has two parallel cavities drilled into it. A slot antenna is etched into the substrate's surface and then lined with platinum, see Figure 2.2.

Figure 2.1: Wireless passive temperature sensor with an integrated cylindrical resonator / antenna.

Figure 2.2: Micro-milling slot antenna on the sensor (left) and the high-temperature measurement setup up to 1050 C using a heat pad and an X-band OEWG antenna (right) [3].

These cavity resonator sensors can be used as passive wireless temperature sensors if their substrates are made from a material with a temperature dependent dielectric constant. The dielectric constant of the substrate is a major factor in determining the resonant frequency of the sensor [4]. As the temperature in the environment around the sensor increases, the temperature of the substrate increases. This increase in the substrate's temperature causes its temperature dependent dielectric constant to increase. This in turn causes a decrease in the sensor's resonant frequency. These shifts in the sensor's resonant frequency can be wirelessly detected by the interrogator antenna. Thus, temperature data can be inferred from the shifts in the sensor's resonant frequency. In [3] and [4], ANSYS High Frequency Structure Simulator (HFSS) was used to simulate the effect of changing the dielectric constant of the substrate on the sensor's resonant frequency. The results of these simulations can be seen in Figure 2.3. The simulation results show that as the dielectric constant was increased to simulate an increase in temperature, the resonant frequency of the sensor decreased.

These cavity resonant sensors were used to perform passive wireless temperature sensing at extreme high temperatures. The sensor from [4] was placed on a heat pad capable of reaching 1000 C. The interrogator antenna was placed over the sensor and protected from the extreme heat. The results of the passive wireless temperature sensing are shown in Figure 2.4. The figure shows that as the temperature increased from 50 C to 1000 C the dielectric constant increased from 9.7 to 11.2 and the resonant frequency decreased from 5.12 to 4.74 GHz which yielded a 0.4 MHz/C sensor sensitivity [4].

The sensor from [3] used a furnace capable of exceeding 1000 C and used a robust

Figure 2.3: Simulated sensor responses versus dielectric constant [3].

Figure 2.4: Measured resonant frequency of the sensor and extracted dielectric constant of alumina versus temperature [4].

interrogator antenna that was also placed into the furnace with the sensor. The results of the passive wireless temperature sensing are shown in Figure 2.5. The figure shows that as the temperature increased from 25 °C to 1050 °C the resonant frequency decreased from 11.05 to 10.71 GHz which yielded a sensor sensitivity range of 0.09–0.78 MHz/°C [3].

Figure 2.5: Measurement results of the temperature sensor resonant frequency [3].

The Integrated Resonator / Antenna Sensors from [3] and [4] showed an ability to survive in extreme harsh environments where the temperature reached 1000 C. The sensors successfully measured these extreme temperatures through passive wireless communication by using the shifts in the sensor's resonant frequency to infer temperature data. However, these designs have a few critical weaknesses. The resonator cavities of these sensors define the sensor's shape. As such, these sensors are forced to take 3-dimensional shapes which have the potential of hindering the aerodynamics in turbine engines. Another weakness is the fabrication process of the sensors. This process is not scalable. The ability to etch and drill the resonator cavities limits the minimum size of the sensors. These sensors also rely on the use of platinum which, unfortunately, significantly increases the cost of the sensors. A final drawback of these sensors is that they do not have a convenient method of placing the sensors onto a component in the turbine engines.

2.3 Surface Acoustic Wave (SAW) Sensors

The Surface Acoustic Wave (SAW) sensor is another innovative technological response to the need for small passive wireless temperature sensors in extreme harsh environments. Over the last several years, SAW devices have been researched for use as passive wireless

temperature sensors [20] [21] [22]. These sensors rely on integrated transducing technology to transform RF electro-magnetic (EM) waves into surface acoustic waves that travel along the surface of the sensor. As the sensor's surface varies due to changes in the environment, like temperature changes, the surface acoustic wave undergoes detectable shifts. This allows the sensor to perform passive wireless temperature sensing. SAW sensors are able to withstand extreme temperatures, offer passive wireless temperature sensing abilities, and have an intrinsic small form factor. SAW sensors are made from piezoelectric substrates that can survive extreme temperatures. Thin film conductive electrode patterns are placed on the sensor's surface [23]. These electrodes function as interdigitated transducers (IDT) and are used to transform received RF signals into electromechanical (surface acoustic) waves that travel along the sensor's surface. Figure 2.6 depicts how a SAW sensor works. An interrogator antenna transmits an RF signal to the SAW sensor. The IDT, on the SAW sensor, receives the RF signal and transforms it into a nano-scale surface acoustic wave [5]. The wave travels down the sensor and is then partially reflected back to the IDT. The surface of the SAW sensor undergoes variations due to the environment changes such as changes in temperature. The variation in the surface of the sensor causes shifts in the surface acoustic wave as it travels along the sensor. The IDT transforms the shifted wave into an RF signal and reradiates it back to the interrogator antenna. The interrogator antenna can detect the shifts in the RF signal and infer temperature data from these shifts caused by variations in the sensor's surface due to changes in temperature.

Both papers [6] and [7] present SAW sensors that successfully performed as passive wireless temperature sensors in extreme harsh environments. The SAW sensor presented in [6] was placed in to a high temperature box furnace capable of reaching 1100 C. See Figure 2.7 for an image of the SAW sensor and experimental setup. The SAW sensor was connected to a vector network analyzer (VNA) which tracked the shifts in frequency due to variation in the sensor's surface as the temperature was increased. The furnace was heated from 350 C to 1100 C and the frequency response of the sensor was recorded. The results of the experiment are shown in Figure 2.8. The figure shows the SAW sensor's center frequency shift as the temperature was increased. The dashed line represents the change in temperature and the solid line shows the shift in frequency. The device started to fail as it reached temperatures

Figure 2.6: Basic operation of a SAW Sensor [5].

greater than 1000 C.

Figure 2.7: (Left) SAW devices located inside the box oven; and (Right) LGS SAW resonator devices packaged on an Inconel plate [6].

Likewise, the SAW sensor presented in [7] was placed into a furnace and wirelessly interrogated as the temperature was increased from room temperature to 600 C. Figure 2.9 shows the SAW sensor's center frequency shift as the temperature increased. The blue curve is the temperature readings over time and the red curve is the frequency response over time. The paper reports that the sensor had sensitivities of 74 kHz/C at 50 C and 180 kHz/C at

Figure 2.8: Resonant frequency response versus time for a SAW resonator [6].

700 C.

Figure 2.9: SAWR frequency shift (right axis) for an inductively coupled, wirelessly interrogated, device inside a furnace as the temperature (left axis) was increased in step increments from room temperature to 600C [7].

SAW sensors have been successfully used as passive wireless temperature sensors. However, SAW temperature sensors with langasite (LGS) substrates, like those presented in [6]

and [7], are known to suffer phase transformations and chemical instability [24] [25]. These issues are revealed at temperatures ≥ 1000 C and have led to sensor failures. This limits the ability of the SAW sensors to perform as passive wireless temperature sensors in extreme harsh environments. Another weakness of the sensors presented in [6] and [7] is that the fabrication process is nontrivial. These sensors also do not have a quick and simple method of being easily placed on the components in turbine engines.

2.4 LC Passive Wireless Temperature Sensors

RF powered inductor / capacitor (LC) wireless passive temperature sensors is another technology that fulfills the need of passive wireless temperature monitoring in the extreme environments found in turbine and jet engines. These sensors are made of a ceramic substrate capable of surviving extreme harsh environments. An inductance coil and a capacitor form the LC circuit and are placed on the substrate's surface. The sensor's capacitor is temperature dependent which causes shifts in the sensor's resonant frequency [26] [27]. These shifts in the sensor's resonant frequency can be wireless detected and temperature data can be inferred from them. An RF signal is transmitted to the LC sensor by an interrogator antenna. The interrogator antenna and LC sensor are magnetically coupled [8]. As the interrogator antenna radiates the RF signal, it excites the LC sensor through mutual inductance. The LC sensor reradiates the RF signal back to the interrogator antenna. The strongest components of the reradiated RF signal are at the LC sensor's resonant frequency. The resonant frequency of the LC sensor is determined by the inductor / capacitor circuit on the sensor. The capacitor is made with a conductive material whose dielectric constant is temperature dependent. As the temperature increases, the dielectric constant increases. This causes an increase in the sensor's capacitance and a shift in the sensor's resonant frequency [8] [9]. Figure 2.10 shows the inductive coupling between the interrogator antenna and the relationship between the temperature and the capacitance and resonant frequency of the LC sensor. These shifts in the LC sensor's resonant frequency are wirelessly detected by the interrogator antenna and can be used to infer temperature data.

The LC sensor, designed in [8], used an alumina substrate to form the basis of the sensor

Figure 2.10: Interaction between an interrogator antenna and LC sensor [8].

since alumina is stable at extremely high temperatures. The design used planar inductor and capacitor components, implementing a LC circuit with a square planar inductor and a parallel plate capacitor, see Figure 2.11. These conductive components were made with elements based on the metal Wolfram (W). They were placed on the surfaces of two substrates and connected by a via. They were then encased by more layers of alumina to protect them from the extreme harsh environment [8].

The ability of this LC sensor to measure extreme high temperatures through passive wireless communications was tested by placing the sensor into a box furnace and connecting the sensor to electrical monitoring equipment. An interrogator antenna, consisting of a spiral of copper wire protected from the extreme heat, was used to radiate on the RF signal to the LC sensor and excite the LC sensor through mutual inductance. The furnace was heated from room temperature to 1200 C. Figure 2.12 shows the resonant frequency decreasing as the temperature increased. The sensor was reported to have a sensitivity of approximately 2 kHz/C [8].

Another LC Sensor design used for passive wireless high temperature sensing was proposed in [9]. This LC sensor used a similar inductor / capacitor system where the capacitor's dielectric constant is temperature dependent. The LC sensor uses an interdigitated capacitor (IDC). This allows the inductor and capacitor to be placed on the same planar surface and removes the need for multiple layers of substrates with vais to connect the conductive components. The sensor can be seen in Figure 2.13. The sensor was fabricated in a 2-step

Figure 2.11: LC sensor fabrication process [8].

Figure 2.12: Resonant frequency shift as temperature increases [8].

process. The first step was to place the square planar inductor on the alumina substrate. The second step was to build the IDC. A rectangle of platinum, which would serve as the

capacitor, was placed next to the inductor on the substrate. Then a laser was used to etch the interdigitated electrodes of the capacitor [9].

Figure 2.13: LC Sensor with planar inductor and interdigitated capacitor (left), interdigitated electrodes of the capacitor etched with a laser [9].

The high temperature passive wireless temperature sensing was performed by placing the LC sensor into a furnace capable of reaching 1100 C. A loop interrogator antenna was placed inside the furnace with the LC sensor and used to excite it. The furnace was heated from room temperature to over 700 C. Figure 2.14 shows the sensor's resonant frequency shift as the temperature was increased. The sensor had a sensitivity of 4.35 kHz/C [9].

Figure 2.14: Resonant frequency vs temperature [9].

While these LC sensors performed successful passive wireless temperature sensing at extreme high temperatures, the sensors have a few weaknesses. The electrical components of the sensor presented in [8] are made from materials that cannot survive the extreme harsh environments of turbine and jet engines. They need to be protected somehow. To protect the components, this design encased them in multiple layers of ceramics, which complicates this sensor's fabrication process. While the sensor presented in [9] can exist on a single planar surface because of its IDC, the process of constructing the IDC by using a laser to etch out the interdigitated electrodes complicates this design's fabrication process. The IDC is also made from platinum which increases the cost of this design.

Chapter 3

New Novel LC Passive Wireless High Temperature Sensor and Sensing Methodology

3.1 Introduction

The ability to monitor the temperature inside jet and turbine engines is critically important for aerospace aircraft engines and turbines used in the US power generation industry. The operating temperature of the jet and turbine engines has been steadily increasing over the last decade and now exceeds temperatures of 1000 C. This increasing of the operating temperature allows the turbines to achieve higher engine efficiencies. However, the wear on machine parts due to the extreme high temperatures has become an increasing concern. The ability to monitor the temperature inside these turbines through passive wireless communications allows the turbines to maintain these high temperatures with minimal variations. This ensures that the engines operate a peak efficiency while minimizing the thermal strain on the turbine comports due to temperature variations. The prominent current methods for monitoring the temperature in jet and turbine engines relies on massive heavy wires to measure the extreme high temperatures. This method has two critical weaknesses. First, these heavy wires cannot be placed on moving parts such as turbine blades. Thus, their usefulness in monitoring the temperature and the system health of the turbine components is limited.

Second, these heavy wires add excessive weight to jet and turbine engines, a key concern for aircraft engines, and are prone to mechanical failures. A few state-of-the-art passive wireless high temperature sensors were discussed in Chapter 2 of this thesis. These sensors demonstrated an ability to monitor temperature in extreme high temperature environments with varying levels of success. However, these sensors had a few common weaknesses. The fabrication processes for these sensors are non-trivial, these sensors rely on the use of platinum and thus their cost is increased, and these sensors do not have a good method for being attached to the components of jet and turbine engines. In this chapter we propose a new novel LC passive wireless high temperature sensor capable of measuring extreme high temperatures. This sensor meets the four requirements for high temperature sensors. These four requirements are: 1) The sensors must be able to operate in extreme harsh environments where temperatures are greater than 1000 C. 2) The sensors must be wireless to allow them to access any section of the turbine engine. These wireless sensors must also be passive as batteries will not function or become impractical at these temperatures. 3) The sensors need to have a small form factor and have low mass. 4) The fabrication of these passive wireless sensors must be simple and low cost [13]. In addition to the design of the sensor, this thesis also proposes a new novel passive wireless temperature sensing methodology.

3.2 System Engineering Approach to Sensor Development

Before going into the design of the new sensor, it is critically important to describe the system engineering approach used in the sensor development and evaluation process. Figure 2.2 shows a system engineering approach to modeling and simulation and test evaluation.

The first phase of the process is the fundamental research. Here one gathers the relevant literature on the problem area and performs a background study on relevant technologies and solutions to this problem. Preliminary mathematical calculations are performed and give a high-level understanding of the problem. This aids in building and developing theoretical models. One then needs to take this theoretical foundation and use it to generate computer

Figure 3.1: System engineering approach to modeling and simulation and test evaluation [10].

models and simulations. This allows one to test the validity and usefulness of the theoretical models. One builds a model of the system and the environment that the system will exist in. Simulations are performed to get an idea of how the system will function. These simulation results give the theoretical performance of the system. The next phase is very important to the process. After generating the theoretical performance of the system, one needs to perform laboratory testing. In the laboratory environment, controlled test of the system operating the environment are performed. After performing the laboratory testing, it is important to perform field testing. Here the sensor is placed in the environment for which it was designed to operate in. The laboratory and field testing show how the sensor actually performs in the environment it was designed for and verifies the accuracy of the modeling and simulation work. This gives the actual performance of the system. A critical part of this process is the feedback loop between the modeling and simulation and the physical testing of the system. The actual performance of the system is fed back into the model and simulations to improve upon their accuracy. This allows for a better system design and a better understanding of how the system behaves in the environment. This feedback process develops the relationship between theory and operational use and is especially important in Wireless applications.

3.3 Sensor Design Overview

This thesis proposes a new novel inductor / capacitor (LC) passive wireless high temperature sensor capable of measuring extreme high temperatures. The sensor is made with an alumina based ceramic material for its substrate and the LC circuit is printed using a conductive ceramic based ink. These ceramic materials have temperature dependent dielectric constants and are capable of withstanding extreme high temperatures. An LC circuit is printed on the sensor and used for passive wireless communication. An interrogator antenna excites the LC circuit through inductive coupling. The LC circuit re-radiates the signal back to the interrogator antenna. The dielectric constants of the ceramic materials increase as temperature increases. This causes an increase in the sensor's capacitance. As the sensor's capacitance increases, the resonant frequency of the sensor decreases. The interrogator antenna can infer temperature data from these frequency shifts. As the temperature of these ceramic materials that make up the sensor increases, the dielectric constants of these materials increases. This increase in the dielectric constant of the ceramic materials causes an increase in the material's capacitance. The capacitance for a parallel plate capacitor is given by

$$C = \frac{\epsilon A}{d}. \quad (3.1)$$

In (3.1), C is the capacitance, ϵ is the dielectric constant of the material, A is the area of the material, and d is the distance between the parallel plates. while the capacitor implemented in the LC circuit is an IDC and not a parallel plate capacitor, the relationship between its capacitance and the dielectric constant remains the same. As the dielectric constant increases due to an increase in temperature, the capacitance of the capacitor will increase.

The change in the capacitance of the sensor cause a shift in the sensor's resonant frequency. As the capacitance increases, the resonant frequency of the sensor will decrease. The equation for a the resonant frequency of a LC resonance circuit is given by

$$f_r = \frac{1}{2\pi\sqrt{LC}}. \quad (3.2)$$

In (3.2), f_r is the resonant frequency of the sensor, L is the inductance of the sensor, and C is the capacitance of the sensor. This equation shows that as the capacitance increases the resonant frequency will decrease.

A RF signal is transmitted through the interrogator antenna. As the RF signal travels through the interrogator antenna, it causes an inductance in the interrogator antenna. This inductance in the interrogator antenna, caused by the RF signal being transmitted, induces a mutual inductance in the LC circuit. This induced inductance in the LC circuit excites the circuit and causes it to re-radiate the transmitted RF signal. The strongest components of the re-radiated signal are at the LC circuit's resonant frequency. Thus, as the temperature changes causing shifts in the sensor's resonant frequency, the re-radiated signal becomes temperature dependent. These shifts in the resonant frequency can be detected by the interrogator antenna and correlated to temperature measurements. This is how tracking a passive wireless temperature sensor's resonant frequency peak can be used to measure temperature. The state-of-the-art sensors discussed in Chapter 2 used this method. However, this method of tracking the resonant frequency peak to measure temperature only considers a few degrees of freedom (the peaks that are tracked). Thus, very little frequency information is being gathered. As such, the system is not very robust. If the resonant frequency is not highly temperature dependent, the shifts will be small and possibly un-trackable. This thesis proposes a new novel method in using frequency information and shifts to measure temperature. Rather than only observing the resonant frequency peak, a large band of RF spectrum is observed. The sensor's frequency response of in this large band is observed and tracked. This yields a wealth of frequency data with many degrees of freedom. Now the system is more robust and can provide more accurate temperature measurements by observing over this large band of spectrum. More importantly though, observing over a large band of spectrum allows for the use of advanced signal processing methods from different application areas like wireless communications, radar, and radio astronomy. In addition, signal process methods used in machine learning and neural networking can now be applied

to estimating the temperature given shifts in the sensor's frequency response. For this thesis, correlation and the minimization of the absolute error were chosen to estimate the temperature given the frequency response of the sensor. These signal processing methods will be discussed in greater detail later in this chapter.

3.4 Modeling and Simulation of Sensor Design

ANSYS Maxwell software was used to perform the modeling and simulation of the LC passive wireless temperature sensors. ANSYS Maxwell is a premier low frequency electromagnetic field simulator. The software utilizes finite element analysis to simulate the inductance, mutual inductance, capacitance, EM fields, and many other key features of the 3D or 2D models of the sensors. The software allows one to select the materials used in the 2D and 3D models. It also allows the user to define the electronic properties of a material. ANSYS Maxwell is also able to build nonlinear equivalent circuits from the 2D and 3D models and perform frequency analysis on these circuits. The use of ANSYS software to perform the modeling and simulation of the sensor provides several critical benefits. The cost of developing the sensor is reduced. Less funds are spent on resources needed to build the sensors. Without the use of the software, numerous physical tests with the sensors would have to be performed. If these tests revealed that a modification had to be made to the sensor, then a new sensor would have to be fabricated each time. However, using the ANSYS software, many of the early variations and issues in the sensor design can be found through modeling and simulation rather than having to perform lengthy physical tests as well as fabricating new sensors for each minor change. Another benefit realized from the use of the ANSYS software is that it allows the 2D and 3D models to be quickly and easily modified. This provides a significant save in time over having to fabricate new sensor for each desired change. This gives greater flexibility in modifying the sensor design. The software can also quickly perform sensitivity tests. These parametric analyses of the sensor design are critical in optimizing the sensor. Running these analysis through the software on a computer saves significant amount of time as these tests would take days of physical testing. It allows for the running of high speed calculations and simulations on a computer that would take

much longer in a physical environment. The ANSYS software also gives control over the sensor design and the environment it is simulated in. This control of the environment is very important at the early stage of designing the sensors. A final key benefit realized from using the ANSYS software, is that it helps design experiment test plans and guides how one will verify that the sensors are performing the way they were design to. Three LC sensors were developed using the ANSYS Maxwell software. The first sensor, Design 1, was the largest design fitting in a 2 inch by 4 in rectangle and was fabricated. Higher temperature passive wireless temperature sensing experiments were performed with this sensor design. The other two sensor designs, Design 2 and Design 3, have a very similar LC circuit as Design 1. However, the inductor and IDC are smaller. Design 2 fits inside of a 3-inch square and Design 3 fits inside of a 2-inch square. Due to fabrication limitations, only Design 1 was fabricated. Design 2 and 3 were only simulated. These designs will be further detailed in this section. The ANSYS Maxwell software was used to develop a 3D model of the inductor for the LC circuit on the passive wireless temperature sensor. A square planar inductor was chosen as this type of inductor can be easily printed or fixed onto a substrate and it exists on a single planar surface. The inductance of a square planar inductor can be calculated using the method presented in [11]. Figure 3.2 shows an example square planar inductor.

Figure 3.2: Square planar inductor [11].

Geometry	k_1	k_2
Square	2.34	2.75
Hexagonal	2.33	3.82
Octagonal	2.25	3.55

Table 3.1: Coefficient for modified wheeler formula [11]

w is the width of the inductor coils, s is the spacing between the inductor coils, d_{in} is the inner diameter, and d_{out} is the outer diameter of the inductor. A modified wheeler formula presented in [11] was chosen to analytically design the inductor. The modified wheeler formula provides a mathematically simple expression defining the inductance of a square planar inductor with good accuracy and is given by

$$L = \frac{k_1 \mu_o (n^2 d_{ave})}{1 + k_2 \rho}. \quad (3.3)$$

In the above equation, $d_{ave} = \frac{1}{2(d_{in} + d_{out})}$, $\rho = \frac{d_{out} - d_{in}}{d_{out} + d_{in}}$ is the fill ratio, k_1 and k_2 are coefficient that represent the geometry of the inductor (see Table 3.1), and μ_o is the permittivity of free space. The fill ratio defines how hollow the inductor is. The larger the difference between the inner and outer diameters of the inductor the larger the fill ratio is and the less hallow the inductor is. From (3.3) it can be seen that the smaller the fill ratio (ρ) the larger the inductance and vice versa. This mathematical expression, (3.3), can be readily transformed into an algorithm to calculate the theoretical inductance given specific physical characteristics of the inductor.

For all our sensor designs, we chose a resonant frequency of 13.5 MHz and used (3.2) and (3.3) to analytically determine the inductance required given a specified capacitance. (3.3) was used to determine the physical characteristics of the initial square planar inductor. For the square planar inductor of Design 1, we used an eight-turn inductor coil. The coil was 1 mm wide with 0.5 mm spacing between turns. The outer diameter was 68.5 mm and in the inner diameter was 46.5 mm, see Table 3.2.

Using these physical characteristics, a 3D model of the square planar inductor was built in ANSYS Maxwell and its inductance was simulated. Figure 3.3 shows the 3D model of the

	w	s	d_{out}	d_{in}	n
Value	0.5	1	68.5	46.5	8

Table 3.2: Design 1 physical specifications of square planar inductor (all values given in mm)

inductor for Design 1. Figure 3.4 shows the fabricated inductors.

Figure 3.3: Square planar inductor for sensor Design 1.

Figure 3.4: Fabricated inductors for sensor Design 1. Inductor printed with silver ink (left). Inductor printed with lithium nickelate (LN) ink (right).

For the square planar inductor of Design 2, we used a fifteen-turn inductor coil. The coil was 0.3 mm wide with 0.3 mm spacing between turns. The outer diameter was 36.2 mm and in the inner diameter was 18.8 mm, see Table 3.3. Design 2 was nearly half the size of Design 1.

Using these physical characteristics, 3D model of the square planar inductor was built in ANSYS Maxwell and its inductance was simulated. Figure 3.5 shows the 3D model of the inductor for Design 2.

	w	s	d_{out}	d_{in}	n
Value	0.3	0.3	36.2	18.8	15

Table 3.3: Design 2 physical specifications of square planar inductor (all values given in mm)

Figure 3.5: Square planar inductor for sensor Design 2.

For the square planar inductor of Design 3, we used a fifteen-turn inductor coil. The coil was 0.15 mm wide with 0.15 mm spacing between turns. The outer diameter was 19 mm and in the inner diameter was 10.3 mm, see Table 3.4.

Using these physical characteristics, 3D model of the square planar inductor was built in ANSYS Maxwell and its inductance was simulated. Figure 3.6 shows the 3D model of the inductor for Design 3.

Figure 3.6: Square planar inductor for sensor Design 2.

To complete the modeling of the LC circuit, a 3D model of the interdigitated capacitor was built in ANSYS Maxwell. An interdigitated capacitor (IDC) was chosen as this type of

	w	s	d_{out}	d_{in}	n
Value	0.15	0.15	19	10.3	15

Table 3.4: Design 3 physical specifications of square planar inductor (all values given in mm)

	w	λ	G	β	α	n
Value	2.5	7	1	1	37	15

Table 3.5: Design 1 Physical specifications of the IDC (all values given in mm, except for n)

capacitor could be easily printed onto various surfaces and substrates. An IDC is specified by the following physical characteristics: number of fingers (n), width of the fingers (w), spacing between the fingers (G), distance between the fingers (λ). Figure 3.7 shows an example of an IDC [12].

Figure 3.7: Interdigitated Capacitor [12].

As in the process of designing the square planar inductors of the three sensor designs, a target resonant frequency of 13.5 MHz was chosen. (3.2) and (3.3) were used to analytically determine the capacitance required given the inductance of the sensor design's inductor. (3.3) was used to determine the physical characteristics of the interdigitated capacitor. A unique interdigitated capacitor was designed for each sensor design. When the IDC was paired with the corresponding inductor the LC circuit would yield a resonant frequency of 13.5 MHz. Tables 3.5, 3.6, 3.7 show the physical characteristics for the interdigitated capacitors for sensor Design 1 – 3 respectively. Figure 3.8 and Figure 3.9 show the 3D models of the IDCs for Design 1 – 3 respectively.

Having built the 3D models of the square planar inductors and the interdigitated capacitors for sensor designs Design 1 – 3, the ANSYS Maxwell software was used to simulated

	w	λ	G	β	α	n
Value	0.3	1.2	0.3	0.3	35	64

Table 3.6: Design 2 Physical specifications of the IDC (all values given in mm, except for n)

	w	λ	G	β	α	n
Value	0.2	0.8	0.1	0.1	20	80

Table 3.7: Design 3 Physical specifications of the IDC (all values given in mm, except for n)

Figure 3.8: Square planar inductor for sensor Design 1 (left), Fabricated IDC for Design 1 (right).

these components inductance and capacitance. For each sensor design, ANSYS Maxwell was used to make an equivalent circuit of the inductor and capacitor connecting them in parallel. Frequency analysis and simulation of these circuits was performed and the simulated resonant frequency of the sensor designs were found. These simulation results will be discussed in the next chapter.

Figure 3.9: Square planar inductor for sensor Design 2 (left) and Design 3 (right).

3.5 Digital Signal Processing Methods Used to Measure Temperature

This section of the thesis details the two advanced signal processing methods used to estimate the temperature of the environment around the sensor. The application of these advanced signal processing methods to the problem of estimating the temperature around the sensor through frequency information and wireless communication is a new novel approach to solving the problem of monitoring temperature in extreme harsh environments through passive wireless communications. The first method used was cross-correlation and the second method was the minimization of absolute error. Both of these advanced signal processing methods were implemented in algorithm form and used in MATLAB to estimate the temperature given the frequency response of the sensor.

Signal correlation is often used in signal ranging applications and digital communication to compare how similar two signals are. These ranging applications involve a radar signal might be transmitted toward a distance object. The reflected signal is observed and correlated with the original transmitted signal to find the delay between the signals. This delay can be used to determine the distance to the object. In the digital communications application, a transmitter is able send a set of possible signals. The receiver needs to de-

termine which of these signals was sent and can use correlation to make this determination [28]. Thus it is only natural to use crosscorrelation to compare the frequency response of our sensor at an unknown temperature to a database of frequency response (termed *temperature signatures* of the sensor at a given temperature) of the sensor at set temperatures. The temperature signature in the database that is the most similar to the the frequency response of the sensor at the unknown temperature yields estimate for the unknown temperature. The autocorrelation function can be defined in [28] by

$$r_{xx}[\gamma] = \sum_{k=-\infty}^{\infty} x[k]x[k - \gamma]. \quad (3.4)$$

This equation can be maximized when $\gamma = 0$ as given by

$$\operatorname{argmax}_{\gamma} r_{xx}[\gamma] = 0 \quad (3.5)$$

where the maximum value is the signal energy given by

$$\max_{\gamma} r_{xx}[\gamma] = \sum |x[k]|^2 = E_x. \quad (3.6)$$

This concept of autocorrelation can be used to compare two different sequences is defined by

$$r_{xw}[\gamma] = \sum_{n=-\infty}^{\infty} x[n]w[n - \gamma]. \quad (3.7)$$

The environment in which (3.7) will be applied is a lag-free environment, thus there is no delay. As such (3.7) can be modified to

$$r_{xw}[0] = \sum_{n=-\infty}^{\infty} x[n]w[n]. \quad (3.8)$$

The above crosscorrelation is implemented in vector form as shown below. Let our database of temperature signatures be defined by $\mathbf{C} = [\mathbf{C}_1, \mathbf{C}_2, \dots, \mathbf{C}_m]$ where $\mathbf{C}_i$ is the i -th temperature signatures in $\mathbf{C}$ in column-vector form and has length n . Let the frequency response of the sensor at the unknown temperature be defined as the column-vector $\mathbf{x}$ of length n . As such the cross-correlation can be computed in vector form by

$$\mathbf{d} = \mathbf{x}^T \mathbf{C}. \quad (3.9)$$

In (3.9), $\mathbf{d}$ is vector of length m and the index of the maximum value yields the temperature signature that is the most similar to the unknown temperature.

It should be noted that in the implementation of using the crosscorrelation to estimate the temperature around the sensor, it is assumed that the sensor exists in an additive noise environment. This assumption yields a linear statistical relationship between a database of frequency responses of the sensor operating at set temperatures and the frequency response of the sensor taken at unknown temperature. Other methods, which do not require statistical linearity such as machine learning or deep learning, can be implanted in place of using cross-correlation to estimate the temperature if the statistical relationship between the database of frequency responses of the sensor operating at set temperatures and the frequency response of the sensor taken at an unknown temperature is not statistically linear.

The second signal processing method used to estimate the temperature given frequency information was the minimization of absolute error. This method is mathematically simple and does not need a long derivation. If the column vector $\mathbf{x}$ is placed into a matrix called $\mathbf{Y}$ which has m columns and $\mathbf{x}$ is stored in each the m columns. The absolute difference between the matrix $\mathbf{Y}$ and $\mathbf{C}$ can be computed by

$$\mathbf{D} = |\mathbf{Y} - \mathbf{C}|. \quad (3.10)$$

One can then sum each column in the difference matrix $\mathbf{D}$. The column that is the minimum yields the temperature signature that is the most similar to the unknown temperature. In this manor the minimization of absolute error can be used to estimate temperature data given frequency information. The application of these two signal processing methods used to estimate the temperature given frequency information is discussed in the next section.

3.6 Experimental Process

This section details the experimental setup and process used to perform high temperature sensing through passive wireless communications using the LC sensors presented in this

thesis. To perform the high temperature sensing experiments, a high temperature testbed was developed. Figure 3.10 show this testbed. A box furnace (shown on the far left of Figure 3.10) was used to heat the sensors. This box furnace was capable of reaching temperatures above 1000 C. The sensors were placed into the box furnace and separated by 6 inches, see Figure 3.11.

Figure 3.10: High temperature testbed.

Figure 3.11: Lanthanum nickelate (LN) based LC sensor placement in box furnace (left), receive sensor (right).

The sensor placed on the right in the box furnace functioned as an interrogator antenna which would excite the sensor on the left which was used to measure the temperature and functioned as the receive sensor. The sensor on the right was connected to the signal generator and the left sensor was connected to the spectrum analyzer which was used to record the sensor's frequency response.

The signal generator would send a tone, sweeping from 10 MHz to 80 MHz, to the interrogator antenna (sensor on the right in the box furnace). The interrogator antenna

would radiate this sweeping tone in the form of an RF signal. the RF signal would excite the receive sensor (sensor on the left in the box furnace) through inductive coupling between the interrogator antenna's inductor and the receive sensor's inductor. This induced inductance causes a current to flow through the receive sensor. The receive sensor re-radiates the RF signal. The re-radiated RF signal is recorded by the signal analyzer. Thus, for a given experimental run, the signal generator would send a sweeping tone through the interrogator antenna to the receive sensor. The frequency response of the receive sensor to the sweeping tone would be recorded by the signal analyzer. An example of this frequency response by the receive sensor can be seen on the monitor on the right of Figure 3.10.

The box furnace would be set to a temperature and steady state would be achieved. The sweeping tone would be sent through the interrogator antenna to the receive sensor. The signal analyzer would record the receive sensor's frequency response to this sweeping tone at the given temperature. This process would be repeated several times for each temperature values that the furnace was set to. The frequency response of the sensor at a given temperature value would be averaged and this averaged result would be called the temperature signature of the receive sensor for that given temperature. The furnace was heated from room temperature to 700 C in evenly spaced increments. At each incremental temperature, the frequency response of the receive sensor was measures several times and then averaged. This yielded the sensor's temperature signature for the incremental temperature. In this way a database of temperature signatures of the sensor at these incremental temperatures was built. The database contained the temperature signatures of the sensor for each incremental temperature between room temperature and 700 C. After building the database of temperature signatures, the furnace would be set to an unknown temperature between room temperature and 700 C. The frequency response of the sensor at this unknown temperature value would be compared to the database of temperature signatures. The temperature signature that was the closest match to the frequency response of the sensor at the unknown temperature would the best estimate for the unknown temperature value. The frequency response of the sensor at the unknown temperature would be compared to the database of temperature signatures using correlation or the minimization of absolute error. By implementing these comparison methods, the value of the unknown temperature could be estimated.

The following algorithms were implemented in MATLAB to use correlation and minimization of absolute error to compare the frequency response of the sensor at the unknown temperature to the database of temperature signatures. The temperature signatures were placed into a matrix where each column represented a unique temperature signature of n rows. The frequency response of the sensor at the unknown temperature was placed into a vector of length n .

As in specified in Section 3.5, let the frequency response of the sensor at the unknown temperature be a column vector $\mathbf{r}$ of length n , and let the temperature signatures be placed in a matrix defined by $\mathbf{C}$, where the m columns represents the m unique signature and the n rows are the returned signal strength (RSS) values at the measured n frequencies.

Correlation Algorithm:

1. Evaluate $\mathbf{d} = \mathbf{x}^T \mathbf{C}$.
2. Find the index of maximum of vector $\mathbf{d}$.

Minimization of Absolute Error Algorithm:

1. Generate a matrix $\mathbf{Y}$ which has the same number of columns and rows as $\mathbf{C}$.
2. Place $\mathbf{r}$ in each column of $\mathbf{Y}$.
3. Evaluate $\mathbf{D} = |\mathbf{Y} - \mathbf{C}|$.
4. For the m columns in $\mathbf{D}$ sum the n rows
 - for $i = 1 : m$
 - $\mathbf{d}_i = \sum_{j=1}^n [\mathbf{D}]_{i,j}$
5. Find the index of minimum of vector $\mathbf{d}$.

Building the sensor of a ceramic material with a temperature dependent dielectric constant which causes the frequency response of the sensor to shift as temperature changes ensures that the sensor has a unique frequency response for a given temperature. A database of these temperature signatures of the sensor at set temperatures can be then built. One can

then estimate the temperature by comparing the frequency response of the sensor at the unknown temperature to the database of temperature signatures. The results of implementing these comparison methods is presented in Chapter 4.

3.7 Chapter Contributions

This chapter presents several contributions to the problem of extreme high temperature sensing and to West Virginia University's (WVU) laboratory capabilities. Foremost, this thesis presents a new novel method of using frequency information from passive wireless communications to measure extreme high temperatures. By observing over a large band of RF spectrum rather than only observing the resonant frequency peak, advanced signal processing methods can be used to correlate shifts in the sensor's frequency response to changes in temperature. As these correlation methods continue to be improved and a larger database is generated, big data analytics from Machine Learning and Neural Networking can be used to estimate the temperature given the frequency response of the sensor. This thesis also presents a novel inductor / capacitor (LC) passive wireless temperature sensor design capable of measuring extreme high temperatures. The establishment of the high temperature testbed gives WVU's laboratories the capability to perform passive wireless temperature sensing from room temperature to over 1000 C. This testbed was built in such a way that existing sensors could be easily removed and new sensor could be easily connected to the RF equipment. The 3D models give the WVU laboratories the ability to quickly make modifications to existing sensor designs and to simulate results of the changes.

Chapter 4

Results

4.1 Introduction

This chapter of the thesis discusses the results of modeling and simulating the LC sensor designs in the ANSYS Maxwell software. It then discusses the results generated using the high temperature testbed to perform high temperature passive wireless temperature sensing with fabricated LC sensors.

4.2 ANSYS Modeling and Simulation Results

This section of the thesis discusses the results of modeling and simulating the inductor / capacitor components of the passive wireless high temperature LC resonance sensors. The ANSYS Maxwell software was used to build 3D models of the square planar inductor and the interdigitated capacitor. Three versions of the sensor were simulated. These versions were Design 1–3 as described in Section 3.4. The LC sensor Design 1 had overall dimensions of 2 in by 4 in, Design 2 was 2 in by 2 in, and Design 3 was 1 in by 1 in. With each sequential sensor design, the sensor's footprint was reduced in order to procedurally arrive at a sensor design that had a sufficiently small form factor. Only Design 1 was fabricated and tested. For each sensor design, the inductance, capacitance, and resonant frequency were simulated. The 3D models of the square planar inductors and IDCs were used to simulate the inductance and capacitance respectively. ANSYS Maxwell was then used to generate an

Sensor Design	Inductance (uH)	Capacitance (pF)	F_{res} (MHz)
Design 1	6.9425	19.815	13.569
Design 2	9.4696	14.182	13.734
Design 3	5.2479	25.527	13.751

Table 4.1: Simulated inductance, capacitance, and resonant frequency (F_{res}) for the modeled sensor designs, Design 1

equivalent circuit of these 3D models. A frequency analysis was performed on the equivalent circuit and the resonant frequency of the simulated sensor was found. Figure 4.1 shows the simulated resonant frequency for sensor Design 1. Table 4.1 shows the simulated inductance, capacitance, and resonant frequency for sensor designs 1–3. The physical dimensions of the square planar inductors and the IDCs were manipulated for each design to reduce the overall size of the sensor while maintaining a resonant frequency near 13.5 MHz.

Figure 4.1: Simulated resonant frequency for sensor Design 1.

As stated in Section 3.2 of this thesis, a very important process in the system engineering approach to research and development is the comparison of simulated results of a modeled system to the actual results of the system operating in the environment it was designed for. In order to verify the simulations' results and the accuracy of the 3D models developed in ANSYS Maxwell, sensor Design 1 was fabricated using a ceramic substrate on which the square planar inductor and the IDC was printed using a silver based ink. The inductance

Sensor Design	Inductance (uH)	Capacitance (pF)	F_{res} (MHz)
Simulated	6.942	19.815	13.569
Fabricated	5.82	19.9	14.789

Table 4.2: Comparison of the simulated sensor and the fabricated sensor of Design 1

of the square planar inductor and the capacitance of the IDC were then measured for the fabricated sensor. Table 4.2 compares the simulated inductance, capacitance, and resonant frequency of the simulate 3D models to the measured inductance, capacitance, and resonant frequency of the fabricated sensor.

As can be seen in Table 4.2, the simulated and measured values for inductance, capacitance, and resonant frequency are close. This means that the 3D models, developed in ANSYS Maxwell, of the sensor are accurate. In addition to being fabricated on a ceramic substrate with silver ink, sensor Design 1 was also fabricated on a ceramic substrate and the square planar inductor and the IDC were printed using a conductive ceramic based lithium nickelate (LN) based ink. Figure 4.2 shows the square planar inductor for the ANSYS 3D model, the sensor with silver ink, and the sensor with LN ink. Figure 4.3 shows the IDC for the ANSYS 3D model, the sensor with silver ink, and the sensor with LN ink.

Figure 4.2: Design 1 square planar inductor for ANSYS 3D model (left), sensor with silver ink (center), sensor with LN ink (right).

One thing that was noted, during the fabrication of these sensors and the measuring of their inductance and capacitance, was that if these sensors were fired their inductance and capacitance would change. Firing a sensor means that, after the fabrication process, the sensor is placed into a furnace and very slowly heated to a specified temperature. The sensor is left in the furnace at that specified temperature for a certain amount of time. This process

Figure 4.3: Design 1 IDC for ANSYS 3D model (left), sensor with silver ink (center), sensor with LN ink (right).

Sensor Design	Inductance (μH)	Capacitance (pF)
Design 1 unfired	5.82	19.9
Design 1 fired to 500 C	5.88	1360

Table 4.3: Inductance and capacitance of sensor with silver ink before and after being fired to 500 C

is performed so that the ceramic substrate and the printed circuit are slowly exposed to very high temperatures. This process burns off any impurities on the sensor and ensures that after this process the sensor should not suffer extreme changes such as significant thermal expansions due to high temperatures. This is done to ensure that the sensor is stable and will not undergo undue stress when it operates in a high temperature environment. However, it was noticed that a side effect of the firing process, was that the inductance and capacitance values of the sensor's square planar inductor and the IDC changed. Table 10 shows the inductance and capacitance of the sensor with silver ink before and after firing it. One can see that firing the sensor had a significant impact on the sensor's capacitance. This fact will be discussed later in this chapter.

4.3 Single-Use High Temperature Passive Wireless Temperature Sensor

This section discusses the high temperature passive wireless temperature sensing results for two Design 1 sensors fabricated with different conductive inks. The first version of the

sensor used a silver ink to print the LC resonance circuit on the ceramic substrate and the second version of the sensor used a LN based ink to print the LC resonance circuit on the ceramic substrate. These sensors were able to successfully measure changes in temperature by using passive wireless communications. These sensors serve as a single-use method for passive wireless measuring of extreme temperatures. For this thesis, single-use is defined as taking the sensor from room temperature to an extreme high temperature in a single instance. This implementation of the sensor does not allow for repeated heatings of the sensor or for the sensor to be left for a significant amount of time at an extreme high temperature. The high temperature testbed shown in Figure 3.10 was used to perform the high temperature sensing experiments. The passive wireless temperature sensing experiments were split into two phases. The first phase would use the silver ink sensors and the second phase would use the LN ink sensors.

For the first phase, two identical sensors with silver ink were used in the passive wireless temperature sensing. Figure 4.4 shows the LC resonant sensor made from ceramics and silver ink. The square planar inductor and IDC were connected to each other in parallel. The two sensors were placed inside the furnace and then high temperature passive wireless temperature sensing was performed as described previously in Section 3.6. The furnace was heated from room temperature to 70 C for the phase 1 and from room temperature to 700 C for phase 2. In each phase, the temperature was raised in set increments and steady state was achieved at each increment. At each incremental temperature, the signal generator would transmit a narrow sweeping tone through the transmit sensor (interrogator antenna) to the receive sensor (receive antenna). The signal analyzer connected to the receive sensor recorded the frequency response of the receive sensor. The frequency response of the receive sensor was recorded multiple times. These frequency responses of the sensor at the incremental temperature was then averaged. This averaged frequency response is the temperature signature of the sensor at the incremental temperature.

Figure 4.5 shows the temperature signatures for the sensor fabricated with silver ink for the temperatures from room temperature to 70 C. It can be seen that the temperature signatures are unique and distinguishable.

Figure 4.6 shows the same temperature signatures as Figure 4.5; however, it is zoomed

Figure 4.4: Design 1 sensor fabricated on ceramic substrate with silver ink.

into the region of 44 MHz – 52 MHz to better illustrate the uniqueness of the temperature signatures. The silver based sensors had a sensitivity of 7.04 kHz/C.

For phase 2, two identical sensors of Design 1 were made with a ceramic substrate and the LC resonance circuit was printed with an LN based ink. Figure 4.7 shows the LC resonant sensor made from ceramics and LN based ink. The square planar inductor and IDC were connected to each other in parallel. These sensors were placed in the furnace in the high temperature testbed. The furnace was heated, in set increments, from room temperature to 700 C. As in phase 1, at each increment, steady state was achieved and the frequency response of the receive sensor was recorded multiple times and then averaged. This averaged frequency response of the sensor at the incremental temperature is the temperature signature of the sensor at that incremental temperature.

Figure 4.8 shows the temperature signatures for the sensor fabricated with silver ink for the temperatures from room temperature to 700 C. It can be seen that the temperature signatures are unique and distinguishable.

Figure 4.5: Temperature signatures for the sensor fabricated with silver ink for the temperatures from room temperature to 70 C.

Figure 4.9 shows the same temperature signatures as Figure 4.8; however, it is zoomed into the region of 44 MHz – 52 MHz to better illustrate the uniqueness of the temperature signatures. The LN based sensors had a sensitivity of 1.88 kHz/C.

Both the LC resonance sensor made with silver ink and the LC resonance sensor made with LN based ink showed unique and distinguishable temperature signatures as the temperature was increased. Thus, these sensors can be implemented as a single-use passive wireless temperature sensors. The temperature signatures of these sensors can be stored in a database. Then, if the quality control of the fabrication process for these sensors is good and consistent, one can compare the frequency responses of the sensor at an unknown temperature to the database of temperature signatures and use the signal processing methods

Figure 4.6: Temperature signatures for the sensor fabricated with silver ink for the temperatures from room temperature to 70 C.

discussed in Section 3.5 to estimate the unknown temperature. In the case of using correlation, the temperature signature in the database, when compared to the frequency response of the sensor at the unknown temperature, that yielded the largest correlation coefficient would be the best estimate for the unknown temperature. In the case of minimizing the absolute error, the temperature signature in the database, when compared to the frequency response of the sensor at the unknown temperature, that yielded the smallest absolute error would be the best estimate for the unknown temperature. In this manor, this thesis presents a successful design of a passive wireless high temperature sensor and successfully demonstrated the passive wireless sensor's ability to measure extreme high temperature through passive wireless communications.

Figure 4.7: Design 1 sensor fabricated on ceramic substrate with LN based ink.

4.4 Multi-Use High Temperature Passive Wireless Temperature Sensor

The goal of the research performed for this thesis was to design and develop a multi-use high temperature passive wireless temperature sensor. To present a viable solution to the challenge of measuring and monitoring the temperature in turbine and jet engines, a sensor needs to be designed in such a way that it will continue to function over repeated heating and cooling cycles of these engines. This thesis defines a multi-use sensor as a sensor whose physical characteristics revert back to their original state after being repeatedly heated up to extreme temperatures and then cooled to room temperature. During this process the sensor must remain undamaged by the heating / cooling, the physical characteristics of the sensor (its dielectric constant, impedance, capacitance, etc.), must remain the same for a given temperature, and the frequency information captured from the sensor at a given temperature must be repeatable. A sensor must exhibit these properties to be consider capable of being

Figure 4.8: Temperature signatures for the sensor fabricated with LN ink for the temperatures from room temperature to 700 C.

used as a multi-use high temperature passive wireless temperature sensor. Now the physical characteristics of the sensor like its dielectric constant have been design to change with temperature, to be temperature dependent. However, after the sensor is heated and then cooled, these characteristics must revert back to their original state. If these characteristics do not revert back to their original state the sensor will not function as a multi-use high temperature passive wireless temperature sensor. This is because if the sensor, after being heated and cooled, does not revert back to its original state, it means that its physical characteristics like its dielectric constant, impedance, and capacitance have changed and taken on new values rather than reverting back to their original values. These new values will cause the sensor to have new and different frequency responses to temperatures. Thus,

Figure 4.9: Temperature signatures for the sensor fabricated with silver ink for the temperatures from room temperature to 70 C zoomed into 44 MHz – 52 MHz. One can clearly see how the peak frequency changes with temperature.

the new frequency response of the sensor at temperature T will not match the original frequency response of the sensor at temperature T . This means that the measurements of the sensor's frequency response at a given temperature are not repeatable. Thus, using methods that compare the frequency information of the sensor will not work. Because of this, peak tracking (used in the sensor designs described in Chapter 2), correlation, and the minimization of the absolute error (advanced signal processing method proposed in this thesis) cannot be used to estimate the temperature around the sensor. This is because after each time the sensor is heated and cooled, the frequency information of the sensor at temperature T changes and will not match its previous state at temperature T .

It is unfortunate to note that, in analysis the data collected in Phase 1 testing of the

sensor with silver ink and Phase 2 testing of the sensor with LN ink, these sensors will not function as multi-use high temperature passive wireless temperature sensors. The following portion of this thesis will demonstrate the sensor's inability to function as multi-use high temperature passive wireless temperature sensors as well as investigate what caused these sensors to fail in this role. Based on the experimental results, it appears that heating these fabricated sensors to extreme high temperatures changes the physical characteristics of the sensors and that the sensors do not revert back to their original state after being cooled.

Figure 4.10 shows the temperature signatures for the sensor with LN based ink. The figures show the temperature signatures of this sensor at 100 C – 700 C (this data is also shown in Figure 4.8 in Section 4.3). This data was collected over two days. During the first day (October 10th), the sensor was heated from 50 C to 450 C in 50 C increments and the temperature signatures were recorded. The sensor was then left overnight at 500 C. The next day (October 11th), the sensor was then heated from 500 C to 700 C in 50 C increments and the temperature signatures were recorded. During these two days nothing in the high temperature testbed was changed or disconnected. Only the temperature of the furnace was raised from 50 C to 700 C in 50 C increments over the two days. One can see that there is a significant difference in the temperature signatures of the sensor over these two days. There is a very wide gap between the two signature groups between 30 MHz and 40 MHz. The gap or significant change in the sensors behavior after it rested at a high temperature overnight was the first clue that heating these sensor to high temperature causes the sensor to undergo a physical change that might not be reversible.

The significant change in the temperature signatures of the sensor taken over the two days caused concern that perhaps there was fault in how the data was being captured from the sensors in the high temperature testbed. To ensure that good repeatable frequency data could be captured from the sensors in the high temperature test bed, the LN based sensors in the furnace were kept at a low temperature of 50 C for five hours. Every hour a temperature signature of the LN based sensors was recorded. Figure 4.11 shows the five temperature signatures of the LN based sensors recorded over the five-hour period. This figure shows that the temperature signatures lie on top of each other and are nearly identical. This means that the measurements made by the sensors at low temperature are repeatable. This

Figure 4.10: The gap in the temperature signatures of the LN based sensor.

is a critical observation. As such, the gap in the temperature signatures shown in Figure 4.10 is most likely due to fact that the sensor was exposed to a high temperature and that this exposure caused a physical change in the sensor that did not revert once it was cooled.

This observation lead to the following hypothesis: that, each time the sensor was exposed to a high temperature, the sensor would undergo a physical change and would not revert back to its original state once it was cooled. To test this hypothesis, the LN sensors in the furnace were heated from 50 C to 700 C and then cooled back to 50 C each day. Figure 4.12 shows the temperature signatures recorded from the sensor at 50 C each day. It can be clearly seen that the temperature signature at 50 C is different on each day. As such, the frequency data collected on one day as the sensor is heated and then cooled will not match the frequency data collected on the next as the sensor undergoes the exact same experiment. Thus, the frequency data recorded from this sensor is unrepeatable. This means that using comparison methods like peak tracking, correlation, and the minimization of the absolute

Figure 4.11: Temperature signatures of the LN based sensor at 50 C captured over five hours.

error to estimate the temperature given the frequency data will be unsuccessful. Figure 4.13 shows the same data as in Figure 4.12, however, it is zoomed into the region of 18 MHz – 28 MHz to better show the difference between the temperature signatures recorded over several days.

The results in Figure 4.12 confirms that when the sensors after being heated to a high temperature and then cooled do not revert back to their original state. The following experiment was performed to gain a better understand of why this was the case. Two more LN based sensor were fabricated. Just like the previous sensors, these sensors were fired to 700 C. However, unlike the previous sensors, the square planar inductor and the IDC were not connected to each other. This was done so that the inductance, capacitance, and impedance of these two components could be measured. One sensor would serve as the control sensor and would be placed in open air and remain at room temperature throughout the whole experiment. The second sensor would be placed into the furnace and once a day be heated from room temperature to 700 C and then cooled down to room temperature. At the start

Figure 4.12: LN based sensor's temperature signatures at 50 C over multiple heating and cooling sessions clearly shows the frequency responses measured at 50 C are very dissimilar.

of each day the inductance, capacitance, and impedance of these sensors' inductors and capacitors were measured. The second sensor was then heated to 700 C and then cooled down to room temperature. This process was repeated for several days. As another control in the experimental process the inductance of an off-the-shelf inductor and the capacitance of an off-the-shelf capacitor were also measure along with their impedances. The off-the-shelf inductor and capacitor were kept at room temperature throughout the whole experiment.

Figure 4.14 shows the magnitude of the impedance measured from the three inductors over the eight days that the experiment was run. The grey dots represent the impedance measured from the control sensor's inductor (the sensor that was not heated but kept at room temperature). The yellow dots represent the impedance measured from the heated sensor's inductor (the sensor that was heated to 700 C and then cooled to room temperature once a day). And finally, the blue dots represent the impedance measured from the off-the-shelf inductor. As one would expect the impedance of the control sensor's inductor and the

Figure 4.13: LN based sensor's temperature signatures at 50 C over multiple heating and cooling sessions zoomed into 18 MHz – 28 MHz.

Figure 4.14: Impedance of the inductors over several days.

Day	R ($M\Omega$)	X ($M\Omega$)	C (pF)
Nov 5th	45.961	-20.543	8.301
Nov 6th	15.597	-0.430	395.543
Nov 7th	29.782	-6.056	26.914
Nov 8th	40.910	-15.237	11.789

Table 4.4: Capacitance and complex impedance measured from control sensor's inductor

Day	R ($M\Omega$)	X ($M\Omega$)	C (pF)
Nov 5th	67.235	-65.754	2.775
Nov 6th	22.977	-5.598	28.324
Nov 7th	55.947	-39.646	4.199
Nov 8th	61.256	-72.431	2.345

Table 4.5: Capacitance and complex impedance measured from heated sensor's inductor

off-the-shelf inductor is relatively flat. However, impedance of the heated sensor's inductor undergoes significant changes. This shows that each time the heated sensor was raised to a high temperature its physical characteristics changed and did not revert back to their original state. It should also be noted that the imaginary part of the complex impedance of the inductors for the LN base sensors (control sensor and heated sensor) was negative. As a result, the inductors were in fact acting like capacitors. Table 4.4 and Table 4.5 shows that these square planar inductors had capacitance rather than an inductance.

Figure 4.15 shows the magnitude of the impedance measured from the three capacitors over the eight days that the experiment was run. The grey dots represent the impedance measured from the control sensor's capacitor (the sensor that was not heated but kept at room temperature). The yellow dots represent the impedance measured from the heated sensor's capacitor (the sensor that was heated to 700 C and then cooled to room temperature once a day). And finally, the blue dots represent the impedance measured from the off-the-shelf capacitor. As one would expect the impedance of the off-the-shelf capacitor is relatively flat. However, both the impedance of the control sensor's capacitor and the heated sensor's capacitor undergo significant changes each day. It seems that the open air had some effect

Figure 4.15: Impedance of the capacitors over several days.

on the control sensor's capacitor that caused it to change each day. This was an unexpected finding. Again, this data shows that the sensor's components are undergoing physical changes and not reverting back to their original state. Figure 4.16 shows the capacitance of the three capacitors over the eight days. One can see that each day the capacitance of the capacitor for the control sensor and heated sensor changes with each day. As expected the capacitance of the off-the-shelf capacitor stays constant.

The results in Figure 4.14 show that each time the sensor is heated the impedance of the inductor changes and does not revert back to its original state once the sensor is cooled down. Figure 4.15 shows that as the sensor is heated the impedance of the capacitor changes and does not revert back to its original state once the sensor is cooled down. It also shows that the capacitors impedance is also similarly affected when left in open air at room temperature. These results show that the physical characteristics of the sensors are change over time and not reverting back to their original values. These changes intern cause a change in the sensor's frequency response that will also not revert back to its original state. This means if one

Figure 4.16: Capacitance of the capacitors over several days.

records the frequency response of the sensor at temperature T and then heats the sensor to a high temperature and then cools the sensor before again measuring the frequency response of the sensor at temperature T , these two recorded frequency responses of the sensor at the same temperature will not match. In other words, the frequency data captured from these sensor is unrepeatable and comparison methods like peak tracking, correlation, and the minimization of the absolute error cannot be used to successfully estimate the temperature. As such these sensors will not function as multi-use high temperature passive wireless temperature sensors. Based on the experimental results, it appears that the materials used to fabricate the sensors are inadequate for the task. It has been shown that it is the physical characteristics of the materials used in making the sensor that are causing the issue. Until these materials can be stabilized or new materials are used, these problems will continue to persist.

Chapter 5

Conclusion

5.1 Conclusion and Summary

As the technologies in the aerospace and electrical power generation fields continue to advance, the operating temperature of the jet and turbine engines used in these fields continues to increase in order to achieve higher engine efficiencies. As such, there is a critical need for a passive wireless temperature sensor capable of monitoring the extreme high temperatures in the jet and turbine engines. This thesis has reviewed current state-of-the-art passive wireless sensing technologies attempting to solve this issue and noted several weaknesses in these sensing systems. This thesis proposed a LC resonance passive wireless sensor design capable of operating in extreme high temperatures and measuring these temperatures. In addition to this, a new novel method of using frequency data to measure the temperature was proposed. Rather than observing a small amount of frequency information (peak tracking), this thesis proposed observing a wide band of spectrum. This gives a wealth of frequency information and many degrees of freedom. This allows for advanced signal processing methodologies from different application areas such as wireless communications, radar, and radio astronomy to be applied to this problem. This thesis proposed using correlation and the minimization of the absolute error to use the frequency data gathered through passive wireless communications to estimate the temperature. The LC resonance sensors were modeled and simulated in ANSYS Maxwell and then fabricated. A high temperature testbed was created to perform high temperature passive wireless temperature sensing with the fabricated sensors. The fab-

ricated sensors were successfully used as single-use high temperature sensors. This thesis also demonstrated, that due to the materials used to make the sensors, these sensors are unable to function as multi-use high temperature sensors. This is because each time these sensors are exposed to extreme temperatures their physical characteristics change and then when the sensors are cooled the changes do not revert back to their original values.

5.2 Future Work

For future work, we suggest the following efforts to overcome the noted deficiencies:

- We want to fire the sensors to 700 C and leave the sensors at this temperature for an extended period of time (more than a few days).
- After these sensors have been fired to 700 C as stated above, set one sensor as the control sensor and one sensor as the sensor to be heated. Measure the inductance, capacitance, and impedance of these sensors and then repeatedly heat one sensor to 700 C and then cool the sensor to room temperature. After the sensor is cooled to room temperature re-measure the inductance, capacitance, and impedance of these sensors. See if the physical characteristics of these sensor change and if once changed do they revert back to their original state.
- If the sensor stated above experience physical changes and then, once cooled, these physical changes revert back to the original state, place both sensors in the furnace. At room temperature, record the frequency response of the receive sensor than heat the furnace to 700 C. Cool the furnace down to room temperature and re-record the frequency response of the receive sensor. Perform this experiment several times. If the frequency responses are the same then the sensors can now likely be used as multi-use high temperature sensors.
- With these sensors, we want to generate a database of temperature signatures and then set the furnace to a random temperature. we will then record the frequency

response of the receive sensor and compare this frequency response to the database using correlation or the minimization of the absolute error.

To overcome material deficiencies of current fabricated sensors, we suggest the following efforts:

- We want to continue to model and simulate sensor designs of a small form factor (under 1 in).
- We need to develop a ruggedized interrogator antenna capable of withstanding extreme harsh environments.
- we want to start implementing modern signal processing approaches such as feature extraction, machine learning, and deep learning that have been developed in other application areas like fingerprint / iris recognition and computer vision.
- We will generate a large database of temperature signatures and investigate the benefits realized from using big data analytics from neural networking to estimate / predict the temperature.

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