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RFID Tag Antenna Based Temperature Sensing Using Shape Memory Polymer Actuation

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***Abstract*— Ubiquitous temperature monitoring is important to boost visibility in applications such as cold supply chain management. Current sensors monitor and log a time history of temperature data, but their cost limits the scale of deployment. In this paper, we propose an ultra-low cost temperature threshold sensor using the UHF RFID tag antenna as a sensing mechanism. Permanent changes are induced in the tag antenna electrical properties upon violation of a temperature threshold. This manifests itself in a change in backscatter power detected at the reader. We demonstrate how these changes are effected via shape memory polymer actuation. Experiments demonstrate that cheap, reliable temperature threshold sensors can be developed which are independent of the material of deployment, orientation of the sensor, which have a read range of over 3 m and which have a customizable critical temperature threshold.**

I. INTRODUCTION

Monitoring critical parameters such as temperature, relative humidity and vibrations is very important in supply chain operations. There are several wireless temperature sensing solutions commercially available today, but expense typically constrains the scale at which they can be deployed in transit operations. Temperature profiles within a cold room are thus inferred based on data points obtained by a limited number of representative sampling points. Unfortunately, temperatures within a cold chain environment tend to fluctuate [1] and with an estimated 30% perishable goods typically spoiling in transit, there is a need for larger scale of sensor deployment in cold chain operations [2]. Ideally, sensors should be deployed at the item or case level in supply chain operations.

Most wireless sensors today possess on-board memory and power to record and maintain a time history of temperature measurements. However the presence of discrete electronic components increases the cost and this limits the scale of deployment. For truly ubiquitous sensing, the sensor nodes themselves need to be very cheap, ideally in the sub $1 price range. In this paper, we examine the potential of UHF RFID tags to serve as ultra-low cost temperature alarm sensors which are capable of detecting temperature violations above a critical temperature threshold by mapping such a change to a permanent change in RFID tag backscatter power signal strength response. We make use of a shape memory polymer based actuation mechanism to trigger this state change, even in the absence of reader transmitted power, in effect designing a low cost non-electric memory mechanism.

Section II introduces some of the prior development work in the area of wireless temperature sensing and the shortcomings that preclude their pervasive deployment. Section III then outlines the design of the prototype of an RFID shape memory polymer based temperature threshold sensor that has the potential to be ubiquitously deployed in supply chain applications. Section IV then outlines the results from experimentation and finally Section V summarizes the advantages of the sensor design while enumerating the trade-offs.

II. RELATED WORK

There has been a lot of prior effort in developing wireless temperature sensors for several diverse applications [3]. While these sensing units are useful for obtaining a limited number of spatial samples in their environment of deployment, the on-board memory and power supply systems make these sensing units expensive and not suited for item or case level tagging in cold chain operations.

The passive UHF RFID infrastructure has several advantages as a potential communication medium for temperature sensing data. In order to stay competitive with alternative technologies such as the bar code, much research effort has gone into improving the feature set of the tag such as lowering the cost of the RFID tag [4], making it less power hungry for improved read range [5] and developing a standardized communication protocol [6]. The net result of this research is a mature low cost, standardized communication framework that can be exploited for applications such as wireless sensing.

There has been prior research into using RFID as a front end to sensor electronics. For instance Sample *et al.* [7] present a passive UHF RFID front end to temperature sensing. There have also been several commercial instances of semi-passive RFID based temperature sensor tags. An excellent review of interfacing sensors with RFID tags can be found in [8]. Sensors with a passive front end can report instantaneous temperature readings at the time of reader query, but cannot record critical state changes in the absence of reader transmitted power. Semi-passive tag sensors can record time history of data but this adds a cost overhead in terms of an on-board battery and memory. Furthermore in the case of sensor-RFID tag integration, the design and assembly of the discrete electronic components adds a cost overhead to the sensing unit and thus we desire a sensing mechanism that makes minimalistic changes to the RFID tag itself and which is capable of logging critical state violations even in the absence

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of reader transmitted power.

We consider an alternative approach of using the RFID tag antenna as a sensing mechanism by mapping violations of critical thresholds in parameters like temperature to changes in the RFID tag antenna's electrical properties [9]. Similarly, Siden *et al.* describe the construction of a humidity sensor based on this principle [10], while Marrocco *et al.* discuss how the dielectric permittivity of different media [11] can be monitored. As prior work, we designed a temperature threshold sensor by using state changes of a fluid dielectric and actuation of a metal plate [12] to induce changes in the electrical properties of an RFID tag antenna upon violation of a critical temperature threshold. Through the design, we also demonstrated the concept of non-electrical memory whereby critical threshold violations are recorded even in the absence of reader transmitted power. While the design proposed in [12] certainly demonstrated proof of concept, it suffered from shortcomings such as dependence on orientation of sensor deployment, cumbersome initialization, poor read range and performance being influenced by the material of deployment. In this paper, we propose the design of a temperature threshold sensor that makes use of a shape memory polymer based actuation to trigger antenna electrical property changes upon violation of a critical temperature threshold. In the sections that follow, we will discuss the design of the sensor, demonstrate proof of concept and discuss the advantages as well as shortcomings of this kind of sensor design.

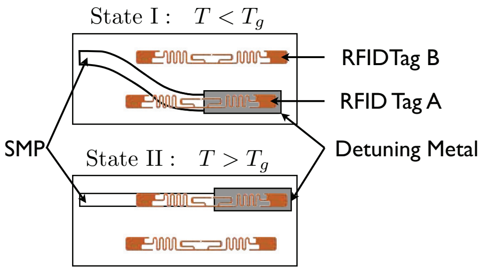
III. SENSING PRINCIPLES

In this section, we consider the design principles for the shape memory polymer based sensor. We first highlight the prototype design and operating principle of the sensor. We then provide an overview of shape memory polymers and how the property called the glass transition temperature relates to the critical temperature threshold that we are interested in monitoring. We then discuss how heat transfer principles can be utilized to select specific dimensions for the temperature sensor casing as an attempt to control the time taken for the alarm mechanism to actuate when subjected to a specified external temperature that violates the critical threshold.

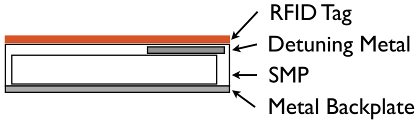
A. Sensor Design

In this sensor design, we make use of the fact that RFID performance degrades in close proximity to metals to trigger a critical state change upon violation of a temperature threshold. We consider the design proposed in Fig. 1(a) and Fig. 1(b). The temperature sensor consists of two RFID tags separated by a distance of 25 mm on a plastic jacket. A bridge made of shape memory polymer (SMP) material with an attached metal plate is used to selectively move a metal plate behind one of the two RFID tags.

As we can see from Fig. 2, the temperature sensor is initialized by placing it below the glass transition temperature, denoted by T_g in Fig. 2(A), so that the polymer enters the rigid state. The sensor is then placed on the goods to be monitored in the cold room and the pin is pulled clear arming the sensor, as shown in Fig. 2(B). If the goods are always kept at or below the threshold temperature, the metal plate remains behind tag A shown in Fig. 1(a) detuning it. Tag A thus responds with a worse backscatter signal relative to Tag B. However, if the sensor is exposed to temperatures higher than the glass transition temperature, then the polymer actuates and the metal plate moves detuning tag B, as outlined in Fig. 2(C & D). Thus tag B now responds with a weaker signal. By observing tag A's response relative to tag B, it is possible to infer that a critical temperature threshold has been violated. A picture of the final temperature sensor prototype is shown in Fig. 3.



(a) Temperature Sensor in Plan



(b) Temperature Sensor in Elevation

Fig. 1. Temperature Sensor Design

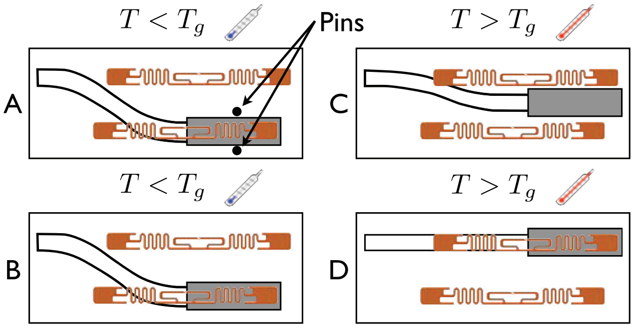


Fig. 2. Temperature Sensor Working

B. Shape Memory Polymers as an actuation mechanism

Shape-memory polymers whose shape-recovery is thermally-induced, can be subjected to large deformations at a temperature above their glass transition temperature, T_g. Cooling the polymer to a temperature below T_g while holding the imposed deformation fixes such deformation of the polymer. The original shape of the polymer may be recovered if the material is heated back to a temperature above T_g. Because of this behavior, shape-memory polymers are ideally suited for use as thermal sensing mechanisms.

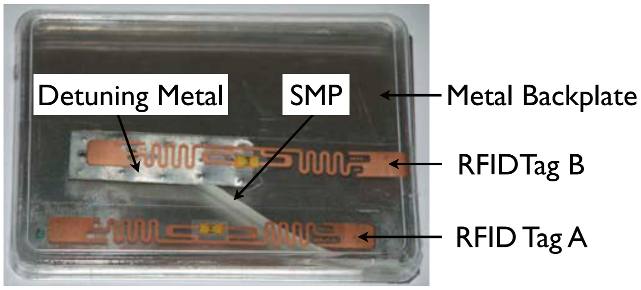


Fig. 3. Temperature Sensor Prototype

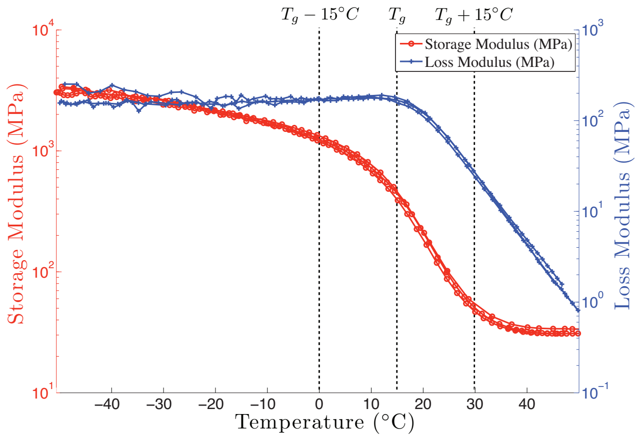


Fig. 4. DMA curves of 50 mol% tBA co 50 mol% PEGDMA

For this study we chose to use the chemically-cross linked thermoset polymer tBA-co-PEGDMA, recently studied by Safranski and Gall [13]. The polymer was synthesized by mixing 50 mol% of the monomer tert-butyl acrylate (tBA) with 50 mol% of the crosslinking agent poly(ethylene glycol) dimethacrylate (PEGDMA) and 0.2% of the photoinitiator 2,2-dimethoxy-2-phenylacetophenone. The solution was mixed using a magnetic stir plate for 2 minutes and then degassed in a vacuum chamber for 10 minutes. The degassed solution was then UV cured for 10 minutes at an intensity of about 30 mW/cm^2. Finally, the polymer was heat-treated at 90 °C for 1 hour to complete the polymerization reaction. The polymer was then cut and polished to the desired dimensions to produce the samples used in the thermal sensing prototypes.

As has been studied in [13], T_g, depends on the polymer chemistry. The relative decrease of molar percentage PEGDMA to tBA produces polymers with higher T_g. In the design of a thermal alarm sensor this is ideal because we can employ the same sensor design and manufacturing procedures to produce sensors which trigger at different temperature ranges. However, the T_g is not a discrete value but rather a range over which the polymer's mechanical behavior changes from a rigid state to a rubbery state. It is important to quantify this behavior because it directly affects the actuation time of the sensor at a given temperature.

In order to understand the behavior of T_g, three samples with the polymer composition mentioned above were tested using dynamic mechanical analysis (DMA). Fig. 4 shows the three curves of the storage and loss moduli for the polymer. The storage modulus is a representation of the stored energy during deformation, while the loss modulus represents the viscous loss of energy of the material. The range of temperature over which there is a significant change in the material's ability to store energy through deformation corresponds to the material's glass transition temperature. The value of T_g is conventionally taken at the peak of the loss modulus, which occurs at approximately 15°C. As mentioned above, the glass transition temperature is not a discrete value, and it can be observed from Fig. 4 that the storage modulus shows significant variation from 0°C to 30°. In the design of sensors the temperature at which the onset of shape-recovery occurs is the most important property of the polymer. We have observed the onset of shape-recovery to occur at the lower bound of the glass transition temperature, that is at approximately 0°C. Therefore we conclude that we must tailor the chemistry of the SMP such that the lower bound of T_g corresponds to the monitoring temperature that we are interested in.

Recently, thermo-mechanically-coupled constitutive models for shape-memory polymers have been developed [14] which are capable of predicting the deformation recovery of the polymer when exposed to a given temperature. In future work, we intend to use these models and finite element analysis (FEA) in the design of temperature sensing devices using SMP's, since they would allow us to design more complex SMP sensors and accurately simulate their temperature dependent recovery behavior.

C. Control of Actuation Time

While actuation of the polymer induces a state change, it is important that the sensor be designed so that the actuation happens after a specified tolerance interval. For example, orange juice cartons may be placed out in the open for a few minutes while they are being transported from a freight truck to a warehouse refrigerator without any detrimental effects and the sensor should not be triggered in these instances. Designing the sensor for a specified tolerance can be approximated as a conduction heat transfer problem and this can be used to select the dimensions of the plastic jacket and shape memory polymer bridge while fabricating the sensor prototype.

We assume an outside temperature, T_{out} and assume that the rate of conductive heat flow into the system due to the temperature differential is equal to the rate at which the jacket, the polymer bridge (SMP) and the air inside the plastic jacket heats up. This can be represented by the following equation

$$K_j A_j \frac{T_{out} - T}{s_j} = (m_a c_a + m_j c_j + m_s c_s)\frac{dT}{dt} \tag{1}$$

where K_j is the conduction coefficient of the plastic jacket, A_j is the total surface area of the jacket, s_j is the thickness of the jacket material, m_j, m_s, m_a are the masses of the jacket, the SMP bridge and the air contained within the sensor and c_j, c_s, c_a are the respective specific heat capacities. We can solve Eq. 1 for time to get the expected time for actuation

$$t_{act} = \frac{s_j(m_a c_a + m_j c_j + m_s c_s)}{K_j A_j} log(\frac{T_{out} - T_{threshold}}{T_{out} - T_{coldroom}}) \quad (2)$$

where $T_{threshold}$ is the critical threshold temperature and $T_{coldroom}$ is the typical temperature inside the cold room in which the goods are being transported. By selecting appropriate dimensions for the plastic jacket and polymer bridge, it is possible to design a sensor that actuates in the neighborhood of t_{act} for a given T_{out}. Note that it is difficult to precisely model heat transfer processes and so this formulation represents a starting point for selecting the sensor dimensions. Precisely verifying the actuation time is the subject of experimental verification.

IV. RESULTS

In this section, we demonstrate the working of the temperature sensor prototype and the results from experiments that were conducted to verify the advantages of the sensor design. We outline these findings in this section.

A. Proof of Concept

To demonstrate that the sensor design works, a shape memory polymer designed to actuate at a mean temperature of 7°C (with an actuation range of ±7.5°C) was subjected to a heating cycle test. The temperature sensor was initialized by placing it in a refrigerator unit at -10^oC for 30 mins to ensure that the polymer hardens and then at an outside temperature of 28°C for a period of about 5 mins. To allow rapid testing, the prototype dimensions were selected so that the polymer bridge would actuate after about 3-5 mins at these temperature conditions. The experiments were conducted using the Impinj Speedway UHF RFID reader and Alien Squiggle UHF RFID tags.

Fig. 5 illustrates the backscatter signal strength received from the tags A and B, described in Fig. III-A, as a function of time for a reader-sensor separation of 1 m. The tags are queried at the rate of 40 reads per second and average values are plotted every 3 s, which would correspond to an average over approximately 120 data points. As we see, initially Tag A has the metal plate behind it and responds with a weak signal relative to Tag B, but as the polymer actuates, the metal plate shifts from a position behind Tag A to a position behind Tag B. This manifests itself in a swap in backscatter signal amplitude and this is clearly seen in Fig. 5.

It is important to examine the range over which the temperature sensor provides reliable performance and so we repeat the experiment over reader-sensor separations of 0.5, 1, 2 and 3m. Fig. 6 represents a plot of differential backscatter power (Tag A relative to Tag B) as a function of time for different read ranges. As we observe from the figure, the flip in differential backscatter signal can be observed over all read ranges demonstrating that the sensor state can be unambiguously determined over a range of 3 m.

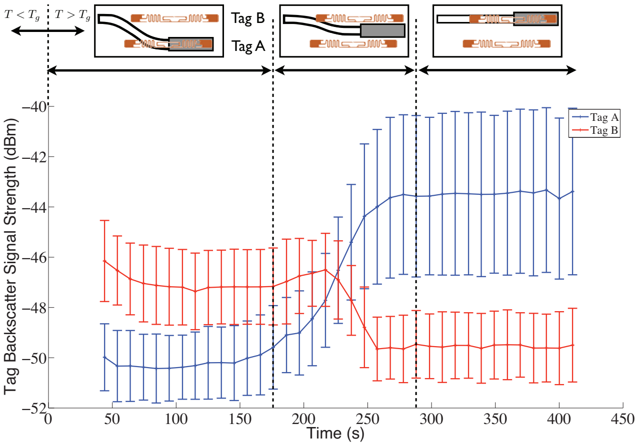


Fig. 5. Performance for a sensor-tag separation of 1 m

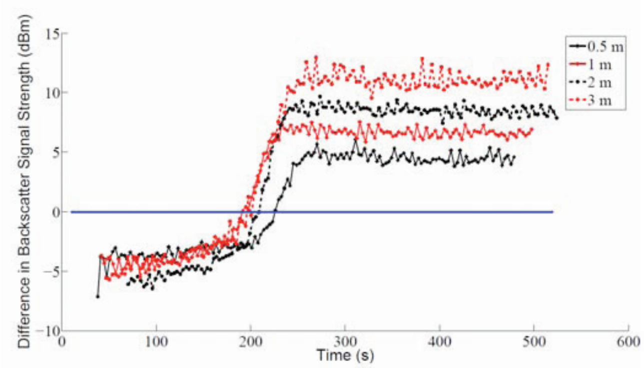


Fig. 6. Performance over different read ranges

B. Sensor Design Applicability

Section IV-A demonstrates that the sensing principle works and as mentioned in Section III-C, the time at which the polymer heats up to a given temperature can be predicted by modeling the system as a conduction heat transfer problem. We can thus approximately predict the actuation time as a function of exposure temperature by selecting the sensor dimensions appropriately. However, it is important to examine how accurately this prediction correlates to observed actuation time and quantify how accurately the sensor actuation corresponds to food spoilage for a broad range of exposure temperatures.

Bobelyn *et al.* [15] present metrics to quantify the quality of fresh produce, like lettuce, and relate degradation of food quality with temperature to a first order Arrhenius exponential decay. They also list estimates of the activation energy E_a and the reaction rate k_{ref} for different types of fresh produce. We make use of the formulation presented in [15] to quantify the time taken for a quality degradation of lettuce with temperature. Fig. 7 illustrates the time taken for the quality of lettuce to decay by 0.2% as a function of temperature. The uncertainty associated with the decay of food quality stem from the uncertainty associated with E_a and k_{ref} as outlined

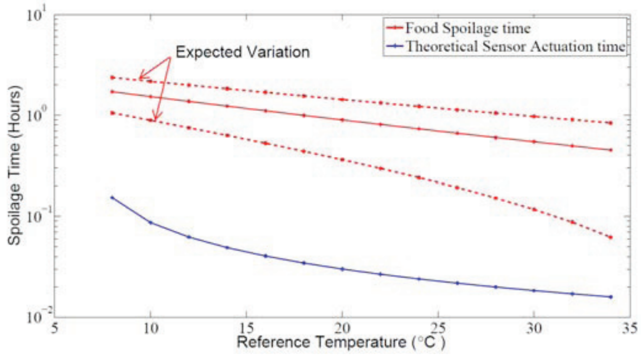


Fig. 7. Sensor Actuation time and Food Quality Decay as a function of outside temperature

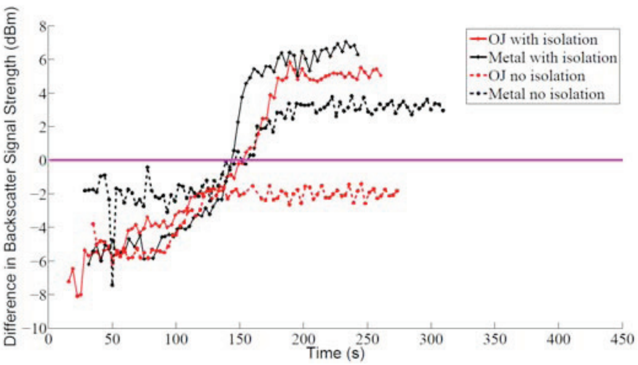


Fig. 8. Effect of Isolation Metal Plate

in [15].

As outlined in Section III-B, we observed that the glass transition temperature for the shape memory polymer is a range. For the polymer considered in this study, the mean glass transition temperature is 15°C, but the polymer starts actuating as early as 0°C, albeit very slowly. The actuation rate of the polymer is thus dependent on what temperature the polymer is currently at while it is heating up on being exposed to an outside temperature. We compute the predicted theoretical actuation time, based on Eq. 2 as the time taken for the polymer to reach 7.5°C, to represent an average of the actuation rate over the 0-15°C range. This predicted actuation time as a function of the exposure temperature is also plotted in Fig. 7. As part of future work, we will improve the estimates of the theoretical computed actuation time by using thermo-mechanical finite element analysis. The theoretical estimates will also be compared with the results of experimental analysis on several batches of prototypes to obtain bounds on the expected variation in the sensor actuation time.

We note that if the sensor actuation time as a function of temperature is always a lower bound to the food spoilage curve, as illustrated in Fig. 7, we can be guaranteed that the sensor state is a conservative guarantee of food quality for all outside temperatures. The tightness of this lower bound can be controlled by varying parameters such as the sensor jacket thickness or by coating the polymer with an insulating wax so as to retard its actuation time but in this paper, we do not investigate this idea in more detail. Precisely controlling the actuation time by observing how well theoretical computations relate to experimentation and deploying the sensor prototype in field trials will be the subject of future work.

C. Effect of material of deployment

It is conceivable that the sensor will be deployed on different products in the cold chain, each of which may affect the RFID tag performance differently. In this study we consider the deployment of the sensor on two surfaces that might commonly be employed in cold chain operations - a metal surface and on an orange juice carton. In order to make the sensor performance agnostic of the material of deployment, we outfit the sensor prototype with a base metal plate as shown in Fig. 1(b). Our theory is that the metal plate would thus shield the tags from the material of deployment.

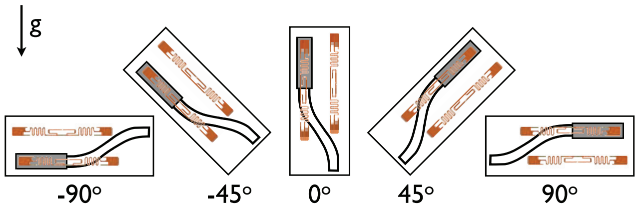


Fig. 9. Different Sensor Deployment Orientations

In order to verify this assumption, we conduct a test to determine the effect of the isolation base metal plate. For a reader-sensor separation of 1 m, we examine the differential backscatter signal strength when the sensor is deployed on an orange juice (OJ) carton and on a metal surface with and without the isolation metal plate. Fig. 8 presents the results.

As we can see from the figure, the differential backscatter signal does not invert in the absence of the isolation metal plate, when the sensor is deployed on the orange juice carton which would introduce ambiguity in interpreting whether or not the juice was subjected to unacceptably high temperatures. However, in the presence of an isolation plate, the flip in relative tag signal strength can be clearly distinguished irrespective of material of deployment. Thus we can conclude that the isolation metal plate is required in the sensor design.

D. Effect of Sensor Orientation

One of the advantages of this sensor design is that it should work independent of the orientation of deployment of the sensor. In this section, we verify that this is the case, by comparing the performance of the sensor in several different deployment orientations. Fig. 9 demonstrates the different orientations considered in the study. As we can see from the figure, some of the orientations involve the shape memory polymer actuation being assisted by gravity and in others the polymer has to actuate against gravity.

Fig. 10 illustrates the differential backscatter signal strength for the orientations described in Fig. 9. As we can see, the

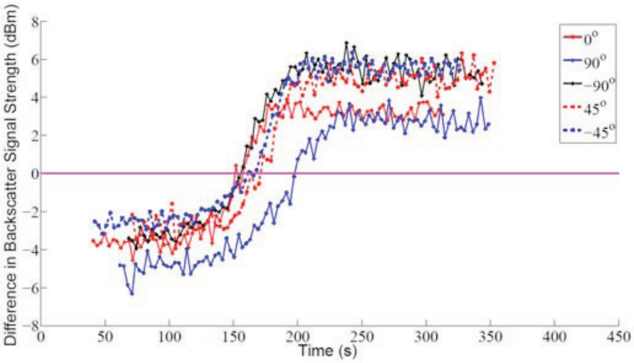


Fig. 10. Effect of Sensor Orientation

orientation does not significantly affect the performance and for all orientations, the inversion in differential backscatter signal strength can be unambiguously determined.

V. CONCLUSIONS

In this paper, we discussed the design of a temperature threshold sensor that registers the violation of critical temperature thresholds by inducing a permanent change in an RFID tag antenna's electrical properties. Furthermore, we highlighted the concept of non-electrical memory to record the violation of temperature states even in the absence of reader transmitted power. We demonstrated how the actuation of a shape memory polymer could be used to achieve this effect and provided insights into how the glass transition temperature could be controlled via the chemistry of the polymer and the typical variability expected.

We demonstrated proof of concept via experimentation and showed that this sensor design can provide reliable state information over distances of 3 m. We also showed that the sensor performance is independent of the orientation of sensor placement and is agnostic of the deployment material. Furthermore, the actuation is a one-way process and so with appropriate packaging this sensor design would be tamper-proof as well. We validated the practical applicability of our sensing paradigm by correlating the sensor actuation to food quality decay and discussed how the sensor design could be fine tuned to accurately represent food quality control better. Since our threshold actuation mechanism makes minimal changes to the RFID tag itself, we can fully leverage the low cost RFID tag manufacturing framework to design ultra low cost sensors. RFID tags today can be purchased for 7-15 cents. The quantity of shape memory polymer required per sensor is about 10 cents and assuming another 50 cents for packaging costs it is not difficult to imagine threshold temperature sensors that can be manufactured in the sub $1 price range. Furthermore, cold chain companies having an RFID infrastructure in place will incur very low setup cost while integrating these sensor nodes into their supply chain operations.

Finally, while our approach certainly has the potential to greatly increase the scale of sensor deployment in cold chain operations, we must understand the associated trade-offs. Our approach can answer the question of whether or not a critical temperature threshold was violated, however information such as the time at which this violation occurred is not recorded. A reduced feature set is the price we pay for lower cost and greater scale of deployment. We may argue that this sensing paradigm would be useful to monitor the state of certain items like perishable food produce where the question of whether or not a state was violated is more important than when. At the same time, this sensing approach would not be suitable for monitoring ultra sensitive and expensive products like vaccines which would be much better benefited by dedicated wireless temperature sensors outfitted with real time alarms and capable of storing time history data. It is thus essential to identify supply chain applications that would most benefit from this sensing philosophy as a technique for increased visibility and food quality control.

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