# RFID-Enabled Temperature Sensor

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**Abstract:** The design of a RFID-enabled temperature sensor is described in this paper. In this sensor, a change in temperature causes structural beams to bend, which results in a proportional displacement of the plates of the capacitor. Plates' displacement results, in turn, in changing the value of its capacitance. The capacitor of the sensor is coupled to the LC resonant network of a passive RFID tag. This makes the tag's resonance frequency dependent on the value of the sensor's capacitance. Hence, by measuring the shift in the resonance frequency, one can measure the change in temperature. COMSOL multiphysics program was used to design the sensor and simulate its performance. Simulation results show that the designed sensor can have a resolution of about 0.0014 °C/Hz. This sensor can be implanted on a tooth or a dental implant to monitor the mouth temperature.

**Keywords:** temperature sensor, comb capacitor, RFID, dental implant

## 1. Introduction

The comb capacitor is a common realization of a MEMS (Microelectromechanical system) temperature sensor [1, 2]. A comb capacitor serves as a variable capacitor whose capacitance changes with temperature. Temperature change causes the fingers of the capacitor to move because of the material thermal expansion. The movement of the fingers changes the overlapping area of the plates, which, in turn, changes the capacitance, accordingly. These sensors have been implemented in harsh or enclosed environments, where remote measurements are preferred. This advantage makes them suitable for use in the human mouth, which has similar environment.

The main problem with using this device inside the mouth is the difficulty to supply the needed power for the device operation. To solve this problem, we propose a novel technique, where we use radio frequency identification (RFID) tag for powering the device and for the transmission of the temperature data. RFID tags, such as EasyTrac-ID, have already been used in veterinarian medicine for the identification of animals by way of sub-dermal insertion [3]. These tags were also modified for use in the human body [4]. To achieve that, the tag size was reduced from 8mm in length to 6mm, and this size reduction allowed for bonding the sensor in composite to the top of a human molar.

A passive rather than an active tag is used in our case. A passive tag does not require any power source for operation. Passive tags are externally powered and read using RF readers. Compared with active RFID tags, passive tags are low power, low-cost, and biocompatible with low-level radiation causing no harm to surrounding tissues. Finally, the use of the RFID tag allows an external receiver to be placed outside the mouth, where there will be no stringent size constraints. Additional components, such as, signal conditioning circuitry can easily be added to this receiver outside of the mouth.

The antenna for a passive RFID tag is simply a large inductance coil. The impinging electromagnetic field received from the reader creates a RF voltage within the tag. The signal is then rectified using a diode and a large capacitor to produce dc source to power the tag and any additional circuitry [5]. A second diode and a small capacitor can be added for use in sending information from the reader to the tag, if necessary. The information is sent from the tag to the reader by reflecting the original signal sent from the reader. This can be accomplished by using a FET as a switch, which dictates whether the antenna is grounded or not, and how much current is able to flow through the antenna [5].

The frequency of operation for our design is chosen from the commonly used RFID frequency ranges. These ranges are low frequency (LF) from 125 to 134.2 kHz, high frequency (HF) of 13.56 MHz, ultra-high frequency (UHF) from 860 to 960 MHz, and microwave frequency at 2.4 GHz. Using one of these frequencies allows for the use of a commercially available reader, instead of designing a new reader, which can be prohibiting for such applications.

Several considerations affected the choice of frequency of operation. For biomedical purposes, a RFID tag operating at LF is generally preferable. Tags used for animal tracking generally work at this frequency [5]. When inductive coupling between a passive tag and its reader is implemented, higher frequency signals are attenuated due to the presence of water in the tissues, which limits signal ranges [5]. Skin depth calculations, done by the authors for tissues, support this claim, as explained later. If the LC network of the tag contacts the tissues, the resonance frequency may change to unpredictable and undesired values, affecting the radio operation [5]. While LF tags have lower data rates than UHF tags, for this application, high data speeds are not needed.

The HF range of operation at 13.56 MHz was ultimately chosen. At this frequency the change in the capacitance results in a noticeable change in the resonance frequency, allowing for achieving acceptable sensitivities. In addition, skin depth calculations have shown that attenuation is not severe to pose problems to the sensor operation. For both LF and HF tags, the near field between the tag and the reader can be expected to decrease by $1/r^3$ with distance [6].

## 2. Design

The design of the comb capacitor was built upon the design presented in [1, 2]. Mathematical modeling have shown that, for the sensor to work properly, the upper beams of the structure should be placed at an angle of 14° from the vertical axis and its anchor; while the lower beams should be aligned with their anchors at a 90° angle. Additionally, the horizontal beams should be tilted 7° upward from the horizontal axis. Together, this created the bent beam structure that can be seen in Fig. 1 below. Each individual beam has a length of 250 µm and a width of 10 µm. The fingers have a length of 90 µm each and is placed 7 µm apart from each other. The device has a thickness of 31 µm. The fingers have an initial overlap of 40 µm at 310 K. As temperature increases, the combs overlapping area increases leading to increasing the capacitance value.

Titanium (Ti), a biocompatible metal, is the material of choice for building this sensor. Therefore, it is widely used in dental implants. Titanium has thermal expansion coefficient of $9.35\text{x}10^{-6}$/°C, which is suitable for this application. Materials with higher thermal coefficients were considered for this design, but they were found not to be biocompatible.

The coil inductor of a RFID tag is used to form a new LC resonant network with the sensor capacitance. The coil inductor of the EasyTrac-ID RFID tag was found to have a diameter of 1.1 mm, or a radius, *a*, of 0.55 mm, a coil length, *l*, of 3.4 mm, and a number of turns, *N, of* 1300 turns, [4]. The above dimensions resulted in an inductance of 0.594 mH for this coil as obtained from Equation (1)*:*

$$L = \frac{\mu_0 \pi a^2 N^2}{l}, \tag{1}$$

where $\mu_0$ is the permeability of the free space for an air coil.

For a resonance frequency of 13.56 MHz, the corresponding capacitance can be obtained from equations (2) and (3):

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

$$C = \frac{1}{L(2\pi f_{res})^2} \tag{3}$$

According to (3), the total capacitance for the LC network should be around 0.232 pF to have a center frequency of 13.56 MHz. The comb capacitor was easily designed around a value of 0.038 pF. A parallel capacitor with a constant value of 0.194 pF can be added so that the required total capacitance of 0.232 pF can be achieved. Hence, the change in the sensor capacitance results in a related change in the resonance frequency.

The Skin depth, δ, for tissue was obtained using Equation (4):

$$\delta = \sqrt{\frac{1}{\pi \mu_0 \sigma f}}, \tag{4}$$

where *f* is the frequency of operation and $\sigma$ is the electrical conductivity of the material used. For tissues, the conductivity can vary greatly depending on the composition of the tissue. The conductivity of the tissues was estimated to be about 0.507 S/m [5]. Based on this estimation, the skin depth was found to be about 20 cm. This value is acceptable for this application, since a reader can be placed 15 cm away from the sensor without discomforting the patient or losing signal power. Using UHF tags will reduce the skin depth to only 1-2 cm, which would not be sufficient to place a reader to read the sensor's signals.

The bandwidth of the RFID tag should be within the frequency range of the reader. Using the minimum and maximum operating temperatures and the associated capacitance values, the device sensitivity of the sensor was found to be 0.0247 fF/K. This means the tag and reader must operate with a bandwidth between 13.572 and 13.269 MHz.

## 3. Sensor Design Using COMSOL Multiphysics

Figure 1 shows the geometrical model of the capacitor obtained using COMSOL, using the dimensions discussed in the Design section above.

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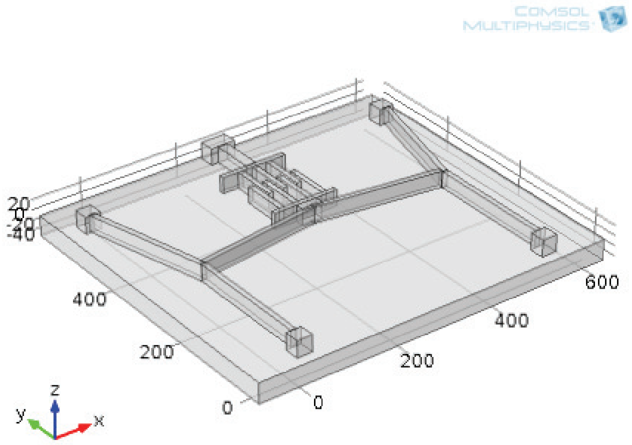
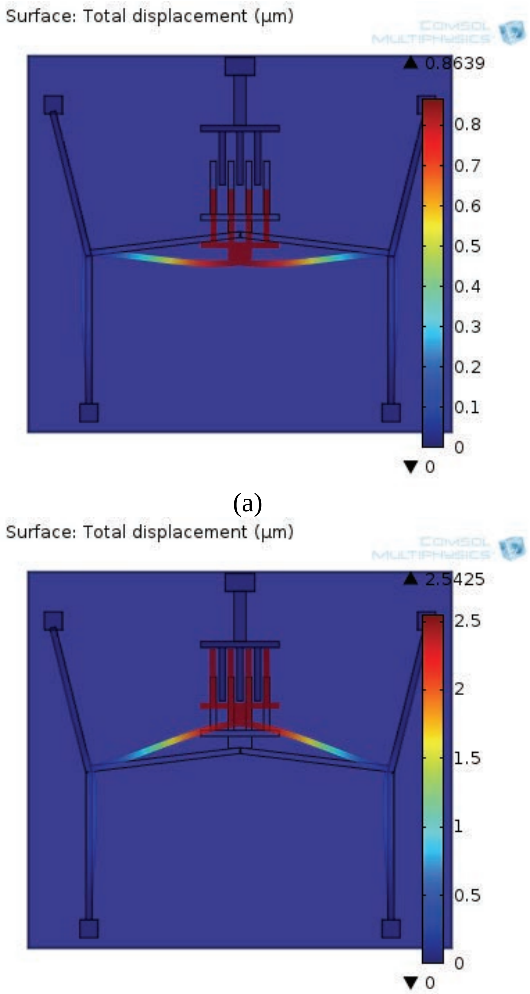


**Figure 1.** Geometrical model of the temperature sensor obtained using COMSOL.

The Joule Heating and Thermal Expansion module in COMSOL was used to show the displacement of the movable comb with temperature. Boundary conditions were specified for the model so that the top comb, the substrate layer of silicon below, and the four corner anchors of the lower comb were fixed in place. The remaining portion of the lower comb was specified to be free to move. The initial temperature was specified to be 310 K, and the external temperature environment was varied across the expected operating temperature of the device, from 275 to 345 K. Figure 2(a) below shows a downward deflection of the lower comb when the sensor is exposed to a temperature of 275 K, while Figure 2(b) shows an upward deflection at a temperature of 345 K. Figure 3 shows a plot of Displacement vs. Temperature over the expected operating range of the sensor. The relationship between the variables appears to be quasilinear over this range.



(a)

(b)

**Figure 2. (a)** COMSOL model of displacement of comb capacitor at 275 K. (b**)** displacement of comb capacitor at 345 K.

The Electrostatics module in COMSOL was then used to determine the capacitance values associated with these displacements. The geometry of the movable combs was changed in the Electrostatics model according to the displacement determined by the Joule Heating and Thermal Expansion module for a specific temperature. COMSOL simulation, shown in Figure 4, shows also a quasilinear relationship between the Capacitance and the Temperature for the sensor.

Equation (2) and the simulation results of Figure 4 were used to obtain the dependence of the resonance frequency on the temperature, In Equation (2), L is the inductance of the coil and C is the combined capacitance value of the tag's capacitance and the sensor's capacitance. The relationship in Figure 5 is also found to be quasilinear relation, and the frequency was found to decreases with the increase in temperature.

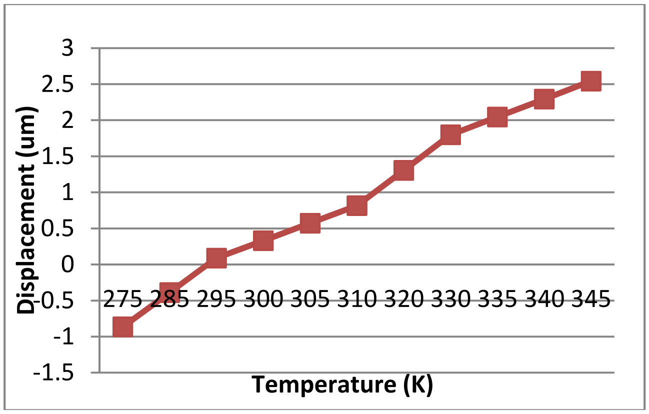


**Figure 3.** Dependence of displacement on temperature, obtained from COMSOL Joule Heating and Thermal Expansion module

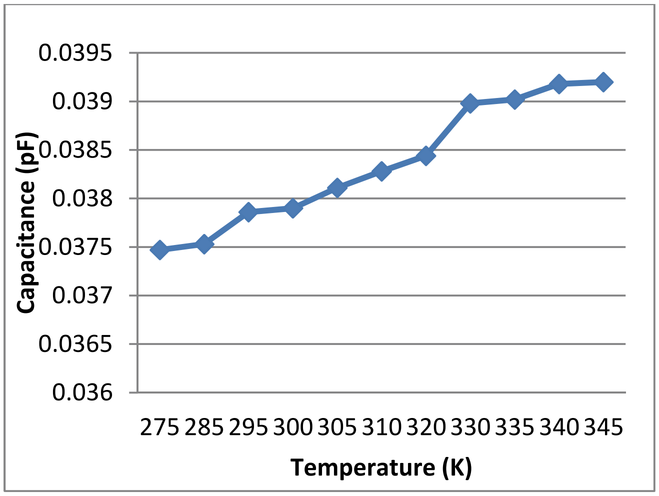


**Figure 4.** Dependence of capacitance on temperature, obtained from COMSOL Electrostatic module.

The maximum attenuation between the signal at 13.56 and the signals with the highest and lowest frequency should not exceed 3 dB [7]. A RFID reader should be chosen to operate at 13.56 MZ and meet the attenuation requirements. The bandwidth resolution, which is the minimum frequency difference between two signals where the reader can identify as two distinct signals, should be at least 10% of the signal separation [8]. Fig 5 shows that for the temperature range, the frequency changes by 50 kHz, or about 700 Hz/

°C. Therefore, a bandwidth resolution of 70-100 Hz would be acceptable. If the scan width of the spectrum analyzer has a setting of 1 kHz/div, the bandwidth resolution requirement would be met. Meeting these specifications will allow the spectrum analyzer to display the data obtained from the capacitive sensor with acceptable accuracy.

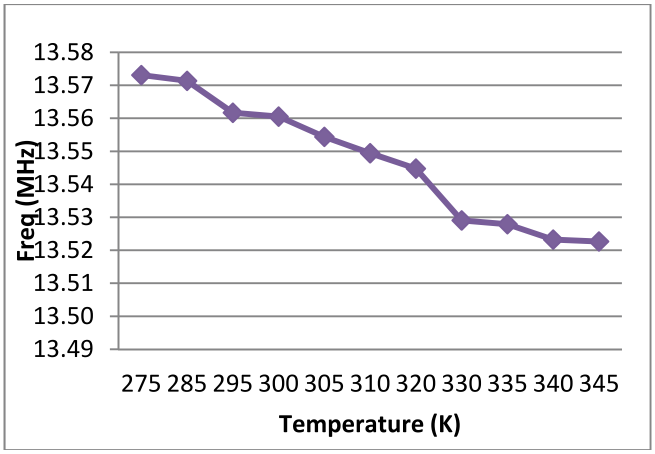


**Figure 5.** Dependence of resonance frequency of the LC resonant network of the RFID tag on temperature.

## 4. Conclusions

We designed a temperature sensor to be attached to a tooth or dental implant to monitor their exposure to temperature. The sensor is realized by a comb capacitor in which the change in temperature causes the displacement of the lower comb, and in turn, causes a change in capacitance.

COMSOL was used to design the sensor physical structure and to simulation its performance. The sensor capacitance is coupled with the capacitance of a RFID tag LC network. This coupling results in changing the resonance frequency proportional to the change in the value of the sensor capacitance. An RFID tag with the main frequency of 13.56 was used in this design. External readers can be used to detect the change in the resonance frequency, and in turn determine the measured temperature. The results indicate that the device will have a very high resolution of about 0.0014 °C/Hz.

## 5. References

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