Flexible Wireless Wall Temperature Sensor for Unsteady Thermal Field

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Abstract. We present a novel flexible wireless wall temperature sensor with high spatio-temporal resolution and its performance evaluation in an unsteady thermal field. A base part of the sensor is made of thermally-stable polyimide and the copper films. Using a Si hard mask fabricated by standard lithography and DRIE process, 1 mm-sized sensing resistor is sputtered on the copper coil. We enhance the time response for each measurement by reducing the frequency sweeping points. It is shown that the accuracy of the present temperature measurement is in acceptable range for most combustion studies, based on a series of error-estimation analyses. The temperature measurement uncertainty of ± 6.4 ºC has been achieved with the measurement time interval as small as 2.48 ms.

1. Introduction
The wall temperature measurement for unsteady thermal fields is one of the major issues in combustion studies [1]. Contact thermometry using thermocouple has been widely used, but it requires wiring and physical contact that would easily introduce external disturbances [1, 2]. As non-contact thermometry, infrared pyrometer and thermographic phosphor are also available, but existing techniques require optical access, which could be problematic in combustion studies [1-4].

To overcome such limitations, we have proposed a wireless wall temperature sensor using TCR (Temperature Coefficient of Resistance) changes of Au thin film [5, 6]. The prototype sensor is successfully fabricated with standard MEMS process and the measured resonant frequency shows a quadratic increase in response to an increase of the temperature. However, the spatial resolution of the temperature measurement is as large as the diameter of the sensor coil, i.e., 10 mm, and its temporal resolution has not yet been examined.

In the present study, we propose a novel flexible wireless wall temperature sensor with improved spatio-temporal resolution.

2. Design of the wireless temperature sensor
The present sensor consists of the following elements: a planar spiral coil, a capacitor, and a resistor with temperature dependence. The sensor coil is inductively coupled with the read-out coil, and the circuit impedance changes in response to the resistance change of the resistor on the sensor. One advantage of this approach is that the sensor consists of passive devices only without any semiconductors, so that it is applicable to high temperature applications. Figure 1 shows the equivalent
Based on the circuit analysis, the phase angle of the read-out circuit impedance $\angle Z_e(\omega)$ can be derived as equation (1) [5, 6], where $L$, $C$, $R$, and $\omega$ represent the inductance, the capacitance, the resistance, and the angular frequency, respectively. Subscripts e and s denote the external read-out circuit and the sensor. $R_p$ is the parasitic resistance due to the sensor coil, and the coupling coefficient $k$ is determined by the self-inductance of the two coils and their mutual inductance $M$, which is highly dependent on their geometric relationship. The resonant frequency is obtained from the extremum condition of equation (1), and its shift is determined by the sensor resistance and thus the temperature.

For the coupled series LCR circuit, the Q factor depends both on the resistance and the mutual inductance $M$. To achieve a higher Q factor for higher accuracy in the resonant frequency, the sensor resistance should be minimized and the mutual inductance should be maximized under constraint of the device. In our previous study [5, 6], however, due to large sheet resistance of the sensor coil with sputtered Au films, the parasitic resistance of the coil itself was large, making integration of the sensor resistor prohibited. Therefore, the sensor coil was used as the sensor resistor, which significantly deteriorates the spatial resolution of the temperature measurement.

In order to suppress the unwanted effect of the parasitic resistance, thickness of the sensor coil should be on the order of 10 $\mu$m. In the present study, we employ a Cu-laminated polyimide film as the sensor substrate. Note that polyimide, which has been widely used for the flexible printed circuits (FPC), is a material with suitable properties to be used in combustion fields: high thermal durability up to 400 °C, chemical stability, and flexibility.

![Figure 1. The equivalent circuit model for the wireless wall temperature sensor (right) and the read-out coil (left).](image1)

$$\angle Z_e(\omega) = \arctan \left\{ \left(1-k^2\right)L^2C^2\omega^4 + \left[R_e + R_p\right]^2C^2\omega^4 + \left(k^2 - 2\right)L^2C^2\omega^4 \right\}$$

(c1) UV

(c2)

(c3)

Polyimide

Photoresist

Cu

Au

Hard mask (Si)

Photo mask

![Figure 2. Sensor fabrication process: Firstly, Cu layers on the polyimide film are patterned into the electrodes and the planar spiral coil. A Si hard mask (figure 3a) is made through the photolithography and Deep-RIE process. Then, thin Au film is sputtered through the hard mask to deposit a sensing resistor as shown in figure 3b.](image2)
3. Fabrication of the sensor

Figures 2a-d show the fabrication process of the present sensor using a 12.5 μm-thick polyimide substrate. Firstly, 18 μm-thick Cu layers laminated on both sides of the polyimide film are patterned into the electrodes for the capacitor and the planar coil. A contact hole is drilled and electroless Au plating is performed for an electrical connection between the top and bottom Cu layers. Then, a Si hard mask for the sensing resistor is microfabricated by a standard lithography and etch-through process with DRIE (MUC-21 ASE-Pegasus, STS) as shown in figure 3a. Finally, an approximately 100 nm-thick Au film with a Cr adhesion layer is sputtered through the hard mask to deposit a sensing resistor (figure 3b), and to compose the sensor as a closed circuit.

Figure 3d shows a photograph of the successfully fabricated prototype sensor with a 1 mm sensing resistor. The measured resistance of the sensing resistor and the designed value of the parasitic resistance are respectively 130 Ω and 1 Ω. Note that the dimension of the resistor can be further reduced to as small as 50 μm for better spatial resolution.

4. Improvement of temporal resolution

When determining the resonant frequency, the sensor is inductively coupled with the read-out coil and its impedance is measured using a network analyzer. In our previous studies, the frequency sweeping required long time, so that the average time for the measurement remained as an order of 100 ms. Thus we try to shorten the measurement time by reducing the number of frequency sweeping points. As shown in figure 4, the measured phase angle data with different scanning points are fitted with

Figure 4. Phase angle of impedance versus the frequency for different number of sweeping points. The graphs are magnified in the vicinity of resonant frequency.

Figure 5. Measurement time interval and fitting error in resonant frequency versus number of sweeping points. The total measurement time includes not only the sweeping time but also time required for data transmission.
equation (1). With decreased number of data points, a fitting error on the resonant frequency is increased. The fitting error and the measurement time interval are plotted as a function of the number of sweeping points in figure 5. Note that the measured data with 601 points are used as a reference. When we decrease the number of sweeping frequency to 7 points, the sweeping time takes approximately 0.6 ms. When the time required for data-transfer is included, it corresponds to 2.3 ms. Due to the increase of fitting error, the uncertainty of the temperature measurement is also increased. However, the uncertainty around 100 °C is estimated to be ± 5.2 °C that should be acceptable for most combustion studies.

5. Performance evaluation in unsteady field

Figure 6 shows an experimental setup for the performance evaluation in an unsteady thermal field. The sensor is fixed on a plate and the read-out coil is attached on the other side with a distance of 1.6 mm. The read-out coil is connected to a network analyzer (ZNB20, Rohde & Schwarz) through a coaxial cable, and the wall surface temperature is simultaneously monitored with a K-type thermocouple once in every 100 impedance measurements. Both the network analyzer and the data acquisition unit are connected to a host PC through Ethernet for the remote control and the data transfer. VISA (Virtual Instrument Software Architecture) is used as an application programming interface with SCPI (Standard Commands for Programmable Instruments) commands.

To provide an unsteady thermal field to the wall surface, the sensor is suddenly approached to a 2
mm distance from a hot plate, which is heated up at 350 ºC beforehand. The measurement is performed until surface temperature reaches 230 ºC. The measured resonant frequency data are converted to the temperature and plotted as a function of the elapsed time as shown in figure 7. The measured data in the vicinity of 225 ºC are magnified as shown in figure 8. The average time for each measurement is 2.48 ms, and the uncertainty of the temperature measurement is found to be ± 6.4 ºC with the 95% coverage. By improving the measurement method, it is expected that the temporal resolution less than 1 ms can also be achieved.

6. Conclusions
We have developed a wireless wall temperature sensor with high spatio-temporal resolution for the use in combustion studies. The sensing system includes the sensor composed by a LCR circuit and the inductively-coupled read-out coil. The sensor is fabricated on the Cu-laminated polyimide film, and an additional 1 mm-sized sensing resistor is formed by standard MEMS process. The parasitic resistance of the coil is markedly suppressed by using the thick Cu layers, so that the additional sensing resistor dominates the whole sensor resistance. The fabricated sensor shows high flexibility, so that it can be fitted well on a curved surface. The sensor performance has been evaluated in an unsteady thermal field. Uncertainty in the temperature measurement of ± 6.4 ºC with the mean measurement time interval of 2.48 ms has been achieved.

7. References
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