Radio Frequency Temperature Measurement System Based on PDC Material

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Abstract. PDC (Polymer Derived Ceramics, PDC) material sensor is a new type of temperature sensor, which has the characteristics of high temperature thermal stability, corrosion resistance, oxidation resistance and creep resistance. It is a high temperature polymer precursor ceramic temperature sensitive material. Using its characteristics, it can solve the problem of high temperature. There is a resonant cavity inside the sensor, and the resonant frequency of the internal resonant cavity will change accordingly when its temperature changes. In this study, a set of RF temperature measurement hardware system was developed using the perturbation method and the corresponding relationship between the resonant frequency and temperature of the PDC material temperature sensor.

1. Introduction
In the aerospace industry, engines or turbines generate extremely high heat when they are working. Due to the harshness of the test environment, general temperature measurement methods and temperature sensors can no longer be adapted to this specific scenario, and the temperature can ensure the normal operation of the engine. And the later evaluation of its performance is an extremely important parameter, which must require the use of special temperature measurement methods and special temperature sensors that can withstand harsh environments such as high temperatures [1]. PDC material passive wireless temperature sensor is an electromagnetic wave resonant cavity sensor. The dielectric constant of the resonant cavity made of special materials will change with the change of temperature, and the change of dielectric constant will directly affect the resonant frequency of the resonant cavity [2]. Through theoretical derivation, establishing the relationship among the three, combined with perturbation measurement technology, you can test the different resonance frequencies at different temperatures, and thus calculate the corresponding temperature value.

Since the passive wireless temperature sensor of PDC material is a single-port device, the traditional method of measuring the resonant frequency of a single-port device requires the use of a large and expensive device such as a Vector Network Analyser. In the case of a changing temperature measurement environment in terms of cost control and size, it is unacceptable, so this method is obviously unrealistic [3]. In actual engineering, how to ensure the accuracy, convenience and cost control of temperature testing under the influence of harsh environments such as high temperature is a good research direction, which also means that there will be better development prospects in the future [4]. Due to the particularity of the PDC material passive wireless temperature sensor, the research of its detection equipment is relatively insufficient. This article is based on the principle of the PDC material wireless passive temperature sensor to design a reliable and durable radio frequency...
temperature measurement hardware system to replace the volume large, expensive equipment has better integration and compatibility than traditional test equipment.

2. Sensor principle

The surface of the PDC material temperature sensor has a layer of silver metal coating, and the inside is composed of SiBCN ceramic material. Different composition materials have different performances. There is an RF resonant cavity for sensing external environmental parameters containing a substrate. The material-derived ceramic (PDC) element is located on the inner surface of the substrate. The RF resonant cavity has a resonant frequency that changes with temperature. Such a sensor for wirelessly sensing changes in the external environment not only needs to include an RF resonant cavity but also it needs an antenna for receiving external signals and sending echo signals, also called RF reader [5]. Figure 1 shows the physical picture of the PDC temperature sensor.

![Figure 1. PDC material temperature sensor physical map.](image)

In a constant temperature environment, the relationship between temperature coefficient and dielectric constant is shown in Equation 2:

\[ \alpha_{\varepsilon} = \frac{1}{t_{\varepsilon}} \cdot \frac{d\varepsilon}{dt} \]  

Where: \( \varepsilon_{\alpha} \) is the resonant frequency of the internal cavity of the sensor, \( \varepsilon \) is the vacuum dielectric constant. The two can be regarded as a negative correlation within a certain degree of temperature change, then

\[ d\varepsilon = \varepsilon_{\alpha} - \varepsilon_{t} \]
\[ dt = t_{r} - t_{1} \]  

Where: \( \varepsilon_{1} \) and \( t_{1} \) are the dielectric constant and temperature value at room temperature; \( \varepsilon_{r} \) and \( t_{r} \) are the dielectric constant and temperature after temperature change, which can be obtained from the above three formulas:

\[ f_{r} = \frac{P_{01}}{2\pi r \sqrt{\mu_{0} \varepsilon_{0} (\varepsilon_{r} + \alpha_{\varepsilon} (t_{r} - t_{1}))}} \]  

In this formula, only \( t_{r} \) is a variable, and the rest of the parameters can be regarded as constants. It can be seen that as long as the resonant frequency of the sensor in the current environment is found, the temperature of the sensor at this time can be obtained through related calculations. This system
uses This principle detects the resonant frequency of the sensor to indirectly measure the temperature at this time.

3. Perturbation measurement technology

Perturbation measurement technology is widely used in the field of high-frequency microwaves. Under high-speed signals, components and transmission lines can no longer be regarded as lumped parameters. At this time, the influence of parasitic parameter effects will be obvious, due to the discontinuity in the propagation path. The signal will produce serious reflections when propagating. This effect is intolerable to the error produced by the result. It is necessary to introduce another measurement parameter to evaluate the object under S parameter, where S11 parameter is used [6].

Since the surface of the sensor has a rectangular antenna that receives and reflects microwaves, and the antenna is integrated with the resonator, when it is scanned by the high-frequency broadband microwave excitation signal, the excitation signal and the inside of the resonant cavity form resonance, and the excitation signal and the reflection signal interact with each other. When interference occurs, standing waves will be generated in the resonant cavity at this time, which is equivalent to the weakest reflected signal of the sensor at this time, most of the excitation signal is absorbed, and when no resonance occurs, the excitation signal will be reflected or even reflected. According to the definition of using perturbation measurement technology to measure the parameters of the sensor, the resonance frequency at this time can be obtained. And when the temperature or pressure changes, its resonance frequency will also change, and the corresponding temperature value can be measured from the relationship between Equation 4. The test schematic diagram of the sensor is shown in Figure 2.

![Figure 2. Schematic diagram of perturbation measurement technology test sensor.](image)

4. System hardware overall design

According to demand analysis, the hardware system mainly includes five modules, namely, radio frequency signal generation module, radio frequency signal transmission and conversion module, radio frequency signal detection and acquisition module, main controller module and external interface display module. The overall hardware design of the specific radio frequency temperature measurement system is shown in Figure 3.

![Figure 3. RF temperature measurement system hardware scheme design drawing.](image)
The main controller module uses FPGA as the main control chip, controls the LMX2592 to send out radio frequency signals through the SPI communication protocol, and amplifies and drives the frequency multiplier to double the frequency through the first-stage power amplifier. After the second-stage power amplification and band-pass filtering, generate 12.6GHz~13.0GHz wideband constant amplitude excitation sweep frequency signal.

The wideband constant amplitude excitation sweep frequency signal as the excitation signal of the sensor will enter port 2 and output through port 1 of the broadband circulator, and then transmit to the probe of the coaxial waveguide through the radio frequency cable, and transmit the excitation signal to the sensor through wireless transmission via the probe. In the antenna and resonator cavity, the sweep frequency excitation signal will form a resonance phenomenon at the resonant frequency of the sensor. At the same time, the reflected signal sent by the sensor is wirelessly transmitted to the coaxial waveguide probe, and the reflected signal enters from port 2 of the broadband circulator, port 3 is output to the RF signal detection and acquisition module.

The reflected signal is checked and adjusted by the power envelope of the signal through the coaxial detector, and it is converted from a radio frequency signal to a voltage signal. The output voltage signal will be converted by an adjustable reverse amplifier circuit, a voltage ratio conversion circuit, and an AD acquisition circuit. Convert the digital signal to the FPGA main controller, and use the FPGA software algorithm to digitally filter, analyse, process and optimize the signal. Finally, the calculated temperature value and relationship curve are transmitted to the host computer and the external interface display module through the serial communication protocol.

5. System software overall design
The software control design diagram of the radio frequency temperature measurement system based on the PDC material wireless passive temperature sensor is shown in Figure 4. The system software control is mainly based on the design requirements of the system and the corresponding hardware devices. The corresponding RTL code is designed through the hardware description language Verilog HDL language. After the design is completed, the relevant modules are simulated and debugged, and then integrated tools are used Convert the code into a netlist file and download it to the FPGA main controller to complete the driver and data processing of the hardware device. The main components of this system logic control module include the total control module, PLL clock frequency division module, LMX2592 sweep frequency signal generation module, data processing module (singularity removal algorithm module, IIR filter module), AD acquisition module, serial communication module (Touch screen interaction module, host computer communication module), etc. The main control module is mainly to instantiate each module.

![Figure 4. RF temperature measurement system software scheme design drawing.](image-url)

The system software control design process is shown in Figure 5. First, initialize the system and wait for the touch screen to send out the sweep start signal and the corresponding sweep parameters; then, control the LMX2592 signal synthesizer to send out the corresponding sweep signal according to
the designed sweep algorithm, and at the same time control the AD chip to collect the echo signals of each frequency point, and perform median filter processing on the collected echo signals to reduce signal clutter and measurement errors caused by signal jitter. The processed data will be stored in the RAM temporary storage module, judge whether the frequency sweep is completed, if not, switch to the next frequency point to continue the frequency sweep; next, when all frequency points are scanned, the S11 curve composed of the effective data of all single frequency point echo signals is limited and averaged. Filter processing, remove the singular point data in the S11 curve, and then send the processed data to the IIR filter module for digital filtering processing to eliminate noise interference in the signal; finally, send the processed data through the serial port transmission protocol Display and analyse on the host computer, fit the relationship between temperature and resonance frequency, calculate the current measured temperature through the fitted relationship, and transmit it to the touch screen for display.

6. System measurement and result analysis

The PDC material wireless passive temperature sensor was tested for heating, the wireless transmission distance between the sensor and the system was 5mm, and the test was carried out under the same experimental conditions. The tested frequency sweep range is 12.6GHz~13.0GHz, the temperature of the heating table changes continuously between 50℃~350℃, and the resonant frequency is recorded every 10℃.

To observe the sensor curve more intuitively, the seven curves tested at 25°C, 100°C, 150°C, 200°C, 250°C, 300°C, and 350°C are integrated. As shown in Figure 6, it can be seen that as the temperature continues to rise, the resonant frequency of the sensor moves to the left, showing a negative correlation. When the temperature rises, the resonant frequency drops, and when the temperature drops, the opposite is true. On the whole, there is a lowest point of -28.22dB and a highest point of -22.28dB. Meet system design requirements.

Figure 6. Sensor curve test analysis under different temperatures
The data of the resonant frequency points are recorded every 10°C between 50°C and 350°C, and the temperature and the sensor resonance frequency are divided into two sections for fitting. The fitting results are shown in Figure 7 and Figure 8. From the above analysis of the hardware of the radio frequency temperature measurement system and the actual test of the sensor, it can be seen that at the working temperature of 50°C~350°C, the resonance frequency of the sensor has a negative correlation with the temperature. Due to the jump of the resonance frequency, the resonance frequency of the sensor changes. The rate is 308kHz/℃, and the temperature measurement accuracy is about ±1.3℃.

**Figure 7.** Fitting curve of the relationship between the temperature of 25℃~180℃ and the resonance frequency

**Figure 8.** Fitting curve of the relationship between the temperature of 180℃~350℃ and the resonance frequency

### 7. Summary

This article is the design of radio frequency temperature measurement system based on PDC material wireless passive temperature sensor. In the article, we analyse the working principle of the PDC material wireless passive temperature sensor, and analyse the overall requirements of the system to determine the overall scheme design of the system, and finally the actual heating test with the sensor. The resonant frequency and curve of the sensor were tested at different temperatures. At the same time, in order to eliminate the system error, the sensor test data was fitted by segment. The final test result is that there is a negative correlation between the sensor's resonance frequency and temperature, which conforms to the previous theoretical derivation. The sensor's resonance frequency change rate is 308kHz/℃, and the system temperature measurement accuracy is about ±1.3℃.

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### References

[1] YX Yu, QF Huang, FS Xia, SAN Haisheng, HAN Qingkai. Effect of Pyrolysis Temperature on Resonant Frequency of PDC-SiBCN Ceramic Based Wireless Passive Temperature Sensors[J]. Journal of the Chinese Ceramic Society, 2016, 3(04): 192-198.

[2] M Weinmann, TW Kamphowe, J Schuhmacher, et al. Design of polymeric SiBCN ceramic precursors for application in fiber-reinforced composite materials[J]. Chemistry of Materials, 2000, 12(8): 2112-2122.

[3] R Zhao, G Shao, Y Cao, et al. Temperature sensor made of polymer-derived ceramics for high-temperature applications[J]. Sensors and Actuators A: Physical, 2014, 219: 58-64.

[4] D Seo, S Jung, SJ Lombardo, et al. Fabrication and electrical properties of polymer-derived ceramic (PDC) thin films for high-temperature heat flux sensors[J]. Sensors and Actuators A: Physical, 2011, 165(2): 250-255.
[5] Y Li, Y Yu, San H. Wireless passive polymer-derived SiCN ceramic sensor with integrated resonator/antenna[J]. Applied Physics Letters, 2013, 103(103): 163505-163505-5.

[6] X Gong, An Li, C Xu. Wireless passive sensor development for harsh environment applications[C]/2012 IEEE International Workshop on Antenna Technology (iWAT). IEEE, 2012: 140-143.