Passive wired SiCN temperature sensor for harsh environment applications

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Abstract. In this paper, we report the design and fabrication of a new temperature sensor by coupling a coplanar waveguide line with a resonator containing thermo-sensitive PDC-SiCN ceramics. A wide-band signal can be transmitted through the coplanar waveguide line and then passes the resonator with the maximum transfer of energy at the resonant frequency of the resonator, i.e. 10.6 GHz. The sensor can be operated in a wide temperature range from 50°C up to 300°C. We find that the resonant frequency of the sensor decreases from 10.331 GHz to 10.281 GHz when the dielectric constant of PDC-SiCN increases from 3.900 to 3.938 and the dielectric loss of PDC-SiCN increases from 0.0042 to 0.0067.

1. Introduction
Sensors that can be operated in high-temperature and harsh environments are highly desired for monitoring the physical condition and operation process of high-temperature systems including turbine engines.[1-4] A detailed understanding of this information is very helpful to improve the efficiency and safety of the high-temperature systems. However, the development of high-temperature sensors is not a trivial matter. The biggest technical challenge is that the sensors must survive the harsh environments associated with the systems, including high temperatures, high pressures, corrosive species, and irradiations.

Although SiC-based sensors have been developed and are now commercially available, they are expensive and cannot be easily applied to large fields. [5-8] the development of high-temperature sensors requires new design principles and new materials. Polymer-derived silicon carbonatite (PDC-SiCN) ceramics have been demonstrated to be very stable and corrosion resistant for temperatures up to 1500°C, which make them good candidates for the design of high-temperature fibers, protective coatings, ceramic matrix composites, and ceramic micro-electro-mechanical systems. [9-17] recently, it has been shown that the dielectric constant of PDC-SiCN varies with temperature. The PDC-SiCN with temperature-dependent dielectric constants is promising for high temperature sensor applications. [18-27].
In this paper, we report the design and fabrication of a new temperature sensor. The sensor consists of two parts mainly: a coplanar waveguide line and a resonator. The resonator contains a thermo-sensitive PDC-SiCN ceramic. A wide-band signal can be transmitted through the coplanar waveguide line and then passes the resonator with the maximum transfer of energy at the resonant frequency of the resonator. We find that the resonant frequency of the sensor varies as a function of the dielectric constant and loss of PDC-SiCN. Because of the transmission of the resonator frequency, the temperature sensor is promise for harsh environment applications.

2. Sensor design and fabrication

2.1. Sensor Design

Fig. 1(a) shows the schematic diagram of the three-dimensional (3-D) configuration of a wire temperature sensor. The sensor consists of two parts mainly: a coplanar waveguide (CPW) line and a resonator. The substrate material for the CPW line is alumina, and the conductive material for the CPW line is a manganese molybdenum alloy, which is stable up to 1600°C. The silver resonator is filled with thermo-sensitive PDC-SiCN ceramics which can be used in atrocious conditions. The CPW line and the resonator are weakly coupled through the coupling slots, which is on the sideway of the resonator. The resonator and the CPW line are simply in contact with the silver. All the dimensions are listed in Fig. 1. For the resonator studied herein, \( H_1/D < 2.03 \), therefore the dominant resonant mode for the resonator is TM_{010}. The resonant frequency \( f_r \) and Q-factor \( Q'(U) \) of the resonator can be accurately measured using network analyzers: [1, 4, 28]

\[
f_r = \frac{1}{2\pi \sqrt{\mu_0 \varepsilon_0 \varepsilon_r}} \frac{\chi_{01}}{D/2}
\]

\[
Q'(U) = \left( \frac{1}{Q_{\text{dielectric}}} + \frac{1}{Q_{\text{metal}}} \right)^{-1} = \frac{f_r}{\Delta f_{3dB}} \frac{1}{1 - \text{mag}(S_{11}(f_r))}
\]

Where \( \varepsilon_0 \) and \( \mu_0 \) are the permittivity and permeability of free space, respectively. \( \chi_{01} \) is the first root of Bessel function of the first kind, i.e., 2.2048. \( \varepsilon_r \) is the relative permittivity of PDC-SiCN ceramic at testing temperatures. D represents the diameter of the cavity.
2.2. Coupling slot design

The sensitivity is one of the crucial elements for the design of a sensor. In order to achieve a high sensitivity, the coupling between the CPW line and the resonator is critical. A coupling slot was designed on the side of the resonator and optimized by using HFSS soft. Fig. 2(a) shows the frequency corresponding to the S11 peak in the simulated for different slot dimensions. The frequency changes from 10.53 to 10.12 GHz for the different combinations of slot widths (3–5.5 mm) and heights (0.4–1.4 mm). It is observed that the frequency decreases as the slot width or height increases.

Additionally, a high sensitivity to the slot size is observed for a large dimension. The peak level of the S11 simulated for large slot dimensions produces low reflection levels but high resolutions. However, this trend does not hold when W is above 5.0 mm. Therefore, W and H are chosen to be 5 and 0.6 mm, respectively, by trading off between the performance and the sensitivity.

Figure 1. (a) Top view of the wire temperature sensor, (b) side and (c) top view of CPW line, (d) side and (e) bottom view of the resonator (r=5.66; h=0.020; H1=1.97; W=5.0; H=0.6; H3=12; W3=80; W2=69.64; t1=0.635; t2=0.005; S=2.2; g=0.4 (unit: mm))

Figure 2. Effect of the coupling slot dimensions on: (a) resonator frequency and (b) reflection level.
2.3. Sensor fabrication
Fabrication of thermo-sensitive PDC-SiCN ceramics.

Amorphous PDC-SiCN ceramics were synthesized by the thermal decomposition of polyvinylsilazane (PVSZ). First, the precursor of PVSZ was solidified by heat treatments at 300°C for 4 hours. The obtained solids were then crushed and ball-milled into fine powders using the high-energy ball milling. Second, the powders were compressed into discs (Φ13×2~3 mm) and then pyrolyzed at 1100°C for 4 hours in a tube furnace under a flow of ultra-high-purity nitrogen. The resultant PDC-SiCN ceramics were polished and prepared as a packing medium for the resonator with the size Φ11.32 mm×1.97 mm.

Fabrication of resonators.
The cavity resonator was made by a silver shell and a PDC-SiCN ceramic core. The metallization of the PDC-SiCN ceramic core is important to minimize the conductor loss. In our fabrication processes, the metallization was performed in two steps: First, a 25μm-thick silver layer was evaporated on the top and bottom surface of a PDC-SiCN ceramic core by using screen printing technology. Then the sample was dried at the oven at 250°C. The side way of the PDC-SiCN ceramic core was then metalized by using screen printing technology at different directions. During the metallization steps, the coupling slots were covered by 5×0.6 mm tapes.

Assembly of the resonator and the CPW line into a sensor. The substrate material for the CPW line was alumina. A manganese molybdenum alloy was brushed on the alumina substrate by using screen printing technology. Conductive silver adhesives were used as a bonder for coupling the resonator with the CPW line.

3. Experimental results

The measurement pattern is shown in Fig. 3(a). Fig. 3(d) shows the photos of the sensor, in which the cavity resonator (Fig. 3(c)) is fabricated on the CPW line (Fig. 3(b)). In order to keep a constant temperature, the sensor was surrounded by cotton insulation. The measurement was performed from 50 to 300°C with a step of 50°C.

![Figure 3. (a) Measurement pattern of the sensor; (b) Photograph of CPW line; (c) Photograph of the resonator and (d) Photograph of the sensor.](image)

The reflection coefficient $S_{11}$ is shown in Fig 4 (a), which shows that the half power beam width (FWHM) of $S_{11}$ becomes wider with the increase of temperature, standing for the gradual loss of resonance signal. The measured $f_r$ and $Q'_r$ of the PDC-SiCN resonator are plotted against temperature in Fig. 4(b). $f_r$ decreases slowly from 10.331 to 10.281 GHz as the temperature increases from 50°C to 300°C. Because the thermal expansion coefficient (CTE) of PDC-SiCN is very small, the change of the
resonator dimension can be neglected. The average measurement sensitivity is found to be 0.200 MHz/oC. $Q'_{r}$ reaches to a maximum value of 217.8 at 50°C and reduces to 140.3 at 300°C.

![Figure 4](image)

**Figure 4.** (a) Reflection coefficient ($S_{11}$), (b) the resonator frequency and Q factor with the test temperature of the sensor.

The decreasing is due to the increased losses of PDC-SiCN and metal mainly, which can be expressed by: [1, 4, 28]

\[
Q_{\text{dielectric}} = \frac{1}{\tan \delta} \quad (3)
\]

\[
Q_{\text{metal}} = \frac{\chi_{011} \frac{\mu_0}{\varepsilon_0 \varepsilon_r}}{2(1 + \frac{D}{2H}) \sqrt{\frac{2\pi f \mu_0}{2\sigma}}} \quad (4)
\]

Where $\sigma$ is the bulk conductivity of the metal. In this study, silver is used for metallization purpose with $6.17 \times 10^7$ S/m, and tan$\delta$ is loss tangent of the dielectric material.

The extracted $\varepsilon_r$ and tan$\delta$ of PDC-SiCN are plotted in Fig. 5. The dielectric constant and loss tangent of PDC-SiCN increase from 3.900 to 3.938 and from 0.0042 to 0.067, respectively, within 50°C–300°C.

![Figure 5](image)

**Figure 5.** Extracted (a) $\varepsilon_r$ and (b) tan$\delta$ versus temperature.
4. Conclusion
A new temperature sensor is designed and fabricated by coupling a coplanar waveguide line to a resonator containing a thermo-sensitive PDC-SiCN ceramic. A wide-band signal can be transmitted through the coplanar waveguide line and then passes the resonator with the maximum transfer of energy at the resonant frequency of the resonator, i.e. 10.6 GHz. The sensor can be operated in a wide temperature range from 50°C up to 300°C. It is observed that the resonant frequency of the sensor decreases from 10.331 GHz to 10.281 GHz when the dielectric constant of SiCN increases from 3.900 to 3.938 and the dielectric loss of SiCN increases from 0.0042 to 0.0067.

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