Flex-circuit resonant chip with Y5V multilayer capacitor for wireless temperature tracking

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This paper reports the first wireless thermometric device enabled using a surface-mount capacitor microchip as the sensing element, offering a low-cost, disposable, and flexible sensor potentially suitable for a wide range of application areas. The device is developed in the form of a resonant-circuit chip, in which a Y5V-type multilayer capacitor microchip that exhibits significant temperature dependence serves as a thermoresponsive element that varies the resonant frequency of the circuit upon a temperature change. The wireless sensor chips prototyped in conjunction with the flex-circuit technology are tested to show their intended function with the frequency responses of up to 129 kHz/°C for ambient temperature variations. Wireless temperature tracking of a fluid-flowing channel is experimentally demonstrated using the prototype.

Introduction: The use of an inductor-capacitor (LC) resonant tank circuit in which the capacitance or the inductance is designed to vary with temperature is an advantageous approach to wireless temperature sensing given its reliable frequency-based reading and no requirement for packaging internal power sources [1–3]. Wireless temperature sensing based on this architecture has been reported through different approaches. They include the use of interdigitated capacitor electrodes coated with temperature-sensitive thin films (e.g. bismuth-doped barium titanate) [1], high-*k* temperature-sensitive ceramic material forming a custom parallel-plate capacitor [2], and micro-particle filled polymer composite acting as temperature-responsive resistors in a radio frequency identification (RFID) like device [3–5]. However, almost all of these devices use special composite materials accompanied by complex preparation processes that lead to high cost in their manufacturing and end products. The Y5V capacitors are class-2 multilayer ceramic capacitors with high permittivity (11,000–14,000) dielectrics based on barium titanate [6]. They are available in a form of surface-mount-device (SMD) microchips with low costs (in the order of \$0.01–0.1/chip depending on types and order amounts). These products provide large capacitances for given volumes, while exhibiting large variations (e.g. up to +22%/−82%) over a wide range of temperature (−30 to +85 °C) [6]. In electronics areas, this large temperature dependence is a drawback in most cases, limiting their application to thermally stable environments. This characteristic, however, could be leveraged to create an application opportunity in capacitive temperature sensing. In particular, these capacitor microchips could serve as the sensing elements in LC-tank circuits for resonant wireless temperature reading. The current work is targeted at this sensing application of the Y5V capacitor. The feasibility of this sensing scheme was shown on a circuit level [7] while no real device has been investigated or developed. The focus of the current study is placed on the development and experimental demonstration of proof-of-concept prototypes of the Y5V-based flexible RF temperature sensor. They are designed and microfabricated with planar inductive antennas toward enabling a battery-less, low-cost wireless sensing chip that offers a broad range of potential applications. The physical flexibility and disposable nature of the device are expected to make it well suited for medical/healthcare applications, for example, continuous remote monitoring of patients' body temperature (Figure 1), and feedback control of hyperthermia treatments clinically used for various cancer therapies [8–10].

Design and prototyping: The developed wireless chips are designed to have planar spiral coils with varying sizes approximately from 22 mm down to 6 mm. The two end terminals of each coil are connected with a Y5V SMD capacitor to complete the LC loop on each device. Figure 2a illustrates the 6 mm sized device design. The coils in the 22 and 6 mm sizes are designed to provide the inductances of 1.3 μH and 120 nH, respectively. Each coil is configured to have two vias that provide connections between the centre of the spiral coil and one of the contact pads for the SMD microchip bonding. The dimensions of the line width/spacing and the via structure scale as the device size increases. The Y5V capacitors with nominal capacitances of 1–10 nF are selected for prototyping in this work. The resonant frequency of the device can be expressed as $(2\pi\sqrt{L\cdot C(T)})^{-1}$, where L is the inductance of the planar coil, and $C(T)$ is the variable capacitance of a Y5V capacitor as a function of ambient temperature, T. A certain temperature change causes a change in the capacitance and thus in the resonant frequency of the device. The resonant frequency (in the order of 10–100 MHz in the current designs) can be wirelessly tracked through an external antenna that is inductively coupled with the chip based on the impedance phase-dip method [11] to determine the temperature change applied to the device.

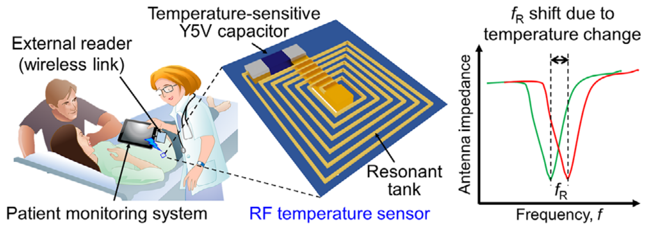

Fig. 1 *Conceptual schematic of the developed wireless temperature sensing chip and its potential medical application*

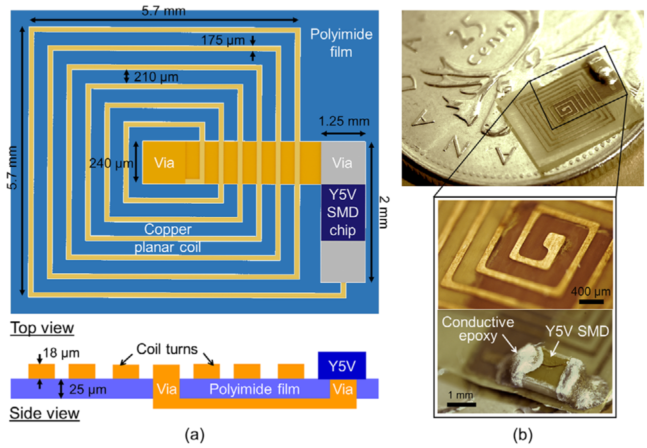

Fig. 2 *Design and fabricated samples of the wireless temperature sensing chip. (a) Top and side views of the design; (b) optical images of a microfabricated prototype on a Canadian quarter (top) and its close-up images (bottom)*

A photolithographic flex-circuit process is used for the fabrication of the sensor's inductor coil. The coil structure is fabricated using a double-sided copper-clad polyimide (PI) film with 25 μm thickness (Pyralux AP9111R, DuPont, DE, USA). The photo-patterning is performed using a dry-film photoresist (Riston FX930, DuPont, DE, USA) thermally laminated on each side of the copper-clad PI. First, one of the capacitor electrodes is formed by wet etching the copper clad on the backside using a patterned photoresist (the front-side clad layer is protected by another photoresist layer during this etching). Next, the PI film is etched in a potassium-hydroxide-based solution to create two via holes into the film from the backside with the corresponding patterned photoresist, so that the bottom of the two via holes are terminated with the clad layer on the front side. Copper electroplating is then performed in a sulfuric acid-based bath to fully refill the via holes, after which the protective layer on the front side is removed. The sample is again laminated with the same photoresist film on both sides for the spiral coil patterning by similar photo-defined wet etching of the clad layer on the front side, followed by the removal of all the resist layers. After a thorough cleaning of the fabricated sample, a Y5V microchip is bonded onto two terminals of the inductor using a conductive epoxy (CW2400, Chemtronics, GA, USA). The 22 and 6 mm devices are integrated with the commercial Y5V SMDs of 10 nF (Series 1206, Yageo Co., Taiwan; dimensions

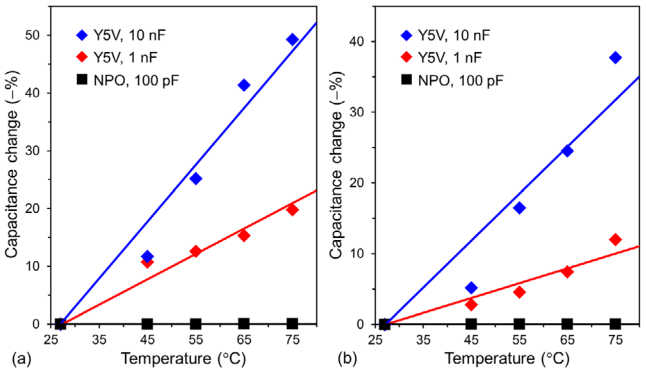

Fig. 3 *Measured temperature dependence of capacitance of the Y5V SMDs used for prototyping and a non-Y5V (NPO) SMD. (a) Capacitance change observed at a frequency of 100 kHz; (b) the same at 1 MHz*

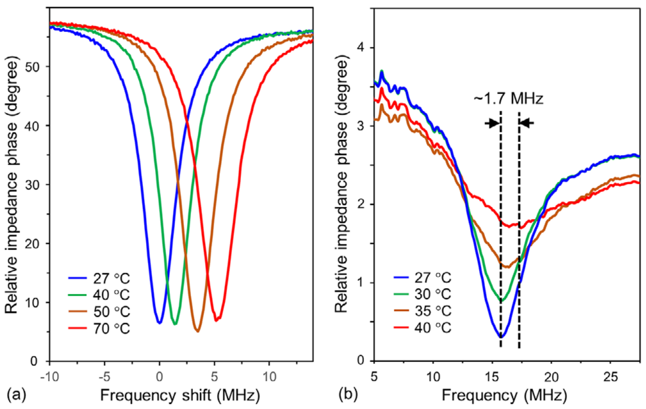

Fig. 4 *Measured frequency responses of the fabricated devices to varying temperatures. (a) 22 mm chip design; (b) 6 mm chip design*

3.2 × 1.6 × 0.25 mm^3) and 1 nF (Series 0805, AVX Co., SC, USA; dimensions 2.01 × 1.25 × 0.5 mm^3), respectively. Figure 2b shows a sample device fabricated for the 6 mm design.

Experimental results and discussion: Prior to the Y5V SMD integration, the capacitances of the 10 and 1 nF microchips were characterized using an inductor-capacitor-resistor meter (4275A, Hewlett Packard, CA, USA) to quantify their thermal dependences, by varying temperature of the standalone chips (with wires bonded for this measurement) from room temperature up to 75°C on a hot plate. The results recorded at two different frequencies (100 kHz and 1 MHz) are shown in Figure 3. The results obtained with a non-Y5V (NPO) capacitor chip (GRM21A5C2J101JWA1D, Murata Manufacturing Co., Japan) were also plotted for comparison. As can be seen, the Y5V capacitances decreased in approximately linear manners for both the samples whereas the changes in the NPO capacitor were negligibly small at either frequency. It was revealed that the particular 10 nF chips used in this study exhibited 2–3 times larger negative shifts with an average temperature coefficient of capacitance of -6.6 to -9.8×10^3 ppm/°C, whereas this coefficient for the 1 nF chip was -2.1 to -4.4×10^3 ppm/°C for the same temperature range.

The wireless measurement of the resonance and its frequency shift due to temperature changes was conducted by establishing an inductive coupling between the device under test and the external loop antenna connected with a spectrum-impedance analyser (4396B, Agilent Technologies, CA, USA), and tracking the frequency of an impedance phase dip that represented the resonant frequency of the device while varying its temperature up to 70°C using a Peltier heater (CP20251, CUI Devices, OR, USA) on which the device was mounted. The measurement results in Figure 4 show that both the devices exhibited increases in their resonant frequencies with temperature rises as predicted from the measured negative coefficients shown in Figure 3 (this measurement used a higher-order resonance for the 22 mm device case to avoid noisy signals found around its primary resonance). The 22 mm device showed an

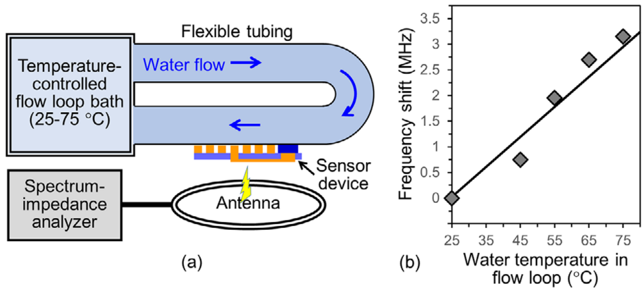

Fig. 5 *Wireless monitoring test on flow loop. (a) Experimental set-up; (b) measured resonant frequency versus flowing fluid temperature*

overall frequency shift of 5.13 MHz with a temperature change between 27 and 70 °C, indicating an average frequency response of 119 kHz/°C (Figure 4a). For the 6 mm device, a frequency shift of ∼1.7 MHz was observed for a temperature change up to 40°C (Figure 4b) revealing a similar average frequency response (129 kHz/°C) as seen in the 22 mm version. It is also observable that this device exhibited a consistent decreasing trend in its phase dip with increases in temperature. Although the exact source of this observed trend is not clear, it could be related to a temperature dependence of resistive loss in the particular capacitor to potentially damp the resonance of the device at elevated temperatures, unlike the case in the 22 mm device that used a different capacitor.

Besides medical application areas, the developed wireless sensor is potentially usable for the process control of chemical productions, including those involving reactive or hazardous chemicals where the continuous temperature monitoring of flowing fluid is essential for safety management. This type of temperature monitoring may be implemented by coupling wireless sensors with the fluidic tubing/piping. As a preliminary test in light of the above application area, an experimental measurement was conducted using a temperature-varying flow loop. As illustrated in Figure 5a, the 22 mm device was fixed on a surface of the plastic tubing connected with a temperature-controlled circulating bath (Polystat Standard Heated Bath, Cole-Parmer Canada Co., QC, Canada) that forced a flow of water in the loop at different temperatures up to 75°C while the device's resonant frequency was wirelessly tracked (as described earlier; to stabilize the tubing temperature, the frequency was read 10 min after each temperature was set in the bath). As can be seen from the measurement result in Figure 5b, the total frequency shift of 3.15 MHz was recorded for the tested temperature range in a relatively consistent manner. This represents an average frequency response of 63 kHz/°C. While this coefficient is somewhat smaller than the level observed earlier (which might have been caused by certain heat loss at the particular contact interface between the tubing surface and the device's Y5V capacitor), this feasibility test verifies the sensor's essential ability in temperature monitoring for fluidic systems.

Conclusion: This study has investigated a wireless resonant sensor chip that exploits the thermal dependence of the Y5V capacitor serving as the temperature sensing element of the device. The proof-of-concept prototypes with different chip sizes were microfabricated in a form of a flexible printed-circuit device integrated with the particular capacitor microchip, potentially enabling low-cost and disposable products. The developed battery-less wireless sensors were experimentally tested to verify the intended concept and feasibility of frequency-based temperature sensing while demonstrating wireless temperature tracking of a flow channel. This working mechanism "potentially" offers opportunities for simultaneous multiparameter sensing via the integration of separate RF resonators formed with other variable capacitors that respond to targeted stimuli beyond temperature [11]. The present study will be followed by further development of the device through optimization of its design and fabrication including packaging of the chip as well as in-depth analysis of the capacitive and frequency responses toward sensitivity improvement.

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