

# SAW Delay Line based IoT Smart Sensing in Water Distribution System

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**Abstract**—Wireless Passive Surface Acoustic Wave (SAW) sensors have attracted great attention in numerous applications. They are powered by interrogating Radio Frequency (RF) pulses rather than batteries. In this study, a wireless passive SAW temperature and pressure delay line sensor was adapted in a designed framework which can control the ambient liquid temperature and pressure and characterised. The experimental results meet the theoretical analysis that the related phase delay of the response signal depends linearly on the temperature (pressure) when the pressure (temperature) keeps constant.

**Keywords**—SAW; sensor; phase; temperature; pressure

## I. INTRODUCTION

Wireless passive SAW sensors provide the capability of sensing physical quantities, e.g., temperature [1, 2], pressure [3], torsion [4], flow rate [5] etc. without direct power supply (batteries are not necessary power sources for sensor nodes). They are powered and activated by absorbing the energy of the interrogation RF pulses. There are many advantages of using the wireless passive SAW sensors apart from their wireless access and passive elements characters, e.g. small size, high sensitivity, ruggedized elements and suitable to use in harsh environment [6].

Internet of Things (IoT) technology has been widely applied to a variety of industrial projects, e.g. healthcare, manufacture, energy consumption, etc. [8-13]. Smart sensors can be a form of IoT, a network of technologies which can monitor both physical and chemical parameters, capture meaningful data, and communicate that data over a wireless network to a computer in the cloud for software to analyse in real time and help determine action steps. Technologies are capable of monitoring objects such as smart water meters and other electronic devices, organisms, or a natural part of the environment such as an area of ground to be measured for moisture or chemical content. A smart device is associated with each object which provides the connectivity and a unique digital identity for

identifying, tracking, and communicating with the object [14, 15]. A sensor within or attached to the device is connected to the internet by a local area connection (such as RFID, NFC, or BTLE) and can also have wide area connectivity. Typically, each data transmission from a device is small, but the number of transmissions can be frequent. IoT involves many, many things interacting with each other to produce actionable information [8-10, 12, 13].

The present work aims to characterise the wireless passive temperature and pressure SAW sensor and evaluate the performance of it for liquid temperature and pressure sensing. The sensor node was adapted into a designed two-layer glass pipe experimental framework to simulate the ambient liquid environment. The adapted SAW sensor node was interrogated by using a vector signal generator, and a signal analyser and an oscilloscope were used for receiving the response signals and the subsequent processing steps. Temperature changes were applied by the water bath, and pressure changes were controlled by the liquid pressure transmission platform.

## II. SENSOR NODE STRUCTURE

The fundamental structure of the wireless passive SAW temperature and pressure sensor is shown in Fig. 1, which consists of a SAW delay line with an antenna connected with the Inter Digital Transducers (IDT). The SAW sensor obtains the necessary energy from the RF signal received through the antenna. In this case, the SAW sensor contains a minimum number of elements and there are no power supply components, such as batteries, in this design. The outside pressure applied through the action point is different from the reference pressure inside the sensor. The pressure differences act on the left part of the substrate, and the temperature affects the whole substrate at the same time by the bonding basis on the right of the substrate. The RF signal can be received and sent through the connected antenna and converted by the IDT. Reflectors are manufactured in parallel with the IDT on the substrate to reflect the SAW. Two

are located at the right side of the IDT ( $R_2$  and  $R_3$ ) and one is on the left ( $R_1$ ). Such a design can fully use the two opposite directions SAW energy propagating from the IDT [7].

The dimensions of the top surface of the substrate change with the change of temperature and pressure. Consequently, the time delays caused by the SAW propagations are different, which leads to the phase shifts. In the case of this SAW sensor, the interrogator transmits a pulse signal, and the sensor responds with a chain of pulses depending on the positions of the reflectors arranged on the substrate's surface. The different time delays between two or more response signals are evaluated. The current pressure and temperature information is acquired from the response signals through the subsequent signal processing.

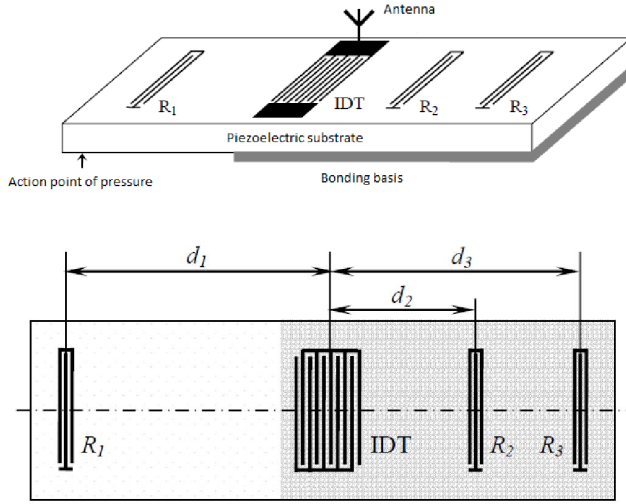


Fig. 1. The structure of the wireless passive delay line SAW temperature and pressure sensor node.



Fig. 2. The photo of wireless passive SAW delay line temperature and pressure sensor node with antenna.

Fig. 2 shows the sensor node of the wireless passive SAW delay line temperature and pressure sensor node with the antenna. To achieve better experiment performance, the performance of various antennas was investigated, the connected

antenna was changed from the spiral type in the previous study [3, 16] to this current type for enhance the signal strength.

### III. THEORETICAL MODEL

Based on the theory of SAW and the sensor structure, the values of temperature and pressure can be determined by the following equations. The initial RF interrogation signal transmitted from the reader antenna  $S(t)$  is given by Equation 1.

$$S(t) = A \cos(\omega_0 t + \theta_0) = A \cos[\theta(t)] \quad (1)$$

where  $\omega_0$  is the initial angular velocity;  $t$  is the time;  $\theta_0$  is the initial phase of the interrogation signal;  $A$  is the initial amplitude of the interrogation signal.

The RF response signal reflected by  $R_i$  ( $i=1, 2, 3$ ) reflector is given by Equation 2.

$$S_i(t) = A_i \cos[\omega_0(t - t_i) + \theta_0] = A_i \cos[\theta_i(t)] \quad (2)$$

where  $t_i$  is time delay of the RF response signal reflected by  $R_i$  ( $i=1, 2, 3$ ) reflector against the interrogation signal;  $A_i$  is the amplitude of the response signal reflected by  $R_i$  ( $i=1, 2, 3$ ) reflector, which is normally a smaller value than  $A$  due to attenuation of propagation.

The time delay  $t_i$  consists of two parts shown by Equation 3, one is  $\tau_i$ , the time delay caused by the SAW propagation from the IDT to the  $R_i$  ( $i=1, 2, 3$ ) reflector and the back way to the IDT, and the other one is  $\tau_e$ , the delay caused by other reasons, e.g. the time delay caused by the RF signal propagates between the antenna of the reader and the antenna of the SAW sensor.  $\tau_e$  is a constant value for all the response signals.  $\tau_i$  can be derived by  $d_i$ , the distance from the IDT to the  $R_i$  ( $i=1, 2, 3$ ) reflector and  $v$ , the velocity of the SAW propagation on the substrate.

$$t_i = \tau_i + \tau_e = \frac{2d_i}{v} + \tau_e \quad (3)$$

From the sensor structure, reflector  $R_2$  and  $R_3$  are used for temperature measurement.  $\varphi_T$  is defined as the phase difference directly indicating the temperature impact of the ambient environment, which is derived in Equation 4.  $\tau_e$  is taken out by the subtraction.

$$\varphi_T = \varphi_3 - \varphi_2 = \omega_0(t_3 - t_2) = \omega_0(\tau_3 - \tau_2) = \omega_0\tau_T \quad (4)$$

where  $\tau_T$  is the time delay of the SAW propagation from  $R_2$  to  $R_3$  and reflected back from  $R_3$  to  $R_2$ .

The relation of  $\tau_T$  and the temperature  $T$  to be sensed is shown in Equation 5.

$$\tau_T = \frac{2(d_3 - d_2)}{v} = \frac{2d_T}{v} = \tau_{T_0}[1 + \alpha(T - T_0)] \quad (5)$$

where  $d_T$  is the distance between  $R_2$  and  $R_3$  on the surface of the sensor substrate;  $\tau_{T_0}$  is the time delay caused by the SAW

propagation from R<sub>2</sub> to R<sub>3</sub> reflector and the back way to R<sub>2</sub> at the initial temperature T<sub>0</sub>; α is the temperature coefficient of the sensor substrate material.

τ<sub>T<sub>0</sub></sub> can be derived by Equation 6, in which d<sub>T<sub>0</sub></sub> is the distance between R<sub>2</sub> and R<sub>3</sub> on the surface of the sensor substrate at the initial temperature T<sub>0</sub>.

$$\tau_{T_0} = \frac{2d_{T_0}}{v} \quad (6)$$

According to the propagation theory of SAW, the initial angular velocity ω<sub>0</sub> is derived in Equation 7, where f<sub>0</sub> the initial frequency corresponding to ω<sub>0</sub>.

$$\omega_0 = 2\pi f_0 \quad (7)$$

Equation 8 shows the relation between the velocity of the SAW propagation on the substrate v and f<sub>0</sub>, in which λ is the wavelength of the SAW propagating on the surface of the sensor substrate.

$$v = f_0 \lambda \quad (8)$$

φ<sub>T<sub>0</sub></sub> is defined as the phase difference directly indicating the temperature impact of the ambient environment at the initial temperature T<sub>0</sub>. Equation 9 shows the relation between φ<sub>T<sub>0</sub></sub> and τ<sub>T<sub>0</sub></sub> in a similar way as Equation 4.

$$\varphi_{T_0} = \omega_0 \tau_{T_0} \quad (9)$$

Summarising Equation 4 – 9, the temperature change ΔT can be derived using the change of the phase difference directly indicating the temperature impact of the ambient environment Δφ<sub>T</sub>.

$$\Delta T = T - T_0 = \frac{\lambda}{4\pi\alpha d_{T_0}} (\varphi_T - \varphi_{T_0}) = \frac{\lambda}{4\pi\alpha d_{T_0}} \Delta\varphi_T \quad (10)$$

Equation 10 shows the linear relation between ΔT and Δφ<sub>T</sub>, which can be used to characterise the SAW sensor device.

From the sensor structure, the time delay t<sub>1</sub> is influenced by both temperature and pressure change. In order to separate the independent impact information caused by pressure change from the response signal reflected by R<sub>1</sub>, compensation method should be used to eliminate the impact caused by temperature change.

Like Equation 4, the phase difference between the response signals reflected by R<sub>1</sub> and R<sub>2</sub> φ<sub>PT</sub> is derived in Equation 11.

$$\begin{aligned} \varphi_{PT} &= \varphi_1 - \varphi_2 = \omega_0(t_1 - t_2) = \omega_0(\tau_1 - \tau_2) \\ &= \omega_0 \tau_{PT} \end{aligned} \quad (11)$$

where τ<sub>PT</sub> is the SAW propagation time difference between SAW propagating from the IDT to R<sub>1</sub> and reflected back to the IDT and it propagating from the IDT to R<sub>2</sub> and reflected back to the IDT.

μ<sub>T</sub> is defined as the average strain caused by temperature change, and μ<sub>P</sub> is defined as the average strain caused by pressure change (see Equation 12 and 13).

$$\mu_T = \alpha(T - T_0) = \alpha\Delta T \quad (12)$$

$$\mu_P = \beta(P - P_0) = \beta\Delta P \quad (13)$$

where β is the pressure coefficient of the sensor substrate material; P is the pressure to be sensed; P<sub>0</sub> is the initial pressure; ΔP is the pressure change.

τ<sub>PT</sub> can be derived by Equation 14.

$$\tau_{PT} = \frac{2(d_1 - d_2)}{v} = \frac{2d_{PT}}{v} = \tau_{P_0T_0}(1 + \mu_P + \mu_T) \quad (14)$$

where d<sub>PT</sub> is the distance difference of d<sub>1</sub> and d<sub>2</sub>; τ<sub>P<sub>0</sub>T<sub>0</sub></sub> is the time difference at the initial temperature T<sub>0</sub> and initial pressure P<sub>0</sub>, which can be derived by Equation 15.

$$\tau_{P_0T_0} = \frac{2d_{P_0T_0}}{v} \quad (15)$$

where d<sub>P<sub>0</sub>T<sub>0</sub></sub> is the distance difference of d<sub>1</sub> and d<sub>2</sub> at the initial temperature T<sub>0</sub> and initial pressure P<sub>0</sub>.

Summarising Equation 11 – 15, φ<sub>PT</sub> can be derived by Equation 16, and φ<sub>P<sub>0</sub>T<sub>0</sub></sub> can be derived by Equation 17.

$$\begin{aligned} \varphi_{PT} &= \omega_0 \tau_{PT} = \omega_0 \frac{2d_{P_0T_0}}{v} (1 + \mu_P + \mu_T) \\ &= \omega_0 \frac{2d_{P_0T_0}}{v} (1 + \beta\Delta P + \alpha\Delta T) \end{aligned} \quad (16)$$

$$\varphi_{P_0T_0} = \omega_0 \frac{2d_{P_0T_0}}{v} \quad (17)$$

where φ<sub>P<sub>0</sub>T<sub>0</sub></sub> is the phase difference between the response signals reflected by R<sub>1</sub> and R<sub>2</sub> at the initial temperature T<sub>0</sub> and initial pressure P<sub>0</sub>.

Therefore, Δφ<sub>PT</sub>, the subtraction of φ<sub>PT</sub> and φ<sub>P<sub>0</sub>T<sub>0</sub></sub> can be derived by Equation 18.

$$\Delta\varphi_{PT} = \varphi_{PT} - \varphi_{P_0T_0} = \omega_0 \frac{2d_{P_0T_0}}{v} (\beta\Delta P + \alpha\Delta T) \quad (18)$$

Therefore, ΔP can be derived by using ΔP and Δφ<sub>PT</sub> (see Equation 19).

$$\Delta P = \frac{v}{2\beta\omega_0 d_{P_0T_0}} \Delta\varphi_{PT} - \frac{\alpha}{\beta} \Delta T \quad (19)$$

The relations between the phase difference change and the temperature and pressure change are derived, which is shown in Equation (10) and (19). The phase difference change is linear to the temperature change and pressure change.

#### IV. EXPERIMENT VERIFICATION

Shown in Fig. 3, the signal generator, the signal analyser and the oscilloscope work as the function of the reader for the wireless passive SAW sensor node. The practical experiment set up is shown in Fig. 4. The temperature is controlled by the water bath, which is connected to the outer layer of the glass tube. Water with specific temperature circulates between the water bath container and the outer layer of the glass tube. The castor oil pressure control platform is connected to the strictly sealed inner chamber of the glass pipe. Based on the Boyle's Law, the pressure applied via the platform is equal to the air pressure sensed by the sensor node. The Function/Arbitrary Waveform Generator (Agilent 33220A) generates the pulse signal to mix with the standard 425 MHz sine wave generated by the ESG Vector Signal Generator (Agilent E4438C). The multiplication result of the two signals is transmitted out as the interrogation signal to the sensor node. The 1 GHz Mixed Signal Oscilloscope (Agilent MSO6104A) and the Spectrum Analyser (HP 8563E) receive and process both the interrogation signal and the response signals. Based on the previous studies in [3], the centre frequency of these sensor nodes is 425 MHz, and the best interrogation pulse width is 1  $\mu$ s. The following experiments are undertaken by the above settings.

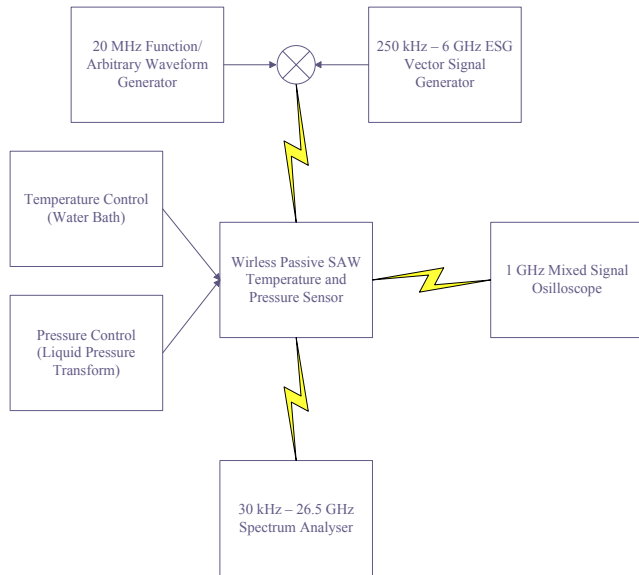


Fig. 3. Wireless interrogation, response and signal analysis with temperature and pressure control.

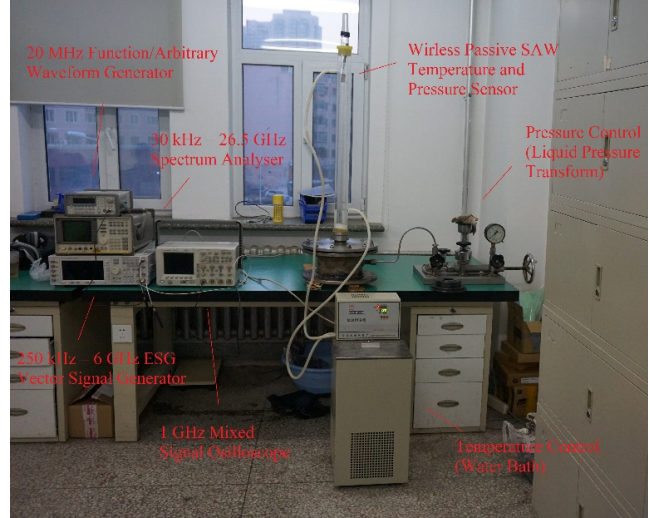


Fig. 4. The picture of the practical experiment set up.

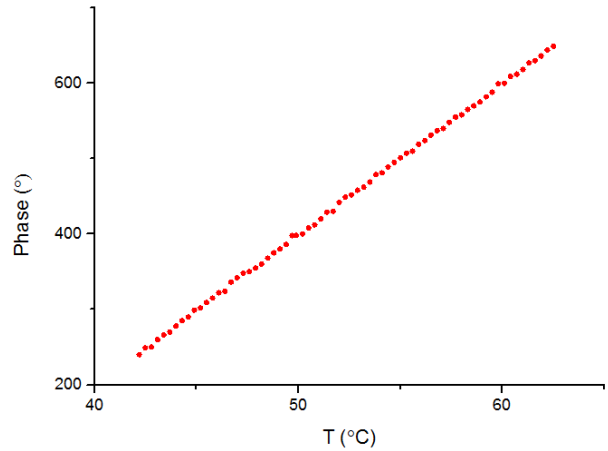


Fig. 5. The relation between the phase delay and temperature when the pressure keeps constant.

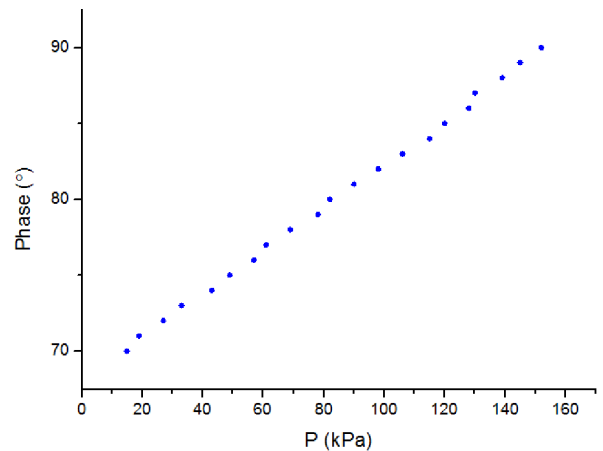


Fig. 6. The relation between the phase delay and pressure when the temperature keeps constant.

The actual temperature and pressure change can be read from the temperature and pressure control platforms, while the experimental values can be obtained through the data of the interrogation and response signals received and processed by the signal analyser and the oscilloscope.

## V. CONCLUSION

A wireless passive SAW temperature and pressure delay line sensor was adapted in a designed framework which can control the ambient liquid temperature and pressure and characterised. The results showed that the related phase delay of the response signal depends linearly on the temperature when the pressure keeps constant, and the related phase delay of the response signal depends linearly on the pressure when the temperature keeps constant. The experimental results meet the theoretical relations well.

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