A Novel Wireless PassiveTemperature-Pressure SAW-based Sensor

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Abstract: A novel wireless and passive surface acoustic wave (SAW) sensor is developed for measuring temperature and pressure. The sensor has two single-port resonators on a substrate. One resonator, acting as the temperature sensor, is located at the fixed end without pressure deformation, and the other one, acting as the pressure sensor, is located at the free end to detect pressure changes due to substrate deformation. Pressure at the free end bends the cantilever, causing a relative change in the acoustic propagation characteristics of the SAW traveling along the surface of the substrate and a relative change in the resonant frequency of the resulting signal. The temperature acts on the entire substrate, affecting the propagation speed of the SAW on the substrate and directly affecting the resonant frequency characteristic parameters. The temperature and pressure performance of this new antenna-connected sensor is tested by using a network analyzer, a constant temperature heating station, and a force gauge. A temperature sensitivity of 1.5015 kHz/°C and a pressure sensitivity of 10.6 kHz/gf at the ambient temperature have been observed by wireless measurements. This work should result in practical engineering applications for high-temperature devices.

Key words: surface acoustic wave, wireless sensor, temperature-pressure

1 Introduction

In recent years, surface acoustic wave (SAW) devices have been widely used in various measurements such as temperature[1], pressure[2], humidity[3-5], gas[6], chemical reagents,[7] and gyroscopes[8,9] owing to their unique features. Among various sensors, SAW-based sensors have many advantages such as small size, low cost, good stability, and high repeatability[10-12]. They also have the advantage of being able to work wirelessly and not needing a battery[13]. A network analyzer transmits the RF pulse to the SAW sensor through an antenna, and then an interdigital transducer (IDT) located on the SAW-based sensor converts the electromagnetic (EM) signal into a SAW, which is propagated on the piezoelectric substrate and is reflected by reflectors on both sides of the IDT. For an object to be tested for a property such as temperature or pressure changes, the resonant cavity formed by the reflectors changes its resonant frequency[14]. The IDT converts the resulting SAW into an EM wave, which is again transmitted back to the network analyzer through an antenna. This is the working principle of SAW-based sensors[15]. The network analyzer can read the change in the resonant frequency, which varies depending on the temperature and pressure increments. Therefore, sensitivity is defined as an incremental change in the signal that occurs in response to an incremental change in temperature or pressure.

A novel temperature-pressure SAW-based sensor is used in this study for parameter monitoring in harsh environments such as high-temperature and high-rotation spacecraft. The sensor has a cantilever structure composed of a piezoelectric base material and an antenna. There are two vertically distributed resonators on the base of the sensor, which are different from the delay line structure of other sensors. One resonator is located at the fixed end of the cantilever beam as a temperature-sensing portion and a temperature-compensation portion for pressure detection. The other resonator is located at the free end of the cantilever beam as a pressure-detecting portion. The temperature acts on the entire substrate, affecting the propagation velocity of the SAW on the substrate and directly affecting the resonant frequency. The deformation of the substrate caused by the pressure affects only the frequency variation of the free-end resonator. Two-port resonators have a different design for the interdigital transducer and the reflective grating, and they achieve a separation of the resonant frequency to realize dual-parameter measurements with the same sensor.

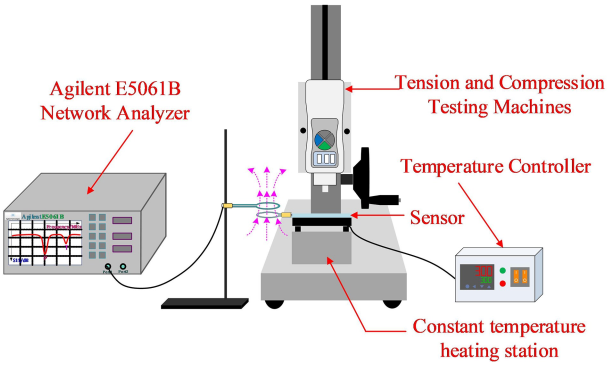


Fig. 1 Schematic diagram of a wireless SAW temperature-pressure SAW-based sensor.

2 Theoretical Analysis

2.1 Design considerations

The goal ofa SAW-based sensor design is to achieve pressure measurement, temperature measurement, and antenna integration in a single-chip design by changing materials, structural parameters, processing techniques, and test methods. This enables the sensor to have a significant resonant frequency offset and sensitive wireless transmission. $LiNbO_3$ (LN, 1 mm thickness) is used for the piezoelectric substrate because it has high SAW propagation speed and a large electromechanical coupling factor K^2 (6%)[16]. The high value of K^2 contributes to greater reflection of the reflector while reducing the insertion loss.

Ina SAW-based sensor, the center frequency f is

$$f = \frac{v}{\lambda} \tag{1}$$

where f is the resonant center frequency of the resonator, v is the wave velocity of SAW, and λ is the wavelength of SAW. The wave velocity v has the following correspondence with the elastic constant c^* and the density ρ of the substrate[17]:

$$v \propto \sqrt{\frac{c*}{\rho}} \tag{2}$$

When strain ε occurs on the substrate of the resonator, the deformation of the substrate leads to a change in the interdigitation λ. A change in the material density and other physical parameters would lead to a change in the wave velocity V of the SAW, which ultimately leads to a change in the resonator center frequency f[18]:

$$f(\varepsilon) = \frac{v(\varepsilon)}{\lambda(\varepsilon)} = \frac{v_0(1 + k'\varepsilon)}{\lambda_0(1 + \varepsilon)} = f_0\frac{1 + k'\varepsilon}{1 + \varepsilon} \tag{3}$$

where k' is a material constant, determined by the substrate of the sensor. The amount of change in the resonant frequency is

$$\Delta f = f(\varepsilon) - f_0 \approx f_0\,\varepsilon(k'-1) \tag{4}$$

When the temperature of the substrate of the resonator changes, the relationship between the SAW wave velocity and the temperature is given by[19]:

$$v(T) = v(T_0) + \frac{\delta v}{\delta T}(T - T_0) + \frac{1}{v(T_0)}\frac{\delta v}{\delta T}(T - T_0) \tag{5}$$

The relationship between the resonant frequency of the sensor and the temperature can be expressed as

$$\frac{\Delta f}{f} = \frac{\Delta v}{v(T_0)} = \frac{1}{v(T_0)}\frac{\delta v}{\delta T}(T - T_0) \tag{6}$$

The interdigital periods of the two resonators are designed to be 200 μm and 220 μm, providing different frequencies for the two resonators. The number of IDT finger pairs and reflector electrodes of the two resonators are set to 10 and 20, and the gap between IDT and adjacent reflectors is 150 μm and 165 μm, respectively. Then, the fixed end of the cantilever beam with the two single-port SAW resonator patterns is clamped using a fixed base. The temperature test end is clamped with a fixed base as the fastening end, and the pressure test end is suspended as a free end.

2.2 Simulation of SAW-based sensor

COMSOL simulation is an effective simulation technique for resonant frequency simulation, admittance simulation, and impedance simulation among SAW-based sensors[20].

Based on the temperature- and pressure-sensitive mechanisms of SAW-based sensors, the two-parameter SAW-based sensor is modeled by COMSOL finite element simulation software. Fig. 2 shows the COMSOL simulation model and simulation results. Two IDTs and reflectors with different resonant frequencies are integrated on an $LiNbO_3$ substrate. With the simultaneous application of a wideband excitation signal to the two IDTs, signals from different IDTs in only a certain very narrow frequency band can be reflected. The frequency of the reflected waves is the frequency of the sensor. It can be seen from the simulation results that the signal generates weak crosstalk during the propagation process, but the received reflected signal still has a separate resonant frequency. The sensor design in a specific frequency band can be achieved by adjusting the period of the resonator.

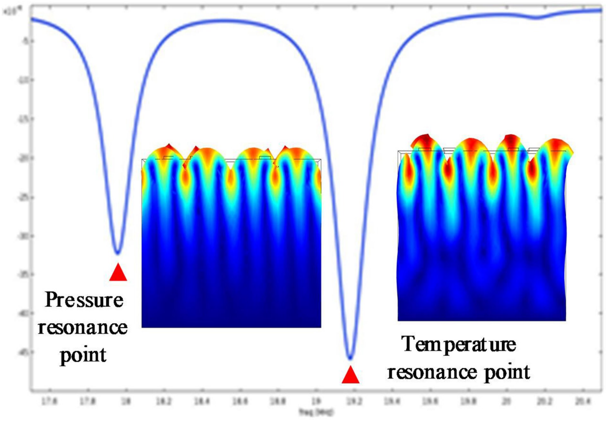


Fig. 2 Simulation of the device using COMSOL.

2.3 Simulation of antenna

The measurement of temperature and pressure by the sensor is done by wireless signal transmission through an antenna. The antenna acts as a means of emitting and receiving radio frequency signals and functions to achieve energy conversion, directional radiation, and directional reception[21]. For the antenna design requirements, the antenna is simulated using Advanced Design System (ADS) simulation software.

Testing of surface acoustic waves in harsh environments requires the use of good interrogation antennas and response antennas to perform long-range wireless detection of the sensor signals. The performance of the two antennas directly affects the quality of the communication system. The following two performance indicators must be met: (1) the type of the antenna and its polarization direction meets the test requirements and anti-interference, and (2) the electrical properties of the antenna. The main indicators are the frequency, bandwidth, and the gain of the antennas[22]. The response antenna should have wide-range, high-gain detection. The interrogating antenna must have a sufficiently large bandwidth to cover all possible frequency variations of the responding antenna during the sensor test. Considering the integration and miniaturization requirements of antennas and sensitive components, this sensor uses a multi-turn loop antenna. As shown in Fig. 3b, the antenna size is designed and optimized using the Advanced Design System software according to the resonant frequency design of the two resonators, and the designed antenna covers the resonator frequency variation range. The antenna, made by changing the outer diameter and number of turns of a coil, is shown in Fig. 3a.

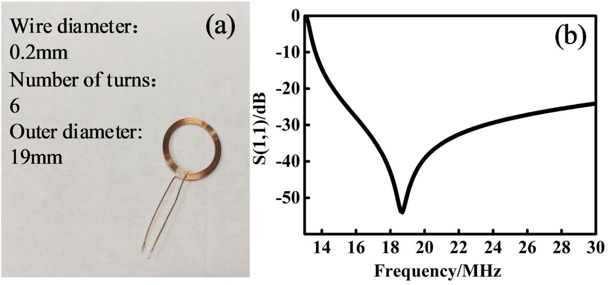


Fig. 3 (a) Photo of the Antenna, (b) ADS simulation of the antenna.

3 Sensor Fabrication

Piezoelectric substrates are soaked in a freshly prepared 3:1 (V/V) piranha (sulfuric acid, hydrogen peroxide) solution for 15 min and then sonicated with propanol and alcohol for 5 min, respectively. This effectively removes any organic substances (such as grease) that may be present on the surface of the piezoelectric substrate, improves the surface finish of the substrate, and enhances metal adhesion in the subsequent metal sputtering step.

A Y-128 $LiNbO_3$ of 1 mm thickness is used as the piezoelectric substrate. The photoresist (PR) is spin-coated, exposed, and then patterned through a standard photolithography process, using magnetron sputtering to deposit a layer of about 300 nm-thick aluminum on the piezoelectric substrate. Then the unexposed photoresist and excess aluminum are removed using acetone in a lift-off process. This is followed by ultrasonication with acetone and rinsing with deionized water to remove any unwanted products. The final, fabricated temperature resonator and pressure resonator are shown in Fig. 4. The edges of the interdigitated lines are free of excess metal adhesion and relatively clear.

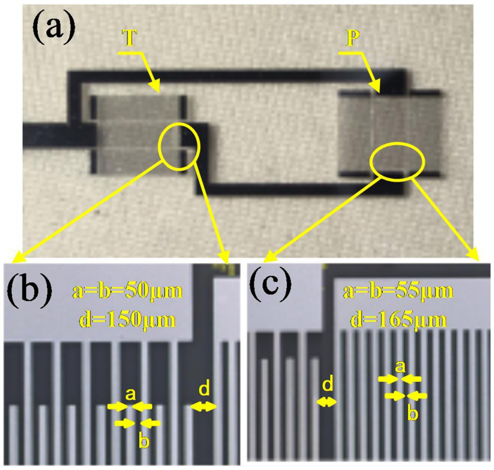


Fig. 4 Partial view of temperature resonator and pressure resonator.

4 Measurement and Discussion

The $LiNbO_3$ substrate with two single-port resonators is fixed on an FR4 base, and the pressure resonator is suspended at one end of the FR4 base to form a cantilever structure. The other end of the FR4 is soldered to the antenna for wireless transmission of signals. Sufficient room is provided on the outside of the pressure sensor to allow movement when a pressure is exerted on the device. The complete surface acoustic wave temperature pressure sensor is shown in Fig. 5.

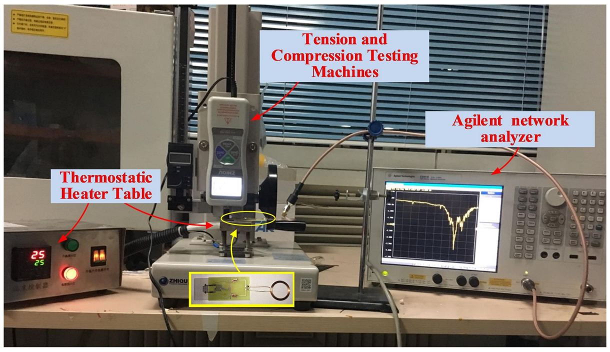


Fig. 5 Measurement equipment of the temperature-pressure SAW-based sensor.

The novel temperature-pressure SAW-based sensor is tested. The measurement equipment consists of the novel SAW-based sensor, a vector network analyzer and a constant temperature heating station, as shown in Fig. 5. The interrogating antenna is connected to the network analyzer (Agilent E5061B) through a coaxial cable to excite the sensor and receive the echo spectrum signal of the sensor. The echo information of the interrogating antenna is analyzed and the corresponding relationship between the environmental parameters is determined. The parameters of the external environment can be estimated by the echo information.

Fig. 7 shows that the resonant frequencies of the pressure and temperature resonators display a decreasing trend with increasing temperature. It also indicates the fitted slope and intercept of the temperature-resonant frequency curve. The resonant frequency changes linearly with increasing temperature, as explained by Equation (6).

According to the temperature resonant frequency of the temperature resonator shown in Fig. 7, the relationship can be expressed as:

$$f_T = 18.38608 - 0.00141 * T \qquad (7)$$

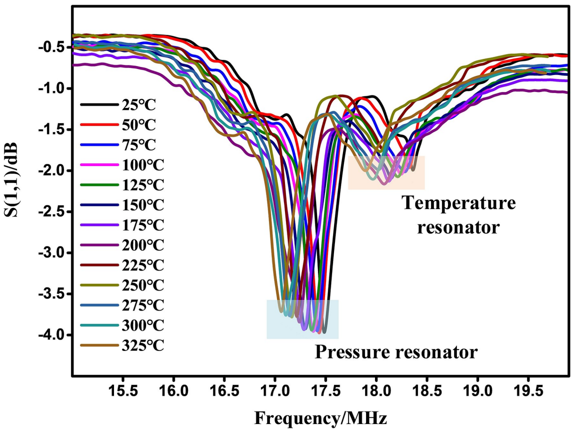
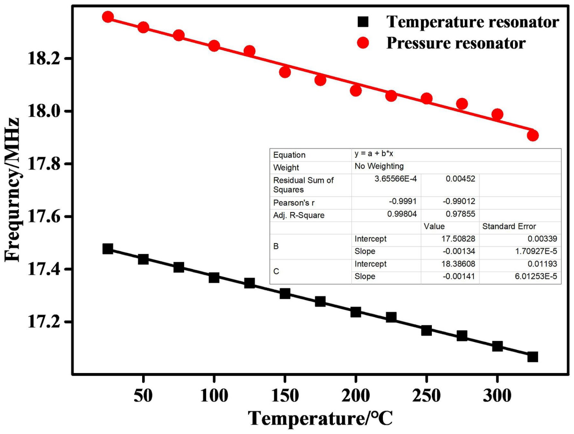


Fig. 6 Measured frequency versus S (1,1) of the sensor under ambient pressure at 25-325 ℃



Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	3.65566E-4	0.00452	
Pearson's r	-0.9991	-0.99012	
Adj. R-Square	0.99804	0.97855	
		Value	Standard Error
B	Intercept	17.50828	0.00339
	Slope	-0.00134	1.70927E-5
C	Intercept	18.38608	0.01193
	Slope	-0.00141	6.01253E-5

Fig. 7 Fitting curve for the pressure resonator and the temperature resonator.

For the temperature resonator, the temperature sensitivity is 1.5 kHz/°C, which is a negative temperature change trend.

Similarly, forthe pressure resonator, the relationship can be expressed as:

$$f_P = 17.50828 - 0.00134 * T \qquad (8)$$

The temperature sensitivity is -1.37 kHz/°C, which is a negative temperature change trend.

Fig. 8 shows the resonant frequency variation of a pressure resonator at different temperatures. Three temperature gradients of 25, 100, and 200 °C are chosen. The pressure test range is 0 to 1000 gf, and the resonant frequency change is recorded for every 200 gf increase in pressure. At the same temperature, the resonant frequency decreases linearly with increasing pressure. As the temperature decreases, the resonant frequency of the pressure resonator decreases, overall. The sensitivity of the pressure sensor is 10.6 kHz / gf at ambient temperature.

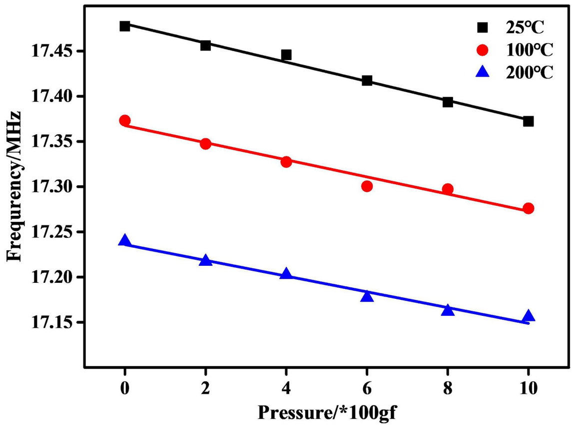
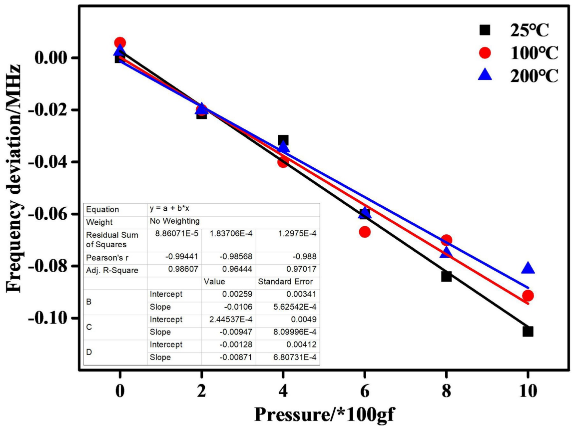


Fig. 8 Pressure measurement.



Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	8.86071E-5	1.83706E-4	1.2975E-4
Pearson's r	-0.99441	-0.98568	-0.988
Adj. R-Square	0.98607	0.96444	0.97017
		Value	Standard Error
B	Intercept	0.00259	0.00341
	Slope	-0.0106	5.62542E-4
C	Intercept	2.44537E-4	0.0049
	Slope	-0.00947	8.09996E-4
D	Intercept	-0.00128	0.00412
	Slope	-0.00871	6.80731E-4

Fig. 9 Pressure sensitivity of the developed pressure resonator.

Fig. 9 shows the use of a temperature resonator to eliminate temperature effects in pressure resonant frequency variations. Using the temperature information of the sensor, a temperature dependent calibration can be performed. As the temperature increases, the slope of the fitted curve gradually decreases and the sensitivity to pressure is reduced. The reason for this effect is that the stress in the temperature resonator is not properly designed because of the clamping device.

5 Conclusions

A wireless passive temperature- and pressure-integrated sensor was developed based on surface acoustic wave technology. Sensors with two resonators proposed by COMSOL simulation were shown to be able to differentiate resonant frequencies. The cantilever beam structure in which the temperature resonator was placed at the fixed end was demonstrated to achieve temperature and pressure measurements.

The SAW-based sensor was tested at 25-325 ℃. The resonant frequency was almost linear, the temperature sensitivity was 1.5 kHz/℃, and the error rate was 2.25%. The pressure test range was 0 - 1000 gf and the pressure sensitivity was 10.6 kHz/gf at ambient temperature. The sensor simultaneously performed pressure and temperature measurements and verified the temperature compensation algorithm to effectively correct pressure measurement inaccuracies. This device will be used for high temperature environmental measurements and will have a broad application prospects.

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