A Wireless Surface Acoustic Wave-based Tire Pressure and Temperature Sensing Module

Hsing-Cheng Chang[1,a], San-Sah Hung[1,b], Ya-Hui Chen[1,c], Ming-Han Tsai[1,d]

[1]Department of Automatic Control Engineering, Feng-Chia University, Taichung, 40724, Taiwan

[a]email:hcchang@fcu.edu.tw, [b]email:sshung@fcu.edu.tw,
[c]email:yhchen@fcu.edu.tw, [d]email:mhtsai@fcu.edu.tw

Abstract. Based on the piezoelectric and temperature effects of lithium niobate ($LiNbO_3$) wafer, this paper presents a design of a one-port resonator-type interdigital surface acoustic wave-based sensing device with a wireless transmission function for measuring vehicle tire pressure and temperature. The sensing components of the proposed device comprised a double-layered 3-D structure for measuring pressure and temperature changes simultaneously. The pressure-sensing film on the top layer of the wafer was formed by anisotropic back-etching. This feature enhanced the sensitivity of the device by 33% compared with sensing components featuring planar structures. Furthermore, the sealed bottom layer of the wafer served as a linear temperature sensor. The proposed sensing module was characterized as having a temperature sensing range of 25–95 °C with sensitivity 4.05 kHz/°C and pressure sensing range of 0–5 bar with sensitivity 8.19 kHz/bar.

Introduction

With the advance of industrial technology, the vehicle industry has set its development goals for enhancing comfort, improving operation and safety, and lowering fuel consumption. Concurrently, tire pressure safety is considered one of the primary means of providing safety and comfort while reducing fuel consumption. In this study, lithium niobate ($LiNbO_3$) wafers were employed to design passive remote surface acoustic wave (SAW)-based sensors, which are characterized by a simple structure, high electromechanical coupling coefficient, low loss, as well as a large temperature range on a linear scale. However, the proposed sensors exhibit a relatively high temperature coefficient (94 ppm/°C) and, thus, a compensation design for the sensor is required [1–5]. SAW components with interdigital transducers (IDT) possess excellent temperature and mechanical properties, as well as lightweight packaging, a high operating frequency, and long lifespan, rendering them suitable for measuring temperature and stress. SAW delay line components and an ID tag structure were employed to develop SAW resonator components and a transponder module to form a wireless system for measuring tire pressure and temperature [6–10].

This paper describes the design of a multifunctional SAW sensing module with a wireless transmission function and reports the analysis of the module design, fabrication, and measurement. Pressure and temperature sensors were integrated into the sensing module as a double-layered structure. By depositing the sensing components on the top and bottom layers, tire pressure and temperature can be measured simultaneously. In addition, the module is compact and achieves high accuracy, sensitivity, and stability. Moreover, using a bulk etching technique to fabricate the film pressure sensors improved the sensing sensitivity, and the SAW temperature microsensor providing temperature compensatory data improved the accuracy of the tire-pressure measurements.

Operational Principle

SAWs are also known as Rayleigh waves, which can propagate along the surface of an elastic body at supersonic speeds. Metallic interdigital electrodes can be formed on piezoelectric substrates for excitation and detection of SAWs. Piezoelectricity refers to the surface electric charge generated

from the polarization of substances in response to applying mechanical stress. The interconversion of electrical signals and SAWs can be realized through the piezoelectric effect, thereby achieving the purpose of SAW sensing. SAWs are composed of two oscillation modes, which are compression (longitudinal) and shear (transverse) waves. SAWs propagating in solid materials can be realized by applying an AC signal to a metallic electrode on the surface of a piezoelectric material. Moreover, wave propagation energy is concentrated at a depth of approximately one wavelength beneath the surface of the piezoelectric material, and the working frequency is associated with the material dimensions.

One-port SAW resonator components are advantageous because of their low insertion loss, low noise jamming, and high resolution. When the central IDT of a one-port (or two-port) SAW component transmits an electrical signal, the induced reverse piezoelectric effect generates a two-way SAW propagation. The side metallic structures reflect the SAW, which then returns to the central IDT and resonates with the next SAW, forming a surface standing wave. Finally, the surface standing wave is converted through the direct piezoelectric effect and output as an electrical signal.

For SAW components designed using IDT electrodes, the SAW propagation speed is the product of the acoustic wave's central frequency and length. The wavelength of a SAW is 4-fold longer than the space between two adjacent IDT electrodes. Concurrently, temperature changes can change SAW frequency and propagation speed, thereby affecting the measurement sensitivity. Therefore, designing a temperature compensation module to maintain temperature stability is critical for SAW component design; furthermore, it can improve the operating temperature range.

Design and Fabrication

To improve the measurement sensitivity, the design of a typical SAW component involves a complex process, which mainly entails collocating the planar sensing structures with delay lines at various angles [5–8]. The proposed one-port SAW resonator component possesses a simple structure, achieves acceptable sensitivity, and uses a microprocessor consisting of three photomasks. Two one-port resonator components were placed in parallel to design a double-layered structure. Therefore, the peak values of the two output signals can be measured, and any change in temperature or pressure can be analyzed. For this process, 128°-XY LiNbO$_3$ piezoelectric wafers were employed as the substrates, and five pairs of Au IDT electrodes with thickness of 0.2 μm, width of 20 μm, and length 10-fold longer than the wavelength. In addition, 100 of the reflective electrodes were positioned to create a delay distance at 3/8 of a wavelength.

This multifunctional SAW sensing module comprised the following three components: sensing electrodes (top structure), back etching (top structure), and sensing electrodes (bottom structure). Fig. 1(j) shows a cross-sectional view of the packaged component. Figs. 1 (a)-(i) show a cross-sectional view of the fabricated microsensor structure. In the fabrication process for the top structure, 500-μm-thick polished LiNbO$_3$ 3-inch wafers were selected for the base followed by applying the RCA method to clean the substrates. A thin film of Au was sputtered onto the surface of the top wafer structure to provide a protective layer for wet etching. During the etching process, photolithography was used to define the configuration of the sensing film, and bulk etching was then performed to produce the pressure-sensing film. The adhesion promoter (HMDS) and positive photoresist (MAP-1225) were then spin coated onto the other surface of the wafer. Subsequently, photo-lithography was applied to pattern the top-structure IDT electrodes. The lift-off method was adopted to form the Au film sensing electrodes. Similarly, the aforementioned process was applied for forming the temperature sensor for the bottom wafer.

The measurement framework of the multifunctional sensing system comprised a frequency sweep module, receiver and excitation antennas, a frequency-to-voltage circuit, sensor carriers, and a human–machine interface (HMI). The HMI was designed using LabVIEW to enable data acquisition and processing, and to capture processed data, and graphically demonstrate dynamic data of frequency and pressure. Simultaneously, the measurement data can be exported as text file or image file for storage and analysis.
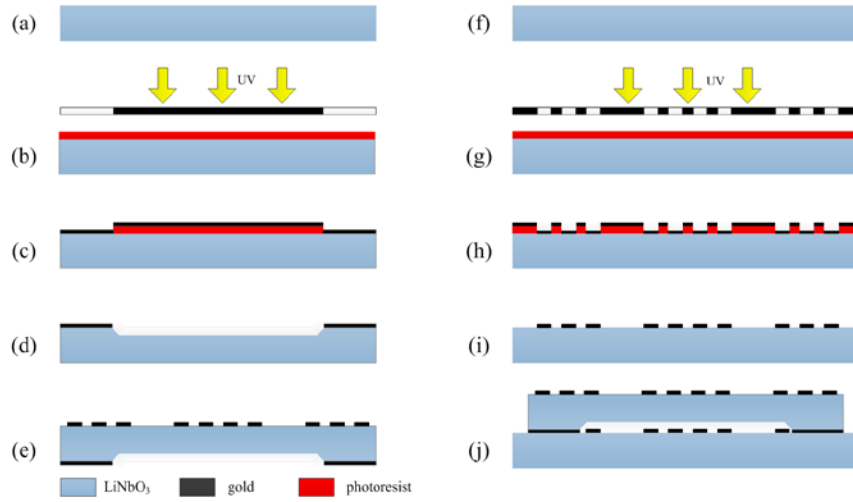
Fig. 1   Cross-sectional view of fabrication process for double-layered SAW sensor. (a) - (e) Back etched SAW pressure sensing structure. (f) - (i) IDT electrodes for the SAW temperature sensing structure. (j) Integrated SAW sensing module.

Fig. 2 shows the measurement framework as a functional block diagram. The SAW sensors collocating with the active transponder module enables wireless tire pressure sensing and measurement. When the tire pressure changes, the SAW's central resonant frequency drifts. Subsequently, the sweep module transmits a radio frequency (RF) signal to the receiver module. The central frequency drift response generated SAWs of various amplitudes. Through the piezoelectric effect, the SAWs were converted into radio signals and coupled with the transponder module for demodulation. The demodulated signals were passed through an analog-to-digital sample convertor and were forwarded to the DSP for recording and analysis, thus enabling calculation of the tire pressure.
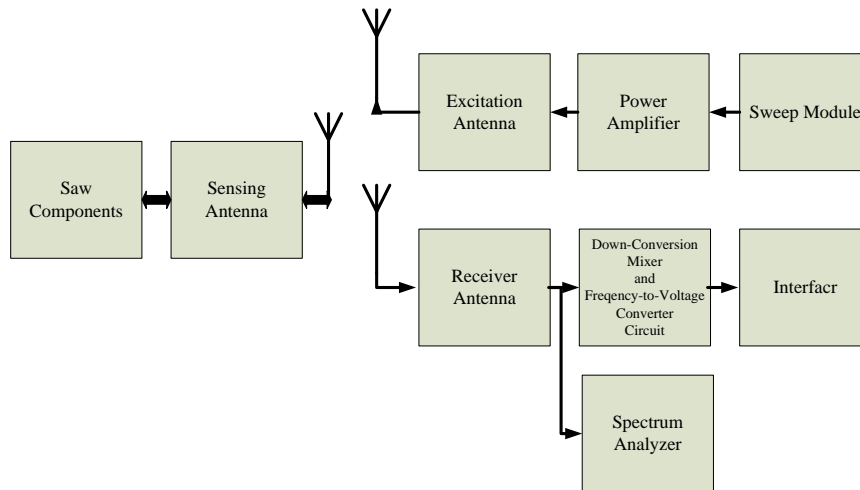

Fig. 2 The functional block diagram of the framework of frequency sweep measurement

Measurement and Analysis

Fig. 3(a) contains photographs of the SAW sensing structures after packaging. As shown in the figure, the IDT is located at the central part of the sensing structure and the metallic reflective structures are located on the sides. In this section, an experimental study was conducted to perform static and dynamic temperature, pressure, and vibration tests, as well as a signal analysis. Fig. 3(b) shows the experimental apparatus that was employed for measuring and testing. Moreover, the angle distribution was measured to analyze the changes in signal transmission and reception. The results indicate that the antenna at a 0° angle and the shortest distance was the most effective configuration;

when the antennas were aligned to other angles, the signal was attenuated. Furthermore, no frequency drifting as a result of vibration was observed during the tire rotation. A repeatability measurement analysis confirmed the high stability in the tire rotation measurement.

Fig. 3   (a) A packaged component, (b) experimental apparatus for measuring tire pressure and temperature.

The SAW resonator sensor utilized the sweep module to perform the wireless tire pressure and temperature measurements on a test tire (Bridgestone, 185/65 R14, 86H). The temperature ranged from 25 to 95 °C (sensitivity: 4.05 kHz/°C) and the pressure ranged from 0 to 5 bar (sensitivity: 5.44 kHz/bar). Fig. 4 shows the relationships of the frequency responses and temperature or pressure changes. As shown in the figure, the stability and repeatability of the sensing responses are relatively favorable. The sensitivity of a comparative entity and the etched film sensing components were 5.44 and 8.19 kHz/bar, respectively, indicating that the etched sensing components increased the sensitivity by 50.1%. However, the etching process was influenced by the temperature. For example, the frequency drift due to temperature affecting pressure can reach 5%; therefore, simultaneous temperature compensation is necessary for the measurement analysis. Moreover, the pressure response sensitivity at various temperatures was 7.991 (25 °C), 8.082 (45 °C), 8.202 (65 °C), and 8.392 kHz/bar (85 °C).
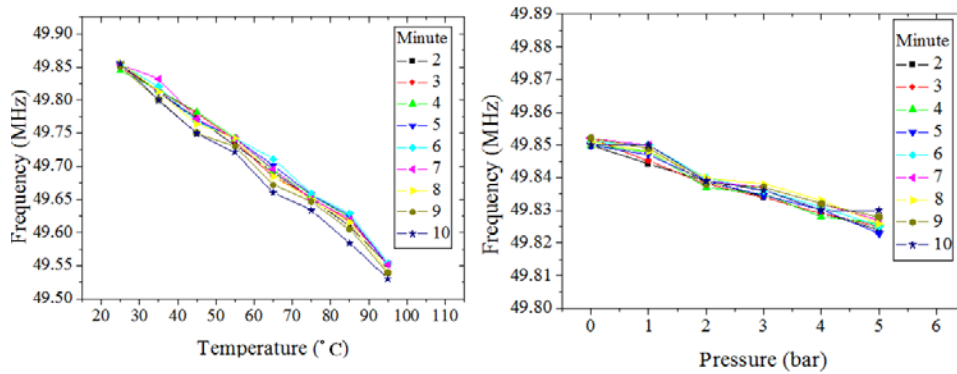

Fig. 4   Measurement analysis of the SAW sensing module: (a) temperature-frequency response; (b) pressure-frequency response.

Tire rotation on vehicles moving at a high velocity is subject to vibration. When the experiment was conducted to measure the cantilever structure of the vibration platform, the sensing components were placed around the tire rim to analyze their vibration; specifically, the relative measuring locations of the vibration platform were distributed horizontally at a distance of 0, 6, 12, and 18 cm from the center of the tire axle. The experiment revealed that the tire rim vibration increased with the vehicle velocity, causing a large frequency drift. The lowest frequency drift occurred at the axle (0 cm), and the vibration amplitude at the outermost measurement location (18 cm) was the largest. However, all of the measured relative frequency drifts were below 0.1%. Therefore, compared with the frequency responses relative to tire the pressure and temperature, the vibration-induced frequency drift can be considered negligible.

Conclusion

The proposed one-port resonator type multifunctional SAW sensing module was characterized by a wireless transmission function, double-layered 3-D structural packaging, and two series of output piezoelectric signals generated by the SAW components. This module can enable estimation of changes in temperature and tire pressure according to the peak values. Concurrently, the formed microsensing components and signal processing module can lead to minimal scaling, reduced cost, and high accuracy in tire pressure and temperature measurements. Therefore, the SAW microsensing components are suitable for temperature and tire pressure measurements within the range of 20 °C–95 °C with sensitivity of 3.942 kHz/°C and 0–5 bar with sensitivity 5.441 kHz/bar. Additionally, the measurement error in the tire pressure was approximately 2.1%. The design of the etched sensing structure improved the pressure measurement sensitivity by 33%.

References

[1] L. Reindl, G. Scholl, T. Ostertag, C.C.W. Ruppel, W.E. Bulst and F. Seifert, "SAW Devices as Wireless Passive Sensors," *Ultrasonics Symposium*, Vol. 1, pp. 359-362, 1996.

[2] G. Scholl, F. Schmidt, T. Ostertag, L. Reindl, H. Scherr and U. Wolff, "Wireless Passive SAW Sensor Systems for Industrial and Domestic Applications," *International Frequency Control Symposium*, Vol. 45, pp. 1161-1168, 1998.

[3] F. Seifert, A. Pohl, R. Steindl, L. Rrindl, M. J. Vellekoop and B. Jakoby, "Wirelessly Interrogable Acoustic Sensors," *Frequency and Time Forum*, Vol. 2, pp. 1013-1018, 1999.

[4] K. Lee, W. Wang, T. Kim and S. Yang, "A novel 440 MHz wireless SAW microsensor integrated with pressure–temperature sensors and ID tag," *Journal of Micromechanics and Microengineering,* Vol. 17, pp.515-523, 2006.

[5] K. Lee, W. Wang, T. Kim and S. Yang, "A novel 440 MHz wireless SAW microsensor integrated with pressure–temperature sensors and ID tag," *Journal of Micromechanics and Microengineering,* Vol. 17, pp.515-523, 2006.

[6] T. L. Li , L. Zheng and H. Hu, " A Novel Wireless Passive SAW Sensor Based on the Delay Line Theory," *Proceedings of the 3rd IEEE Int. Conf. on Nano/Micro Engineered and Molecular Systems,* pp. 467-470, 2008.

[7] Binder, G. Bruckner, N. Schobernig and D. Schmitt, "Wireless Surface Acoustic Wave Pressure and Temperature Sensor With Unique Identification Based on LiNbO$_3$," *IEEE Sensors Journal*, Vol. 13, pp. 1801-1805, 2013.

[8] V. Kalinin, " Wireless physical SAW sensors for automotive applications," *Ultrasonics Symposium (IUS), 2011 IEEE International*, Vol. 10, pp. 212-221, 2011.

[9] H. Oh, W. Wang, K. Lee, I. Park and S. S. Yang, "Sensitivity Improvement of Wireless Pressure Sensor by Incorporating A Saw Reflective Delay," *International Journal on Smart Sensing and Intelligent System*, Vol. 1, pp. 941-954, 2008.

[10] T. Li, H. Hu, G. Xu, K. Zhu and L. Fang, "Pressure and Temperature Microsensor Based on Surface Acoustic Wave in TPMS," *Electronics Letters*, Vol. 45, pp. 341-361, 2010.