

# Temperature and Strain Response of a Surface Acoustic Wave Sensor

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## ABSTRACT

A multifunctional temperature and strain sensor is being investigated. The sensor has been fabricated on a Langasite substrate and uses Surface Acoustic Wave (SAW) technology. The SAW sensor responds to a single physical change by changing both the frequency and the phase. However, when two physical parameters change, such as temperature and strain, the effects are combined making it difficult to separate out a single measurement. A common solution to this issue is to measure temperature using a second sensor. While devices such as these have been developed, none provide temperature and strain from a single device. We have identified regions where only a thermal response is present in the phase data for SAW devices on Langasite. The measurement of temperature alone allows us to compensate the strain measurements and achieve temperature and strain from a single device.

**Keywords:** Multifunctional, sensor, Surface Acoustic Wave, SAW, strain, temperature, Langasite.

## 1 INTRODUCTION

Strain gages have been used to monitor load conditions and fatigue, and to detect cracks in airframes [1]. Multifunctional sensors, such as those described here, can provide more information while adding negligible weight. SAW devices have been demonstrated to work in environments from cryogenic to high temperatures and are immune to vibration, radiation, and pressure changes [2]. They can be designed to be small passive wireless sensors that are capable of operation in harsh environments like those found inside of aerospace structures.

## 2 BACKGROUND

In June of 1975 the first patent for a SAW strain sensor was awarded [3]. This system used two SAW devices with one being stressed and the other was used as a reference. The first temperature sensor patent was awarded in 1981 [4]. A system that measures both temperature and strain was proposed in 1989 [5]. It used two SAW resonators placed to take differential measurements. The first wireless strain sensor was developed in 1997 [6]. A wireless passive strain and temperature system has been developed [7]. It uses two SAW devices, one as a strain sensor and one unstrained device as a temperature sensor. While other SAW strain and temperature sensors have been developed,

none provide both temperature and strain measurements from a single device [8]. A strain sensor has been developed that uses a Lithium Niobate substrate, and it does not incorporate temperature compensation or measure temperature [9]. The strain response of Langasite in comparison to Quartz and Lithium Tantalate has been investigated, however, temperature effects were not included [10]. The temperature effects using phase measurements on Langasite have been reported, but strain effects were not included [11].

## 3 EXPERIMENTAL SETUP

The SAW devices are fabricated on Langasite ( $\text{La}_3\text{Ga}_5\text{SiO}_{14}$ ) (LGS) substrates. The sensor has four Orthogonal Frequency Coded (OFC) reflector banks which spread the device's response across multiple frequencies through the use of OFC reflectors [12]. The device has two identical tracks, where each reflector bank is comprised of four sets of gratings (Fig. 1). Two tracks were required due to fabrication constraints. The gratings in each track reflect a different frequency and are arranged sequentially in ascending order as they are positioned further from the interdigitated transducer (IDT). To avoid interference, the reflector banks in each track are positioned on either side of an IDT with spacing such that the reflections do not overlap in time.

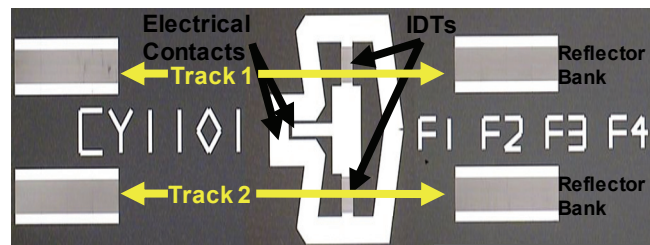


Fig. 1. SAW OFC strain sensor. The tracks are shown in yellow, the IDTs, reflector banks, and electrical contacts are all identified in black.

When the SAW device expands from tension or thermal expansion the result is a decrease in the operating frequency, while contraction from compression or thermal cooling will result in an increase of operating frequency. These changes are due in part to the change in the stiffness parameters and a change in the average propagation velocity of the surface acoustic wave.

For this investigation an OFC SAW strain sensor and a foil strain gauge were bonded onto a stainless steel bar (Fig. 2). The bar is 304 stainless steel, 45.75 cm long, 5 cm wide and 0.635 cm thick. Stainless steel was chosen because it has a Young's modulus (193 GPa) that is close to that of Langasite (110~188 GPa depending on the orientation). The conventional strain gauge is a general purpose 350  $\Omega$  foil strain gauge part number WK-13-125AD-350W from Vishay. A type K thermocouple was placed in contact with the bar between the SAW sensor and the strain gauge. The bar was configured for cantilever loading.

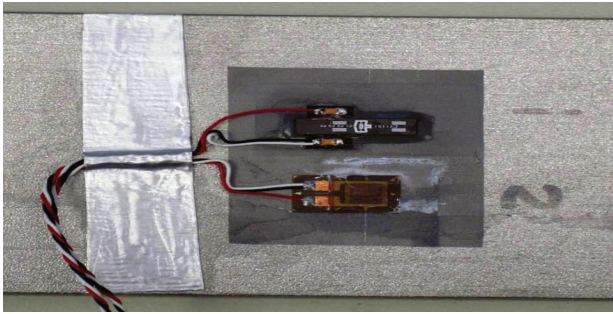


Fig. 2. Close up of Strain Gauge and SAW sensor attached to a stain steel bar (Thermocouple is not shown).

The OFC SAW sensor is connected to an Anritsu 2026B 6 GHz Network Analyzer, which is in turn connected to the host computer through a USB interface. The strain gauge is connected to a NI 9236 quarter bridge analog module. The type K thermocouple is connected to a NI 9219 universal analog module. Both modules are installed in a cDaq 9178 chassis which connects to the host computer through another USB interface. The host computer is a laptop running LabVIEW for synchronization and control of the network analyzer, and cDaq system. The LabVIEW program also collects and stores the data.

#### 4 RESULTS

The SAW sensor measurements were obtained by exciting the SAW device with the vector analyzer while simultaneously measuring the S parameters, specifically the reflection coefficient  $S_{11}$ . For each desired strain measurement, the data received from the SAW sensor consists of 20005 complex data points over the range of 430.05 to 431.05 MHz. The magnitude of the signal at each frequency for four conditions is shown in Fig. 3. The four conditions are: room temperature (nominally 23.1°C  $\pm$ 0.15°C) without any loading, room temperature with a 0.500 kg load, elevated temperature (nominally 29.8°C  $\pm$ 0.57°C) without any loading and elevated temperature with a 0.500 kg load.

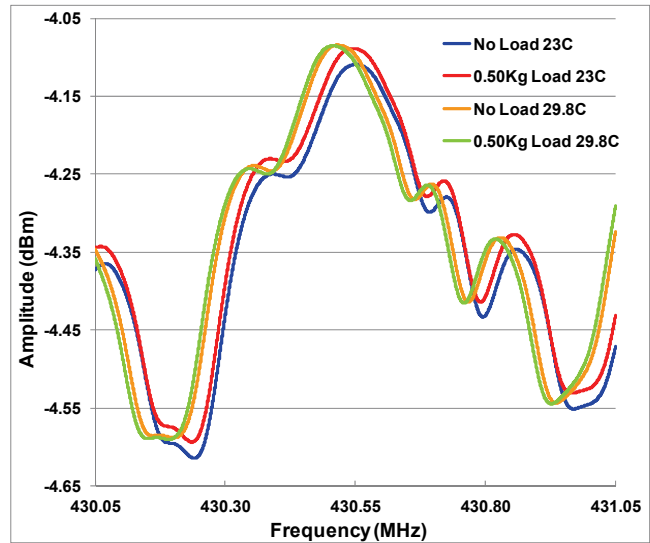


Fig. 3.  $S_{11}$  Change in amplitude as a function of frequency for four conditions.

The frequency shift is proportional to both strain and temperature changes. Increasing strain and/or temperature both cause a shift to a lower frequency. The frequency shift is measured through cross correlation of the first data set at room temperature with all subsequent data sets. To test the strain measurement capabilities of the SAW sensor, the cantilevered test specimen was subjected to mechanical strain (tension) from a 0.500 kg mass at room temperature (nominally 23.1°C  $\pm$ 0.15°C), which induced an average strain of 16.8  $\mu\epsilon$ . The frequency shift results are converted to strain using a conversion factor of 0.000914  $\mu\epsilon$ /Hz [13]. The results are given in Fig. 4.

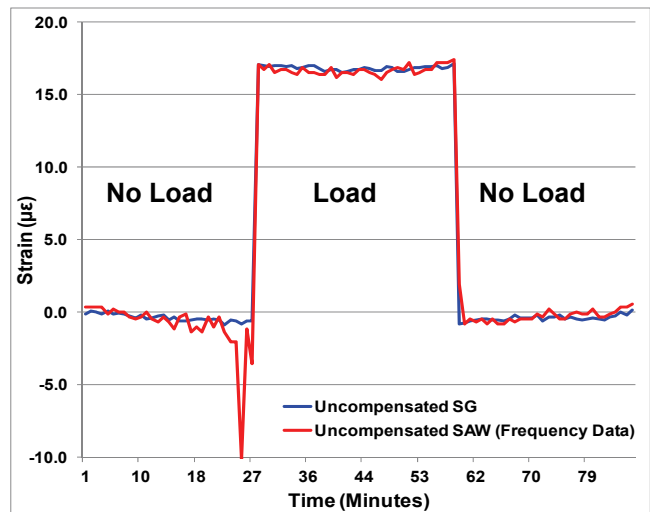


Fig. 4. Strain measurements by a strain gauge and a SAW sensor using the frequency method at 23.1°C $\pm$ 0.15°C.

The SAW strain measurements are in good agreement with the strain gauge when the temperature is held constant.

Next the temperature was elevated slightly to a nominal temperature of  $29.8^{\circ}\text{C} \pm 0.57^{\circ}\text{C}$  and again the 0.500 kg mass was applied and removed. The temperature was not held constant but was allowed to vary slowly. The uncompensated results highlight the effects of temperature on strain measurements whether they are from a strain gauge or from a SAW sensor (Fig. 5).

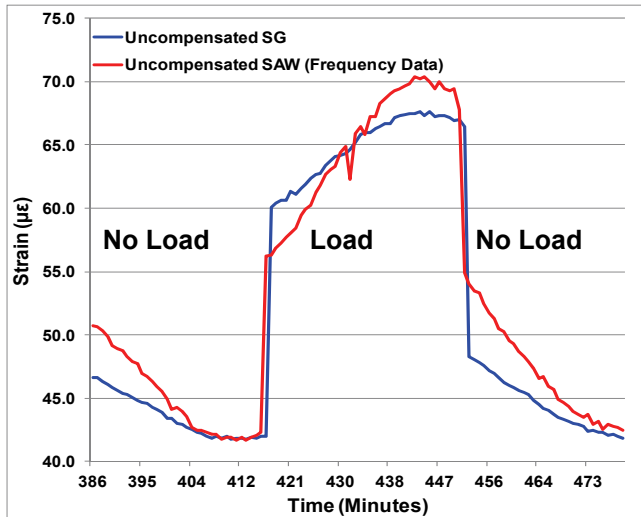


Fig. 5. Uncompensated strain measurements made by a strain gauge and a SAW sensor using the frequency method while the temperature varies around a nominal temperature of  $29.8^{\circ}\text{C} \pm 0.57^{\circ}\text{C}$ .

Both sensors exhibit altered signals which are caused by the slowly changing temperature. The measurements have both a static offset of  $41.8\mu\epsilon$  caused by temperature and an aberration that matches the dynamic temperature changes. To eliminate these errors in the measurement the phase information was investigated.

Although the phase can be calculated for all of the  $S_{11}$  amplitude points, a single point can be used for temperature measurements if it is chosen correctly. Although the phase shifts are proportional to both strain and temperature variations, there are several places where the traces converge. Each of these areas was investigated; however, the optimal frequency for temperature compensation was determined to occur at 430.90 MHz (Fig. 6). The unwrapped phase data was calculated from the complex frequency data points for the same four conditions presented earlier (Fig. 3), the results are given in Fig. 6.

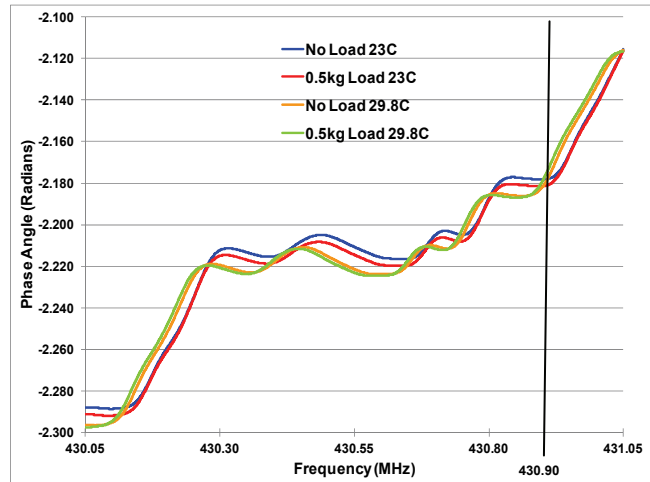


Fig. 6. Unwrapped phase angle variations due to loading and temperature changes.

An examination of the phase data (Fig. 6) identified that the data point at 430.90 MHz is affected mainly by the temperature and has negligible strain effects.

Since the SAW phase response can be used to measure temperature, the phase information was used to determine the temperature variations during the elevated temperature test. For this test the temperature was raised to  $29.8^{\circ}\text{C}$  and allowed to vary slowly  $\pm 0.57^{\circ}\text{C}$  (Fig. 7). A 0.500 kg mass was placed on the bar and removed.

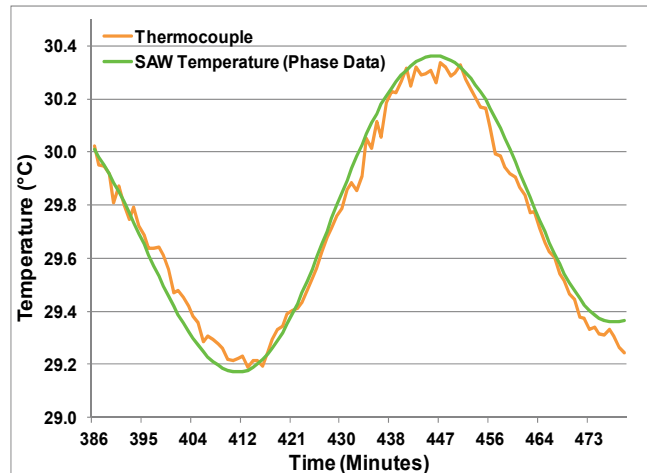


Fig. 7. Temperature measurements from a thermocouple and a SAW sensor using the phase method at a nominal temperature of  $29.8^{\circ}\text{C}$ .

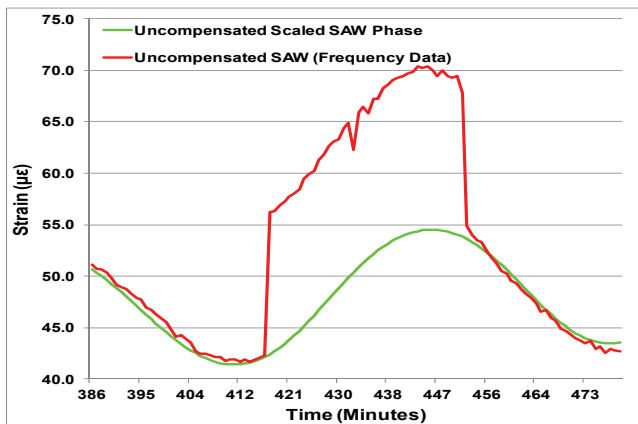


Fig. 8. SAW sensor uncompensated strain measurements and scaled SAW phase measurement at a nominal temperature of 29.8°C.

The temperature measurements made using the phase method closely agree with those from the thermocouple (Fig 7). The phase measurements are filtered using a low pass FIR filter and therefore look smoother than the raw thermocouple data. The phase temperature data can also be used to compensate the strain measurements from the frequency method (Fig. 8). The temperature compensation was accomplished by scaling the filtered SAW phase data to match that of the SAW frequency data after it has been correlated. The scaled phase data is then subtracted on a point by point basis from the frequency data. The results are more accurate strain measurements (Fig. 9). The initial compensated SAW data closely agrees the strain gauge measurements that have been compensated using the thermocouple.

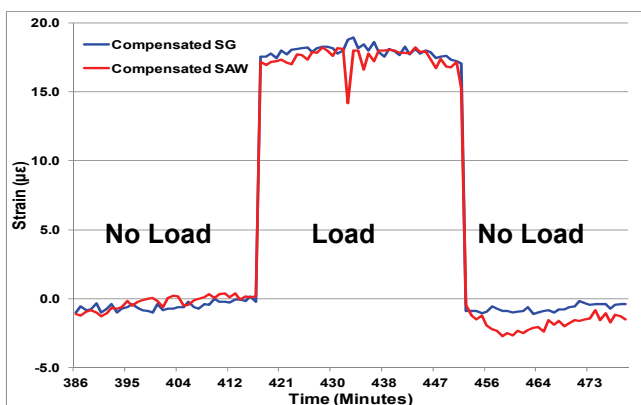


Fig. 9. Temperature compensated strain measurements from a strain gauge and SAW sensor at a nominal temperature of 29.8°C.

## 5 CONCLUSIONS

A multifunctional SAW strain and temperature sensors has been presented. The phase method has been demonstrated to be effective at temperature compensating the strain measurements while also acting as a temperature

measurement. The strain measurements were compensated for both static and dynamic temperature variations. Unfortunately, this technique requires post processing and is only valid over a small range. Therefore, more work is needed to optimize the technique to provide more accurate results and make it applicable across a wider range of values. The phase method introduces a small amount of noise, however, further optimization may be able to reduce this noise and enable a single SAW device to make both temperature and strain measurements. Reducing the mass and volume sensors by making them multifunctional will make them more applicable to aerospace applications such as NASA's Vehicle Safety Systems Technology program.

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