Fast Phase Analysis of SAW Delay Lines

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Abstract. Today continuous wave (CW) radar systems have been established as a standard method to interrogate surface acoustic wave (SAW) delay line sensors. They provide an ideal solution with high accuracy and reasonable reading distances for low dynamic measured quantities, which do not change fast in time. But their relatively long reading cycles [1] makes them unsuitable for high dynamic measurements. This paper illustrates a concept of an interrogation principle based on a pulse radar system which allows decreasing the reading cycle of a SAW delay line to a minimum of about 3 µs given by the physical dimension of the SAW delay line tag itself [2, 3].

Keywords: SAW · Surface Acoustic Wave Sensor · SAW sensor interrogation · Pulse radar · I/Q-demodulation

1 Introduction

Today surface acoustic wave (SAW) sensor technology is a state of the art technology to measure physical quantities like temperature, pressure and force. As a passive radio sensor technology don't need either any external power supply or additional electronic circuitry to operate, which enables them to operate almost without any limitations in their life time and makes them very robust against hazardous environmental conditions, e.g. high temperatures up to 400°C, hard radiation and strong electromagnetic interference [3].

A sensor system based on SAWs consists of a SAW tag and a reader unit (Fig. 1) which excites the sensor with a radio signal similar to the signals used in common radar systems. State of the art reader units, utilize continuous wave CW radar to interrogate the sensor. There are three different types of CW radars: Frequency modulated (FMCW), frequency stepped (FSCW) and switched frequency stepped (S-FSCW) continuous wave radar [4, 5]. All three radar types are using an RF ramp within the ISM band of 2.4 GHz. The duration of one sweep reaches from 100 µs (FMCW) to 125 ms (FSCW) and is limited by the used technology [1]. This results in one measurement per 100 µs (in FMCW), but usually, to improve the signal to noise ratio in order to increase accuracy and reading distance, the mean of several sweeps is taken. For measurements with low dynamic, i.e. which do not change fast in time, the used method is sufficient, but for high dynamic applications such as vibrations, accelerations or fast moving objects the applied method is not adequate and another interrogation principle is needed. In this paper we will present an interrogation principle, which uses

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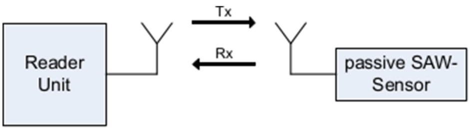


Fig. 1. Wireless transmission between reader unit and passive SAW sensor.

short pulses to interrogate a SAW delay line sensor, which enables to reduce the interrogation cycle to the limits of the sensor chip itself rather than to the limits of the reader technology.

2 SAW Sensor Delay Line Principle

SAW sensors use the propagation speed of SAWs on a plain polished piezoelectric substrate. The propagation speed depends on the material properties of the substrate which on the other hand are sensitive to environmental influences, for instance changing temperature of the substrate changes its elasticity constant which directly effects the wave propagation. The SAW is about 10^{-5} slower as the propagation of electromagnetic waves – therefore the name “SAW Delay Line Sensor”.

The excitation occurs by metallic structures, the so called interdigital transducers (IDTs), arranged on the surface of the substrate. In the simplest case, the structure looks like two interlocking combs as shown in Fig. 2. If an alternating electrical signal is applied to the IDT, the piezoelectric substrate will expand and contract according to the applied electric field which generates a mechanical wave – surface acoustic wave – propagating across the substrate’s surface. Vice versa a SAW passing the IDT generates an electric signal which can be measured on the connections of the IDT.

Delay line sensors use the propagation delay τ between two points on the substrate. Arranging two IDTs oppositely with a certain distance d according Fig. 3, a two port SAW delay line has been created. Applying a signal on the input IDT results in a time shifted and attenuated signal on the output IDT.

A big disadvantage of two port delay line SAW sensors is the fact that they have two ports which makes them not very suitable for wireless applications because additional radio frequency (RF) circuitry is needed directly on the SAW chip to separate the incoming and outgoing RF signals. Since SAW sensors are dealing with

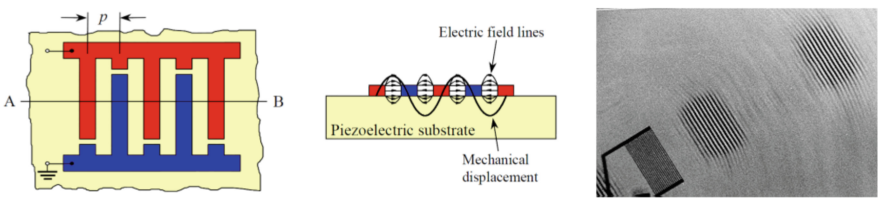


Fig. 2. Top view of an interdigital transducer on the left side, and its AB-cross section in the center. Propagating wave packages generated by an IDT on the left side [3].

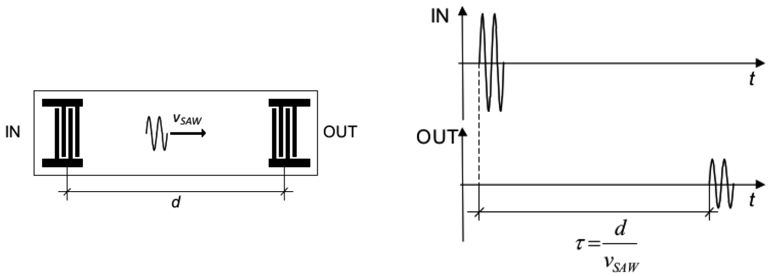


Fig. 3. IDT arrangement and input and output signals of a two port SAW delay line sensor.

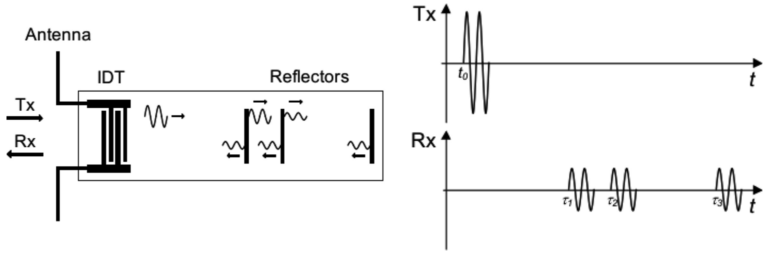


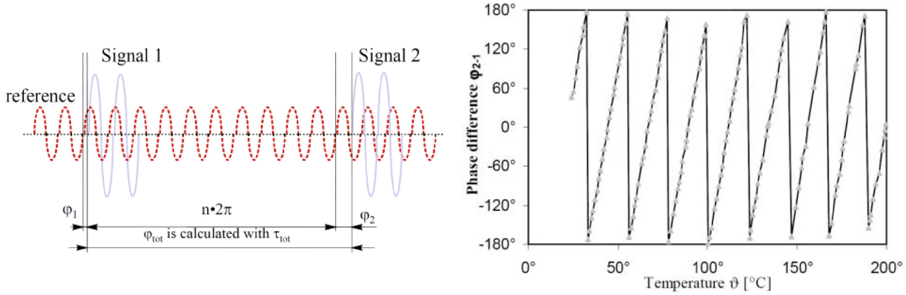
Fig. 4. IDT arrangement and input and output signals of a two port SAW delay line sensor.

waves, it is possible to use reflection to overcome this problem. In the simplest case we just take the second – or output – IDT and just let it open. The incoming wave front will see a not suitably matched interface which results in a reflection – or partial reflection – of the wave back to first – or input – IDT. This concept can be expanded to a one port multi reflective SAW delay line by arranging multiple reflectors on the substrate. Figure 4 illustrates a one port delay line sensor with three reflectors.

The reflectors are designed in a way that one portion of the SAW will be reflected while the other portion of the SAW will pass the reflector and propagate towards the next reflector where again a portion will be reflected and so on. Finally the received signal of a SAW delay line sensor is a sum of time shifted sinusoids.

3 Time Delay Measurement

The measurement of time delay between the transmitted and received signals can be done in different ways. One method is to measure the time duration of the envelope between transmitted and received pulses by a counter. Another method is evaluating the phase shift between the received pulses and a reference oscillation which is in-phase with the transmitted pulse as shown in Fig. 5a. Evaluating the phase shift may



(a) Phase measurement to increase measurement accuracy [7]

(b) Phase ambiguity over a wide measurementrange [8]

Fig. 5. Evaluation of phase difference to increase measurement accuracy [3]

increase the resolution significantly by a factor of 100. For large measurement ranges, especially in the case of temperature measurement, the phase shift caused by the measured value can be larger than 2π, or even several multiple of 2π, so that a phase ambiguity, shown in Fig. 5b, occurs. To evaluate absolute values, at least three reflectors are needed [3, 7, 8].

4 Sensor Interrogation Principle with Cosine Bursts

As already stated, the fundamental principle of SAW delay line sensors is using, the variation of propagation speed of SAWs. Evaluating the signal delay allows to calculate the desired measurement quantity. The Signal delay can either be determined in the frequency domain, using CW radar, or in the time domain using pulse radar.

Instead of using a frequency modulated continuous wave, a sequence of pulsed cosine bursts (Fig. 7a) in the ISM-band at 2.4 GHz will be sent to the SAW sensor. Figure 6 shows an overview of the system with a minimal set of components to describe the theoretical aspects of the principle.

The impulse response of the SAW-sensors $h_{SAW}(t)$ can be assumed as a sequence of weighted Dirac impulses shown in Fig. 7b where each Dirac impulse corresponds to a reflector of the SAW-Sensor. It is well known that in the time domain the output signal of a system is the convolution of the input signal with the impulse response of the system. Therefore the received signal is a repeating sequence of the transmitted signal shown in Fig. 7c.

The transmitted signal $s_t(t)$ can be described as a cosine function with amplitude A, angular frequency ω and phase shift ϕ multiplied with a rectangular function:

$$s_t(t) = A \cdot \cos(\omega t + \phi) \cdot \sqcap(t). \tag{1}$$

As mentioned above the received signal $s_r(t)$ is a sequence of delayed bursts. It can be described as a sum of the transmitted signal shifted by τ_i and attenuated by α_i and α_p

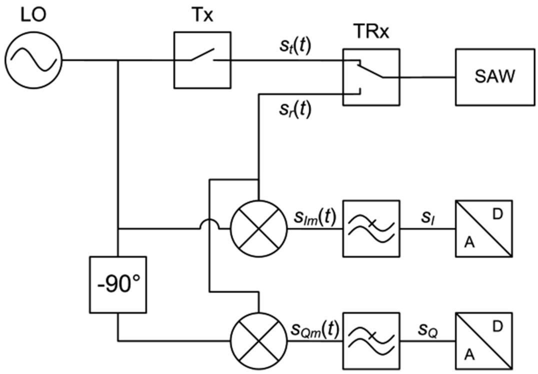
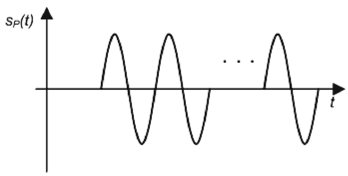


Fig. 6. IDT arrangement and input and output signals of a two port SAW delay line sensor.

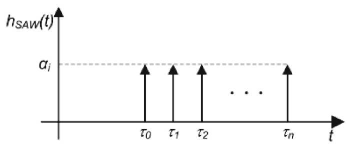
where α_i is characterized by the impulse response of the SAW-Sensor and α_p is the overall attenuation of the transmission path

$$s_r(t) = \sum_{i=1}^{n} A\alpha_i\alpha_p \cos(\omega(t-\tau_i)+\phi)\cdot \sqcap(t-\tau_i). \tag{2}$$

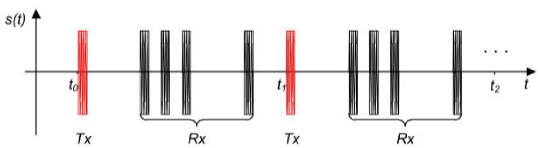
After receiving the signal, it will be demodulated by an in-phase quadrature demodulator (I/Q-demodulator). In I/Q-demodulation the received signal $s_r(t)$ is split



(a) Transmitted cosine burst



(b) Model of the impulse response of an ideal reflective delay line sensor



(c) Transmitted request sequence (Tx) and received response sequence (Rx) of a delay line SAW sensor

Fig. 7. Pulse radar sensor interrogation signal.

into two branches, the in-phase branch and quadrature branch. In the in-phase branch the received signal $s_r(t)$ will be mixed with the original oscillation generated by the local oscillator,

$$s_{Im}(t) = A\cos(\omega t + \phi) \cdot \sum_{i=1}^{n} A\alpha_i\alpha_p \cos(\omega(t-\tau_i)+\phi) \cdot \sqcap(t-\tau_i), \tag{3}$$

while in the quadrature branch, the received signal will be mixed with the local oscillation shifted by −90° or -–π/2 respectively

$$s_{Qm}(t) = A\cos\left(\omega t + \phi - \frac{\pi}{2}\right) \cdot \sum_{i=1}^{n} A\alpha_i\alpha_p \cos(\omega(t-\tau_i)+\phi) \cdot \sqcap(t-\tau_i). \tag{4}$$

For further considerations we will neglect that the received signal is a sum of bursts and look at each element of the sum separately. This is permitted because the single bursts are isolated in time and do not interfere with each other. This results for the in-phase sequence into

$$\begin{aligned} s_{Imi}(t) &= Acos(\omega t+\phi) \cdot A\alpha_i\alpha_p cos(\omega(t-\tau_i)+\phi) \\ s_{Imi}(t) &= A^2\alpha_i\alpha_p cos(\omega t+\phi)cos(\omega(t-\tau_i)+\phi) \end{aligned} \tag{5}$$

And for the quadrature sequence into

$$\begin{aligned} s_{Qmi}(t) &= Acos\left(\omega t+\phi-\frac{\pi}{2}\right) \cdot A\alpha_i\alpha_p cos(\omega(t-\tau_i)+\phi) \\ s_{Qmi}(t) &= A^2\alpha_i\alpha_p cos\left(\omega t+\phi-\frac{\pi}{2}\right)cos(\omega(t-\tau_i)+\phi) \end{aligned} \tag{6}$$

From the trigonometric product-to-sum identity [6] it is known that a product of two cosines can be expressed as a sum of two cosines where the argument of the two summands is the sum and the difference respectively, of the arguments of the two factors, divided by 2.

$$\cos(x) \cdot \cos(y) = \frac{1}{2}[\cos(x-y) + \cos(x+y)] \tag{7}$$

Applying the trigonometric identity to the two signals $s_{Imi}(t)$ and $s_{Qmi}(t)$ results into

$$s_{Imi}(t) = A^2\alpha_i\alpha_p \frac{1}{2}[cos(\omega\tau_i) + cos(2\omega t - \omega\tau_i + 2\varphi)] \tag{8}$$

and

$$s_{Qmi}(t) = A^2\alpha_i\alpha_p \frac{1}{2}[sin(\omega\tau_i) + sin(2\omega t - \omega\tau_i + 2\varphi)] \tag{9}$$

Because the frequencies of both signals are equal, the time dependent component in the argument of the left cosine function vanishes and results in a DC-component. Due to the addition of the arguments in the right cosine function, a harmonic oscillation with twice the frequency of the original carrier signal is being obtained. In practice this term usually has no relevance and will be filtered out by a low pass filter. This finally results in the two expressions

$$s_{Ii}(\tau_i) = \frac{A^2 \alpha_i \alpha_p}{2} cos(\omega \tau_i) \tag{10}$$

and

$$s_{Qi}(\tau_i) = \frac{A^2 \alpha_i \alpha_p}{2} sin(\omega \tau_i) \tag{11}$$

Now there are the two signals s_{Ii} and s_{Qi}, both have the same amplitudes. By dividing them they will be canceled out which results in

$$\frac{s_{Qi}}{s_{Ii}} = \frac{sin(\omega \tau_i)}{cos(\omega \tau_i)} \tag{12}$$

Since the tangent of an angle φ_i is the ratio of the sine to the cosine, one can calculate the angle by taking the inverse tangent:

$$\tan(\varphi_i) = \frac{sin(\varphi_i)}{cos(\varphi_i)} = \frac{s_{Qi}}{s_{Ii}} \Rightarrow \varphi_i = \tan^{-1}\left(\frac{s_{Qi}}{s_{Ii}}\right) \tag{13}$$

The result represents a direct determination of the phase shift between reference oscillation and received bursts from the delay line by computing the inverse tangent of the quotient of the sampled and A/D-converted quadrature and in-phase signal levels.

5 Matlab/Simulink Simulation

The previously discussed interrogation concept has been verified by simulation in Matlab/Simulink. Since signal paths in Simulink are only unidirectional, i.e. signals can only propagate in one direction, the Simulink model differs slightly from the discussed model in Fig. 6. Especially a one port SAW delay line sensors is not able to model with only one port, so it has been realized as two port system but with the same behavior, Fig. 8 shows the modeling of the SAW delay line. Due to the fact that there transmitted and received signals do not share the same transmission paths, the TRx switch in Fig. 6 is obsolete as well and is therefore not modeled in the Simulink simulation. Figure 9 shows the simulation model, with burst generation, SAW delay line modeling, in-phase and quadrature mixing and low-pass filtering.

Running the simulation results in the following signals: The local oscillator generates a continuous cosine signal which is split into two branches. The first one feeds the switch, which generates the cosine bursts (yellow signal in Fig. 10a) sent to the SAW delay line. The output of the SAW delay line is a sequence of attenuated and delayed copy of the input signal (magenta signal in Fig. 10a). The output of the SAW delay line is then fed to the I/Q-demodulator where on one hand it is directly mixed with the signal of the local oscillator and on the other hand with the 90° phase shifted signal of the local oscillator which results in the two signals shown in Fig. 10b. After low pass filtering we get the DC-like signals in Fig. 10d and e, where the phase shift can be calculated by sampling the signal levels of the in-phase and quadrature channels.

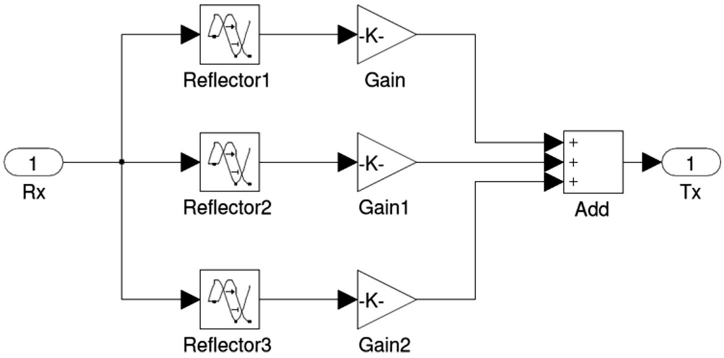


Fig. 8. Simulink sub system block.

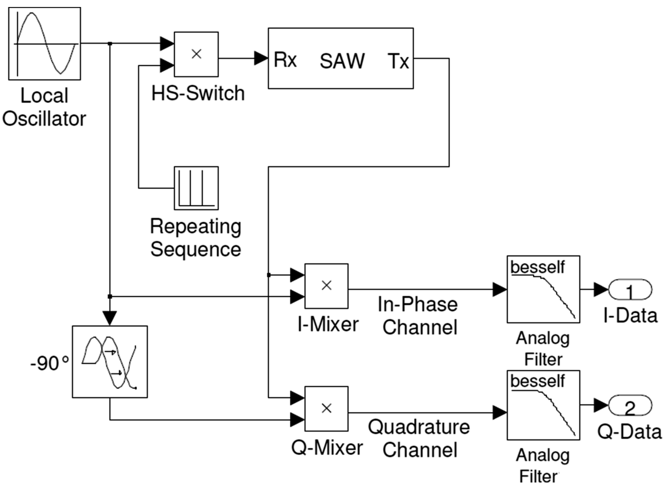
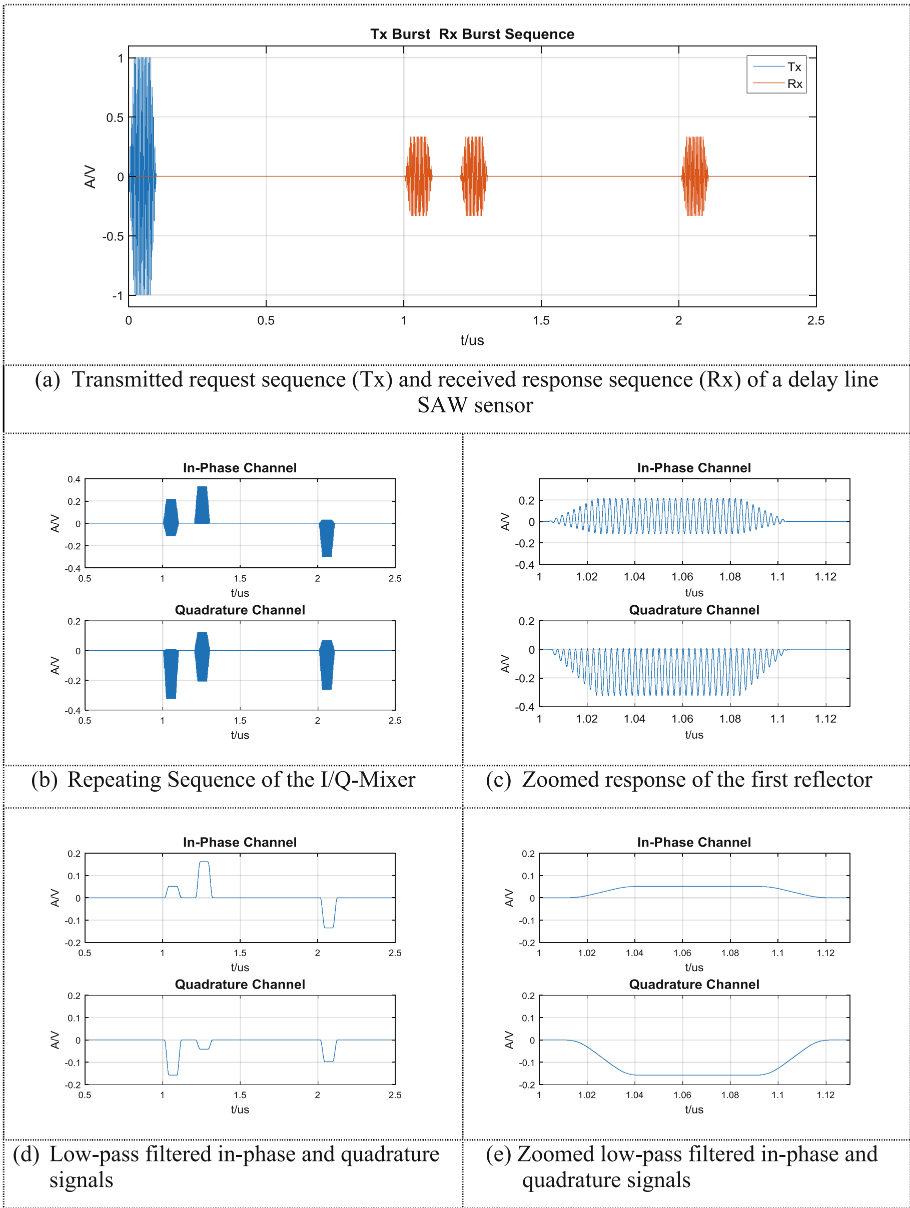


Fig. 9. Simulink model of the analog interrogation system.



(a) Transmitted request sequence (Tx) and received response sequence (Rx) of a delay line SAW sensor

(b) Repeating Sequence of the I/Q-Mixer

(c) Zoomed response of the first reflector

(d) Low-pass filtered in-phase and quadrature signals

(e) Zoomed low-pass filtered in-phase and quadrature signals

Fig. 10. Signal processing chain of transmitting and receiving signals in the Matlab/Simulink simulation. (Color figure online)

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