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DIGITAL SIGNAL CONDITIONING TO READ PHASE DIFFERENCE FOR SURFACE ACOUSTIC WAVE (SAW) SENSOR

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ABSTRACT

Surface Acoustic Wave (SAW) technology rapidly expands in modern sensing applications. Temperature, pressure and gases can be measured by SAW structure, configurable to be interrogated wirelessly. Presently, SAW sensor signal conditioning is mainly oriented to read the input-to-output phase difference by using analog circuits. Digital solutions are few (or not) explored, and its feasibility to process SAW signals in real conditions is unknown. This article studies two digital methods based on cross-correlation function and Fourier transform. Here is explained how good (or accurate) these methods read the phase difference when one of its input signals has considerable noise and attenuation, situation very common in SAW technology. This study has never been performed up to now and particular attention is given here to prove its feasibility. Our outcomes indicated that cross-correlation has better results than Fourier transform. In attenuation, cross-correlation reads the phase difference properly, but it is recommendable to apply smooth filtering when noise is significant. This function was developed by LabVIEW platform, whose noise and attenuation were included.

Keywords: phase detector, cross-correlation, Fourier transform, sensor, signal conditioning, surface acoustic wave (SAW).

1. INTRODUCTION

Surface Acoustic Wave (SAW acronym) is a piezoelectric structure adaptable for RF filtering and sensing applications. The future-generation 5G network is exploring SAW RF filters as it provides good performance and reduced size in laptops and phones [1]. In sensor applications, SAW has demonstrated good features to readout (or detect) gases [2] [3], temperature [4], pressure [5] with the advantage of being wireless interrogated [6]. This anticipate that SAW might become the next IoT sensor for industrial and commercial applications.

The development of SAW sensors implies a work in materials and signal conditioning. As a typical sensor is composed of sensitive material, SAW includes this sensitivity through its piezoelectric substrate or a nanomaterial deposited on top of its substrate. Because SAW sensor modifies its output signal as a function of the measurand, the conditioning circuit removes unwanted components from its output and extracts the value of the measurand typically represented by the input-to-output phase difference.

This article explores a digital technique applied to a SAW temperature sensor, which is in process of developing in our facilities. Most reported SAW sensors use the analog component AD8302 [7] for this conditioning, reported in functionalized SAW sensors for the detection of hazardous gases [8], analysis of palladium and yttrium-palladium alloy layers used for hydrogen detection with SAW device [9] and one-port portable SAW sensor system [10]. The datasheet of this phase detector describes very good functionality but it is unspecified its response in case of any of its two inputs is noisy and significantly attenuated, which commonly occurs in SAW sensor. The digital exploration is attractive as it might reveal advantages in terms of good response under noise and attenuation compared to analog solutions.

Our exploration consisted of determining how accurate two digital methods, known as cross-correlation function and Fourier transform, read the phase difference of SAW signals in real conditions. In this work, these methods were developed in software whose signals were sine waveforms, and one of them was phase shifted, noisy and attenuated. The response of both methods was observed while the level of noise, attenuation and phase changed. Because cross-correlation showed good results, it was developed by LabVIEW. It was revealed that this method is sensitive to noise, and it is recommended to apply a smooth filter to have a stable response.

2. FOUNDATIONS OF SAW SENSOR

Surface Acoustic Wave is known as the propagation of acoustic (or mechanical) waves on the surface of a solid exhibiting elasticity. Artificially, these waves can be induced by a structure composed of metal electrodes (called Inter Digital Transducer - IDT acronym) deposited on a piezoelectric substrate. There are basically two variants of this structure: one contains two-separate IDT, and the other one integrates a single IDT and a reflecting barrier. In either, the waves travel between the separation of two IDTs or IDT-barrier across a region called delay path. Internally, an IDT has the shape of a comb with periodicity, where the separation of one periodic form is known as wavelength. [11]. Figure-1 shows the two-variant SAW along with its characteristics.

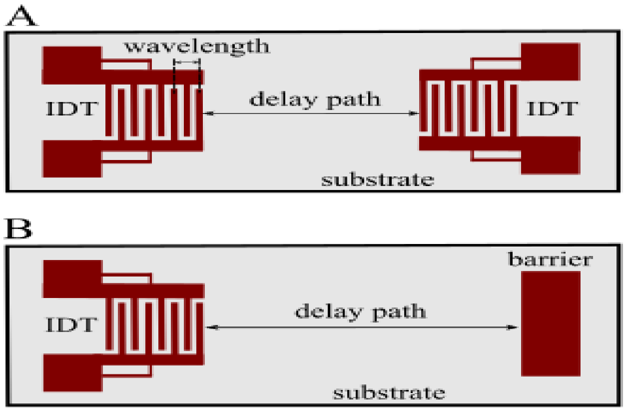

Figure-1. Two types of SAW structures. (A) two-IDTs SAW. (B) IDT-barrier SAW.

In both structures, the waves are induced by the principle of piezoelectricity characterized by two effects, named here as direct and inverse: 1) direct effect: when an electrical field polarizes a piezoelectric crystal, the materials undergoes a mechanical deformation; and 2) inverse effect: when a piezoelectric crystal is subject to a mechanical stress, an electrical polarization comes out. The operating principle of a two-IDT SAW can be explained in this way: when one IDT is excited by an alternating electrical field, the substrate deforms as a cause of direct effect. Because the substrate has elasticity, this deformation induces mechanical waves traveling across the surface of the substrate. Once these waves arrive to the other IDT, the mechanical deformation is transduced into an alternating electrical field produced by the inverse effect. In case of a IDT-barrier SAW, the induced wave is mostly reflected by the barrier up to reaching the single IDT. Then, the returned wave is transformed into an electrical signal [12] [13].

From now on, this article focuses on the two-IDT SAW because its signal conditioning is of our interest. This device is electrically characterized by its insertion loss and phase response. Figure-2 shows the typical insertion loss curve, expressed in dB, which approximates to a sinus cardinal square function; and the phase response illustrates a linear behavior. In particular, the curve of insertion loss is commonly negative because the output signal is attenuated[1]. In real conditions, these curves are perturbed by uniform noise.

The synchronous frequency f_s is a parameter associated to SAW response, expressing the value of frequency at which the insertion loss is maximum. This can be obtained by:

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

Where v is the propagation velocity of the substrate and λ is the wavelength. The propagation and wavelength directly depends on the type of piezoelectric crystal and IDT width, respectively. As such, a high synchronous frequency is obtained by either a very thin electrode width or a crystal exhibiting high propagation velocity.

3. CONSIDERATIONS FOR SAW SENSOR SIGNAL CONDITIONING

A two-IDT SAW has been broadly reported to work as a sensor. Because the wave propagation medium is accessible and sensitive, a variation of temperature, pressure (or force) and conductivity on substrate surface is replicated to the output signal [14] [15]. Under this, a SAW temperature sensor is built by a temperature-sensitive substrate connected to a signal conditioning circuit.

The way how the sensor information is present defines the specifications of the signal conditioning. For SAW temperature sensor, the literature reports this information is present as an input-to-output frequency shift [16] [17]. It means that the temperature can be read by changes in magnitude or phase between input and output signals. As shown in Figure-2, the phase response is linear compared to insertion loss. This implies that it is more appropriated to extract this information by the phase, rather than magnitude, to get a linear behavior sensor.

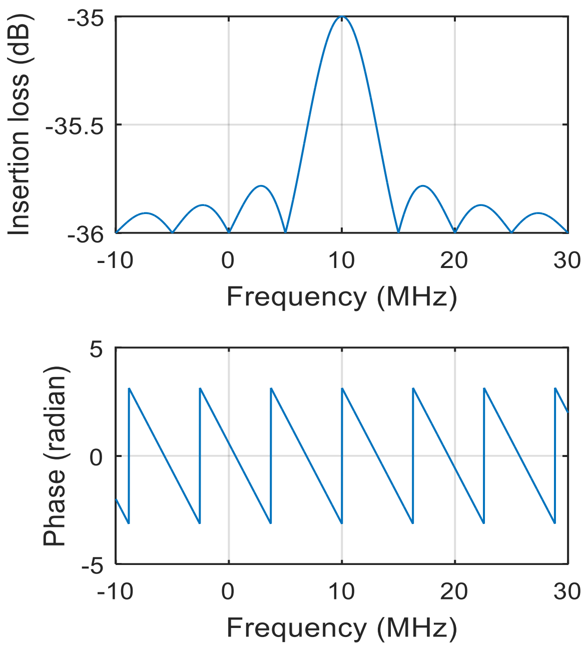

Figure-2. SAW frequency response. It is represented by two curves named insertion loss and phase.

4. METHODS OF SIGNAL CONDITIONING

This section describes two alternatives for SAW digital signal conditioning, oriented to read the input-to-output phase shift subject to noise and attenuation.

A way to read this shifting is to apply the cross-correlation function to SAW signals. The cross-correlation is defined as the measure of tracking between two variables [18]. In our case, these variables are discrete-time signals whose cross-correlation is expressed by:

$$r_{xy}(l) = \sum_{n=-\infty}^{\infty} x(n)y(n-l), \quad l = 0, \pm 1, \ldots \tag{2}$$

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Where *x(n)* and *y(n)* are the sampled input and output SAW sinusoidal signals, and the index *l* is the lag parameter associated to the cross-correlation. Because these signals are periodic (sinusoidal waveforms), the equation (2) is transformed by:

$$r_{xy}(l) = \frac{1}{N}\sum_{n=0}^{N-1} x(n)y(n-l) \qquad (3)$$

Where N is the period of the signal. The technique to read the phase shift consists of applying the equation (3), resulting in an output exhibiting a maximum peak. The time-axis location of this peak reveals, therefore, this shifting. This maximum appears because a sinusoidal-square operation occurs when *y(n-l)* moves and locates exactly in-phase with *x(n)*.

The other alternative is to apply the Fourier transform to input and output signals. The Fourier transform is defined as a method to convert a time-variant signal into a frequency representation [19]. In discrete-time, this method is expressed by:

$$X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{2\pi i}{N}kn} \qquad k = 0, 1, 2 \ldots \qquad (4)$$

Where x_n is a sequence of the sampled signal, i is the imaginary number associated to Fourier, and N is the sequence number. Computationally, the equation (4) is developed by the Fast Fourier Transform (FFT) algorithm [20] [21]. Because the frequency domain reveals the angle of the signal, the SAW phase shift is obtained by the subtraction between output and input angles.

Simulations were carried out to determine how good the cross-correlation and Fourier transform read the SAW phase shift when the output signal contains noise and attenuation. The first simulation consisted of observing the cross-correlation response when the input signal was 1 Vpp and 1 Hz; and the output signal contained an induced phase shift of $\pi/2$ radian (equal to 1.5708 radian), attenuation of -20dB and signal-to-noise ratio of 5 (assuming uniform white noise). Figure-3 shows these signals, sampled at a rate of 60 Hz.

The results showed that both techniques read the SAW phase shift but there are slight differences. In cross-correlation, Figure-4A illustrates the output signal as a function of time, where the maximum peak appears. This peak is located at 0.25 seconds (that is, 1.571 radian[1]), which coincides with the induced phase. In Fourier transform, Figure-4B illustrates the output phase as a function of frequency, whose phase of output signal appears (marked in red color) along with other phases caused by noise. At 1 Hz, the frequency of output signal, there is a phase shift of 1.6218 radian which is different compared to the 1.5708 radian induced. Based on it, we consider that cross-correlation offers a better response compared to Fourier.

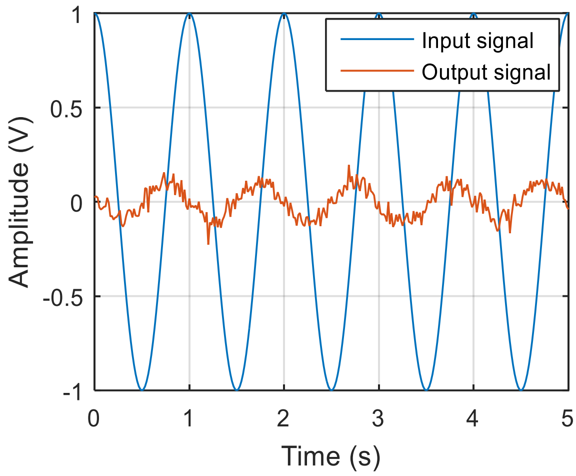

Figure-3. SAW input and output signals. The output signal is attenuated, out-of-phase and noisy compared to input.

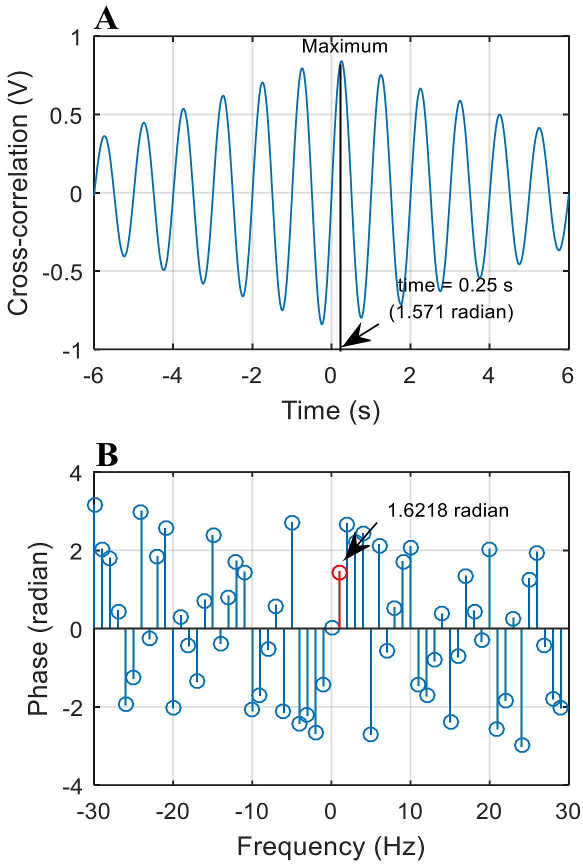

Figure-4. Response curve of cross-correlation and Fourier transform. (A) the cross-correlation finds a time (or value of radian) located at its maximum. (B) the Fourier method directly delivers the phase.

The response of cross-correlation and Fourier transform subject to small phase shift was observed. In this simulation, the output signal was initially lagged from π/n to π, where n varied from 1 to 20, and the phase was measured by cross-correlation and Fourier transform.

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Figure-5A-B shows the trace of initial vs measured phase shift, where the circles represent the obtained phases. Ideally, these circles should obey the dash line illustrated. In both figures, the measured phases follow this line, but there are slight differences in the range from 0 to 0.5 radian, meaning that errors might come up for very small phase shifting.

Moreover, the reading of phase shift in different noise levels was also analyzed. In simulations, the signal-to-noise ratio of the output signal changed from 1/30 to 1, a fixed phase shift of $\pi/2$ was induced, and this shifting was measured by cross-correlation and Fourier transform. Figure-6 shows the values of signal-to-noise ratio as a function of measured phase shift. The circles should follow the constant black-line of $\pi/2$radian but there are variations, and Fourier transform shows more dispersion than cross-correlation. Therefore, we concluded that cross-correlation is less affected by noise.

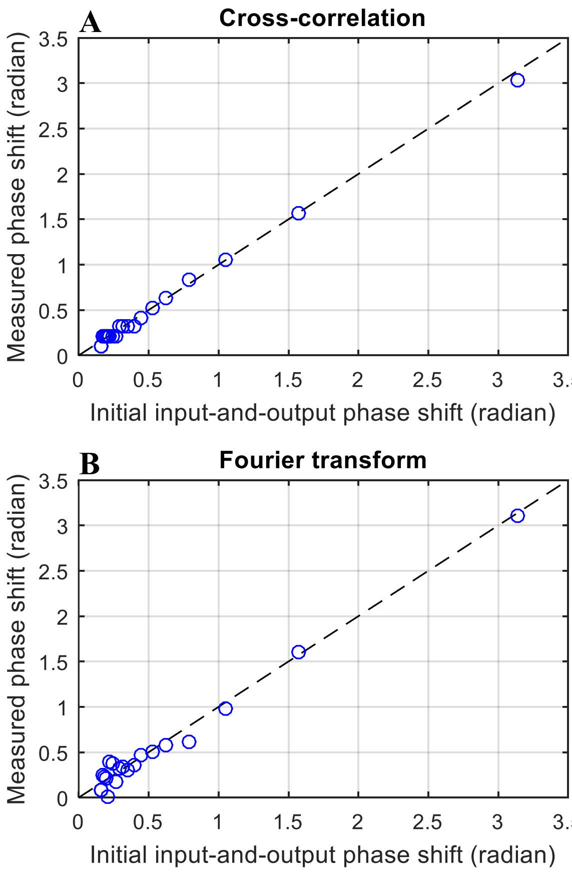

Figure-5. Curves of cross-correlation and Fourier transform when the phase varies. It is observed that the Fourier plot has more fluctuations in the range from 0 to 0.5 radian compared to the cross-correlation.

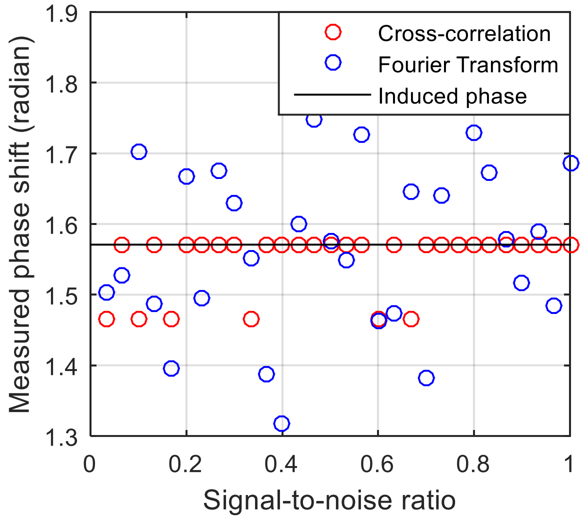

Figure-6. Plot of phase shift when the signal-to-noise changes. It is observed that the Fourier transform has more dispersion compared to cross-correlation.

5. CROSS CORRELATION ON LABVIEW

Because cross-correlation showed good response, this method was developed by LabVIEW, explained in this section. Our application simulates the input and output SAW signals represented by cosine waveforms whose level (defined as voltage peak, Vp acronym), phase shift (units of radian), noise level (units of Vp) can be adjusted. Additionally, the cross-correlation function was applied to them for reading its phase difference. Figure-7A shows the panel frontal of this application, which includes numeric controls and indicators to display, adjust signals and plotting the cross-correlation output. The measured phase difference was visualized on the down left-hand, expressed in radian. Figure-7B shows the block diagram (that is, the graphical source code) containing elements to create and connect the SAW signals with cross-correlation function.

By this application, the accuracy (or response) of measured phase shift was first observed. Thus, the input signal set 1Vp and 1 Hz, and output signal fixed 0.1Vp and induced phase shift of -0.876 radian. Under this conditions, the measured phase was -0.859 radian. In different phase shifts, it was obtained a phase close to its induced. Therefore, we considered cross-correlation technique offers a good response. Then, the measuring of phase shift under uniform noise was analyzed. With the same previous signals but the output containing uniform noise of 0.07 Vp, the outcome showed fluctuations around -0.859 radian. So, although the simulations in section IV showed that the cross-correlation is not sensitive to noise, in reality this technique does transmit it to the output. Therefore, it is recommended to integrate a smoothing filter into the SAW output signal, or after the cross-correlation function to obtain a stable phase reading. Additionally, when the output signal was strongly attenuated, the phase shift was measured without inconvenient.

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6. CONCLUSIONS

Digital signal conditioning is an attractive solution for SAW sensor. Cross-correlation and Fourier transform were studied in order to explore its response in conditions of noise and attenuation. Because the cross-correlation method showed better response in noisy conditions compared to Fourier, this method was implemented by LabVIEW. This revealed that the noise will be always present at the output signal causing fluctuations to the measured phase-shift, which indicated that a smooth filterer should be integrated to obtain a stable phase reading.

As the cross-correlation method developed by LabVIEW showed easy-implementation and good response, our next step is to develop this method in an embedded system (e.g. FPGA or microcontroller) connected to our SAW in process of developing. It is envisaged to integrate a smooth filter of type mean, median or Savitzky-Golay to minimize noise. Also, this embedded system has to include an ADC high resolution and high sample frequency as SAW signals can be in the order of tens (or cents) of MHz.

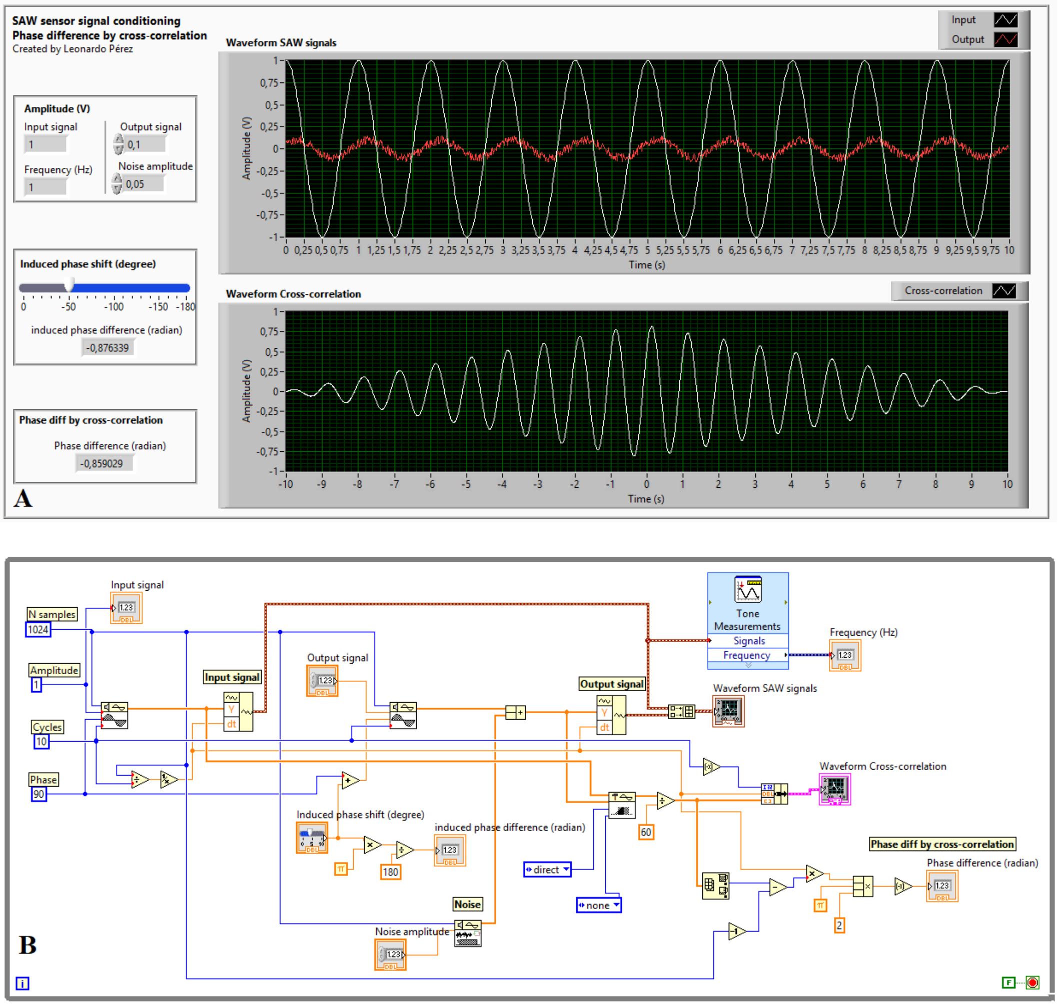

Figure-7. Application of cross-correlation method on LabVIEW. (A) Front panel. (B) Block diagram.

REFERENCES

[1] S. Mahon. 2017. The 5G Effect on RF Filter Technologies. in IEEE Transactions on Semiconductor Manufacturing. 30(4): 494-499.

[2] A. Ayes, P. R. Ohodnicki, R. J. Lad and M. P. da Cunha. 2019. Enhanced Hydrogen Gas Detection Using SAW Sensor Through Oxygen Pre-Treatment. 2019 IEEE International Ultrasonics Symposium (IUS), Glasgow, United Kingdom. pp. 189-192.

[3] L. Perez-Cortes *et al.* 2016. Functionality of Surface Acoustic Wave (SAW) transducer for palladium-platinum-based hydrogen sensor. Sensors and Actuarors A. 251: 35-41.

[4] K. Stroganov, T. Kronidov, B. Luylin, V. Kalinin and V. Plessky. 2014. SAW temperature sensors for

electric power transmission lines. 2014 European Frequency and Time Forum (EFTF), Neuchatel. pp. 157-159.

[5] B. Liang *et al*. 2011. A novel implantable saw sensor for blood pressure monitoring. 2011 16th International Solid-State Sensors, Actuators and Microsystems Conference, Beijing. pp. 2184-2187.

[6] H. Tan, X. Chen, J. Ma and Y. Tan. 2016. A design of substation temperature online monitoring system based on SAW temperature sensor. 2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE), Chengdu. pp. 1-4.

[7] Analog devices. 2016. AD8302: RF/IF gain and phase detector. Miami: Analog-Dev Docs.

[8] Claude P. Gros, Meddy Vanotti, Christophe Theron, Valentin Quesneau, Valérie Soumann, *et al*. 2018. Functionnalized Surface Acoustic Wave Sensors for the detection of hazardous gases. 2018 IEEE SENSORS, New Delhi, India. pp. 1-4, ff10.1109/ICSENS.2018.8589669ff. ffcea-02367537f.

[9] M. Vanotti, V. Blondeau-Patissier, V. Moutalier, S. Ballandras. 2015. Analysis of palladium and yttrium-palladium alloy layers used for hydrogen detection with SAW device. Sensors and Actuarors B. 217: 30-35.

[10] V. Nguyen, O. Peters, U. Schnakenberg. 2017. One-port portable SAW sensor system. Measurement Science and Technology. 29(1).

[11] Morgan D. 2007. Surface acoustic wave filters. Burlington: Elsevier. pp. 2-3.

[12] Campbell C. 1998. Surface Acoustic Wave devices for mobile and wireless. San Diego: Academic press. pp. 48-49.

[13] L Perez-Cortes *et al.* 2017. Conception and realization of a SAW sensor based on a nanostructured-catalytic material for the detection of carbon monoxide and hydrogen, Th: Ph., Université Grenoble Alpes. pp. 1-2.

[14] Tang *et al.* 2015. Water pressure sensing based on wireless passive SAW technology. Int. conference on computing and control for the water industry. 119: 892-900.

[15] Mujahid A. & Dickert F. L. 2017. Surface Acoustic Wave (SAW) for Chemical Sensing Applications of Recognition Layers. Sensors (Basel, Switzerland), 17(12): 2716. https://doi.org/10.3390/s17122716.

[16] G. Bruckner, J. Bardong. 2019. Wireless Readout of Multiple SAW Temperature Sensors. MDPI sensor. 19: 2-15.

[17] Tortissier *et al.* 2009. Langasite based surface acoustic wave sensors for high temperature chemical detection in harsh environment, Proceedings of the Eurosensors XXIII. pp. 963-966.

[18] L. Rabiner, R.W. Schafer. Digital processing of speech signals. Signal processing Series. NJ: Prentice Hall. 1: 147-149.

[19] R. Bracewell. The Fourier Transform and Its Applications. McGraw-Hill, ISBN 978-0-07-116043-8.

[20] J. Walker. 1996. Fast fourier transform. CRC Press. 2(3).

[21] K. Rao, D. Kim, J Hwang. 2010. Fast fourier transform: Algoritms and applications. Springer. 1: 11-119.