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High-Sensitivity Open-Loop Electronics for Gravimetric Acoustic-Wave-Based Sensors

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***Abstract*—Detecting chemical species in gas phase has recently received an increasing interest mainly for security control, trying to implement new systems allowing for extended dynamics and reactivity. In this work, an open-loop interrogation strategy is proposed to use radio-frequency acoustic transducers as micro-balances for that purpose. The resulting system is dedicated to the monitoring of chemical compounds in gaseous or liquid-phase state. A 16 Hz standard deviation is demonstrated at 125 MHz, with a working frequency band in the 60 to 133 MHz range, answering the requirements for using Rayleigh- and Love-wave-based delay lines operating with 40-μm acoustic wavelength transducers. Moreover, this electronic setup was used to interrogate a high-overtone bulk acoustic wave resonator (HBAR) microbalance, a new sensor class allowing for multi-mode interrogation for gravimetric measurement improvement. The noise source still limiting the system performance is due to the analog-to-digital converter of the microcontroller, thus leaving open degrees-of-freedom for improving the obtained results by optimizing the voltage reference and board layout. The operation of the system is illustrated using a calibrated galvanic deposition at the surface of Love-wave delay lines to assess theoretical predictions of their gravimetric sensitivity and to compare them with HBAR-based sensor sensitivity.**

I. Introduction

Current systems for detecting potentially toxic gases are generally cumbersome and complex. For continuous, real-time monitoring, direct detection sensors are well-adapted because they do not require preliminary sample processing; optical [1], electrochemical [2], and gravimetric acoustic sensors (better known as microbalances) [3] have been developed and successfully tested for such purposes. Most of the literature focuses on improving the transduction principle [4]–[6], either by replacing propagating waves with evanescent waves which, by being confined close to the transducer surface, improve the signal-to-noise ratio [surface plasmon resonance (SPR) and Love-mode SAW sensors]. In this work, the effort is oriented toward the development of embedded electronics for gaseous chemical species detection using RF transducers. One of the aspects of this dedicated application is the ability to automatically identify an optimal operating frequency point within the pass band of the device, and then to generate a clean, continuous wave signal at this given frequency with sub-hertz resolution.

The basic principle of gravimetric acoustic wave sensors consists of the measurement of the phase velocity variations resulting from an adsorbed mass or a layer thickness change atop the device during chemical reaction: this phase velocity is dependent on the boundary conditions of the propagating surface acoustic waves and is affected either by the guiding layer's properties or thickness. A common method exploits bulk acoustic waves, yielding the well-known concept of quartz crystal microbalances (QCMs) [7]. The gravimetric sensitivity of a QCM is directly related to its thickness, and as a consequence, to its fundamental frequency f_0. Particle deposition on one side of the resonator modifies its resonance conditions and thus allows for gravimetric detection. Furthermore, it is possible to functionalize the surface with specific reactants to provide information on the concentration of the adsorbed (target) species in the medium surrounding the sensor [8].

In this work, the development of a dedicated embedded instrument is proposed, based on a full software control for the open-loop monitoring of delay lines. As opposed to the closed-loop (oscillator) strategy, in which performance is strongly depending on the environment of the acoustic transducer and might yield to a lack of oscillation if the damping of the acoustic waves is not compensated for by the amplifier, an open-loop strategy provides, beyond the actual acoustic parameters, the data needed for measurement even using a poorly performing transducer. Indeed, in an open-loop strategy, the large dynamic range (dc to 2.7 GHz) of the in-phase and quadrature (I/Q) demodulator needed to extract the phase and magnitude information at each frequency yields improved robustness of the measurement system—the transducer and associated electronics—compared to the closed-loop strategy [3]. However, reaching comparable noise levels with the former strategy is challenging. As a consequence, an embedded frequency-sweep network analyzer has been developed and optimized to meet these specifications, based on a high-stability frequency source to synthesize the frequency scanning signals.

For that purpose, a direct digital synthesizer (DDS)-based oscillator is implemented to provide a flexible RF probe signal, and a low-noise phase detector is fed by an amplitude-controlled signal. This low-noise electronics is used in parallel with a versatile wide-band I/Q demodulator for the preliminary characterization of the transfer function of any type of sensor and for selecting the opti-

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mum operating frequency used throughout the gravimetric detection experiment.

The first part of the paper describes the basic principles of the interrogation—in particular, the RF signal synthesis and the proposed approach for detection resolution improvement. The resulting electronic setup is used for calibrating Love-wave devices using an electro-deposition process, allowing for an accurate control of the amount of material deposited atop the device. Finally, a new class of sensors based on high-overtone bulk acoustic wave resonators (HBARs) is tested using the developed equipment.

II. Basic Principles

A. Radio-Frequency Signal Controls

Probing gravimetric acoustic wave-based sensors need to synthetize RF signals: the working frequency is within the 60 to 133 MHz range, consistent with the use of 40-µm wavelength Rayleigh wave or Love mode surface acoustic wave sensors. The RF probe signal is generated by an Analog Devices AD9954 direct digital synthesizer, controlled by an ARM7-core based ADuC7026 microcontroller through the serial peripheral interface (SPI) link. To perform differential measurements, two transducers are probed simultaneously, one coated with a sensing layer and the other one kept free as a reference. Because the two devices exhibit different working conditions, either because of manufacturing differences or because of the sensing layer coating, the probing signals have to be generated by two independent DDSs. Each RF signal is split into a reference channel and a measurement line. A programmable attenuator is tuned to generate an output signal of the reference line exhibiting a power close to the signal going through the measurement line.

A coarse measurement mode uses an integrated I/Q demodulator (AD8302, Analog Devices Inc., Norwood, MA), see Fig. 1, with a large bandwidth, yielding a standard deviation of 0.3° on the phase detection output, consistent with the performance of most frequency-sweep RF network analyzers, providing an output similar to the S_{21} parameter classically used to characterize SAW delay lines.

The setpoint—the selected frequency at which all measurements will be performed during the chemical reaction—is computed once a full-band (100 to 150 MHz) frequency sweep has been achieved, allowing for the identification of the maximum transmitted signal, $\max(|S_{21}|)$. Identifying this setpoint, the closest mid-scale crossing condition of the S_{21} phase is sought for, at which the I/Q demodulator exhibits the strongest linearity characteristic and the analog-to-digital converter provides the widest dynamic range. Once the operating frequency has been finely tuned, this setpoint is used throughout the chemical reaction monitoring, and the evolution of magnitude and phase of the I/Q demodulator output is recorded as a function of time.

Because of the noise level (associated with the large bandwidth of 30 MHz inducing excessive thermal noise) of the AD8302 demodulator, this coarse scanning approach had to be improved for more accurate measurement by adding a manual phase-detection process—using the SYPD-2 phase detector by Mini Circuits (Brooklyn, NY)—with an automatic gain controller (AD8367, Analog Devices Inc.) which provides a constant RF signal power from the SAW sensor to the phase measurement by SYPD-2 device. The phase detector is completed with programmable, high-gain, low-noise operational amplifiers for signal shaping. This low-bandwidth (143 kHz cutoff frequency) circuit exhibits a noise level small enough for the signal-to-noise ratio to be independent on the operational amplifier stage gain, but limited by the phase velocity fluctuations of the SAW delay line caused by operating condition variations.

A second limitation is induced by the DDS synthesizer, whose phase noise is about -115 ± 5 dBc/Hz. The phase variation caused by the synthesizer phase noise can be calculated using

$$\Delta\varphi_{\mathrm{rms}} = \sqrt{2 \times 10^{L_{\mathrm{c}}(f)/10} \times \mathrm{BW}}, \quad (1)$$

where $\Delta\varphi_{\mathrm{rms}}$ is the phase variation in radians, L_{c} is the phase noise, and BW is the bandwidth; (1) is deduced from [9]

$$L_{\mathrm{c}}(f) = 10 \times \log\left(\frac{1}{2} \times S_{\Delta\varphi}(f)\right) = 10 \times \log\left(\frac{1}{2} \times \frac{\Delta\varphi_{\mathrm{rms}}^2}{\mathrm{BW}}\right), \quad (2)$$

where $S_{\Delta\varphi}(f)$ is the ratio of the noise power measured in a sideband over a bandwidth of 1 Hz to the carrier power.

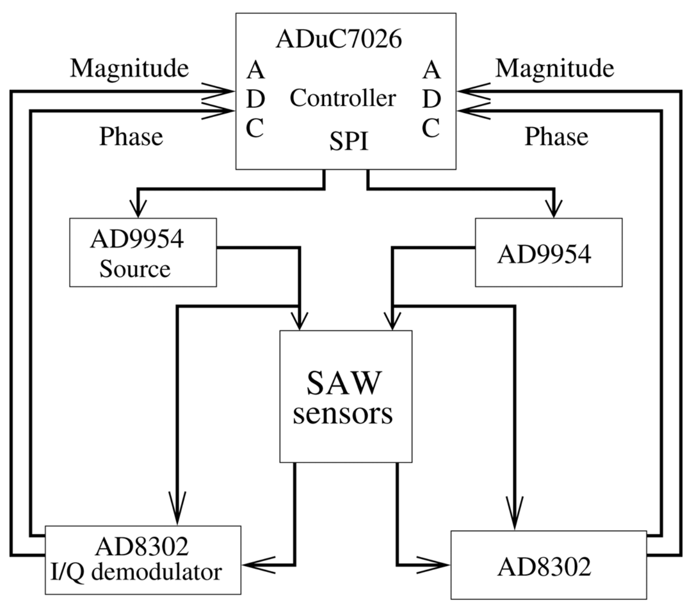

Fig. 1. General diagram of two SAW sensors probing electronics, including an ADuC7026 microcontroller, AD9954 direct digital synthesizer, and AD8302 I/Q demodulator.

TABLE I. STANDARD DEVIATION IN BITS, DEGREES, AND HERTZ OF FREQUENCY/PHASE MEASUREMENTS ACCORDING TO PHASE VARIATION IN SAW CHARACTERIZATION USING I/Q DEMODULATOR AND PHASE DETECTOR WITH DIFFERENT LOW-NOISE AMPLIFIER GAINS (SEE [23]).

Standard deviation unit	I/Q demodulator AD8302	Phase detector SYPD-2		
		Gain = 1	Gain = 4.5	Gain = 17.4
Bits	26.3	20.3	11	30
Degrees	0.10	0.967	0.012	0.0082
Hertz	222.8	195.9	23	16

The bandwidth is determined by the cut-off frequency of the low-pass filter (143 kHz) yielding a phase variation caused by the synthesizer of about $\sqrt{2.10^{-120/10} \times 143.10^3}$ = 30 m°.

The phase measurement is averaged over 16 samples, yielding a reduction by a factor of $\sqrt{16} = 4$ of the phase noise, and thus a phase variation of 7.5 m° close to the observed 8.2 m° phase measurement standard deviation when using a 17.4 gain value of the low-noise amplifier (Table I).

The programmable gain of the amplifiers is set using an analog multiplexer. All setpoint identification and gain control tasks are controlled by the same ADuC7026 microcontroller.

The main issue when increasing the gain after the low-noise phase-detection circuit is the limited working range of the phase detection range: because the 0 to 180° range no longer fits on phase domain in the analog-to-digital converter voltage range, saturation occurs for large mass variations yielding large acoustic velocity shifts. Hence, a phase tracking and unwrapping strategy is implemented, as discussed in Section III.

B. S_{21} Parameter Measurement

1) Coarse Measurement: For preliminary characterization of the delay line, the AD8302 I/Q demodulator provides a magnitude output of 29 mV/dB and a phase output of 10 mV per degree, the latter exhibiting a poor linearity close to the measurement boundaries (0 and 180°). The frequency selection strategy focuses on selecting a setpoint at which the reference and measurement signals are in quadrature, yielding the best dynamic range and linearity of the output voltage with respect to the phase between the input reference and measurement signals. Fig 2. **[AU1: Please cite Figure 2.]**Fig. 3 shows a typical S_{21} characterization of a Love-mode SAW delay line performed with the developed setup, in the 120 to 130 MHz range and a characterization using a commercial network analyzer.

2) Improved Accuracy: To improve the phase measurement resolution, a low-bandwidth phase detector is associated with low-noise amplifiers. The phase detector provides a low voltage-versus-phase coefficient (8 mV/°) but with a noise level low enough to be amplified with a substantial gain, as discussed before.

Using variable-gain amplifiers, the S_{21} phase characterization of SAW delay line phase behavior is a function of frequency (by a frequency sweep) with gains ranging from 1 to 16: switching from one gain to another is controlled by the ADuC7026 microcontroller through an analog switch.

Fig. 4 shows the evolution of the transfer function when increasing the amplifier gain. The digitized phase measurement noise level is independent of the gain: the noise level is either due to the analog-to-digital conversion step, solely due to the unstable reference of the internal voltage used by the conversion stage, or the unoptimized board layout when separating the analog and digital parts of the power supplies.

This method, which focuses on the phase measurement around the analog-to-digital converter (ADC) mid-range, causes the system to saturate if the phase shifts during the reaction, a condition which is quickly met for the highest gains. A first strategy to avoid this situation is to continu-

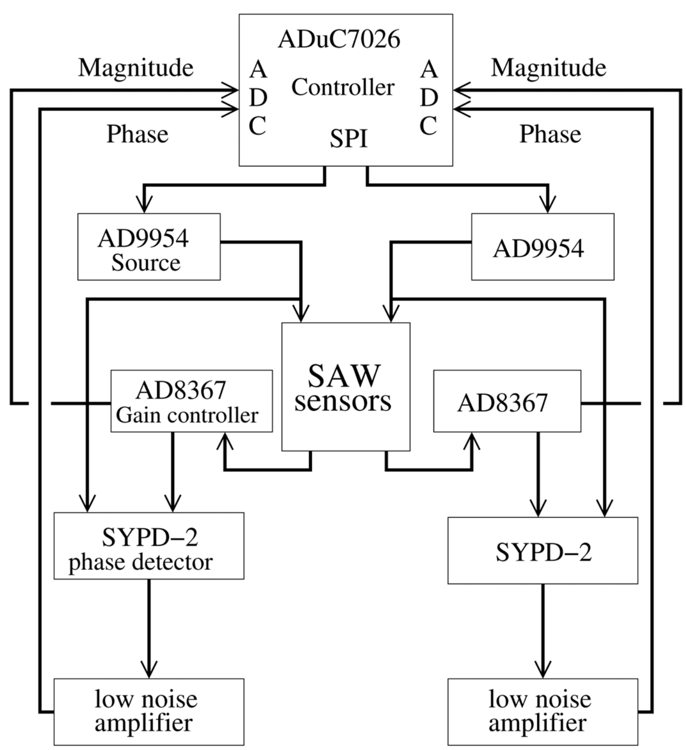

Fig. 2. General diagram of the two SAW sensors interrogation electronic setup including high-accuracy functionalities using automatic gain controller AD8367 and phase detector SYPD-2 with low-noise amplifier stage.

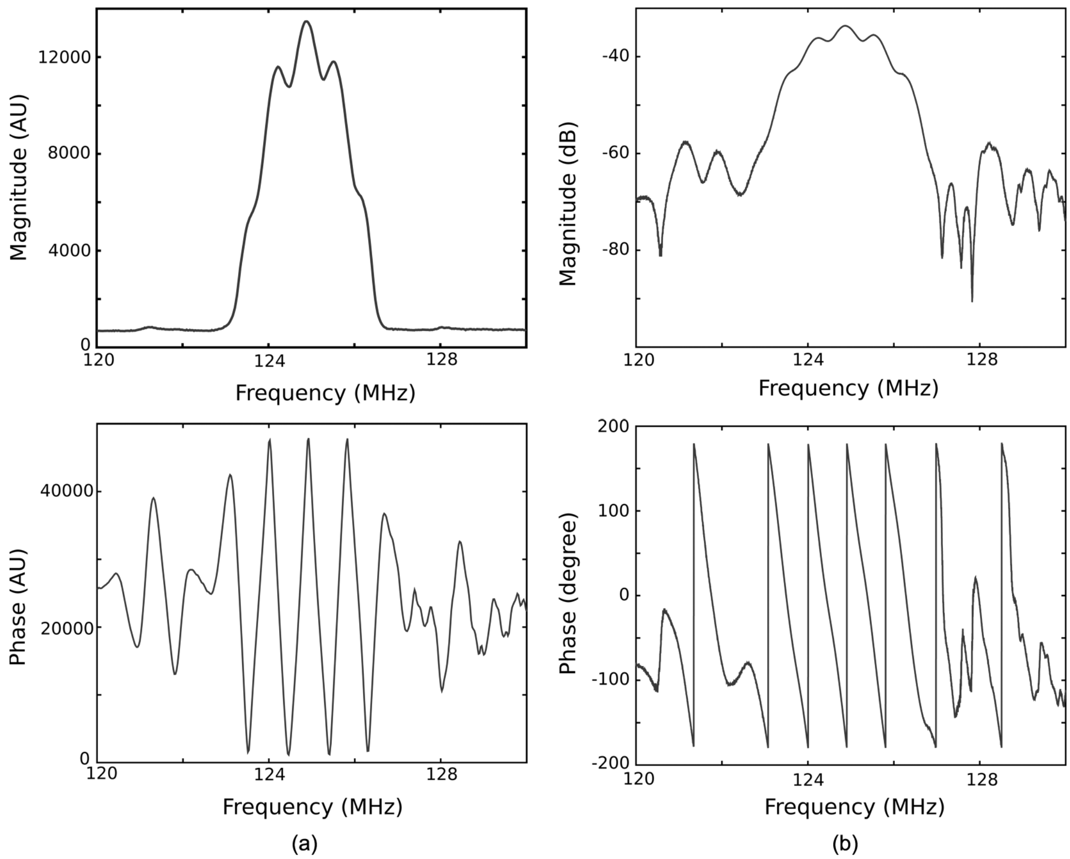

Fig. 3. Magnitude (top) and phase (bottom) characterization of a Love-mode SAW delay line. Comparison between the measurements obtained using the embedded electronics (a) and Agilent Technologies E5071B commercial network analyzer (b). As opposed to a network analyzer characterization providing a phase measurement in the 0 to 360° range, one can note the lack of sign information in the phase output of the AD8302, yielding phase measurements in the 0 to 180° range.

ously track the phase, and to control the frequency to keep the phase close to a setpoint near the ADC mid-range. An alternative strategy requires a preliminary calibration of the phase frequency slope, to allow the phase to slowly drift toward one of the range boundaries, and once reached, to control the frequency to bring the measurement back to the ADC mid-range.

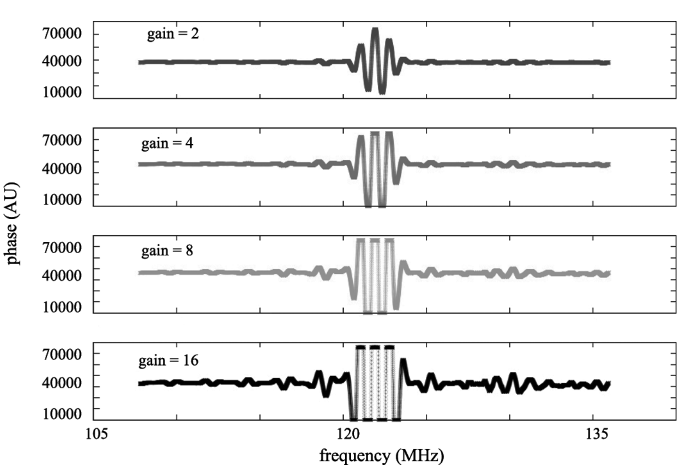

Fig. 4. High-resolution phase characterization of a Love-mode SAW delay line using four different gains of the low-noise amplifier stage.

The former method was found to be effective for slowly varying signals. The frequency is recorded as the measured quantity and the phase only provides an error signal to control the efficiency of the digital feedback control loop. However, an algorithm which requires phase tracking induces limits on the chemical reaction kinetics, as will be shown later (Section III).

The latter method only requires reprogramming the DDS when the phase signal comes close on to the ADC boundaries. The phase-frequency slope is characterized for each new transducer, and is solely a function of the acoustic wave velocity, which slightly changes for a given kind of acoustic waves (Rayleigh or Love) during a sensing experiment. Furthermore, this frequency-phase slope depends on the amplification gain. Therefore, an array with defined slopes is stored in the memory of the microcontroller for each kind of transducer and for each gain.

C. Noise Level Comparisons

During the coarse qualification step, the typical noise level sampling on a 16-bit range is converted to a phase standard deviation of 0.1° (according to a frequency standard deviation of 223 Hz for the tested sensor), at least two orders of magnitude worse than typical closed-loop oscillator noise level. The improved electronics exhibits a constant gain-independent noise level (Table I): hence, the relative noise level decreases as the gain increases. The resulting phase noise level then corresponds to a standard deviation of $8.2° \times 10^{-3}$ (according to a frequency standard deviation of 16 Hz for the tested sensor). This noise level is still worse than that achieved using an oscillator strategy, but because it does not depend on the operational amplifier gain and is principally attributed to the ADC noise, faster sampling rates together with digital averaging and improved analog circuit layout provide paths toward improving this result. Considering a possible detection of three times the noise level, this electronics setup provides the possibility to detect phase variation of $24.6° \times 10^{-3}$.

III. Electro-Deposition Reaction Monitoring

Copper electro-deposition has been used for calibrating the gravimetric sensitivity of acoustic sensors [10] exploiting an independent estimate of the deposited metal mass through the measurement of the current generated by the potentiostat [11], [12]. When using a closed-loop strategy to keep the phase measurement within the measurement range of the ADC at highest gain, the fast reaction rate and large phase shift provide a challenging measurement condition for validating the phase tracking algorithms.

The generation of the potentiostat voltage driving and electro-deposition parameters (counter electrode voltage and current) are controlled and monitored by the same microcontroller that is driving the SAW monitoring circuits, yielding data synchronization. A typical experimental cycle is shown in Fig. 5, with a negative current indicating copper reduction (deposition on the working electrode) and a positive current indicating oxidation (copper removal from the working electrode). Reversibility is a selective criterion for implementing this experiment because it provides the means for quickly testing various acoustic phase measurement and tracking algorithm parameters. Simultaneous to the current monitoring, the acoustic phase and magnitude at fixed frequency are recorded (Fig. 6). For the largest gains, as used when recording the data plotted in Fig. 6, the feedback loop on the emitted frequency to keep the phase within the measurement range of the ADC induces a phase wrapping. In fact, if the phase value is near the saturation area of the ADC (below 0.2 V and above 2.3 V), the operating frequency is adjusted to get a phase value in the middle range of the ADC [Fig. 6(top)].

High-resolution phase reconstruction is obtained by unwrapping, as shown in Fig. 6. As one can see in this figure, the original 16-bit resolution has now been increased to a 17-bit resolution using the given gain of 4 at maximum gain (16); an additional 4-bit resolution improvement is obtained with no significant increase of the noise level.

The quantity of copper deposited on the sensitive surface of each device is determined by

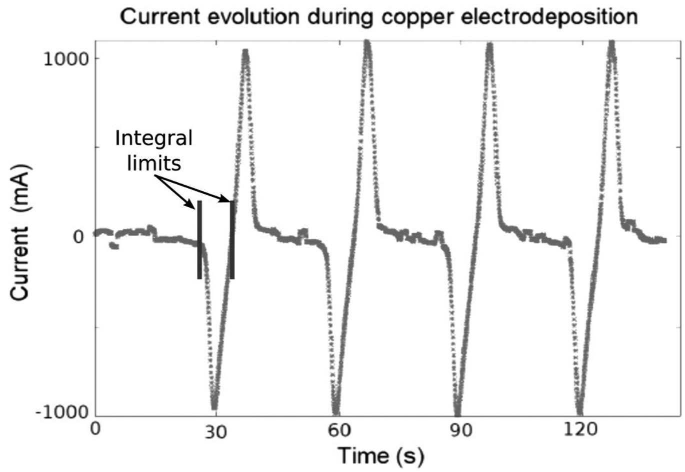

Fig. 5. Current monitored during copper electro-deposition reactions and point selection defining the limit for integral calculation.

$$M_{\mathrm{Cu}} = \frac{m_{\mathrm{Cu}} \times \sum i(t)\delta t}{96440 \times n_{\mathrm{e}}}, \tag{3}$$

where M_{Cu} is the mass of the copper deposited (in grams), m_{Cu} is the molar weight (in grams/mole), and $\sum i(t)\delta t$ is the number of charge transferred during electro-deposition. The charge of one mole of electron (C) is 96 440 and n_{e} is the number of electrons transferred during reduction, given by

$$\mathrm{Cu}^{2+} + 2e^{-} \leftrightarrow \mathrm{Cu}. \tag{4}$$

The electro-deposition current is converted in voltage by the potentiostat, and its characteristics enable the inverted conversion after the copper deposition to determine the current evolution of the chemical reaction. The time between each recorded point is fixed by the microcontroller according to 1000 points per period of 15 to 30 s, thus changing the deposited mass on the sensor sensitive surface. To determine the deposited mass, the integral of the

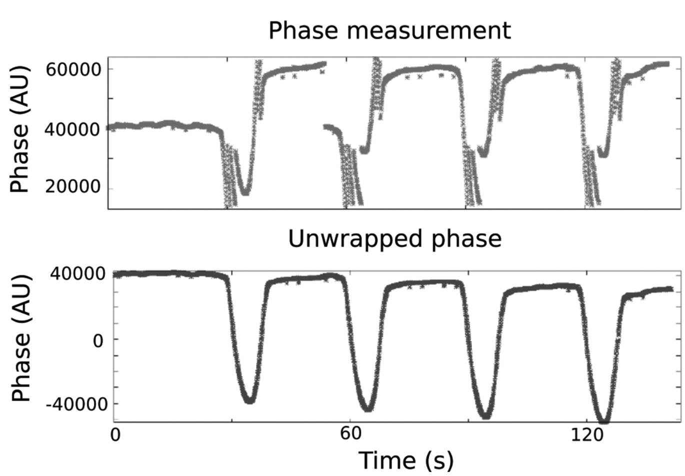

Fig. 6. (top) Recorded phase values during electro-deposition with feedback and (bottom) unwrapped phase information by unwrapping.

current during copper reduction is performed during the time delay defined as in Fig. 5. Knowing the sampling time and current value, the deposited mass can be calculated using (3).

Using this result, combined with the mass–frequency dependence, relative to the Love-wave device, gravimetric senstivity is determined by using

$$S = \frac{\Delta f}{f_0} \times \frac{A}{\Delta m}, \quad (5)$$

where Δf is frequency shift in hertz, f_0 is the interrogation frequency in hertz, Δm is the deposited mass in grams, A is the sensitive zone area in square centimeters, and S is the gravimetric sensitivity in square centimeters per gram.

The resulting mass sensitivity of the SAW acoustic sensor, which requires both accurate acoustic phase and potentiostat current measurements, are consistent with previous estimates: a value of 180 ± 20 cm^2/g is consistent with acoustic velocity gradient with respect to the guiding layer thickness from modeling [13] and with previous experimental estimates [11].

The embedded electronics are limited by the speed of phase tracking, which might not be able to cope with chemical reactions exhibiting fast kinetics. Electrodeposition reaction is one example of such a fast reaction. The time of reprogramming the DDS and the measurement of the phase is of $\Delta t = 12$ ms. Considering this time and the gravimetic sensitivity measured ($S = 180$ cm^2/g) in this experiment, the maximum speed of variation of the thickness of the deposited copper on the sensing surface measured with the embedded electronic can be calculated. Our analysis follows.

The relationship between the phase variation and the frequency value (used for the gravimetric sensitivity determination) is fixed by the sensor structure and determined using a frequency sweep (Fig. 3):

$$\Delta f \times \alpha = \Delta \varphi, \quad (6)$$

where α is the relationship constant in bits/hertz.

Using (5), the frequency variation becomes

$$\Delta f = S \times \frac{\Delta m}{A} \times f. \quad (7)$$

Using (6) and (7), $\Delta\varphi/\Delta t$ can be written

$$\frac{\Delta \varphi}{\Delta t} = \frac{S \times \frac{\Delta m}{A} \times f \times \alpha}{\Delta t}. \quad (8)$$

The mass variation can be expressed as thickness variation Δh of a layer made of a material of density ρ:

$$\frac{\Delta m}{A} = \rho \times \Delta h. \quad (9)$$

Hence,

$$\frac{\Delta \varphi}{\Delta t} = S \times \rho \times f \times \alpha \times \frac{\Delta h}{\Delta t}. \quad (10)$$

The phase variation $\Delta\varphi$ occurring during Δt must be smaller than half the range of the ADC, or a conservative value of 32 765 for a 16-bit ADC:

$$S \times \rho \times f \times \alpha \times \frac{\Delta h}{\Delta t} < \frac{\text{half range}}{\Delta t}. \quad (11)$$

The numeric application gives a speed of increasing (or decreasing) of the thickness on the sensing area of 1.6 µm/s using the I/Q demodulator. This maximum speed is reduced to 100 nm/s by using the low-noise phase measurement with a gain of the amplification of 16.

IV. Measurements of HBAR-Based Sensors

As explained previously, electro-deposition reaction monitoring is useful to compare the gravimetric sensitivities of several sensors. The developed electronics are then used to determine the gravimetric sensitivity of an acoustically-coupled HBAR [14]. This type of transducer consists of two resonators very close to one another to allow for evanescent wave coupling between the two resonators apart from the electrodes.

The use of this type of resonator is motivated by its ability to provide several overtones and the possibility to read high gravimetric sensitivity in a similar approach to what was achieved using thin-film bulk acoustic resonators [15], [16]. The idea then is to combine both characteristics to provide an enhanced analysis of adsorbed media compared with single-mode devices. Moreover, research has been done for temperature compensation [17], [18], allowing a robust mass detection versus environmental temperature variations.

The HBAR consists of a stack of layers. A thin piezoelectric layer is used to excite bulk waves in a high-quality substrate, providing a wideband multimode ray spectrum as explained in [19]. In this work, a 15-µm (YXl)/163 $LiNbO_3$ layer is used to excite pure shear waves in an AT-cut quartz substrate according to [20]. On the free surface of the quartz substrate (the back side of the sensor), the sensing functional layer or working electrode on which the copper will be reversibly plated is deposited.

Based on the electrical characterization of the transducer provided by the electronics, the working frequency (Fig. 7) is selected to correspond to a downward slope of the phase variation in the frequency sweep characterization. As previously explained, HBAR-based sensors provide several overtones, and one of them is chosen here to determine the gravimetric sensitivity of the corresponding mode.

The electronics provide raw values of phase variations related to the aforementioned electro-deposition information. To convert phase variations in relative frequency variations used in the equation of gravimetric sensitivity

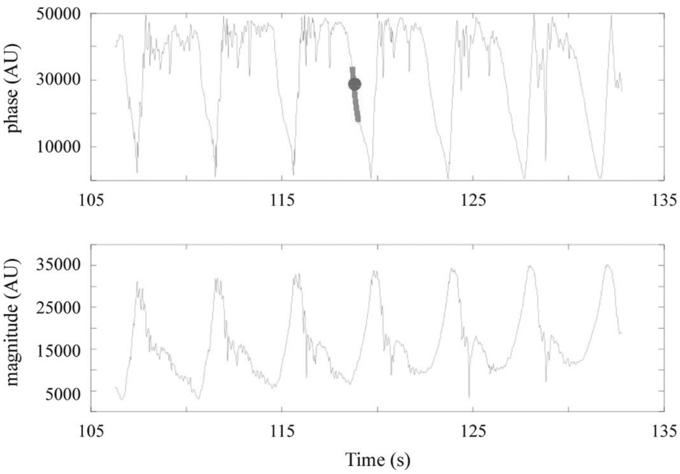

Fig. 7. (top) Phase and (bottom) magnitude of the transfer function (S_{21}) of an acoustically coupled HBAR used for gravimetric measurement. The circle is located at the interrogation frequency. The thick solid line represents the frequency/phase range for phase-to-frequency conversion.

(5), a second-degree polynomial fit is performed for determining the relation between raw values of phase and frequency variations. The conversion requires selection of several points that must encompass all the values read during the electrochemical deposition corresponding to the chosen range (thick solid line in Fig. 7) around the working frequency (point). The polynomial fit is used to determine the relation between phase and frequency in the selected range to increase the number of points (up to 10 000) which define the phase value read during the experiment. A search of the closer recalculated point of phase between each recorded phase point during the reaction is performed to evaluate the effective frequency for which the conversion between phase and frequency variations is provided.

Obtaining several different results of the gravimetric sensitivity from 2.2 to 13 cm^2/g depending on the deposited mass from 1.7 to 2.6 μg emphasizes the difficulty for taking into account parameters such as viscosity and surface roughness which impact the frequency and signal magnitude as well [21], [22]. Experimental simulations must be completed to identify the phenomena related to the frequency shift during the electrochemical deposition of copper and to improve the gravimetric sensitivity.

V. Conclusion

An approach based on synchronous detection principles using an accurate phase detector has been developed for gravimmetric surface or bulk wave sensors. An improvement by a factor of 16 of the resolution of phase measurement has been demonstrated, providing the possibility to detect phase variation down to $24.6° \times 10^{-3}$. The resolution gain has been achieved by reducing the system bandwidth, which is nevertheless sufficient for monitoring most chemical reactions at a few hertz sampling rate at most. This embedded frequency sweep electronics, operating almost like a network analyzer, combines the robustness of an open-loop strategy for assessing the operation of the sensor, and provides the resolution needed for practical gas detection applications which may correspond to sub-ppm concentration, yielding very small phase shifts (typically $100° \times 10^{-3}$).

The electronics have been developed to operate in the 60 to 133 MHz and 200 to 500 MHz ranges, allowing for testing various sensor configurations, operating points, and system architectures. A particular possibility to probe various resonances of a HBAR has been developed, allowing for a wide frequency range characterization of surface phenomena. This functionality is particularly attractive for dissociating frequency-dependent effects (viscosity for instance) from more classical adsorption effects, and therefore enhanced the system accuracy and reliability.

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[23] Supplementary material.**[AU2: What kind of supplementary material is being cited? Is there a way for readers to access this material, or is it unpublished data?]**

David Rabus followed a university course in Besançon, where he obtained a master's degree in electronics and microsystems. He is completing a Ph.D. degree in the Time and Frequency Department of the FEMTO-ST institute targeted toward the development of innovative sensors for the detection of chemical compounds and associated electronics. His interests include embedded electronics, acoustic-wave-based gravimetric sensors, and general instrumentation.

Jean-Michel Friedt obtained his Ph.D. degree in 2000. He worked as a postdoctoral fellow in IMEC, Leuven, Belgium, on acoustic and optical biosensors for characterizing organic thin film properties before joining the group of S. Ballandras in 2004 at FEMTO-ST, Besançon, France, for the development of passive sensors interrogated through a wireless link. He has been an engineer with the company SENSeOR since its creation in 2006, hosted by the Time and Frequency Department of FEMTO-ST. His interests include scanning probe microscopy, passive radio-frequency sensors and the associated radar-like electronics implemented as software-defined radio, and the combination of optical and acoustic methods for characterizing thin films.

Sylvain Ballandras was born in Strasbourg in 1965. He joined the CNRS in 1991, after receiving his Ph.D. degree in engineering sciences from the Université de Franche-Comté. From 1991 to 1995, he was working on SAW devices and was involved in the development of micromachining technologies (LIGA, stereo-photolithography). In 1995, he developed his research activities in the frame of a common laboratory between Thomson Microsonics (TMX) and the CNRS, entitled LPMX. He joined TMX in 1997 for a one-year industrial training project. From 1999 to 2005, he was responsible for the research group entitled Acoustique et Microsonique at the LPMO. In October 2003, he was promoted to Research Director at the CNRS, in the newly created FEMTO-ST Institute in Besançon. In 2004, he created its consulting office to answer specific demands from industry. In June 2005, he left the responsibility of its research group to assume the direction of the joined laboratory between TEMEX and FEMTO-ST devoted to SAW filters and sensors. In 2006, TEMEX gave rise to SENSeOR, a spin-off company devoted to acoustic-wave-based sensor applications, with which Sylvain Ballandras was strongly involved. In 2008, he set a new research group (CoSyMA) joining the Time-Frequency Department of FEMTO and moved to the Besançon's national engineering school ENSMM. Sylvain Ballandras also benefitted from the 25.2 agreement of the French research rules to join SENSeOR as a scientific adviser since the end of 2009. Since 2011, he has been preparing the creation of his company, frec|n|sys, devoted to the design, fabrication, and commercialization of acoustoelectric radio-frequency devices, and he has been detached from CNRS since January 2013. The company was created in February 2013 and exploits a set of industrial equipment owned by the University of Franche-Comté. Sylvain Ballandras is a member of IEEE.

Gilles Martin was born in 1963. An electronics engineer by training, he has specialized in instrumentation (time/frequency) and analog electronics. He has worked on various research projects (CNES and DGA). He has also participated in the Cofrac laboratory: calibration for time measurements stability and phase noise of clocks references (cesium, rubidium, and ultra-stable quartz oscillators OCXO). He worked for 9 years on passive sensors (SAW) through industrial contracts, with the establishment of networks of subcontracting for the realization of interrogators. Since 2008, he has been involved in the platform Components and Systems Micro-Acoustics and the electronic service of the FEMTO-ST Institute.

Émile Carry was born in 1977. He received his Ph.D. in engineering science in 2007 at the Department of Optics of the FEMTO-ST Institute. His work focused on achieving a near-field apertureless optical microscope operating in aqueous media. In 2008, he obtained a position as assistant professor in electronics at the Université de Franche-Comté. His teaching focuses on digital electronics and embedded systems. He joined the Time and Frequency department of the FEMTO-ST Institute at the same time, and his area of research focuses on SAW sensors and volume (HBARs).

Virginie Blondeau-Patissier joined the LPMO in 2001, after obtaining her Doctorate of Science in physics and chemistry at the University of Burgundy. The following year, she obtained a position as assistant professor at the University of Franche-Comte. Since then, she has been working in the Institute FEMTO-ST on surface acoustic wave devices and technologies of microfabrication dedicated to microtechnology. She has thus been able to develop acoustic sensors dedicated to various applications, including the development of chemical sensors for toxic gases (anhydrous hydrofluoric acid, hexa-, carbon monoxide, hydrogen, etc.). Gradually, her interest has focused on the development of surface wave microbalances in liquid media and associated electronics.

In parallel, Virginie Blondeau-Patissier is working on the characterization of materials by X-ray photoelectron spectroscopy (equipment purchased in 2003 at her request and she is responsible within the Central Technology MIMENTO FEMTO-ST). She participates in numerous studies initiated by different laboratories and companies (Utinam, Schlumberger, CEA, etc.) to characterize deposits and substrates.