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Implementation of a Segmented PLL for Readout of Highly Sensitive SAW Magnetometers

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Abstract: In order to integrate highly sensitive magnetometers based on surface acoustic wave (SAW) sensors into clinical applications, some fundamental challenges regarding their readout must first be overcome. The present paper proposes a readout concept that is based on a phase-locked loop (PLL) to demodulate a frequency-modulated (FM) signal. The presented demodulator is designed to meet three fundamental requirements: it is able to tolerate the frequency drift of the sensor system, it is able to demodulate low frequency as well as low amplitude and broadband signals, and it is sufficiently inexpensive and simple to be scaled for arrays. Preliminary measurements demonstrate that the chosen topology meets these requirements to a satisfactory extent, indicating its potential for broader implementation in clinical settings.

Keywords: magnetic field sensing, magnetoelastic surface acoustic wave, ME sensor, PLL demodulator, readout electronics, SAW

1 Introduction

The introduction of interdigital transducers [1] (IDT) in 1965 led to a significant development in the field of sensor technology, particularly in the area of surface acoustic wave (SAW) sensors [2, 3]. These sensors demonstrated remarkable potential for applications in a variety of measurement scenarios, and their functionality continues to be a subject of ongoing research and development [4]. In addition to their use in biosensors for the detection of gases and biological molecules [5, 6], these sensors have also found application in the measurement of electric [7] and magnetic fields [8–10], among other applications.

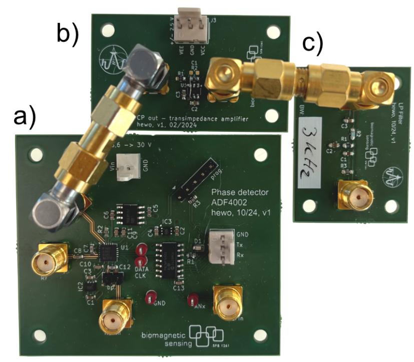

Fig. 1: Photo of the analogue part of the segmented PLL. a) is the phase detector, b) the trans-impedance amplifier, and c) the low-pass filter.

However, the domain of magnetic field measurement, with a specific emphasis on biomedical applications, introduces unique and challenging aspects. For instance, it involves the detection of small magnetic fields in the time domain. This necessitates a reliable measurement at the detection limit of the system in real-time and without significant post-processing of the signal. When employing a homodyne readout structure [11], the detection of chemical substances or molecules is usually accomplished by observing a frequency change within a range that exceeds 10 hertz [12]. In the context of the sensor technology presented here, it is necessary to detect frequency changes in the mHz regime in real-time. This detection must be conducted despite the fact that the core frequency of the frequency modulated (FM) signal remains unknown and unstable.

The sensor system discussed in this paper consists of three segments, which can be subdivided according to function and domain. The input of the system is formed by the SAW oscillator, whose output contains the detected magnetic signal in FM form. The second part of the system is the analogue part of the segmented phase-locked loop (PLL) and is the main focus of this work. It consists of a phase detector, a trans-impedance amplifier, and a low-pass (LP) filter. The combined circuits used are shown in Fig. 1. Digital signal processing, consisting

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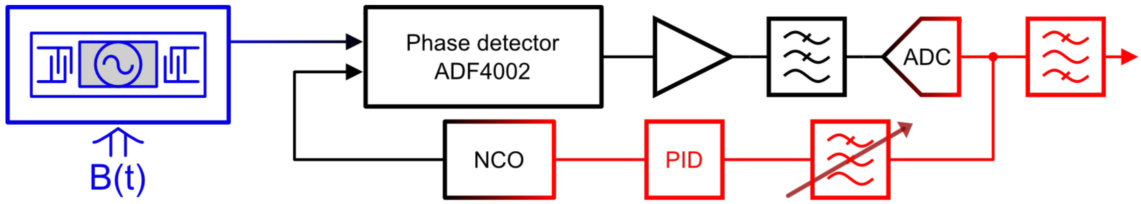

Fig. 2: The block diagram shows a comprehensive representation of the sensor system. Blue: SAW oscillator (converts magnetic signal to FM modulated signal). Black: analog components (phase detector, trans-impedance amplifier, LP filter). Red: digital components (PID controller, adjustable LP filter, BP filter). ADC and NCO are transitions between analog and digital domains.

of an analog-to-digital converter (ADC), a numerically controlled oscillator (NCO), various filters, and a controller for the NCO, is the third part of the system.

2 Materials and Methods

The following section discusses the individual elements of the circuit shown in Fig. 2. In addition, the setup for the evaluation of the system is briefly discussed.

2.1 SAW oscillator

The SAW oscillator is the transducer that converts the magnetic signal of interest into an FM voltage signal. It consists of the SAW sensor and its circuitry to form a self-oscillating system.

SAW Sensor

This study explores a sensor on a piezoelectric ST-cut quartz substrate. An acoustic wave is generated via the inverse piezoelectric effect at the IDTs, which are configured as 25 pairs of double fingers with a width of 3.5 µm each. They were fabricated by DC magnetron sputtering using a VON ARDENNE CS730S cluster tool. The IDTs consist of a 300 nm gold layer encapsulated by two 100 nm chromium adhesion layers. The emitting and receiving IDTs are designed in a delay line oriented at 90° to the crystallographic x-axis of the quartz, allowing the generation of shear-horizontal acoustic waves, commonly known as Love waves. To guide these Love waves along the surface of the substrate, a 40 µm thick SiO_2 layer was deposited by plasma-enhanced chemical vapor deposition. The SiO_2 layer was structured with tapered edges by inductively coupled plasma reactive ion etching [10]. The magnetic layer of the sensor consists of a 150 nm thick amorphous magnetostrictive material, $(Fe_{80}Co_{20})_{78}Si_{12}B_{10}$, fabricated by ion beam deposition using a NORDIKO 3000 system. A 5 nm tantalum layer serves a dual purpose: as an adhesion layer below the magnetostrictive film and as a passivation layer above. The deposition process was conducted in a magnetic field to create a preferred anisotropy parallel to the delay line orientation, which enhances the sensitivity [13].

Oscillator Circuit

The oscillator circuit under consideration is electrically equivalent to the circuit presented in [14]. The noise power of the built-in amplifier is constrained by a limiter and subsequently band-limited by the SAW sensor. The resulting band-limited noise is then used as a positive feedback signal within the amplifier. The system will oscillate at a frequency f_0 that satisfies the Barkhausen stability criterion [15] as soon as this criterion is met. The velocity of the SAW is influenced by the magnetostrictive material on the SAW sensor as a function of the external magnetic field, which means that the frequency f_0 is directly dependent on the external magnetic field. However, within the bandwidth of the SAW sensor, there are different frequencies that meet the Barkhausen criterion. Consequently, the exact frequency at which the system will initiate oscillation cannot be predicted a-priori.

Oscillator Sensitivity

The SAW sensor has a resonance frequency f_{res} of 146.3 MHz and a magnetic sensitivity G_{mag} of 7442.1 rad/T in a magnetic zero field. The phase noise $S_{\varphi n}$ of the sensor, measured at an offset frequency of 19.44 Hz, is $-125.9\,\mathrm{dB\,rad^2/Hz}$. The theoretical Limit-of-Detection (LOD) for the SAW in the case of mono-frequency excitation is calculated using $LOD_{19.44\,\mathrm{Hz}} = \sqrt{S_{\varphi n}}/G_{mag}$ to $68\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$. The electrical sensitivity G_{el} of the sensor is given as −8.4587 µrad/Hz and is also taken into account in the calculation of the FM sensitivity G_{FM} of the oscillator. The calculation of G_{FM} is achieved by employing the expression $G_{FM} = G_{mag}/|G_{el}|$ to 879.81 MHz/T. This results in a minimal frequency resolution at $LOD_{19.44\,\mathrm{Hz}}$ of 84 mHz. It is imperative that the electronics are capable of resolving frequency variations of at least 84 mHz to ensure that the performance of the sensor is not compromised. The most significant non-magnetic disturbance for the behavior of the oscillator is a change in operating temperature. The system's temperature coefficient, denoted as ΔG_{temp}, is measured as $6.45\,\mathrm{kHz/K}$. This coefficient is identified as the primary driving force behind the system's persistent drift.

2.2 Analog Electronics

The analog component of the readout system is comprised of the three elements shown in Fig. 1.

Initially, the phase and frequency of the SAW oscillator and the output of the NCO are compared using the phase frequency detector in the ADF4002 from ANALOG DEVICES. It is important to note that this comparison is not made at the operating frequency of the oscillator, but rather at an intermediate frequency (IF). This IF is obtained by down-converting the two signals using internal frequency dividers. The R divider for the measurement signal was set to 14 and the N divider for the reference signal (from the NCO) to 2. This results in the signal being evaluated at an IF of approximately $10.5\,\mathrm{MHz}$, and the NCO requiring an output frequency of approximately $21\,\mathrm{MHz}$. The IF has been chosen such that the divider causes only a minor influence on the system, so that the use of sinusoidal signals at the reference input of the ADA4002 is still possible without any problems, and so that a modulation of $100\,\mathrm{mHz}$ in the time signal can be detected visually in preliminary tests with an emulated FM signal. The result of the signal comparison is emitted in the form of a pulsed current via the charge pump output of the chip, with a current of $\pm 5\,\mathrm{mA}$.

The current signal is converted into a voltage signal by a transimpedance amplifier and amplified by a factor of $500\,\mathrm{V/A}$. The amplifier used is an LTC6268 from ANALOG DEVICES, and the amplification factor is set using a $500\,\Omega$ resistor in the feedback loop. It is noteworthy that the amplification factor has been selected so a signal of $5\,\mathrm{mA}$ corresponds to full drive of the amplifier.

The subsequent LP filter performs the first real demodulation of the measurement signal. At this stage, the bandwidth of the magnetic signal is limited. It is important to ensure the cutoff frequency of the filter is at least two times higher than the highest signal frequency and significantly lower than the IF. Unlike a classic PLL, it is not necessary to define a phase offset. It's enough to keep the phase constant. If phase manipulation is needed, it can be done digitally.

2.3 Digital Signal Processing

Digital signal processing is currently PC-based. The digitisation of the signal is facilitated by the NI USB-4431 data acquisition device (DAQ) from NATIONAL INSTRUMENTS. This signal can be used to control the NCO, a SMBV100A vector signal generator from ROHDE & SCHWARZ, via an adjustable low-pass filter, or it can be used to reconstruct the magnetic measurement signal via a band-pass (BP) filter. The advantage of this topology lies in the cascading of analog and digital filters. In conventional PLL demodulators, a trade-off has to be made. Consequently, either the LP in the feedback is extremely narrow-band. This results in low phase noise for the system, but also leads to a strong bandwidth limitation of the entire system and significantly increases the settling time when the oscillator frequency is unknown. Alternatively, the filter can be designed to be broadband, thereby enabling the transmission of the entire target signal. However, this choice results in an increase in phase noise, which places significant restrictions on the achievable LOD. The utilization of closed-loop control employing a downstream digital filter facilitates the integration of the merits inherent in both concepts.

2.4 Metrological Evaluation

An initial metrological evaluation was conducted at the Physikalisch-Technische Bundesanstalt in Berlin. For this purpose, the SAW sensor was aligned with the DALAC,in the center of the BMSR-2.1, a high-performance magnetic shielded room, so that its sensitive axis was pointing to the magnetic test field. Further details on the measuring environment can be found in [16]. An evaluation of the sensor and the system can be carried out under nearly ideal conditions. Noise measurements were conducted, as were measurements with various alternating magnetic fields at a frequency of $19.44\,\mathrm{Hz}$. These measurements are designed to obtain the system LOD for single frequency excitation under the most reproducible conditions.

3 Results

The calculation of the monofrequency LOD for the system is equivalent to the procedure given in Sec. 2.1. The LOD can be derived through the calculation of the ratio of the noise at a specific frequency to the sensitivity of the system at the same frequency. Utilizing the measurements shown in Fig. 3, the noise is determined as $174.5\,\mathrm{\mu V/\sqrt{Hz}}$ at $19.44\,\mathrm{Hz}$. The sensitivity is calculated from the quotient of the spectral peak at $19.44\,\mathrm{Hz}$ and the field of $10\,\mathrm{nT}$ applied at this frequency, yielding $491.9\,\mathrm{kV/T}$. Consequently, the system $\mathrm{LOD}_{19.44\,\mathrm{Hz}}$ is calculated as $354.7\,\mathrm{pT/\sqrt{Hz}}$.

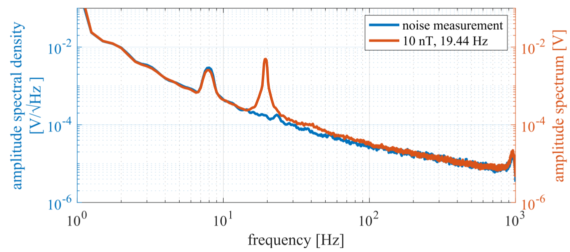

Fig. 3: The figure shows the spectrum of the noise measurement of the system (blue, left axis) and the spectrum at an excitation of $10\,\mathrm{nT}$ at $19.44\,\mathrm{Hz}$ (orange, right axis).

4 Conclusion

The system presented in this study has an LOD which already comes quite close to the theoretical limit of the SAW sensor: it is only a factor of approximately five away. The findings demonstrate the feasibility of constructing high-precision SAW-based magnetometers that do not necessitate the utilization of costly, highly specialized laboratory equipment for operation. The authors are confident that the system can be further improved by taking the following two steps, thereby achieving the objective of a multichannel SAW sensor system which is not constrained by its electronics. The first step involves integrating the digital components of the system, including digitization, into a commercially available microprocessor. The present design, however, is constrained by the DAQs maximum frame rate, which restricts the speed of the control loop to $20\,\mathrm{Hz}$. Consequently, the demodulation does not always take place within the linear range of the phase comparator, thereby reducing the system's sensitivity. Secondly, the IF can be set to $1\,\mathrm{MHz}$ or less. Consequently, the impact of the NCO phase noise can be further mitigated, and low-cost, precise, chip-based clock generators are available as NCOs.

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Author Statement

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References

[1] White, R. M., & Voltmer, F. W. (1965). Direct Piezoelectric Coupling to Surface Elastic Waves. Applied Physics Letters, 7(12), 314-316.
[2] White, R. M. (1985, 16-18 Oct. 1985). Surface Acoustic Wave Sensors. IEEE 1985 Ultrasonics Symposium,
[3] Liu, B., Chen, X., Cai, H., Mohammad Ali, M., Tian, X., Tao, L., ... & Ren, T. (2016). Surface acoustic wave devices for sensor applications. Journal of Semiconductors, 37(2).
[4] Delsing, P., Cleland, A. N., Schuetz, M. J. A., Knörzer, J., Giedke, G., Cirac, ... & Westerhausen, C. (2019). The 2019 surface acoustic waves roadmap. Journal of Physics D: Applied Physics, 52(35).
[5] Länge, K., Rapp, B. E., & Rapp, M. (2008). Surface acoustic wave biosensors: a review. Analytical and Bioanalytical Chemistry, 391(5), 1509-1519.
[6] Hirst, E. R., Xu, W. L., Bronlund, J. E., & Yuan, Y. J. (2008, 2-4 Dec. 2008). Surface Acoustic Wave Delay Line for Biosensor Application. 2008 15th International Conference on Mechatronics and Machine Vision in Practice,
[7] Fransen, A., Lubking, G. W., & Vellekoop, M. J. (1997). High-resolution high-voltage sensor based on SAW. Sensors and Actuators A: Physical, 60(1), 49-53.
[8] Webb, D., Forester, D., Ganguly, A., & Vittoria, C. (1979). Applications of amorphous magnetic-layers in surface-acoustic-wave devices. IEEE Transactions on Magnetics, 15(6), 1410-1415.
[9] Smole, P., Ruile, W., Korden, C., Ludwig, A., Quandt, E., Krassnitzer, S., & Pongratz, P. (2003, 4-8 May 2003). Magnetically tunable SAW-resonator. IEEE International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum, 2003. Proceedings of the 2003,
[10] Kittmann, A., Durdaut, P., Zabel, S., Reermann, J., Schmalz, J., Spetzler, B., ... & Quandt, E. (2018). Wide band low noise Love wave magnetic field sensor system. Scientific reports, 8(1), 278.
[11] Parker, T. E., & Montress, G. K. (1988). Precision surface-acoustic-wave (SAW) oscillators. IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 35(3), 342-364.
[12] Wolff, U., Dickert, F. L., Fischerauer, G. K., Greibl, W., & Ruppel, C. C. W. (2001). SAW sensors for harsh environments. IEEE Sensors Journal, 1(1), 4-13.
[13] Schell, V., Müller, C., Durdaut, P., Kittmann, A., Thormählen, L., Lofink, F., ... & Quandt, E. (2020). Magnetic anisotropy controlled FeCoSiB thin films for surface acoustic wave magnetic field sensors. Applied Physics Letters, 116(7).
[14] Wolframm, H., Weisheit, F., Quandt, E., & Höft, M. (2024). Dedicated SAW Oscillator for Sensing Applications 2024 IEEE International Instrumentation and Measurement Technology Conference (I2MTC).
[15] Barkhausen, H. (1935). Lehrbuch der Elektronenröhren und ihrer technischen Anwendungen (Vol. 4).
[16] Elzenheimer, E., Knappe-Grüneberg, S., Zerfowski, J., Evans, W., Grüneberg, F., Höft, M., ... & Voigt, J. (2025). Key Metrics and Experimental Test Bench for Assessing Highly Sensitive Magnetometers in Research. IEEE Sensors Journal, 25(2), 2432-2455.