DESIGN AND SIMULATIONS OF MIXED TRANSDUCING CIRCUITS FOR A CMOS MICROFLUXGATE MAGNETOMETER

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ABSTRACT
This article presents design and simulations of transducing circuits for a novel CMOS microfluxgate magnetometer. The microfluxgate features dual-core material and two 3-D excitation coils formed by wire-bonding techniques and four planar pick-up coils. The transducing circuits consist of both excitation and sensing circuits and is the mixture of digital and analogous design. To obtain enhanced sensitivity of the fluxgate, the excitation and sensing circuits are designed based on the second harmonic extraction operation. The circuit layout and simulations including devices and the whole circuits have been completed using HSpice simulator. The successfully verified application specific integrated circuits (ASIC) can secure the future system integration of CMOS microfluxgate sensors.

KEY WORDS
CMOS, microfluxgate, magnetometer, transducing circuits, simulation, ASIC.

1. Introduction

Fluxgate magnetometers are a class of vector-type devices employed to measure dc or low-frequency ac magnetic fields. They are actively sensitive to the fields from 0.1 nT up to 1 mT with achievable resolution down to 10 pT. Though fluxgate sensors have been investigated since late 1920s, these sensors are still evolving and being applied in many engineering systems. Recently PCB-based or silicon-based technologies have been employed to manufacture microfluxgate sensors and some novel sensor structures have been proposed [1-3]. Our previous work on a CMOS microfluxgate sensor revealed that the maximum responsivity of 8.1 V/T with the second harmonic and 110 kHz excitation frequency, and the minimum magnetic field noise of 2.6 nT/√Hz at 1 Hz under 20-kHz excitation can be achieved [4-5]. It is noted that the accuracy and sensor responsibility may decrease when the dimensions of microfluxgate sensors become more miniature. Therefore, appropriate design of the interfacing circuits to excite/sense the output signal from the microfluxgate is necessarily important.

In this study, the dual-core microfluxgate device mainly features with two 3-D excitation coils formed by wire-bonding techniques and four planar pick-up coils embedded in silicon substrate through CMOS process. The proposed device configures miniature dimensions and is fully compatible with standard IC process, as illustrated in Figure 1. The square microfluxgate chip is measured 2.5 mm in length and manufactured by TSMC CMOS process.

Along with recent development of magnetoresistors, anisotropic magnetoresistance (AMR), giant-magnetoresistance (GMR), and tunneling magnetoresistance (TMR) sensors and superconducting quantum interference devices (SQUID) can be readily found [6]. However, these devices still suffered from, e.g. low-temperature operation, expensive configuration cost, zero-drift or low-frequency noise. The main applications of fluxgate magnetometers are used in geophysics and space aviation. An academic report for space applications of fluxgate sensors were recently reviewed [7]. Current fluxgate compasses are mainly exploited for aircraft and vehicle navigation. Herein, we propose a transducing circuit design including analogue and digital waveform that can excite and read out the signals from the sensor combined with the second harmonic characteristics, and the circuit diagram and simulation are completed. The feasibility of the CMOS circuits design is verified by HSpice simulator.

Figure 1. Schematic of the microfluxgate magnetic sensor
2. Circuit Design

2.1 Previous Design

Figure 2 demonstrates the typical fluxgate sensing circuits [7]. Through the second harmonic detection circuit, it can detect the shift of hysteresis curve of the fluxgate magnetometer, which is able to identify the output voltage relative to the external magnetic fields. The oscillator can generate the reference signal and provide the excitation current to drive the fluxgate device. The second reference signal output is generated from the frequency doubler, and the phase shifter can adjust and correct the signal phase more effectively. The mixer will mix the reference and output signals from the fluxgate. By using the feedback coil this configuration is able to enhance the linear range of the fluxgate. The measurement of the fluxgate will be limited without the feedback coil because of the saturation effect of the fluxgate. This saturation will influence the linearity and sensitivity of the sensor as it causes the poor signal behaviour. When extending the feedback coil to the sensing circuit, the feedback coil can keep the excitation vibration center of magnetic fields around the zero magnetic point, thus raising the measurement range of the field-to-voltage transfer coefficient of the fluxgate.

For measurement, we use SRS SR830 lock-in amplifier to extract the multiple-harmonic characteristic of the micro fluxgate. SR830 has PSD (phase sensitive detector) that can detect specific frequency and phase of the sensor, and filter the noise to measure the signal correctly. It is previously found that much better signals referred to the 1st, 2nd and 4th harmonics can be obtained, and we assume that they together can get better characteristics of the fluxgate [4]. In addition, a recent ASIC design based on second-harmonic operation for microfluxgate sensor featuring the excitation and sensing circuits was also reported [8], and its system diagram is shown in Figure 3.

![Figure 2](image-url)

**Figure 2.** The typical transducing circuits for fluxgate sensors [5].

2.2 Novel Design

To improve the disadvantages of traditional drive circuits, such as design complexity and high power consumption, novel mixed circuits including analogous and digital modules are proposed in the paper. Based on the similar concept proposed in [8], the new proposal of block diagram for the transducing circuits is shown in Figure 4, and is composed of excitation circuit and sensing circuit. The former includes an oscillator, a frequency divider, a 16-bit shift register and a multiplexer; the latter consists of an instrument amplifier, a mixer and low-pass filter, respectively.

![Figure 3](image-url)

**Figure 3.** Block diagram of the ASIC for a microfluxgate sensor proposed in [7]

![Figure 4](image-url)

**Figure 4.** Block diagram of the transducing circuits for a microfluxgate sensor in this study.

In the excitation circuit, the sinusoidal wave from a 6.4 MHz oscillator is processed by the subsequent frequency-divider to generate the square excitation at 1.6 MHz for clock signal and the square input signal at 0.8 MHz for both 16-bit shift register and the excitation coil. The input signal for the excitation coil is processed into 25 kHz to saturate the magnetic cores. The 16-bit shift register produces 16 sets of square signals with 180 degree phase delay each other for the multiplexer (16 to 1) that can adjust the input phase angle by dividing 16, i.e. 11.25 degree per division. By choosing one of the 16 sets of phase delay which is identical or close to that of the signal from the microfluxgate. The square wave is then processed by a frequency divider to be 50 kHz as the same as the 2nd harmonic of the excitation signal. In the sensing circuit, the output voltage of the pick-up coil is...
sensed by an instrumentation amplifier (IA) with a gain of 200. The signal from the IA is taken by a mixer with the second harmonic reference from the multiplexer. The phase of the reference wave is adjusted to maximize the field-to-voltage sensitivity. The mixer output is finally processed by a low-pass filter to read out the output voltage of the magnetometer, which is linearly proportional to the external magnetic fields.

With the digital implementation of the excitation circuit, the proposed circuit design not only reduce the chip area, but also regulate the phase angle more precisely without the use of variable resistors. As a result, the novel design can enhance the simplicity and stability of the system circuit and make a technical achievement in terms of chip dimensions, unit cost and power consumption.

3. Design of Transducing Circuits

3.1 Excitation Circuit

The fully digital circuit for magnetic excitation of the magnetometer are designed and described as follows:

3.1.1 Oscillator

The single-end RC ring oscillator is made of several inverters, resistors and a capacitor to provide the square wave. An over-current protection resistor and RC time-delay components are adopted. Known by the circuit design principles, the oscillating frequency can be determined as 6.4 MHz.

3.1.2 Frequency Divider

The frequency divider is composed of two sets of RS flip-flop, four AND gates and an inverter, i.e. the JK flip-flop, which is able to reduce the input frequency by half. The signal of full frequency is input at CK terminal and the square signal of half frequency is output from the Q terminal, as shown in Figure 5.

3.1.3 Shift Register and Multiplexer

The 16-bit shift register combined with 16 typical D-type flip-flops (DFF) is designed, as shown in Figure 6, and followed by a 16:1 multiplexer, as shown in Figure 7, respectively. When the value of $V_{\text{select}}$ in Figure 7 is at logic high level of $V_{DD}$ and $V_{\text{out}}$ is equivalent to $V_{\text{in1}}$, $M_{N1}$ and $M_{P1}$ transistors are turned on while $M_{N2}$ and $M_{P2}$ transistors are turn-off state. On the contrary, the transistors of $M_{N1}$ and $M_{P1}$ are turned off while $M_{N2}$ and $M_{P2}$ transistors turn into turn-on state if $V_{\text{out}} = V_{\text{in2}}$ and $V_{\text{select}}$ is at low signal of $V_{SS}$. By using four control lines ($V_{\text{select0}} \sim V_{\text{select3}}$) mentioned above, one can generate sixteen combinations to select different sets of phase delay to output the signal to a divider, and it will be considered a clock signal sent to a mixer to extract the second harmonic wave from the microfluxgate sensor later.

3.2 Sensing Circuit

3.2.1 Instrument Amplifier

Due to the change of magnetic flux in the dual cores resulted from an external magnetic fields, the voltage of the pick-up coil measured would be different and amplified by operational amplifiers. These operational amplifiers are designed using two-stage structure that features high gain and high amplitude. The gain of the instrument amplifier is designed as 200. The circuit diagram is illustrated in Figure 8.
3.2.2 Mixer

The analogous switch shown in Figure 9 receives the clock signal of 50 kHz from the multiplexer and extracts the second harmonic components of 25 kHz signal from the instrument amplifier. A low-pass filter (LPF) with a cut-off frequency of 10 kHz is allocated to sieve off noise and output the voltage of the pick-up coil.

4. Layout-Design and Post-Simulation

The layout is configured in a digital-analog mixed environment using Laker tools and the circuits are simulated based on HSpice software. All circuits are fabricated with TSMC18 1P6M CMOS process kit which is set up in HSpice to extract all corners or parameters of SS, SF, TT, FS and FF situations in transistors. The fabricated IC chip measured as 1.5 mm square is shown in Figure 10 with the separate digital and analogous parts. Major post-simulation results are briefly presented as follows.

4.1 Oscillator

The post-simulation results of oscillator with a frequency of 6.4 MHz are shown in Figure 11.

4.2 Frequency Divider

It is verified that a input clock signal of 3.2 MHz can be divided as a 1.6 MHz square wave. The post-simulation results of frequency divider are shown in Figure 12.

4.3 Multiplexer

The post-simulation results of digital multiplexer are shown in Figure 13. The input signals Vin1 through Vin16 are from 10 mV to 160 mV with a 10 mV increment. When V_{select} is 0000, the output voltage of V_{out} is 10 mV, which is the first clock signal. Another operation illustrated in Figure 14 shows that the output voltage of V_{out} is 130 mV when V_{select} is 1100 and identified as the 13th clock signal.
Figure 13. Post-simulation results of 16:1 Multiplexer for 16 output amplitudes (up); $V_{\text{out}} = 10$ mV when $V_{\text{select}} = 0000$ (bottom, not in scale)

Figure 14. Post-simulation results of 16:1 Multiplexer for 16 output amplitudes (up); $V_{\text{out}} = 130$ mV when $V_{\text{select}} = 1100$ (bottom, not in scale)

4.4 Instrument Amplifier

The post-simulation results of instrument amplifier with a gain of 200 are shown in Figure 15. A 3 mV-amplitude wave is input and the amplitude of 600 mV is successfully obtained.

Figure 15. Post-simulation results of instrument amplifier at 5 corners

4.5 Sensing Signal

The post-simulation results of mixer and low-pass filter are shown in Figure 16. With the amplitude range from 0.1 V to 0.9 V, the input signal is 0.5 V under 25 kHz and 0.9 V DC reference and the second harmonic components are thus extracted.

Figure 16. Post-simulation results of the sensing signals at 5 corners

5. Conclusion

Novel design and simulation of CMOS transducing ASIC for a microfluxgate magnetometer are reported in this article. Based on the detection of the second harmonic signal, the circuit layout and simulations including individual devices and the interface circuits have been implemented. The feasibility of the circuitry function has been verified by HSpice simulation. The future work will be further integration of a CMOS-MEMS micro-fluxgate sensor with the ASIC we achieved.

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References

[2] Hae-Seok Park, Jun-Sik Hwang, Won-Youl Choi, Dong-Sik Shim, Kyoung-Won Na, Sang-On Choi,


