Measurement 122 (2018) 1–5

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Noise analysis and improvement of a micro-electro-mechanical-systems fluxgate sensor

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ARTICLE INFO

Keywords:
Fluxgate sensor
DC blocking
MEMS
Noise

ABSTRACT

An integrated micro solenoid fluxgate sensor with a Co-based amorphous core is presented in this work based on the Micro-Electro-Mechanical System (MEMS) technologies. As the advantage of miniaturization, the micro fluxgate sensor is found to be operated under wide excitation frequency range of 100 kHz–1 MHz. Ultra-low frequency noise (< 0.1 Hz) always arises in zero field time-domain signal acquisition under full excitation frequency range. An additional broadband transformer is placed before the excitation end of the sensor to eliminate the ultra-low frequency noise. The noise power density of the sensor working at 600 kHz is analyzed. The result shows the noise is 1.15 nT/Hz$^{1/2}$@1 Hz without the transformer and 0.11 nT/Hz$^{1/2}$@1 Hz with the transformer, while the noise rms level is 5.38 nT and 0.23 nT in the frequency range of 50 mHz–10 Hz respectively. For the MEMS micro fluxgate sensor, more stringent electromagnetic compatibility design for the sensor signal system is needed to eliminate additional noise derived from the electromagnetic radiated interference and the voltage disturbance.

1. Introduction

As the most popular high precision vector sensor for static or low frequency magnetic field measuring applications, Micro-Electro-Mechanical System technologies (MEMS) is being introduced in the fluxgate sensor for miniaturization and integration [1–8]. The signal-to-noise ratio (SNR) is the key parameter of the fluxgate sensor to determine the absolute measuring precision. Limited by the device dimension, SNR of the MEMS micro fluxgate sensor has a considerable gap in comparison with the traditional macro fluxgate sensor.

The influence of several factors in the noise behavior of the fluxgate sensor is summarized in the previous literatures, including core material [9,10], sensor structure [11] and the electronic circuit signal [12]. Tejedor [9] and Moldovanu [10] explained the reduction of the Barkhausen noise in the stress-annealed Co-based ribbon core as compared to the as-quenched one in a fluxgate magnetometer respectively. Ripka reported the race-track fluxgate sensor with low noise and stable offset due to the high shape anisotropy and closed core structure [11]. Based on the large Matteucci effect, Dimitropoulos applied a new signal extraction technique for the micro fluxgate sensor that is superior to the conventional second-order-harmonic concept, as far as sensitivity and signal-to-noise ratio are concerned [12].

The conclusion also is appropriate for the MEMS micro fluxgate sensor. There are quite a lot of researches about the intrinsic noise of the core material, which to a large extent determines the detection limit of the fluxgate sensor. Farrell et al. explained the limit of the fluxgate sensitivity due to Barkhausen noise for permalloy thin film core [13]. Koch et al. presented that domain wall motion is the mechanism that limited conventional multi-domain fluxgate resolution and achieved the noise of a single-domain fluxgate sensor is 1.4 pT/Hz$^{1/2}$@1 Hz of ring core and 3.5 pT/Hz$^{1/2}$@1 Hz of rod core [14,15]. On the basis of materials research, there are also many innovative designs for the fluxgate sensor structure. The larger number of wires core structure in the orthogonal fluxgate sensor was proved to be beneficial to not only high sensitivity but also low noise [16–18].

The noise originating from core material and sensor structure can be defined as magnetic noise, which is the noise source to influence the magnetization process of the core. In the fluxgate sensor of difference design, another important noise source is the excitation noise that is superimposed to the excitation current into the excitation coils. Especially as the excitation frequency greatly improved for the micro fluxgate sensor, tiny disturbance of the excitation waveform will affect the signal stability and the detection limit of the micro fluxgate sensor. Butta et al. used a low ac excitation current and a large dc bias in fundamental mode orthogonal fluxgate sensor to drop the noise down to 7 pT/Hz$^{1/2}$@1 Hz [19].

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https://doi.org/10.1016/j.measurement.2018.03.007
Received 5 September 2016; Received in revised form 21 March 2017; Accepted 5 March 2018
Available online 06 March 2018

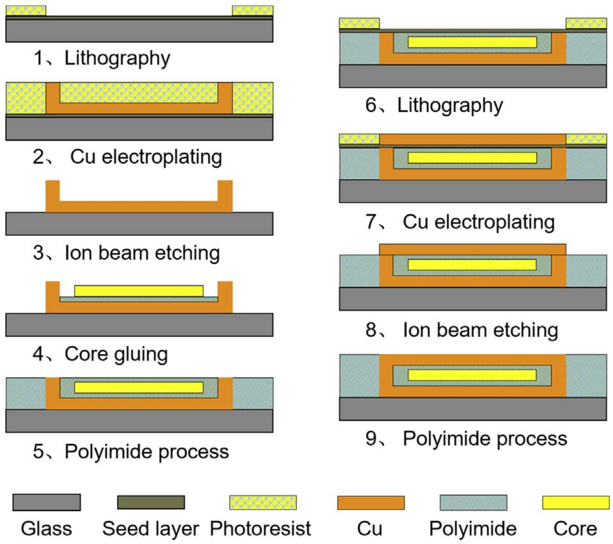

Fig. 1. The micro-fabrication steps of the micro fluxgate sensor.

In this paper, a micro fluxgate sensor with a Co-based amorphous core is fabricated and used to research the noise behavior of the micro fluxgate sensor. By adding redundancy broadband dc insulation design, the influence of the excitation noise on the noise behavior of the sensor is researched.

2. Fabrication and test

The fabricated sensor has four sections of solenoid windings to be used as excitation coils at the end of the core and a section of solenoid windings to be used as detection coils in the middle of the core. The standard MEMS technology is used to prepare sensor's coils, mainly including thick photoresist-based UV lithography and electroplating techniques. In addition, the process consists of separate core preparation and then core gluing into the prepared coils. Fig. 1 shows the process steps of the micro fluxgate sensors. The core is etched from Metglas 2714A amorphous alloy ribbon. The rectangle core shape is chosen for improved sensitivity in longitudinal direction compared to the ring core shape, and has an unequal width structure between longitudinal and transverse direction (ratio of 3:1) for high suppression of cross field according to the law of magnetic circuit. For more fabrication details please refer to our previous paper [20].

The dimension of the fabricated sensor is approximately 10 mm × 2.7 mm (not including pads). The thickness of the sensor is approximately 120 µm (not including the substrate). Fig. 2 shows the schematic view Fig. 2(a) and microphotography Fig. 2(b) of the micro fluxgate sensor. The excitation coils have 63 turns and the detection coils have 59 turns. Both the line width and the line spacing of the coils are 50 µm, and thickness is 25 µm. The measured resistance of the excitation coils is 2.5 Ω, measured by HP E4194A IMPEDANCE/GAIN-PHASE ANALYZER. The longitudinal width of the magnetic core is 600 µm. The magnetic core has a thickness of approximately 15 µm.

As shown in Fig. 3, an open loop test system based on second harmonic operation principle is established to test the sensor. Tektronix AFG 3022 function signal generator is used to produce a sine wave excitation signal. A PCB power amplifier working below 1 MHz is used to amplify the sine signal into the sensor. SR844 lock-in amplifier is used to extract the second harmonic from the output voltage of the detection coils. Under testing, the device and the solenoid (providing a uniform test field H parallel to the detection coil axis) are placed inside a magnetic shield with six-layer soft magnetic ribbons. The test field is controlled by KEITHLEY 2450 source meter connected to the solenoid.

Serial capacitor usually is used to block DC component of the excitation current [21]. Considering the test frequency range of the micro

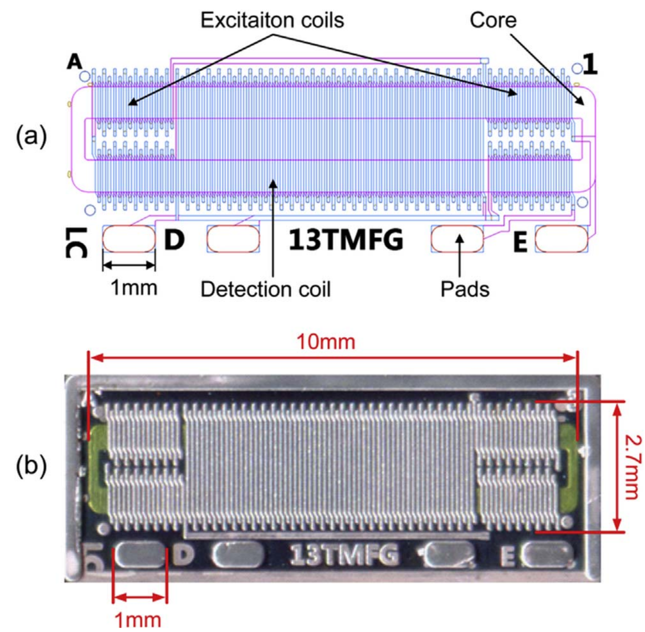

Fig. 2. Schematic view of the micro fluxgate sensor: (a) the geometrized structure graph; (b) the microphotography.

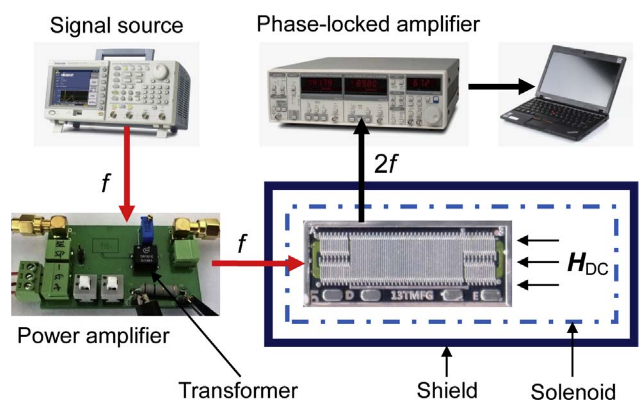

Fig. 3. Block diagram of the test system.

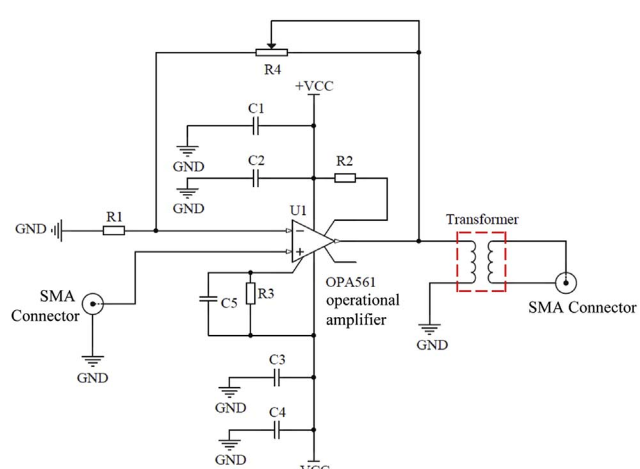

Fig. 4. Diagram of the power amplifier.

fluxgate sensor is wide in the actual test, 100 kHz–1 MHz, suitable capacitance values are not easy to select. Although the power amplifier circuit itself contains dc insulation parts, as shown in Fig. 4, an additional serial transformer DA101C (turns ratio of 1:1, excitation