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Designing a Planar Fluxgate Using the PCB Technology

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Abstract

The development of novel methods, scientific devices and means for measuring magnetic fields generated by ultra-low current is among promising directions in the development of medical equipment and instruments for geodetic surveys and space exploration. The present work is to develop a small sensor capable of detecting weak magnetic fields, which sources are biocurrents, radiation of far space objects and slight fluctuations of the geomagnetic field. Scientists estimate the strength of such magnetic fields as deciles of nanotesla.

The key requirements for the sensors of ultra-low magnetic field are: resolution, noise level in the measurement channel, temperature stability, linearity and repeatability of the characteristics from one produced item to another. The aforementioned characteristics can be achieved by using planar technologies and microelectromechanical systems (MEMS) in such advanced sensors.

The work describes a complete R&D cycle, from creating the computer model of the sensor under study to manufacturing of a working prototype. To assess the effect of the geometry and material properties, the Jiles–Atherton model is implemented which, unlike the majority of the models used, allows considering the non-linearity of the core, its hysteresis properties and influence of residual magnetization.

The dimensions of the developed sensor are 40×20×5 mm, while the technology allows its further diminishment. The sensor has demonstrated the linearity of its properties in the range of magnetic field strength from 0.1 nT to 50 μT for a rms current of excitation of 1.25 mA at a frequency of 30 kHz. The average sensitivity for the second harmonic is 54 μV/nT.

Keywords: magnetometer, planar fluxgate, magnetic induction, Jiles–Atherton model, printed circuit board.

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Проектирование планарного феррозондового датчика по технологии печатных плат

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Разработка новых методов, научных приборов и средств для измерения магнитных полей, создаваемых сверхслабыми токами, является одним из перспективных направлений в развитии медицинской техники, геодезических и космических исследований. Целью данной работы являлась разработка малогабаритного датчика, способного детектировать слабые магнитные поля, источниками которых могут быть биотоки, излучения далёких космических объектов и слабые флуктуации магнитного поля земли. Учёные оценивают величины таких магнитных полей в десятые доли нанотесла.

Среди ключевых требований к датчикам сверхслабого магнитного поля можно отнести разрешающую способность, уровень шумов в измерительном канале, температурную стабильность, линейность и повторяемость характеристик от изделия к изделию. Предлагается добиться этих характеристик путём применения планарных технологий и микроэлектромеханических систем при изготовлении современных датчиков.

В работе описан полный цикл исследования, от создания компьютерной модели исследуемого датчика до изготовления рабочего прототипа. Для оценки влияния геометрических параметров и влияния свойств материала использована модель Джилса–Атертона, которая, в отличие от большинства используемых моделей, позволяет учесть нелинейность сердечника, его гистерезисные свойства и влияние остаточной намагниченности.

Габариты разработанного датчика составляют 40×20×5 мм и технически возможно его уменьшение. Разработанный датчик продемонстрировал линейность характеристик в диапазоне от 0,1 нТл до 50 мкТл при среднеквадратическом токе возбуждения 1,25 мА на частоте 30 кГц. Усреднённый коэффициент преобразования по второй гармонике составляет 54 мкВ/нТл.

Ключевые слова: магнитометр, планарный феррозондовый датчик, магнитная индукция, модель Джилса–Атертона, печатная плата.

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Introduction

The measurement of magnetic fields is among crucial problems in the fields of space and geophysical studies [1–2], systems for navigation, orientation and stabilization [3], in quantum computer shields [4–6], magnetic resonance imaging, visualization of brain functions, fault detection and non-destructive testing [7] and many other areas. One more example of magnetometer implementation is a magnetic vacuum system that allows minimizing the influence of external magnetic fields on electronics. Such systems use passive and active methods for shielding magnetic fields. Passive methods are based on the shields from materials with high magnetic permeability. In active methods, the magnetic field is compensated using a system of coils. The coils are a part of a system with feedback; the magnetic field strength is measured by the sensors located in the vicinity of the shielded object. To measure absolute magnetic field strength, magnetic vacuum systems primarily use fluxgate magnetometers; however, the increased quality of magnetic vacuum requires improved characteristics, in particular, the fluxgate sensitivity.

Another important field where fluxgates are used is magnetocardiography [8–10], which differs from widely used electrocardiography by its non-invasive character and high sensitivity.

Existing SQUID-based magnetocardiographers [11] provide high-quality diagnostics of cardiovascular diseases; however, such complexes are affordable only for a small range of diagnostic and treatment centers. This substantiates the issue of the development of a sensitive magnetic measuring sensor with a lower price as compared to SQUID-magnetometers. In a number of articles, the researchers have confirmed the possibility of applying fluxgates for measuring the parameters of cardiac activity [12–14]. One of the advantages of fluxgates is the possibility of its miniaturization and manufacturing by PCB or MEMS technology.

The present article describes a prototype of a generic fluxgate manufactured by the PCB technology.

Fluxgate design

When creating a generic fluxgate sensor, to achieve maximum sensitivity and minimal noise level, three directions can be distinguished:

− optimization of the planar geometry of the sensor;

− enhancement of the methods for its excitation and processing of the measurement information;

− implementation of novel nanostructured materials for the magnetic core of the fluxgate.

In current work we chose the direction connected with the optimization of the planar model of the sensor geometry. Figure 1 depicts the planar design of the fluxgate. The dimensions of the sensor are 40×28×2 mm.

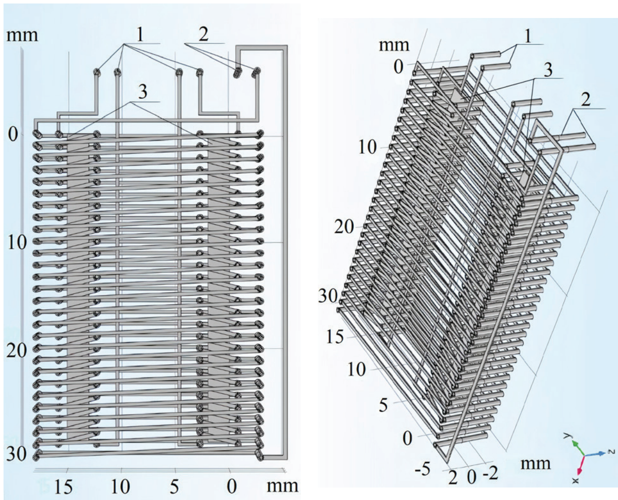


Figure 1 – Fluxgate 3D model: 1 – excitation coils; 2 – measurement coil; 3 – ferromagnetic core

The key element of the fluxgate is the ferromagnetic core. The material of the core was a strip from FINEMET® FT-3H amorphous alloy (Hitachi Metals, Ltd., Japan). The chosen material possesses high permeability, which will allow decreasing the excitation current. In addition, high permeability promotes high induction, while high resistivity decreases eddy-current losses.

To assess the operability of the suggested design, a finite-element modeling was performed in COMSOL software (COMSOL, Inc., Sweden).

The hysteresis properties of the core material were presented using the Jiles–Atherton hysteresis model. Table 1 contains the model parameters presented as diagonal matrices.

Figure 2 presents the magnetization curve plotted for the implemented core material.

At the first stage of modeling, a sinusoidal current of 1.5 mA with a frequency of 25 kHz was fed to the excitation coil of the fluxgate with constant magnetic induction of 9 µT along the sensitivity axis of the fluxgate. Figure 3 plots the dependence of the induced EMF in the fluxgate excitation coil on time and input voltage in the pickup coil. For illustrative purposes, the temporal dependence of the induced EMF amplitude is shown at a scale of 1:1000.

Table 1

Jiles–Atherton model parameters of Finemet FT-3H core

Parameter	Value	Unit
Interdomain coupling: α	{4.33, 3.952, 4.33}	$\times 10^{-6}$
Saturation magnetization: M_s	{1.31, 1.33, 1.31	A/mm
Domain wall density: *a*	{3.8, 3.11, 3.8}	A/m
Magnetization reversibility: *c*	{736, 652, 736}	$\times 10^{-3}$
Pinning loss: *k*	{4.11, 3.38, 4.11}	A/m

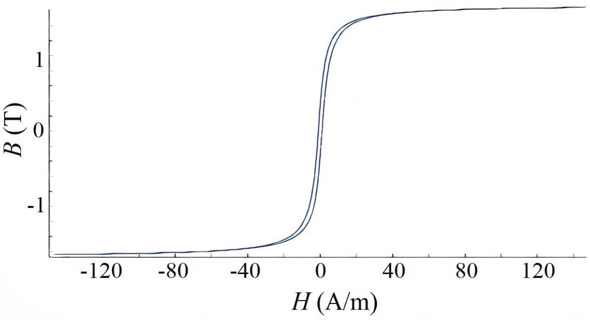


Figure 2 – Hysteresis loop for the core from FINEMET® FT-3H material

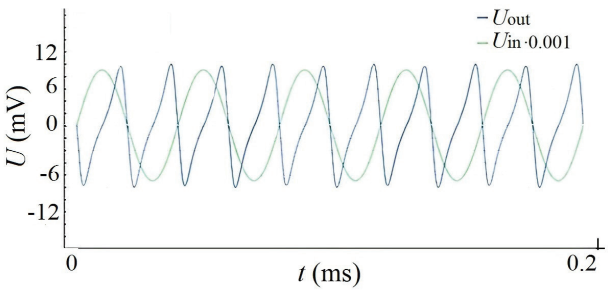


Figure 3 – Input and output signal timing behavior at exciting current of 1.5 mA

Evidently, the output signal of the fluxgate is dominated by the second harmonic of the excitation signal frequency. Over an equal time period, the number of peaks of the output signal is twice larger than that of the input signal. Therefore, the operability of the model is confirmed in line with the conventional differential fluxgate operation theory.

Figure 4 shows the fluxgate output signal spectrum recorded at various values of acting magnetic induction. The excitation conditions are the same.

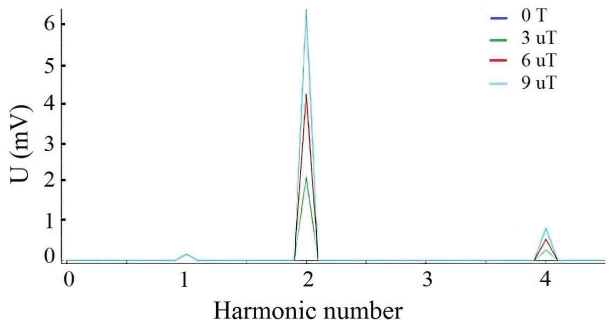


Figure 4 – Dependence of spectral characteristic of the output signal on the ambient field strength at an excitation current of 1.5 mA

Obviously, the amplitude of the second harmonic linearly depends on the ambient magnetic field strength. Interestingly, the signal spectrum also contains the fourth harmonic which also depends on the ambient magnetic field strength.

Therefore, the modeling results have confirmed the operability of the design.

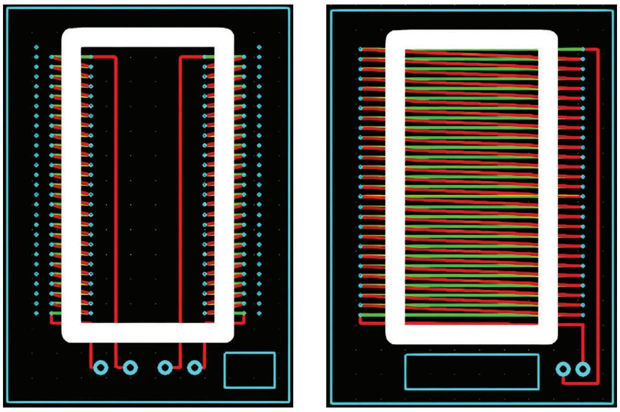
Experimental specimen manufacturing

The experimental specimen of the planar fluxgate was manufactured as follows.

Using the PCB technology, four separate printed circuit boards were made on a textile laminate substrate: two identical boards with excitation coils and two identical boards with pickup coils. The topology of the printed circuit boards is presented in Figure 5.

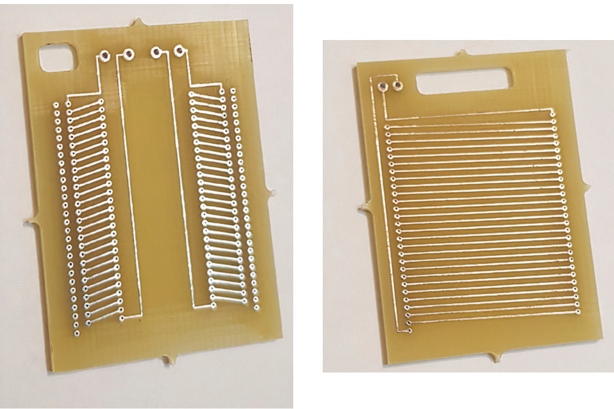
The conductors on the printed circuit boards were made from copper and then coated by a terne layer.

Figures 6*a* and 6*b* demonstrate the photographs of the manufactured circuit boards with the elements of the planar fluxgate.



a *b*

Figure 5 – Planar fluxgate printed circuit board topology of exciting (*a*) and measurement (*b*) coils. Red lines indicate conductors on the top layer of the printed circuit board, green lines indicate conductors on the bottom layer of the printed circuit board, cyan lines indicate vias, white lines indicate a ferromagnetic core



a *b*

Figure 6 – Photographs of the manufactured printed circuit boards with the elements of the planar fluxgate: *a* – printed circuit board with excitation coil; *b* – printed circuit board with pickup coil

The ferromagnetic core produced from FINEMET® FT-3H material by mechanical cutting was adhered to the opposite side of the first board with the excitation coil. The adhesive used was LOCTITE® STYCAST 2850FT (Henkel AG & Co. KGaA, Germany). To cure the adhesive, LOCTITE® Catalyst 24 LV (Henkel AG & Co. KGaA, Germany) hardener was used with a ratio of the adhesive to the hardener of 100:6. The duration of complete curing was about 36 hours. The adhesive was cured in a vacuum chamber at a pressure no more than 10^{-6} atm.

To manufacture proper excitation coil, the first board with the excitation coil and adhered core was sandwiched with the second board with the excitation coil. The excitation coils on the two boards were connected through the vias. Then, the boards were soaked with the LOCTITE® STYCAST 2850FT adhesive with further curing in the vacuum chamber at a pressure less than 10^{-6} atm.

After curing, the bonded boards with the excitation coil were sandwiched from the both sides with the boards with the elements of the pickup coil. The boards were connected with the elements of the pickup coil through the vias by a copper wire with a diameter of 0.05 mm.

Experimental

The performance test of the sensor included the experimental determination of the dependence of the second harmonic amplitude in the fluxgate output signal on the amplitude and frequency of the excitation current under a magnetic field strength of 45 µT induced by a system of axial coils [15]. The experimental scheme is presented in Figure 7.

The scheme in Figure 7 includes a Fluke 5520A Multi-Product Calibrator (Fluke Corporation, USA) that was used to excite the fluxgate with a sine signal with a preset amplitude and frequency. A multimeter Agilent 3458A (Agilent Technologies, USA) was used to measure the excitation current of the fluxgate. A PXI-1042Q platform (NI, USA) with a PXI-5124 module (NI, USA) was used to digitize and analyze the spectrum of the fluxgate excitation signal and its output voltage (amplified beforehand through the amplification section of the synchronous amplifier [16]) proportional to the measured magnetic induction. The experimental data are given in Table 2.

Following the data from Table 2, the maximum sensitivity was achieved at a frequency of fluxgate excitation of 30 kHz with an rms current of excitation of 1.25 mA.

To determine the sensitivity and the measurement range, the fluxgate was placed in the center of the system of axial coils [15]. A high-precision current source was used to set a direct current amplitude flowing through the system of coils, so the magnetic field induction in the center of the system would vary from 0.1 nT to 50 µT. All the measurements of the amplitude of the second harmonic in the fluxgate output signal were averaged. To do so, 1000 measurements were automatically registered at a set current value and then averaged.

The measured amplitudes of the second harmonic in the fluxgate output voltage varying with the magnetic induction are presented in Table 3.

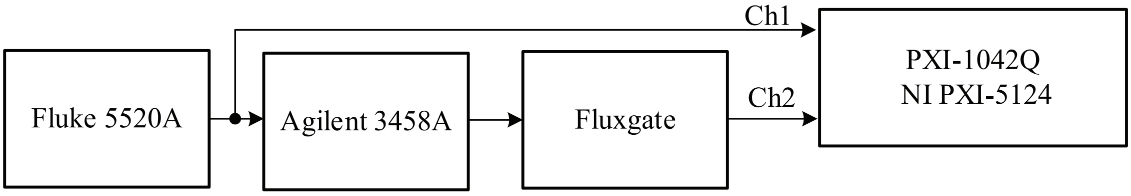


Figure 7 – Block diagram of the fluxgate testing

Table 2

Dependence of the amplitude of the second harmonic on the amplitude and frequency of the excitation current

Frequency [kHz]	Current [mA]					
	0.25	0.5	0.75	1.0	1.25	1.5
	Voltage [V]					
20	0.13	0.42	1.23	2.05	2.42	2.38
30	0.19	0.57	1.32	2.14	2.56	2.52
40	0.15	0.39	1.22	2.03	2.36	2.29
50	0.09	0.12	0.17	0.27	0.34	0.29
60	0.05	0.11	0.13	0.19	0.22	0.15
70	0.01	0.05	0.07	0.18	0.21	0.19
80	0.008	0.021	0.056	0.17	0.19	0.16
90	0.007	0.019	0.051	0.14	0.17	0.15
100	0.006	0.012	0.037	0.13	0.15	0.12

Table 3

Amplitudes of the second harmonic in the fluxgate output voltage varying with the magnetic induction

Magnetic induction [µT]	0.0001	0.001	0.005	0.01	0.05	0.1	0.5
Voltage [mV]	0.0052	0.0548	0.261	0.542	2.71	5.68	28.3
Magnetic induction [µT]	1	5	10	20	30	40	50
Voltage [V]	0.0564	0.268	0.545	1.082	1.623	2.165	2.641

Following the analysis of the data from Table 3, the fluxgate is suitable for measuring the magnetic induction up to 50 µT. Its characteristics remain linear in the range of measured induction from 0.1 nT up to 50 µT. The average sensitivity for the second harmonic is 54 µV/nT.

Conclusion

A computer model was elaborated that allows assessing the sensitivity of the developed magnetic field sensor with due consideration of the hysteresis properties of the material. Based on the technological capabilities, the models were developed that allow manufacturing the elements of excitation and pickup coils using the PCB technology. At present stage, the dimensions of the sensor are 40×20×5 mm.

A working sensor prototype was manufactured. The technological process of device assembly was developed. The measurement scheme was developed and the sensor's sensitivity was tested.

The optimal frequency and excitation current were determined that allow achieving the maximum sensitivity of the sensor. The measurement range of the developed sensor was estimated.

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The conclusion on the viability of fluxgate implementation for measuring weak magnetic fields was made, including in magnetocardiography, geodesy and space exploration.

Further decrease of the width of the printed conductors that compose the excitation coils and the pickup coil of the converter with the increase of their density on the circuit board will increase the induction and excitation frequency keeping the excitation current amplitude unchanged. Further improvement of the cutting and leaching technology for the ferromagnetic core is necessary to decrease the converter noise and manufacture identical fluxgates using the technology of microelectromechanical systems.

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