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FLUXGATE MAGNETOMETER FOR MEASURING ULTRA LOW MAGNETIC INDUCTION

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Abstract – The paper describes an experience in developing one-component magnetometer based on a miniature planar fluxgate sensor for measuring ultra low magnetic induction and operating at extremely low temperatures. A fluxgate magnetic sensor was fabricated in PCB technology with geometric dimensions 10×6×2 mm. The linearity error of the developed magnetometer is about 1.9 % of full scale and its maximum sensitivity is about 99 V/mT.

Keywords: magnetometer, planar fluxgate sensor, magnetic induction, PCB technology

1. INTRODUCTION

Ultra low magnetic field sensing and measuring have acquired numerous applications in aerospace and geophysical exploration, navigation and mapping, nondestructive testing, and military equipment [1-3]. The magnetic sensors are intended for ferromagnetic objects (for example, weapons or vehicles) detection, magnetic label reading, magnetic three-dimensional position tracking, etc. [1, 4]. Each of these applications provides specific requirements to the sensor performance. The most important specifications include magnetic field resolution, range, sensitivity, linearity, offset, power consumption, size, spatial resolution, noise and temperature coefficients [5]. Resent two decades, various techniques and magnetic sensors have been developed to measure the low and the ultra low magnetic field from 10-12 to 10-4 T with high sensitivity and linearity, and low noise [6-9].

Nowadays, one of important problems is measurement of ultra low magnetic fields at extremely low temperatures, for example, to provide operation of a superconducting quantum computer that is very sensitive to an influence of external magnetic fields [10]. High precision measurement of the magnetic fields with use conventional methods is difficult at the operating temperature up to 20 mK.

Measurement of magnetic field using superconducting quantum interference devices (SQUID) is difficult because of the periodicity of their current-flow characteristics [11]. Moreover, need for liquid-helium coolant makes the complete SQUID rather bulky and heavy [12]. The SQUID has high cost and power consumption of several watts.

Ultra low magnetic field can be measured using magnetoresistive (AMR and GMR) sensors. However, their utilization is limited by high thermal dissipation and low temperature stability [13]. Also, this type of magnetic sensors is characterized by lower sensitivity comparatively to SQUIDs and fluxgates.

Fluxgates most widely used as sensors of absolute magnetic field at low temperatures [14]. The fluxgate is less sensitive than SQUID, but can measure rapidly changing field of high amplitude. Fluxgates are preferable to other magnetic field sensors due to their ability to operate in harsh environments and endurance against magnetic, temperature and mechanical shocks [15].

The conventional structure of a fluxgate sensor shown in Fig. 1 consists of two coils: a primary (excitation) coil and a secondary (pick-up) coil, wrapped around a common high-permeability ferromagnetic core.

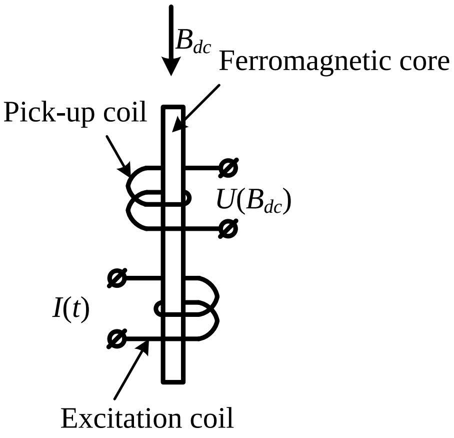

Fig. 1. Conventional structure of a fluxgate sensor

AC current $I(t)$ is applied to the excitation coil that produces a magnetic field periodically saturating the soft ferromagnetic core. If the external measured DC magnetic field B_{dc} equals to zero, then the voltage $U(B_{\mathrm{dc}})$ is induced in the pick-up coil. This voltage has the same frequency and form as the excitation current. If the external measured DC magnetic field B_{dc} does not equal to zero, the voltage $U(B_{\mathrm{dc}})$ additionally contents second harmonic and also higher order even harmonics. Peak values of these harmonic components appeared are proportional to the value of external magnetic field to be measured.

Thus, the fluxgate output signal amplitude described by the formula:

$$U(B_{\mathrm{dc}}) = -N_{\mathrm{pick}} S \frac{dB(t)}{dt} = \\ = -N_{\mathrm{pick}} S \frac{d}{dt} f\left(H_{\mathrm{dc}} + \frac{N_{\mathrm{exc}} I(t)}{l} \right), \tag{1}$$

where H_{dc} is the measured magnetic field, A/m; N_{pick} is the number of wire turns of the pick-up coil; N_{exc} is the number of wire turns of the excitation coil; S is the cross section of the pick-up coil, mm^2; l is the length of the excitation coil, m; $I(t) = I_0 \sin(2\pi f_{exc} t)$ is the sinusoidal excitation current at frequency f_{exc}.

When developing fluxgate sensors it is necessary to simplify construction of their core and coils and to reduce their weight and dimensions. Currently, rather common fluxgate construction type is a planar sensor that utilizes print circuit coils instead of coil being wound around a bulk ferromagnetic core.

The remainder of the paper describes an experience in developing one-component magnetometer based on a miniature planar fluxgate sensor for measuring ultra low magnetic induction up to 1 nT and operating at extremely low temperatures.

2. DESIGN OF FLUXGATE SENSOR

There are special requirements to fluxgate sensors to measure magnetic field of extremely low temperature, such as low heat capacity and thermal dissipation, small thermalization time, low outgassing. Planar design was chosen to reduce heat capacity and thermal dissipation of the fluxgate sensor. This approach has allowed to minimize the sensor overall dimensions and weight, and to simplify its windings implementation.

A single-layer printed-circuit board (PCB) technology was utilized to minimize a cost and to simplify tuning parameters of the fluxgate. In accordance to this technology, four separate PCBs were manufactured: two for implementation excitation winding (see Fig. 2) and two for pick-up winding (see Fig. 3).

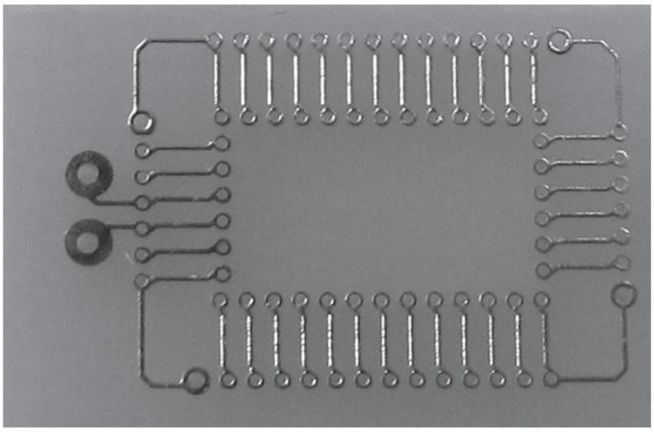

Fig. 2. Excitation winding

The excitation winding was produced in the following way: a soft magnetic core was glued on a clear side of the first PCB (see Fig. 4). Clear side of the second PCB was superimposed on the first PCB with a core to create the full excitation winding by means of soldered connections of corresponding conductors through specially drilling holes. The connections were made with copper-clad niobium titanium wires of 0.05 mm diameter.

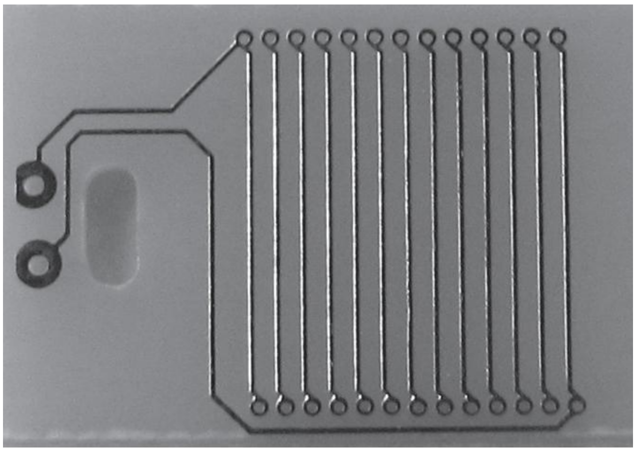

Fig. 3. Pick-up winding

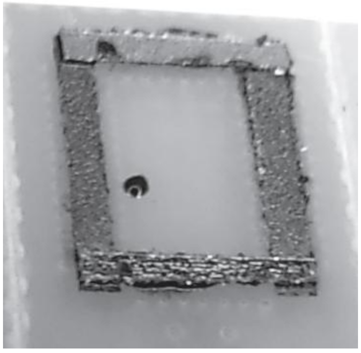

Fig. 4. Soft magnetic core

Windings were made of copper which has a high thermal conductivity at low temperatures. Copper wires were coated with a layer of lead-tin alloy with the superconductivity transition temperature about 5.3 K to impart superconducting properties to the windings. The coating was applied by hot air solder leveling. After soldering, excitation winding was impregnated by two-component epoxide resin Stylecast 2850 FT.

After drying, PCBs with pick-up windings were superimposed on each of sides of the two connected excitation winding PCBs. Connections of the pick-up windings were made using the same niobium titanium wire as earlier.

The soft magnetic core Finemet® manufactured by Hitachi Metals Ltd. of a soft ferromagnetic composite material by means of a special heat treatment [16-17], which provides formation of nanocrystals in the material. The nanocrystals impart a unique physical properties to Finemet, such as high saturation magnetic flux density comparable with that of an amorphous iron; high magnetic susceptibility comparable with that of materials based on amorphous cobalt; low magnetization reversal losses of the core not exceeding 20 % of that of amorphous iron core; extremely low magnetostriction, and so on. These properties allow to improve metrological characteristics of the fluxgate when replacing conventional core material on Finemet.

The arrangement of the fluxgate sensor windings is shown in Fig. 5 and the assembled sensor is shown in Fig. 6.

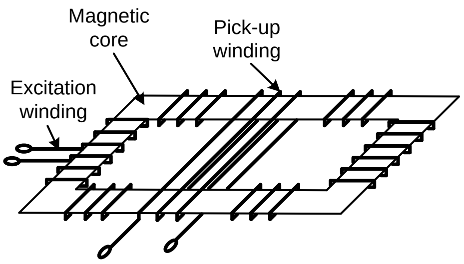

Fig. 5. The arrangement of the fluxgate sensor windings

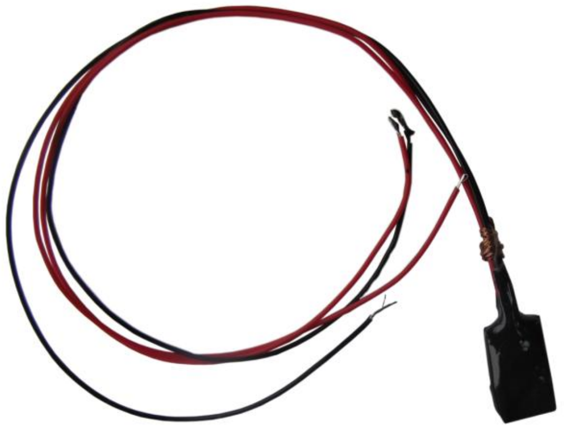

Fig. 6. Assembled sensor

The geometrical dimensions of the sensor are 10×6×2 mm.

3. FLUXGATE SENSOR SIGNAL CONDITIONING

In order to generate the AC excitation current and to process the pick-up coil output signal a block-diagram of signal conditioning was developed (see Fig. 7). The output signal is proportional to an external measured magnetic induction.

Master oscillator was realized with logical elements and switches to generate unipolar square wave with frequency equal to $4f_{\text{exc}}$ for the fluxgate sensor excitation. Two series-connected D-flip-flop were used to set the frequency signal to be equal to f_{exc} and the duty cycle to be equal to 2. Signal from the D-flip-flop 2 with frequency f_{exc} is applied to the control input of the modulator; a DC voltage from variable reference voltage (REF) is applied to the signal input of the modulator. As a result, the modulator outputs bipolar signal with the duty cycle equal to 2 and the frequency f_{exc}. This signal, via the voltage to current converter, supplies the excitation winding of the fluxgate sensor.

Signal from the pick-up winding is amplified by a broadband amplifier and is inputted to a synchronous detector. Second input of the synchronous detector receives a signal from the D-flip-flop 1 with frequency $2f_{\text{exc}}$.

As a result, output signal of the synchronous detector is proportional to an amplitude of second harmonic in voltage $U(B_{\text{dc}})$, which corresponds to the measured magnetic induction value. The extracted signal is filtered by a lowpass filter, and, through negative feedback resistor R, sets the compensation current in fluxgate excitation winding and is supplied to the ADC.

The master oscillator is assembled on HEX inverting Schmitt trigger 74HCT14; D-flip-flops is performed on HCF4013; voltage reference is assembled on AD584; the modulator circuit and a synchronous detector are realized using balanced modulator/demodulator AD630.

The broadband amplifier is built on operational amplifiers AD797 and the ADA4627-1, the lowpass filter is implemented on operational amplifier OP270.

The voltage to current converter uses EL2099 amplifier. It is a monolithic operational amplifier featuring high output current capability and was able to provide a high speed of operation. It uses current mode feedback to achieve wide bandwidth, and is stable in unity gain configuration. With power supplies ±15 V, it was able to deliver ±11 V into 25 Ohm at slew rates of 1000 V/ms. Differential gain and phase errors of EL2099 are 0.03 % and 0.05° respectively, and -3 dB bandwidth is 50 MHz. The features listed make this device almost ideal to supply the excitation winding of the fluxgate sensor.

Appearance of the unit signal conditioning with fluxgate sensor is shown in Fig. 8.

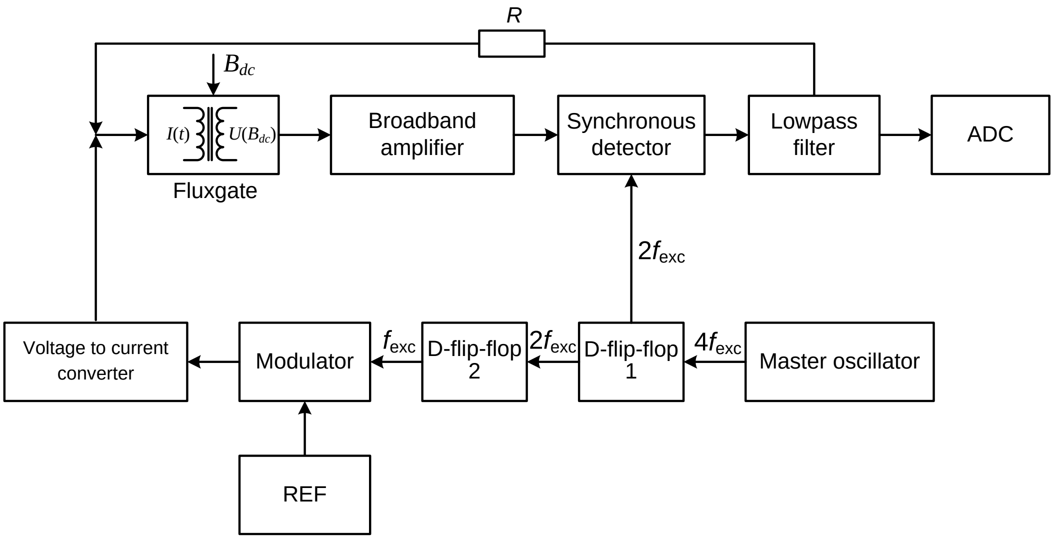

Fig. 7. Block-diagram of the fluxgate sensor signal conditioning

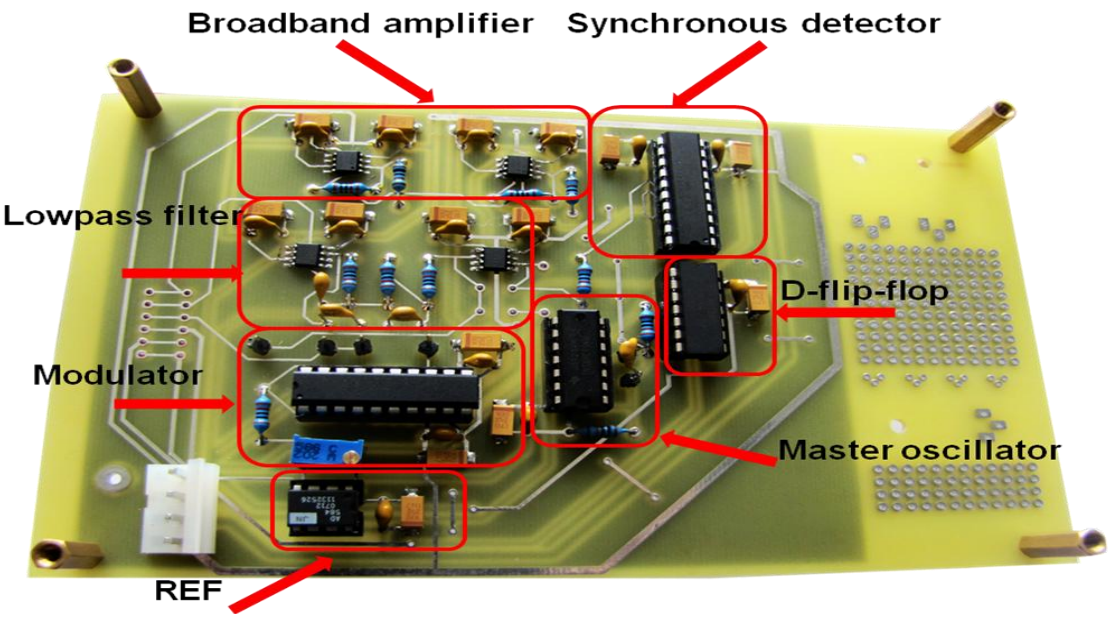

Fig. 8. Unit signal conditioning

4. EXPERIMENTAL RESULTS

Resistances of excitation and pick-up coils were measured at different temperatures to verify fluxgate sensor operation at extremely low temperatures using the multimeter Agilent 3458A. The measurement results are shown in Table 1.

Table 1. The measurement results of resistances of excitation and pick-up coils

	Temperature, K		
	298	77	4.2
Resistance value of the pick-up coil, Ohm	3.90512	0.39034	0
	3.90537	0.39037	0
	3.90557	0.39028	0
	3.90601	0.39027	0
	3.90648	0.39030	0
Resistance value of the excitation coil, Ohm	2.85809	0.28321	0
	2.85912	0.28326	0
	2.84712	0.28324	0
	2.85316	0.28319	0
	2.85471	0.28317	0

It is evident from Table 1 that, at temperature close to the absolute zero, winding are in the state of superconductivity. Coils resistance measurement results show a satisfactory quality and suitability of the developed fluxgate sensor to operate at extremely low temperatures.

Testing the developed prototype magnetometer and determination of its conversion factor, sensitivity, linearity and range were carried out by direct measurements of the magnetic induction inside the system shields. Different values of the measured external magnetic induction were obtained by means of a specially developed axial coils system [18-19]

The Mag-01H magnetometer (Bartington Instruments Ltd., England) was used as the standard during the measurements. Mag-01H magnetometer allows to measure one component of the magnetic induction with a resolution of not more than 1 nT in the temperature range from 300 K to 4 [20].

The measurement results of conversion factor of the developed magnetometer are shown in Table 2.

Table 2. The results of conversion factor measurement

Magnetic induction measured with Mag-01H, nT	Developed magnetometer readings, V	Conversion factor, V/mT
1	$98.9\cdot10^{-6}$	98.9
	$98.8\cdot10^{-6}$	98.8
	$98.7\cdot10^{-6}$	98.7
	$99.0\cdot10^{-6}$	99.0
	$99.1\cdot10^{-6}$	99.1
98	$9.703\cdot10^{-3}$	99.01
	$9.701\cdot10^{-3}$	98.99
	$9.709\cdot10^{-3}$	99.07
	$9.705\cdot10^{-3}$	99.03
	$9.704\cdot10^{-3}$	99.02
9000	$89.0922\cdot10^{-2}$	98.9913
	$89.0917\cdot10^{-2}$	98.9907
	$89.0918\cdot10^{-2}$	98.9908
	$89.0924\cdot10^{-2}$	98.9915
	$89.0921\cdot10^{-2}$	98.9912

The measurement results of magnetic induction are shown in Table 3.

Table 3. The results of magnetic induction measurement

Magnetic induction measured with		Absolute error, nT
Mag-01H, nT	developed magnetometer, nT	
9920	9803	117
4976	5027	51
1982	2015	33
998.1	1007	8,9
497	503	6
198	201	3
98	99	1
50	51	1
20	21	1
10	10	0
5	5	0
2	2	0
1	1	0
-1	-1	0
-2	-2	0
-5	-6	1
-10	-10	0
-20	-19	1
-50	-48	2
-97	-98	1
-199	-197	2
-498	-489	9
-998.7	-987.2	11,5
-1993	-1974	19
-4982	-4952	30
-9950	-9758	192

It clear from the data of Table 2 that the conversion factor of the developed magnetometer is equal to 99 V/mT. The data of Table 3 allow to calculate the magnetometer linearity error that appeared to be equal to approx. 1.9 % of full scale in the range ±10000 nT; at that, the magnetometer sensitivity is 1 nT in the range of ±1000 nT and 10 nT in the range of ±10000 nT.

CONCLUSIONS

In this work, a characterization of PCB fluxgate magnetic sensor, based on the simplified single-layer PCB technology, has been reported.

A single axis fluxgate magnetic sensor was fabricated in PCB technology with geometric dimensions 10×6×2 mm. A block-diagram for conditioning the fluxgate sensor signals was presented.

Coils resistance measurement results of the fluxgate sensor showed a satisfactory quality and suitability of the magnetometer to operate at extremely low temperatures.

The linearity error of the developed magnetometer is about 1.9 % of full scale and its maximum sensitivity is about 99 V/mT. These characteristics provide an opportunity to use the developed magnetometer for measurement of ultra low magnetic fields with sensitivity 1 nT in the range of ±1000 nT and 10 nT in the range of ±10000 nT.

Further investigations are aimed at the creation of a 3D magnetometer prototype based on the three positioned orthogonally to each other fluxgate sensors and increasing the sensitivity of the magnetometer.

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