DOI 10.5162/sensor2017/A1.4

A New Approach For a Planar Miniaturized PCB Based High Sensitivity Fluxgate Sensor Design

M. Lenzhofer[1], M. Ortner[1], G. Schulz[2], J. Stahr[2]
[1] CTR Carinthian Tech Research AG, Europastrasse 12, 9524 Villach, Austria
[2] AT&S Austria Technologie & Systemtechnik AG, Fabriksgasse 13, 8700 Leoben, Austria
martin.lenzhofer@ctr.at

Abstract

In many sensor applications, for example proximity switches, current-, torque-, angle- or position sensors, Hall-effect elements are used. Such devices require strong magnetic fields in the order of millitesla to generate a valid output signal. In that context Fluxgate sensors are a better choice as they can detect much weaker fields, but are limited by current technology to large and heavy sensor heads and show high power consumption. State of the art Fluxgate sensors are constructed from solid ferromagnetic cores and copper wire-wound coils. The presented innovative new planar sensor design, just uses standard PCB laminates combined with different magnetic materials, which is fabricated using subtractive PCB etching technology with trace widths and line spaces as small as 75µm making it possible to build up sensor devices with dimensions of just 18 x 6 mm², while obtaining large sensitivities of up to 4.5mV/µT.

Key words: Fluxgate sensor, Hall-effect element, magnetic sensors, planar PCB sensor, magnetic materials, magnetic field measurement, magnetic field

Introduction

The modern printed circuit board (PCB) is not just a carrier for assembled components and necessary to realize the electrical connections between the devices anymore, but with modern fabrication technologies - trace widths down to and below 75µm in standard subtractive etching processes and the implementation of new materials is possible and therefore provide additional functionality of the board. In this context the direct realization of an integrated magnetic sensor based on pure PCB technology, the planar Fluxgate, is of great interest enabling numerous possible applications like e.g. the realization of a galvanically isolated current measurement on traces in inner layers. Such solutions feature a high level of flexibility for the user and are extremely cost-effective at the same time.

Fluxgate sensor devices use an induction based principle to measure the static magnetic field inside a soft-ferromagnetic core. The elementary system detects a single component of the magnetic field, the one parallel to the core. However, smart layouts that combine several elementary systems can provide 2D and 3D field measurements. The resolutions of Fluxgate sensors are typically in the microtesla and nanotesla range, thus bridging the gap between the inexpensive Hall type sensors and the very elaborate SQUID sensors.

The most popular signal processing method of a Fluxgate type sensor is the detection of the second harmonic component of the sensor output voltage, performed by means of a phase sensitive detector usually receded by a bandpass filter if using standard analogue techniques. Nowadays, some other principles exist that offer the possibility to measure the applied field within the digital domain, [1].

The classical description of the Fluxgate principle is given in [2], while a proposal for a PCB based Fluxgate sensor is presented by Marchesi [3] and Bruno Ando [4], where they developed planar Fluxgate structures in different configurations that also form the basis of this work.

The Fluxgate sensor principle is based on two magnetic propagation paths in a ferromagnetic core that is periodically saturated by the excitation coils where the magnetic flux is oppositely orientated along the two paths. Inside the core an external (DC-)field to be measured superposes with the field from the excitation coils. The positive and negative superposition of the two fields in the core leads to an imbalanced saturation behaviour along the two paths. The imbalance, which corresponds directly to the external magnetic field, is picked up by a sensing coil. The name of the device comes from this “gating” of the flux that occurs when the core is saturated.

State of the Art Planar Fluxgate

This common configuration was transferred to a planar structure, by Marchesi [3], by splitting the receiving coil into two parts and was differentially arranged to each side of the excitation coil, Figure 1. The magnetic flux of the planar excitation coil is guided outward by the magnetic film structures which saturates even at weak fields due to its thickness.

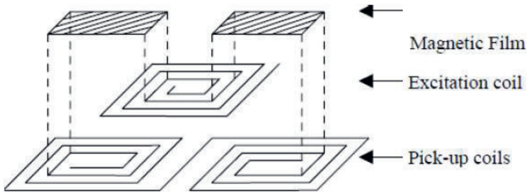

Fig. 1. State of the art setup of a planar Fluxgate sensor to realize with PCB technology, [3].

If no external magnetic field is applied, the two sensing coils, which are connected in antiseries, show an output voltage that is ideally zero. Figure 2, shows three different cases, when the external magnetic field is zero or non-zero with two different values.

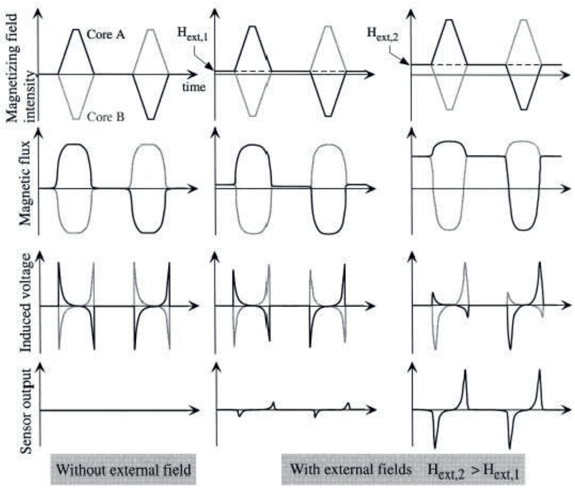

Fig. 2: Fluxgate principle explained with the waveform of the magnetic field and the induced voltage, [3].

Based on the awareness of Marchesi’s work and focusing on the PCB solution, it is the goal of this work to improve the planar technology by making it geometrically smaller, more sensitive than the state of the art setup and additionally reduce the power requirements at the same time.

Figure 3 shows the output of the device developed by Marchesi. His setup features two layers, one for the excitation and one for the pick-up coils with a separated core film on top as indicated in Figure 1. For the magnetic film the soft magnetic metallic glass Vitrovac 6025X [7] was used. The size of this original setup is 65 x 31 mm². Depending on the applied current in the excitation coil, which ranges between 500mA and 800mA, an average sensitivity of just 0.4mV/µT for a measurement range of ±100µT at a frequency of 10kHz was estimated by Marchesi. In the course of the development presented in this paper the originally structure was verified and the results of Marchesi could be confirmed. The original 1D sensing structure can easily be extended to two dimension, see [3].

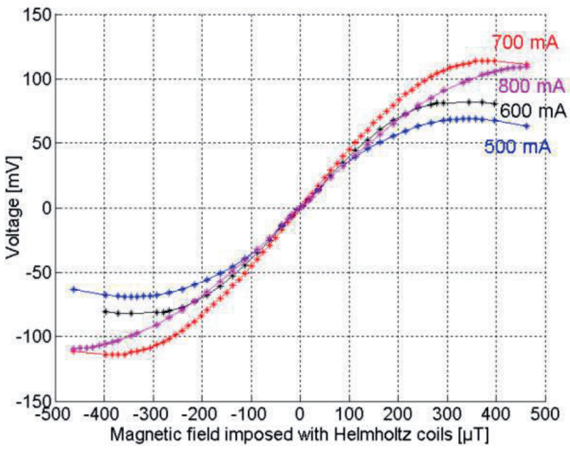

Fig. 3: Fundamental harmonic component of the differential output voltage of a single axis Fluxgate with different excitation current peak values, [3].

Improved Planar Fluxgate Sensor Proposal

To improve the planar Fluxgate layout we propose in a first step to increase the coils windings for improved sensitivity of the pick-up coils and reduced power consumption of the excitation coil. For maximal efficiency we propose a multilayer layout where the three coils are arranged adjacent to each other in planar stacks. While this step requires little innovation it is challenging from a fabrication point of view.

In a second step we propose to use a double-core structure as depicted in Figure 5. The lower core is fabricated of a soft ferromagnetic material with different characteristics than the upper one and can also be of a different thickness. It serves two purposes: Firstly, while operating in the linear range of its hysteresis curve it greatly enhances the magnetic circuit

DOI 10.5162/sensor2017/A1.4

(blue in Figure 5) improving again the power consumption. Secondly, when the lower core saturates at a different time as the upper core the two effects enhance each other, leading to potentially larger sensitivities.

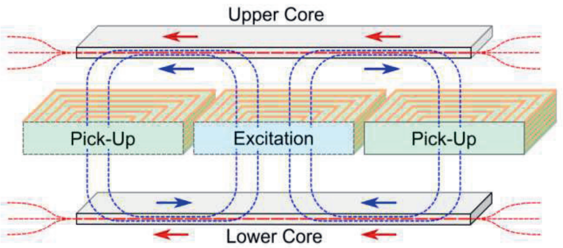

Fig. 4: Sketch of the proposed setup. The operating field excited by the excitation coil is depicted in blue while the external field is depicted in red.

Experimental Setup and FEM Simulation

The experimental setup is based on a four-layer PCB where each coil contains a total of 60 turns covering a total surface of just 18 x 6 mm². The layer stack-up is formed by a 120µm FR4 core and prepreg material with similar thickness and 35µm copper for each layer. All the traces are formed by photolithography and etching processes with trace and gap widths of 75µm respectively. The current geometry with a realized line-space of 75µm shows the limitation of the actual possible subtractive etching process. Further miniaturizations are possible, but require a technology change in the production process. For the upper core a cobalt-based magnetic alloy sheet of the type Metglas™ [6] with an ultra-high relative DC permeability of 1e6 and a low saturation magnetization of 0.57T is adhered on top of the PCB. The dimensions of the core are 18 x 1 mm² with a thickness of only 15µm. The isolation to the copper traces is realized with the applied solder stop mask. For the second core a ferromagnetic alloy composition material of the type VITROVAC [7] with a higher saturation of 0.99T and a lower relative permeability of approximately 1330 is adhered on the back side. The second core has the same dimensions as the first one but features a thickness of 23µm. A picture of the experimental structure can be found in Figure 5.

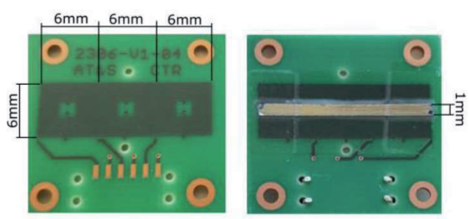

Fig. 5: Front and back side of the experimental setup with and without adhered core structure.

The experimental structure is analyzed by means of a 3D magnetostatic FEM simulation using datasheet values for the material parameters and a homogenization for the coil structure. All simulations were performed with the FEM tool ANSYS Maxwell v.18, [8]. The 3D solvers attempt a direct solution of the H-field resulting from the imprinted current distribution and magnetic polarization in Maxwell's equations.

The geometric parameters of the core as well as different material parameters were evaluated. In fact, the current experimental system layout is a result of an optimization by the simulation. Figure 6 shows a 3D view of the simulation model. The pick-up coils were not included as they do not influence the magnetic circuit but are designed to optimally detect it. The two cores are depicted in two shades of blue. The orange coil has been homogenized.

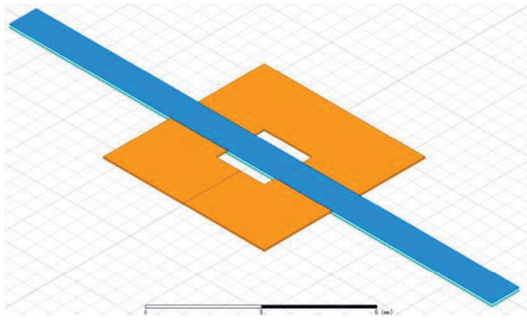

Fig. 6: Setup of the simulation model.

Figure 7 shows the magnetic field amplitude as a function of the position along the central axis of the core for different excitation currents. In this simulation a similar material (METGLAS) was chosen for both cores with thicknesses of 15 and 45 µm respectively to avoid difficulties with simulation convergence when dealing with such thin sheets of nonlinear magnetic media.

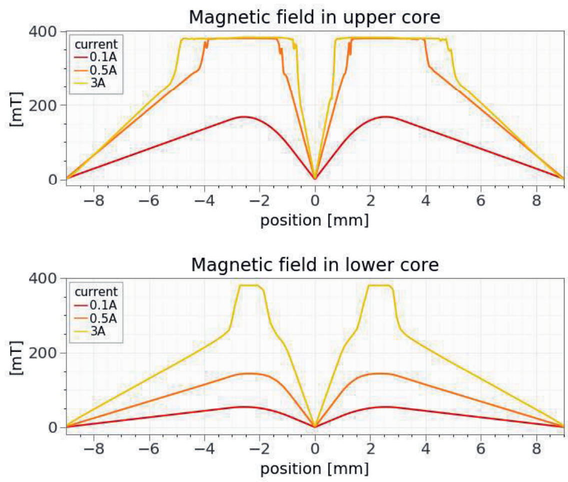

Fig. 7: Core magnetization from an FEM simulation.

Notice how the upper core saturates before the lower core does as well and that with increasing flux the core saturation spreads outward. The FEM simulations lead to several general insights:

1. Each core can be formed as one single piece and does not require to be separated as in the original setup.
2. The planar magnetic circuit behaves differently than a classical 3D one. Forming the core as a closed loop yields no improvement. This was also confirmed experimentally.
3. Excitation coil and pick-up coils can be placed directly next to each other for maximal efficiency.
4. There is an optimal core length that is smaller the total length of the coil setup as can be expected from the saturation behavior depicted in Figure 7.

Calibration and Measurement of the Sensor Design

For readout the concept of extracting the amplitude of the second harmonic component [3, 4] of the excitation signal is used. With cost-effectiveness for an application in mind, a compact and inexpensive sensor design should also just require an inexpensive and simple read-out module. To that end a small circuit is developed that can directly be connected to the USB interface of a standard computer. While Marchesi uses an analogue concept realized with high performance measurement equipment, the developed circuit just consists of a microcontroller, a simple 2nd order Sallen-Key low pass filter stage, built up by standard operational amplifiers, and an instrumentation amplifier to connect the pick-up coils to the ADC input of the microcontroller.

The excitation signal of 100kHz is generated with the PWM unit and is routed to the filter stage which converts the square wave to a sinusoidal wave form to supply the excitation coil. Additionally a PWM signal with 200kHz, that samples the fundamental 2nd harmonic component within the measured signal, is generated and triggers the ADC unit. These two frequencies are not in phase with each other, but are shifted due to the delay in the signal path. This phase shift must be adjusted to yield a maximal sensitivity of the system during the calibration procedure after start-up. Figure 8 shows the developed electronic circuit which includes a USB interface, the dc-dc converters to supply the circuit and the controller circuit with the filter stage and the instrumentation amplifier.

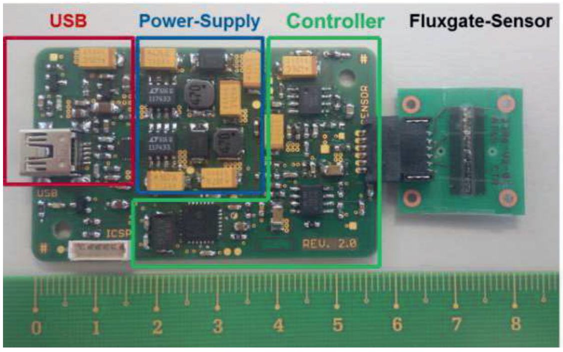

Fig. 8: Developed measurement control unit for reading out the new Fluxgate sensor.

The complete sensor device is calibrated and tested in a self-made Helmholtz coil. As a reference detection method a high precision Fluxgate sensor of the type FM302 [9] is used. Figure 9 shows the sensor output voltage as a function of the applied external magnetic field when supplying the excitation coil with a 100kHz signal of 3Vpp resulting in an excitation current of 100mA.

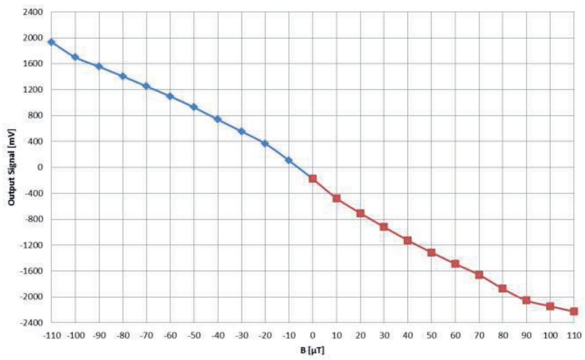

Fig. 9: Measurement result of the new planar Fluxgate sensor.

The measurement signal in Figure 9 includes the gain of the amplifier circuit which is around 4.3 in this particular case. An average sensitivity of 4.5mV/µT was observed for the low excitation current of 100mA for the sensor-head layout depicted in Figure 5. Despite the crude assembly method – the core ribbons were cut with scissors and adhered with scotch tape – the output shows an unexpected high level of linearity. The observed small bumps are easily explained by variations in the system geometry, the imperfect Helmholtz coil assembly, small external stray field influences and other experimental imperfections.

Comparison to the Original Layout

In comparison to the original design by Marchesi, with dimensions of 64.2 x 31.3 mm² the newly developed sensor measures only 18 x 6 mm², see Fig. 10, and shows great potential for further miniaturization.

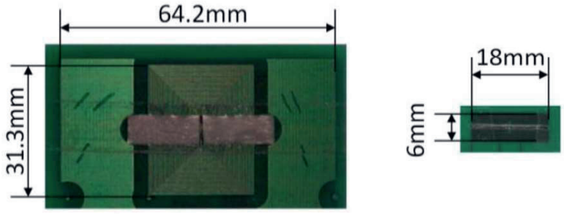

Fig. 10: Geometric comparison of the state-of-the-art Fluxgate sensor realized by Marchesi compared to the new developed structure.

While the miniaturization of the newly developed structure can be attributed to much more advanced fabrication technology the double-core layout combined with the higher operation frequency results in sensitivities of 4.5mV/µT while the original system shows only 0.4mV/µT. At the same time the supply current of the new layout is just 100mA leading to an excitation voltage of about 3Vpp. The original design requires a supply current of at least 600mA.

This corresponds to an improvement of the signal sensitivity of the new design by a factor of about 11, while the size of the sensor was reduced by a factor of roughly 19 in area together with a reduction of the supplied current in the excitation coil by a factor of at least 5.

Conclusion

In this work a new layout for a planar Fluxgate structure was proposed, constructed and tested. The new setup features an advanced multi-layer coil design and a double core structure applied on the top and the bottom side of the sensor. It was shown, that the new layout is a vast improvement over the state-of-the-art design featuring improved sensitivity, reduced power consumption and a much smaller size.

Future development aims at the possibility of developing even compacter layouts with lower power requirements, possibly multidimensional, that can directly be implemented in the PCB fabrication process to function as integrated current sensors or for application as magnetometers in geometrically limited environments.

Acknowledgement

This project has been supported by the COMET K1 centre ASSIC Austrian Smart Systems Integration Research Center. The COMET – Competence Centers for Excellent Technologies- Programme is supported by BMVIT, BMWFW and the federal provinces of Carinthia and Styria.

References

[1] G. Vèrtesy, Pulse-Position Type Fluxgate Sensors; Encyclopedia of Sensors, Vol. X, pp. 1-27, ISBN: 1-58883-056-X, (2006)

[2] V. Vacquier, Rev. Sci. Instrumentation, Vol. 18, 483, (1947).

[3] M. Marchesi, Fluxgate Magnetic Sensor System for Electronic Compass, PHD, https://pdfs.semanticscholar.org/ced4/72da17e6324bbf51a26227d7995c5d56b429.pdf

[4] B. Andò, S. Baglio, V. Caruso, V. Sacco, A. Bulsara, Multilayer Based Technology to Build RTD Fluxgate Magnetometer, Sensors & Transducers Magazine (S&T e-Digest), Vol. 65, Issue 3, pp. 509-514, (2006)

[5] Baschirotto, A.; Dallago, E.; Malcovati, P.; Marchesi, M.; Venchi, G. A fluxgate magnetic sensor: From PCB to micro-integrated technology. IEEE Trans. Instrum. Meas. 2007, 56, 25–31.

[6] METGLAS, Magnetic Alloy – Product Brochures, http://www.metglas.com/tech/ , 2017

[7] VAC, Soft Magnetic Materials and Semi-finished Products, PHT-001, VACUUMSCHMELZE, www.vacuumschmelze.com, 2002

[8] ANSYS Inc. Complete Maxwell 3D, User's guide REV6.0, www.ansys.com, 2012

[9] Projekt Elektronik, Teslameter FM 302 für AS-Aktivsonden, Datenblatt Teslameter FM 302, Version 0201-1, www.projekt-elektronik.de, 2016