Fluxgate Magnetic Sensor in PCB Technology

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Abstract – In this paper a single axis fluxgate magnetic sensor developed using printed circuit board (PCB) technology is presented. The behavior of the fluxgate device was analyzed with software tools based on the finite element method. The results of the simulations were validated experimentally on fabricated prototypes. The magnetic sensitivity of proposed planar sensing element is about 0.46 mV/µT at 10 kHz and 700 mA current excitation.

Keywords – Planar fluxgate; Amorphous core; Magnetic sensors, FEM

I. INTRODUCTION

Fluxgate sensors measure dc or low-frequency ac magnetic fields [1-4]. They are sensitive to the magnetic field parallel to the sensor structure and can achieve resolutions down to 10 pT over a magnetic field range of about 1 mT [5, 6]. The basic structure of fluxgate, schematized in Fig.1, incorporates two coils: a primary (excitation) and a secondary (pick-up) coil, wrapped around a common high permeability ferromagnetic core. The excitation current Iexc passing through the excitation coil produces a field that periodically saturates the soft magnetic material of the sensor core (in both directions).

Fig. 1. Fluxgate principle a) core not saturated b) core saturated

In saturation, Fig. 1 b), the core’s permeability drops and the DC flux associated with the DC magnetic field B0 to be measured decreases. The name of the device derives from this “gating” of the flux that occurs when the core is saturated. When the measured field is present second harmonic, and also higher order even harmonics, appear in the voltage Vind, induced in the sensing (pick-up) coil. These harmonic components are proportional to the field to be measured and represent the sensor output. Fluxgate sensors are reliable devices, working over a wide temperature range. Resolutions of 100 pT with 10 nT absolute precision are the typical performance of commercially produced devices. However, fluxgate sensors can potentially reach 10 pT resolution and 1 nT long-term stability. Most dc fluxgate magnetometers have a cut-off frequency of several Hertz, but when necessary, they can work up to kiloHertz frequencies. The offset drift with temperature may be well below 0.1 nT/°C, while the sensitivity temperature coefficient is usually around 50–30 ppm/°C. However, some fluxgates are compensated up to 1 ppm/°C.

In recent years the most common type of fluxgate adopted has been the planar fluxgate magnetic sensor that utilizes planar coils instead of coil wrapped around the ferromagnetic core. In this differential structure, the quantity proportional to the measured external field is the amplitude of the fundamental harmonic of the differential output voltage [1, 7]. The frequency of this harmonic is twice the frequency of the current excitation.

To create a planar fluxgate magnetic sensor we considered printed circuit board technology. The choice in favor of PCB technology derived primarily from its reduced cost and easy fabrication.

The first task was choosing a suitable model to analyze the sensor. In literature we can find different models to analyze fluxgate magnetic sensors (i.e. [8, 9]). However, when the coils are not wrapped around the core [10] the classic formulation cannot be used and in this case the only option is to use correction factors or to perform simulations with appropriate software. To analyse the magnetic characteristics one can use software based on the finite element method (FEM).

In this work we present the performance of one axis fluxgate magnetic sensor created using printed circuit board technology and validated by FEM analysis.

II. THE PROPOSED SENSOR

The proposed fluxgate sensor is shown in Fig. 2 and consists of one planar excitation coil with a thickness of 30 µm, consisting of 30 turns with 400 µm pitch. The output voltage is obtained from two pick-up coils, with a
thickness of 17 µm, with 30 turns and a 400 µm pitch, placed in differential configuration. The excitation and sensing coils are placed on two different metal layers in a multilayer PCB structure, at a distance of 50 µm. The total device size is 64x31 mm².

The ferromagnetic sheet core with a thickness of 25 µm is a special amorphous alloy known under the trade name of VITROVAC 6025X [11]. It was chosen primarily because of its extremely high relative permeability (µᵣ ≅ 100000). Its magnetic induction at saturation is 0.55 T. The rectangular shaped material was glued onto the PCB structure with adhesive, as shown in Fig. 3.

III. SIMULATION RESULTS

The Flux3D® software that we utilized for the simulations is based on the finite element method [12].

The main issue in the setup of the model was to create a good mesh after taking into account the geometrical configuration of the ferromagnetic material, which is a rectangular sheet with dimensions 17000x7000x25 µm. The critical dimension is its 25 µm thickness, which leads to a large number of elements in the mesh (288259 volume elements). The mesh obtained is shown in Fig.4.

The first analysis step was to evaluate the minimum peak current excitation value that guarantees the ferromagnetic material will saturate. Using different magnetostatic analyses we evaluated that a peak current of about 700 mA saturated the Vitrovac, as shown in Fig.5.

The second analysis step was performed by taking the following into account: a sinusoidal excitation current of 700 mA of peak amplitude and 10 kHz of frequency, the geometrical model proposed in Fig.5 and a field of 150 µT coplanar to the PCB and parallel to the ferromagnetic material. The results of this transient magnetic simulation are shown in Fig. 6. The simulation shows a differential output voltage in accordance with the fluxgate principle. The output voltage obtained has an amplitude of 0.11 V that implies the device has good sensitivity.

IV. EXPERIMENTAL RESULTS

To characterize the fluxgate sensor we need a current generator to supply the excitation coil and Helmholtz coils to create a constant and uniform magnetic field.

The current generator schematic and the Helmholtz coils are shown in Fig.7 and Fig.8, respectively. It is also necessary to use a DC current generator to guarantee that the magnetic field produced by the Helmholtz coils is constant (the resistance of the coils could change with temperature if constant voltage is applied).
For this reason, the current generator shown in Fig. 9 was built.

The first measurement performed was the evaluation of the voltage induced on the two sensing coils by the excitation coil without the ferromagnetic material. This analysis is necessary to evaluate the coupling between the excitation and the sensing coils. In fact, because of geometrical tolerance in PCB technology, a misalignment between the excitation and sensing coils can result in an offset voltage for the device. Fig. 10 shows that, in our case, the two induced voltages are very similar and hence the coupling is symmetrical.

Following this, the output voltage of the fluxgate sensor was measured with the Earth’s magnetic field coplanar to the PCB and parallel to the ferromagnetic material under the condition of a 700 mA peak at 10 kHz of sinusoidal current excitation (Fig. 11). The differential voltage output has a value of about 90 mVpeak-peak.

The differential voltage output with the Earth’s magnetic field coplanar to the PCB surface and orthogonal to the ferromagnetic material is shown in Fig. 12. As expected, the output voltage is significantly lower than the previous case although not zero because of the non ideality of both the device and experimental setup.
To verify the simulation result, a field of 150 $\mu$T, coplanar to the PCB and parallel to the ferromagnetic material, was imposed on the device using the Helmholtz coils.

The differential output voltage, compared to the case when the Earth’s magnetic field is imposed, increased at a value of about 0.2 V peak-peak, as shown in Fig. 13.

The linearity and the sensitivity of the sensor in the range of $\pm$400 $\mu$T were then evaluated using a sinusoidal current excitation of 700 mA peak at a frequency of 10 kHz.

The differential output voltage from pick-up coils was analyzed with a 3562A Hewlett Packard Dynamic Signal Analyzer to extract the value of the fundamental harmonic. This voltage is plotted in Fig. 14 against the external magnetic field. The sensor shows good linearity in the range of $\pm$100 $\mu$T with a sensitivity of 0.46 mV/$\mu$T.

The response of the sensor when the peak of the excitation current was varied between 500 and 800 mA was analyzed and the results are shown in Fig. 15. All fluxgate structures have a precise excitation current value that maximizes its sensitivity [13]. This value is related to the magnetic field that saturates the material and to the topology of the sensor. Table 1 shows that in this case the best value over the $\pm$100 $\mu$T range was obtained with 700 mA.

If power consumption is a key issue, the excitation current peak can be decreased to 500 mA given that sensitivity is lower. Any other reduction of the excitation current peak is impractical because the fluxgate principle is assured only when the ferromagnetic material is saturated.

V. DISCUSSION

The software simulation gave good results. Under the same operating conditions, the error between simulation and experimental results regarding the differential output voltage, was close to 15% (Fig. 16). The major drawback of this simulation approach was the prolonged computation time, that for transient time analysis was about 120 hours on a P4 2.4 GHz processor. We obtained much shorter...
times when the simulator was used to investigate the minimum value of excitation current peak necessary to saturate the ferromagnetic material. In this case the static analysis time was reduced at 1 hour.

The proposed fluxgate magnetic sensor structure does not require electroplating or sputtering processes for ferromagnetic material deposition because very thin (25 µm) amorphous metal is commercially available with very good magnetic characteristics. This approach was also considered in [14] using an integrated fluxgate solution. An integrated one axis fluxgate capable of sensing the Earth’s magnetic field is our future target. To this end we must remember that reducing sensor size also decreases sensitivity (in accordance with Faraday’s Law and the reduced section of sensing coils). The lower sensitivity value can be compensated by increasing the frequency of the excitation current and the number of sensing coil turns.

In Fig.17 we show the sensor output at various frequencies under the imposed conditions of 700 mA current peak and 25 µT external field. In the range 10 kHz to 45 kHz the sensor output increased its value. We are aware that a frequency increase limit exists influenced by ferromagnetic permeability and capacitive coupling.

According to the different technological limits for metal width and metal spacing in the PCB technology, integrated process allows the number of turns of sensing coils to be increased as well.

VI. CONCLUSIONS

A single axis fluxgate magnetic sensor was fabricated in PCB technology and analyzed with FEM simulation. The sensor was characterized using Helmholtz coils to impose an external magnetic field at various excitation current peaks and current excitation frequencies.

The one axis fluxgate proposed shows good sensitivity, about 0.46 mV/µT at 10 kHz and 700 mA, in the ±100 µT range and good linearity. Therefore, it is able to detect the Earth’s magnetic field.

This work has demonstrated that the FEM tool used can be exploited to effectively predict the performance of small size planar fluxgate structures. Hence, we also plan to use this design procedure to implement fluxgate sensors based on the integrated circuit process.

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