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Printed circuit board integrated fluxgate sensor

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Abstract

We have developed a cheap and simple trilayer printed circuit board (PCB)-based technology, adapted for the fabrication of fluxgate magnetic sensors. The two outer layers of the PCB stack comprise the electrical windings of the fluxgate, while the inner layer is made of patterned amorphous magnetic core with extremely high relative magnetic permeability ($\mu_r \approx 100{,}000$). The output voltage and the sensitivity of the fluxgate devices have been studied as a function of the external field and of the geometry of the magnetic core. We have found a relatively high sensitivity of 18 V/T at an excitation current frequency of 10 kHz. The results obtained clearly show the potential of this miniaturised fluxgate device for application as a magnetic field sensor.

Keywords: Fluxgate sensor; Sensitivity; High permeability; Compass; Vitrovac®; Printed circuit board (PCB)

1. Introduction

In recent years, many magnetic sensing devices have been dramatically reduced in size, thanks to the advanced development of microfabrication technologies. An example of such device for the sensitive detection of magnetic fields is the magnetic fluxgate sensor [1–3]. A fluxgate consists of a magnetic bulk or ribbon core and electrical windings for the realisation of the excitation and detection coils around the magnetic core. Recently, several fluxgate sensors have been demonstrated, which were directly integrated on Si-wafers. In these applications, the magnetic material, which is at the heart of the fluxgate operation, is deposited using a vacuum deposition method or by electroplating technologies on Si [4–8].

In contrast to previous work based on Si microfabrication technology, we propose a new and inexpensive hybrid printed circuit board (PCB)-like technology for the realisation of fluxgate magnetic sensors [9]. The fluxgate devices are built up of three layers of which the outer layers carry the Cu winding coil patterns and the inner layer is a patterned high permeability ferromagnetic sheet core with a thickness of 25 μm. For this work, a particular alloy, known under the trade name Vitrovac® 6025, (composition $(Co,Fe,Mo)_{73}(Si,B)_{27}$), was chosen primarily because of its extremely high relative permeability ($\mu_r \approx 100{,}000$) [10]. Both magnetic metal and copper layers are patterned using standard lithographic techniques. In between the magnetic metal and copper layers, there is a foil of solid epoxy glue (Prepreg® typically 100 μm) for insulation and assembly. Such material is well known in the assembly of multilayer PCB structures. Connection between the outer copper patterns is realised by electroplating methods to complete the windings. These fluxgate devices are about 600 μm thick, with lateral dimensions of approximately 1 cm.

2. Fluxgate design

Fig. 1 shows a design diagram for a fluxgate sensor with rectangularly shaped magnetic core. Two excitation coils of five windings each are symmetrically positioned around the inner detection coil (also with five windings). All windings are around the inner magnetic part of the structure; flux closure of the magnetic circuit is obtained via the two outer 'legs' of the magnetic core. Moreover, we have introduced two air gaps (of length L_g) in the magnetic core. Gap lengths L_g have been varied between 0 and 1 mm, to investigate their influence on the sensitivity and the magnetic field detection range. A photograph of a finished rectangular fluxgate sensor is displayed in Fig. 2.

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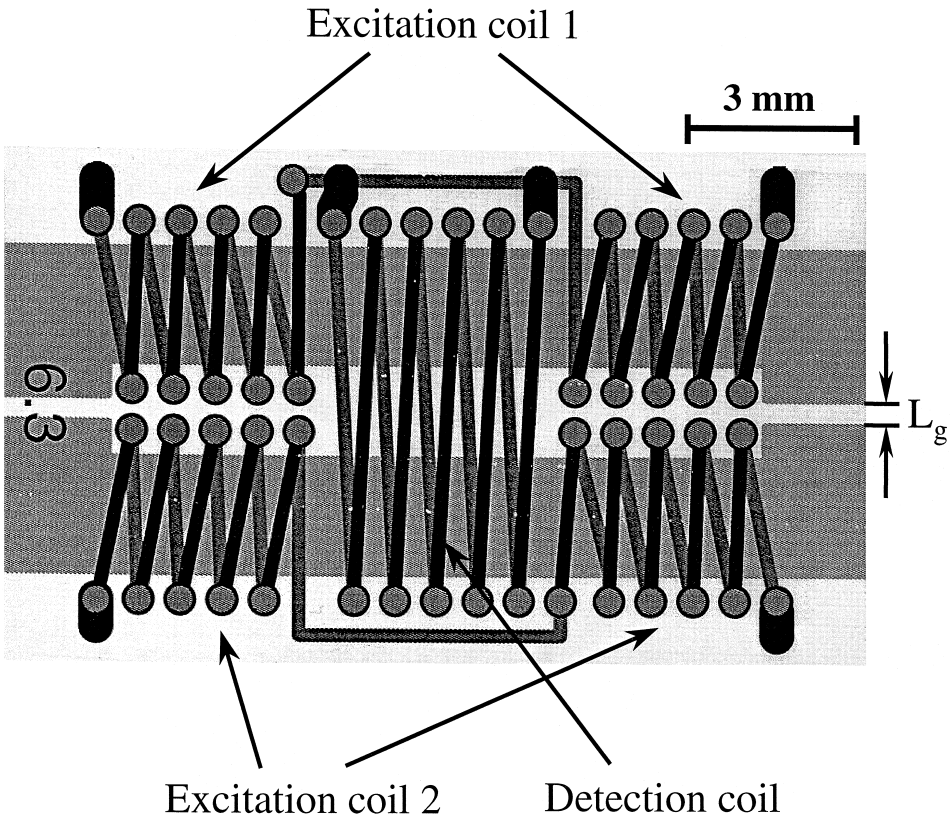

Fig. 1. Schematic diagram of a fluxgate sensor with rectangularly shaped magnetic material showing air gaps with length L_g.

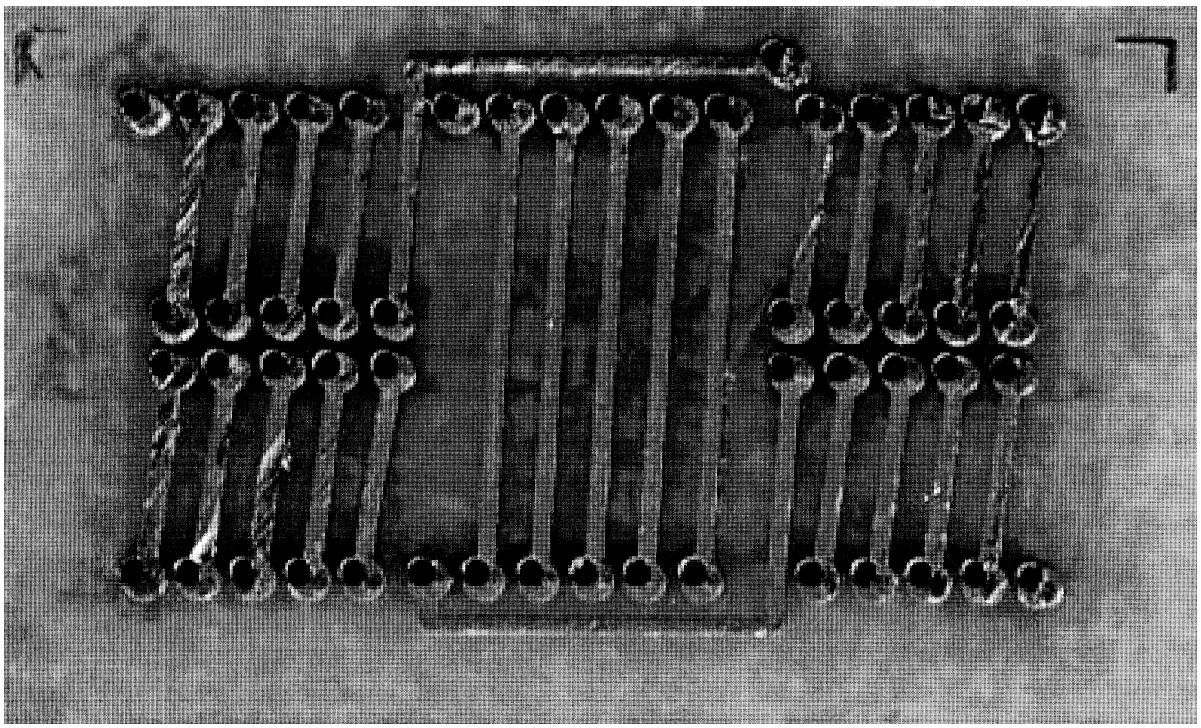

Fig. 2. Photograph of a finished rectangular fluxgate sensor.

3. Experimental results and discussion

The principle of a fluxgate is based on the external magnetic field dependent periodical saturation of the ferromagnetic material. The combined action of the external field (to be measured) and excitation coils, driving the ferromagnetic core in saturation, leads to the generation of higher order harmonics of the fundamental excitation frequency in a detection coil surrounding the magnetic core. The second harmonic of the output can be measured using a lock-in technique, and is proportional to the external field for a certain field range (typically 0.01–100 μT).

3.1. Dependence on the air gap

Fig. 3a represents the second harmonic voltage V_{2f} of the detection coil as a function of the external field B_{ext} for various gap lengths L_g, and at a frequency of 10 kHz for an excitation current I_e of 300 mA_{p-p}. B_{ext} is applied in-plane perpendicular to the detection coil, as shown

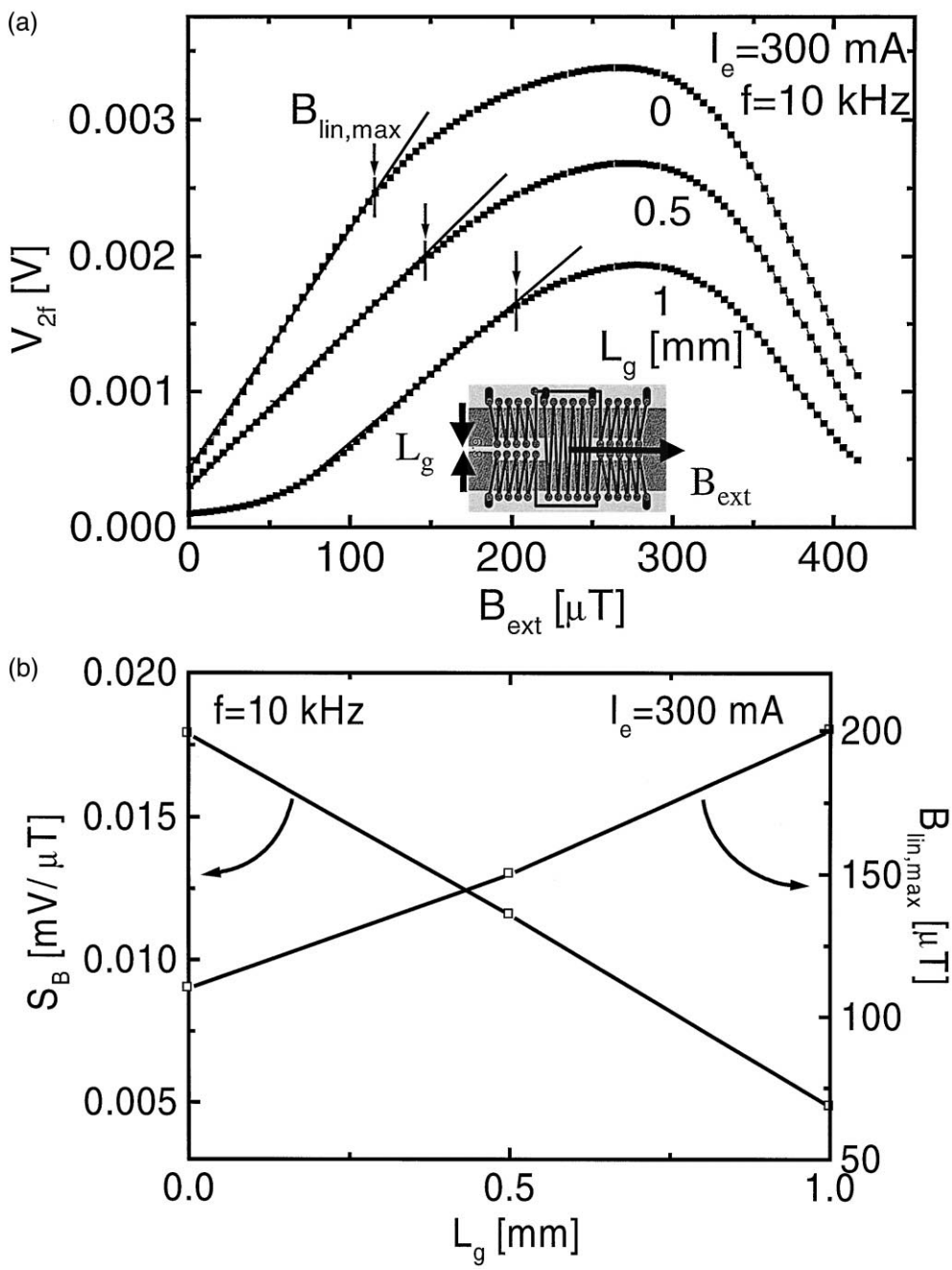

Fig. 3. (a) Second harmonic voltage V_{2f} of the detection coil of a rectangular fluxgate sensor as a function of B_{ext} for various gap length L_g at a frequency $f = 10$ kHz and for an excitation current I_e of 300 mA. (b) Sensitivity $S_B = (dV_{2f})/(dB_{ext})$ and maximum of the linear range $B_{lin,max}$, determined from the curves of a).

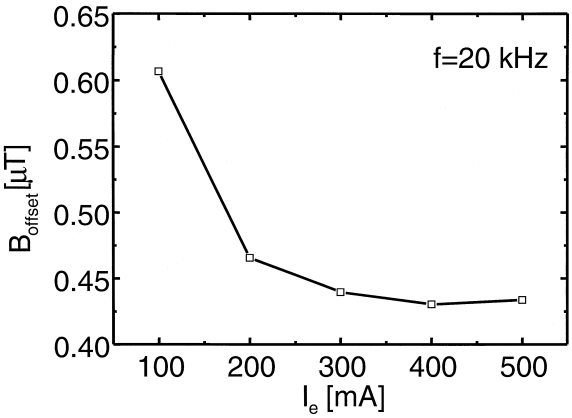

Fig. 4. Magnetic offset B_{offset} of the fluxgate sensor as a function of excitation current I_e at 20 kHz, for the rectangular fluxgate without gap.

schematically by the arrow in the insert of Fig. 3a. The three curves are characterised by a linear slope at small B_{ext}. For $L_g = 0$ mm, one notes a limiting field for this linear range ($B_{lin,max}$) of 110 μT, while the maximum value of V_{2f} is around 280 μV. For $L_g = 0.5$ and 1 mm, the maxima of the linear ranges $B_{lin,max}$ are shifted to higher values, while the maximum of the curves is around the same external field $B_{ext} = 280$ μT. Hence, the slopes of the linear parts of the $V_{2f} - B_{ext}$ curves decrease with increasing gap length L_g. This graph clearly shows that, by choosing a certain air gap L_g, one can select the fluxgate sensor's sensitivity and its linear magnetic field range.

Fig. 3b shows the sensitivity $S_B = (dV_{2f})/(dB_{ext})$ and the maximum of the linear range $B_{lin,max}$, determined from the curves of Fig. 3a. One notes a decrease of the sensitivity S_B and an increase of the maximum of the linear range $B_{lin,max}$ with increasing gap length L_g. In fact, S_B decreases with L_g. It has been established previously that $S_B \sim \mu_4^*$ [4] where μ_r^* is the effective relative permeability decreasing with L_g. By choosing a certain air gap L_g, it hence is possible to make a compromise between the sensitivity and the magnetic field detection range.

3.2. Magnetic offset of the fluxgate sensor

To evaluate the minimum detection limit of our fluxgate sensing devices, we have performed measurements of the magnetic offset of the fluxgate sensor B_{offset}. We have measured the voltage V_{2f} for a rectangular fluxgate, when cycling B_{ext} from zero to saturation and back to zero. From the value of V_{2f} at this point, one can calculate the offset by using the fluxgate's measured sensitivity curves. The results of such procedure are shown in Fig. 4 as a function of excitation current I_e at 20 kHz. One observes a decreasing B_{offset}, i.e., an improved minimum field detection limit, with increasing I_e. The reason for this behaviour has to be sought in the better defined magnetic saturation state at high applied I_e (smaller width of magnetic hysteresis curve at high I_e). The observed values of B_{offset} for our fluxgate sensor clearly are well below the value of the earth's magnetic field, enabling application of our devices for example as a magnetic compass.

4. Conclusions

We have developed a cheap new hybrid PCB-based technology, for the realisation of fluxgate sensors with output characteristics that are equal to and even surpass those of previously reported devices. The V_{2f} response of rectangular fluxgate sensors has been studied as a function of the gap length, the excitation current and excitation frequency. By appropriate selection of those parameters, one can select the fluxgate sensor's sensitivity and the linear magnetic field range. This new hybrid PCB/magnetic metal foil technology offers new possibilities for less expensive and facile realisation of high sensitivity fluxgate sensors.

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