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Electroplated multi-ring core planar fluxgate

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Abstract

In this paper we studied multi-ring planar fluxgate with different number of rings. In particular we investigated the effect of the number of rings on the sensitivity and noise of the sensors. Multi-ring cores were expected to return lower noise due to mutual compensation of uncorrelated noise of every ring. Nevertheless, we observed an increase of noise for cores with higher number of rings. We believe this is due to non-uniform composition of the electroplated film, which make the inner rings magnetostrictive and therefore source of larger noise.

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Keywords: fluxgate, noise, sensitivity, planar, multi-ring, correlation.

1. Introduction

Fluxgate sensors are traditionally based on tape wound ring. An alternative is a planar core either composed of single layer of tape cut or etched in the desired shape or in the form of thin film of magnetically soft material electroplated or sputtered on a substrate. This type of fluxgate recently attracted large interest because it is well suited for integration either in CMOS technology [1] or in MEMS [2].

While for tape wound cores the geometry has already been studied [3], the geometry of planar fluxgate has still to be investigated. In this paper we propose four different configurations with either single ring or multiple rings and we compare the achieved results in terms of sensitivity and noise. The main purpose is to observe the effect of multiple rings on the noise. Having multiple narrow rings instead of a wide ring can return lower noise as long as the noise of the single rings are uncorrelated. This is achieved if the rings are magnetically independent by having air

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gap between them. Therefore, we expect lower noise for multiple rings due to mutual compensation of the noise in the rings. Theoretically, the noise should drop as the square root of the number of the rings.

2. Cores configurations

The cores have been electroplated in four different configurations. Three of them consist of 2 mm width rings with different radius and different number of rings: type A has one ring with 13.5 mm mean radius, type B has two rings with 11.5 mm and 15 mm mean radius and finally type C has three rings with 10 mm, 13.5 mm and 17 mm radius. The choice of such radii was made in such a way to have a constant mean radius of the sensor as a whole and keep any comparison fair; if we simply chose to start with a small ring and add additional external rings with larger radius the mean radius of the sensor would increase and any comparison with the respect of the demagnetizing factor (towards the measured field) could be misleading. Additionally we manufactured also type D core, with a single ring having inner radius 10.5 mm and external radius 10.6 mm. Also in this case the mean radius is the same as for type A, B and C; the total width of the ring is 6 mm as for type C, however there is not air gap every 2 mm as in type C core but the whole core is composed of a single ring. The purpose of this fourth type of ring was to test the effect of different demagnetizing factor with a constant width of the magnetic material. Fig. 1 shows the four type of rings used in this work.

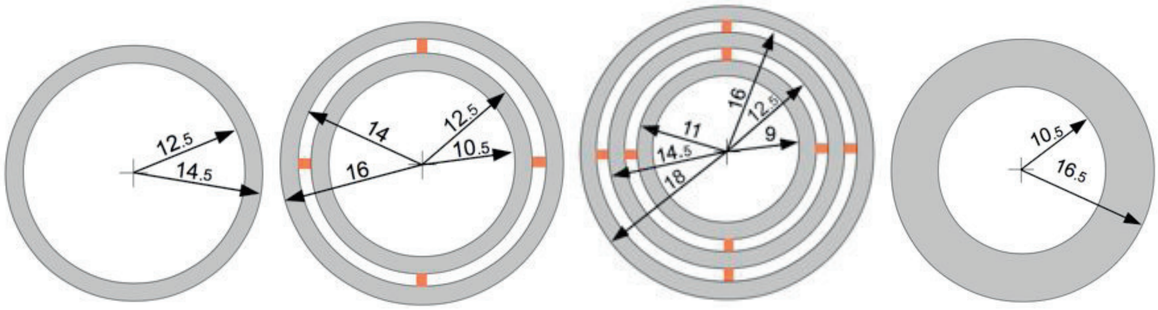

Fig. 1. Configuration and dimensions of the cores.

3. Cores electroplating

The cores have been electroplated over a 9μm thick Cu substrate on 0.25 mm thick fiberglass layer using a watt type bath composed of $FeSO_4 \cdot 7H_2O$ (8 g/l), $NiSO_4 \cdot 6H_2O$ (125 g/l), $NiCl_2 \cdot 6H_2O$ (20 g/l), H_3BO_3 (40 g/l), saccharin (6 g/l) in de-mineralized water. The temperature of the bath was automatically adjusted to 55°C and mechanical stirring was provided in the middle of the core in order to assure a constant flow rate all over the circumference of the rings. The anode was composed of a platinum grid 4 cm above the substrate to electroplate. Connecting terminals on the copper rings were connected at $\pi/2$ radiant distance to have constant current density along the circumference. The current density was adjusted to 15 mA/cm^2, as this was seen to provide $Fe_{21}Ni_{79}$ composition of the film. The pH of the bath was adjusted from initial 2.0 to 2.8 by adding few drops of KOH to the solution.

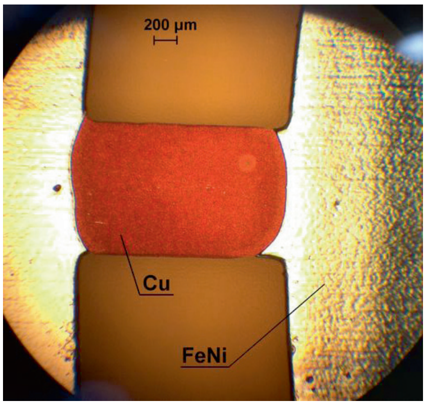

Fig. 2. (a) Connection pad between rings in a type C core. The FeNi film is electroplated only on the rings.

The time of deposition was 15 minutes in all cases, bring a magnetic film of 4 μm thickness (the estimation was made by the charge and previous thickness measurement by Talystep). The connecting pads to the current terminals as well as between rings in the multi-rings configuration had been covered by acid resistant paint before electroplating. In this way the magnetic film was growing only on the rings (Fig. 2). We electroplated only four sensors (one for every type) for each bath. In order to avoid any effect of the bath degradation for the last deposition we inverted the order of the types of sensors every time. In this way we can rule out differences for a particular type of core because electroplated always as first or last. In order to have statistically meaningful data we electroplated five cores for each configuration.

4. Noise measurement and sensitivity

The cores have been used as cores for fluxgates. The excitation current was 2 App at 20 kHz and a 150 turns pick-up coil was wound around the core. The second harmonic was extracted from the induced voltage by lock-in amplifier. Tuning capacitor was connected in parallel to the pick-up coil to maximize the second harmonic sensitivity. The noise of the sensors was measured placing the sensor in a four-layer shielding. As commonly done for fluxgate sensors we measured the noise spectral density and we considered the value at 1 Hz as reference of the noise of the sensor.

In Fig. 3 we can see the noise spectral density of all the cores, while in Tab. 1 the values of sensitivity together with average noise are shown.

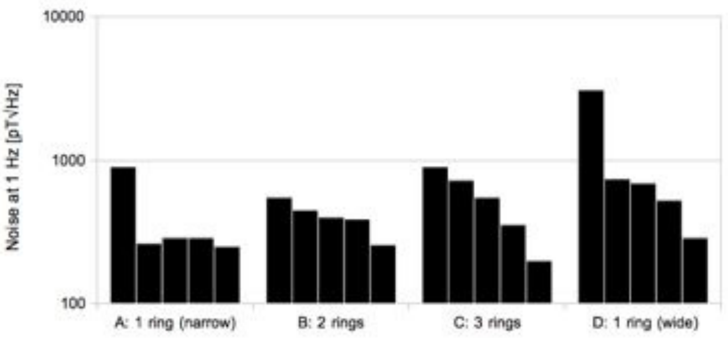

Fig. 3. Noise spectral density at 1 Hz for all types of cores.

Table 1. Average sensitivity with tuned pick-up coil and median noise spectrum at 1 Hz.

Sensor type	Sensitivity [kV/T]	Noise at 1 Hz [pT/√Hz]
A: 1 ring narrow	16.1	288
B: 2 rings	42.0	400
C: 3 rings	87.9	550
D: 1 ring wide	87.8	691

As we can see, the sensitivity increases as we add rings to the configuration. While for 1 narrow ring the sensitivity is 16.1 kV/T, for two ring it more than doubles (42 kV/T) and for three ring it become more than five times larger (87.9 kV/T). However, the same value of sensitivity is achieved using type D, that is a single ring with 6 mm wide cross section instead of three 2 mm wide rings. This indicates that higher sensitivity is achieved due to better tuning thanks to larger inductance of the core rather, whereas the effect of the demagnetizing factor is negligible.

More interesting are the results on the noise. The noise varies from sample to sample as usual for fluxgate, but we can observe that, on the contrary to what we expected, we achieved the lower noise with a single narrow ring (type A). A possible explanation for this result was the presence of connecting pads of copper between rings in multi-rings configuration. These pads were not electroplated, therefore the rings are magnetically separated; nevertheless they are electrically connected by the copper pads. This might cause local eddy currents of larger amplitude due to larger cross sectional area of the copper substrate, as in the cause of type D core. Therefore, we removed the connecting pads in the three ring configuration in order to have the rings both magnetically and electrically independent. Nevertheless, we did not observe any significant change of noise. Therefore, we can rule out this cause for a larger noise. Another possible explanation is a non-uniformity of the rings. The connectors of the electroplating current were indeed connected only on the external ring; then the current was flowing from the external ring to the inner one(s). Therefore the current density could be non-uniform for all the rings, but be higher in the external rings directly connected to the source of current an progressively lower in the internal ring. This would give a different composition of the film and finally arise of magnetostriction. In order to verify this hypothesis we measured the BH loop of the single rings in type C core.

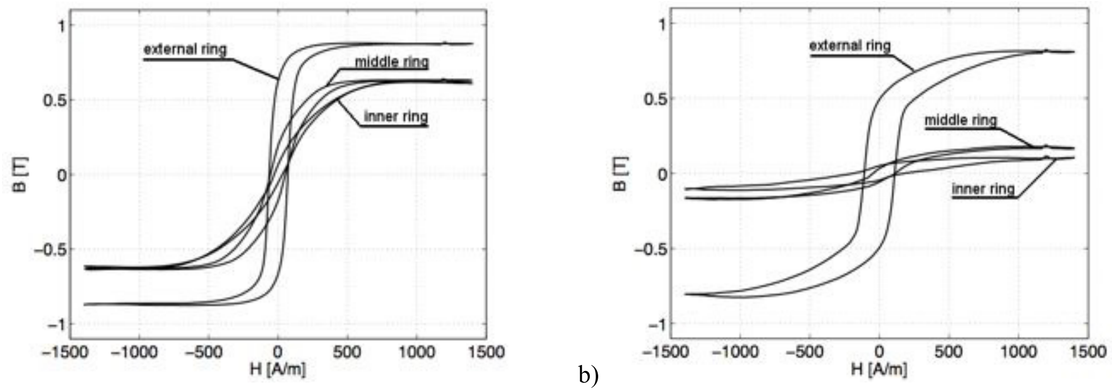

Fig. 4. BH loops of the single rings in a type C core without (a) and with (b) extensional stress.

In Fig. 4a we can see that the BH loops of the rings are significantly different. The external ring has larger saturation value than the middle and inner rings. This indicates that the inner rings have higher amount of nickel. This is confirmed in Fig. 4b, where we show the BH loops of the same rings measured bending the ring over a 322 mm radius. While the change in the external ring is limited (indicating a low magnetostriction) for the middle and inner cores a strong magnetostriction is observed. As magnetostriction is a source of noise in these sensors [4], it is favourable to have a single narrow ring where the current density is uniform and the magnetostriction is easily minimized all over the core. Alternatively, we must consider connecting current terminals to each ring of multi-ring configuration to have constant potential on all rings, but this would significantly complicated the production process.

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