ULTRASENSITIVE MAGNETOMETERS BASED ON ROTATIONAL MAGNETIC EXCITATION

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Abstract

Three new types of fluxgate magnetometers are presented in this paper, able to monitor the three components of the ambient field, all of them based on the principle of rotational excitation field. The first type is based on Yttrium- Iron Garnet (YIG) single crystal film, magnetized with rotational field on its plane, where the 2nd, 4th and 6th harmonics offer the three components of the ambient field with sensitivity better than 1 pT at 0.2 Hz, its size being 25 cm^3. The second type is based on permalloy film, where the rotational excitation field on its plane offers change of magnetoresistance with sensitivity better than 10 pT at 1 Hz, uncertainty of 1 ppm and size ~ 8 cm^3. The third type, is based on amorphous film, where the rotation field mode offer sensitivity better than 100 pT at 1 Hz, uncertainty of 10 ppm and size ~ 10 mm^3.

Introduction

Current technology of magnetic field sensors allows their use in applications such as mining activities, near surface monitoring, automotive & industrial engineering applications etc. The expansion of their use is prohibited by conflicting factors of sensitivity, size and cost. Moreover, three-dimensional magnetic field sensors with sensitivity better than 1 pT in the bandwidth of 1 Hz, integrated in a relatively small size, are yet to be developed.

The state of the art in magnetic field measurements, being also the primary standard in field measurement, is the superconducting quantum interference devices (SQUID) which are based on the Josephson effect-junction. Although, in principle, SQUIDs are able to measure the magnetic quantum, their sensitivity is limited by the sensor electronics and becomes finally of the order of 0.1 – 1 pTat a frequency of 0.2 – 0.5 Hz. The need of cryogenic operating conditions increases costs and operational properties of SQUID sensors.The second best type of magnetic field sensors is the proton magnetometer. These sensors are based on the Zeeman effect, controlled by the magnetic field. The sensitivity of these devices is of the order of 1 pTat 1 Hz. These devices can operate in normal temperature conditions but their size is rather large.

Fluxgate magnetometers use the non-linearity of the magnetization loop of soft magnetic materials [1-3]. Ideally this loop should be a un-hysteretic ramp, flattening at the saturation or anisotropy fields. Excitation and search coils are used to operate fluxgates, while hybrid systems, including conductive means in either excitation or signal detection, have also been designed. The signal processing may include monitoring of the second and higher harmonics of the excitation frequency, or phase shift measurements. Signal conditioning can be either open loop output detection or closed loop current correction feedback. Fluxgates measuremagnetic fields much weaker and slower than the excitation field. An important factor lowering the fluxgate sensitivity is Barkhausen noise of active magnetic medium. The sensitivity of the fluxgate to an external magnetic field is dependent on the sensitivity, hysteresis and non-linearity of the magnetic susceptibility of its sensing core. Typical sensitivity of fluxgates is 10-100 pTHz^{-1}.

The motivation of this paper is to demonstrate new types of magnetometers based on the rotating magnetization principle, offering advanced sensing and operational characteristics.

The new magnetometers

The first type of the proposed fluxgate is based on the use of a single crystalline magneto-dielectric layer of yttrium iron garnet grown by liquid phase epitaxy on a non-magnetic gadolinium gallium garnet substrate active medium [4]. The magnetic anisotropy of this set up is a combination of the magnetic crystallographic anisotropy and the induced uniaxial magnetic anisotropy formed by crystallization process and can be modified by magnetic-heat treatment and shape anisotropy contribution. The easy magnetization axes of this element are out of plane, preferably in the (111) crystallographic orientation. The magnetization field is delivered by two perpendicular coils, offering sinusoidal field of the same frequency ω and ω/2 phase shift; thus it is rotating on top of the sensing element plane, as illustrated in Figure 1. The dielectric behavior of the sensing element does not permit eddy currents, while its single crystal structure eliminates the presence of the Barkhausen noise. This way, the fluxgate principle of this structure is completely different than the rest of fluxgates, being solely dependent on the inclination of the anisotropy axes. The changes of the output response are dependent on the ambient field and do not suffer eddy current and Barkhausen noise.

Thus, extracting its three first even harmonics, the three components of the ambient magnetic field vector h_x, $h_y$and h_z are determined: the coefficients of the second, forth, and sixth harmonics components are dependent upon the component of measured magnetic field h_x, $h_y$and h_z, and the permanent component of the perpendicular magnetization component is proportional to the perpendicular component of measured field h_z.

The measurement of the three components is based on the induction response of the rotating fluxgate:

$$M_z = M_s \left(\begin{aligned} &\frac{h_z}{H_{S\perp}} - \frac{\alpha_1^2}{2}\frac{h_z}{H_\parallel} + \frac{\alpha_1}{3}\sin 3\omega t - \frac{\alpha_1\alpha_2}{2}\cos 3\omega t - \frac{\alpha_1\alpha_2}{2}\cos 9\omega t + \\ &\qquad + \frac{\alpha_1}{2}\frac{h_x}{H_\parallel}\sin 2\omega t + \frac{\alpha_1}{2}\frac{h_y}{H_\parallel}\cos 2\omega t - \\ &\qquad - \frac{\alpha_1}{2}\frac{h_x}{H_\parallel}\sin 4\omega t + \frac{\alpha_1}{2}\frac{h_y}{H_\parallel}\cos 4\omega t - \frac{\alpha_1^2}{2}\frac{h_x}{H_\parallel}\cos 6\omega t \end{aligned} \right)$$

where α_1, $\alpha_2$and $H_{S\perp}$, are parameters of the sensing element depending on its characteristics of magnetic anisotropy and have a meaning of effective field of shape anisotropy, $H_U = K_U / M_s$, $H_1 = K_1 / M_s$, $H_2 = K_2 / M_s$, and K_1, K_2 are the first and the second cubic magnetocrystallographic anisotropy constants of the iron garnet crystals:

$$\alpha_1 = -\frac{\sqrt{2}}{6}\frac{6H_1 + H_2}{H_{S\perp}}, \ \alpha_2 = \frac{1}{18}\frac{1}{H_\parallel}\left(H_2 - \frac{(6H_1 + H_2)^2}{6H_{S\perp}} \right), \ H_{S\perp} = 4\pi M_s - 2H_U - H_1 + H_2 / 9$$

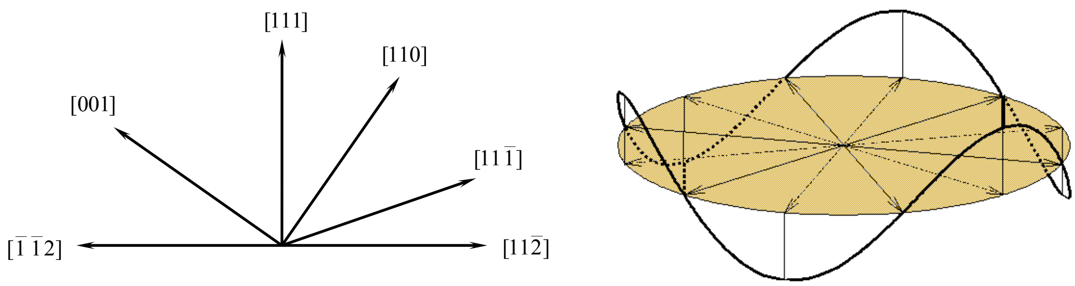

Fig. 1.*The yttrium iron garnet crystal (111) crystallographic orientation (left); in-plane excitation results in out-of-plane magnetization process (right), allowing for vector field measurements*

The sensing elements are fabricated from epitaxial iron garnet structure grown by liquid phase epitaxy on non-magnetic substrate, while the film layer is deposited on both sides of substrate. Double sided sensing elements are used, placed inside the magnetization excitation systems. Sensitivity and uncertainty measurements have been performed at the Laboratory of Physical Metallurgy, National TU of Athens, using the experimental set-up illustrated in Figure 2.

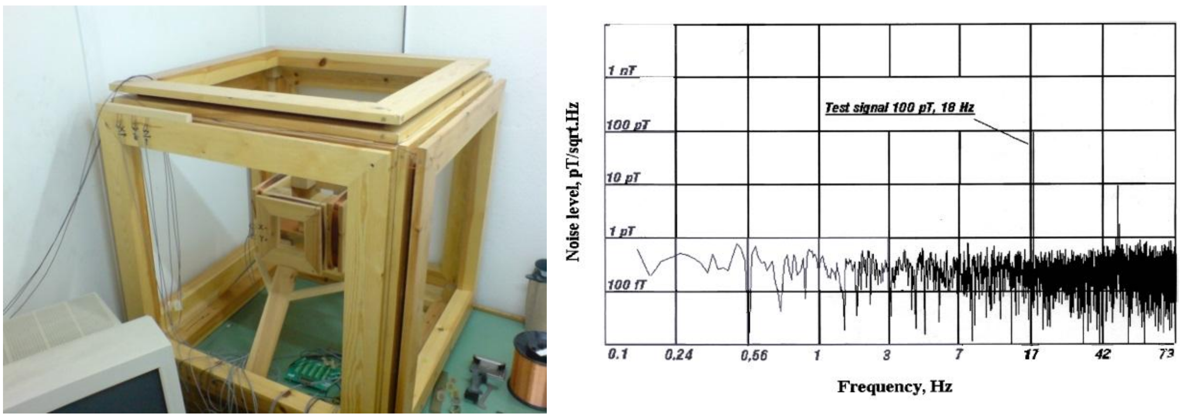

Fig. 2 *Experimental set-up (left) and results (right) measuring the sensitivity of the YIG fluxgate*

The second fluxgate sensor [5] is implementing an isotropic soft magnetic thin film, magnetically excited by means of a rotational magnetic field $\mathrm{H}_o \sin\omega t$, with $H_o > H_k$, H_k being the anisotropy field of the thin film. It is applied on the plane of the film by means of either two orthogonally arranged current conductors transmitting field of $\mathrm{H}_o \sin\omega t$ and $\mathrm{H}_o \cos\omega t$ respectively, or two couples of planar coils connected in series and transmitting the same amount of field. Such a rotational magnetic field, having amplitude larger than the anisotropy filed of the soft thin film, overcomes the Barkhausen jump field limits and makes the soft thin film to behave as super-paramagnetic material. Two different types of fluxgates have been developed. The first type used transport (conducting) means of monitoring the change of the magneto-resistance (still composing a flux-gate effect), as illustrated in Figure 3. The second type is based on a combined amorphous ribbon fluxgate - Hall-effect arrangement capable of measuring the three components of a three-dimensional quasi dc magnetic field (Figure 4).

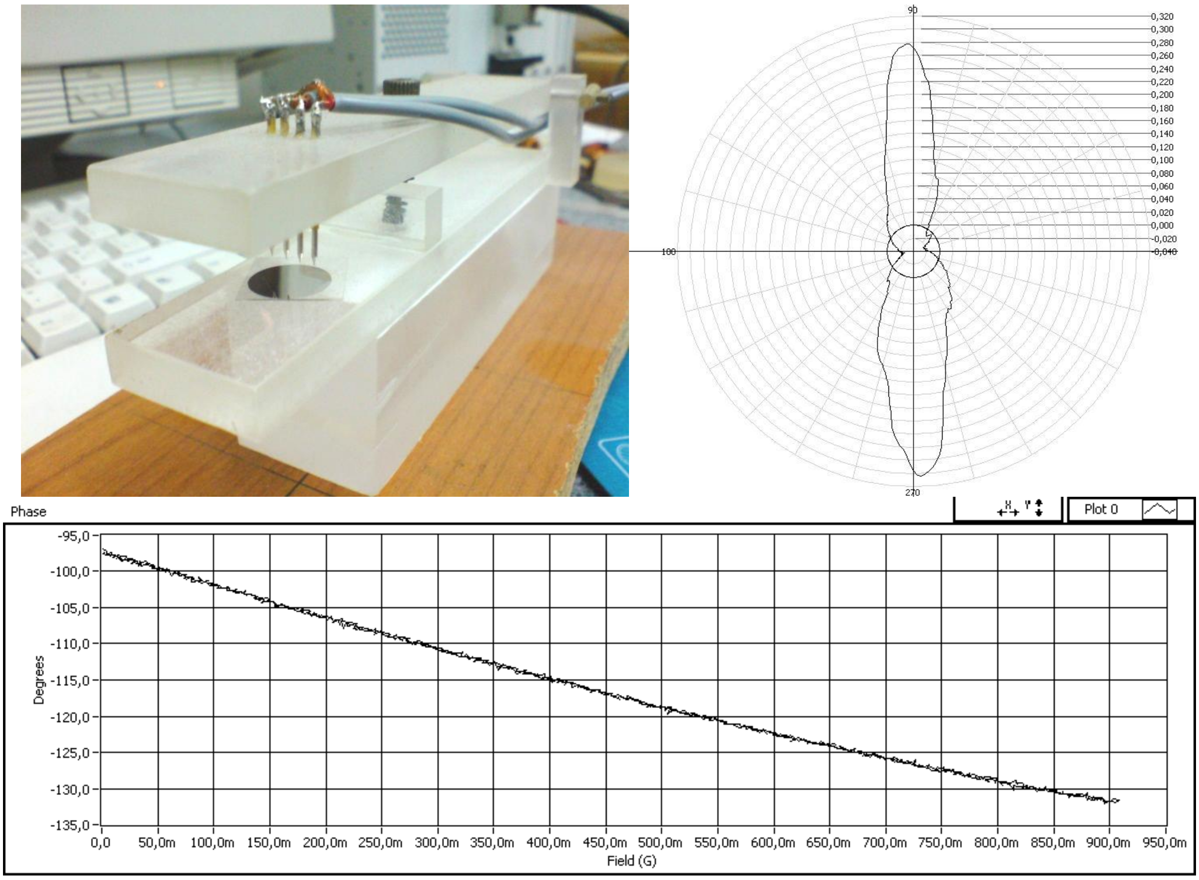

Fig. 3 *Conductive means of measuring fluxgate response (top left), corresponding on-plane field measurements (top right) and calibration curve of one field component*

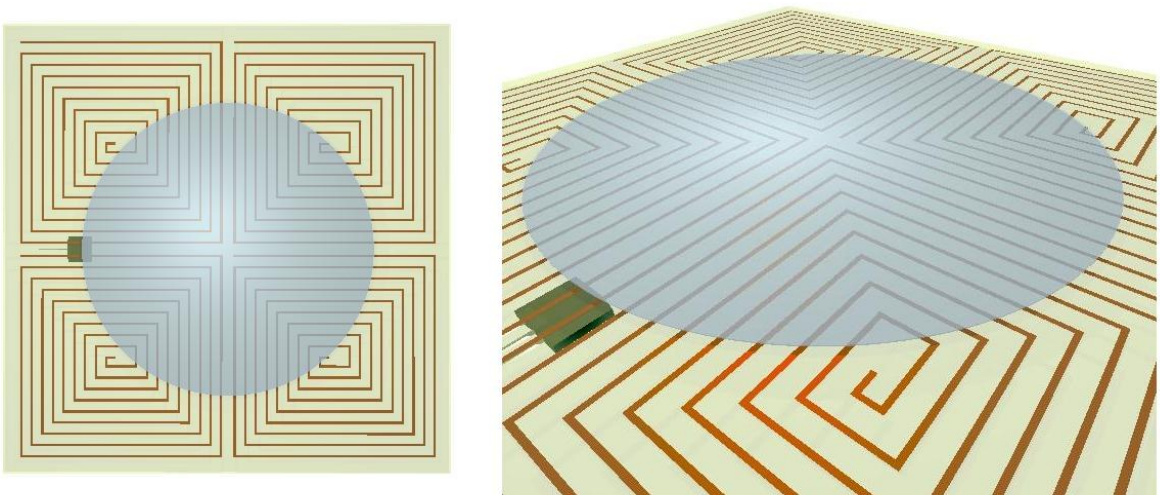

Fig 4 *Fluxgate-Hall effect hybrid three-dimensional field sensor*

The proposed device involves a thin, isotropic, circular magnetic core, the magnetization of which is driven to saturation, by means of a rotating excitation-field produced by four printed planar coils. That way, the core magnetization rotates, without Barkhausen jumps inducing a flux-density change that is sensed by a Hall device positioned at the edge of the core. The presented sensor consists of a discrete Hall device, electronic modulation – demodulation circuitry and a circular amorphous core, packaged on a PCB board. However, the system can easily be implemented on a single silicon-chip, by means of standard CMOS technologies. In this case, the amorphous core is attached onto the chip that contains the Hall device, planar coils, and electronic circuitry, according to a state-of-art low-temperature post-process. The phase modulation of the Hall sensor (which is much more sensitive than the amplitude Hall modulation) is illustrated in Figure 5.

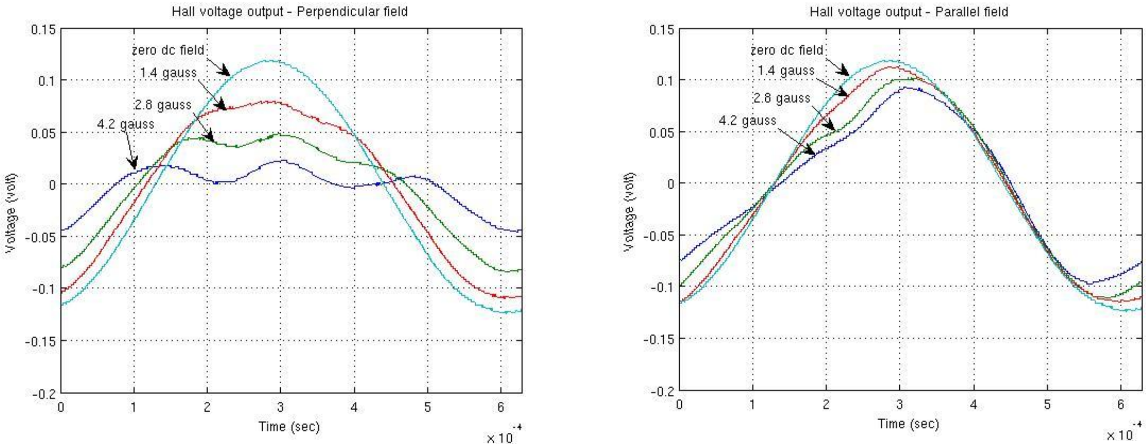

Fig. 5 *Phase modulation of the Hall hybrid due to the presence of ambient field in two directions*

Conclusions

Three new types of fluxgates have been proposed in this paper. All of them are based on rotating field applied on the surface of the sensing elements. The first sensor employs yttrium iron garnet, extracting the vector field components from the 2nd, 4th and 6th harmonic with sensitivity better than 1 pT below 0.2 Hz. The second sensor is using thin permalloy film with magneto-transport measurement, offering uncertainty better than 1 ppm. The third sensor uses phase shift modulation of Hall sensor, demonstrating sensitivity of 100 ppm and ASIC manufacturing possibility.

Acknowledgements

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