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Low-noise tunneling-magnetoresistance vector magnetometers with flux chopping technique

Van Su Luong [a,c], Jen-Tzong Jeng [b,*], Chih-Cheng Lu [a,*], Hua-Yi Hsu [a]

[a] Graduate Institute of Mechatronic Engineering/Department of Mechanical Engineering, National Taipei University of Technology, Taipei 10608, Taiwan
[b] Department of Mechanical Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung 80778, Taiwan
[c] International Training Institute for Materials Science, Hanoi University of Science and Technology, Hanoi 100000, Viet Nam

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ABSTRACT

A concept for a low-noise three-axis magnetometer consisting of tunneling magnetoresistance (TMR) sensors and a flux chopper was designed, implemented, and characterized in this work. The TMR sensors used in this study were the model of TMR2102D from Multidimension Technology Inc. Three TMR sensors were aligned orthogonally on a printed circuit board (PCB) and mounted inside a cylindrical flux chopper. The cylindrical flux chopper including a soft magnetic shielding tube and enameled copper wires was 16 mm in length and 8 mm in diameter. The shielding tube was made of a cobalt-based soft magnetic ribbon, Metglas-2714A, from Metglas Inc. The flux chopper modulated the external magnetic flux density using the fluxgate effect, which made the sensors respond to the quasi-static field at the chopping frequency. The demodulated output showed a reduction in low-frequency noise to the level of 0.17 nT/$\sqrt{}$Hz@1 Hz. To demonstrate the technical feasibility for electronic compass application, the demodulated output of the vector magnetometer prototype was recorded by rotating the device in Earth's magnetic fields about a fixed axis. The Cartesian components B_x, B_y, and B_z of the Earth's fields at various azimuth angles were retrieved by performing a calibration algorithm to correct the non-orthogonality caused by the misalignment of TMR sensors and the chopper. The calibrated outputs were linear and orthogonal to each other with an angle error less than 1° and nonlinearity of 0.7%, indicating that the chopping technique is useful to realize an extremely low-noise three-dimensional magnetometer for the geomagnetic application.

1. Introduction

Three-dimensional (3D) magnetic sensors play important roles in multiple applications, such as position sensing, automotive application, and geomagnetic navigation [1]. In recent decades, various kinds of vector magnetometers, including fluxgate sensor, Hall sensor, anisotropic magnetoresistance (AMR) sensor, giant magnetoresistance (GMR), and tunneling magnetoresistance (TMR) sensor, were developed for applications in low-cost and low-power geomagnetic measurements [2–13]. Among them, TMR is the most promising technology to realize a micro 3D magnetometer with low-noise and low-power, which are crucial criteria to the emerging portable and wearable electronic devices. To build a 3D magnetometer, many techniques were introduced [2–5]. The simple method is to use three magnetic sensors with their sensing directions along the three coordinate axes, i.e. *x*-, *y*-, and *z*- axes [2]. An alternative way is to use planar sensors and a magnetic flux guide [3–5]. However, for all of the designs mentioned so far, the experimental tolerances and environmental effects lead to the non-orthogonality between three sensing directions. Notably, this problem could be well solved using a calibration algorithm [14]. The first TMR 3D magnetometer was developed in 2002 by Tondra et al. [2,15] and the noise floor archived was around a few nanotesla. But until recently, the typical noise level of a commercial 3D TMR magnetic field sensor is still high. The noise level is about 10 nT/$\sqrt{}$Hz at above 10 Hz [16]. As the $1/f$ noise behavior exists, the noise level is even higher at a lower frequency region. Therefore, a feasible solution to the $1/f$ noise problem is a crucial study for a 3D TMR magnetometer intended for quasi-static low-field applications. To deal with the noise problem, several extrinsic methods have been reported, including TMR arrays [17], flux concentrator [18], and flux chopping techniques [19–21]. It was reported that the $1/f$ noise in TMR is mainly caused by the fluctuation of resistance [22,23]. The reduction in noise can be expected with a series array of *N* TMR elements because the total output is boosted by *N* times, while the weakly correlated fluctuation of resistance is increased only by $\sqrt{N}$. With a parallel array, the total

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[*] Corresponding author.
E-mail addresses: jtjeng@kuas.edu.tw (J.-T. Jeng), cclu23@ntut.edu.tw (C.-C. Lu).

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output is the same while the fluctuation of resistance is reduced by $\sqrt{N}$. For both cases, the field noise gives the same noise reduction ratio of $\sqrt{N}$. However, with the array method, the $1/f$ behavior remains. In this way, the overall sensing area is quadratically increased with the reduction ratio. The other methods, such as the flux concentrator, can suppress the field noise by enhancing the sensitivity. However, the magnetic hysteresis induced by magnetic thin film results in the drift in dc level of the sensor output. Feasible methods to suppress the $1/f$ noise are an ac biasing [24] and voltage chopping [25], which are similar to the chopping technique commonly applied in optical measurements. The two kinds of electrical chopping methods can suppress the low-frequency noise arising from the charge-induced fluctuation. However, for TMR sensors, the $1/f$ noise originates from both electrical and magnetic fluctuations [26]. Thus, the noise due to the instability of magnetization cannot be overcome by the electrical chopping method. Notably, the magnetic flux chopping technique, which was invented by Jander's group [19], is a promising method to reduce both the magnetic and electronic $1/f$ noise. The successful implementations of flux chopper have been reported in recent years [20,27]. The oscillating flux concentrator [27] and the modulating magnetic shielding [20] are both viable methods to "chop" the external magnetic flux, so as to reduce the low-frequency magnetic noise. Nevertheless, the unstable magnetization state of mechanical flux chopper makes it ineffective for suppressing the extremely low-frequency noise. In fact, the hysteresis could be minimized by modulating the permeability of flux chopper [19]. It was shown that the shielding flux chopper was capable of reducing low-frequency noise by a factor above 20 at frequencies below 1-Hz [20]. To build a low noise three-axis magnetometer with a shielding flux chopper, a challenge is that at least three sets of flux-chopped TMR sensors must be used in a compact size. Hence we designed and proposed a new concept for low-noise vector magnetometers comprising three high-sensitivity TMR sensors and a magnetic flux chopper in this study. The flux chopping technique was successfully applied to the TMR sensors and proven to suppress the low-frequency noise using a single flux chopper, which allows future integration of the system into a single package. The non-orthogonality problem was also well solved by using a calibration algorithm. The noise and sensitivity characterizations were performed and discussed, and the feasibility for geomagnetic application was demonstrated.

2. Experimental details

2.1. Design of magnetometer and measurements

The design of a 3D magnetometer using TMR sensors and a shielding chopper is shown in Fig. 1. The sensing elements were the TMR2102D sensors, from the Multidimension Technology Inc. [28]. The TMR sensor is in a full Wheatstone bridge configuration consisting of four tunnel-junction arrays, as depicted in Fig. 1(c). The packaging size of the DFN8 type is 3 mm × 3 mm × 0.75 mm, and the linear range is ±30 Oe with a nonlinearity of 1% at the full scale. The intrinsic sensitivity is about 4.9 mV/V/Oe in the full-scale operation range up to ±90 Oe of saturation field [28]. Three TMR sensors were aligned orthogonally on a print circuit boards (PCB) with the sensing directions along three-dimensional coordinates, as shown in Fig. 1(b). These sensors were placed in the center of a cylindrical chopper tube, which is 16 mm in length and 8 mm in diameter. The core of the chopper is made of a cobalt-based amorphous soft magnetic ribbon, Metglas-2714A, from Metglas Inc. [29]. The magnetizing field for chopper operation was induced by the enameled copper wire coil threading through and wrapping the tube. The field strength to saturate the core of the chopper is above 0.1 Oe. The chopping signal generator and phase sensitive detection (PSD) were carried out digitally using a data acquisition (DAQ) device, which is the multifunction device of the model USB-6216 from National Instruments Inc. The outputs of three TMR sensors were pre-amplified via a three-channel instrumentation amplifier, INA111 from Texas Instruments Inc. A 1 kHz square wave chopping signal was generated by the DAQ, and then it was amplified via a power amplifier to induce a 200 mA chopping current. The current switched the magnetization of the core between the saturation and unsaturation, thus turning the magnetic flux ON and OFF. The sensitivity of the device was determined through the slope of a Volt/Tesla curve. To measure noise, the system was placed inside a tri-layer magnetic shielding chamber. A dynamic signal analyzer, model SR780 from the Stanford Research Systems, was used to record the noise spectrum. To measure the azimuth response, the device was fixed on a manual rotation stage. The software-based PSD and device calibration were performed by a commercial LabVIEW program.

2.2. Calibration algorithm

The 3D magnetometer aims to operate at a very low frequency below 1 Hz. Therefore, the magnetometer has been tested as an electronic compass with a calibration algorithm. Although the sensing directions of three sensors were aligned as orthogonal as possible to each other, the actual sensing directions were found to be non-orthogonal, owing to the misalignment of the three sensors on the separate PCBs as well as the flux bending effect of the chopper. To overcome this problem, the conversion algorithm employing voltage-to-field transfer matrix was performed. Suppose that the Earth's field is in an arbitrary direction relative to the magnetometer, the Cartesian components B_x, B_y, and B_z are

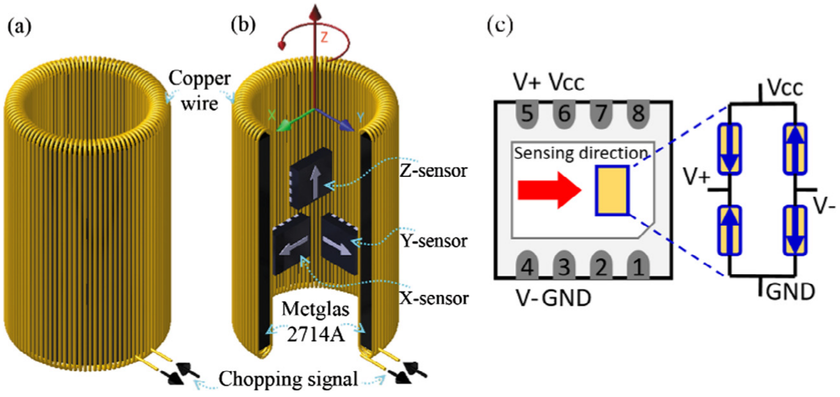

Fig. 1. Design of the three-axis TMR magnetometer with a flux chopper: (a) side view, (b) quadrant cross section view, and (c) structure of the DFN8-TMR2102D sensor [28].