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An orthogonal fluxgate-type magnetic microsensor with electroplated Permalloy core

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Abstract

In this paper, we present a new microfabricated orthogonal fluxgate sensor structure. The sensor consists of an electroplated copper excitation rod surrounded by an electroplated Permalloy layer and has planar pick-up coils for signal detection. The use of electroplating leads to a low-cost fabrication process and the use of planar pick-up coils provides easy integration with CMOS processes. The fabricated sensor has an excitation independent linear range of ±200 μT, a sensitivity of 510 μV/mT, and an average power dissipation of 8.1 mW for 100 mA-peak sinusoidal excitation current at 100 kHz frequency. The equivalent magnetic noise is 95 nT/$\sqrt{\text{Hz}}$ at 1 Hz, and the RMS noise is 215 nT for 10 Hz bandwidth.

Keywords: Magnetic Sensors; Fluxgate Sensors; Orthogonal Fluxgate; Electroplated Permalloy; CMOS Compatible

1. Introduction

Fluxgate-type magnetic sensors are used in the magnitudnal and directional measurement of DC or low-frequency AC magnetic fields. Their typical application areas are electronic compasses, current sensors, magnetic ink reading, detection of ferrous materials, and non-destructive testing [1,2]. The main advantages of fluxgate sensors are their low offset drift, high sensitivity, and linearity. On the other hand, limited magnetic field operating range and high perming are still the problems of contemporary fluxgate sensors [3].

In this paper, we present a new microfabricated orthogonal fluxgate sensor structure with a measuring range independent of the applied excitation magnetic field. Previously reported microfabricated fluxgate sensors use the parallel configuration [4,5]. In the parallel configuration, the sensing and detection mechanisms are dependent on each other in such a way that a sensor with a higher linear range requires more excitation magnetic field for proper operation due to the demagnetization effect. However, in the orthogonal configuration, once the excitation mechanism is designed, the measuring range can be adjusted by modifying only the core length [6,7]. Because of these advantages, we developed a CMOS compatible process flow that enables the realization of an orthogonal fluxgate sensor with microfabrication techniques.

2. Orthogonal sensor structure and operating principle

Fig. 1 shows the new orthogonal fluxgate microsensor structure. A non-magnetic excitation rod is coated by a ferromagnetic material forming a closed loop for the excitation magnetic field. Such a configuration of the ferromagnetic core provides the orthogonality between the excitation magnetic field and the measured external magnetic field. Due to the closed magnetic loop and low-resistance excitation rod, the core can be saturated by relatively small power consumption.

Fig. 2 illustrates the operating principle of the orthogonal fluxgate sensor based on the magnetization curve of the ferromagnetic material. The magnetization curve represents the change in the magnetization of a material with the applied magnetic field. This relation can be formulated as:

$$\Delta\mathbf{B} = \mu_0\Delta(\mathbf{H} + \mathbf{M}) \qquad (1)$$

where μ_0 is the permeability of air, **B** the flux density inside the core, **H** the applied magnetic field, and **M** is the magnetization of the ferromagnetic material. The symbol Δ represents the local

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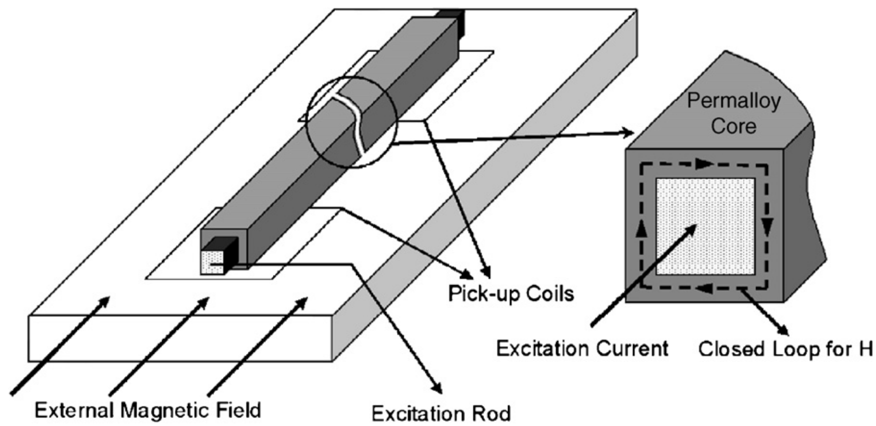

Fig. 1. The sensor structure.

variation of the value around a given point. The magnetization of the material is a function of the applied magnetic field such that

$$\Delta\mathbf{M} = \boldsymbol{\chi} \times \Delta\mathbf{H} \tag{2}$$

$\boldsymbol{\chi}$ being the susceptibility tensor of the material, whose relation to the relative permeability $\boldsymbol{\mu}_r$ is:

$$\boldsymbol{\mu}_r = \boldsymbol{\chi} + \mathbf{I} \tag{3}$$

where $\mathbf{I}$ is the identity matrix.

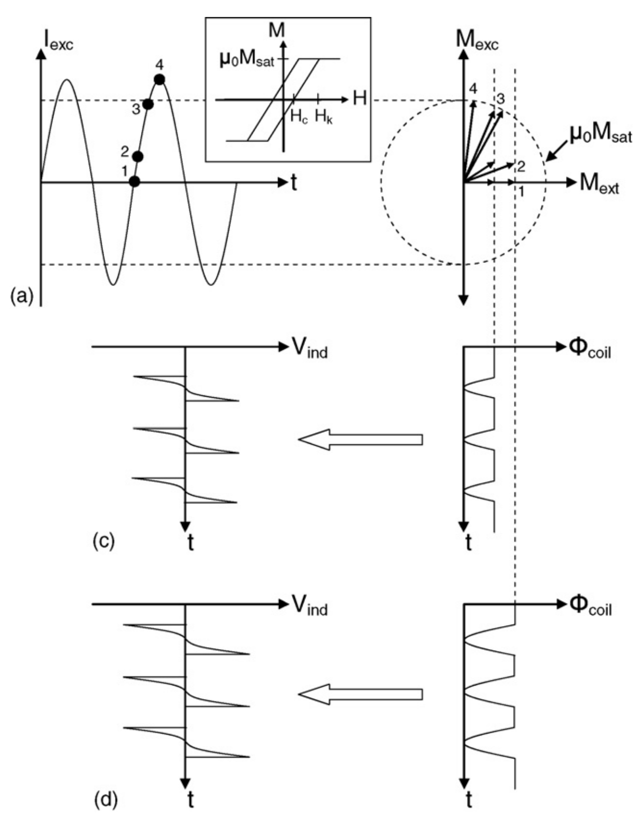

Fig. 2. (a) The sinusoidal excitation current and the **M**–**H** curve of the material. (b) The magnetization vector **M** inside the core with two orthogonal components M_{exc} and M_{ext}. (c and d) The flux passing trough the pick-up coils and the resulting induced voltages for two different external magnetic field values.

In Fig. 2a a sinusoidal excitation current I_{exc} passing through the excitation rod of the sensor is shown. This AC current generates a periodic magnetic field $\mathbf{H}_{exc}$ inside the ferromagnetic core. The magnetization of the ferromagnetic core reaches the saturation M_{sat} two times for each period of the excitation according to the M–H curve of the ferromagnetic layer (Fig. 2a). If no external magnetic field is applied, the vector **M** is in the direction of the excitation field $\mathbf{H}_{exc}$. However, in the presence of an external magnetic field, the **M** vector is composed of two mutually perpendicular components, M_{exc} and M_{ext}, resulting from the excitation magnetic field and external magnetic field, respectively. By increasing the excitation magnetic field $\mathbf{H}_{exc}$ with increasing I_{exc}, the M_{exc} component of vector **M** starts to increase (y-axis in Fig. 2b). However, it can increase up to a value, which is equal to $\mu_0 M_{sat}$, which is the highest possible magnetization inside the ferromagnetic core. This is illustrated by the dashed circle in Fig. 2b. The component M_{ext} stays unchanged up to the excitation field values $H_{exc} \approx H_k$. This is represented by the points and arrows 1 and 2 in Fig. 2a and b. For H_{exc} values higher than H_k, the ferromagnetic core saturates and this forces the M_{ext} component of vector **M** to decrease and to reach the minimum for the peak value of the excitation field H_{exc} (points 3 and 4). When H_{exc} decreases to smaller values, the $\mathbf{M}_{ext}$ component starts to increase again, and returns back to its initial value. This cycle creates a periodic change in the flux passing through the pick-up coils Φ_{coil} resulting in an induced voltage across their terminals (Fig. 2c and d). The even harmonics of this induced voltage is proportional to the external magnetic field [3].

The orthogonality of the excitation and external magnetic fields makes the detection mechanism independent of the excitation mechanism. So, one can benefit from the demagnetization effect of the core in the sensing direction to arrange the measuring range of the sensor while the excitation mechanism stays unchanged. Due to the demagnetization effect, the apparent relative permeability μ_{app} of the core deviates from its intrinsic value in the sensing direction. This can be expressed as [8]:

$$\mu_{app} = \frac{\mu_i}{1 + N(\mu_i - 1)} \tag{4}$$