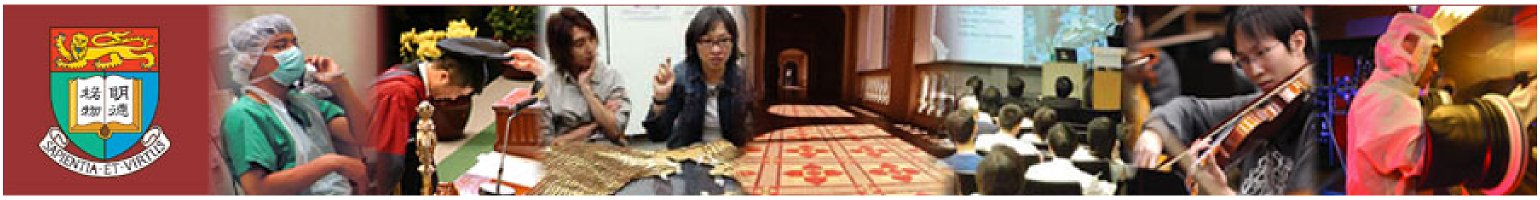

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A Novel Bar-Shaped Magnetic Shielding for Magnetoresistive Sensors in Current Measurement on Printed Circuit Boards

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This paper presents the study of a novel bar-shaped magnetic shielding for magnetoresistive (MR) sensors in current measurement on printed circuit boards (PCB). The main physical principles of the shielding effect were studied by using the analytical model of magnetic flux concentration. Finite element analysis (FEA) simulations were used to simulate the shielding effects with changing geometrical parameters of the bar-shaped magnetic shielding. The dependences of the shielding effect on the parameters of length, width and thickness were analyzed. It shows that these parameters are critical for designing magnetic shielding. This new concept of magnetic shielding for MR sensors in current measurement on PCB was experimentally tested and verified in a laboratory setup. The experimental results verify the feasibility and effect of this novel magnetic shielding for MR sensors.

Index Terms—**Finite element analysis (FEA), magnetic flux concentration, magnetic shielding, magnetoresistive (MR) sensors.**

I. Introduction

MAGNETORESISTIVE (MR) sensors can offer a flat frequency response from dc to megahertz magnetic fields [1]. This significant advantage makes them attractive for multi-frequency current measurement on printed circuit boards (PCBs) by sensing the magnetic field [2]–[4]. Magnetic shielding is typically needed for suppressing the magnetic noise from the surrounding environment [5]. Traditionally, magnetic shielding is achieved by enclosing the sensor and the targeting magnetic source. However, the enclosure-type shielding does not work in some situations, e.g., on PCBs where the noise source and signal source can both be in proximity to the sensor.

In this work, we proposed a new design concept of magnetic shielding based on magnetic flux concentration (MFC) [6], [7]. Magnetic flux concentrators are used to concentrate and divert the magnetic noise away from the sensing direction of the MR sensor. The magnetic shielding is designed to be in the form of a pair of bar-shaped flux concentrators made of material with very high relative permeability, such as mu-metal (nickel-iron alloys, $\mu_r \approx 10^4 \sim 10^5$), sandwiching the MR sensor, and it is oriented along the electric current to be measured (Fig. 1). The magnetic field emanating from the electric current to be measured is along the sensing direction of the MR sensor. The shielding attracts and concentrates the surrounding magnetic noise, forcing the magnetic noise vector to rotate to the insensitive direction of the MR sensor. Thus, the magnetic noise cannot enter into the sensing direction of the MR sensor. On the other hand, the shielding does not affect the magnetic field signal from the electric current, which is in the sensing direction of the MR sensor. In this work, the main physical principles of this novel shielding design were studied. The dependences of the shielding effect on the geometrical parameters were analyzed. Finite element analysis (FEA) was conducted for optimizing the design of the bar-shaped shielding.

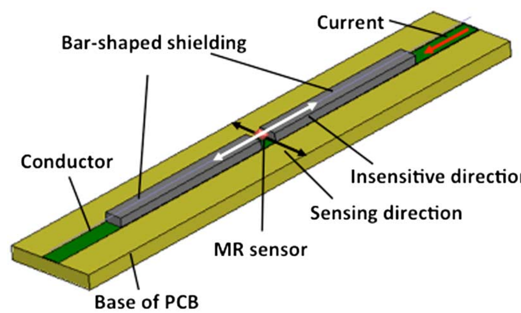

Fig. 1 Model of the bar-shaped magnetic shielding.

II. Magnetic Shielding Model Based on Magnetic Flux Concentration

High permeability material in an external magnetic field tends to attract and concentrate magnetic flux lines and change the original magnetic field distribution. The stronger the MFC effect, the more the magnetic field distribution is changed. As a result, the magnetic flux density vectors inside the material and outside the material are changed in both the direction and the amplitude. As an example, a high permeability rod-shaped magnetic object, subject to a uniform external magnetic field, is simulated with FEA. The magnetic field flux density vectors are shown in Fig. 2. When the directions of the magnetic field vectors are parallel with the rod axis [Fig. 2(a)], it concentrates the magnetic flux lines into itself and significantly changes the distribution of outside magnetic field. It can be observed that some magnetic field vectors even change direction and become perpendicular with their original direction. Fig. 2(b) shows the simulation of the case that the direction of the magnetic field vectors is angled with the rod axis. It is found that the magnetic field vectors which are near the ends of the rod are attracted and change directions. These magnetic field vectors become almost parallel with the rod axis. Fig. 2(c) shows the case that the magnetic field vectors are perpendicular with the rod axis. It can be seen that the high permeability material rod can hardly affect the

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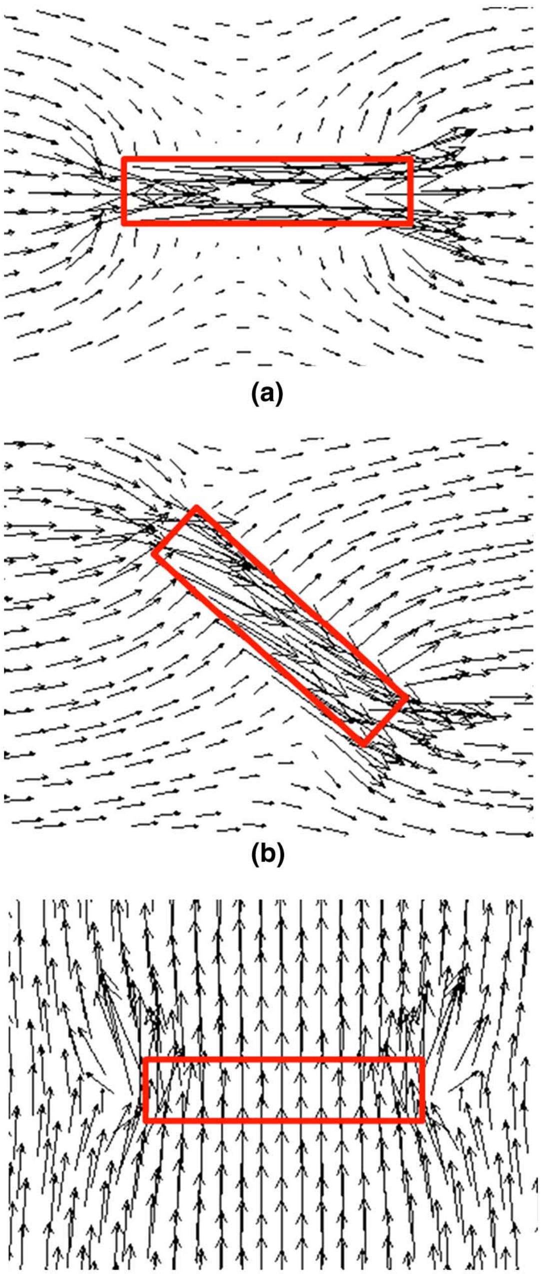

Fig. 2 Simulation results of the magnetic vector when a single high permeability rod is immersed in magnetic field. (a) Magnetic vector is parallel with the rod axis. (b) Magnetic vector is 45 degrees angled with the rod axis. (c) Magnetic vector is vertical with the rod axis.

distribution of the magnetic field. The magnetic field vectors at both ends of the rod only slightly change their direction.

The MFC effect of the rod-shaped concentrator immersed in uniform distributed magnetic field $\mathbf{H}_0$ can be analytically studied. Its inside magnetic flux density $\mathbf{B}$ is related to its inside magnetic field $\mathbf{H}$ by the relation:

$$\begin{aligned}\mathbf{B} &= \mu_0(\mathbf{H}+\mathbf{M})\\ &= \mu_0(1+\chi_v)\mathbf{H}\end{aligned} \tag{1}$$

where μ_0 is the vacuum permeability, $\mathbf{M}$ is the magnetization of the material, and χ_v is the volume magnetic susceptibility. The volume magnetic susceptibility is related to the relative permeability μ_r of the material by $\chi_v = \mu_r - 1$. The internal magnetic field $\mathbf{H}$ is the result of external field $\mathbf{H}_0$ adding demagnetizing component $\mathbf{H}_d$, $\mathbf{H} = \mathbf{H}_0 + \mathbf{H}_d$. For the rod-shaped concentrator, having an axis in the x direction, $\mathbf{H}_d$ is related to $\mathbf{M}$ by [8]

$$(\mathbf{H}_d)_x = -N_x\mathbf{M}_x \tag{2}$$

where N_x is the x-direction demagnetizing factor. As a result, we have

$$\mathbf{H}_x = (\mathbf{H}_0)_x - N_x\chi_v\mathbf{H}_x. \tag{3}$$

The inside magnetic field is determined by N_x which entirely depends on the geometry of the rod, while χ_v which is only related to the material. The N_x is determined by

$$N_x = \frac{4.02\log_{10}(m) - 0.92}{2m^2}, \quad m \geq 10 \tag{4}$$

where m is the length to diameter ratio (L/d) of the rod. In order to study the MFC effect within the rod, we define the magnetic gain $G = \mathbf{B}/\mathbf{B}_0$, where $\mathbf{B}_0 = \mu_0\mathbf{H}_0$. From (1) and (3), we can obtain

$$\begin{aligned}G &= \frac{\mathbf{B}_x}{\mathbf{B}_0} = \frac{\mu\mathbf{H}}{\mu_0\mathbf{H}_0}\\ &= \frac{\mu_r}{1+N_x(\mu_r-1)}.\end{aligned} \tag{5}$$

The magnetic gain G of a rod (relative permeability material $\mu_r = 10000$) immersed into a magnetic field with the field vector direction 45 degrees to the rod axis can be calculated with (5). Fig. 3 shows the magnetic gain inside the rod as a function of m and the corresponding variations of the angle ϕ between the magnetic vector direction inside the rod and the rod axis. It can be seen that, as m increases, the maximum value of magnetic gain increases and the largest magnetic gain is obtained when the angle ϕ is the smallest. Consequently, a magnetic rod with certain aspect ratio can change the magnetic vector direction and provide magnetic shielding effects.

III. Design of Magnetic Shielding and Experimental Proof

Based on the above physical analysis on the magnetic flux concentration of a magnetic rod, a simple magnetic shielding was designed for MR sensors in current measurement on a PCB. Firstly, since the circuit conductor is band-shaped, it is not easy to install magnetic rods on the circuit. Therefore, bar-shaped magnetic flux concentrators are used instead [9]. Besides, based on our simulation, it is found that the direction of the inside magnetic vector is changed more significantly than the vicinal magnetic vector. In other words, it is not easy to control the vicinal magnetic vector direction with only one magnetic rod. Therefore, two separate bar-shaped magnetic shieldings are adopted for suppressing the magnetic noise effectively in the sensing zone. Fig. 4 shows the two bar-shaped magnetic flux concentrators sandwiching an air gap with width of g where the magnetic sensor is placed. For the shieldings with defined material ($\mu_\mathrm{r} \approx 10^4$), the shielding effect is evaluated with the angle θ between magnetic noise vector and the insensitive direction of

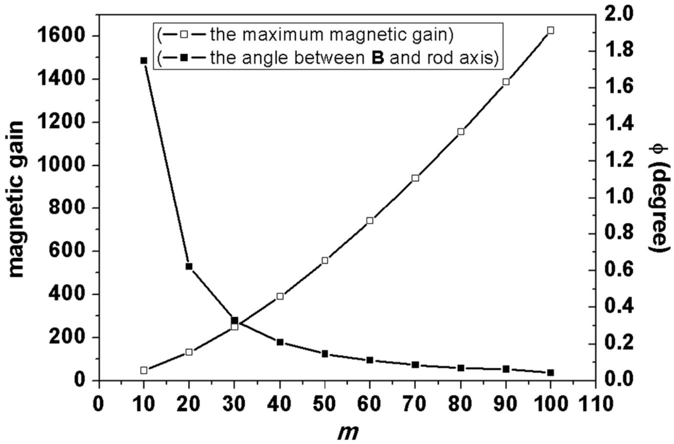

Fig. 3 Calculation and FEA simulation results of the high permeability rod in magnetic field. Magnetic gain G as a function of m (the length to diameter ratio of the rod) is denoted by empty square. Angle ϕ between the inside magnetic flux density vector and the x-axis as a function of m is denoted by solid squares.

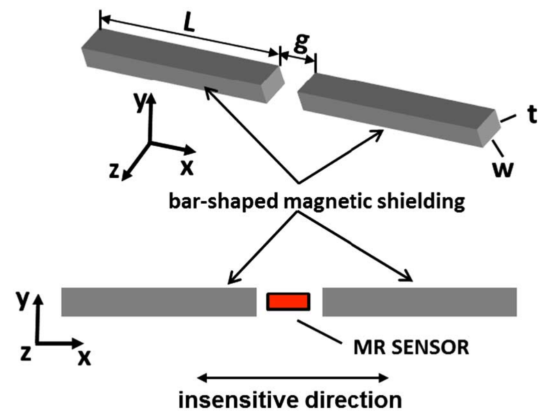

Fig. 4 Geometries of two bar-shaped magnetic shieldings and the schematic diagram of the installation of the shieldings with a MR sensor. Sensing zone is at the gap between the two magnetic shieldings.

the MR sensor in the sensing zone. With the initial $\theta = 45°$, the dependence of θ in the sensing zone on bar-shaped shielding length L, width w and thickness t is simulated by FEA method and analyzed. Since the available GMR sensor in this work is in the size range of millimeters, the g between the shieldings is defined as $\mathrm{g} = 5$ mm.

Here we investigated the relation between the angle θ and the length of the shielding. When the width and thickness are defined as 2 mm and 1.5 mm, the direction of the magnetic noise vector in the sensing zone can be simulated with different shielding length. As shown in Fig. 5, the variation of the angle θ with the magnetic noise vector is simulated. As the width and thickness are constant, when the shielding length increases, θ decreases which denotes that the direction of the magnetic noise vector is gradually aligning with the insensitive direction of the MR sensor.

On the other hand, with the shielding length and thickness defined as 70 and 2 mm, the relation between θ and the shielding width is simulated. Fig. 6 shows that θ increases when the width increases from 1 to 1.5 mm. Since the increasing width leads to increasing shielding cross-section area, the concentration effect is weakened. As a result, the shielding effect is weaker. As the width further increases from 1.5 to 5 mm, it leads to

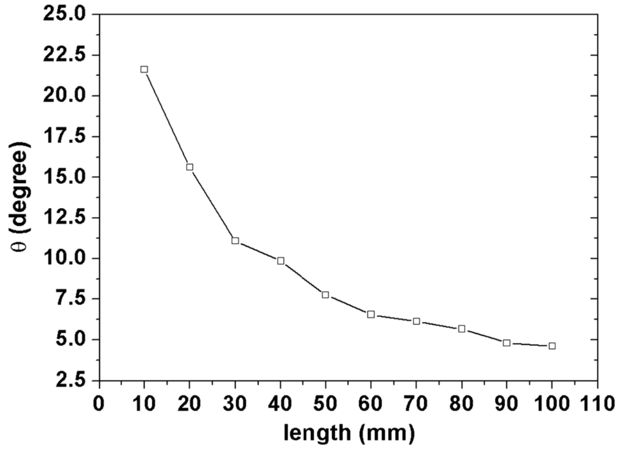

Fig. 5 Simulation results of the angle θ between magnetic noise vector and the insensitive axis of MR sensor with the variation of bar-shaped shielding length.

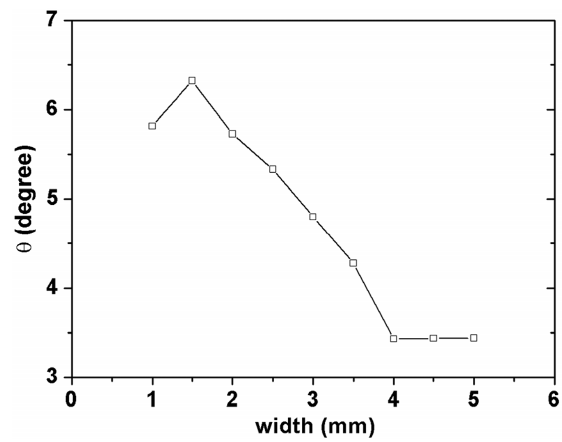

Fig. 6 Simulation results of the angle θ between magnetic noise vector and the insensitive axis of MR sensor with the variation of shielding width.

the strengthening of the concentration effect since the shielding volume increases and more magnetic flux lines are absorbed into the shielding. θ decreases rapidly to less than 3.5 degrees. As the width further increases beyond 4 mm, θ does not decrease anymore because the strengthening of the concentration due to increased shielding volume is canceled by the weakening of the concentration due to increased cross-section area.

As the shielding length and width are defined as 70 and 4 mm, one can find that θ increases when the shielding thickness increases from 0.5 to 5 mm (Fig. 7). As explained, the increasing θ is induced by the increasing cross-section area of the shielding. When the thickness continues to increase, more and more magnetic flux lines are concentrated. This effect offsets the weakened concentration induced by the increased shielding cross section. As a result, θ nearly keeps constant as the thickness increases from 2.5 to 5 mm.

In order to verify the shielding effect of the bar-shaped magnetic shielding, a laboratory setup including a GMR sensor (NVE AA002-02e) and coils which provide magnetic noise were established as the testbed. The configuration of the shieldings, GMR sensor, and the PCB circuit with an electric current line is the same as in Fig. 1. The shielding ($\mu_\mathrm{r} \approx 10^4$) was designed with length of 75 mm, width of 2 mm and thickness of 1.5 mm. The circuit is energized with 1 A dc current. The magnetic signal emanated from this 1 A dc current is 6 Gauss

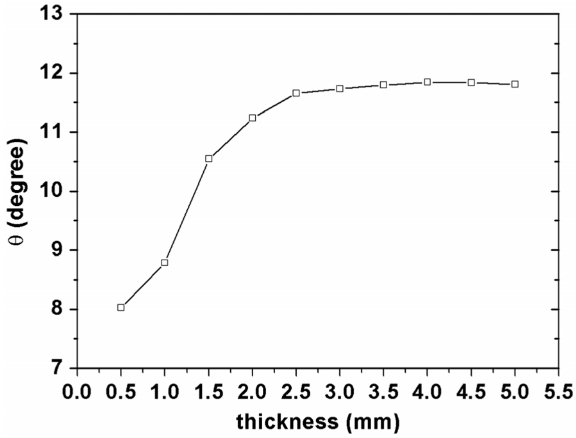

Fig. 7 Simulation results of the angle θ between magnetic noise vector and the insensitive axis of MR sensor with the variation of shielding thickness.

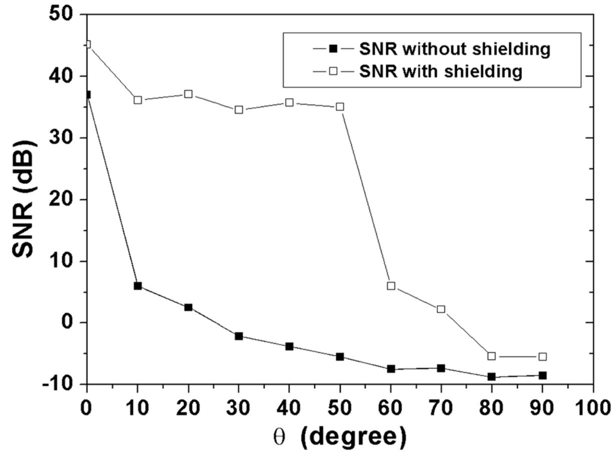

Fig. 8 Experimental results of the variation of SNR with the angle θ between the magnetic noise vector and the insensitive direction of the MR sensor.

in the sensing zone between the bar-shaped shieldings. The magnetic noise provided by the coils is 12 Gauss in the sensing zone. In Fig. 8, when the angle θ between the magnetic noise vector and the insensitive direction of the GMR sensor changes from 0 degrees to 90 degrees, more and more magnetic noises enter into the sensing direction of the GMR sensor. It is found that, without the shielding, the signal-to-noise ratio (SNR) decreases rapidly from 37 dB to below 10 dB as the angle increases from 0 degrees to 10 degrees. The SNR drops further as the angle increases beyond 10 degrees. With the shielding, the SNR maintains above 35 dB until the angle increases beyond 60 degrees. When the angle is greater than 60 degrees, most magnetic noise enters into the sensing direction of the GMR sensor. As the width (around 4 mm) of the GMR sensor is larger than the width (2 mm) of the bar-shaped shielding, the shielding was not large enough to encompass the GMR sensing area. In other words, the designed shielding was not optimized for this GMR sensor. This leads to the rapid decrease of SNR when the angle between the magnetic noise vector and the insensitive direction of the GMR sensor is larger than 60 degrees.

IV. Conclusion

This paper presents the study of a new design concept of magnetic shielding whereby bar-shaped magnetic flux concentrators are used to concentrate and divert the magnetic noise away from the sensing direction of the MR sensor. The physical principles of magnetic flux concentration was studied and used to analyze the shielding effect of the high-permeability object. The magnetic shielding was designed to be in the form of a pair of bar-shaped flux concentrators. FEA simulations were conducted to study the effects of geometrical parameters on the shielding effect. Based on the simulation results, the shielding performance of the bar-shaped magnetic shieldings were tested and verified in our laboratory setup. It demonstrates that the magnetic noise can be effectively eliminated with this novel shielding design.

Acknowledgment

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