FLUX CONCENTRATOR OPTIMIZATION EXPLOITING SATURATION FOR MICROMACHINED AC MAGNETIC FIELD SENSORS

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ABSTRACT

We introduce a planar magnetic flux concentrator (MFC) designed for magnetic field sensors. The MFC comprises permanent magnets and high-permeability soft magnetic components, enabling the integration of DC magnetic bias and AC magnetic field amplification within a single device set. Finite element method (FEM) simulations demonstrate a 26-fold amplification of AC magnetic signal with the introduction of the MFC. Additionally, a further 11% enhancement is achieved by sizing the soft magnetic components to intentionally induce saturation in specific portions of the magnetic circuit. The proposed design presents a promising path for improving magnetic sensor performance while addressing challenges associated with DC biasing and signal loss.

KEYWORDS

Magnetic flux concentrator (MFC), MEMS resonant sensors, finite element method (FEM), saturation-exploiting design, permanent magnets, soft magnetic components.

INTRODUCTION

Magnetic flux concentrators (MFCs) play a vital role in boosting the sensitivity of magnetic field sensors [1], [2], [3], particularly those detecting ultralow time-varying (AC) magnetic fields [4], [5], [6]. Typically, MFCs are structured symmetrically with an air gap at the center, specifically designed to accommodate the magnetic field sensor. Composed of high-permeability soft magnetic material, MFCs effectively guide and concentrate magnetic flux lines through the airgap where the sensor is situated. This leads to an amplification of the external magnetic field, thereby enhancing the magnetic field detection capability of the sensor. Given that many magnetic sensors are commonly fabricated using MEMS or CMOS technology [7], [8], [9], [10], MFCs are generally designed as planar structures, which facilitates the on-chip fabrication and integration process.

Research based on finite element method (FEM) simulations has revealed that the magnetic amplification characteristics of planar MFCs are shape dependent. P. M. Drljača conducted a study on the tradeoff between amplification and saturation using various concentrator shapes such as bar-shape, T-shape, and triangle shape [11]. X. Sun examined the magnetic gain and linear working range of typical-shaped MFCs at the micrometer scale [12], while X. Zhang investigated the impact of geometry and size parameters on MFC performance, validating the simulation results through experimental tests [13]. Among these typical shapes, trapezoidal MFCs were favored for their excellent concentration performance and widest linear work range. Recent work by Y. Huo, employing trapezoidal mu-metal (NiFeMo) MFCs, showcased a 25-fold increase in the sensitivity of a magnetostriction-based MEMS resonant magnetic field sensor without raising the noise floor or reducing the bandwidth [14].

Such magnetostrictive magnetic sensors utilize magnetostrictive films that require an external DC magnetic bias to operate efficiently [14]. However, it can be challenging to provide this DC bias with minimal stray fields within the MFC construct while not magnetically 'shorting out' the desired AC signal. To address this challenge, we show a saturation-exploiting design that further improves the performance of this class of magnetic sensors

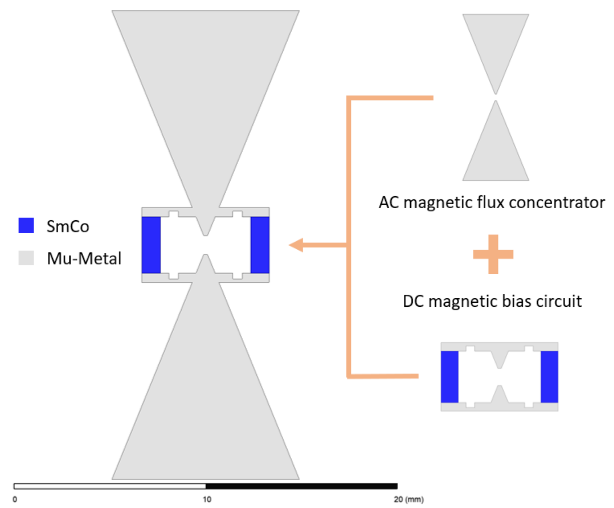

Figure 1: Schematic of DC-biased MFC for AC field measurement.

(Fig. 1). The design can be conceptualized as a composite of trapezoidal AC MFCs and a DC magnetic bias circuit. Central to our proposed design is the intentional induction of saturation in specific portions of the magnetic circuit. By carefully sizing the soft magnetic components, we achieve an extra enhancement of 11% in AC flux concentration. This saturation-exploiting strategy not only improves sensor sensitivity but also mitigates signal loss and minimizes interference from stray fields, thereby optimizing the overall performance of MEMS resonant sensors in magnetic field detection applications.

In this paper, we begin by introducing the DC magnetic bias circuit and the strategy for manipulating the DC magnetic field at the air gap. Experimental results demonstrate our capability to tune the field from 2 mT to 16 mT effectively. Following this, we will present the FEM simulation results of the DC-biased MFC and discuss the efficacy of exploiting yoke saturation to improve sensor performance.

DESIGN OVERVIEW

DC Magnetic Bias Circuit

The DC magnetic bias circuit comprises two primary components: the magnet, which generates the DC magnetic field, and the yoke, responsible for guiding the magnetic flux to the central air gap where the sensor is located [see Fig. 2(a)]. To achieve optimal performance for the sensor, different DC magnetic field strengths may be required. This can be achieved by adjusting the thickness of the magnets and yokes. Additionally, strategic notches can be introduced into the yoke to either fine-tune the DC magnetic bias field or deliberately induce saturation [see Fig. 2(b)]. Furthermore, bar-shaped shunts made of high-permeability material can be added on top, bottom, or both sides of the magnets to further attenuate the magnetic field by magnetically 'shorting-out' part of the magnetic field [see Fig. 2(c)]. In our design, SmCo permanent magnets supply the DC magnetic bias, with mu-metal serving as

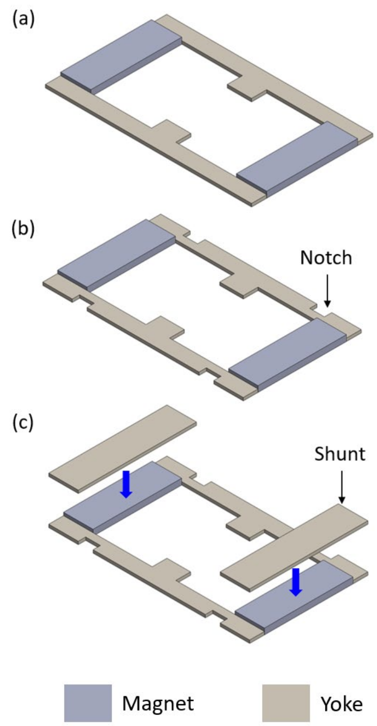

Figure 2: Schematic of DC magnetic bias circuit and tuning strategy. (a) Layout of magnets and yokes. (b) Adding notches to fine-tune the DC magnetic field and induce saturation. (c) Incorporating shunts to attenuate the magnetic field.

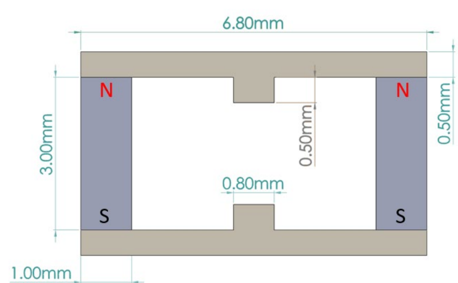

Figure 3: Top view of the magnetic circuit displaying magnets and yokes, including length dimensions. The magnetostrictive-based MEMS resonant sensor is to be placed within the central air gap.

both the high-permeability magnetic yokes and shunts, efficiently guiding the magnetic flux.

To validate the tunability of the DC magnetic bias circuit, we constructed several variants of the bias circuits and measured the magnetic field at the central air gap. The detailed dimensions of the reference layout are provided in Fig. 3. The SmCo magnets, sized 1 mm by 3 mm, were linked by the mu-metal yokes, which were 500 µm in width and 6.8 mm in length, featuring central protrusions to guide the magnetic flux across the 2 mm air gap. Both components provided various thickness options within the range of several hundred micrometers. SmCo and mu-metal components were laser micromachined from commercial sheets using an IPG Photonics IX280-DXF green laser and assembled accordingly. The magnetic flux density at the central air gap was measured by a Gaussmeter (Model GM2, AlphaLab). Table 1 shows the measurement results for various SmCo magnet and Mu-Metal component thicknesses, as well as the presence or absence of notches in the yoke arms and shunts across the magnets. Our results demonstrate a wide range of DC bias tunability, ranging from 2 mT to 16 mT.

Saturation-exploiting DC-biased MFCs

In this section, we explore the integration of the DC bias circuit and the trapezoidal MFCs to simultaneously achieve DC bias and AC amplification, as shown in Fig. 1. The MFCs and permanent magnets are connected through highly permeable yoke arms to supply DC bias to the sensor-containing air gap. Based on the results outlined in the previous section regarding the DC bias circuit, we find that there are various solutions to achieve a specific DC field. For instance, we can opt for relatively thin magnets with thick yokes, thick magnets with thin yokes, or even thicker magnets with notched thin yokes. However, incorporating shunts in AC MFC geometries is not recommended as they can 'short out' the AC signals (i.e., guide the AC signal through a path that is not the sensor-containing central air gap). Among these potential solutions, our objective is to identify the most effective approach for AC signal amplification. To mitigate this issue, intentional saturation can be induced in the yoke arms. This can be achieved by adding notches to the yoke arms, which play a crucial role in restricting the side path for the AC magnetic signal, thereby maximizing the routing of the AC signal into the sensor-containing air gap.

A three-dimensional finite element model was developed to compare the performance of different magnetic systems and investigate the impact of deliberate saturation using Ansys Maxwell3D. The model setup is illustrated in Fig. 4. A sinusoidal current with a frequency of 1 kHz and an amplitude of 1 A was applied to the 20 cm diameter Helmholtz coils, generating an

Table 1. Measurement results of DC magnetic flux density with different part variations.

Magnetic flux density (mTesla)	Part variations			
	Thickness of SmCo magnets (µm)	**Thickness of Mu-Metal components (µm)**	**Notches on yoke arms**	**Shunts**
16.0	300	400	No	No
11.7	300	200	No	No
7.3	200	100	No	No
6.3	200	100	Yes	No
5.5	200	100	Yes	Only on top
2.0	200	100	Yes	Both on top and bottom

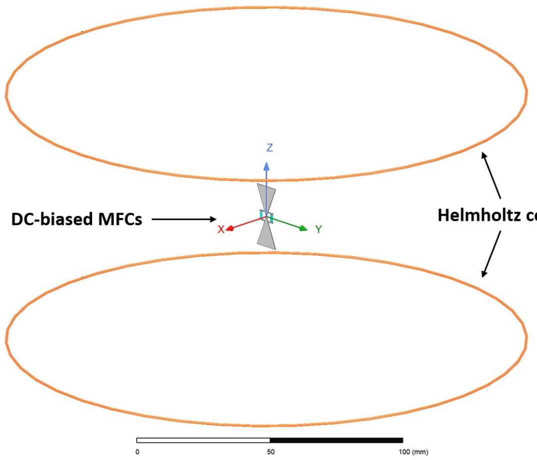

Figure 4: Overview of the finite element model.

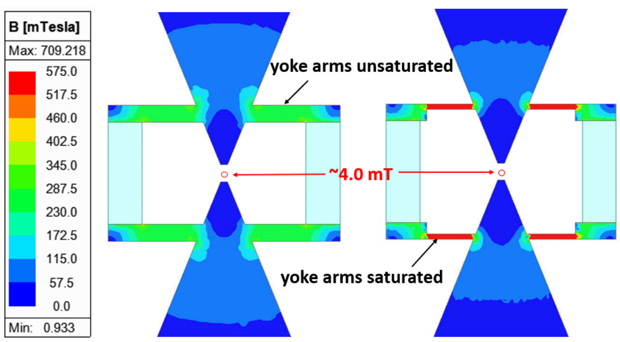

Figure 5: Finite element simulations of magnetic flux density in the unsaturated (left) and saturated (right) yoke structure.

external AC magnetic signal along the z-axis for sensing. This signal underwent amplification by DC-biased MFCs positioned parallel to the AC signal and centered between the two coils. The DC bias section adhered to the dimensions depicted in Fig. 3, while the trapezoidal concentrator had a short edge of 200 µm, a long edge of 10 mm, a length of 12 mm, and an air gap of 500 µm. Transient simulations were conducted, and the magnitude of magnetic flux density at the central air gap was recorded in the time domain.

Initially, simulations were performed to analyze the AC signal without any MFCs. Subsequently, two MFC configurations were compared, both utilizing SmCo28 magnets and mu-metal as the MFC material. Mu-metal has a saturation flux density of approximately 600 mT. The mu-metal components had a uniform thickness of 200 µm in both configurations. The first configuration involved the simple addition of 30 µm thick SmCo magnets to the DC-bias circuit and the MFCs. This setup provided a 4 mT DC bias field without saturating the magnetic field of the yoke arms. In contrast, the second configuration utilized thicker magnets (40 µm) and incorporated notches in the yoke arms to achieve a similar DC bias field (3.9 mT) while intentionally saturating the yoke arms. The magnetic field distribution within the yoke structures is visualized in Fig. 5.

The magnitude of the AC signal was then compared across the three cases mentioned above. Without the DC-biased MFCs, an AC signal magnitude of 8.8 µT was obtained at the central air gap. However, upon introducing the DC-biased MFCs, the AC signal

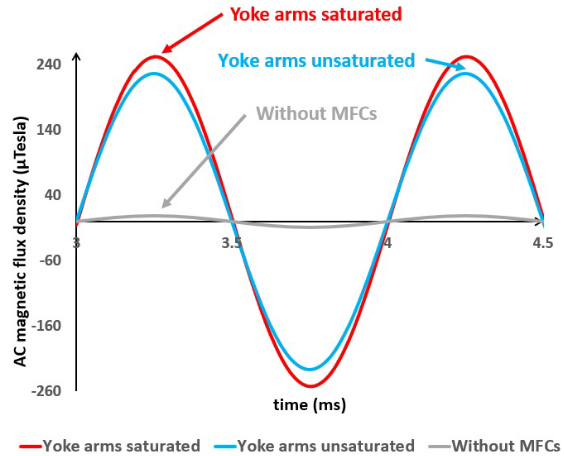

Figure 6: AC magnetic flux density at the central air gap as a function of time. Note the amplitude improvement from the flux concentrators, and the further improvement from the intentional saturation of the DC yoke arms.

magnitude increased to 227.2 µT, resulting in a 26-fold amplification of the AC signal. By further increasing the thickness of the SmCo magnets and implementing notches to saturate the yoke arms, an additional 11% increase of the AC signal amplification was achieved, reaching 252.4 µT. The simulated AC signals (isolated from DC bias) of the three cases are shown in Fig. 6, illustrating the efficacy of exploiting yoke saturation to improve sensor performance.

In this study, we utilized SmCo magnets with a relative permeability of approximately unity, comparable to that of air. It is worth noting that magnetic materials with higher relative permeability, which exhibit greater propensity to conduct magnetic flux, may lead to higher AC signal loss. Consequently, the potential improvement in AC amplification through the induction of saturation in the yoke arms would theoretically be greater with such high-permeability magnets. Further experiments are needed to explore this aspect and validate the potential benefits of saturation in enhancing sensor performance.

CONCLUSION

This study presents a design of planar DC-biased MFCs composed of permanent magnets and high-permeable components to provide simultaneous DC bias field and AC field amplification for magnetic field sensors. FEM simulation is employed to investigate the magnetic amplification characteristics. Through intentional saturation of specific portions of the magnetic circuit, an 11% enhancement in AC flux concentration is achieved using appropriately sized soft magnetic components. These results underscore the potential of DC-biased MFCs to boost sensor sensitivity and performance, presenting a promising path for improving magnetic sensor performance while addressing challenges associated with DC biasing and signal loss.

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