

Article

Magnetic Flux Concentration Technology Based on Soft Magnets and Superconductors

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Abstract: High-sensitivity magnetic sensors are fundamental components in fields such as biomedicine and non-destructive testing. Flux concentration technology enhances the sensitivity of magnetic sensors by amplifying the magnetic field to be measured, making it the most effective method to improve the magnetic field resolution of magnetic sensors. Superconductors and high-permeability soft magnetic materials exhibit completely different magnetic effects. The former possesses complete diamagnetism, while the latter has extremely high magnetic permeability. Both types of materials can be used to fabricate flux concentrators. This paper compares superconducting and soft magnetic flux concentration technologies through theoretical simulations and experiments, investigating the impact of different structural parameters on the magnetic field amplification performance of superconducting and soft magnetic concentrators. This research is significant for the development of magnetic focusing technology and its applications in weak magnetic detection and other fields.

Keywords: magnetic flux concentration; superconductor; soft-magnet; magnetic sensor



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1. Introduction

Weak magnetic detection technology is a crucial component of modern sensing technologies and has significant applications in geological and marine exploration, geomagnetic navigation, non-destructive testing, and biomagnetic signal detection [1–6]. The core of weak magnetic detection technology is high-sensitivity magnetic sensors. Currently, the magnetic field resolution of most types of magnetic sensors can only achieve the microtesla (μT) to nanotesla (nT) range [7], which is insufficient to meet the higher precision requirements of magnetic field measurements at the picotesla (pT) to femtotesla (fT) level (such as magnetocardiography and magnetoencephalography).

Flux concentration technology focuses and locally enhances the external magnetic field, making it a crucial method for improving the magnetic field resolution of magnetic sensors. Flux concentrators (FC) are mostly made of soft magnetic materials with high permeability. In the magnetic field environment, high permeability materials have the effect of converging magnetic field lines, which can make the internal magnetic field strength of the high permeability material greater than the external magnetic field. This kind of FC initially adopts a conical structure [8]. Subsequently, Schneider et al. [9] employed CMOS technology to fabricate funnel-shaped flux concentration structures based on permalloy material, significantly increasing the sensitivity of magneto-transistors. Drljaca et al. [10] conducted preliminary studies on the magnetic field amplification characteristics of two-dimensional thin-film flux concentrator structures of various shapes. They analyzed the relationship between the amplification factor and the ambient magnetic field for T-shaped, triangular, and funnel-shaped concentrators and designed high-sensitivity Hall sensors.

Moreover, researchers also explored the application of FCs to enhance the sensitivity of giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR) sensors [11–16]. Guedes A et al. [14] increased the sensitivity of the GMR sensor from 0.2%/Oe to 3.8%/Oe with a magnification of 19 times by using an FC prepared by soft magnetic materials; Chaves et al. [17] employed multi-stage FCs to enhance the sensitivity of TMR sensors to 72%/Oe, with an amplification factor exceeding 100 and achieved a noise level of 97 pT/Hz^(1/2) at 10 Hz.

In addition to high-permeability soft magnetic materials, superconductors can also achieve magnetic focusing. D. Robbes et al. [18] first proposed that if superconductors are designed as closed loops with special structures, the external magnetic field can be amplified hundreds or even thousands of times. M. Pannitier et al. [19–23] prepared the GMR-Superconducting composite magnetic sensor for the first time by using the superconducting FC, which improved the magnetic field resolution of GMR by more than 100 times. On this basis, H. Dyvorne et al. [24] improved the sensitivity of GMR devices by nearly 1000 times by adjusting the size of superconducting FCs. Subsequently, Wu, Hu et al. respectively, combined the Superconducting FC with TMR devices, which increased the sensitivity of TMR devices by more than 1000 times, and the magnetic field noise level reached 1 pT/Hz^(1/2) at 1 Hz [25–31].

This paper combines theoretical simulations and experimental methods to compare superconducting and soft magnetic FCs. It investigates the effects of factors such as structure and dimensions on the performance of superconducting and soft magnetic FCs.

2. Simulation and Results

2.1. Soft Magnetic Flux Concentrators

2.1.1. Principles and Simulation Model

High permeability soft magnetic materials will gather ambient magnetic fields. Under the influence of an external magnetic field, the magnetic induction intensity inside the soft magnetic material is:

$$B_{in} = \mu_0 \mu_r H \quad (1)$$

where μ_0 is the free space's permeability, μ_r is the relative permeability of the soft magnetic material, and H is the magnetic field strength acting within the soft magnetic material. When the length of the soft magnetic material is finite, the magnetization induced by the external magnetic field will generate a demagnetizing field H_d inside the soft magnet, which is in the opposite direction of the external magnetic field. The demagnetizing field is related to the geometry of the material:

$$H_d = -NM \quad (2)$$

where N is the demagnetizing factor, and M is the magnetization. Thus, the magnetic field strength inside the soft magnetic material can be expressed as:

$$H = H_{ext} - N(\mu_r - 1)H \quad (3)$$

Based on Equations (1)–(3), it can be obtained that:

$$B_{in} = \mu_0 \frac{\mu_r}{1 + (\mu_r - 1)N} H_{ext} \quad (4)$$

When the magnetic sensor is very close to the soft magnetic material, it can be approximated that the magnetic induction intensity acting on the sensor is B_{in} . Currently, the amplification factor of the soft magnetic material is:

$$G_m = \frac{\mu_r}{1 + (\mu_r - 1)N} \quad (5)$$

From Equation (5), by using high-permeability soft magnetic materials and optimizing the structure to reduce the demagnetizing factor, the magnetic field in the sensitive area of the magnetic sensor can be enhanced (as shown in Figure 1a). However, since the demagnetizing factor is a complex function of the shape and magnetization state of soft magnetic materials and often has no analytical solution, finite element simulation methods are required.

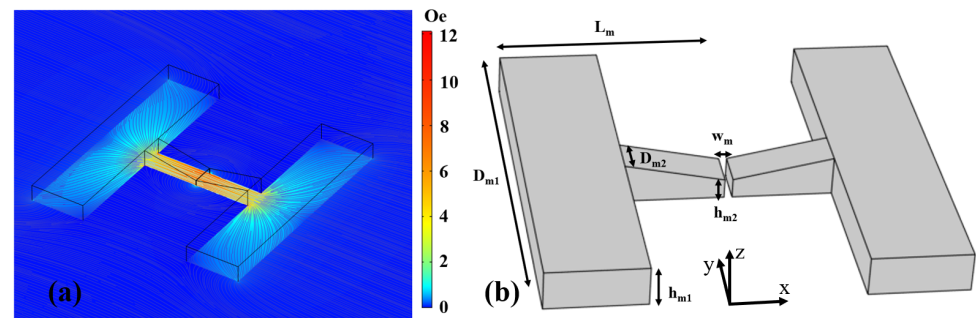


Figure 1. (a) Magnetic field distribution of soft-magnetic FC (the background magnetic field is set to 1 Oe, along the x -direction). (b) Schematic diagram of the T-shaped magnetic FC.

We established a simulation model of the soft magnetic FC using COMSOL Multi-physics (6.0) finite element simulation software. The model includes two identical soft magnetic structures. This paper focuses on the T-shaped magnetic FC. Figure 1b shows a schematic diagram of the T-shaped magnetic FC, with its initial structural parameters listed in Table 1. Except for the outer edge thickness h_{m1} , the length of the magnetic concentrator L_m , and the width of the central air gap w_m which are variable, the other structural parameters are fixed values. In our study, Permalloy was selected as the material for the magnetic FC, and the background magnetic field is along the x -direction. We used the magnetic fields, no currents(mfnc) module in COMSOL to simulate the magnetic field gain factor at the center of the air gap of the magnetic FC.

Table 1. Initial structural parameters of T-shaped magnetic FC.

Parameters	D_{m1}	D_{m2}	L_m	h_{m1}	h_{m2}	w_m
Unit (mm)	20	2	10	1	1	1

2.1.2. Simulation Results

We varied h_{m1} , L_m , and w_m , respectively, and calculated the impact of these parameters on the performance of the T-type soft magnetic FC. During the simulation calculations, whenever one variable changed, the other variables were kept constant.

The variation of the magnetic field amplification factor G_m of the soft magnetic FC with h_{m1} is shown in Figure 2a. As h_{m1} increases from 1 mm to 10 mm, G_m slowly rises from 10.55 to 10.87 and then gradually decreases to 10.7. It is evident that increasing h_{m1} does not significantly enhance G_m . Furthermore, G_m does not monotonically increase with h_{m1} ; instead, it reaches a maximum value when h_{m1} is 6 mm. The main reason is that the demagnetization factor of the T-type soft magnetic FC in the magnetic field-sensitive direction increases with the rise in h_{m1} , which greatly affects the enhancement of G_m . When h_{m1} exceeds 6 mm, the impact of the demagnetization factor surpasses the increase of the magnetic field sensing area brought by the rise in h_{m1} , thus leading to a decreasing trend of G_m . Since increasing h_{m1} does not significantly improve the magnetic field gain factor but increases the volume and mass of the soft magnetic FC, we set h_{m1} as 1 mm in subsequent studies.

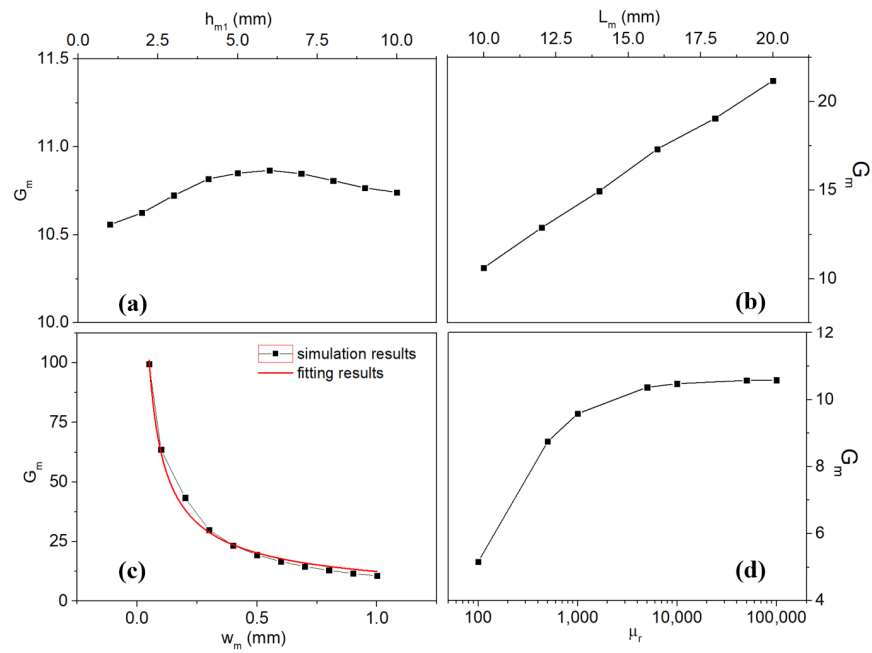


Figure 2. (a) The variation of the magnetic field amplification factor G_m with (a) h_{m1} , (b) L_m , (c) w_m , and (d) μ_r .

The variation of G_m with L_m is shown in Figure 2b. As L_m increases from 5 mm to 20 mm, G_m increases in an approximately linear manner from 10.55 to 21. This is because increasing the length of the soft magnetic structure reduces its demagnetization factor, thereby enhancing the magnetic field gain.

Figure 2c shows the variation of G_m With the air gap w_m . G_m increases rapidly with w_m decreasing, which is due to the large air-gap reluctance and magnetic leakage phenomenon of soft magnetic FC. Reducing w_m effectively lowers the magnetic reluctance and reduces magnetic leakage of the air gap. At the same time, we found that w_m and G_m are approximately inversely proportional (fitting results in Figure 2c) when w_m reaches 50 μm (the typical size of GMR and TMR devices), G_m exceeds 98.

The magnetic field gain factor depends not only on the geometric structure of the device but also closely on the magnetic permeability of the soft magnetic material. In this regard, we studied the influence of the permeability of soft magnetic materials μ_r on G_m (as shown in Figure 2d). It can be seen that G_m increases significantly with the rise in μ_r and tends to saturate when μ_r exceeds 5000, indicating that when μ_r is sufficiently high, the soft magnetic FC experiences almost no magnetic leakage, and thus G_m no longer changes significantly. In this study, we selected permalloy, which has a magnetic permeability of up to 100,000, making it an ideal material for the soft magnetic FC. In contrast, magnetic materials such as silicon steel and ferrite, due to their lower magnetic permeability, would adversely affect the magnetic field gain factor.

2.2. Superconducting FC

2.2.1. Principle and Simulation Model

The structure of the superconducting FC is shown in Figure 3a, which is a closed superconducting loop containing a constriction. Below the superconducting transition temperature, when an external magnetic field passes through the superconducting FC vertically (along the z -direction), the induced current will be generated in the superconducting loop to offset the external magnetic flux passing through the superconducting loop due to the zero resistance of the superconductor and the Meissner effect:

$$I = \frac{B_a S}{L} \quad (6)$$

where B_a is the external magnetic induction intensity, S and L are the effective areas and self-inductance of the superconducting FC. When the induced current passes through the constriction of the superconducting ring, the current density increases locally, and a strong local magnetic field is formed (Figure 3b). Assuming that the induced current is evenly distributed in the constriction, then:

$$B_c = \frac{\mu_0 I}{2w_s} \quad (7)$$

where w_s is the constriction width. It should be stated that Equation (7) is valid at the top and bottom of an infinitely wide plate of current. Since the thickness of the superconducting constriction is much smaller than the width, it can be treated as an infinitely wide plate. The magnetic field gain factor of the superconducting FC can be obtained as follows:

$$G_s = \frac{\mu_0 S}{2w_s L} \quad (8)$$

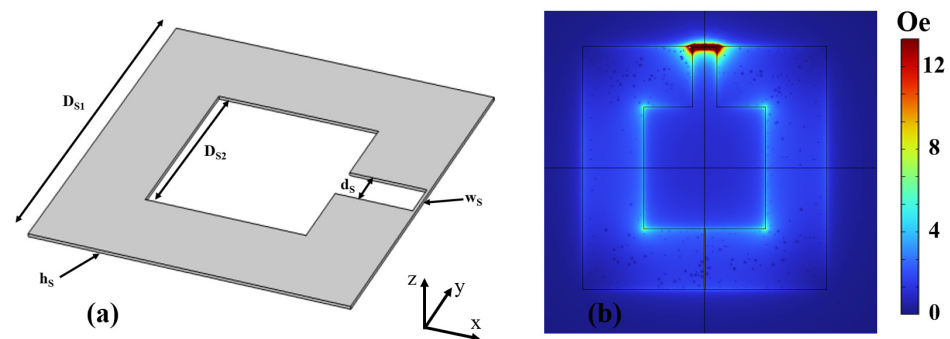


Figure 3. (a) The structure of the superconducting FC. (b) Magnetic field distribution of superconducting FC (the background magnetic field is set to 1 Oe, along the z-direction).

As seen from Equation (8), the magnetic field gain factor can be improved by increasing the effective area of the superconducting FC, reducing the width of the constriction, and lowering the self-inductance. However, the loop inductance of the superconducting FC is a complex function of shape and often lacks an analytical solution. Additionally, the supercurrent within the superconductor is not uniformly distributed but exhibits a skin effect. Therefore, finite element simulation methods are required.

We used COMSOL Multiphysics (6.0) software to establish a three-dimensional finite element model of the superconducting FC. The superconducting FC adopts a square structure, with its structural parameters shown in Table 2. Except for the edge of the inner square D_{s2} and the width of the constriction w_s , all other structural parameters are fixed values. In our study, YBCO was selected as the material for the superconducting FC. The non-linear resistivity of YBCO is described by the E-J power law:

$$\rho = \frac{E_c}{J_c} \left| \frac{J}{J_c} \right|^{n-1} \quad (9)$$

where J_c is critical current density, which is 2×10^8 A/m² for YBCO bulks. E_c is the characteristic electrical field, which is 10^{-4} V/m and acted as the critical current criterion. The n -value is set to 15 in this model [32].

Table 2. Initial structural parameters of superconducting FC.

Parameters	D_{s1}	D_{s2}	h_s	d_s	w_s
Unit (mm)	20	10	0.001	2	1

2.2.2. Simulation Results

The variation of the amplification factor G_s of the superconducting FC with D_{s2} is shown in Figure 4a. As D_{s2} increases from 2 mm to 18 mm, G_s firstly increases from 59.5, reaches a maximum value of 75 at $D_{s2} = 10$ mm, and then gradually decreases to 59. To explain this phenomenon, we calculated the variations of L and S with D_{s2} (shown in Figure 4b). It can be seen that S increases almost linearly with D_{s2} , while the relationship between L and D_{s2} is approximately parabolic. Since G_s is directly proportional to S and inversely proportional to L , and G_s first increases and then decreases.

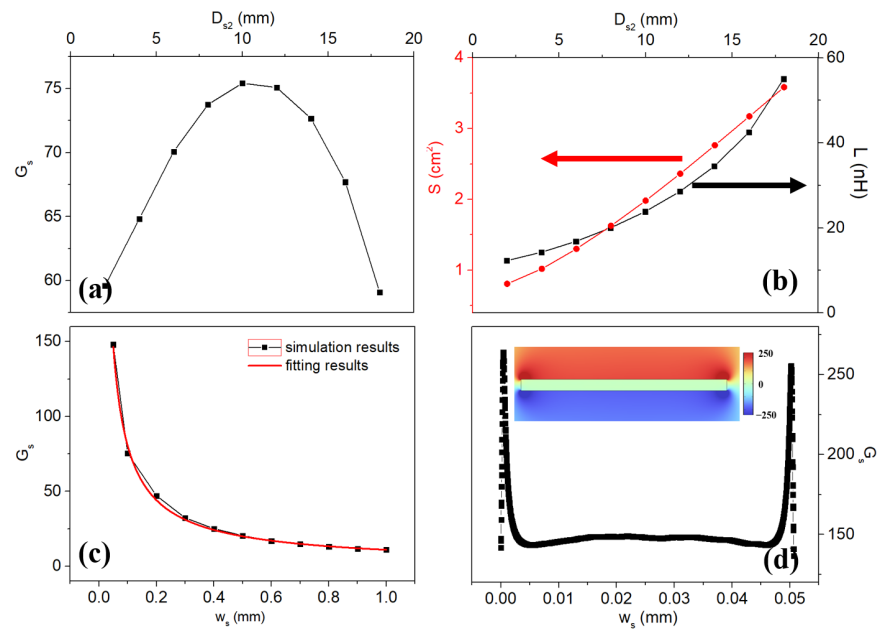


Figure 4. (a) The variation of G_s with D_{s2} . (b) The variations of L and S with D_{s2} . (c) The variation of G_s with w_s . (d) The distribution of G_s on the surface of the superconducting constriction.

Figure 4c shows the variation of G_s with w_s . It can be observed that G_s is approximately inversely proportional to w_s (fitting results in Figure 4c), which is consistent with Equation (8). It is worth noting that the supercurrent inside the superconductor is not uniformly distributed; instead, the London penetration depth exists, which affects the uniformity of the magnetic field on the surface of the constriction. Figure 4d shows the distribution of G_s on the surface of the superconducting constriction. It is not difficult to see that at the edges of the constriction, G_s exhibits sharp peaks. The main reason is the skin effect of the superconducting current, which causes a higher current density at the edges of the constriction. Nevertheless, the magnetic field is uniform in most areas in the center of the narrow zone, which can provide a stable and uniform magnetic field environment for magnetic-sensitive components such as magnetoresistance.

3. Experimental Results and Discussion

From the above simulation results, both the soft magnetic FC and the superconducting FC exhibit excellent magnetic field amplification characteristics. To verify the theoretical results, highly sensitive tunnel magnetoresistance (TMR) is used as a magnetic-sensitive element in this paper. The specific fabrication process of TMR is consistent with that in Ref. [21]. Figure 5a shows the series structure of the fabricated TMR.

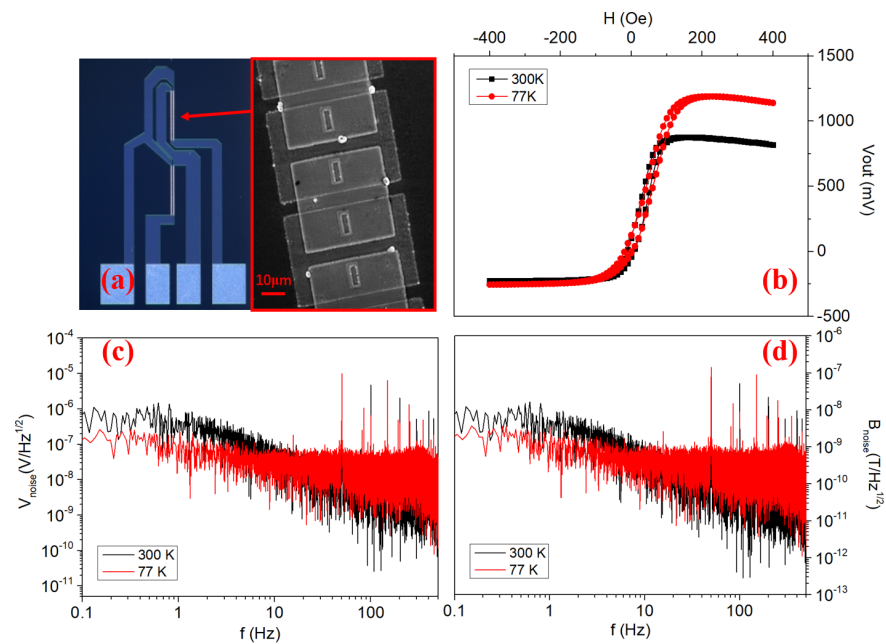


Figure 5. (a) The series structure of the fabricated TMR. (b) Voltage–magnetic field response curve of TMR at room temperature and 77 K. (c) Voltage noise and (d) magnetic noise spectrum of TMR at room temperature and 77 K.

Figure 5b shows the voltage–magnetic field response curve of the TMR device at room temperature and 77 K, with the TMR device biased at 1 V. By calculating the slope of the curve near zero field, the sensitivity of the TMR at room temperature and 77 K is 9.1 mV/V/Oe and 7.1 mV/V/Oe, respectively. The decrease in sensitivity at low temperatures is due to the influence of the magnetic domain flipping of the free layer of the TMR. Figure 5c shows the voltage noise spectrum of the TMR device at room temperature and 77 K. The low-frequency voltage noise of the device decreases at low temperatures, indicating that the magnetic moment disturbances due to thermal excitation are a major factor in generating low-frequency noise in the TMR. Lowering the temperature effectively suppresses these magnetic moment disturbances. Figure 5d shows the magnetic noise spectrum of the TMR. Despite the sensitivity of TMR decreases at low temperatures, its magnetic noise is still lower than at room temperature.

Both types of FCs are combined with the TMR device using flip-chip bonding technology. The inset of Figure 6a shows the fabricated TMR–soft magnetic and the TMR–superconducting composited magnetic sensor. To compare the magnetic field amplification characteristics of the two types of FCs, the soft magnetic FC and the superconducting FC used in this study have the same external dimensions (20 mm × 20 mm), and the gap width of the soft magnetic FC and the constriction width of the superconducting FC are both set to 500 μm.

Figure 6a shows the sensitivity comparison of the two composite magnetic sensors. The sensitivities of the TMR–soft magnetic and TMR–superconducting composited magnetic sensor reach 135 mV/V/Oe and 138 mV/V/Oe, respectively, with the corresponding field amplification factors being 14.8 and 19.4. The experimental results are generally consistent with the simulation results, validating the accuracy of the simulations. With the same dimensions, the superconducting FC has a higher amplification factor. However, due to the decreased sensitivity of the TMR device at low temperatures, the sensitivities of the two composite magnetic sensors are almost the same.

Figure 6b,c show the voltage noise of the two composite magnetic sensors compared with that of the TMR without magnetic FC. The soft magnetic FC causes a certain increase in the TMR’s noise (the voltage noise at 1 Hz increases by 50%), whereas the voltage noise of the TMR device combined with the superconducting FC does not show a significant change.

The primary reason is that under the influence of environmental thermal disturbances, magnetic domain disturbances occur within the soft magnetic FC and bring additional noise. In contrast, the magnetic field gain of the superconducting FC is derived from the supercurrent. Due to the zero-resistance characteristic of the superconductor, the supercurrent hardly introduces any additional noise.

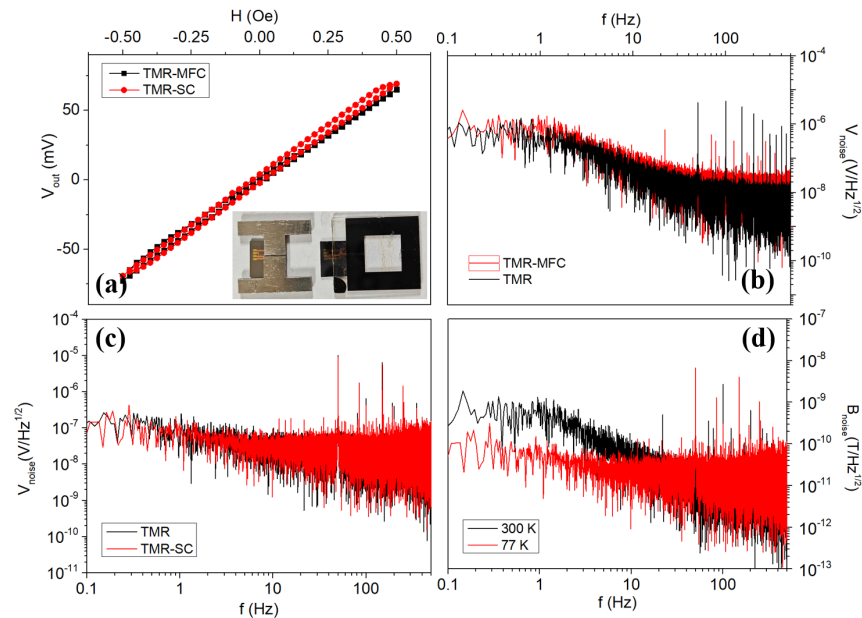


Figure 6. (a) Sensitivity comparison of TMR-soft magnetic (TMR-MFC) and TMR-superconducting (TMR-SC) composited magnetic sensor. The voltage noise of (b) TMR-soft magnetic and (c) TMR-superconducting magnetic sensors compared with that of the TMR without magnetic FC. (d) Magnetic noise of the two composite magnetic sensors.

Figure 6d shows the magnetic noise of the two composite magnetic sensors. At 1 Hz, the magnetic noise of the TMR-superconducting and the TMR-soft magnetic composited sensor are $580 \text{ pT/Hz}^{(1/2)}$ and $65 \text{ pT/Hz}^{(1/2)}$, respectively. The comparison shows that with the same dimensions, the TMR-superconducting composited sensor exhibits superior magnetic field detection capability.

4. Conclusions

Flux concentration technology is widely used to enhance the detection performance of magnetic sensors. This study conducted simulations and experimental research on two different types of flux concentrators: soft magnetic and superconducting. The following conclusions were obtained:

- 1 The main factors affecting the magnetic field amplification performance of the soft magnetic FC include permeability, demagnetizing factor, and gap width. First, the magnetic field amplification factor of the soft magnetic FC increases with the addition in permeability and starts to saturate when the permeability exceeds 5000. Secondly, enlarging the aspect ratio of the soft magnetic FC can effectively reduce the demagnetization factor and improve the magnetic field gain factor. Finally, the air gap should be minimized to reduce magnetic leakage. In practical applications, the size and gap width of the soft magnetic FC should be reasonably designed according to the size requirements of the sensor and the magnetic-sensitive element.
- 2 The main factors affecting the magnetic field amplification performance of the superconducting FC include the effective area, the self-inductance of the superconducting loop, and the width of the constriction. With the external dimensions of the superconducting FC determined, the ratio of the inner to outer radii of the superconducting

loop should be set to 1:2, while minimizing the width of the constriction as much as possible. It should be noted that reducing the width of the constriction decreases the magnetic field amplification area and reduces the magnetic field range. In practical applications, the width of the constriction and other parameters should be reasonably designed according to the size requirements of the sensor and the magnetic-sensitive element (e.g., the size of the TMR junction region).

- 3 At the same size, the superconducting FC exhibits superior magnetic field amplification performance. Additionally, since the superconducting FC operates in a low-temperature environment, the thermal noise of the magnetic-sensitive element (TMR) can be effectively reduced, thereby enhancing magnetic field resolution. However, it is important to note that the superconducting FC requires low-temperature cooling equipment (such as refrigerators or liquid nitrogen). Therefore, in practical applications, the choice of flux concentrator should be made based on the specific application scenarios.

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Conflicts of Interest: The authors declare no conflicts of interest.

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