

Preparation of a high- T_c superconducting magnetic flux transformer with a 100 mm bore coil and static magnetic field transfer at 77 K

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Herein, superconducting magnetic flux transformers with pickup coils of diameter 100 mm were prepared using a commercial RE123 high critical temperature (high- T_c) superconductive tape. A superconducting flux transformer requires closed circuit containing a superconductive joint, which is difficult to prepare for a cuprate high- T_c superconductor. Using the cut-and-wind method, seamless and large-bore coils were equipped to the flux transformer; these features are advantageous for non-destructive estimation and geological magnetic survey. The magnetic flux transfer of the applied static field caused by the spontaneously induced superconductive shield current at the liquid nitrogen temperature was confirmed, and the efficiency in the static field transfer, depending on the inductance of the coils in the flux transformer, was estimated.

1. Introduction

From the viewpoint of practical use, the most characteristic and interesting property of superconductors is persistent current due to the absence of electrical resistance. The electrical current induced in a closed superconducting circuit is maintained persistently because there is no energy dissipation resulting from zero resistance¹⁾. The superconductors also exhibit the characteristic property of the Meissner–Ochsenfeld effect²⁾. Superconducting shielding current is induced spontaneously by applying a static magnetic field to compensate for the ambient field and conserve the magnetic field inside the superconductor. In contrast to the induction current on a metal conductor induced by the application of an alternative magnetic field, a superconductive shielding current is generated by a static magnetic field³⁾. Moreover, when the magnetic field is applied to a partial area of the closed superconducting circuit, a new magnetic field is generated in the other area of the circuit through transmission of the spontaneous current. This implies that the magnetic field penetrating a partial region of the closed superconducting circuit is transferred to another region by the transformation between the magnetic field and superconducting current. This is the working principle behind a superconducting magnetic flux transformer.

A superconducting magnetic flux transformer is practically used in a highly sensitive magnetic measurement system to transfer the magnetic field of a sample to a sensitive sensor insulated by a magnetic shield^{4), 5)}. A niobium wire is used in an actual flux transformer, and liquid helium cooling is necessary for operating the apparatus. In contrast, although a cuprate high- T_c superconductor (HTS) is convenient to operate under liquid nitrogen cooling, the HTS is not currently applied to the superconducting magnetic flux transformers. This is because preparing a superconducting joint at the wire edge to fabricate an HTS loop of the superconducting closed circuit is difficult. The superconducting state in all parts of the closed loop is indispensable for superconducting flux transformers. For a superconducting metallic wire, a superconducting joint that is operable at liquid helium temperature can be fabricated by welding or soldering using a superconducting solder^{6), 7)}. Several jointing methods have been proposed for cuprate HTSs. However, all these methods have significant challenges that need to be addressed: 1) Solder materials such as lead and bismuth show superconductivity approximately at the liquid helium temperature; therefore, the soldering joint at the liquid nitrogen temperature functions only as a low-resistance joint⁸⁾⁻¹⁰⁾, which certainly differs from a superconducting joint connecting the quantum phase of both sides. 2) Joints using deposition of superconductor and insulator layers enable multi-turn coil^{11), 12)}; however, high vacuum equipment is required for their preparation and the sample size is

limited to the size of the vacuum apparatus. 3) Material re-melting in the welding joint damages its crystallinity and oxygen concentration and degrades the cuprate superconducting phase, thereby resulting in the disappearance of superconductivity. In recent studies, diffusion joining has been proposed to preserve the crystallinity of the superconducting phase¹³⁾⁻¹⁵⁾. However, these methods has limitations such as large size of the joint region and the long process time for oxygen diffusion treatment. For these reasons, HTS flux transformers have been prepared in a planar form using patterned HTS thin films¹⁶⁾⁻¹⁸⁾. For these devices, owing to the geometrical restrictions, single-turn loop structures and loop diameters smaller than the width of the substrate are permissible. From the viewpoint of convenient refrigeration, applying an HTS flux transformer to field inspection technique such as the non-destructive evaluation for a large object or resource exploration is profitable. It is important to note that, for these applications, it is essential for the flux transformer to have a large bore loop collects magnetic flux and a multi-turn loop transforms the magnetic flux to the superconducting current.

In this study, we prepared an HTS flux transformer with a seamless loop and measured the flux-transfer efficiency of an applied magnetic field at liquid nitrogen temperature. We used a commercial HTS tape conductor as the basis and adopted a topological shape forming method without joints to prepare the HTS flux transformer composed of a seamless closed loop^{19), 20)}. This method allows an HTS loop with a bore size larger than the width of the basis by vending and spreading a long and thin through-hole made in a planar HTS monofilament tape. The method also allows a multi-turn coil by plural slitting in the HTS tape and stretching the slits in mutually opposite directions alternately. The flux-transfer efficiency was considerably affected by the coil inductance and the ratio of the inductance between the pickup coil (magnetic flux corrector) and the input coil (sensor interface) of the HTS flux transformer. We varied the bore diameter and number of turns of the coils and measured the change in the flux-transfer efficiency depending on their inductance.

2. Experimental methods

2.1 Preparation of a seamless superconducting loop using the cut-and-wind method

An REBa₂Cu₃O_y (RE123) 2G-HTS tape conductor (SuperPower Inc.) was used as the substrate material for the HTS magnetic flux transformer. The monofilament tape of width 12 mm was shaped by the cut-and-wind method to prepare a seamless and wide-diameter closed loop (Fig. 1(a)). A through-hole slit on the tape was engraved using a diamond wheel of 0.1 mm thickness. A trench to the base metal was made by chemical etching. The HTS

tape consisted of four layers: a top copper layer (20 μm), a protective silver layer (2 μm), an RE123 superconducting layer (1 μm), and a Hastelloy C-276 basis including a textured buffer layer (50 μm). The copper, silver, and superconducting layers were chemically removed using 5% hydrochloric acid +35% aqueous hydrogen peroxide, 1% aqueous ammonia +35% aqueous hydrogen peroxide, and 1% hydrochloric acid, respectively. An approximately circular shape with an inside diameter of 100 mm was obtained by stretching the through-hole slit in mutually opposite directions, perpendicular to the tape face, as shown in Fig. 1 (a). A cylinder made of the glass epoxy with an outside diameter of 100 mm was then placed in the tape. Using this method, it was possible to build a multi-turn loop coil by making multiple slits on the tape and stretching alternate slits in opposite directions, as shown in Fig. 1 (b).

The closed HTS circuit equipped with a two-loop part, a pickup coil as the magnetic field sensing part, and an input coil as the interface with the magnetic sensor functions as a superconductive magnetic flux transformer^{4), 5)} (Fig. 2). The device was built by preparing a loop at each end of the HTS wire tape using the abovementioned method. It was possible to prepare the HTS loop using the cut-and-wind method and chemical etching, although the loop diameter was small (5 mm). This structure can be considered as a seamless closed loop of the HTS wire since no joint region from welding or other methods exists in the circuit.

2.2 Measurement of magnetic field transfer in an HTS flux transformer

After the preparation of the HTS magnetic flux transformer, its static magnetic field transfer property at 77 K was estimated. Fig. 3 shows a schematic diagram of the measurement system used in this study. A Helmholtz coil (diameter = 308 mm) was used to apply a static magnetic field to the HTS flux transformer. The pickup coil of the HTS flux transformer was installed at the center of the Helmholtz coil. A static magneto-impedance (MI) sensor (Aichi Micro Intelligent Corp. MGM-1DS) was set in a foamed polyethylene cylinder. The cylinder with the sensor was placed either at the center of the input coil (prepared by the cut-and-wind method) or facing the etched small input coil across the 5 mm thick foamed polyethylene. The temperature of the MI sensor was maintained at approximately the room temperature through thermal insulation using foamed polyethylene from a liquid nitrogen cooling bath so that the sensor was operable in this measurement system. A static magnetic field was applied to the pickup coil, and the magnetic field was transferred to the input coil of the HTS flux transformer. The length of the magnetic flux transformer was designed such that the distance between the coils was sufficiently long to

suppress the interference of the applied field to the MI sensor. The thermal drift of the MI sensor and magnetic field interference at the sensor location were verified using a liquid nitrogen bath without the HTS flux transformer.

The magnetic field transfer properties depending on the diameter and number of turns of the coils were measured. In addition, a permalloy core (cube of side 5 mm) was provided adjacent to the etched small input coil, expecting a change in its inductance.

3. Results and Discussion

3.1 Results

3.1.1 Magnetic field transferring property of HTS flux transformer

The HTS flux transformer shown in Fig. 2 (left) was prepared to confirm the magnetic flux transfer property. A pickup coil with a 100 mm bore and an etched 5 mm bore input coil were aligned perpendicularly. Fig. 4 shows the static magnetic field applied to the pickup coil and the magnetic field measured by the MI sensor facing the input coil. Fig. 4 also represents the measurement of the magnetic field in the MI sensor with the HTS flux transformer, whose line is partially heated to eliminate the superconducting current in the circuit, and a background measurement of a field distribution of the Helmholtz coil at the MI sensor position shown in bottom left of Fig. 3 without an HTS flux transformer. The magnetic field transfer increases proportionally to the applied field only with in the presence of an HTS flux transformer of which whole circuit is cooled at 77 K.

3.1.2 Efficiency of magnetic field transfer depending on the inductance of the coils

The magnetic fields transferred to the input coils of the HTS flux transformers with different structures, such as single-turn pickup coil structure, two-turn pickup coil structure, and permalloy-cored input coil structure are represented in Fig. 4. The magnetic field transfer efficiency, which is the ratio of the magnetic field detected by the MI sensor to the applied field, is reduced in the two-turn pickup coil structure of an HTS flux transformer and increases in the cored input coil structure.

To estimate the relation between the transferred field and the inductance of the coils, we built an HTS flux transformer whose both loop coils were prepared by the cut-and-wind method. This structure enables the variation of the bore size and self-inductance of both loop coils. Fig. 5 shows the magnetic field transferred to the input coil, whose bore size was fixed at 60 mm for the pickup coil with varying bore sizes. In addition, Fig. 6 shows the magnetic field in the input coils for various bore sizes, and the bore size for the pickup coil was fixed

at 60 mm. Fig. 5 shows that the transfer efficiency of the applied field to the input coil increases with an increasing bore size of the pickup coil. The rate of increase in the transferred magnetic field appears to be proportional to the ratio between the diameters of pickup and input coils than to the ratio between the corresponding cross-sectional areas. This tendency is similar to the result shown in Fig. 6, where the transfer efficiency of the applied field increases with the ratio of the diameters of the pickup and input coils of an HTS flux transformer. However, the intensities of the magnetic field in the input coils are different despite the same diameter ratio of 3:2 for each coil. The magnetic field transfer efficiency is larger for the HTS flux transformer containing a 90 mm bore pickup and 60 mm bore input coils than that for the HTS flux transformer containing a 60 mm bore pickup and 40 mm bore input coils.

3.2 Discussion

We used a commercial RE123 type HTS tape to fabricate the HTS flux transformer from the viewpoint of operation at liquid nitrogen temperature. This material has superior properties against magnetic flux creep phenomenon in the high-temperature range compared to the Bi-system superconductor, which is another potential candidate for HTS materials. A manufacturer guaranteed a bending diameter of approximately 20 mm in the face vertical direction of the HTS tape, and we estimated that the critical current (I_c) of the HTS tape with a diameter of curvature of 25 mm was not degraded at 77 K. Twist forming of tape type conductor is sometimes applied to fabricate a multi-turn coil structure²⁰⁾. A multilayered thin film, such as this HTS tape, tends to break to peel off between the substrate and the upper layer for a compound stress including shear stress caused by forming process such as twisting of the tape. Simple tensile or compressive stress is applied to the tape by this method to prepare a multi-turn loop structure; therefore, we assume that the proof strength of the film is high for fabricating a small-bore multi-turn coil.

We prepared an HTS flux transformer using an RE123 tape from these viewpoints and estimated its magnetic properties. The magnetic flux transfer occurs when the entire device was cooled at 77 K, as shown in Fig. 4. The magnetic field observed in the input coil is only a minute field, according to the distribution of the applied magnetic field in the radial direction of the Helmholtz coil in the HTS flux transformer, in which the small part of the closed circuit is partially heated. This implies that the magnetic field transfer is due to the superconducting shielding current in the HTS loop²¹⁾, which is induced by the application of the static field rather than the flux pinning property in the HTS tape. Therefore, this device

built an HTS closed circuit that is necessary to realize a magnetic flux transformer. The transferred magnetic field is proportional to the applied static field, and it is unsaturated in the applied magnetic field of up to 100 μT . This implies that the I_c of the HTS loop is higher than the maximum current induced in the loop by the applied field. To estimate the super current induced in the HTS flux transformer indicated at the top of Fig. 2, we used the same manufacturing lot of the HTS tape and prepared an open loop sample of the same size and shape as the etched input coil. By inducing 1.67 A of DC in the open coil using a current source, the coil generated a magnetic field of 25 μT , which is same as that generated by the input coil of the HTS flux transformer in an applied field of 100 μT . This means the induced current in the HTS flux transformer in an applied field of 100 μT is approximately 1.7 A, while the I_c measured by manufacture was 312 A of the HTS tape in a 12 mm width.

The transfer efficiency of the magnetic field in this loop structure of the HTS flux transformer is limited to 25% of the applied field. The magnetic field transfer efficiency is the ratio of B_s to B_{ex} , and the relationship between them will be given by equation (1).

$$B_s = kI_s = \frac{k\Phi_{ex}}{L_p + L_i} = \frac{kN_p A_p B_{ex}}{L_p + L_i} \quad (1)$$

where, B_s , B_{ex} , and I_s are the magnetic field transferred to a magneto sensor combined with an input coil, the magnetic field applied to a pickup coil, and the signal current flowing in the loop, respectively. L_p and L_i are the inductances of the pickup coil and input coil, respectively. N_p is the number of turns of the pickup coil, A_p is the area of the pickup coil, and k is a parameter that relates B_s and I_s . Eq. (1) indicates that the magnetic field transfer between the pickup and input coils depends on the inductance of each coil, and the most efficient transfer in the superconductive magnetic flux transformer is observed at $L_p = L_i$ ⁵⁾. We attempted to change the inductance of the coils; hence, a two-turn pickup coil and an input coil with a ferromagnetic core were prepared for this device. The magnetic field transfer efficiency of the device containing the two-turn pickup coil is reduced by approximately half of the value of the transfer efficiency of the device containing a single-turn pickup coil (Fig. 4). The flux interlinkage, N_p , in Eq. (1) increases in the two-turn coil. Moreover, the coil inductance, L_p , increases proportionally to the square of the number of turns in the coil by analogy with a solenoid coil. Consequently, the magnetic flux transferred to the MI sensor is reduced in the two-turn pickup coil. In contrast, the device using a

ferromagnetic core with the input coil transfers the magnetic field more efficiently by up to 43%. It is considered that the magnetic coupling between the input coil and the MI sensor, M , is enhanced despite the increase in the input coil inductance L_i with effective permeability by the ferromagnetic core. To estimate the relationship between the field transfer and inductance of the coils, the HTS flux transformer equipped with two parallelly aligned loop coils was prepared by the cut-and-wind method, which enables to change diameter of the coils. The magnetic field transfer efficiency, depending on the diameter of the loop coils in the HTS flux transformer, is represented in Figs. 5 and 6. The magnetic field transfer efficiency of the superconducting flux transformer is assumed to be maximum for $L_p = L_i$ in Eq. (1). However, the maximum value of the transfer efficiency is 38% in the device containing a 60 mm bore input coil and a 90 mm bore pickup coil, as shown in Figs. 5 and 6. In addition, the device equipped with a larger pickup coil is more efficient in magnetic field transfer, even for the same ratio between diameters of the pickup and input coils (3:2). Although the cross-sectional area of the solenoid coil is an explicit factor of its inductance, the change in the transfer efficiency is observed to be proportional to the ratio between the diameters of the pickup and input coils rather than the ratio between the corresponding cross-sectional areas.

In this study, we observed that the magnetic field transfer efficiency increased with an increase in the coil diameter ratio by up to 3:2 in the formed input coil. Moreover, the efficiency decreased for the coil diameter ratio of 20:1 in the etched input coil. A suitable design exists to realize more efficient magnetic flux transfer. Magnetic coupling between the input coil and the magneto sensor strongly affects the transfer efficiency of the magnetic flux. In spite of the decrease in the magnetic flux transfer due to inductance mismatch between the coils, the design using small bore and multi-turn input coils is expected to contribute to strong magnetic coupling to the sensor, and increase the field transfer efficiency. This design have been used previously for conventional superconducting flux transformers²²⁾. In addition, the magnetic field transfer efficiency is reduced by a leakage of the magnetic flux in the line between the coils or the magnetic shield property of the HTS flux transformer. From these viewpoints, inductance management should be considered to result in further improvement of the HTS flux transformer. By enlarging the self-inductance of an input coil using a multi-turn coil and improving the mutual inductance by a direct mount of the magneto sensor, which is operable at 77 K, on an input coil, further improvement in the magnetic field transfer efficiency can achieve a magnetic flux compression of more than 100%. In the studies on highly sensitive magnetometers using a non-cooling magneto sensor

and magnetic flux condensers using a high permeability material²³⁾, the HTS flux transformer as the flux condenser is simultaneously considered for being applied for non-destructive estimations²⁴⁾. It is possible to increase the sensitivity of these hybrid magnetometers by directly mounting a small sensor such as an AMR-GMR device or a Hall device on the circuit line. It is also feasible to reduce the noise in low temperature operations of such magnetometers. Although measuring the field in close proximity to the circuit line is effective to increase the sensitivity of these hybrid sensors, the largest field near the input coil prepared by the cut-and-wind method was measured on the central axis of the coil in our configuration. In this study, we used the evaluation kit of an MI sensor. The evaluation kit operates at approximately the room temperature and halts at the liquid nitrogen temperature. Additionally, the MI sensor is set 5 mm behind the edge of the head module. Owing to these restrictions, close contact of the sensor with the circuit line of the HTS flux transformer is unrealized in the study. However, it is possible to fabricate a highly sensitive magnetometer using the HTS flux transformer and directly mounting the cooled sensor, including the HTS-SQUID, for future developments. The HTS flux transformer is thought to be useful for field inspection because of its ease at cooling and its magnetic property under the influence of static field. Therefore, a highly sensitive magnetometer using a large-bore HTS flux transformer is expected to resource exploration or non-destructive evaluation targeting a large object.

4. Conclusions

An HTS magnetic flux transformer equipped with seamless closed loop coils was prepared by the cut-and-wind method, and the magnetic flux transfer between two loops of the device was confirmed under applied static magnetic field at 77 K. The superconductive shield current was induced by the applied static magnetic field because superconductivity over the entire circuit was maintained by the seamless closed circuit structure. The efficiency of the magnetic field transfer varied depending on the inductance ratio and the inductance of the input and pickup coils; in the most efficient transfer, the intensity of the magnetic field transferred to the input coil was 43% of the applied field of the pickup coil. Amplification of the magnetic field, i.e., the increase in the intensity of the transferred field compared to that of the applied field, was not confirmed. However, this can be accomplished by both optimizing the design of the HTS flux transformer and modifying the magnetic coupling by direct mounting of the magnetic sensor, which is operable at 77 K, on the HTS flux transformer. This technique can be expanded to fabricate a multi-turn coil with a larger

diameter and is highly applicable to the gradiometer structure of the HTS flux transformer²⁵⁾,²⁶⁾, which eliminates effect of geomagnetism from measurement of magnetic field. HTS flux transformer is expected to be used for precise field inspection technology for non-destructive evaluation²⁷⁾,²⁸⁾ by virtue of its convenience for refrigeration to operate the device and sensitivity to static field, which is superior to permeability within a deep region of the object²⁹⁾.

Acknowledgments

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Figure Captions

Fig. 1. Schematic diagram of the cut-and-wind method used for fabricating seamless HTS loops. a) Fabricating a seamless loop from an HTS tape and b) fabricating a seamless loop with a multi-turn loop structure.

Fig. 2. HTS flux transformer containing a seamless closed circuit. The pickup coil of the device is formed by the cut-and-wind method, and the input coil is formed by the cut-and-wind method for parallel alignment device or by etching method for perpendicular alignment device.

Fig. 3. Schematic illustrations for measuring magnetic properties of the HTS loop flux transformer.

Fig. 4. Magnetic field transfer from applied field in the pickup coil to the input coil of the HTS flux transformer in perpendicular alignment design.

Fig. 5. Magnetic field transfer of the HTS flux transformer in parallel alignment design. The input coil bore size is fixed to 60 mm for different bore sizes of the pickup coil.

Fig. 6. Magnetic field transfer of the HTS flux transformer in parallel alignment design. The pickup coil bore size is fixed to 60 mm for different bore sizes of the input coil.

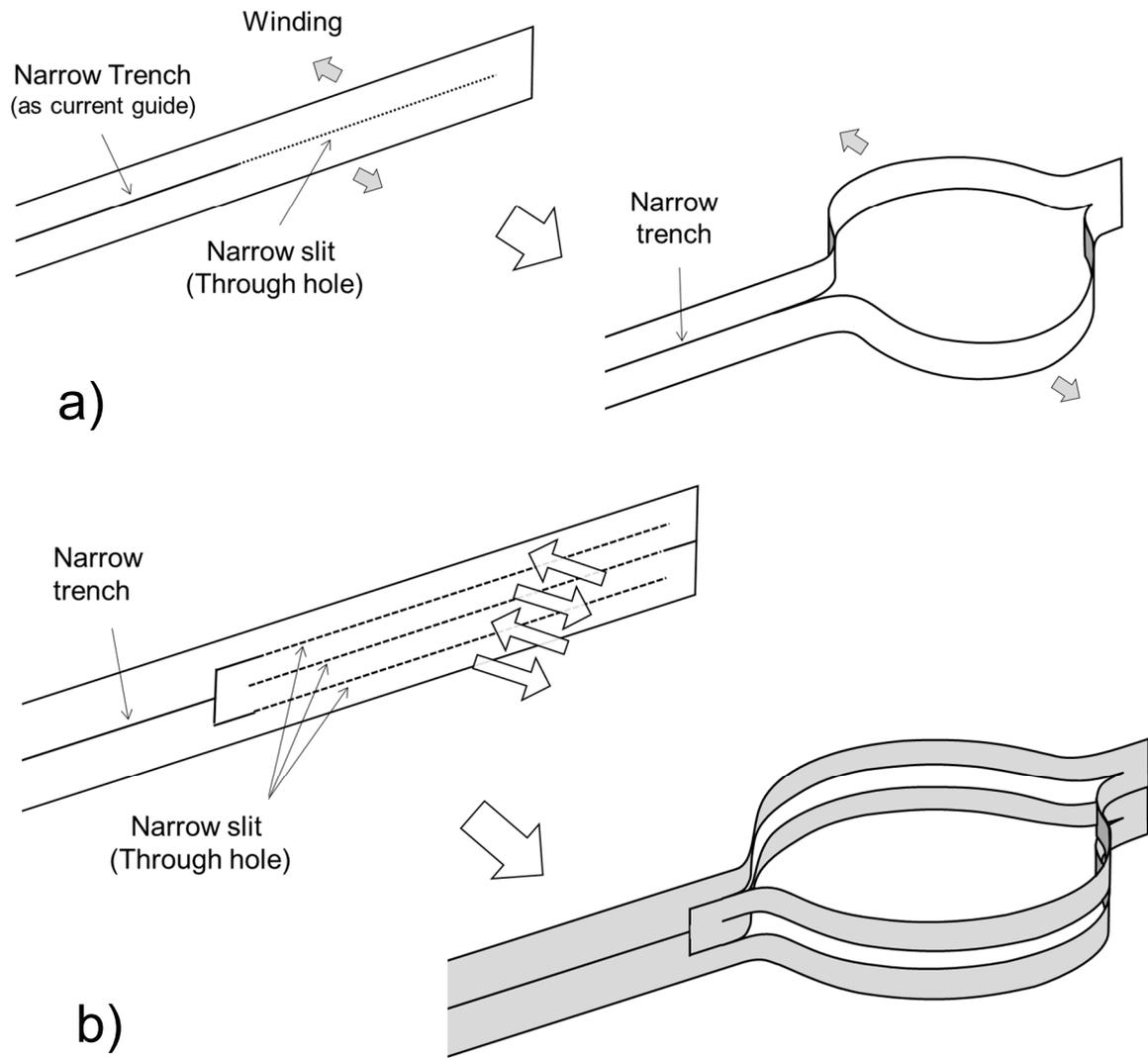


Fig. 1.

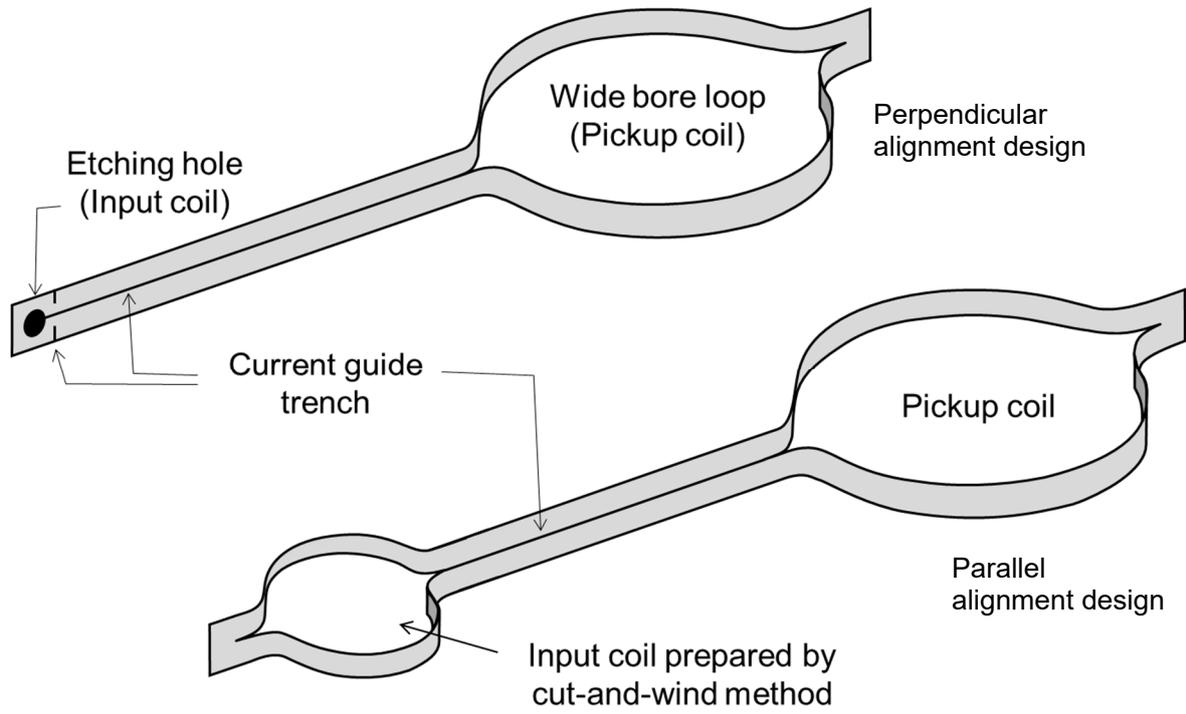


Fig. 2.

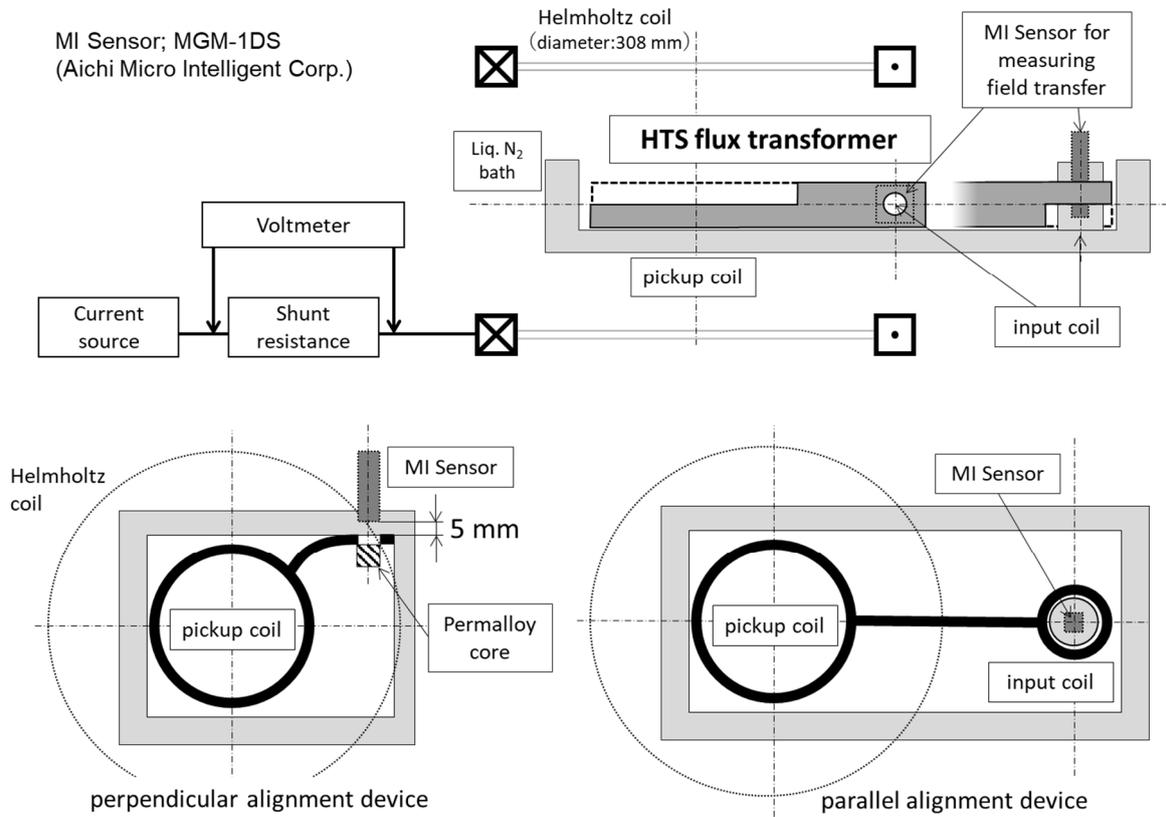


Fig. 3.

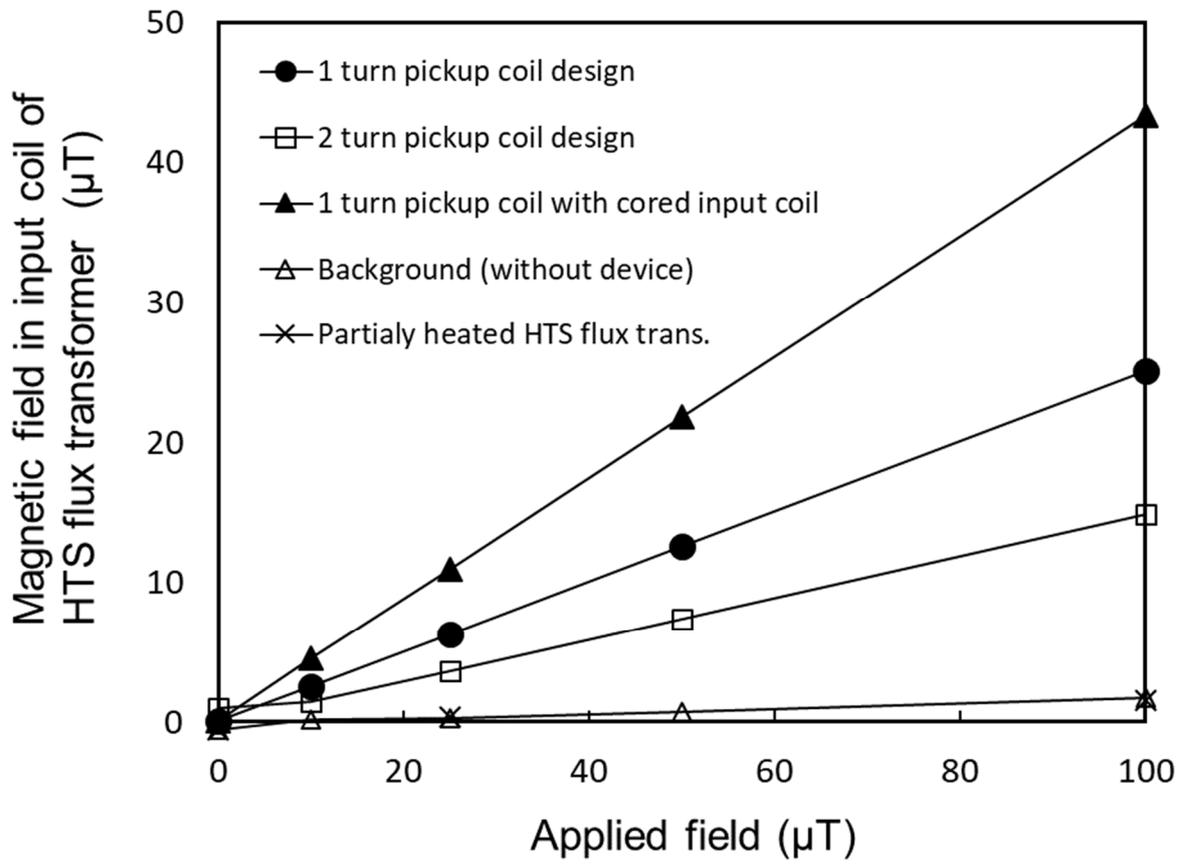


Fig. 4.

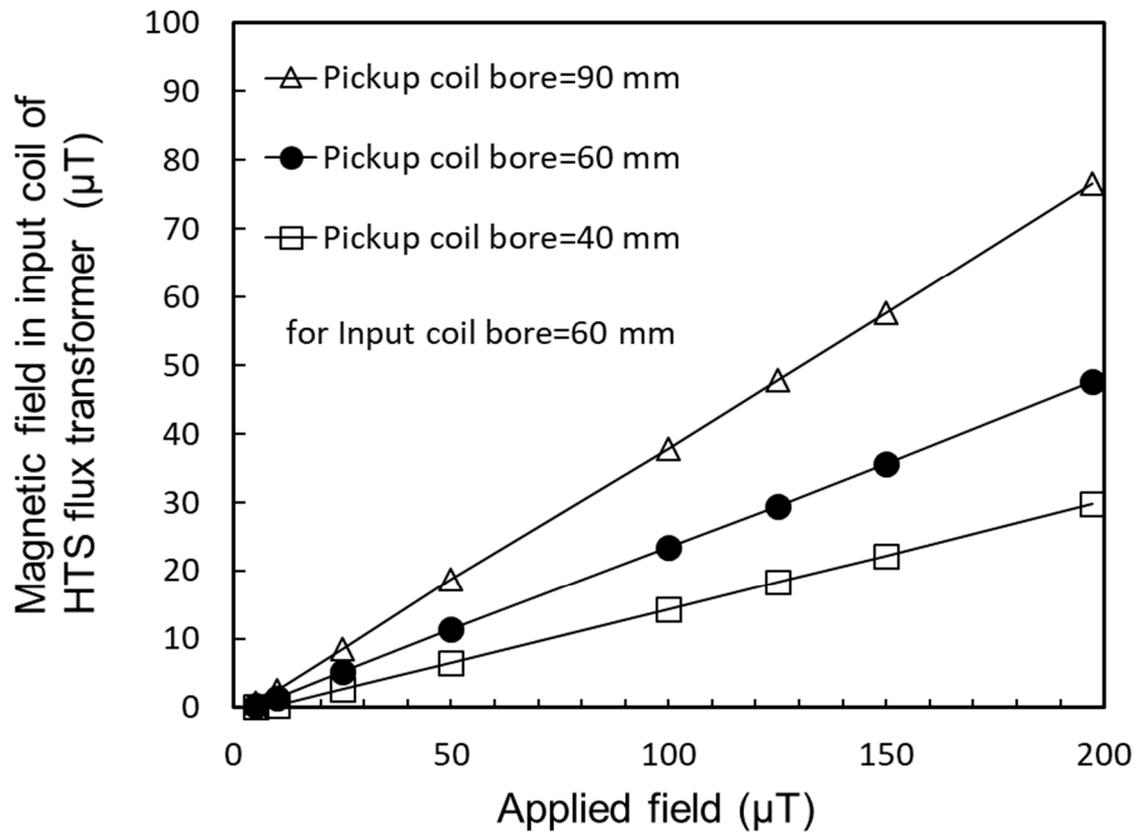


Fig. 5.

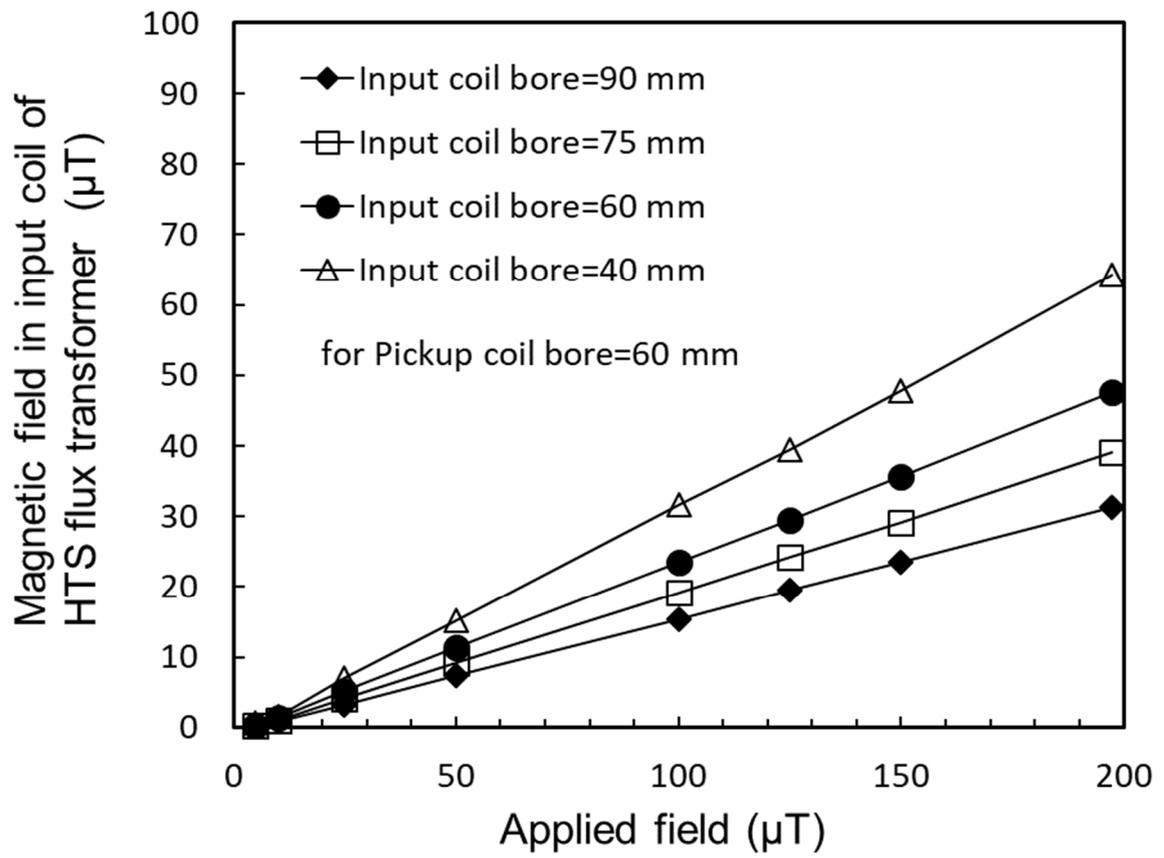


Fig. 6.