Fabrication of Multipole Magnets with Enhanced Flux Density Using Anisotropic Bond Magnets for Miniature Optical Pickup Devices

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A prototype magnetizing fixture was designed based on magnetic flux patterns simulated using the three-dimensional finite-element method of the JMAG software package. Rectangular shaped anisotropic bond magnets with dimensions of 6×12×24 mm were magnetized to multipoles using the prototype and a pulse power source. The result was significant enhancement perpendicular to the surface component of magnetic flux density ($B_z$) in the hard-axis compared with $B_z$ for conventional simple magnets, of which the front and back surfaces are magnetized to opposite polarities. Moreover, $B_z$ reached the close value for the Halbach arrayed magnet, 0.24 T, with the same body size fabricated for the attainment target. The enhanced $B_z$ was attributed to the cusp field formed by the flux from both side coils. Demonstrations indicated that the cusp field out of the easy-axis could be efficiently enhanced due to focusing of the flux.

Key words: anisotropic bond magnet, magnetizing fixture, Halbach array, multipole magnet

1. Introduction

Miniature (on the scale of several millimeters) optical pickup devices have been equipped in present audio-visual players. The pickups require motion to avoid sound skipping due to vibrations and/or scratches on media, and the principle used to satisfy this requirement is the electromagnetic-force generated between magnetic fields and coils. Nd-Fe-B sintered magnets doped with Dy atoms are adopted in the present pickups to provide an efficient magnetic flux. However, due to unstable supply and price increase of Dy, alternative permanent magnets that are both cheaper and provide efficient magnetic flux are required for the manufacture of pickups in the future. We have focused on Dy-free Nd bond magnets (BMs) as one type of permanent magnet, which are not only cost efficient but also provide advantages in the molding small and multiplex body magnets. However, the BMs still have a problem in that the flux density ($B$) is much smaller than that of the Nd-Fe-B-Dy sintered magnets. Therefore, we have focused on a Halbach array of BMs to improve $B$.

The Halbach arrayed magnets (HAMs) are generally produced by bonding several standard magnetic pieces, the front and back surfaces of which are magnetized to opposite polarities, and the resultant multipoles appear on the surfaces of the HAMs. The HAMs exhibit unique features that augment the magnetic fields on one side, and in contrast, cancel the magnetic field on the other side. Therefore, enhancement of the flux density on one side can be expected just as much as the flux is canceled on the other side. In recent years, HAMs have been widely used for highly efficient electromagnetic devices, in addition to mechanical devices such as electric motors, tape recorders and undulators at synchrotron radiation facilities.

However, HAMs are still subject to serious problems in mass production, because HAMs require bonding processes using adhesives and/or fixtures. Such processes increase both the difficulty in precise assembly and the mass production costs, which make it impossible to produce a number of miniature or large sized HAMs. Therefore, technology to provide BMs with multipoles like HAMs by a magnetizing process applied to simple bodies of bond magnets will be necessary to solve these problems. Application of a polar anisotropic magnetizing process to isotropic magnets has been reported by some groups. In contrast, the materials investigated in this study are anisotropic BMs with a scale of several millimeters.

The present work was thus intended to propose the optimum magnetizing fixtures and anisotropy in bond magnets for enhanced $B$. In addition, analysis of the specific patterns of $B$ was conducted to verify the effects of the proposed process.

2. Experimental and analysis procedure

Figures 1(a) and (b) show the magnetizing fixtures designed in this study. The yoke consists of one top and two side excitation coils constructed with 5 turns of 1.5
mm diameter Cu wires. A pulse power source consisting of condenser banks is used to excite magnetic pulse fields in each coil. The pulse duration generated in the power source was 130 μs. All the coils were connected in series, so that the top and side pole pieces are excited to the S- and N-poles, respectively. A BM with dimensions of 6×12×24 mm was placed in the air gap surrounded by these pole pieces, and a flux comes from both the side and top coils, as shown by the dashed lines in Fig. 1(a). The three planar BMs of HAM (see Fig. 3) as well as the planar BM itself (see Fig. 4) were fabricated using the conventional air core coil with an applied pulse field 9 T for a comparison purposes. Subsequent to magnetizing the BM, the body was measured using a flux meter. An M-H loop was measured using a pulse tracer.

Anisotropic BM materials in this study were Wellmax SSB-18MF with \( B_e \) of 0.90 T and \( \mu H_{c2} \) of 0.58 T. Two types of anisotropic BMs were prepared with the easy-axis (E.A.) pointing in the direction of the \( z \)- or the \( x \)-axis. Numerical calculation for the static field using the three-dimensional finite-element method of the JMAG software package was performed to analyze the detailed flux distribution patterns.\(^{13}\)

![Fig. 1](image)

**Fig. 1** (a) Schematic illustration of magnetizing yoke structure and circuit diagram of the pulse power source. (b) Photograph of the magnetizing yoke. (c) BM structure and definition of coordinates, where the gray areas represent the Hall-probe scan area for both the front and back sides of the BMs.

3. Experimental results

3.1 Optimum HAM structure in miniature optical pickups (JMAG simulation)

\( B_z \) from a HAM is generally dependent on the size ratio of the elements of the magnet pieces that constitute the HAM. To determine the optimum size ratio \( w_1/w_2 \) for the strongest \( B_z \) at the front surface, \( B_z \) was calculated using the JMAG software. Figure 2(a) shows the calculated \( B_z \) as a function of \( w_1/w_2 \). Here, the outer size of the HAM body modeled in this calculation was set to be 2×4×8 mm, because this is the same size of the magnets equipped in the present optical pickups. The strongest \( B_z \) appeared at \( w_1/w_2 = 2 \), but decreased at other \( w_1/w_2 \) ratios.

Figure 2(b) shows cross-sectional vector mapping for \( B_z \) (not \( B_r \)) when \( w_1/w_2 = 2 \). The typical patterns that augment the magnetic fields on one side, cancel the magnetic field on the other side. Based on these results, \( w_1/w_2 = 2 \) was determined as the optimal size ratio of HAM structure for the model in this investigation.

3.2 \( B_z \) pattern for the HAM constructed of the three planar BM elements (for a comparison)

Figure 3(a) shows the distribution pattern of \( B_z \) for the HAM with dimensions of 6×12×24 mm. The outer body size was 3 times that of the model investigated in Fig. 2. Furthermore, the size ratio of the HAM was also \( w_1/w_2 = 2 \), so that the strongest \( B_z \) value could be expected. The Hall-probe was scanned at both the front \( (z = +4 \text{ mm}) \) and back \( (z = -4 \text{ mm}) \) sides of the HAM. At the front side, focused and constant \( B_z \) was observed in the \( x \) and \( y \) directions, respectively. In contrast, \( B_z \) observed at the back side was weak. These same features were also observed in the vector mapping results shown in Fig. 2(b).
The scanning planes in the front and back side of the HAM correspond to $z = +4$ mm and $-4$ mm, respectively. The outer body size of the HAM was $6 \times 12 \times 24$ mm. (b) $B_z$ obtained by line measurement as a function of $x$. The coordinates in this geometry are defined in Fig. 1(c).

Figure 3(b) shows $B_z$ obtained by line measurement along $x$ at $(y, z) = (0, +4)$ and $(0, -4)$, which correspond to the front and back sides, respectively. Parabolic behavior was observed for the front side. The sign of $B_z$ was opposite near the edge of the HAM, which corresponds to the return components of the flux. Note that a maximum $B_z$ of 0.24 T was obtained as the optimized value. Here, we determined $B_z = 0.24$ T as our attainment target in this study. However, although the sign of $B_z$ for the back side was the same, $B_z$ was much lower than the front side.

### 3.3 $B_z$ pattern for the conventional planar BM (for a comparison)

Figure 4(a) shows the distribution pattern of $B_z$ for the planar BM with dimensions of $6 \times 12 \times 24$ mm. The BM was made of the same magnetic compounds (Wellmax-S5B-18MF) as the HAM examined in section 3.2. Magnetization was conducted using our developed process with an excitation current of 20 kA.

Figure 4(b) shows $B_z$ obtained by line measurement along $x$ at $(y, z) = (0, +4)$ and $(0, -4)$, which correspond to the front and back sides, respectively. The range that exhibited a homogeneous $B_z$ distribution was large compared with that of the HAM shown in Fig. 3(b). A similar distribution pattern was observed between the front and back sides, although a much smaller $B_z$ was observed. Note that the maximum $B_z$ was measured to be 0.17 T and 0.16 T for the front and back sides, respectively, which were much smaller than those of the HAM.

### 3.4 Dependence of the BM anisotropy on the magnetizing pole arrangement

Figure 5(a) shows line measurement data of $B_z$ patterns for the planar BM magnetized using our developed process. When E.A. points in the $x$ direction,
To achieve our attainment target of $B = 0.24$ T, the optimum excitation pulse current ($I_{ex}$) was examined. Figure 6 shows a summary of the maximum $|B_z|$ as a function of $I_{ex}$ for the BM in Fig. 5(a). The maximum $|B_z|$ increased monotonically with $I_{ex}$ for the front side, and the same behavior was obtained for the back side. It was again confirmed that $|B_z|$ for the front side at $I_{ex} = 20$ kA reached 0.23 T, which is slightly smaller than 0.24 T. As determined from the total flux ($\phi$) for the entire magnet body as a function of $I_{ex}$, $\phi$ was saturated at 20 kA. Therefore, $B = 0.23$ T may be the best result for the developed magnetizing fixtures.

### 4. Discussion

The results indicate that the developed magnetizing fixtures provided enhanced (maximum) $B_z$ close to the HAMs, despite the planar body shape. Moreover, the case of E.A. // x was not the required anisotropy for the BMs in the present process. To discuss the mechanism for the strong $B_z$ obtained in the H.A., focus was made on two components: the magnitude of the magnetization ($M$) in the direction of the H.A. and the cusp field formed by the flux from the E.A. (x direction).

Figure 7(a) shows the $M$-$H$ loop for a test piece made of the same anisotropic BM measured using a pulse tracer. It should be noted here that a hysteresis was observed for the H.A. which resulted in a small magnitude of remanence. Figure 7(b) shows the second

![Fig. 6 Excitation pulse current ($I_{ex}$) dependence of maximum flux density ($|B_z|$) for the front and back sides of BM in Fig. 5(a). The two dashed lines represent the peak $B_z$ for the HAM, which corresponds to the front side in Fig. 3(b), and the conventional planar BM, which corresponds to the front side in Fig. 4(b). The inset shows the total flux ($\phi$) of entire magnet body as a function of $I_{ex}$ measured using a flux meter.]

![Fig. 7 (a) $M$-$H$ loop for a cubic test piece with dimensions of 5×5×5 mm. The solid and dashed lines represent data measured with the external field pointed in the directions of the E.A. and H.A., respectively. (b) Second quadrant of the $B$-$H$ loop, i.e., the demagnetization curve, obtained from the $M$-$H$ loop in (a). The open square represents $B_z$ at the (x, y, z) = (6, 0, 4), i.e., the center position 1 mm above the front surface, for actual magnets with dimensions of 6×12×24 mm. The dot-dashed line is the permeance ($\mu_0$) line with the slope of 0.35.]

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3.5 Optimum excitation pulse current applied to the magnetizing yoke for maximum $B_z$.
quadrant of the $B^*H$ loop, i.e., the demagnetization curve, calculated using the simple relation between $B$ and $M$: $B = \mu_0 H + M$. $B$ for the E.A. and H.A. were obtained as 0.88 T and 0.21 T, respectively. Considering the demagnetization field, the actual $B$ was decreased. Here, we assumed the actual $B$ in the demagnetization curve for the E.A. as the peak $B_z$ value (0.18 T) at $(x, y, z) = (6, 0, 4)$, as measured in Fig. 4(b), which is represented by the open square symbol in Fig. 7(b). The permeance factor ($P = B / \mu_0 H$) in $z$ direction of the planar BM was estimated to be 0.35. $P$ was generally determined by the demagnetization coefficient ($N$) due to the body shape ($P = 1/N - 1$); therefore, the actual $B$ in the demagnetization curve for the H.A. was expected to be 0.04 T, as indicated by the intersection between the demagnetization curve for the H.A. and the $P$ line. However, the value was extremely small, which indicates that the cusp field formed in $z$ direction may dominate the strong $B_z$ of the planar BM magnetized by the present process (0.23 T).

The cusp field is generally considered to be balanced out of the facing point of the flux. In the present magnetizing fixtures, different $B_z$ may be observed between the front and back sides due to the excitation by the top coil. The difference in $B_z$ was found to be 0.06 T for $I_{ex} = 20$ kA (see Fig. 6). The difference is still slightly smaller than that of 0.08 T, which corresponds to the difference between $B_z$ in the front side (+0.04 T) and back side (-0.04 T) for H.A. estimated from Fig. 7(b). While further analysis of the flux patterns is required to complete the explanation, the effect of the top coil was qualitatively clarified. This implies that $B_z$ can be controlled within the remanence range in the H.A. by independently varying the magnitude of excitation by the top coil.

With respect to optical pickup device application, magnetizing of the present miniature magnets with dimensions of $2\times4\times8$ mm is indispensable. While the demonstration in this work used a 3 times larger model, the manufacturing of $1/3$ sized fixtures may provide the same magnetizing patterns. For mass production, a specified yoke, such as with a wide pole piece, would have to be designed so that a number of magnets can be simultaneously magnetized.

5. Summary

Assuming the application of optical pickups, studies on optimal magnetizing fixtures to achieve the flux density of HAMs were performed using a 3 times larger model. The optimum magnetizing yoke consisted of two side coils and one top coil connected in series. The required anisotropy of the BMs is with the E.A. pointed in the $x$ direction, parallel to the flux from the side coils. As determined from the demagnetization curve for the E.A. and H.A., the cusp field formed by the flux from both side coils dominates the maximum $B_z$, and $B_z$ is expected to be controlled within the magnetization range of the H.A. In the case where the E.A. is parallel to $z$, no enhanced $B_z$ is observed. These demonstrations indicate that the cusp field out of the E.A. could be efficiently enhanced due to focusing of the flux, which is close to the flux pattern for HAMs.

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Received Feb. 04, 2015 : Accepted Mar. 27, 2015