# Development of brushless MEMS micromotor with multilayer ceramic magnetic circuit

M. Takato, Y. Yokozeki, K. Saito, and F. Uchikoba

***Abstract*—**This paper proposed an electromagnetic induction type brushless MEMS micromotor with a multilayer ceramic magnetic circuit. The developed micromotor was combined with the silicon structural parts by a micro electro mechanical systems (MEMS) fabrication process and a ceramic circuit by a multilayer ceramic technology. The MEMS process realized miniature structural parts. The multilayer ceramic technology could form a miniature three-dimensional structure coil. The dimensions of sideways, endways and height of the fabricated MEMS micromotor were 11 mm, 11 mm and 5.5 mm, respectively. The developed MEMS micromotor was controlled by the motor driving circuit. The maximum rotational speed was 4200 rpm at the input frequency of 69.9 Hz. The developed MEMS micromotor with the load weight of 53.7 mg showed the rotational motion, and the rotational speed was 2254 rpm.

***Keywords*—**Electromagnetic induction type, MEMS, Micromotor, Multilayer ceramic technology

## I. Introduction

MICROMOTORS are used for various fields such as portable electronic devices or a micro stage [1-11]. To achieve the micromotor, miniature components are requires. Conventionally, the structural components are fabricated by a mechanical machining process. However, it is faced to the limitation of the miniaturization. Therefore, micro electro mechanical systems (MEMS) process has been focused for the micromotors. The MEMS process can fabricate the miniature component that has both a high-aspect-ratio and a high-accuracy. Moreover, this process is suitable to combine with the control integrated circuit (IC) because it is based on the IC production process.

Many researches of the MEMS micromotor have been reported such as an electrostatic type. In the MEMS process, the fabricated structures are formed in a planar structure. Therefore, the electrostatic type is suitable to MEMS micromotor because this type is based on the planar structure [5-9]. Previously, the MEMS electrostatic micromotor that showed the rotor diameter of 120 μm and the rotational speed of 50 rpm was reported [9]. However, the electrostatic type motor requires high voltage and it shows low torque. On the other hand, the commercial size motor is usually uses an electromagnetic induction type because it shows a high torque by low voltage. The conventional electromagnetic induction type motor has a magnetic circuit that is formed by a winding wire as a three-dimensional structure. However, the winding wire is a problem for the miniaturization because it is difficult to combine with the MEMS structure. Therefore, the MEMS electromagnetic induction type motor adopts a spiral structure coil [10-11]. The spiral coil pattern can be fabricated by sputtering or deposition coating of the MEMS process. However, the spiral coil has some problem for the miniaturization. The spiral pattern is characterized by extending to a planar direction. Therefore, the magnetic circuit requires the large area for catching the divergence magnetic flux and increasing the turn number. Large area of the coil pattern requires a long length coil, and it shows high internal resistance. Many researchers solve these problems by forming the complex three-phase pattern of the coil structure.

In this paper, we focused a multilayer ceramic technology. The multilayer ceramic technology is used for the miniature electro components such as a ceramic conductor and a ceramic inductor. This technology can realize the miniature three-dimensional pattern without the winding wire. In this technology, ceramic sheets that are made from mixture of ceramic powder and organic materials are used. The fabricated ceramic sheets are formed an electrode on the surface of the ceramic sheet. The electrode pattern is made from a conductor paste and it is patterned by the screen printing technology. The through-via pattern is shaped by the drilling machining and filling the conductive paste by the screen printing technology to connect between an upper layer and a lower layer. The patterned ceramic sheets are stacked for forming the three-dimensional pattern inside the ceramic material. The laminated specimens are firing, and then, the miniature electro components are achieved.

In this paper, we propose the electromagnetic induction type MEMS micromotor that has millimeter scale structural body. To realize the miniaturization, the developed motor is combined with the MEMS structural parts and the multilayer ceramic magnetic circuit. Moreover, the developed MEMS micromotor is a brushless motor and it is controlled by a developed motor driving circuit. The brushless motor is not a mechanical contact. Therefore, it is suitable to the miniaturization because a

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frictional force is a profound effect to the micromotor. In the driving circuit, hall IC is used for detecting the rotational motion of the motor. The developed MEMS micromotor is discussed the rotational motion and the ceramic material of the magnetic circuit. In addition, the comparison the results between the driving circuit and the waveform generator is discussed.

## II. Design of Electromagnetic Induction Type MEMS Micromotor

### A. *Electromagnetic Induction Type MEMS Micromotor*

Fig. 1 shows the design of the developed electromagnetic induction type MEMS micromotor. An axial gap type three-phase alternating current synchronous motor is employed for designed MEMS motor because it shows the stable rotational motion. Schematic illustration of the cross-sectional image of the developed MEM micromotor is shown in Fig. 2. This motor is combined with the silicon structure and the ceramic magnetic circuit. The sideways, endways and height of the developed motor are 11mm, 11 mm and 6 mm, respectively. A 2-pole ring-shaped neodymium magnet is attached to the rotor inside the silicon structural parts. The outside diameter, inside diameter, and height of the magnet are 8 mm, 2 mm, and 0.5 mm, respectively. The diameter of the rotary shaft is 600 μm. The magnet and flux-capturing magnetic circuit are arranged beneath the rotor. The multilayer ceramic coils for the magnetic circuits are setting and holding in the silicon case. The hall IC that detects the rotational motion of the rotor is attached to the top frame of the silicon structure.

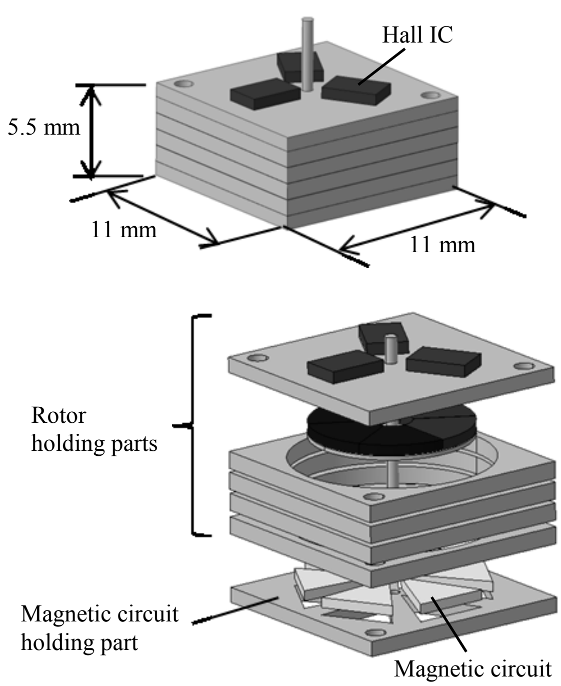


Fig. 1 design of developed electromagnetic induction type MEMS micromotor (a) overall view (b) development view

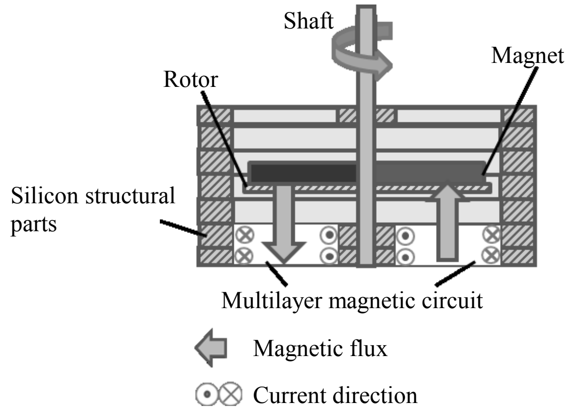


Fig. 2 schematic illustration of cross-sectional image of MEMS micromotor

### B. *MEMS Structural Parts*

The structural parts of the MEMS micromotor are fabricated by the MEMS process. The MEMS parts are a top frame, holding parts for the rotor and the magnetic circuit. The top frame has the cavity structure for setting the hall IC. The upper layers that are holding the rotor are formed the circle pattern of the diameter is 10.0 mm. The lower layers for holding the multilayer ceramic magnetic circuit are formed the six square patterns. The dimensions of the base and the height of all square patterns are 3.64 mm and 3.90 mm, respectively. The fabricated multilayer ceramic magnetic circuit is set to the through-square pattern. The rotor is made from the silicon, and the diameter is 8.01 mm. Fig. 3 shows the design of the structural silicon parts of the developed MEMS micromotor.

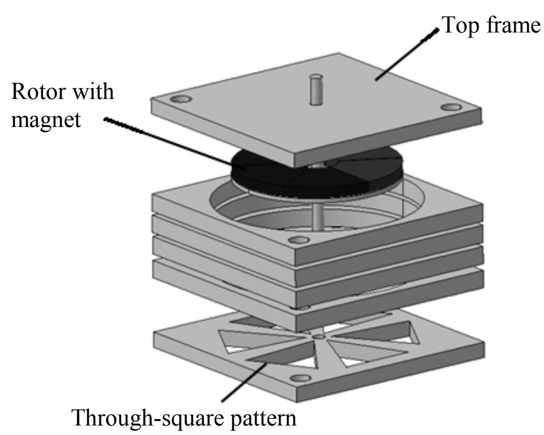


Fig. 3 design of silicon structural parts of developed MEMS micromotor

### C. *Multilayer Ceramic Magnetic Circuit*

The magnetic circuit is made from low-temperature co-fired ceramic (LTCC) that is mixture with the alumina powder and glass powder. LTCC is usually used for insulation material of the ceramic multilayer substrate. The conductive pattern such as the electrode and the coil pattern is silver paste. The printed pattern of the silver paste shows 15/16 turn coil pattern. And then, the multilayer ceramic magnetic circuit has 30-turn helical

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coil by laminating the 36 patterned ceramic sheets. The multilayer ceramic coil that is used for the magnetic circuit is square shape. The dimensions of the base and the height of square multilayer ceramic coil are 3.5 mm and 3.9 mm, respectively. An electrode formed on the reverse face of the circuit applies a driving voltage to the magnetic circuit via a connected wire. Fig. 4 shows the design of the multilayer ceramic coil for the magnetic circuit.

The magnetic circuit for the micromotor requires connection into the three-phase coil. Therefore, the fabricated six ceramic coils are connected to the opposite coils in series each other. The ceramic coils that are divided into three pairs are connected in a star arrangement. Fig. 5 shows the schematic illustration of the arrangement of the multilayer ceramic coil for the magnetic circuit.

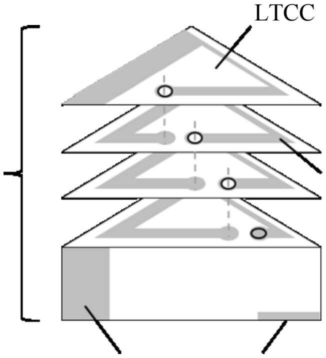


Fig. 4 design of multilayer ceramic coil for magnetic circuit

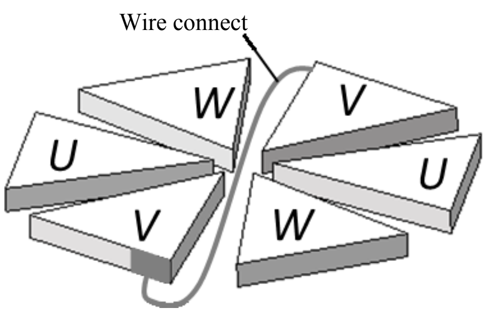


Fig. 5 schematic illustration of the arrangement of multilayer ceramic coil for the magnetic circuit

### D. Motor Driving Circuit

The fabricated driving circuit is employed a three-phase output DC/AC converter. Driving pulse is a rectangular waveform. To detect the rotational motion of the developed MEMS micromotor, the hall IC is used. The output of the hall IC is amplified, and it is inputted into the driving circuit. Fig. 6 shows the schematic illustration of the connection of the driving circuit and the developed three-phase synchronous MEMS micromotor. Fig. 7 shows the circuit diagram of the single phase driving circuit.

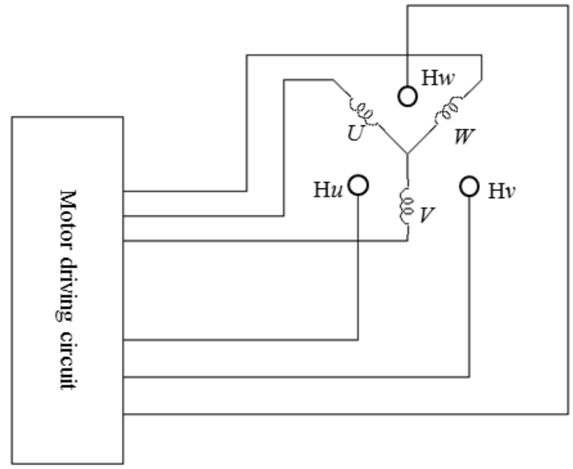


Fig. 6 schematic illustration of connection of driving circuit and developed MEMS micromotor

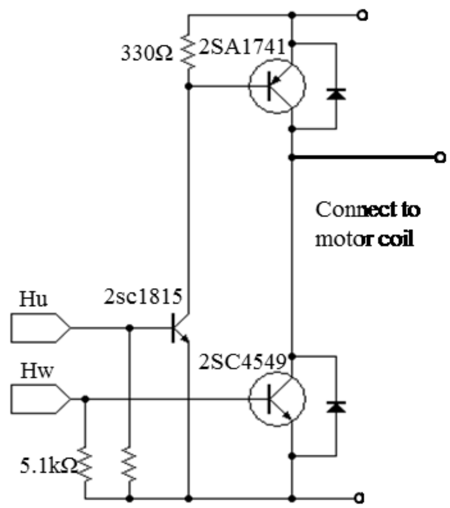


Fig. 7 circuit diagram of single phase driving circuit

## III. Fabrication Procedure and Rotational Experiment

### A. MEMS Process

In the MEMS process, the structural parts and the rotor were fabricated from single crystal silicon wafer. The photolithographic process was used for the pattering. Each silicon wafer was washed, deposited with an aluminum layer by physical vapor deposition, and coated with a photoresist. The designed pattern was exposed to the resist layer and developed by soaking in the developer. The aluminum layer on the specimen was then chemically etched, leaving an imprint of the designed pattern. The patterned wafer was dry etched by high-aspect-ratio inductively coupled plasma etching combined with a Bosch process [12]. The parts were achieved after removing the aluminum and washing. Through these processes, the silicon parts were fabricated. The obtained parts were

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assembled by hand. Fig. 8 shows the schematic illustration of the MEMS process.

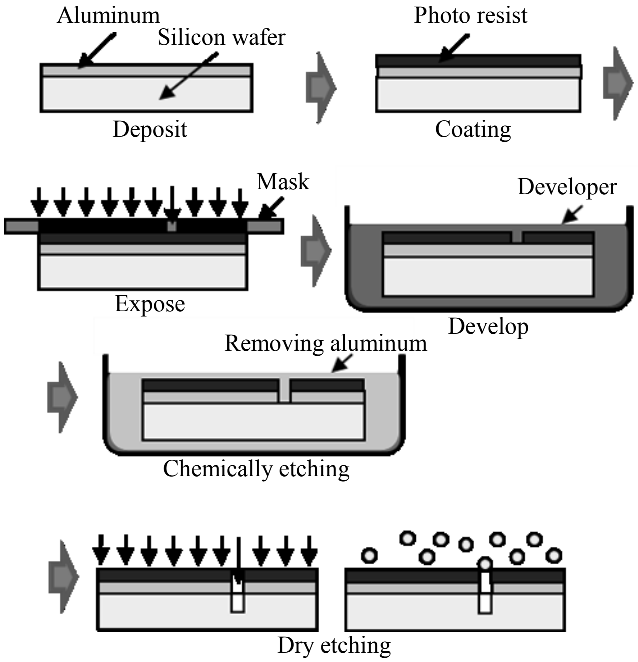


Fig. 8 schematic illustration of MEMS process

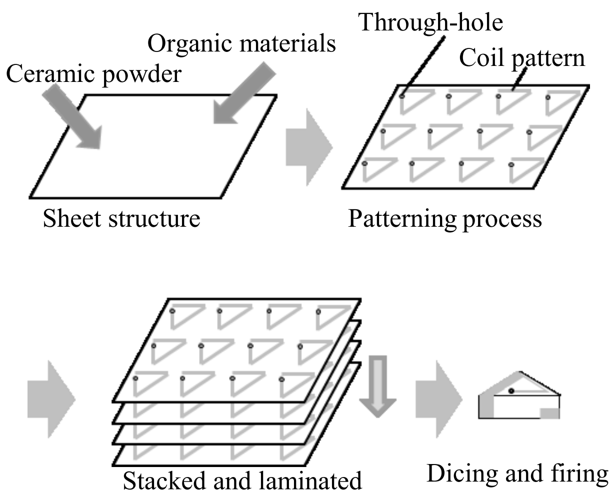


Fig. 9 schematic illustration of the multilayer ceramic technology

### B. *Multilayer Ceramic Technology*

The conventional multilayer ceramic process is called green sheet process in which slurry is formed in the sheet structure. In the fabrication process, the slurry was a mixture of the LTCC powder, binder, dispersing agent, plasticizer, and organic materials. The sheet structure was formed by the doctor blade method. The through-hole for connecting the upper and lower layers was formed on the ceramic sheet. The coil pattern and via pattern were printed to the LTCC green sheet by screen printing technology. Multiple sheets were stacked, and the multilayered specimen was diced into the designed part. Finally, the specimen was fired and the outside electrode was formed. Fig. 9 shows the schematic illustration of the multilayer ceramic technology.

### C. *Rotational Experiment*

In the rotational experiment by the fabricated driving circuit, DC power sources were used for the driving circuit and hall IC, each other. The driving waveform of the interphase voltage was measured by an oscilloscope. The rotational motion was observed by the motion of the flag that attached to the motor shaft.

Moreover, the rotating by the waveform generator was experimented to compare with the rotational motion by the driving circuit. Fig. 10 shows the arrangement of the rotation experiment. The coil was subjected to a driving voltage generated by a waveform generator. Three input voltages, phase-shifted by 120°, were applied to the three single-phase coils. The input voltage was measured by the oscilloscope.

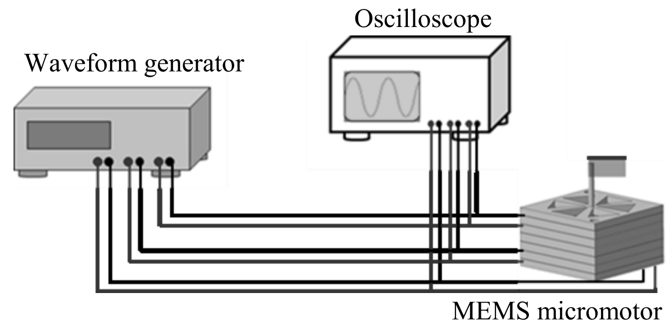


Fig. 10 arrangement of rotational experiment by waveform generator

## IV. Results and Discusses

Fig. 11 shows the fabricated MEMS structural parts. The diameters of the through-circle pattern for holding the rotor and the rotor were 10.0 mm and 8.01 mm, respectively. In the lower layer for holding the multilayer ceramic coil formed six square patterns that were arranged to be shifted by $\pi/3$ radian. The dimensions of the base and height of the through-square patterns were 3.64 mm and 3.90 mm, respectively. The size of the hole for the shaft was measured by the by an optical confocal microscope. The diameter of the holes fell within 619 μm to 622 μm. Designed diameter of the hole was 620 μm, and the size error was found less than ± 3 μm.

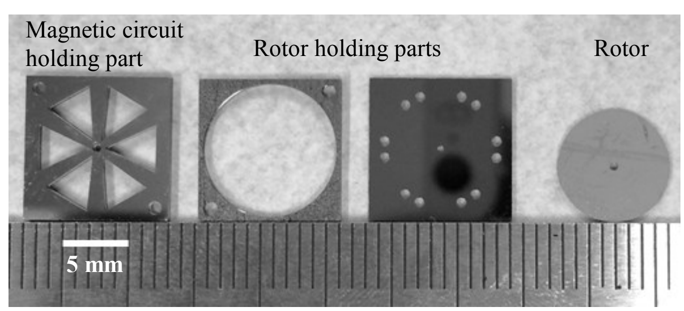


Fig. 11 fabricated MEMS structural parts

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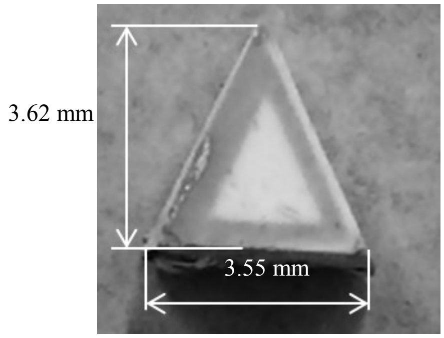

Fig. 12 fabricated multilayer ceramic coil for magnetic circuit

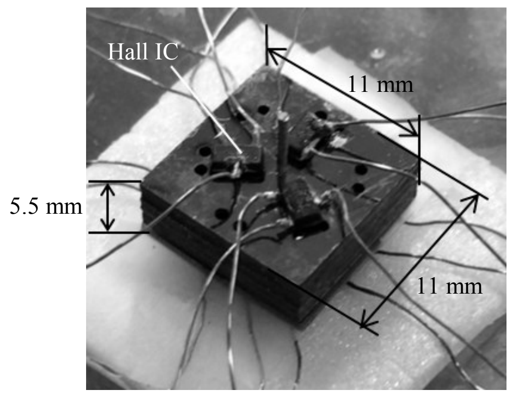

Fig. 13 assembled MEMS micromotor with MEMS parts and magnetic circuit

Fig. 12 shows the fabricated multilayer ceramic coil for the magnetic circuit. The average dimensions between the six ceramic coils of the base, height and thickness were 3.55 mm, 3.62 mm and 1.46 mm, respectively. As a result, the miniature three-dimensional structure coil was realized by the multilayer ceramic technology. The maximum and minimum clearance between the multilayer ceramic coil and the through-square pattern on lower silicon layer for holding the magnetic circuit were 473 μm and 54.6 μm, respectively. Therefore, it was possible to combine with the fabricated multilayer ceramic coils and the MEMS structural parts. However, the achieved output values of inductance showed the dispersion.

Fig. 13 shows the fabricated MEMS micromotor that was combined with the MEMS structural parts and the multilayer ceramic magnetic circuit. The sideways, endways and height were 11 mm, 11 mm and 5.5 mm, respectively. In this figure, the three IC for detection the rotational motion of the rotor was attached to the top frame. The dimension between the rotor and the IC was 800 μm.

In the rotational experiment, the rotational motion was observed by a high-speed camera. Fig. 14 shows the rotational motion of the fabricated MEMS micromotor at the stable rotational motion of 4200 rpm. The line in this figure shows the position of the flag that attached to the shaft. In the rotational experiment, after driving the motor drive circuit, the rotational speed increased from the stopped state. And then, the rotor showed the stable motion at 4200 rpm after about 5 seconds. Fig. 15 shows the waveform of the input voltage at the stable motion. By this result, the frequency was 69.9 Hz, and the input voltage of the *U* phase, *V* phase and *W* phase were 3.2 $V_{p-p}$, 2.1 $V_{p-p}$ and 2.1 $V_{p-p}$, respectively. The output waveform shows the deformation. The reason of the deformation of the output waveform is the difference of the property of the multilayer ceramic coil. The proposed MEMS micromotor required six separated coil structures, and these coils were paired by wire connecting. This problem will be solved by fabricating the paired coil pattern in the single ceramic coil structure and forming the connecting pattern on the bottom layer.

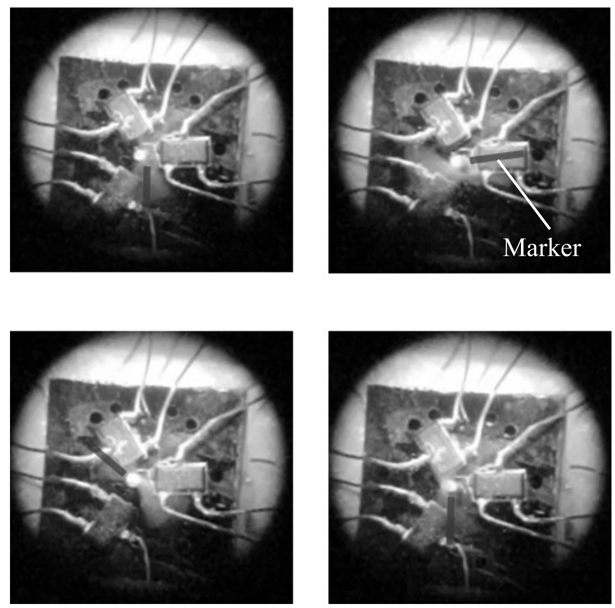

Fig. 14 rotational motion by driving circuit

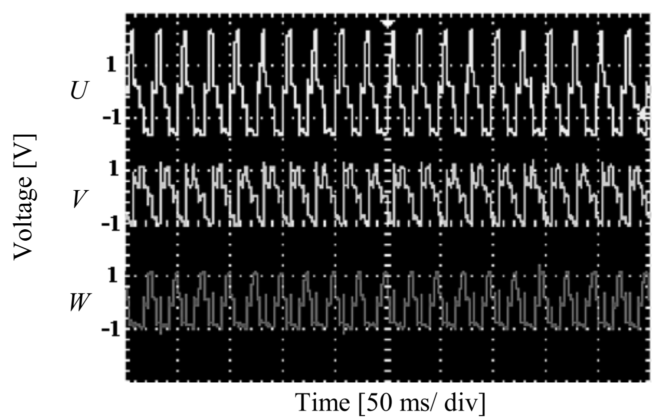

Fig. 15 output waveform of driving circuit

Table 1 results of rotational speed with load weight.

| Weight [mg] | Rotational speed [rpm] | Initial torque |
|---|---|---|
| 0 | 4200 | Not require |
| 53.7 | 2254 | Not require |
| 107.4 | 1440 | Require |
| 161.1 | 660 | Require |

The rotational motion of the fabricated MEMS micromotor that had a weight as a load was shown in table 1. In these results, the fabricated MEMS micromotor showed the rotational speed of 2254 rpm with 53.7 mg weight. However, the rotational motion with the weight of 107.4 mg and 161.1 mg required an initial torque. In this paper, the fabricated ceramic coil was not introduced the magnetic material and a deflection yoke. Therefore, the magnetic flux from the magnet that attached to the rotor was diverging. For achieve more large torque, it is required to introduce the ferrite ceramic material as the magnetic material.

The results were compared at the driving methods. The result of the rotational speed that was generated by the waveform generator was 480 rpm at 8Hz. The reason of the difference was the time of the synchronization. By the waveform generator, the input frequency was changed discretely. However, the driving circuit changes the input voltage continuously. In the future work, the driving circuit and hall IC will be constructed into the MEMS structural parts. It will realize the miniaturization of the MEMS micromotor that including the driving circuit.

## V. Conclusion

This paper proposed the electromagnetic induction type brushless MEMS micromotor. The developed MEMS micromotor was combined with the MEMS structural parts and the multilayer ceramic coil for the magnetic circuit. The dimensions of sideways, endways and height of the MEMS micromotor were 11 mm, 11 mm and 5.5 mm, respectively. The MEMS structural parts constructed the upper layer for holding the rotor, the lower layer for holding the magnetic circuit, and the rotor that was attached to the 2-pole magnet. The six multilayer ceramic coils were arranged in the through-square pattern that was formed on the silicon lower layer. The dimensions of the base, height and thickness of the multilayer ceramic coil were 3.55 mm, 3.62 mm and 1.46 mm, respectively. By using the multilayer ceramic technology, the miniature three-dimensional structure coils were achieved without the winding wire.

The fabricated electromagnetic induction type MEMS micromotor was controlled by the motor driving circuit. The maximum rotational speed was 4200 rpm at the input frequency of 69.9 Hz. Moreover, the fabricated micromotor with the load weight of 53.7 mg showed the rotational motion, and the rotational speed was 2254 rpm.

The maximum rotational speed was compared between the driving circuit and the waveform generator. The rotational speed when the micromotor was controlled by the waveform generator was 480 rpm. The reason of the difference was the time of the synchronization. In the driving circuit, the hall IC was used for detecting the rotational motion. As a result, the driving circuit could change the input frequency continuously. In the future work, the driving circuit and hall IC will be constructed into the MEMS structural parts.

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