Multilayer magnetic circuit for millimeter scale MEMS air turbine generator

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Abstract. The multilayer magnetic circuit for the millimeter scale MEMS (Micro Electrical Mechanical System) air turbine generator is proposed in this paper. The dimensions of the fabricated air turbine generator were 3.6 mm, 3.4 mm and 3.5 mm, length, width and height, respectively. The air turbine was fabricated by the MEMS technology. Multilayer magnetic circuits were fabricated by the green sheet process. The achieved output voltage and output power of the generator were 6.2mV and 1.92μVA respectively. Moreover, the optimization of the ceramic magnetic circuit for the generator was performed to improve the output power. In this experiment, the horseshoe shape circuit and step-wise shape circuit were compared on the output power by the spindle machine. When two kinds magnetic circuit were compared, the output power of the step-wise shape circuit was higher than that of the horseshoe shape circuit. The output voltage and the output power of the step-wise shape circuit were 28mV and 1.53 mVA when load resistance of 0.512 Ω was connected.

1. Introduction

Miniaturization of electronic equipment such as smart phones and PCs has been progressed. Therefore, in the field of the energy, both small size and high power density are required for various applications. Although lithium secondary batteries have been used as the small and high power density source, the power density is approaching to the theoretical limit. In response to this problem, miniaturized electrical generators have been studied as one of the candidates for exceeding the lithium battery.

For example, piezoelectric vibration-powered micro generators have been studied [1, 2]. However, these generators have used for the purpose of accumulating power from environment by means of the harvesting, because its power is too small to be used for main power source.

On the other hand, UMGT (Ultra Micro Gas Turbine) was reported by MIT group [3]. It was a remarkable generator because of its extremely high energy density in small size. The generator was fabricated by the MEMS (Micro Electrical Mechanical System) technology. And then, many studies on MEMS micro generator started. A lot of studies on the MEMS micro generator have been focused on electrostatic type [4]. The advantage of this type is that the components are based on planar structure, and then the MEMS technology can form the planar structure rather easily. However, the output current of the electrostatic type is small because of its charge saturation and its high internal impedance. In a usual commercial size generator, electromagnetic induction type has been used because the electromagnetic induction type shows low output impedance and high output power. In this commercial size generator, the three dimensional winding wire for the magnetic circuit and magnetic materials for the coil core are used. From view point of the output power, the electromagnetic induction type is desirable for the MEMS miniaturized generators. In fact, many studies have been performed recently. However, the winding wire is usually designed in the planer structure such as spiral, meander or equivalent because the miniaturization of the three dimensional winding wire is difficult. The miniaturized electromagnetic induction type generators have reached mill watt to watt class [5,6,7]. These researches proposed the complex three phase windings of copper conductor, and the coil pattern was arranged on a plane substrate. However, the planar structure coil forms only a small area geometrically because the conductor is placed parallel on the surface. Also the turn number of the coil canǿt increase. Moreover, the magnetic materials such coil cores for the MEMS generator have not been reported. Therefore, long length coil is required for catching the magnetic flux. As a result, the conductor resistance results in high and then the output power reduces. When the magnetic material is placed for coil core, it is possible to shorten the conductor length because the magnetic flux is focused in the magnetic material of the small area. The shorter length results in the less conductor loss. Considering these, the three dimensional coil such as helical structure and magnetic materials are expected to increase the output power of the miniaturized generator.

In order to realize the helical structure and the magnetic material in the magnetic circuit, multilayer ceramic technology is effective. Multilayer ceramic technology can form the multilayered circuit inside the structure. Therefore, the monolithic structure and three dimensional helical coil are achieved. In addition, ferrite ceramic material shows excellent magnetic property. Therefore, it is thought that applying the multilayer ceramic technology to the magnetic circuit of the MEMS generator is promising. In this paper, we propose the MEMS air turbine generator with the multilayer ceramic magnetic circuit. Also, we explain the optimization of the ceramic magnetic circuit for the generator.

2. Experimental Procedure

2.1 Design and fabrication process of the MEMS air turbine generator.

The proposed MEMS air turbine generator is the electromagnetic induction revolving-field type. The schematic illustration of the proposed generator is shown in Figure 1. The designed dimensions are 3.5 mm, 3.5 mm and 3.5 mm, length, width and height, respectively. The upper structure which is the air turbine is made of the silicon material. The lower structure which is the magnetic circuit is made of the magnetic ceramic material.

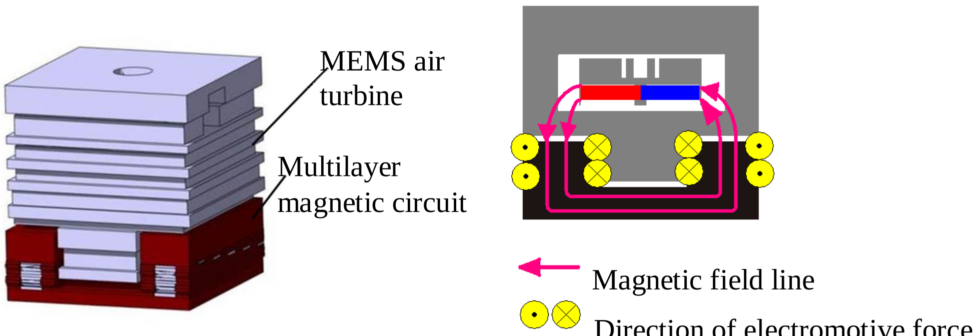

Figure 1. Schematic illustration of the proposed MEMS air turbine generator.

The air turbine parts are made of 7 silicon layers. Figure 2 (a) shows the schematic illustration of the air turbine parts. The upper layers are formed the air passage. Through this passage, air is passed to the stator. The ring shape magnet was attached to the rotor and placed inside the hole of the stator. The lower layers are formed for the passage to the fluid dynamic bearing system. The rotor and each layer were fabricated by the photolithography process. The designed dimensions of the air turbine are 3.0 mm, 3.0mm and 3.0 mm, length, width and height, respectively. Figure 2 (b) shows the schematic illustration of the multilayer magnetic circuit. In this structure, the magnetic circuit formed the horseshoe shape. The pocket of this magnetic circuit is formed to attach with the MEMS air turbine. Therefore, it is possible to realize the structure that has short distance between the magnet and the magnetic circuit. The designed dimensions are 3.5 mm, 3.5 mm and 1.6 mm, length, width and height, respectively. The coil is patterned inside twin square poles. The total turn number of the coil is 18. The magnetic material is nickel cupper zinc ferrite with the permeability of 900. The compositional ratio is 49.2Fe_2O_3-8.8NiO-10CuO -32ZnO. Silver is used for the coil pattern.

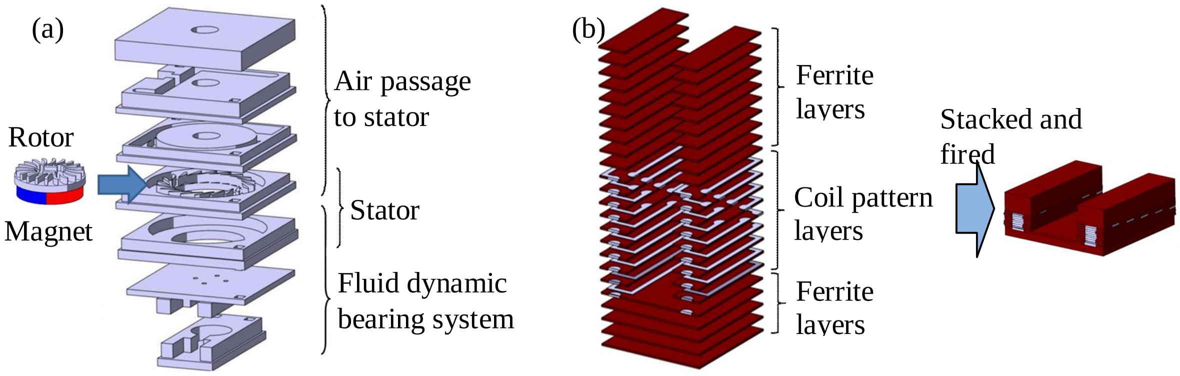

Figure 2. Schematic illustration of air turbine components (a), multilayer magnetic circuit (b).

The multilayer magnetic circuit is fabricated by the green sheet process. In this process, the slurry is made for forming the sheet structure. This sheet is called the green sheet. The slurry in our fabrication was made of the mixture of the ferrite ceramic powder, binder, dispersing agent, plasticizer and organic materials. The through hole was machined and then the coil pattern was printed on the ferrite green sheet by the screen printing technology. The material of the coil pattern was silver paste. The multiple sheets were stacked. The multilayered specimen was diced into the designed part. Through this process, the obtained specimen was planar structure. However, in order to apply the multilayered magnetic circuit for the generator, more complicated structure is required. Therefore, the each part was combined for the design structure. After that, the specimen was fired in the electric furnace. Through this process, the objective structure was completed. Figure 3 shows the schematic illustration of the fabrication process for the complicated structure.

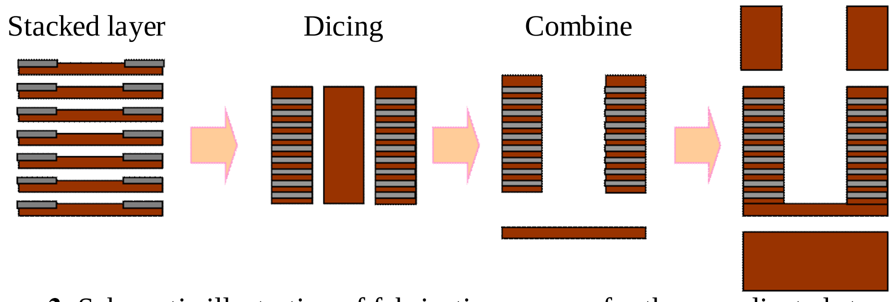

Figure 3. Schematic illustration of fabrication process for the complicated structure.

2.2 Evaluations of the power generation.

The power generation of the fabricated air turbine generator was evaluated. The compressed nitrogen gas was injected to the generator. In this experiment, the rotational speed and the output voltage were measured. Load resistances were connected to the output of the magnetic circuit. The output waveform was measured by an oscilloscope. Figure 4 shows the arrangement of the measurements.

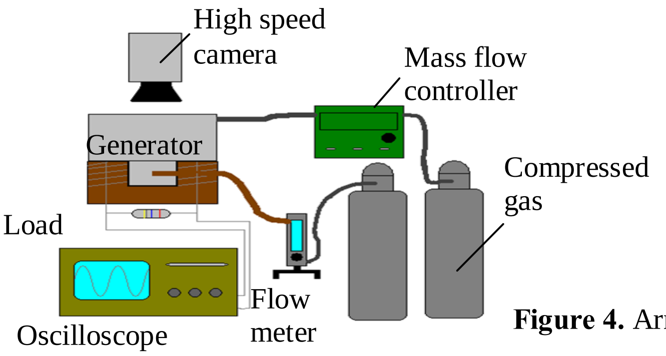

Figure 4. Arrangement of the measurements.

Also additional experiment was performed for the optimization of the magnetic circuit. In this experiment, two structures of the magnetic circuit were fabricated and compared. One of the magnetic circuit was horseshoe shape structure that was same structure as the MEMS air turbine. The other structure was step-wise shape that the magnetic material is surrounding the magnet. In the both structures, the turn number was 24 turns and the size was 3.5 mm and 3.5 mm, length and width, respectively. The height was 1.2 mm in the horseshoe shape, and 2.0 mm in the step-wise shape. Each magnetic circuit was shown in Figure 5. In this evaluation, a spindle machine was used for power evaluations, because the different structures of the air turbine are required for each magnetic circuit. The arrangement of the measurements is shown in Figure 6.

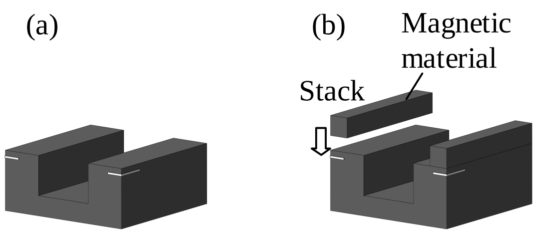

Figure 5. Schematic illustration of the horseshoe shape circuit (a), step-wise shape circuit (b).

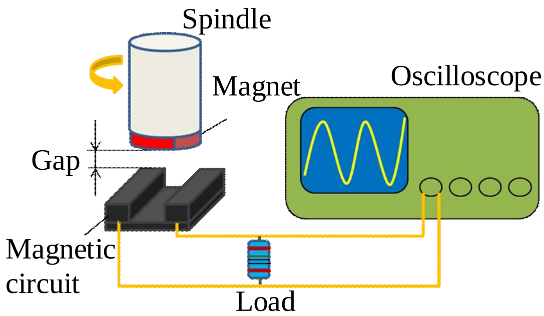

Figure 6. Arrangement of the measurements by the spindle machine

3. Evaluations and Discussion

The fabricated component of the air turbine is shown in Figure 7. In this turbine, the rotor and stator size are important factor. The designed diameters of the rotor and stator were the 1580 μm and 1600 μm, respectively. And the measured diameters were 1578.27 μm and 1603.32 μm, respectively. Therefore, it is found that the error was quite small. The appearances of the multilayer magnetic circuit are shown in Figure 8. It is observed that the complex structure was achieved. The dimensions of the magnetic circuit for the air turbine generator were 3.55 mm, 3.38 mm and 1.16 mm, length, width and height, respectively. Inductance and DC resistance were 6.25 μH and 1.2 Ω.

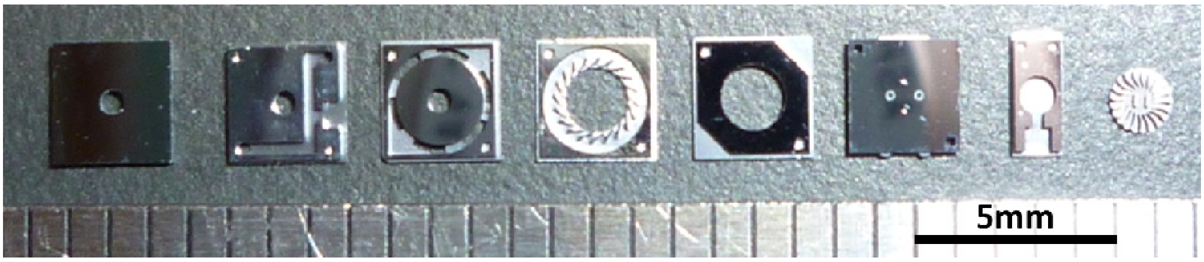

Figure 7. Photograph of the fabricated turbine components.

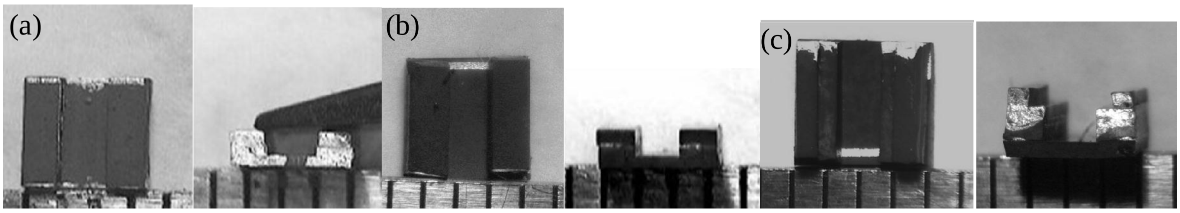

Figure 8. Photograph of the magnetic circuit for the air turbine generator (a), horseshoe shape for the optimization experiment (b), step-wise shape(c).

Figure 9 shows the fabricated MEMS air turbine generator. Dimensions of the MEMS air turbine were 3.6 mm, 3.4 mm and 3.5 mm, length, width and height, respectively. The waveform of the output voltage is shown in Figure 10. The rotational speed was derived from this data. The maximum rotational speed was 58,000 rpm on the condition of 0.28MPa. The load resistance of 20 Ω was connected to the output of the magnetic circuit. The reason of the 20 Ω is matched internal resistance in this time and the maximum output power is achieved. In this case, the maximum output voltage and the output power of the generator was 6.2mV and 1.92μVA respectively. The measured output power was about 19 % of the theoretical power. The reason is thought to be the magnetic flux leakage.

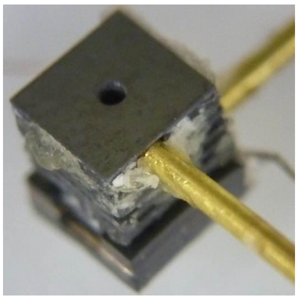

Figure 9. Fabricated generator.

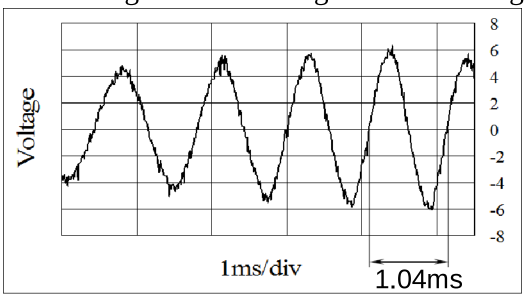

Figure 10. Waveform of the output voltage.

In the optimization experiment, the two magnetic circuit specimens were evaluated (Figure 8 (b) and (c)). The dimension of the horseshoe shape circuit were 3.25 mm, 3.49 mm and 1.34 mm, length, width and height, respectively. Inductance and DC resistance were 5.85 μH and 0.94 Ω. The dimensions of the step-wise shape multilayer ceramic circuit were 3.40 mm, 3.47 mm and 1.88 mm, length, width and height, respectively. Inductance and DC resistance were 5.35 μH and 0.53 Ω.

The load resistance of 1 Ω was connected to both the horseshoe shape magnetic circuit and the step-wise shape magnetic circuit. The rotational speed of the spindle machine was 380000 rpm. In the results, the output voltages were 26.8 mV and 38.4 mV. Therefore, the maximum output powers were 0.72 mVA and 1.47 mVA. The step-wise shape magnetic circuit showed the larger output power than the horseshoe shape magnetic circuit. Figure 11 shows the results of a FEM analysis of the magnetic flux in both magnetic circuits. Figure (a) shows the horseshoes shape structure, and (b) shows the step-wise shape structure. In the horseshoe shape structure, the leaked flux is observed around the upper part. In the step-wise shape structure, it is observed that the leakage is quite small. For these results, it is found that the magnetic material surrounding the magnet improved the output power.

In addition, the load resistance dependence of the output voltage and the output power were measured in the step-wise shape specimen. Figure 12 shows the measured value and the theoretical curve. The theoretical curve was calculated taking account of the internal resistance and the self-inductance. The error was small between the measured value and the theoretical value. The maximum output power of 1.53 mVA was obtained when the load of 0.512 Ω was connected. The load value was close to the internal resistance of 0.53 Ω.

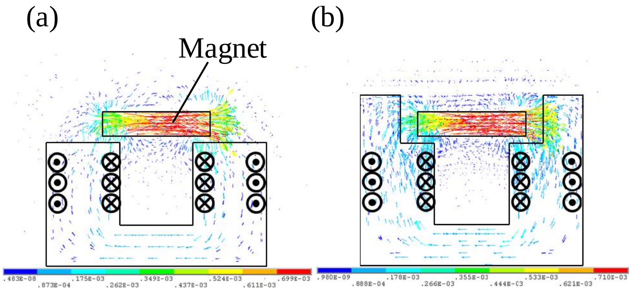

Figure 11. The results of a FEM analysis of the magnetic flux in the horseshoe shape (a), and step-wise shape (b).

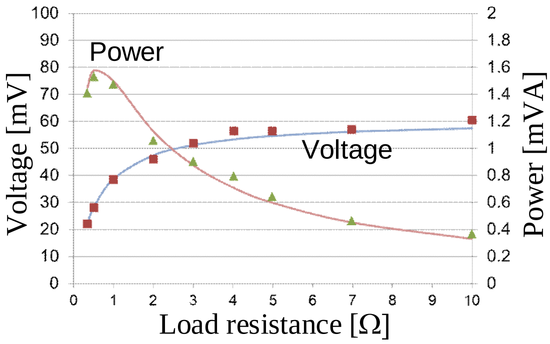

Figure 12. The graph of the output value and the theoretical value.

4. Conclusion

In this paper, the MEMS air turbine with the multilayer magnetic ceramic circuit was fabricated. The sizes of the fabricated generator were 3.6 mm, 3.4 mm and 3.5 mm, length, width and height, respectively. The maximum output voltage and the power of the generator was 6.2mV and 1.92μVA respectively. Moreover, optimization of the ceramic magnetic circuit for the generator was performed using two kinds of magnetic circuits that were the horseshoe shape and the step-wise shape. In the evaluation, the spindle machine of 380000 rpm was used instead of the MEMS air turbine. The maximum output voltage of the horseshoe shape and the step-wise shape magnetic circuits were 26.8 mV and 38.4 mV, respectively. The maximum output power was 0.72 mVA and 1.47 mVA, respectively when the load resistance was 1 Ω. The step-wise shape magnetic circuits showed better property than the horseshoe shape circuit. The reason is thought that the magnetic material around the magnet suppressed the flux leakage. In addition, the load resistance dependence of the output voltage and the output power was measured. Also, the measured voltage and power were compared to the theoretical value that was calculated taking account of the internal resistance and the self-inductance. The maximum output power of 1.53 mVA was obtained when the load of 0.512 Ω was connected.

Acknowledgements

The sample of this study was fabricated by the facility of Research Center for Micro Functional Devices Nihon University. Also, this study is supported by JSPS KAKENHI Grant Number 22560254 and Project of CST Nihon University. The author appreciate the supports.

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