Fabrication of a micro-coil pulsed magnet system and its application for solid state physics

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Abstract. Micro-coil pulsed magnet system has been constructed with a single turn coils fabricated by photolithograph method on a printed circuit board. For the current switches, several different types of fast turn-on switches such as MOSFET switches, air-gap switches and optically triggered air-gap switches were tested and compared their properties. With 2100 V of charging voltage, about 10T of magnetic field was successfully generated at more than 1 Hz of repetition frequency. For the application of the micro-coil system to solid state physics, possible are discussed.

1. Introduction
For spin-related researches in solid state physics, local spin manipulation is sometimes very important method to obtain magnetic properties of samples [1]. Recently, K. Mackay et al. have succeeded in fabricating a micrometer size single turn coil and generating strong magnetic fields over 50 T [2,3]. This technique can be applied to solid state physics as spin relaxation measurements, because of its local properties in both space- and time-domain [4].

For the application of the micro-coil technique, it is important to confirm controllability and reproducibility of the field generation. In this paper, we have tested micro-coil system with several different shapes of coils and switches and discussed them in the light of controllability for the application.

2. Construction of pulsed magnetic field system
Our purpose is to make a system generating pulsed magnetic fields with 100 nsec duration using a flat single turn coil of a sub-millimeter inner diameter. Single turn coil was fabricated with a simple photolithography method which is generally used to make electronic circuit boards. For the circuit board fabrication, several different types of cupper-coated thin insulating boards are provided. We choose glass epoxy boards because of their stiffness and low dielectric loss.

For the base material, we adopted commercial cupper clad board for the printed circuit board(PCB). Coil pattern was drawn on the transparent film for the photo-design (Sunhayato PF-10) with an ink-jet printer (Canon PIXUS iP-8600). The minimum line width successfully drawn and etched on the PCB was less than 0.2 mm.

For the conductive part of the board, enough thickness cupper is needed to avoid raise of temperature during the magnetic field generation. If we generate 10 T of magnetic field as a 10 nsec sinusoidal wave with a coil of the inner radius \( R_i = 0.2 \) mm and the outer radius \( R_o = 0.5 \) mm, the heat generation can be estimated to be about \( 2.9 \times 10^4 \) Joule. Since the thickness of the copper part of the
PCB is about 35 μm, resulting increase of the coil temperature is estimated to be less than 70 degree in the adiabatic condition. In practical conditions, Joule heating generated in the micro-coil rapidly diffuses into large electrode part, 35 μm thickness is considered to be enough to avoid thermal destruction of the coil. Single turn coil part of the photo-etched circuit board is shown in figure 1. Capacitors of up to 30 nF were directly soldered between the two electrodes of the single turn coil which can be charged by high voltage power supply up to 5000 V.

For an efficient generation of pulsed magnetic fields, low-resistance and high-speed switches are needed. We have used several different types of fast turn-on switches such as air-gap switches, optical triggered air gap switches and MOSFET switches. In the case of MOSFET, high speed switching of less than 10 nsec turn-on time can be easily achieved, however, upper limit of the current for the single MOSFET is several tens of amperes, which is too low for the generation of enough high magnetic fields. Thus, we used a transistor switch unit (BEHLKE HTS-31-80), which has 10 nsec turn-on rise time and can be used up to 3000 V and 800 A pulse generation. Figure 2 shows a typical coil voltage generated with the transistor switch unit as a function of time. It is clear that high-speed switching of less than 30 nsec was realized using this switch. We have calculated the resistance and inductance of the coil with several different $R_{in}$ and $R_{out}$ as shown in figure 3. With 100 MHz frequency of the current, effective imaginary (inductive) resistance can be estimated to be about 0.2 Ω. However, from the fitting of the measured coil voltage $V_{coil}$, circuit inductance is 5 times as large as calculated inductance. This large value of inductance mainly comes from the leads of capacitors and switch circuit.

To reduce such additional inductances, compact design of the circuit, namely, use of small devices is needed. In the case of the transistor unit, dimensions of the switch are more than 200 mm ×50 mm ×35 mm and it inevitably results in rather long wirings. As an alternative candidates for the current switch, we adopted a ceramic arrester. The ceramic arrester is a short-circuit device for avoiding large spike voltages across an electronics circuit. The structure of the ceramic arrester is a simple spark gap switch packaged in a ceramic can in which an inert gas is sealed for stabilize spark voltage. Because of the size is small and the maximum current is large, we can reduce lead-inductance with the device. Figure 4 shows typical coil voltages measured with a circuit with the ceramic arrester switch circuit. In this case, the additional inductance due to the switch can be reduced to be a half of the above transistor switch unit, however, the inductance of the leads of capacitor remained unchanged.

To estimate the absolute value of the generated magnetic fields, a fast microscopic magneto-optical measurement system is needed because the inside space of the coil is very small and the pulse duration

Figure 1. Photograph of photo-etched circuit board. $R_{in}$=0.2mm and $R_{out}$=0.5mm.

Figure 2. Coil voltage measured with three different charging voltages. Power MOSFET module switch was used.
is very short. At present, we have no such system and the accurate estimation could not be performed. However, from the coil voltage measurements, we can estimate the magnetic field. In figure 4, we show a fitting curve of measured coil voltage with a simple dumped oscillation equation,

$$V_{coil} = V_0 e^{-t/\tau} \cos t / t_0,$$

where $\tau$ and $t_0$ are dumping time constant and oscillation frequency of the voltage. With this fitting, we found $\tau$ and $t_0$ are $1.7 \times 10^{-7}$ and $1.3 \times 10^{-7}$ sec, respectively. From these time constants, the resistance and the inductance of the present circuit are $0.61 \ \Omega$ and $5.2 \times 10^{-8} \ \text{H}$, respectively. Maximum current flowing in the circuit is estimated to be about 1500 A for the case of $V_{\text{charge}} = 2100 \ \text{V}$. Calculation of the magnetic fields simulating the real single turn coil dimensions reveals that the maximum field is about 9.9 T. In this condition, coil and circuit is stable for more than 100 pulses generation of about 1 Hz repetition, suggesting much larger current and higher magnetic field generation can be realized in this system.

For the present system, still two thirds of the charging voltage is applied to the additional inductances in switch and capacitors and the field generation is limited by them. From the calculation, the main part of the additional inductance comes not from the capacitance and switch but from the leads between them. Thus, the change of the design to realize connection of the capacitance and switch to the circuit without thin leads will make the maximum field three times as large as the present case.

Timing for triggering this switch can be determined only by the charging voltage and the trigger voltage is sensitive to the temperature of the switch. However, we found that the switch can be triggered by flashing light when the charging voltage is above the 80% of the trigger voltage of the switch. Using this method, we can stabilize the timing and charging voltage.

Figure 3. Result of calculation of inductive resistance $R_{in}$ and maximum field with different size of micro-coil. $R_{in}$ was calculated with frequency of 100 MHz.

Figure 4. Measured coil voltage triggered with ceramic arrester switch at $V_{\text{charge}} = 2100 \ \text{V}$. Estimated maximum magnetic field is about 10 T.
3. Applicability to the solid state physics

For the application of the micro-coil system to solid state physics, we should consider how to make up the disadvantages. One serious problem of the system exists in the inhomogeneity of magnetic fields. Measurements of magnetic-field-dependence of the physical properties demand a homogenous field distribution. From the simulation as shown in figure 5, distribution of the magnetic field of the single turn coil is highly inhomogeneous. To improve it, double layered coil is effective. As shown in the figure, arrangement of two same coils with a 0.25 mm gap highly improve the field distribution. This type of double coil configuration can be easily achieved with use of double sided PCB.

Another disadvantage of this system is the shortness of the pulsed fields. In the case of the coil with $R_n=200$ μm, inductance of the coil part can be estimated to be $10^{-9}$ H and the pulse width without additional inductance of capacitance and switch leads becomes less than 10 nsec. However, one can easily deform the pulse shape with a slight change of additional inductances. In fact, we succeeded to get a longer pulse generation with use of additional inductance between capacitances.

In summary, we have tested several types of micro-coil pulsed magnet system with use of photolithography fabrication of PCB and successfully generated about 10 T of magnetic field. From the estimation of the circuit resistance and inductance, the maximum field can be increased with changes of the circuit. Finally, we examined possibilities to improve the homogeneity and the width of the magnetic fields generated with micro-coil.

References

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