Sub-THz Wave Magnetic Resonance Force Microscopy with a Gyrotron

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***Abstract*—A sub-THz wave magnetic resonance force microscope (MRFM) has been developed with a CW gyrotron ($TE_{22,8}$ mode, *f*~299.23 GHz) at University of Fukui. We have successfully measured the MRFM signal at *B* > 10 T, from the free radical spins in a bis-diphenylene-phenyl-allyl (BDPA) crystal sample attached on a cantilever. Sub-THz wave MRFM will be a key technology to achieve the atomic-scale spatial resolution in MRFM, and for the MRFM quantum computer.**

I. Introduction And Background

MAGNETIC Resonance Force Microscopy (MRFM) is the unique detection method which enables the magnetic resonance imaging in the microscopic sample area[1]. In MRFM, extreme signal sensitivity and signal selectivity have been achieved by a combination of the laser interferometer and a cantilever. As a result of the advancement of signal sensitivity due to the improvements of a ultra-thin cantilever, the measurement of 1 electron spin resonance has been successfully performed by IBM group[2]. Now, they have put on the target on the 1 nuclear spin MRFM measurements.

Berman have proposed a nuclear spin quantum computer[3], based on the MRFM measurement of 1 electron spin resonance at 280 GHz. However, there is no former MRFM data at such high frequency. Most experiments have been done in the frequency range below 2~3 GHz, and even ~10 GHz X-band experiments could be classified as high frequency MRFM experiments[4]. Until recently, the highest frequency record was 23 GHz with a klystron[5].

St. Andrews group has significantly improved this situation[6], and they have demonstrated the MRFM measurements at 93.5 GHz with a Gunn oscillator (*P* ~ several tens of mW) and a quasi-optical system. However, other MRFM experiments have been usually performed with microwave power of more than ~1 W, and such a high power ESR experiment is not common in the millimeter and submillimeter wave region.

A gyrotron is the unique light source, which make the high power ESR experiments possible in the millimeter and submillimeter wave regions[7-9]. Many high frequency pulse and continuous wave (CW) gyrotrons have been developed at University of Fukui, and the highest frequency record of a gyrotron is up to ~1 THz[10]. We have attempted to apply a gyrotron for the MRFM for the first time.

II. Sub-THz Wave MRFM System

Figure 1 shows the schematic diagram of the sub-THz MRFM system with a gyrotron CW-1. The gyrotron operates in the fundamental $TE_{22,8}$ mode at $f \sim 299.23$ GHz and the output power is $P \sim 1.7$ kW at the window. $\Delta f \sim 2$ MHz and there is 2~3 % power fluctuation inherent to the cathode power supply.

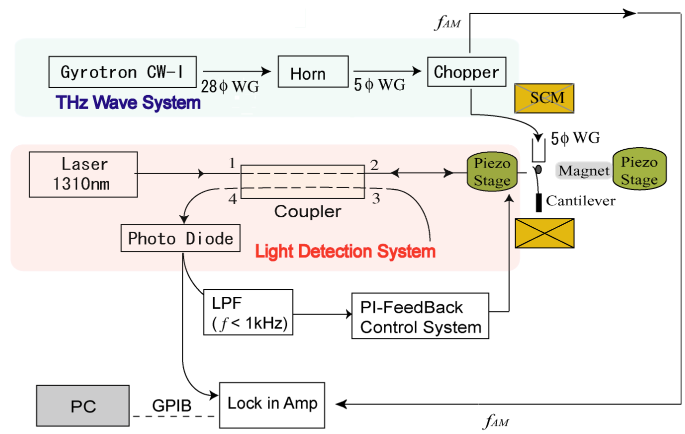

Fig.1 Schematic diagram of the sub-THz wave MRFM system.

The sub-THz wave is transmitted to the 17 T superconducting magnet (SCM) by a 28ϕ circular copper wave guide. The sub-THz wave is once irradiated to the air just above the magnet, and then received by a horn at the top of the MRFM probe. A chopper positioned below the horn modulates the amplitude of the sub-THz wave, and then it is transmitted to the sample position by a 5ϕ circular wave guide in the vacuum probe (~10^{-6} Torr).

For the magnet and the laser fiber positioning system, we have made 2 sets of titanium 3D piezo stages, following the design of a commercial product from Attocube. To control these 3D piezo stages, we have used ANC150 (Attocube).

Our fiber optic interferometer is composed of a 1310nm laser diode (Thorlabs, S1FC1310), a directional coupler, and a photodiode (PD). The output current from a PD is converted to a voltage signal at a 1 MW resistor. The fiber-to-cantilever spacing is adjusted by using the fringe of the laser interferometry with a piezo-feedback circuit. The amplitude of a cantilever oscillation is measured at a lock-in amplifier (Stanford Research, SR830).

For a cantilever, we have used a commercial Si_3N_4 product (Olympus, BL-RC150VB) of spring constant $k_c = 0.006$ N/m. The resonance frequency of a free cantilever is $f_c = 13\sim16$ kHz, and value of the quality factor is ($Q \sim 500$) at the room temperature and in high vacuum (~10^{-6} Torr). The force sensitivity is about $F \sim 10^{-15}$ N as described before [4].

To make the magnetic field gradient at the sample, we have used particle of a magnetite sand. A 0.1-mm-scale magnetite sand was glued on top of the thin-sharped quartz rod. The magnetization of a magnetite sand is sufficiently saturated under the field of $B > 1$ T at the room temperature. The position of a magnetic particle is adjusted by a 3D piezo stage.

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III. EXPERIMENTAL RESULTS

For the sample, we have used a tiny stick BDPA crystal. The thickness is ~30μm, and the length is ~170μm. The sample was mounted on a cantilever with epoxy glue, then the resonance frequency of the cantilever has dropped to 1.22 kHz due to the mass of the sample and epoxy glue. The estimated weight of the sample is ~100ng. When the external magnetic field is applied, the resonance frequency has gradually changed owing to the effect of the anisotropy field, and the resonance frequency is f_c=1.115 kHz at B~10.8 T. Q value of the sample loaded cantilever is ~200.

Figure 2 shows the first sub-THz MRFM signal obtained by magnetic field sweep measurement at the ESR frequency of 299.23 GHz. The vertical axis shows the oscillation amplitude of a cantilever. There is a fairly large spurious signal (40~50nm) made by the amplitude modulation of the sub-THz wave, and in addition, MRFM signal is observed at B~10.745 T. The maximum oscillation amplitude of MRFM signal is ~15nm, and this value corresponds to the magnetic force of F=0.45 pN, where $F = k_c z_c / Q$, k_c~ 0.006 N/m, z_c ~ 15 nm, and Q ~ 200. As far as we know, this is the first success of the MRFM measurement from the radical spins under the external field of B > 10 T with the sub-THz wave.

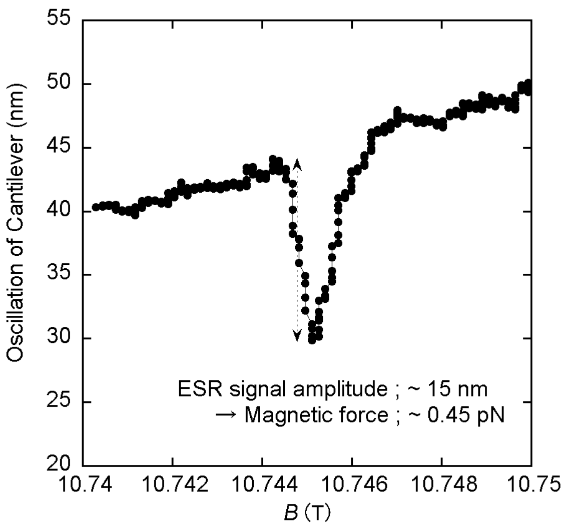

Fig. 2 299.23 GHz MRFM signal from a ~100 ng BDPA crystal

Figure 3 shows the change of the ESR field made by departing the magnet from the sample about ~90 μm. A magnetite particle is at the distance of ~0.3 mm from the sample after the movement. The magnetic field gradient is determined to be $\partial B/\partial z$ ~ 15 T/m for the experiments in Fig. 3.

The magnetic moment of resonant electron spins can be estimated from $M = F/(\partial B/\partial z)$. In Fig. 3, cantilever oscillation amplitude varies from 2~30 nm, so we use F = 0.6~9 pN and $\partial B/\partial z$ ~ 15 T/m, then we get M = 4~6 x 10^{-14} J/T. This is approximately the magnetic moment of 4~6 x 10^9 electron spins.

It seems that the S/N ratio is worse in Fig. 3 than in Fig. 2, and this is caused by the frequency instability of a chopper. When the 100 W power sub-THz wave is irradiated, the air is substantially heated, and this heated air has often caused the 0.5~1 Hz instability in the chopper frequency. When there is a slight difference between the cantilever resonance frequency and the chopper frequency, then this instability has largely influenced the S/N ratio.

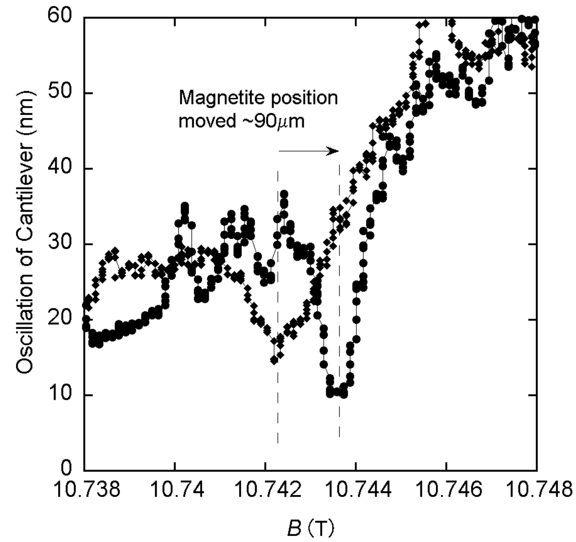

Fig. 3 The change of the ESR field made by departing the magnet from the sample about ~90 μm. The magnetic field gradient is determined to be $\partial B/\partial z$ ~ 15 T/m.

IV. SUMMARY

The sub-THz wave MRFM system have been developed with a CW gyrotron at University of Fukui. We have successfully measured the MRFM signal at 299.23 GHz under the magnetic field of 10.7 T, which have significantly improved the world highest frequency record of the MRFM experiment. About 4~6 x 10^9 resonant electron spins have been detected in the demonstrated MRFM measurements.

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