Abstract of Ph.D thesis

Studies on Electro-Mechano-Optical Transducer for Signal Detection of Nuclear Magnetic Resonance

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I. Introduction to EMO transducer

Nuclear magnetic resonance (NMR) is a powerful analytical tool indispensable in physics, chemistry, and biology for exploring the structure and dynamics of materials. Although NMR deals with electrical singals at radio frequencies, the sensitivity of the measurement of the radio frequency is generally low. Therefore, a variety of efforts have been made to improve the sensitivity of NMR by increasing the intensity of NMR signals. In order to further improve the sensitivity of NMR, it is important not only to increase the signal but also to reduce the noise. One straightforward way of the latter is to cool the circuit down to cryogenic temperatures to reduce Johnson noise, but operation at ambient temperature would find interest in a lot of practical applications.

Electro-Mechano-Optical (EMO) NMR, an emerging NMR detection technique with signal upconversion from radio-frequency to optical regimes via Si_3N_4 nanomembrane, is expected to be a low-noise detection technique for NMR. In EMO NMR, a metal is deposited on a membrane resonator, and used as a capacitor electrode in an LC resonant circuit; the NMR signal generated in the LC resonant circuit together with a drive signal with an appropriate frequency vibrates the membrane by oscillating the amount of charge on the membrane. At the same time, the metal deposited on the membrane is also served as a mirror on one side of the optical cavity. We can measure the displacement of the membrane by injecting a laser into the optical cavity and thereby observing the modulation of the intensity of the reflected light. Here, the Johnson noise in the LC circuit is the same for both conventional NMR and EMO NMR. In conventional electrical NMR, in addition to the Johnson noise, the noise of the amplifier is added, limiting the sensitivity. EMO NMR, on the other hand, adds noise due to the Brownian motion of the membrane, but the contribution of this noise can be made little by optimizing the experimental parameters. Therefore, EMO NMR is expected to be more sensitive than conventional electrical methods.

However, despite the success of the proof-of-principle EMO NMR first in literature (Takeda *et al.*, 2018), it was far from practical use. In order to use EMO NMR for chemical analysis as well, it is necessary to improve on the three points: high sensitivity, high stability, and miniaturization. In this thesis, we attempted to solve these problems by taking the approaches described in the following Chapters.

II. Lightweight nanomembrane transducer

In the previous study (Takeda *et al.*, 2018) of EMO NMR, the frequency of the drive signal was close to the frequency of the signal to be observed, which caused the contamination of phase noise in a drive signal and significantly reduced the sensitivity of EMO NMR. To separate the frequency of the drive signal from the observation frequency, we reduced the weight of the membrane resonator to increase its characteristic frequency, which prevented the phase noise of drive signal from contaminating signal of interest. We demonstrate up-conversion of rf signals at 42.74 MHz by 6 orders of magnitude in frequency to an optical regime, resulting in the sensitivity of EMO NMR was improved by a factor of ca. 20 compared to the previous work (Takeda *et al.*, 2018), although the transfer efficiency of the system being 1.1×10^{-7} was comparable to (Takeda *et al.*, 2018). The improved sensitivity allowed us to study the transient response of the membrane oscillator to electrical excitation due to nuclear induction, which revealed the detection bandwidth of current EMO NMR was found to be limited to ca. 100 Hz.

III. Metasurfaced nanomembrane transducer

We created a structure called metasurface as a optical mirror on spatially separated area from the metal-deposited electrode. In addition, the (2,2)-mode of the characteristic oscillation of the membrane oscillator is allowed to mediate the electrical and optical signals. By placing the electrode and the mirror in such a way that both contain the antinodes, the separated electrode and mirror can be implemented without sacrificing the strengths of both the electromechanical and optomechanical couplings. We demonstrate up-conversion of rf signals at 175.2 MHz by 6 orders of magnitude in frequency to an optical regime with the transfer efficiency of 2.3×10^{-9}. The use of metasurface suppresses the absorption of light by the membrane and enables stable measurements for a long time. Now that the transducer was found to be robust against laser heating, the transfer efficiency would further be improved by employing the laser beam with higher power, which can decrease the optical shotnoise contribution in EMO transducer.

IV. Probe for EMO NMR use in a superconducting magnet

We have developed a compact EMO NMR probe, which enables us to align the optical system and perform optical detection in a limited space, with a minimum electrical wiring, compatible with superconducting magnet used in NMR for chemical analysis. The developed module was made by non-magnetic parts, except for a tiny spring in the contact probes. We have successfully acquired ^{13}C NMR signals of benzene using the INEPT method, a widely used NMR technique in chemical analysis.

V. Conclusions

EMO NMR, which combines hybrid quantum technology and NMR, is expected to be more sensitive than conventional NMR methods by increasing the electromechanical coupling strength and the optomechanical coupling strength. Reducing the gap between the electrodes of the membrane capacitor would effectively improve the electromechanical coupling strength, which is essential for future improvements.

The limited bandwidth of EMO NMR can be a problem for chemical analysis because the information is in the frequency distribution of the signal emitted by the sample. However, there is generally a trade-off between the bandwidth of a probe and its sensitivity, which is a problem that inevitably arises when probes are made more sensitive, not only in EMO NMR. In EMO NMR, however, the optomechanical/electromechanical cooling of the membrane oscillation mode, which damps the mechanical oscillation by using interaction-based feedback, can overcome this problem, thus enabling both high sensitivity and wide bandwidth detection.

Future direction is real application to chemical analysis, and development of EMO probes for various purposes. EMO NMR, which has so far been the subject in physics, has now come into the realm of NMR in chemistry. The SCM-compatible probe for EMO NMR can be combined to a metasurfaced, thermally stable membrane with the capacitor electrode separately on the membrane, which is much less affected by laser heating compared to the rf-to-light transducer using the metal mirror on the membrane, allowing for long-term, stable operation at ambient temperatures.

References

Takeda, K., K. Nagasaka, A. Noguchi, R. Yamazaki, Y. Nakamura, E. Iwase, J. M. Taylor, and K. Usami (2018), Optica **5** (2), 152.