Microcantilevers are very sensitive force sensors; they have been used not only as probes for atomic force microscopes (AFMs), but also as tools for magnetic measurements.\(^1\text{-}^4\) These cantilevers have an advantage over superconducting quantum-interference device magnetometers in that they can be used under magnetic fields larger than 10 T, and even under pulsed magnetic fields.\(^5\) In recent years, application of this technique has been extended to quantum oscillation measurements,\(^1\) susceptibility anisotropy measurement of exotic materials,\(^6,7\) and magnetic resonance force microscopy.\(^8,9\) The cantilever displacement \(\Delta d\) can be measured using various detection methods. The most popular of these is beam-deflection detection, which is implemented in commercial AFMs. On the other hand, piezoresistive,\(^1,2\) capacitive,\(^3,4\) and optical interferometric detection\(^5\) methods have been used for magnetic measurements because of the limited sample space within a cryostat. Among these, optical interferometric detection is the most sensitive; it can detect \(\Delta d\) as a change in the interference intensity with a sensitivity of less than 10 pm. However, because the interference intensity changes sinusoidally against \(\Delta d\), it is difficult to use this technique to measure \(\Delta d\) values that are comparable to the laser wavelength \(\lambda\) in real time. This is one of the reasons that piezoresistive and capacitive cantilevers have been preferred for use under high magnetic fields.

This paper presents a method for broadening the dynamic range of optical interferometric detection of cantilever displacement. The key idea of this method is the use of a wavelength-tunable laser source. The wavelength is subject to proportional-integral control, which is used to keep the cavity detuning constant. Under this control, the change in wavelength is proportional to the cantilever displacement. Using this technique, we can measure large displacements (>1 \(\mu\)m) without degrading the sensitivity. We apply this technique to high-frequency electron spin resonance spectroscopy and succeed in removing an irregular background signal that arises from the constantly varying sensitivity of the interferometer.

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condition for the measurements of Hemin in later discussions.

As shown in Fig. 2, \( d \) is derived from the fit for Eq. (1) or from the \( \lambda \) values at two adjacent maxima or minima, as \( d = \lambda_{\text{adj}}/2(\lambda_{\text{m}} - \lambda_{\text{m}+1}) \). However, it is time-consuming to repeatedly measure \( V(\lambda) \) during a field-swept experiment. Instead, we used \( V \) as a feedback signal and kept the cavity detuning \( d/\lambda \) constant using a software-based proportional-integral control (\( \lambda \)-control hereafter). The voltage set point \( V_{\text{set}} \) was determined to be \( V_{\text{set}} = 45.3 \text{ mV} \). At this voltage, \( d/\lambda = 1/8 + n/4 \) \( (n = 0, 1, 2, \ldots) \), and the maximum sensitivity was obtained. The feedback loop time was typically 1–3 s, which was limited by the update interval of the tunable laser.

Under \( \lambda \)-control, \( d(B) \) is given as \( d(B) = d(0)\lambda(B)/\lambda(0) \). However, in practice, this equation is not adequate for precise measurement for a number of reasons. First, the wavelength-sweeping resolution of the laser source we used was 1 pm, which limited the resolution of a \( \Delta d \) measurement to above 0.5 nm. Furthermore, the slow update rate gave rise to an error from the setpoint (see the inset in Fig. 3). Hence, a correction term is needed. The modified relation considering these factors is given as

\[
d(B) = \frac{d(0)}{\lambda(0)} \left[ \lambda(0) + \frac{\partial \lambda(0)}{\partial V} |_{V_{\text{set}}} (V - V_{\text{set}}) \right]. \tag{2}
\]

Here, we used the fact that \( V - V_{\text{set}} \) is almost linearly related to the change in \( \lambda \) as long as it is much smaller than \( A \). The correction term corresponds to the first-order term of the Taylor series expansion of \( \lambda(0) \) around \( V_{\text{set}} \), whose value can be derived from the intensity curve shown in Fig. 2. Figure 3 shows \( \Delta d \) when a 130 ng sample of DPPH was mounted. To demonstrate the effectiveness of the correction, we changed the field-sweep rate between the sweep-up (+0.5 T/min) and -down (−0.2 T/min) directions. Although the uncorrected \( \Delta \lambda \) fluctuated between 0.8 and 1.7 T in the rapidly up-sweep field because of the control error of \( V \), the error’s influence disappeared after correction. We can see excellent agreement between the sweep-up and -down traces outside of the low-field region, where the influence of the magnitization hysteresis of dysprosium should be considered.

Figure 4(a) shows \( \Delta d \) when a 16 ng sample of Hemin was mounted. The change in \( V \) without \( \lambda \)-control is shown in Fig. 4(b). It was found that the cantilever self-oscillates in certain magnetic field ranges. Such oscillatory behavior has been found in optomechanical microresonators, including microcantilevers, as well as in AFMs utilizing fiber-optic interferometers. It originates in the light-induced force \( F_{\text{light}} \) (the photothermal force or radiation pressure) from photons inside the optical cavity. \( F_{\text{light}} \) depends upon the cavity detuning factor and damps the cantilever positively or negatively depending on its value. In this experiment, the regions where \( dV/d\lambda < 0 \) and \( dV/d\lambda > 0 \) correspond to the positively and negatively damped regions, respectively. Because such oscillation is a nuisance for \( \Delta d \) measurement, we set \( \lambda(0) = 1490.5 \text{ nm} \) in the positively damped region (see Fig. 2) and kept the detuning constant during the measurement.

We observed a larger displacement (\( \Delta d = 2.90 \mu\text{m} \) at 4 T) for Hemin than for DPPH. The accuracy of the absolute values of \( \Delta d \) was confirmed by counting the fringes of the interference intensity \( N \), which were found in the data without \( \lambda \)-control. In Fig. 4(b), we can see approximately 3.8
fringes. Thus, we obtain $\Delta d = (1/2)\lambda(0)N \approx 2.8 \mu m$, which shows fairly good agreement with the result obtained by $\lambda$-control. For larger $\Delta d$ measurements, the reduction in light reflection at the warped cantilever results in a decrease in $V_r$. This would be the main source of the error in such an experiment, because cavity detuning can no longer be kept constant. If this problem is resolved by further development, such as integration of a focusing lens, the maximum measurable displacement, $\Delta d_{\text{MAX}}$, will be determined by the tunable range of $\lambda$, which is estimated to be $\Delta d_{\text{MAX}} = 7.8 \mu m$ for the initial conditions $\lambda(0) = 1473 \text{ nm}$ and $d(0) = 100 \mu m$.

$\lambda$-control is also useful for measurements utilizing AC modulation and lock-in detection. As an example, we demonstrate the application to HFESR spectroscopy, which is a technique for probing the local spin properties of materials. Although conventional ESR measurements are performed using the cavity perturbation or transmission methods,$^{15,16}$ ESR can also be detected as a change in magnetization because the spin-flip transition process accompanying ESR changes the occupancy of the spin states.$^{17-21}$ Thus far, combinations of piezoresistive cantilevers and the light-modulation technique have been very successful in enhancing the spin sensitivity even in the terahertz region.$^{21,22}$ However, the fact that the DC magnetization component deflects the cantilever and changes the cavity detuning has posed a problem for fiber-optic detection. This causes a large fluctuation in the background signal and makes it difficult to observe ESR absorption. Therefore, it is desirable to use a technique to compensate for $\Delta d$ and keep the cavity detuning constant.

HFESR measurement can be performed by adding some millimeter-wave components to the setup for magnetization measurement (Fig. 1). We used an oversized circular waveguide to cover a broad frequency range between 80 and 160 GHz. The amplitude of a millimeter wave emitted from a Gunn oscillator was modulated at $f_{\text{mod}} = 1 \text{ kHz}$ by switching the bias voltage using a TTL signal from a synthesizer. Because a small AC signal is superimposed onto the DC signal at the detector output, it was removed before calculating $V - V_{\text{set}}$ by setting the integration time of the voltmeter to be much larger than $1/f_{\text{mod}}$.

Figures 5(a) and 5(b) show the ESR spectra of DPPH and Hemin, respectively. The intrinsic $g$ factor of DPPH is $g \approx 2.003$, which corresponds to a resonant field of 2.86 T at 80 GHz. Because we used the dysprosium rod to convert the magnetization into a magnetic gradient force, its local field, $B_{\text{local}}$, shifted the absorption peak towards a lower frequency. It also made the internal magnetic field inhomogeneous, which resulted in broadening of the line width from its intrinsic value ($\approx 20 \text{ G}$). For the measurement of Hemin, $\lambda$-control was indispensable for avoiding the optomechanically induced self-oscillation that disturbs the AC modulation technique. Thus, these data were taken in the positively damped condition as a magnetization measurement in Fig. 4(a). The $g$ factor was determined by measuring the ESR at multiple frequencies. The resonant frequency–magnetic field diagram of the ESR signal is shown in the inset of Fig. 5(b). The slope and intercept on the horizontal axis of the linearly fitted line correspond to $g = 5.51$ and $B_{\text{local}} = 0.404 \text{ T}$, respectively. This result is consistent with a highly anisotropic $g$ factor ranging from $g_\perp \sim 2$ to $g_\parallel = 6$, where $g_\perp$ and $g_\parallel$ are the values obtained when the magnetic field is applied perpendicular or parallel to the basal plane in the Hemin molecule, respectively.$^{23}$

Without $\lambda$-control, the influence of the varying sensitivity was seen in the irregular shape of the background signal [Fig. 5(a)]. On the other hand, the data obtained using $\lambda$-control were on the smooth off-resonant background. The off-resonant signal had a tendency to evolve as the millimeter-wave power increased. This indicates that it originated in the modulation of the sample magnetization under periodic photothermal heating. When the magnetization curve is described by a Brillouin function, the temperature increase $\Delta T$ is found to cause the change in magnetization, $\Delta M_{\text{thermal}} = (\partial M_z/\partial T)|_{B=0} \Delta T \propto B(\partial M_z/\partial B)|_{B=0} \Delta T$. This explains the behavior shown in Fig. 5. We also confirmed that $\Delta M_{\text{thermal}}$ approaches zero again in the high-field limit where $\partial M_z/\partial B \approx 0$.

A similar feedback control for $\Delta d$ measurement is also achieved using piezoelectric transducers (PZTs).$^{24}$ In that case, $d$ is kept constant by compensating for $\Delta d$ with extension or compression of the PZT. $\Delta d$ is obtained from the voltage applied to the electrodes. The advantages of $\lambda$-control over the PZT method are stability and ease of use. Although the hysteresis, nonlinearity, and temperature dependence of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig5.png}
\caption{(a) HFESR spectra of DPPH at 80 GHz with (red) and without (blue) $\lambda$-control. Arrows show the directions of the field sweep. Inset shows the expanded data around the ESR signals after the smooth background signals are subtracted. (b) HFESR spectra of Hemin with $\lambda$-control. The light powers are 41, 16, and 10 mW at 130, 140, and 160 GHz, respectively. Inset shows the resonant fields at each millimeter-wave frequency. Solid line is the linear fit for the data points.}
\end{figure}
the piezoelectric coefficient should be considered for PZT devices, the present method does not require any calibration. In particular, it is useful for measurements at cryogenic temperatures, where a large PZT is needed to obtain a movable range larger than 1 µm because the piezoelectric coefficient decreases to one-fifth to one-tenth of the value at room temperature.

In conclusion, we developed a magnetization measurement system using a microcantilever and a fiber-optic interferometer. By controlling \( \lambda \) such that the cavity detuning was kept constant, we succeeded in measuring \( \Delta d \) up to 3 µm without degrading the sensitivity. We demonstrated the applicability of this method to AC modulation and the lock-in detection technique by performing HFESR spectroscopy.

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