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Paper

Photo radiation pressure at resonance of frequency modulated micro cantilever

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Abstract: We demonstrated high-sensitivity measurement of photo-radiation pressure by applying frequency modulation (FM) detection for the resonance phenomenon of the micro-cantilever structure. We constructed a system to detect minute displacements using the optical-lever method and achieved a noise density of approximately $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ from the thermal vibration measurement. The resonance frequency shift was positive, which meant repulsive forces acted on the metal surface by way of the force generated due to incidence of the laser beam on the stainless-steel (SS) cantilever. For an incident light of 1 mW intensity, a vibration amplitude of 0.687 nm and a radiation pressure of $0.378\,\mu$N were measured experimentally.

Key Words: photo detection, MEMS, cantilever, photo pressure, frequency modulation

1. Introduction

Semiconductor photodetectors convert photon energy into electrical signals by separating holes and electrons via the photoelectric effect or by the internal electric field within the p-n junction. However, these processes face issues such as shot noise and the limitation of the conversion speed to produce electric signals [1]. Signal processing technology that amplifies and mixes signals used in optical communications requires the development of devices that not only measure, but also operate and control photons [2]. A MEMS (micro electromechanical system), manufactured using semiconductor microfabrication technology, is one such device that can operate as well as control photons [3–6]. One example of such a MEMS device is a micro cantilever, used as a standard detector in many fields because of its simple structure, easy manufacturing, and good vibration characteristics [7–12].

To study the measurement and manipulation of light using MEMS devices, it is essential to have a technique to detect the interaction between photons and cantilevers with high sensitivity. In this study, we constructed a dedicated micro-displacement detector, then estimated its displacement detection

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sensitivity using the vibration amplitude, caused by Brownian motion, in a commercially available silicon cantilever. Next, a stainless-steel (SS) cantilever with a symmetrical structure was fabricated, and the photo radiation pressure generated due to the incidence of laser light (intensity-modulated to be at the same frequency as the structural resonance of the cantilever) was experimentally evaluated.

2. Method

2.1 Experimental setup

An optical lever displacement detection system was employed to measure the vibration characteristics of the cantilever when laser light was incident. Figure 1(a) shows a schematic diagram of the entire system, and Fig. 1(b) shows an external view of the system inside a soundproof box, in darkroom conditions.

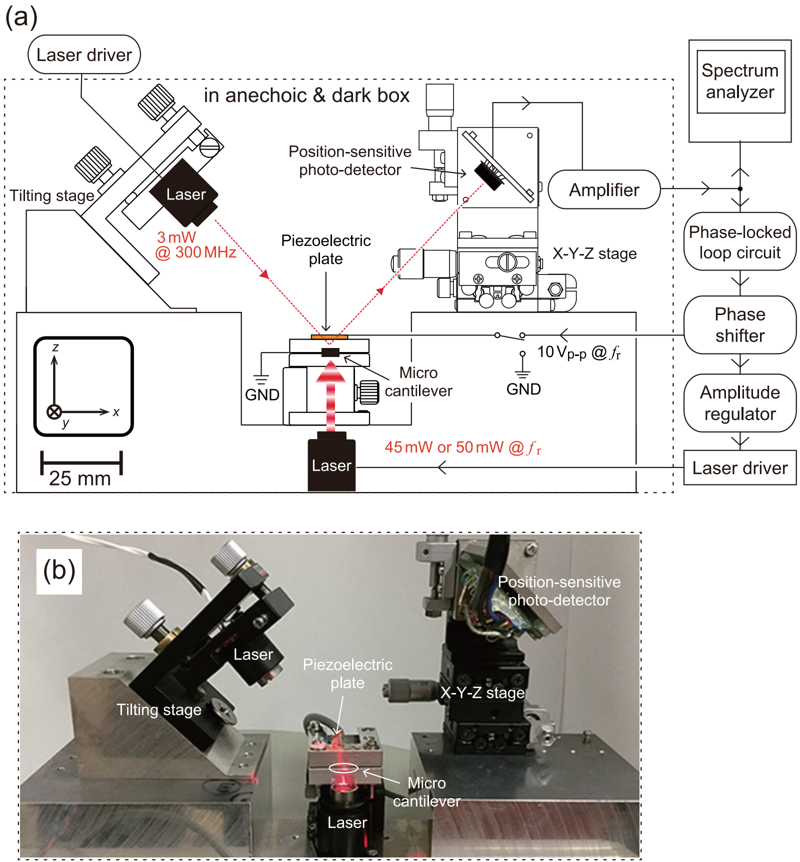

Fig. 1. (a) Schematic diagram of the entire system, (b) External view of the system inside a soundproof box in darkroom conditions.

The laser used for the optical lever displacement detection mechanism was a semiconductor laser diode (AlGaInP Laser Diodes: HL6312, Hitachi). The wavelength of light was 635 nm and the optical output value was adjusted to 3 mW, based on the accurate measurement from a power meter (8230E, ADCMT). Since the 3 mW output of laser light for this displacement detection was only one-fifteenth of other laser light used to generate the photo radiation pressure discussed later, the pressure and energy of the laser light for the detection were ignored. A laser driver (IP500, Thorlabs) was used to adjust the emission intensity of the laser light, and a high-frequency superposition method [13] was used to reduce noise. The noise was generated due to interference and was reduced by modulating the driving current of the laser to a high frequency and by making the laser oscillation multi-mode to reduce coherence [14]. The optical path length from the laser emission port to the cantilever was approximately 40 mm. The laser element had a focusing lens with laser spot diameter focused to approximately 300 μm, which was obliquely incident [15].

For displacement detection using the optical lever method [16], the reflected light from the back of the cantilever was measured using a four-segmented photodetector (S4349, Hamamatsu Photonics). The photocurrent was obtained from a voltage signal using the current-voltage conversion circuits. This photodetector was equipped with a manual fine-tuning x-y-z stage (TSD-255SL, SIGMA KOKI) to enable precise alignment adjustment. In our system, very-small-amplitude vibration close to the resonance frequency of the cantilever was detected. In fact, a stable cantilever excitation was maintained by a self-excited oscillation loop produced by a phase shifter, and a voltage signal corresponding to the amount of resonance frequency shift (Δf) was obtained [17, 18].

For the next step, which was to generate the photo radiation pressure, a different semiconductor laser diode (AlGaInP Laser Diodes: HL6548FG, Hitachi) was used as the laser light source. An aspheric collimation and focusing lens pair (LT230260P, ThorLabs) was used for the optical transmission of the laser beam. Here, the wavelength (λ) was 660 nm, and the laser light output was adjusted as per the experimental conditions. Specifically, two separate conditions were used. The intensity of the laser was modulated at 45 mW and 50 mW at the resonance frequency of the cantilever (f_r [Hz]). The intensity modulation of the laser light was done using a laser driver (ALP-6323LA, Asahi-data-systems).

2.2 Resonance frequency of cantilever structure

It is known that the primary resonance frequency (f_r) of a cantilever structure can be calculated by Eq. (1) [19],

$$f_r = \frac{1.8751^2}{2\pi l^2}\sqrt{\frac{EI}{\rho A}} \tag{1}$$

where E [Pa] is the Young's modulus, I [m^4] is the second moment of area, ρ [kg/m^3] is the material density, and A [m^2] is the cross-sectional area of the cantilever. For this study, two types of micro cantilevers (shown in Fig. 2) were prepared. One was a commercially available silicon cantilever, and the other a custom-made stainless-steel (SS) cantilever.

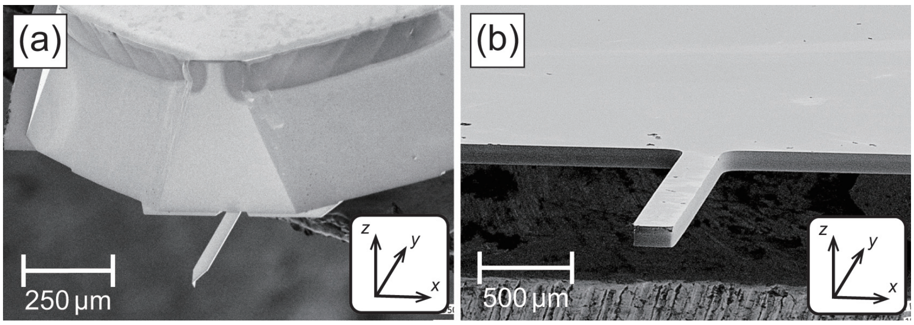

Fig. 2. Scanning electron microscopic images of the used cantilever, (a) silicon cantilever, (b) stainless-steel (SS) cantilever.

A commercial (OMCL-AC240TM, OLYMPUS) silicon cantilever was used as the force sensor of the atomic force microscope (AFM). From its catalog data for length (l) 240 μm, width (w) 40 μm, and thickness (t) 2.7 μm, the resonance frequency f_r was calculated as 67.5 kHz using Eq. (1).

The cantilever of the AFM had an approximately 100 nm coating on each side, of aluminum (Al) on the back side to reflect the laser beam for displacement detection, and of platinum (Pt) on the probe side, used to investigate conductive materials. Since Al and Pt were coated on the silicon base material, when the entire cantilever was warmed by the incidence of laser light, stress was generated due to the difference in the coefficients of thermal expansion of these materials [20]. Hence, it was necessary to consider not only the photo radiation pressure, but also the thermal stress caused by the different materials of the cantilever. Therefore, we employed the AFM cantilever only for the evaluation of the developed displacement detection system.

On the other hand, we designed and manufactured a micro cantilever made of stainless-steel (Fe-Cr-Ni alloy, SUS304), with length (l) 2 mm, width (w) 200 μm, and thickness (t) 100 μm. Substituting these values into Eq. (1), the calculated resonance frequency f_r was 20.6 kHz. Since the cantilever was mirror-polished, displacement was measured by detecting the reflected laser light.

The stainless-steel (SS) cantilever had two advantages over the silicon cantilever. First, since the SS cantilever was made solely from the SUS304, no stress was generated as there was no difference in the coefficients of thermal expansion of the cantilever material. Second, since structural symmetry of the cantilever was ensured, repulsive or attractive forces could be easily distinguished from its bending direction. Hence, it could be inferred that the lever displacement was simply proportional to the magnitude of the force applied to the SS cantilever. More importantly, as for the generation of radiation pressure when the laser light was incident on the metal, the resonance frequency of the SS cantilever increased if it was acted upon by repulsive forces and decreased if it was acted upon by attractive forces [21, 22].

2.3 Sensitivity of displacement detection

We evaluated the sensitivity of displacement detection by measuring the thermal noise spectrum of the silicon cantilever using a spectrum analyzer (N9010A, Keysight). Figure 3 shows the vibration spectrum of the silicon cantilever obtained at room temperature.

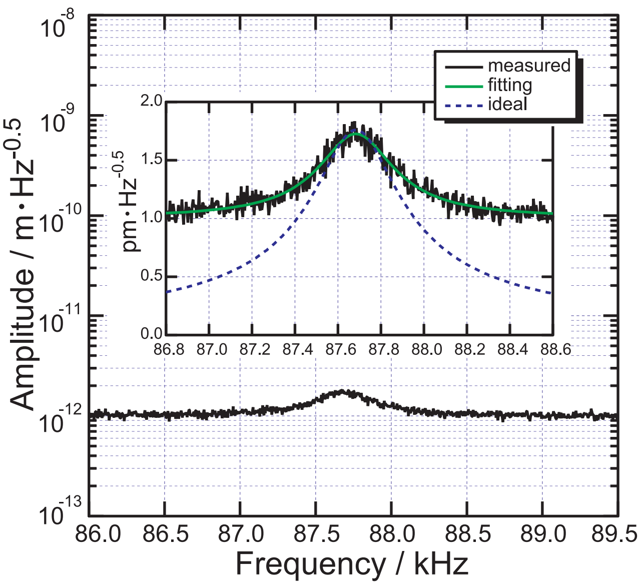

Fig. 3. Thermal vibration spectrum of the silicon cantilever.

From the thermal vibration spectrum characteristics, the resonance frequency (f_r) of the silicon cantilever was calculated to be 87.7 kHz and the mechanical Q-factor (Q_l) was calculated to be 280. Here, the difference from the catalog value was presumed to be due to the difference in etching conditions during the cantilever manufacturing process. Specifically, it was expected that the length (l) was 8.6% shorter and the thickness (t) was 8.6% thinner than the design value.

The thermal vibration spectrum (N_th) of the cantilever was approximated by Lorentz function as shown in Eq. (2), when the mechanical Q-factor was sufficiently large [14, 24],

$$N_\mathrm{th} = \sqrt{\frac{2k_\mathrm{B}T}{\pi\, k_z\, Q_l\, f_r \left\{ \left[1 - \left(\frac{f_d}{f_r}\right)^2\right]^2 + \left[\frac{f_d}{f_r \cdot Q_l}\right]^2 \right\}}} \tag{2}$$

where k_B is Boltzmann's constant, T is room temperature (300 K), Q_l is the Q-factor of the Si cantilever, f_r is the resonance frequency of the Si cantilever, and $k_z = 2\,\mathrm{N/m}$ (design value) is the spring constant of the silicon cantilever. Furthermore, the theoretical curve of the thermal noise spectrum [25] was calculated by substituting Q_l and f_r into Eq. (2).

As shown Fig. 3, the measurement points (black points), the fitting curve (green solid line), and the blue dotted line show the theoretical curves of the thermal noise spectrum expressed by the

Eq. (2). From these results, the noise density of displacement detection was found to be approximately $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$, which demonstrates that this system had sufficient detection sensitivity.

2.4 Estimation of photo pressure

We calculated the force acting on the surface of the SS cantilever when the incident laser light was completely reflected. The photo pressure of the laser light of 1 W (1 joule [J] per second [s]) within $1\,\mathrm{m}^2$ was calculated using the momentum of the incident light, obtained after multiplying the number of photons (approximately $3.3 \times 10^{18}\,/(\mathrm{s} \cdot \mathrm{m}^2)$) by the momentum p (N·s) of 1 photon (Planck's constant, h divided by wavelength, λ). As a result, the photo radiation pressure on the metal [1] was estimated to be approximately $3.3 \times 10^{-9}\,\mathrm{N/m}^2$, i.e., $3.3 \times 10^{-9}\,\mathrm{Pa}$. When the entire surface area of the SS cantilever ($l \times w$) was irradiated with incident laser light, the light reflection changed momentum (p) by reversing its direction. In this case, we also considered the photo pressure, as the resulting reaction force would be double the change in the momentum of light, and the SUS304 has a reflectance of 65% at the wavelength of 650 nm [24]. Thereby, we estimated that an optical pressure of $10.7\,\mu\mathrm{N}$ per 1 mW of the laser light acts on this SS cantilever.

3. Results and discussion

3.1 Verification of photo radiation pressure

Figure 4 shows the frequency spectrum for the conditions where the laser light was incident (light emission intensity: 45 mW or 50 mW), or was not incident (black line), on the lower side of the SS cantilever. When the laser light was not incident, the SS cantilever had a structural resonance frequency (f_r) of 16.367 kHz, due to vibration induced by a piezoelectric plate installed near the cantilever. Here, the vibration amplitude detected was 20.4 nm.

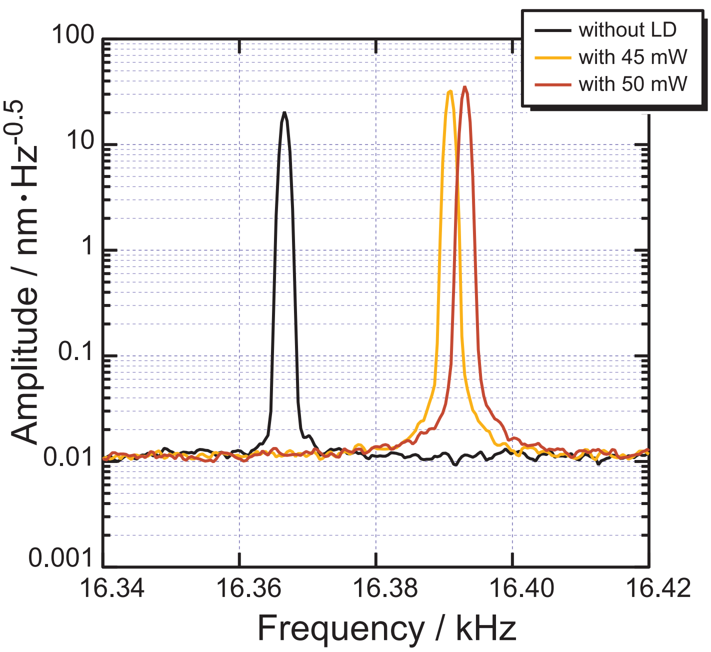

Fig. 4. Frequency spectrum without/with laser irradiation directly below the SS cantilever.

The difference between the designed value and the measured one was presumed to be due to the reduced film thickness (t) of approximately $82.2\,\mu\mathrm{m}$, caused by wet etching and mirror polishing during fabrication of the SS cantilever. From the material properties and the resonance frequency (f_r), the spring constant [19] was determined to be approximately 551 N/m.

When the 45 mW laser light was incident directly below the SS cantilever, it oscillated at 16.391 kHz, and the vibration amplitude detected was 32.3 nm. In other words, the SS cantilever was kept at a stable vibration with its resonance frequency shifting by +24 Hz. This suggests that the cantilever received continuous photo radiation pressure due to repulsive forces corresponding to the vibration amplitude of 11.4 nm.

When the 50 mW laser light was incident directly below the SS cantilever, it oscillated at 16.393 kHz, and the vibration amplitude detected was 35.8 nm. As in the previous case, the cantilever again experienced stable vibration, but this time its resonance frequency shifted by +26 Hz. This suggests that the cantilever received continuous photo radiation pressure due to repulsive forces corresponding to the vibration amplitude of 14.2 nm.

Hence, it was confirmed that the difference in the vibration amplitude increased by 3.43 nm because of the difference in 5 mW between the 45 mW and the 50 mW incidence. Thus, we described that corresponding to the incident light intensity of 1 mW, a vibration amplitude of 0.687 nm and a radiation pressure of 0.378 μN were calculated to be acting on the SS cantilever. In addition, we theoretically calculated the photo pressure to be 10.7 μN/mW (see section 2.4). The conversion ratio of the laser light to the SS-cantilever as photo pressure was calculated to be approximately 3.53%.

3.2 Deformation due to temperature rise

Figure 5 shows the simulation results of the cantilever temperature when the laser beam irradiated the backside region of the SS cantilever with heat flux at 50 mW. Specifically, we applied a finite element analysis (FEA) tool, known as Autodesk Inventor Nastran, for the SS cantilever using numerical simulations for processes such as motion dynamics and heat transfer. The material parameters in the numerical simulations were 500 J/(kg·K) for specific heat, 16.2 W/(m·K) for thermal conductivity, and 17.0 μm/(m·K) for the linear thermal expansion coefficient, respectively. The SS cantilever absorbed 35% of the energy of the incident laser as heat [23]. The temperature of the SS cantilever reached a maximum of 383 K. Based on the calculation results, we believe that heat was transferred to the base material of the SS cantilever, which was acted as a heat sink, and dissipated to the air to reach the certain temperature.

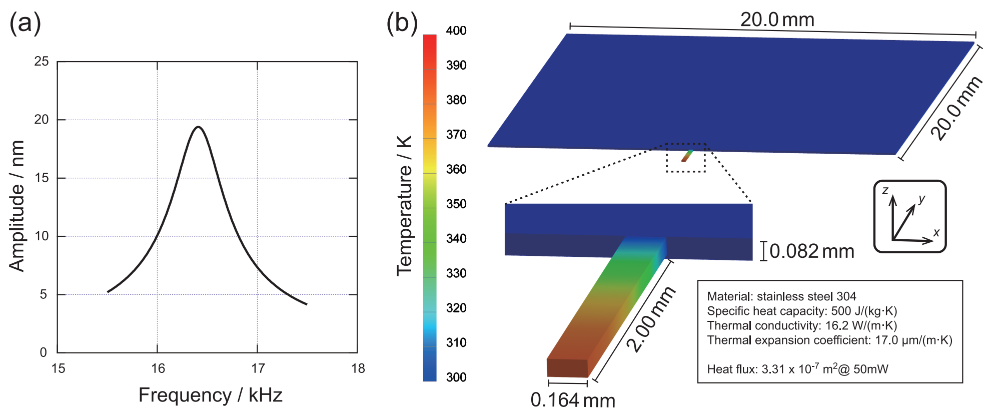

Fig. 5. The results of using the finite element method to calculate the SS cantilever characteristics. (a) The vibration amplitude versus frequency without laser light. (b) The temperature rises when the laser irradiated the SS cantilever.

We calculated that the SS cantilever was elongated by approximately 12.9 μm due to the temperature increase caused by the absorption of the laser light. However, based on Eq. (1), when the cantilever length (l) was extended by thermal expansion, its resonance frequency was clearly reduced. We have measured the increase of the resonance frequency due to the repulsive force caused by the photo radiation pressure of the laser on the cantilever. In other words, our series of measurements could be discussed without accounting for the thermal phenomena due to light absorption at the cantilever.

4. Conclusions

In this study, we demonstrated the interaction of laser beam irradiation with a micro cantilever and achieved high-sensitivity measurement of its vibration. By actively utilizing the structural resonance of the stainless-steel (SS) cantilever, we experimentally detected that the cantilever receives a vibration of 0.687 nm and a repulsive force of 0.378 μN as radiation pressure per 1 mW of incident laser light intensity.

It was estimated that the effect of the photo radiation pressure on the output energy of the laser beam was approximately 3.53%, converted to the SS cantilever vibration at resonance frequency. This led us to conclude that the heat absorption by the cantilever appears by way of energy dissipation due to the off point of the laser beam. To reduce energy dissipation, another control loop is required to precisely track the irradiation position of the laser beam on the cantilever. Since the thermal influences and vibration dynamics are strongly dependent on the experimental environment, we can construct a similar measurement system under vacuum conditions. That is, it will be measured much smaller photo radiation pressure as the mechanical Q-value increases.

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