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Miniature actuator driven photothermally using a shape-memory alloy

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A miniature actuator, in which a shape-memory alloy is driven photothermally by a laser diode, is described. The force of 9.8 mN and the displacement of 58 μm were obtained by irradiation with a laser power of 10 mW for the shape-memory alloy. The cutoff frequency for the vibration amplitude of this actuator was 0.2 Hz.

I. INTRODUCTION

The purpose of this work is to develop an optical miniature actuator which can drive a miniature pump for flowing liquid. Piezoelectric actuators, which are conventionally utilized in miniature mechanical devices,[1] are driven electrically. Therefore, it is difficult to operate such devices using noncontact control. Miniature or microdevices must be connected electrically to the electric power source through lines. The problem of the energy source for driving actuators is very important in the design of miniature or micromechanical devices. Optically driven actuators are useful because noncontact control is possible and the structure is simple. However, studies on optical actuators are few in number.

On the other hand, photoacoustic or photothermal effects can generate vibration on materials without contact.[2-4] Several applications to nondestructive diagnostics such as the detection method for delamination in layered materials,[5] the inspection of solder joints,[6] and the spectroscopic study of GaAs wafers[7] have been proposed. Moreover, noncontact sensors such as the vacuum gauge[8] and the liquid density sensor[9,10] have been devised. In addition to the above sensors, an attempt to develop the actuator using excitation of a progressive plate wave due to the photothermal effect has recently been reported.[11] However, the actuator showed very small vibration amplitude (<0.1 μm), and could not generate the additional force.

Shape-memory alloys are sometimes utilized as materials for miniature actuators.[12,13] However, shape-memory alloys are usually driven by electrical heating. In this work, we have fabricated a miniature actuator using the shape-memory alloy which is driven photothermally by a laser diode, and have shown that it has larger displacement and force than those fabricated from the other materials excited photothermally.

II. EXPERIMENTAL WORK

The schematic view of the experimental apparatus is shown in Fig. 1. A wire with a diameter of 0.3 mm made of a Ti-Ni alloy, which had a shape memory in a straight line at a temperature of 40 °C, was used. It was bent into a U shape with a radius of curvature of 2.5 mm. One side of the U-shape wire was fixed on the base plate, and the upper portion of the other side was adhered to a cantilever made of SUS 304. The wire is memorized in one way; it cannot return to its original shape once its temperature exceeds 40 °C, even if it cools down to a temperature below 40 °C. The cantilever plays the role of the spring for returning the wire to its original shape when the temperature of the wire falls below the shape-recovery temperature. The point A, shown in Fig. 1, was irradiated with a laser diode (wavelength is 830 nm) through an objective lens (magnification is 10, and focal length is 16 mm). The intensity of the laser beam was chopped electronically by an oscillator with a repetition frequency ranging from 0.01 to 10 Hz. When the wire was irradiated by the laser diode, the force due to the shape recovery at point A resulted in lifting of the cantilever by a displacement, x, against the elastic force of the cantilever. The cantilever returned to the original position when the laser diode was turned off.

The displacement of this actuator was monitored as follows. The tip of the shape-memory alloy, point B shown in Fig. 1, was irradiated from the transverse direction by a He-Ne laser which was focused at a point 5 mm away from the shape-memory wire through the other objective lens. The He-Ne laser beam with the shadow of the wire was projected on a screen which was placed at a position 1200 mm away from the wire, and the displacement of the shadow was measured. The absolute magnitude of the displacement of the actuator was determined using the geometrical relationship between the wire diameter and the width of the projected shadow on the screen. The displacement or the vibration amplitude was monitored electrically by detecting the He-Ne laser beam through a slit with a photomultiplier which was placed at a position 50 cm away from the wire. In order to estimate the force created by the shape-memory alloy, a weight is attached to point B.

The displacements of the cantilever without a load and that with a load (weight) were measured for several values of laser power. The frequency dependence of the vibration amplitude of these optical actuators was also measured.

III. RESULTS AND DISCUSSION

Figure 2 shows the displacement, x, of the cantilever without a load as a function of the laser power which irradiates the shape-memory alloy. A very large displacement (typical value of 58 μm for the laser power of 10

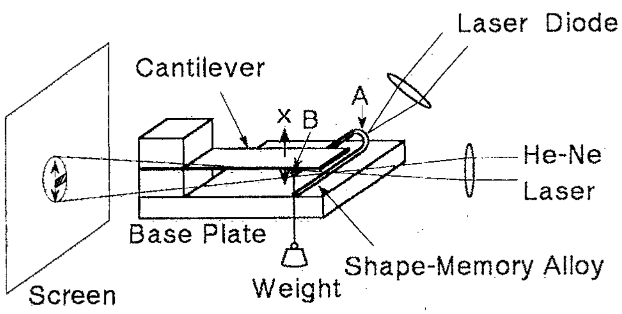

FIG. 1. Schematic view of the experimental apparatus.

mW) compared with that for the other materials excited photothermally was observed. With increase of the laser power, the displacement increased linearly.

The tip of the cantilever is lifted against the elastic force, kx (k is a spring constant) of the cantilever. The force created by the laser diode can be estimated by evaluating the spring constant of the cantilever. A weight was attached at position B and the displacement resulting from weighing down of the wire was measured. The value of k was estimated to be 1.7×10^2 N/m. The theoretical value of the spring constant, k_1, for the cantilever of the rectangular plate and that of k_2, for the wire can be given by the following equations:[14]

$$k_1=EWT^3/(4L^3), \tag{1}$$

$$k_2=3E\pi D^4/(64L'^3). \tag{2}$$

Here, E is Young's modulus ($=19.7\times10^{10}$N/m^2) for SUS 304, and 2×10^{10} N/m^2 for Ti-Ni shape-memory wire). Symbols W, T, and L are the width ($=2$ mm), thickness ($=0.2$ mm), and length ($=18$ mm) of the cantilever of the rectangular plate, respectively. Symbols D and L' are the diameter ($=0.3$ mm) and the length ($=8$ mm) of the shape-memory wire, respectively. The equivalent spring constant, k, for two springs connected in parallel is given by the sum of k_1 ($=1.3\times10^2$ N/m) and k_2($=0.46\times10^2$ N/m). The calculated value of the spring constant is almost equal to the experimental one. Figure 3 shows the force as a function of the laser power. The solid line shows the values calculated from kx using the spring constant

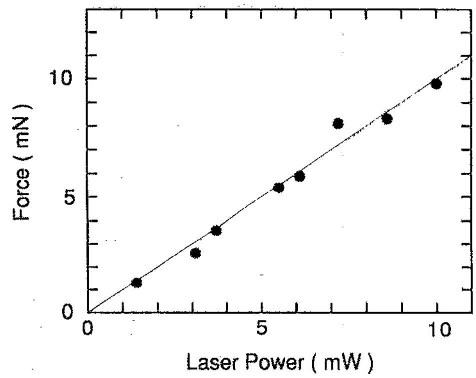

FIG. 3. Force from the actuator as a function of the laser power. Solid line shows the calculated values.

obtained experimentally and the results shown in Fig. 2. Black circles are experimental values, which were obtained by measuring the laser power which can lift the cantilever back to its original position from the position resulting from use of the weight. The typical irradiation of laser power of 10 mW can lift the 1 g weight ($=9.8$ mN) which weighs down the cantilever by 58 μm.

The displacement of the cantilever lifted with the constant laser power of 10 mW was measured with variation of the weight at B. Figure 4 shows the displacement as a function of the force applied to the actuator. The displacement decreased linearly with the increase of the force, being similar to a piezoelectric actuator.

Time response of actuators utilizing shape-memory alloys is usually slow. Figure 5 shows the vibration amplitude of the actuator as a function of the chopping frequency of the laser diode for the laser power of 10 mW without a load. The cutoff frequency is estimated to be about 0.2 Hz. Transient function, $V(t)$, of the displacement of this actuator as a function of time at the frequency, f, can be given approximately as follows:

$$V(t)=58[1-\exp(t/T)] \ (\mu\text{m}). \tag{3}$$

Here, time constant T was experimentally estimated to be 2.8 s. With substitution of the time constant and $t=1/2f$ into Eq. (2), calculated values on the vibration amplitude as a function of the frequency are obtained, which are

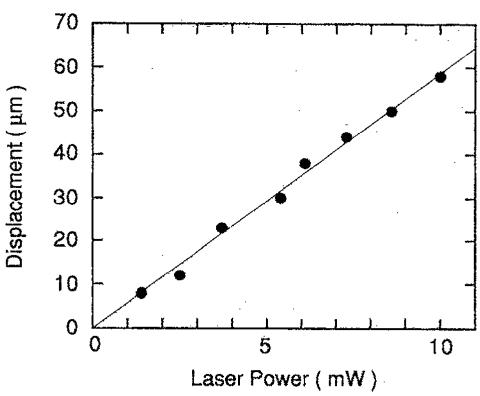

FIG. 2. Displacement of the cantilever without a load as a function of the laser power.

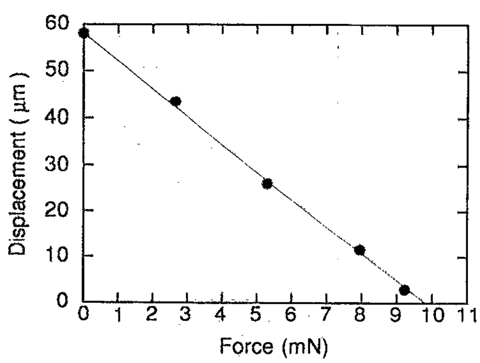

FIG. 4. Displacement as a function of the force applied to the actuator for the constant laser power of 10 mW.

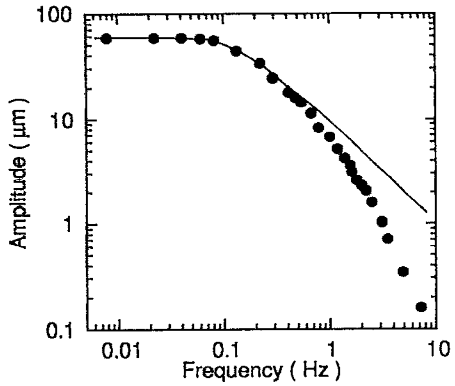

FIG. 5. Frequency dependence of the vibration amplitude of the actuator for the laser power of 10 mW without a load. The solid line represents the calculated values.

shown by the solid line in Fig. 5. Although calculated values agree with experimental ones at a frequency of below 0.5 Hz, the latter values decrease rapidly compared with the former values at a frequency of above 0.5 Hz. This difference shows that the transient function for a time of less than 1 s cannot be approximated with Eq. (3).

The optical miniature actuator fabricated in this study has large vibration amplitude and force compared with other materials vibrated photothermally, and may be useful for devices such as the shutter for neutral beams in vacuum. Although a shape-memory wire with a diameter of 0.3 mm has been used in this work, a thicker one which is irradiated with higher laser power will be necessary for developing a miniature actuator more powerful than that in this work. On the other hand, in order to fabricate an optical microactuator, it may be effective to use the technique on the Ti-Ni sputter-deposited film developed by Bush *et al.*[15] along with a micromachining technique.

An optical miniature actuator has been fabricated utilizing photothermal vibration for the shape-memory alloy. The actuator has shown large vibration amplitude and relatively strong force compared with previous reports. The cutoff frequency of the vibration amplitude was about 0.2 s. Since this actuator contains no internal electrode systems, it may be suitable for use under conditions where access is limited. Moreover, in the case where it is driven in liquid, it may be useful because no damage to the liquid, such as electrolysis, can occur.

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