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Wireless Soft Actuator Based on Liquid-Gas Phase Transition Controlled by Millimeter-Wave Irradiation

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Abstract— **We propose a wireless soft actuator controlled thermally by millimeter-wave irradiation. The actuator is composed of low boiling point liquid sealed in a soft bellows. By irradiating high-power millimeter-waves, the liquid can be evaporated to generate a strong mechanical force. We characterize the force and work extracted from the bellows as a function of the liquid volume and temperature. We then demonstrate the wireless actuation by irradiating a millimeter-wave on the bellows. We also evaluate its dynamic response by modulating the millimeter-wave. Our approach provides novel usage and design space of soft actuators.**

Index Terms— **Soft robot applications, force control, low boiling point liquid, gas-liquid phase transition, millimeter-waves**

I. Introduction

Flexible and lightweight actuators can provide safety and comfort when used around the human body for applications such as medical care, nursing care, and power assist suits. A typical example of a pneumatic actuator is McKibben-type artificial muscles [1], in which a mechanical force is obtained by injecting air into an elastic material such as rubber. However, they require a large pump or regulator in order to obtain a strong force, which makes it challenging to reduce the size and weight of the system. Instead of using a pump, soft materials responsive to noncontact external stimuli such as light [2-3], electric field [4-5], magnetic field [6-7], and heat [8-9] have also been used to drive actuators [10] although the output force of those actuators still needs to be enhanced. Recently, wirelessly controllable actuators based on gas-liquid phase transition have been developed [11-14]. By heating the liquid, a strong force can be generated via evaporation using a lightweight actuator. The earlier studies used ethanol as working fluid [12], but recently Novec7000 [15] has gained more attention for its lower boiling point of 34 °C.

In this study, we propose to heat the liquid Novec7000 wirelessly by irradiating a millimeter-wave with a frequency of about 95 GHz (a wavelength of about 3 mm) as conceptually illustrated in Fig.1. The Novec7000 can be heated by millimeter-waves due to dielectric losses, in the same way as water is heated by a microwave oven [16]. In this study, we seal the liquid in a 1D bellows made of polymer and irradiate a millimeter-wave to control the liquid-gas phase transition. While Boyat *et al.* [11] used a magnetic field as a means of wireless power transfer to a heater in the liquid, it necessitates a pair of receiver and transmitter coils in- and outside of the container, posing limitations on the geometrical configuration as well as the size of the actuator. In addition, since the heat transfer from the heater to the liquid occurs only locally, the heater must be properly soaked in the liquid regardless of the posture of the actuator. We, on the other hand, directly heat the liquid by externally irradiating a millimeter-wave through the bellows. As compared with laser heating [12-14], the use of millimeter-waves allows higher transmissivity against various dielectric materials such as plastics, fabrics, and paper than lasers, which often exist in multi layers in the irradiation path from the source to the liquid. As an example of such a situation, we demonstrate that the actuator placed inside a plastic box can open the lid when irradiated from the outside. In the following sections, we provide a rigorous quantitative analysis of available forces with a bellows-type 1D actuator, and then experimentally characterize the mechanical force and work available from this actuator. We also investigate the dynamic response of the actuator by modulating the irradiation. Our approach provides novel usage and design space of soft actuators.

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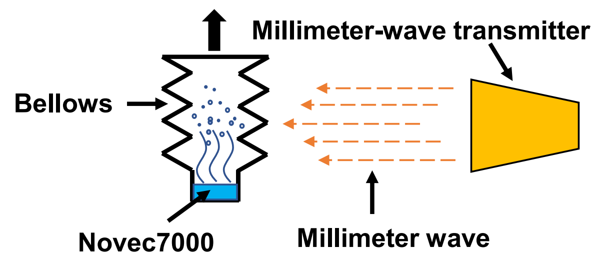

Fig. 1. Wireless actuator driven by millimeter-wave irradiation.

II. Mechanical Properties of Bellows

The actuator used in this study is composed of a commercially available polyethylene bellows, which is low-cost and lightweight (Tokyo Garasu Kikai Co., Ltd. Part number: 161-23-31-23). The bellows can expand and contract one-dimensionally for efficient work extraction and quantitative characterization. Moreover, while polar polymers such as nylon, acrylic 31 and acrylic resin 36 have an absorption coefficient of about 0.2 cm^{-1}, polyethylene, which is a non-polar polymer, have about 0.01 cm^{-1} for millimeter-waves with frequencies at 95 GHz [17]. Therefore, the Novec7000 contained in the actuator can be heated efficiently. Before sealing the liquid, we preprocess the bellows to shrink the equilibrium length by applying heat during compression. We then connect a syringe through an injection needle as shown in Fig. 2(a). This syringe allows us to measure the amount of air or liquid to be injected into the bellows. We firstly check if the volume of the bellows varies linearly with the change of the axial length, in the absence of the liquid. For this purpose, we inject air into the bellows

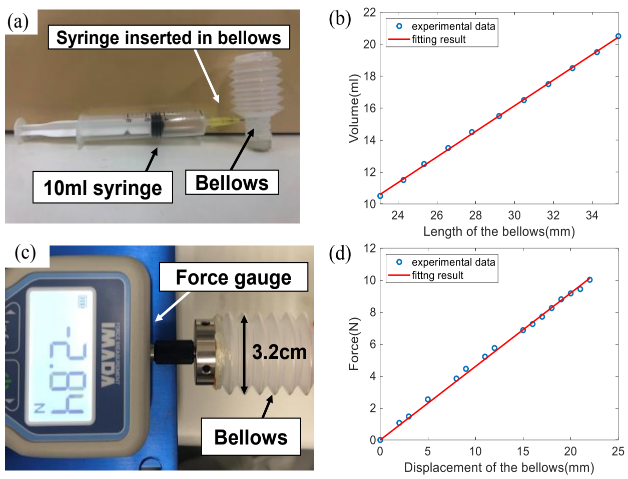

Fig. 2. (a) Bellows connected to an external syringe through an injection needle. (b) Relation between the length and the volume of the bellows. (c) Force gauge attached to the top face of the bellows. (d) Relation between the displacement and the restoring force of the bellows during spontaneous restoration.

through an injection needle from a syringe and measure the amount of the displacement. The result confirms linearity with a length-to-volume conversion coefficient of 0.80 ml/mm (Fig. 2(b)). We next characterize the spring constant of the bellows itself, again in the absence of the liquid, based on the relation between the displacement and the corresponding restoring force during spontaneous restoration. We measure the restoring force by a digital force gauge attached to the tip of the bellows which are not sealed (Fig. 2(c)). The spring constant was determined to be 0.46 N/m (Fig. 2(d)).

III. Evaluation of the Actuator

A. Mechanical Force Extracted from the Bellows

When the liquid Novec7000 is sealed in the bellows, the mechanical force and work available through the thermally controlled gas-liquid phase transition depends on the amount of the initial liquid volume. To investigate the effect of the liquid volume, we collect a known volume of the liquid Novec7000 in the syringe (Fig. 3(a)) and heat it by a heat gun, instead of irradiating the millimeter-waves, to fill the bellows with the gas mixture of the vaporized Novec7000 and the air originally sealed in the bellows (Fig. 3(b)). The initial volume of the liquid is increased from 0.02 ml to 0.10 ml in a step of 0.02 ml. We cease heating at a timing when all the liquid is vaporized, at which the temperature can be regarded as 34 °C, the boiling point of Novec7000. The generated force is measured by sandwiching the bellows of the equilibrium length between the force gauge and a rigid wall (Fig. 3(c)). When heating Novec7000, the force acting from the inside of the bellows arises from the pressure of the gas mixture of Novec7000 and the air originally sealed in the bellows. The force acting from the outside of the bellows arises from the reaction of the force gauge and the atmospheric pressure at the room temperature (Fig. 3(b)). To account for the contact area of the force gauge, we define the outer radius of the upper surface of the bellows L, the inner radius of the column connected directly to the force gauge l, and the atmospheric pressure P_0. The force F_N by the gaseous Novec7000 in the bellows is expressed as follows.

$$F_N=\left(\frac{acRT_2}{V}\right)L^2\,\pi \tag{1}$$

where a, c, R, T_2 and V express the initial volume of the liquid, volume molarity at 25 °C and 1 atm, gas constant of Novec7000, the temperature after heating and the total volume of the syringe and bellows, respectively. Here, $(acRT_2)/V$ represents the partial pressure of Novec7000 derived from the ideal gas law assumption, and ac represents the amount of substance of Novec7000 in the actuator. Meanwhile, according to the equation of state of the gas, the pressure is inversely proportional to volume and proportional to temperature, hence the force F_{IA} by air in the bellows can be expressed as follows.

$$F_{IA}=P_0\left(\frac{T_2}{T_1}\right)\left(\frac{V\text{-}a}{V}\right)L^2\,\pi \tag{2}$$

where T_1 is the room temperature before heating. The external atmospheric force F_{OA} is expressed as

$$F_{OA}=P_0\left(L^2\text{-}l^2\right)\pi \tag{3}$$

Therefore, the force F_{FG} displayed on the force gauge can be expressed as follows from the relation of force balance.

$$F_{FG}=F_{IA}+F_N\text{-}F_{OA} \tag{4}$$

where $F_{IA}+F_N$ expresses the force generated by Novec7000 and the air inside the actuator based on Dalton's law, stating that the pressure of the mixed gas is the sum of the partial pressures of each gas. In Fig. 3(d), the orange line shows the calculated result of F_{FG} using Eq. (1)-(4) with P_0=101 kPa, L=10.9 mm, l=2.25 mm, T_1=298 K, T_2=307K, V=11.1 ml, c=0.007 mol/ml and R=8.31 J/(K･mol). We find that the experimental value begins to increase in proportion to the

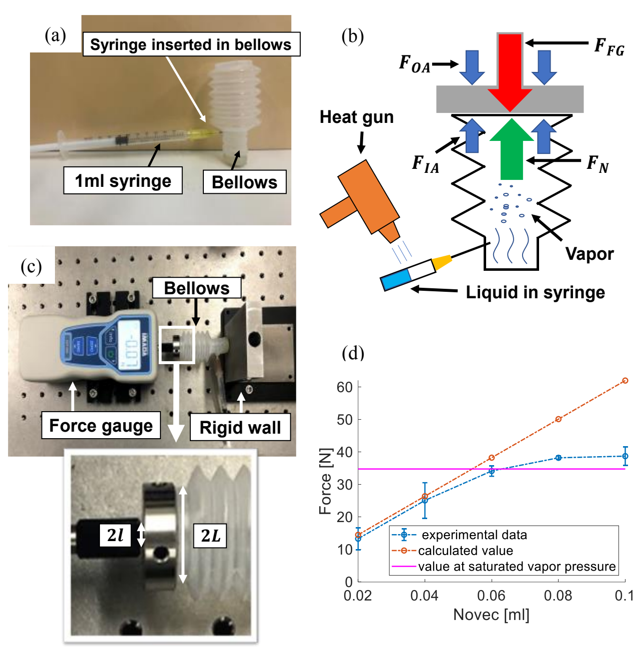

Fig. 3. (a) Bellows connected with a 1 ml syringe through an injection needle. (b) Experimental setup of force measurement. (c) Forces acting on the bellows (d) Relation between the Novec7000 liquid volume and the generated force. The results are the average of five measurements and the error bars indicate standard deviation.

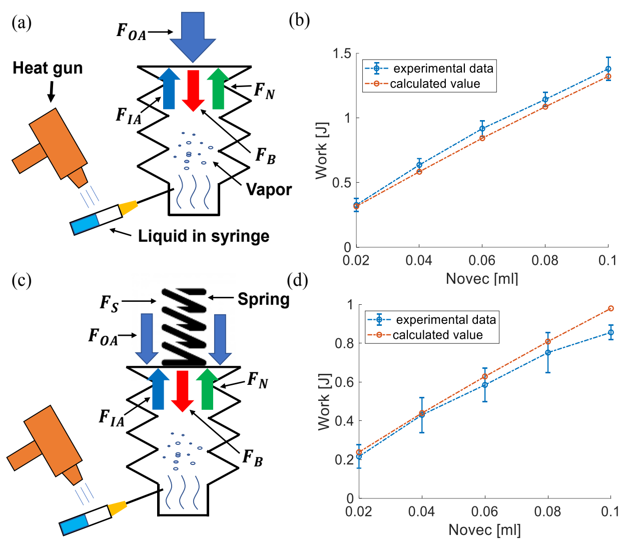

Fig. 4. (a) Forces acting on the top face of the bellows. (b) Relation between the Novec7000 liquid volume and work against the air. The results are the average of five measurements and the error bars indicate standard deviation. (c) Forces acting on the top face of the bellows when a spring is connected. The other end of the spring is connected to a rigid wall. (d) Relation between Novec7000 liquid volume and work against the air and the spring. The results are the average of five measurements and the error bars indicate standard deviation.

initial liquid volume of Novec7000 but begins to saturate at about 38 N above 0.08 ml. This result can be explained in terms of the saturated vapor pressure as follows. During the force measurement, the volume of the bellows is kept constant. Therefore, if there exists a sufficient amount of the liquid Novec7000, its partial pressure in the gaseous phase in the bellows eventually reaches the saturated vapor pressure. Here, the saturated vapor pressure is expressed as follows.

$$\ln P = -3548.6/T + 22.978 \tag{5}$$

where P [Pa] and T [K] express the saturated vapor pressure and the gas temperature [15]. In Eq. (5), T is limited to the range of 243 to 438. Using Eq. (5), the saturated vaper pressure at 34°C, which is the boiling point of the Novec7000, is calculated to be 91.1 kPa. The minimum amount of the liquid to obtain this pressure in the bellows after evaporation is thus estimated to be about 0.056 ml. When the initial liquid volume before heating is less than 0.056 ml, it is estimated that the generated force is proportional to the initial amount of liquid based on the equation of state of gas. To verify this estimation, we investigate the extracted force as a function of the initial liquid volume as shown in Fig. 3(d). As shown in Fig. 3(d), the experimental values begin to deviate from the calculated values around 0.06 ml. We consider this is because the Novec7000, evaporated in the syringe and injected into the bellows, is air-cooled and partially condensed back to liquid. Indeed, when the liquid volume is 0.08 ml or 0.1 ml, we observe that the liquid in the syringe is evaporated completely right after heating, but subsequently the inner surface of the bellows becomes wet.

B. *Mechanical Work Extracted from the Bellows*

We next consider the mechanical work that can be extracted from the bellows. It should be noted that the available work is load dependent. We thus investigate both cases of constant workload and workload with a restoring force. We firstly measure the work exerted on the air in free-space from the bellows while changing the liquid volume. Here, the liquid in the external syringe is heated with a heat gun again. In this experiment, the amount of the displacement of the bellows is measured first, and the volume change is calculated using the length-to-volume conversion coefficient obtained in Fig. 2(b). It should be noted that the top surface of the bellows is not fixed, so that the bellows can freely expand against the restoring force of the bellows itself. The free expansion stops when F_{OA}, F_{IA}, F_N and the restoring force F_B of the bellows are all balanced. Since the force gauge is removed, F_{OA} is modified to the following expression.

$$F_{OA} = P_0 L^2 \pi \tag{6}$$

Using the length-to-volume coefficient h, the volume increases by hx when the displacement of the bellows is x. Therefore, F_{IA} and F_N are expressed as follows, respectively.

$$F_{IA} = P_0 \left(\frac{T_2}{T_1}\right)\left(\frac{V-a}{V+hx}\right) L^2 \pi \tag{7}$$

$$F_N = \left(\frac{acRT_2}{V+hx}\right) L^2 \pi \tag{8}$$

The bellows restoring force F_B can be expressed using the spring constant k_B measured in Fig. 2(d).

$$F_B = k_B x \tag{9}$$

Thus, the balance of all the forces is described as

$$F_N + F_{IA} = F_B + F_{OA} \tag{10}$$

By solving the eq. (10) for x, the mechanical work exerted on the air W_1 can be expressed as $W_1 = P_0 hx$. In Fig. 4(b), the orange line shows calculated W_1 using Eq. (6)-(10) with h=0.80 ml/mm and k_B=0.46 N/mm. The mechanical work increases as the initial liquid volume increases. When the liquid volume is 0.1 ml, the extracted work is 1.4 J.

When using the actuator in practical scenes, the load is sometimes an elastic object that presents a reactive force, which includes human skin as an example. In this study, we model such a situation by connecting an external spring with a spring constant k_S to the top face of the bellows as a workload. Considering the elastic force F_S of the spring, the balance of the forces after the expansion is described as follows.

$$F_N + F_{IA} = F_B + F_{OA} + F_S \tag{11}$$

where $F_S = k_S x$ is the restoring force of the spring. The displacement x is obtained by solving the Eq. (11). The mechanical work W_2 exerted to the outside from the bellows is the sum of the elastic energy stored in the spring and the work for the air, which is expressed as follows.

$$W_2 = P_0 hx + \frac{1}{2} k_S x^2 \tag{12}$$

In Fig. 4(d), the orange line shows the calculated W_2 using Eq. (12) with k_S=1.0 N/mm. We also calculate that the elastic energy stored in the external spring can be maximized to be 8.6×10^{-2} J when k_S=3.6 N/mm. This calculation helps to estimate the optimal condition to extract mechanical work using this actuator.

IV. Actuator Control by Millimeter-Waves

A. Millimeter-Wave Absorption of Novec7000

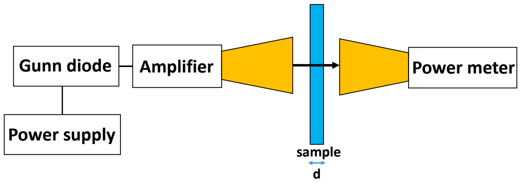

Fig. 5. Schematic of millimeter-wave absorption characterization of liquid Novec7000.

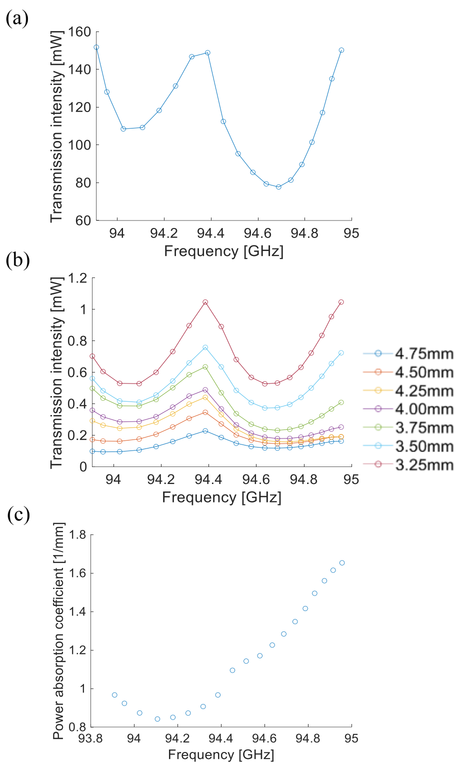

Fig. 6. (a) Frequency characteristics of the millimeter-wave transmitter used in this study. (b) Transmission spectrum of the sample with different thicknesses. (c) Frequency characteristics of the extracted absorption coefficient of Novec7000.

Here we consider irradiating a millimeter-wave on the liquid Novec7000 for wireless heating. To begin with, we measure the absorption coefficient of the liquid Novec7000 for millimeter-waves with frequencies around 95 GHz. The experimental setup is schematically illustrated in Fig. 5. The transmitter includes a Gunn oscillator and amplifier. The millimeter-waves are then launched from a rectangular horn antenna. We prepare liquid Novec7000 samples in seven plastic containers with different thicknesses, i.e. path lengths. The transmitted waves are then received by another horn antenna of the same shape, and the signal power is measured with a power meter. The plastic container used was 3D printed with PLA, and its thickness of which ranges from 3.25 mm to 4.75 mm in increments of 0.25 mm. According to the Lambert's law, the logarithm of the ratio of the incident and transmitted wave powers is proportional to the thickness of the sample [18]. In this study, we compare the transmitted wave powers from samples of different thickness to factor out the millimeter-wave attenuation due to the reflection or absorption in the container. The relation between the change in the sample thickness and the transmitted wave power is as follows.

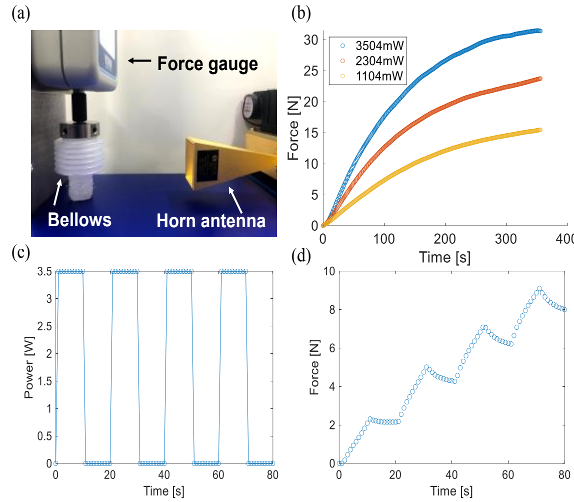

Fig. 7. (a) Millimeter-wave irradiation on the bellows. (b) Temporal change of the force for continuous irradiation with different intensities. (c) Switching of the millimeter-wave power. (d) Temporal change of the force when switching the millimeter-wave as in (c).

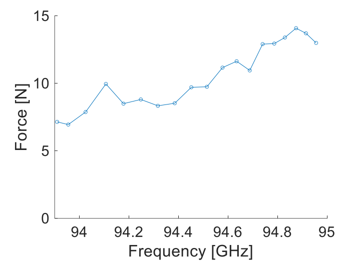

Fig. 8. Generated force at different frequencies when the irradiation power is fixed at 1 W.

$$\ln\left(\frac{I}{I'}\right) = \mu\Delta d \tag{13}$$

where, I, I' express the transmitted wave powers when the sample thickness is d and $d+\Delta d$, respectively, and μ is the absorption coefficient of the liquid. Here, d is fixed at 3.25 mm, and Δd is increased by 0.25 mm. The output power of the transmitter used in this study is characterized as a function of the frequency as shown in Fig. 6(a), where the millimeter-wave is modulated with a square wave of 150 Hz with a duty ratio of 30%. We then measure the samples with different thickness inserted between the transmitter and the power meter, to extract the absorption coefficient (Fig. 6(b)). In result, the absorption coefficient is estimated to be 0.97 mm^{-1} at 94.4GHz, which is large enough to regard that the irradiation is mostly absorbed by Novec7000 rather than the plastic container. We find that the higher frequency involvers greater absorption (Fig. 6(c)).

B. Dynamic Response

We evaluate the performance of the actuator composed of Novec7000 sealed in the bellows heated by the millimeter-wave. In this experiment, the initial volume of Novec7000 is 0.5 ml, and the millimeter-wave is irradiated for 357 seconds using a horn antenna from a position 6 cm away from the bellows (Fig. 7(a)). The aperture area A of the horn antenna is 27.7 mm × 22.6 mm. The beam launched from an aperture can be collimated over the distance so-called Rayleigh range of about 40 cm, which is given as $2A/\lambda$, where λ is the wavelength. Although we do not use a lens in this study, it is possible to adjust the wave convergence or focusing with a lens. Here, the frequency of the millimeter-wave is 94.4 GHz, and the power is changed to 3.5 W, 2.3 W, and 1.1 W. The slope of the curves in the vicinity of the origin is varied to 0.157 N/s, 0.128 N/s, and 0.076 N/s, respectively. We confirm that the higher irradiation power leads to the faster response of the mechanical force (Fig. 7(b)). When using actuators, their response time is an important factor. We thus characterize the temporal change of the force by switching the irradiation of 3.5 W. The switching scheme is shown in Fig. 7(c). The force increases when irradiated but decreases when stopped as shown in Fig. 7(d). The rise curve is nearly linear with respect to the exposure time at a rate ranging from 0.19 N/s to 0.27 N/s while the fall curve shows exponential decays with a decay rate ranging from 0.14 s^{-1} to 0.47 s^{-1} due to air-cooling. As confirmed in Fig. 6(c), the millimeter-wave absorption of Novec7000 is frequency dependent. Hence, the generated force of the bellows is also considered to be frequency dependent. To see this effect, we vary the irradiated frequency from 93.9 GHz to 95.0 GHz. The distance between the bellows and the horn antenna is again 6 cm, and the irradiation is continued for 246 seconds. To irradiate a constant power to the actuator irrespective of the frequency, we compensate for the frequency characteristics of the transmitter shown in Fig. 6(a) by adjusting the duty ratio of a square wave modulation of 1.2 MHz so that the effective output becomes constant at 1.0 W. In this way, we confirm that the generated force increases at the higher frequencies when the irradiation power is constant (Fig. 8). This tendency is consistent with the frequency dependent absorption coefficient of Novec7000 characterized in Fig. 6(c).

In the end of this section, we consider application possibilities of the proposed actuator. The actuator is small and lightweight and can generate a large force wirelessly. Importantly, the millimeter-waves can be transmitted through various dielectric materials such as plastics, fabrics, papers, etc. Hence, the actuator can be embedded inside or surrounded by those materials. To experimentally demonstrate this possibility, we place the actuator in a polystyrene container, and irradiated a millimeter-wave from the outside (Fig. 9). We clearly observe that the lid of the container is opened by the actuator. In this experiment, there is no syringe connected to the actuator, and the weight of the actuator is only 4 g, which could be reduced further by thinning the bellows wall thickness. The polystyrene container is not required to be optically transparent since the millimeter-waves can penetrate it. The capability of generating forces controlled through walls, shields, or clothing could be usable for power assist suits as well as for household and rescue robots. With the current limited actuation speed, applications such as rehabilitation and posture correction are suited. [12] also suggested that their actuator could be used for rehabilitation, but to get maximum

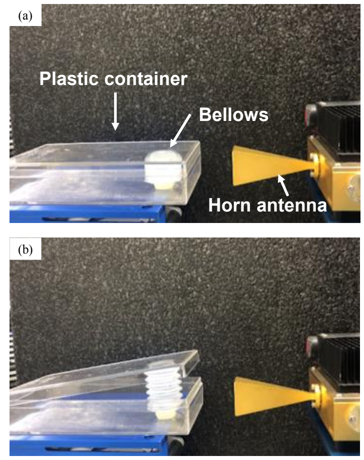

Fig. 9. Millimeter-waves irradiation on the actuator in a polystyrene container can open the lid.

force with their actuator, the temperature must be raised to 140 °C because they used ethanol whose boiling point is 78 °C. This is too dangerous to use for the purpose of assisting human movement. In contrast, boiling point of Novec7000 is 34 °C and thus our actuator has a high affinity with the human body in terms of temperature. Another advantage of the millimeter-waves is their high spatial selectivity attained by beamforming. In our experiments, the beam has been formed by the high-gain horn antenna and therefore been fixed. However, the use of phased arrays enables dynamic control the beam direction [19]. This enables, for example, to selectively heat individual actuator in an array to implement more complex motions like origami as demonstrated in [20-22]. While we have relied on free-space radiation to deliver the millimeter-waves to Novec7000, the waves can also be transmitted contactlessly by using near-field coupling in the vicinity of surface waveguides [23].

V. Discussion

We have analyzed and characterized the force generated from liquid-gas phase transition of the Novec7000 in a 1D bellows. The force is thermally controlled by the saturated vapor pressure. To maximize the force, it is important to prepare a sufficient amount of the initial liquid inside the bellows so that the partial pressure of the evaporated liquid equals to the saturated vapor pressure. Since the saturated vapor pressure increases with the temperature, the force continues to increase until the liquid is completely evaporated, regardless of the heating method. We have also confirmed that extracted work W_1 from the bellows is about 1.4 J with an initial liquid volume of 0.1 ml of Novec7000 in Section III-B. Our calculation shows that in order to increase W_1, the length-to-volume coefficient h should be increased and spring constant k_B should be decreased, respectively.

Han *et al.* [12] used ethanol as a working fluid. The boiling point of the ethanol is 78 °C, which is higher than that of the Novec7000, 34 °C. The specific heat is 2.4 kJ/(kg·K) at 298 K [24] and is about twice that of the Novec7000. Considering these two factors, the Novec7000 can be evaporated with less power consumption. Boyat *et al.* [11] and Hiraki *et al.* [13]

used the Novec7000 in their studies. In [11], the working contact area of their actuator is almost the same size as ours. However, their maximum force of about 20 N is smaller than 38 N in this study. This is probably because the temperature after heating was lower than in our experiment. In [13], the force generated by laser heating for 15 seconds is about 7.5N, and it is also mentioned that more expansion is likely to involve breakage of the pouch. They can generate more force by increasing the durability of their actuators. Regarding the extension of the actuator, in [11], the thickness increases from about 2 mm to about 8 times the initial thickness when the liquid volume of Novec7000 is 0.6 ml. In [12], the total length increases from 58mm to 93.4mm when the used ethanol is 0.5ml whereas our actuator extended from 34.5 mm to 51.5 mm with 0.1 ml of Novec7000. Therefore, our actuator can be expanded efficiently even with a small amount of liquid.

VI. CONCLUSION

In this study, we have proposed a wireless soft actuator based on the gas-liquid phase transition of low-boiling point liquid Novec7000 controlled by millimeter-wave irradiation. The actuator can be made of commercially available polyethylene bellows. After preprocessing the bellows, we have sealed a fixed amount of the liquid Novec7000 and then characterized the mechanical force and work obtained from the bellows. We have confirmed that the force and work vary as a function of the initial liquid volume. The generated force approaches a constant value as the liquid amount increases due to the saturation vapor pressure. When an external spring is connected to the bellows, the work extracted from the bellows is stored as elastic energy in the spring. Analysis shows that there exists the optimum spring constant to maximize the stored elastic energy. Based on the preparations as above, we have investigated the control of the actuator by millimeter-wave heating. We experimentally characterized the millimeter-wave absorption coefficient of Novec7000. The output force increases as the irradiation power increases and also as the frequency increases. We also investigated the dynamic response of the actuator by switching the millimeter-wave. We then discussed application possibilities owing to the transmissivity and spatial selectivity of the millimeter-waves. We demonstrated that the lid of a plastic container can be opened wirelessly by delivering heat with a millimeter-wave through the wall.

An important future work is to make the actuation faster. As discussed in Fig. 7(d), the decay time of the force is much longer than its rise time. Therefore, reducing the decay time is a key to speed up the actuation. Reducing the decay time will be realized by enhancing cooling. For this purpose, using the actuator in a cold environment is one approach. More generally, maximizing convective air-cooling by increasing the surface area of the bellows or using materials with a high heat exchange coefficient will be important.

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