Transparent and Soft Haptic Actuator for Interaction With Flexible/Deformable Devices

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ABSTRACT

This study presents a transparent and soft haptic actuator based on an electroactive polymer designed to create abundant haptic sensations in flexible/deformable next-generation devices and to convey them to users. The haptic sensations are created in the form of vibrations and vary depending on the amplitude and frequency of the vibrations. The haptic actuator consists of a transparent and soft dielectric layer and two transparent and soft ionic conductive layers. The dielectric layer is sandwiched between the two ionic conductive layers, and is compressed in the thickness direction when an electric field is applied to the two ionic conductive layers. When the applied electric field is removed, the proposed haptic actuators are rapidly restored to their initial configuration. Owing to this effect, the actuator can easily create vibrations that are sufficiently strong for human perception. In this study, three different dielectric elastomers (silicone rubber, poly urethane, and acrylic polymer) are used for the dielectric layer. Experiments are conducted to investigate the haptic performance of the proposed soft vibrotactile actuators using an accelerometer. In the case of the silicone rubber-based actuator, the measured acceleration at the resonant frequency (80 Hz) is 1.408 g (g = 9.8 m/s²) and the response time is approximately 2.8 ms. Furthermore, the perceived intensity of the stimuli generated by the proposed actuator is verified by perceptual experiments. The results indicate that the proposed actuator can selectively stimulate human mechanoreceptors with sufficient perceptual strength.

INDEX TERMS

Flexible device, foldable device, haptic feedback, vibration actuator, vibration motor.

I. INTRODUCTION

Currently, the paradigm of electronic devices is rapidly shifting from conventional rigid devices to next-generation flexible and deformable devices whose shapes are changeable (e.g., foldable phones, stretchable displays, and rollable displays) owing to their advantages including high mobility, high expandability, and improved ergonomic structure. Most components (the touch screen, battery, electronic components, and other components) of flexible and deformable devices should be flexible to successfully realize the paradigm shift. Several flexible electronics and soft components have been extensively introduced and developed for such devices [1]–[5]. Although flexible and deformable devices provide a better experience to users, it is necessary to further increase their usability, level of user immersion, and user satisfaction by inserting haptic actuators. These haptic actuators should be soft to maximize the haptic performance in flexible and deformable devices. Furthermore, the haptic actuators should exhibit high optical transparency to generate a haptic sensation on a visual display component.

Promising candidate materials for transparent and soft vibrotactile actuators are electroactive polymers (EAPs) [6]–[9]. In general, EAPs are categorized into ionic and non-ionic EAPs. An ionic EAP is deformed by the migration or diffusion of ions inside it. Although ionic EAPs exhibit a large displacement under a low operating voltage, the actuation force is insufficient to stimulate human mechanoreceptors. Moreover, the response time is excessively slow to generate various haptic sensations. Numerous researchers are
currently focused on nonionic EAPs for producing various haptic sensations. Nonionic EAPs exhibit fast response and create relatively large actuation forces.

Furthermore, they can hold strain under a DC voltage input and exhibit a high operation efficiency [10–12]. Several studies have focused on dielectric EAP (dEAP)-based haptic actuators [13–16]. Kim et al. suggested a transparent and stretchable graphene-based haptic actuator consisting of an optically clear adhesive (OCA) film as the dielectric layer and graphene as the electrode. Although this OCA-based actuator has a large displacement, small thickness, and high stretchability, its response time is excessively slow to cover a wide operating frequency bandwidth. Ankit et al. developed an acrylic polymer (3M VHB tape)-based haptic actuator that can operate over a wide frequency range. This actuator includes silver nanowires and PEDOT:PSS as the electrode. Kim et al. proposed a transparent haptic module based on a soft elastomer and silver nanowire electrodes to simulate the surface roughness of a target object. Although the surface texture of a target object was haptically simulated, it exhibited a relatively low transmittance owing to the periodic void pattern and the slight complexity of the fabrication process.

In this paper, we propose a new soft and optically transparent haptic actuator with a fast response time, broad operating frequency range, simple structure, and simple fabrication process. The proposed haptic actuator consists of a transparent and soft dielectric layer sandwiched between transparent and soft ionic conductive layers. We used the most well-known transparent and soft dEAPs (silicone rubber, polyurethane (PU), and acrylic polymer) as the dielectric layers. Subsequently, we investigated the dielectric and mechanical properties affecting the haptic performance of the proposed actuator and measured its optical properties. In the study, poly(acrylamide) (PAAm) hydrogels were used to form the transparent and soft ionic conductive layers. Based on the three dEAPs and PAAm hydrogels, three vibrotactile actuators were fabricated, and their frequency and electric field responses were verified to compare the effects of the three dEAPs on the actuation performance. The PU actuator exhibited the highest electromechanical energy conversion although its dielectric breakdown strength corresponded to the lowest value (approximately 25 V/μm). Conversely, the silicone rubber (with the lowest relative permittivity among the three dEAPs)-based actuator presented the highest dielectric breakdown strength. It can be operated until 50 V/μm, and exhibited the highest vibration acceleration at 50 V/μm. The experiments revealed the relationship between the material properties (dielectric and mechanical properties) of the dielectric layer and the actuation performance. Furthermore, we verified that the proposed vibrotactile actuators can selectively stimulate human mechanoreceptors by adjusting the frequency and can also control the vibrational strength of the actuators. The proposed transparent and soft vibration actuator developed in this study is expected to be applicable to flexible and deformable devices.

**FIGURE 1.** (a) Structure of proposed transparent and soft vibrotactile actuator and (b) fabricated transparent and soft vibrotactile actuator (red, dash line) on logo of KOREATECH.

**II. DESIGN AND FABRICATION OF TRANSPARENT AND SOFT VIBROTACTILE ACTUATORS**

**A. STRUCTURE OF TRANSPARENT AND SOFT VIBROTACTILE ACTUATOR**

Fig. 1(a) shows the structure of the proposed transparent and soft vibrotactile actuator consisting of a transparent and soft dielectric layer (a dEAP) and two transparent and soft ionic conductive layers (PAAm hydrogels). The dielectric layer was sandwiched between the two transparent and soft ionic conductive layers. We prepared three dEAPs (silicone rubber, PU, and acrylic polymer) with high stretchability and high transparency as candidates for the dielectric layer. The size of the proposed actuator was 15 mm × 15 mm × 300 μm. The logo of KOREATECH could be clearly seen although the fabricated actuator is placed on it (Fig. 1(b)).

**B. FABRICATION OF TRANSPARENT AND SOFT DIELECTRIC LAYERS**

Fig. 2 shows the fabrication process of the dielectric layer. Although a dielectric layer can be fabricated by various coating methods (e.g., knife coating, bar coating, and roll coating), we used the spin coating method to rapidly and easily produce uniform thin films. A silicon wafer was mounted on a spin coater and subsequently fixed via vacuuming. To easily peel the dielectric films from the silicon wafer, we first coated poly(vinyl alcohol) (PVA) on the wafer. Specifically, water was prepared in a glass vial heated to 170 °C on a hot plate. Subsequently, 2 wt% PVA with respect to the weight of the water was carefully poured into the heated water. The solution was stirred by a stirring machine at 500 rpm for 2 h to fully dissolve PVA. The PVA solution was cast on the silicon wafer mounted on the spin coater. The wafer was rotated at 200 rpm for 10 min and subsequently annealed at 100 °C for 1 h in an oven.

As mentioned above, in this study, three dEAPs (silicone rubber, PU, and acrylic polymer) were prepared as candidate
materials for the dielectric layer of the proposed vibrotactile actuator. The silicone rubber (Waker, Elastosil P7670) mixture was synthesized by mixing parts A and B of Elastosil P7670 in a mixing weight ratio of 1:1. The PU (Smooth-on, Clear Flex™30) mixture was prepared by mixing parts A and B in a volume ratio of 1:1. A commercially available transparent and soft double-sided adhesive tape (3M, VHBTM F9469PC), which is one of the most extensively used dEAPs was used as the acrylic polymer.

The PVA-coated wafer was fixed on the spin coater, and pre-elastomer mixtures (silicone rubber and PU) were carefully poured on the wafer. The rotating speed and duration of the spin coater were adjusted based on the desired thickness of the dielectric layer. After spin coating, the pre-elastomer mixture-coated wafer was cured at 100 °C for 2 h in an oven. To remove the elastomer, the cured wafer was soaked in hot water (80 °C) for 3 h. After conducting the aforementioned series of procedures, thin dielectric elastomers were obtained.

An ionic conductive layer was realized by fabricating a pre-gel solution of the PAAm-hydrogel. We poured 2.25 M of acrylamide monomer (Sigma Aldrich, A8887) and 2 M of LiCl (Sigma Aldrich, 746460) in deionized water (50 mL) and completely dissolved them. A crosslinking agent (N,N-methylenebisacrylamide) (Sigma Aldrich, 146072) 0.06 wt%, a photo initiator (2-hydroxy-4′-(2-hydroxyethoxy)-2-methylpropiophenone) (Sigma Aldrich, 410896) 0.16 wt%, and an accelerator (N,N,N′,N′-tetramethylethylenediamine) (Sigma Aldrich, T22500) 0.25 wt% of the acrylamide monomers were added to the solution.

C. OPERATING PRINCIPLE OF TRANSPARENT AND SOFT VIBROTACTILE ACTUATORS

Fig. 3 shows the operating principle of the proposed actuator. The ions in the transparent and soft electrodes are randomly oriented in the absence of an electric field. Once an electric field is applied to the transparent and soft ionic conductive layers, free anions move toward the anode, whereas free cations move toward the cathode. Thus, oppositely charged ions are collected on the upper and lower surfaces of the dielectric layer, and the two surfaces attract each other.
This causes the dielectric layer to contract in the thickness direction and expand in the longitudinal direction. When the applied electric field is removed, the actuator returns to its original shape owing to the elastic restoring force of the polymer.

### III. MATERIAL PROPERTIES OF VARIOUS DIELECTRIC MATERIALS FOR TRANSPARENT AND SOFT HAPTIC ACTUATORS

The dielectric and mechanical properties of a dEAP are the two most important factors for maximizing the haptic performance of a dEAP-based vibrotactile actuator. In this section, we present the analysis of the dielectric and mechanical properties of the three prepared samples (silicone rubber, PU, and acrylic polymer) to optimize the haptic performance of the proposed actuator. As the dielectric property (relative permittivity, $\varepsilon_r$) increases, the electrostatic pressure between two electrodes proportionally increases [17]. The relative permittivity of the prepared samples (dielectric materials) was measured using an impedance gain-phase analyzer (AMETEK Scientific Instruments, 1260A) with a dielectric interface (AMETEK Scientific Instruments, 1296A) at 25°C. The samples were mounted with a sample holder (AMETEK Scientific Instruments, 12962A) with a built-in micrometer that can precisely measure their thickness. The dielectric properties of the samples were measured by changing the frequency from 1 Hz to 1 MHz at intervals of 10 Hz with 1 Vpp. Fig. 4 shows the results of the relative permittivity of the three prepared samples (silicone rubber, PU, and acrylic polymer). The results indicate that in the overall frequency range (1 Hz–1 MHz), PU has the highest relative permittivity (approximately 6.79 at 100 Hz), whereas silicone rubber presents the lowest relative permittivity (approximately 2.96 at 100 Hz). Based on the results, we expect that the PU-based actuator will exhibit a higher Maxwell’s stress than the others that are based on the acrylic polymer or silicone rubber.

As mentioned before, the mechanical properties of a dielectric material are important factors. The displacement of the proposed actuator in the z-direction is inversely proportional to its Young’s modulus. Thus, as the softness of the dielectric material increases, the displacement of the actuator in the z-direction increases. However, if the dielectric material is excessively soft, the vibration strength generated by the vibrotactile actuator becomes weaker.

The mechanical properties of the dielectric materials were observed by measuring their tensile strain–stress relationships. The samples were prepared in a dumbbell shape (ASTM D638 type V) and fixed to the crosshead of a universal testing machine (UTM, Zwick/ Roell, Z0.5) mounted with a precision load cell (Zwick/ Roell, Xforce P 100 N). The speed of the crosshead of the UTM was maintained at 0.5 mm/s during the test. We strained the samples until failure. Fig. 5 displays the measured strain–stress curves of the three prepared samples. The acrylic polymer exhibits the highest elongation (>870 %) among the prepared samples. The softest material is the acrylic polymer (lowest Young’s modulus), whereas the stiffest material is PU (highest Young’s modulus). Although there is a difference between the observed elongations of the three prepared samples, all the elongations are soft and exceed 600%. It is expected that PU with the highest relative permittivity and highest Young’s modulus will exhibit the highest electromechanical energy conversion. However, PU may possess a low dielectric breakdown strength owing to its high relative permittivity. Conversely, silicone rubber with the lowest relative permittivity can operate under high electric fields.

The optical transmittance of the prepared samples was observed to verify whether the transmittance was sufficient for applications in flexible and deformable displays. To measure the optical transmittance of the prepared samples, we used an ultraviolet–visible spectrophotometer (Agilent, Cary 100 UV–Vis). Fig. 6 presents the measured optical transmittance of the prepared dielectric samples. The optical
transmittance of all the samples exceeds 88.3% in the visible spectrum (400–700 nm) [18]. Silicone rubber exhibits the highest transmittance (over 93%) at 555 nm [19]. Although silicone rubber and acrylic polymer present low optical transmittance, the values were sufficiently high, allowing their application to a display.

IV. PERFORMANCE EVALUATION OF PROPOSED VIBROTACTILE ACTUATOR

Tactile information is generally delivered to humans by four primary tactile mechanoreceptors (Merkel’s disk, Meissner’s corpuscles, Ruffini endings, and Pacinian corpuscles), which exist in the skin. The four mechanoreceptors are activated via different stimuli and possess their own operating frequency bandwidths [20]. Therefore, it is necessary to develop a vibrotactile actuator with a wide operating frequency range to generate various haptic sensations for the users. Furthermore, the magnitude of the vibrations generated by the proposed vibrotactile actuator should be easily controlled.

We fabricated three vibrotactile actuators based on the prepared dielectric samples (silicone rubber, PU, and acrylic polymer) to compare their influence on the actuation performance. We evaluated the actuation performance of the fabricated vibrotactile actuators by the following three experiments. First, we investigated their frequency response using an accelerometer by changing the input frequency from 1 Hz to 300 Hz at intervals of 10 Hz under a fixed applied electric field of 20 V/µm. Second, we investigated the breakdown voltage of each vibrotactile actuator, near which we observed its frequency response. Finally, we measured the haptic behavior of each vibrotactile actuator at its respective resonant frequency by varying the amplitude of the input signal from 0 V/µm to 20 V/µm at a step size of 1 V/µm (the input signal was increased from 20 V/µm to 50 V/µm at a step-size of 5 V/µm).

Fig. 7 shows the experimental environment for evaluating performance of the fabricated vibrotactile actuators. (GSInstech, Protek 9305), a high-voltage amplifier (Trek Inc., Trek 10/40A-HS), a fabricated vibrotactile actuator, a mass of 100 g, an accelerometer (Briel&Kjær, Charge Accelerometer type 4393), an oscilloscope (Tektronix Inc., MSO/DPO 2000), and a PC.

A sinusoidal input signal was generated by the function generator and subsequently amplified 1,000 times by the high-voltage amplifier, so that it could be applied to the vibrotactile actuator. The vibrotactile actuator was placed on a sample plate, and the accelerometer with an attached mass of 100 g was placed on the upper surface of the actuator. The accelerometer measured the vibrational acceleration generated by the actuator, which was transmitted to the oscilloscope to visually verify the result. All the measured data were collected using a PC.

Fig. 8(a) presents the measured vibrational accelerations (peak-to-peak) generated by the fabricated vibrotactile actuators in accordance with the frequency of the input signal. The breakdown voltages of the three motors differ. Therefore, the electric field applied to the actuators was fixed at 20 V/µm, corresponding to the lowest breakdown electric field among the three vibrotactile actuators. The maximum vibrational acceleration (resonant peak) of the PU-based actuator was observed at 0.46 g at 130 Hz. Additionally, the silicone rubber- and acrylic polymer-based actuators exhibited maximum accelerations of 0.28 g (at 180 Hz) and 0.264 g (at 141 Hz), respectively. The results indicate that the PU-based actuator is the optimal candidate for a soft and transparent haptic actuator. However, as mentioned previously, the three actuators possess different input breakdown electric fields. Therefore, it is important to investigate the haptic behavior of the three actuators at their respective near-input breakdown electric fields.

Fig. 8(b) shows the haptic behaviors of the actuators at their maximum input electric fields. The maximum vibrational acceleration of the silicone rubber-based vibrotactile actuator was observed as 1.408 g at 80 Hz under the maximum applied electric field (50 V/µm). Conversely, the PU and acrylic polymer-based actuators exhibited maximum accelerations corresponding to 0.46 g (at 130 Hz) under an electric field of 20 V/µm, and 0.852 g (at 141 Hz) under an electric field of 40 V/µm, respectively.
We measured their vibration outputs while varying the input voltage from 0 to their own breakdown electric field at their resonant frequencies. The results indicated that the vibration amplitudes of the vibrotactile actuators can be controlled by the input voltage. Fig. 8(c) presents the measured accelerations of the fabricated vibrotactile actuators by increasing the applied electric field. The measured vibrational accelerations of the fabricated actuators increased proportionally to the applied electric field. This suggested that the vibration intensity generated by the fabricated vibrotactile actuators can be controlled by the applied electric field. The observed results (Figs. 8(a)–(c)) clearly revealed that the vibrotactile actuators can selectively stimulate human mechanoreceptors by adjusting the frequency and can also control the vibrational strength of the actuators.

The voltage-induced deformation decreases as dielectric layer hardens. The higher the relative permittivity of the dielectric layer, the higher the vibration acceleration of the actuator. In view of these factors, it is concluded that the dielectric property of the dielectric layer exhibits a trade-off relationship with its mechanical properties. Therefore, it is important to appropriately adjust the dielectric property of the dielectric layer and its mechanical properties to obtain the desired actuation performance. Furthermore, high relative permittivity occasionally causes a negative effect (it causes a lower dielectric breakdown strength). The silicon rubber-based haptic actuator with the highest breakdown voltage is not excessively hard or soft and exhibits the optimal performance among the three prepared samples under the maximum input electric field.

We verified the response time of silicone rubber as shown in Fig. 9. The experimental environment is the same as that in Fig. 7. A sinusoidal input with an electric field of 50 V/µm was applied to the silicone rubber-based haptic actuator. The input signal and the vibration acceleration generated by the actuator were simultaneously observed by an oscilloscope. We verified two points: one ($t_1 \approx 12.4$ ms) where the input electric field reached the first peak of the maximum electric field (50 V/µm), and the other ($t_2 \approx 15.2$ ms) where it attained the first reasonable peak (90% of the maximum acceleration). The verified response time (approximately 2.8 ms) was sufficiently fast to stimulate human skin without delay [20].

In addition, we verified the reliability of the proposed silicone rubber-based haptic actuator. A sinusoidal input with an electric field of 50 V/µm was applied to the proposed haptic actuator. The input frequency was set as 80 Hz, which is a resonant frequency of the actuator. Fig. 10 shows the measured acceleration for 300,000 cycles. We can see a slight
V. PERCEPTUAL EXPERIMENT

The human skin is stimulated by a vibrotactile actuator when the vibrational force is sufficient to overcome its mechanical impedance. Most soft vibrotactile actuators have a light vibration part, which causes an apparent mass reduction on contact with human skin. The light mass of the vibrating part in a soft actuator can reduce the perceptual strength of the vibration compared to those of other heavier/rigid actuators, even though they generate vibrations of the same amplitudes. Therefore, we investigated the perceived vibration intensity for the proposed soft actuator by a perceptual experiment. Furthermore, we compared our actuator with the conventional flexible actuators. Twelve subjects (10 males and 2 females; 23–37 years, mean age: 28.08 years, and standard deviation: 5.35 years) participated in this perceptual experiment. None of the participants reported a sensory disorder related to this experiment. All the subjects were explained the objective and procedure of the experiment, and they signed a standard consent form. After the experiment, all the participants were paid 10,000 KRW (approximately 10 USD).

The objective of this perceptual experiment was to determine the amplitude of the comparison stimulus that a subject feels equally strong as each standard stimulus. This is called as the point of subjective equality (PSE) in a psychometric function for intensity discrimination. We prepared two actuators for this perceptual experiment. One was the proposed transparent and soft vibrotactile actuator to create the standard stimuli. The other one was a mechanical mini-shaker (Brüel&Kjær, model 4810; its dynamic mass is 18 g) to generate the comparison stimuli. A mini-shaker, which can precisely generate vibrations with a minimized external disturbance, is suitable for creating the comparison stimuli. Thus, mini-shakers have been extensively used for tactile perceptual research [21], [22].

All the signals for the standard and comparison stimuli were calculated using a computer and generated by a data acquisition board (DAQ) (National Instrument, USB-6251) with a resolution of 16 bits. During the experiment, we attached an acrylic plate of size 15 mm × 15 mm on the top of the moving part of the mini-shaker to provide the same possible contact area as that of our soft actuator. This was because the detection threshold of a human can vary with the contact area [23]. The subjects were requested to place their index fingers on the proposed vibrotactile actuator and the mini-shaker, respectively, and to wear an earmuff (3M, Peltor Optime 105) to block the sound noise generated by both the actuators. In this experiment, we focused on determining the PSE at four frequencies (80, 150, 230, and 300 Hz). At each frequency, a standard stimulus, which was generated by the proposed actuator, was provided to the subjects at its maximum amplitude (50 V/µm) in a sinusoidal waveform. Sinusoidal comparison stimuli (generated by the mini-shaker) were presented to the subjects at the same frequency, and their amplitudes were controlled to obtain the PSE. In this study, we applied the one-up, one-down interleaved staircase method [24]. We randomly selected the initial amplitudes of the comparison stimuli in the ranges of 1.9–2.0 g (for 80 and 150 Hz) and 3.0–3.2 g (for 230 and 300 Hz) for the downward staircase and between 0.5 and 0.55 g (for all the frequencies) for the upward staircase. In each trial, a subject was provided two stimuli (standard and comparison) sequentially with an inter-stimulus interval (ISI) of 0.2 s. Each stimulus was provided for 1 s. After experiencing both the stimuli, the subject specified the stronger vibrational stimulus. If the subject reported that the comparison stimulus was weaker than the standard one, we increased the amplitude of the comparison stimulus by a specific step size. Conversely, we decreased the amplitude by the step size. We determined the initial step size as 4 dB, and halved it every reversal point for each staircase (upward and downward). Each staircase was completed when five reversal points were observed. The PSE was calculated from the average of the latest six reversal points (three points in the upward staircase and the other three in the downward staircase).

Fig. 11 shows the result of the perceptual experiment. The means of the PSEs were 0.748 g at 80 Hz, 1.161 g at 150 Hz, and...
1.48 g at 230 Hz, and 2.207 g at 300 Hz. We estimated the perceptual magnitudes of the measured PSEs in terms of the decibel sensation level (dB SL, 20log10(amplitude/absolute threshold)) using the absolute thresholds of the index finger extracted from [23]. The estimated magnitudes were 19.6 dB SL at 80 Hz, 23.2 dB SL at 150 Hz, 21.7 dB SL at 230 Hz, and 20.8 dB SL at 300 Hz. These suggest that the magnitude generated by the proposed actuator is approximately 10 times stronger than the absolute threshold.

In Fig. 12, we compare the measured PSEs of the proposed haptic actuator and other flexible actuators [25], [26]. At 80 Hz, the PSE of the proposed actuator is approximately 3.75 times stronger than those of the conventional flexible actuators. At higher frequencies, the proposed haptic actuator exhibits over 1 g, whereas the previous is under 1 g. Particularly, the measured PSE of the proposed actuator is much higher than those of the conventional actuators at 300 Hz.

VI. CONCLUSION

In the study, we developed a transparent and soft vibrotactile actuator with a simple structure, broad operating frequency range, fast response time, and simple fabrication process. To verify the effects of the dielectric and mechanical properties of the dielectric layer, we prepared three different dielectric samples: silicone rubber, PU, and acrylic polymer. We observed the dielectric and mechanical properties of the prepared samples and measured their optical transmittance. Using these samples, we fabricated three vibrotactile actuators of the same size and evaluated their actuation performance. For the silicone rubber-based actuator, the maximum acceleration (the resonant peak) corresponded to 1.408 g at 80 Hz under an electric field of 50 V/µm. Conversely, the PU- and acrylic polymer-based actuators presented maximum accelerations of 0.46 g (at 130 Hz) under an electric field of 20 V/µm and 0.852 g (at 141 Hz) under an electric field of 40 V/µm, respectively. The results indicated that all the three actuators generated vibrations over a broad bandwidth (1 Hz–300 Hz). Furthermore, the findings confirmed that we can control the intensity of the vibrations generated by the vibrotactile actuators by changing the amplitude of the applied electric field and also tune the vibrational frequency by adjusting the input frequency. Moreover, we verified that the proposed vibrotactile actuator presents a fast response time (approximately 2.8 ms). From the perceptual experiment, we confirmed the perceived intensity of the vibrations generated by the proposed actuator at 80, 150, 230, and 300 Hz. The results of the perceptual experiment exhibited that the proposed vibrotactile actuator can create sufficient stimuli. We think that it is required to improve the bonding force between the dielectric layer and ionic conductive layers with maintaining their stretchability. With further improvements, it is expected that the proposed actuator can be easily attached to arbitrary shaped visual display units or be effectively applied to various next-generation devices to create various haptic sensations. Some example devices are shape-changing devices; wearable gadgets; transparent, flexible, and rollable displays; and advanced see-through displays.

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