Multicomponent Olfactory Display Using Solenoid Valves and SAW Atomizer and Its Blending-Capability Evaluation

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***Abstract*— An olfactory display for blending many ingredients at any recipe was developed. It consists of microdispensers based upon solenoid valves and surface acoustic wave atomizer. The accuracy and stability were much improved compared with previous olfactory display using micropumps. Then, its blending capability was tested using sensory test such as triangle test. It was found that the scent blended in the proposed olfactory display was identical to the one blended in advance in the liquid phase. Finally, the durability of the amorphous Teflon coating used for enhancing atomization capability was investigated. The durability of the amorphous Teflon coating was much improved when the concentration of silane-coupling agent was modified.**

***Index Terms*— Olfactory display, SAW atomizer, micro dispenser, solenoid valve, sensory test, Teflon coating.**

I. Introduction

An OLFACTORY display is a gadget to present scents to a user. It can be used in multimedia contents and virtual reality since olfaction takes important role in emotion [1].

The simplest device to present a smell is an aroma diffuser. It can be used to just fill a room with a certain scent. On the other hand, an olfactometer is used if accurate control of smell is indispensable even if it is bulky and expensive [2]. The olfactory display is required when spatio-temporal variation of scent is necessary.

Several types of olfactory display has been so far studied. X-Y addressable odor-releasing system was proposed [3]. Only one PDMS micro chamber among many ones specified by X and Y addresses released a scent. Other olfactory display utilizing polymer-phase transition between sol and gel phases was studied [4]. It worked quietly since it did not contain an air pump and a fan. Nakaizumi *et al.* [5] developed a scent projector using an air cannon. Only a specified person can sniff the smell, whereas his/her neighbors do not perceived it. Odor-source localization in virtual space was reported by Yamada *et al.* [6]. Matsukura *et al.* [7] developed an equipment called smelling screen. A user feels as if the odor source were located at a certain point of the screen. Recently, scent generators worn around a neck were reported. Although their structures were very simple, they were wearable [8], [9].

Moreover, a cross-modal effect was studied using olfactory display. A pseudo-taste display was developed to perceive taste when only visual and olfactory information was provided [10].

Our group focused on multi-component olfactory display to express a variety of scents. We have studied many types of multi-component olfactory display to blend many ingredients using mass flow controllers [11], solenoid valves [12]. However, smell-persistence problem should be overcome when the vapor of low-volatile compound flows through tubes. Thus, the olfactory display using SAW atomizer and micro pumps was developed [13]. However, its behavior was not stable due to micro pump. Thus, the micro pump was replaced with a micro dispenser based on a solenoid valve to spout a tiny liquid droplet [14]. In this paper, we have developed 8-component olfactory display and confirmed its blending capability.

II. Principle of Olfactory Display

We have developed an olfactory display using SAW device and eight solenoid valves. Its principle is illustrated in Fig. 1. The solenoid valves emit tiny amount of liquid droplets of odorants from the reservoirs to the surface of the SAW device. The SAW device atomizes the odorant liquids forcibly due to SAW streaming phenomenon [15], [16]. A user can perceive the scent when the mist is inhaled.

The problem of the previous method using micro pump is shown in Fig. 2. The liquid droplet driven by the micro pump is supplied through a thin stainless tube. The diameter of the tube should be as small as possible to obtain a tiny droplet. The liquid droplet gradually grows up until it touches the substrate surface. Since it is difficult to keep the distance between the tip of the thin stainless tube and the substrate surface constant, the amount of liquid droplet changes according to the situation. Moreover, the thin stainless tube is often clogged because the micro pump power is too weak.

The solenoid valve used here has the function of jetting a liquid droplet instead of switching the fluid flow. The amount

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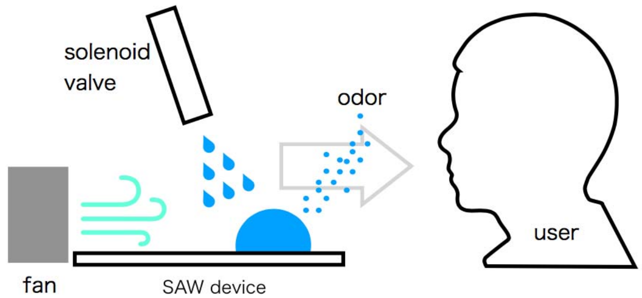

Fig. 1. Concept of proposed olfactory display.

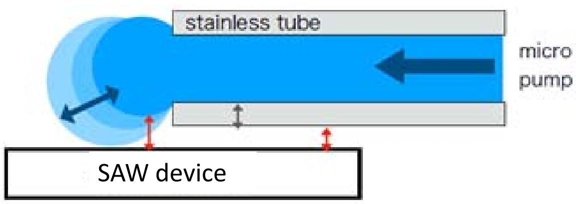

Fig. 2. Problem of olfactory display using micro pump.

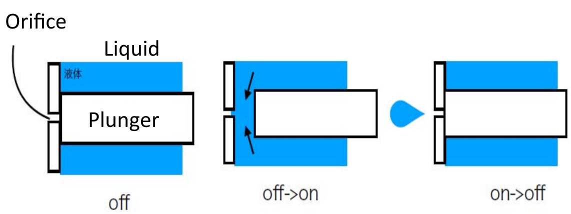

Fig. 3. Principle of micro dispenser based on solenoid valve.

of supplied liquid is highly dependent of its pressure load in case of micro pump, whereas that solenoid valve is not influenced by the pressure load because of its jetting property. Thus, the amount of supplied liquid is much more stable than that supplied by the micro pump.

The previous work used just a single solenoid valve [14]. Although only one solenoid valve is drawn in Fig. 1 for simplicity, multiple solenoid valves were actually used in the present study. The principle of micro dispenser based on the solenoid valve is shown in Fig. 3. The plunger was driven by an electromagnetic coil with its sufficient power. Since its outlet is completely closed during OFF phase, the precise pressure control is not required. The plunger rapidly moves to draw liquid in front of it during short ON phase and then, moves back to the original location to spout a tiny liquid droplet. The amount of the liquid per pulse was a few nano liter.

Another candidate of the micro dispenser is an inkjet device [17], [18]. However, the precise pressure control is required for the inkjet device even if the amount of liquid droplet is very small. Moreover, its self-priming capability is weak.

III. Experimental Setup

The block diagram of whole system is illustrated in Fig. 4. Its photo around SAW device is also shown in Fig. 5.

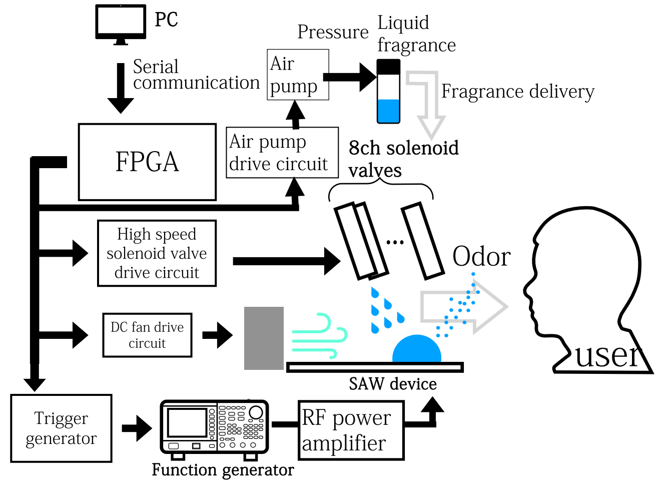

Fig. 4. Block diagram of whole system.

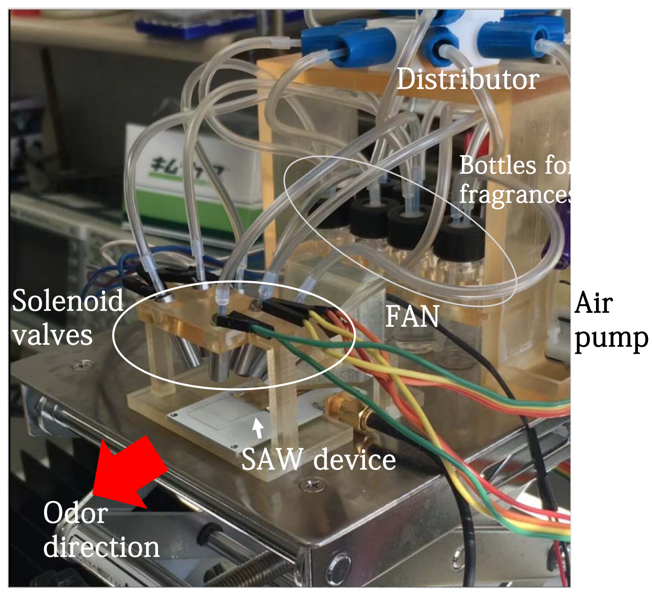

Fig. 5. Photo of developed olfactory display.

The FPGA board (Terasic, DE1-SoC) receives the command from PC through USB UART interface (FDDI Inc, FT232RL). The digital circuit in FPGA was described using VHDL and the program for CPU core (Altera, NIOS II) was written in C language. It generated the trigger signal for the function generator (Tektronix, AFG3021C), connected to a SAW device through an RF power amplifier (Mini Circuits, ZHL-5W-1). RF burst signal ($80V_{p\text{-}p}$) with the repletion cycle of 1s and with the 10% duty cycle was supplied to SAW device.

The SAW device used in this experiment is shown in Fig. 6. Its substrate is 128° rotated Y-CUT X propagation. This substrate was used because of high electromechanical coupling coefficient. The operation frequency was 9.6MHz since driving power for the liquid droplet was stronger than the previous device (61MHz). It has 21 pairs of the electrodes for the excitation and 32 pairs for the reflector. The electrode material was Cr/Au. The area effective for the atomization was 8.9mm × 16mm. SAW device was coated with thin

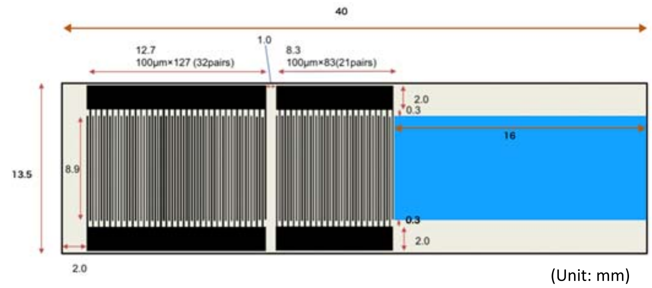

Fig. 6. Configuration of SAW device.

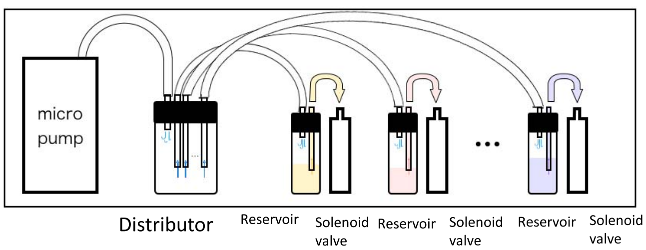

Fig. 7. Method to deliver liquids to solenoid valves.

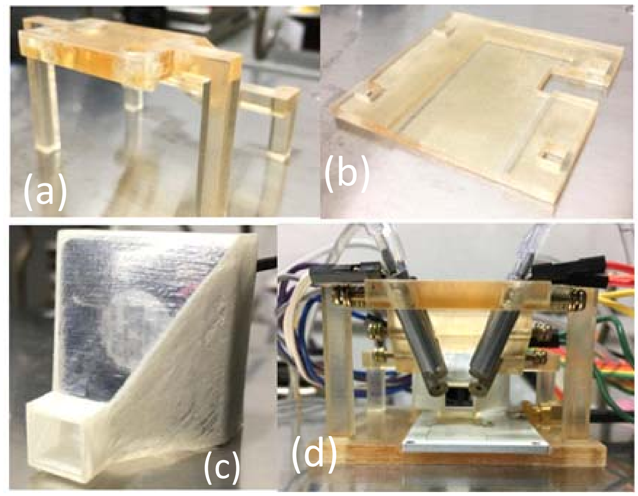

Fig. 8. Adaptor for holding solenoid valves: (a) adaptor without solenoid valves, (b) bottom plate, (c) cover for DC fan, and (d) assembled odor blender.

amorphous Teflon film to raise the atomization efficiency [19]. Moreover, SAW device was mounted on the PCB made of aluminum.

The FPGA board also generated the 2ms pulses supplied to the eight solenoid valves (Lee, INKA2438510H) through the driver circuits (ST microelectronics, ULN2803A). Each solenoid valve was independently controlled according to the command from PC.

DC fan (Sichoh, Co, F3010EB-12UVC) was placed behind SAW device to send the scent to a user's nose. The air pump (Oken Seiko Co., FF-180SH-13230) was used to help liquid flow into the solenoid valve. DC FAN and the air pump were controlled by FPGA board through the driver circuit using discrete transistors (2SC1815).

The tube connection from the air pump to the solenoid valves through reservoirs is shown in Fig. 7. Although the solenoid valve has self-priming capability to some degree, it is not sufficient. It is necessary to apply the pressure to the liquid so that the liquid can get into the solenoid valve even if there are bubbles.

The reservoir was placed above the solenoid valve, and the weight of the liquid itself was used as a pressure source at first. However, it was not successful since the liquid height more than 6cm was necessary. Then, the vials (5mL) were used as reservoirs placed at any place. The air pump instead of liquid weight was used as a pressure source. The air from the air pump was distributed to the eight reservoirs connected to the solenoid valves as is shown in Fig. 7. The tube used for the connection was Tygon tube (o.d.: 3.18mm, i.d.: 1.59mm) and a 9-way connector composed of 8-way and 3-way connectors (Omnifit: OM1006, OM1003) were used as distributors.

Another important issue is to design the adaptor for the solenoid valves. As mentioned earlier, the area in the SAW device used for the atomization was 8.9mm x 16mm. All the liquid droplets spouted from the eight solenoid valves should fall within this area. Since the area for the liquid droplet becomes larger as the solenoid valve becomes away from the substrate, this point should be taken into account together with the size of the solenoid valve (Diameter: 5.8mm). The cylindrical cone from the orifice of the solenoid valve was assumed to express the region where the liquid droplets spread. Then, the layout of the solenoid valves was determined using 3DCG software (Blender Foundation, blender 2.74).

The acrylic adaptor was made using 3D printer (Keyence, AGILISTA-3000). The material has resistance to ethanol, i.e., the solvent for most of fragrances. Although we have made several types of the adaptors, its final structure is shown in Figs. 8(a)-(d). Fig. 8(a) shows the adaptor before inserting the solenoid valves. Fig. 8(c) shows the cover for DC Fan to form relatively narrow air stream above the SAW device. Fig. 8(d) is the front view of the olfactory display. SAW device, solenoid valves and DC fan with the cover were mounted on the adaptor.

Finally, we made the software based on GUI on the platform of Matlab (Mathworks Inc). The parameters for the solenoid valves such as frequency etc can be set up using this software. It is also possible to write the control sequence in CSV file in advance. The program read the CSV file and send the parameters to FPGA according to the description of that file.

IV. Evaluation of Olfactory Display Performance

The sensory test was performed to evaluate the olfactory display performance. Final purpose of this experiment is to confirm the blending capability of our olfactory display since we have not confirmed it in the previous work of single solenoid valve [14].

A. Experiment on Scent Detection

The first experiment was to confirm whether a user can detect the presented scent. The water, i.e., odorless liquid, was presented twice and the scent was presented once. The user

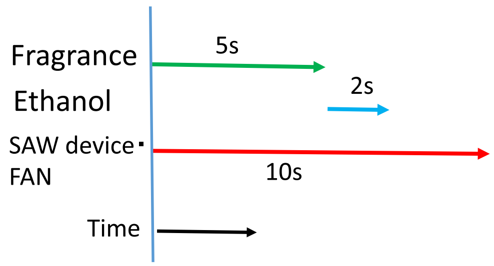

Fig. 9. Timing sequence of scent/water presentation of one cycle.

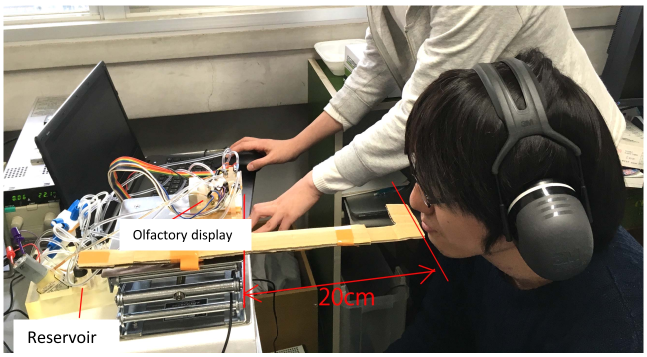

Fig. 10. Scene of sensory test.

was requested to answer which time the scent was presented. The timing sequence of one cycle is shown in Fig. 9.

The sample was atomized for 5s and then, pure ethanol was atomized. Moreover, SAW device worked without liquid supply for 3s. The latter 5s was necessary to clean up the surface of SAW device. Three scents such as cis-3-hexen-1-ol (leaf alcohol), chocolate flavor and mint one were used here. Chocolate and mint flavors were provided by T.Hasegawa Co Ltd. They were diluted with ethanol. The dilution ratios of leaf alcohol, chocolate flavor and mint one were 9:1, 12:1 and 6:1 (v/v), respectively. The drive frequency of the solenoid valve for water, chocolate flavor and mint one was 15Hz and the one for leaf alcohol was 5Hz.

A user was 20cm away from the device and the height of the device was adjusted using a jack so that its height could be the same as the user's nose. The user was asked to close his/her eyes and to wear an earmuff during the experiment. The scene of the experiment is shown in Fig. 10. A deodorizer was operated during the experiment. The ventilation was performed between the experiments. The all subjects were males with the ages between 22 and 31. The number of participants was 15. The experimental result is tabulated in Table 1.

Since this was a triangle test, the correct answer rate by chance was 1/3 [20]. The null hypothesis that the scent was the same as that of water was rejected in all cases when the level of significance was 5%. Thus, we can say that a user perceives the scents of leaf alcohol, chocolate and mint. Although it is natural to perceive the scent with sufficient concentration, we should confirm whether a user can perceive them prior to the experiment on blending. Although peoples' sensitivities to leaf alcohol was high, it was not used in later experiment taking the harmony with other two ingredients into account.

TABLE I

EXPERIMENT ON DISCRIMINATION BETWEEN WATER AND SAMPLE

Discrimination	Water and mint	Water and chocolate	Water and leaf alcohol
Number of correct answers	10	10	15

TABLE II

RESULT OF DISCRIMINATION BETWEEN MINT AND CHOCOLATE-MINT FLAVORS (NUMBER OF CORRECT ANSWERS: 10)

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1st time	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
2nd time	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
3rd time	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Answer	1	1	1	3	1	2	2	2	3	2	2	2	3	1	3
Correct ness	1	1	1	0	1	1	1	1	0	1	0	0	1	0	1

B. Experiment on Blending Scents

We performed the triangle test to discriminate between each single scent and mixture. Then, we performed the test to discriminate between the mixture from the olfactory display and the one blended in advance.

The main point is to confirm whether the scent blended in our device is the same as that blended manually in advance in the liquid phase. We can make a variety of scents using this device if this point is guaranteed.

The single scents used here were mint and chocolate flavors and their mixture was chocolate-mint flavor. The mixture composition of chocolate-mint flavor was 1:1 using the diluted samples prepared in the previous section. We chose chocolate and mint flavors as samples for the following two reasons. First, the scent of chocolate flavor is completely different from that of mint flavor. Secondly, most of people have experience of tasting chocolate-mint flavor and they know what chocolate mint is.

In the first experiment, the mint flavor was presented twice and chocolate-mint flavor was presented once. A subject was asked to answer which time the chocolate-mint flavor was presented. In the next experiment, the chocolate flavor was presented twice and the chocolate-mint flavor was presented once. He was asked to answer which time the chocolate-mint flavor was presented. Finally, the chocolate-mint flavor was presented twice and chocolate and mint flavors were simultaneously atomized once. He was asked to answer which time the chocolate and mint flavor was blended in our device. The number of participants was 15 and their ages were between 22 and 50. All the participants were males. Their results are tabulated in Tables 2-4. In the rows between 1st time and 3rd time, zero means the scent spouted twice, whereas one means the scent spouted only once. In the row of "correctness", one means the correct answer, whereas zero means the false answer.

TABLE III

RESULT OF DISCRIMINATION BETWEEN CHOCOLATE AND CHOCOLATE-MINT FLAVORS (NUMBER OF CORRECT ANSWERS: 11)

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1st time	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
2nd time	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
3rd time	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Answer	2	1	2	1	2	2	1	2	2	2	3	3	3	3	3
Correctness	0	1	0	1	0	1	0	1	1	1	1	1	1	1	1

TABLE IV

RESULT OF DISCRIMINATION BETWEEN CHOCOLATE-MINT FLAVOR AND SCENT BLENDED IN OUR DEVICE (NUMBER OF CORRECT ANSWERS: 4)

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1st time	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
2nd time	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
3rd time	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Answer	2	1	2	2	2	1	3	3	1	1	3	3	2	2	3
Correctness	0	1	0	0	0	0	0	0	0	0	1	1	0	0	1

The discrimination between the flavors is discussed here. The null hypothesis that the mint was the same as chocolate-mint one was rejected using the result in Table 2 when the level of significance was 5%. Thus, we can say that the scent of mint flavor is different from that of chocolate-mint flavor.

The null hypothesis that the chocolate was the same as chocolate-mint one was rejected using the result in Table 3 when the level of significance was 5%. Thus, we can say that the scent of chocolate flavor is different from that of chocolate-mint flavor. The results in Tables 2 and 3 indicates that the scent of each ingredient is different from that of the blended one.

Finally, the null hypothesis that the chocolate-mint flavor was the same as the scent blended in our device was accepted using the result in Table 4 when the level of significance was 5%. Thus, we can say that our proposed olfactory display can make the scent the same as that of the flavor manually blended in advance in the liquid phase.

V. IMPROVEMENT OF SAW ATOMIZER

We confirmed the blending capability in the previous section. Moreover, we improved the coating method of amorphous Teflon required for enhancing the efficiency of atomization [19]. The nature of the substrate surface changes from hydrophilic to hydrophobic one after Teflon coating. Since the liquid droplet has sphere-like shape on the hydrophobic surface, the area of the droplet in contact with the substrate surface is much smaller than that for the hydrophilic surface. Thus, the energy for detaching liquid from the substrate surface decreases.

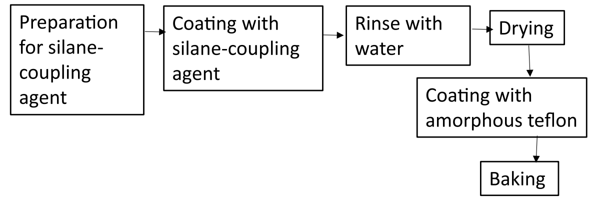

Fig. 11. Process of amorphous Teflon coating.

TABLE V

RESULT OF EXPERIMENT ON ADHESION

Concentration of silane-coupling agent (wt %)	Number of cycles before coating detachment
0.3	495
0.5	160

Although the efficiency was improved after coating, there still remained the problem of the coating durability. At first, the coating itself was atomized when RF voltage was supplied to SAW device. Thus, the silanization process was previously introduced to strengthen the adhesion of the coating. We modified the parameter to enhance its durability in this paper.

The process of Teflon coating is shown in Fig. 11. The silanization (Silane-coupling agent: 3-aminopropyltriethoxy silane, Shinetsu Chemical Co. Ltd) was performed using a dip coater (DC 4300, Aiden), was rinsed with pure water for 1 minute and then was dried in the air for 30 minutes. Thereafter, SAW device was coated with the amorphous Teflon (CTL-107MK, Asahi glass) diluted with dedicated solvent (CT-SOLV100K, Asahi glass) using the dip coater. The dip coating was performed twice at the speed of 1.7 mm/s. The thickness of the coating was approximately 400nm, which was measured using QCM (Quartz Crystal Microbalance) with gold electrodes. Finally, the SAW device coated with amorphous Teflon was baked at 180 °C.

Next, the experimental condition is described. 75nL of ethanol was provided to SAW device every 4s using the solenoid valve described earlier. RF burst of 9.6MHz (170Vp-p) with 10% duty cycle was supplied to the SAW device every second. The experiment was conducted for 3 minutes and was stopped for 3 minutes. This cycle was performed repeatedly.

Previously we used the aqueous solution of sliane-coupling agent of 0.5% (w/w) [19]. Moreover, we prepared for the aqueous solution of 0.3 % (w/w) and the same coating procedure was performed. The test was performed until the coating removal occurred.

The result is shown in Table 5. It indicates that the durability was three times improved when the concentration of the silane-coupling agent became lower. Its reason is speculated as follows. When the concentration of the silane-coupling agent was too high, thick silanization layer formed on the substrate might prevent its molecule from contacting the amorphous Teflon coating. Then, the adhesion might decrease. Since the various concentration of silane coupling agent has not been so far tested, there is still room for the further improvement of the adhesion.

VI. Conclusion

We have developed the multi-component olfactory display using micro dispensers based upon solenoid valves and SAW atomizer. The accuracy and stability of dispensing liquid droplet was much improved compared with previous micro pump. Moreover, the sensory test revealed that the scent blended in the proposed olfactory display was identical to the one blended in advance in the liquid phase although there was possibility that each ingredient scent reached a user's nose without mixing and he/she felt each ingredient scent separately. Thus, the proposed olfactory display can contribute to the scent creation perfumers or flavorists want although they currently consumes much time and labor. Moreover, it can also contribute to the scent reproduction using odor components [21].

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References

[1] T. Nakamoto, Ed., *Essentials of Machine Olfaction and Taste*. Hoboken, NJ, USA: Wiley, 2016.

[2] B. N. Johnson and N. Sobel, "Methods for building an olfactometer with known concentration outcomes," *J. Neurosci. Methods*, vol. 160, pp. 231–245, Mar. 2007.

[3] H. Kim *et al.*, "An X–Y addressable matrix odor-releasing system using an on–off switchable device," *Angew. Chmie Int. Ed.*, vol. 50, pp. 6771–6775, Jul. 2011.

[4] D. W. Kim, "Aroma chip using a functional polymer gel," in *Human Olfactory Displays and Interfaces: Odor Sensing and Presentation*, T. Nakamoto, Ed. Hershey, PA, USA: IGI-Global, 2013, pp. 384–400.

[5] F. Nakaizumi, Y. Yanagida, H. Noma, and K. Hosaka, "SpotScents: A novel method of natural scent delivery using multiple scent projectors," in *Proc. IEEE Virtual Reality Conf.*, Mar. 2006, pp. 207–212.

[6] T. Yamada, S. Yokoyama, T. Tanikawa, K. Hirota, and M. Hirose, "Wearable olfactory display: Using odor in outdoor environment," in *Proc. IEEE Virtual Reality Conf.*, Mar. 2006, pp. 199–206.

[7] H. Matsukura, T. Yoneda, and H. Ishida, "Smelling screen: Development and evaluation of an olfactory display system for presenting a virtual odor source," *IEEE Trans. Vis. Comput. Graphics*, vol. 19, no. 4, pp. 606–615, Apr. 2013.

[8] D. Dobbelstein, S. Herrdum, and E. Rukzio, "inScent: A wearable olfactory display as an amplification for mobile notifications," in *Proc. ISWC*, Sep. 2017, pp. 130–137.

[9] J. Amores and P. Maes, "Essence: Olfactory interfaces for unconscious influence of mood and cognitive performance," in *Proc. CHI*, May 2017, pp. 28–34.

[10] T. Narumi, S. Nishizaka, T. Kajinami, T. Tanikawa, and M. Hirose, "Augmented reality flavors: Gustatory display based on edible marker and cross-modal interaction," in *Proc. CHI SIGCHI Conf. Human Factors Comput. Syst.*, May 2011, pp. 93–102.

[11] T. Nakamoto, S. Ustumi, N. Yamashita, T. Moriizumi, and Y. Sonoda, "Active gas/odor sensing system using automatically controlled gas blender and numerical optimization technique," *Sens. Actuators B, Chem.*, vol. 20, pp. 131–137, Jun. 1994.

[12] T. Nakamoto and H. P. D. Minh, "Improvement of olfactory display using solenoid valves," in *Proc. IEEE Virtual Reality Conf.*, Mar. 2007, pp. 171–178.

[13] K. Hashimoto and T. Nakamoto, "Tiny olfactory display using surface acoustic wave device and micropumps for wearable applications," *IEEE Sensors J.*, vol. 16, no. 12, pp. 4974–4980, Jun. 2016.

[14] S. Kato and T. Nakamoto, "Control system of micro droplet using microdispenser based on solenoid valve and its application for highly efficient SAW atomizer," (in Japanese), *IEEJ Trans.*, vol. 138, no. 6, 2018.

[15] S. Shiokawa, Y. Matsui, and T. Ueda, "Liquid streaming and droplet formation caused by leaky Rayleigh waves," in *Proc. IEEE Ultrason. Symp.*, vol. 1. Oct. 1989, pp. 643–646.

[16] M. Kurosawa, T. Watanabe, and T. Higuchi, "Surface acoustic wave atomizer with pumping effect," in *Proc. MEMS*, 1999, pp. 25–30.

[17] T. Nakamoto, H. Takigawa, and T. Yamanaka, "Fundamental study of odor recorder using inkJet devices for low-volatile scents," *IEICE Trans. Electron.*, vol. E87-C, no. 12, pp. 2081–2086, 2004.

[18] D. B. Wallace *et al.*, "Determination of the olfactory threshold using a piezoelectric microdispenser for neurodegenerative disease diagnostics," *Meas. Sci. Technol.*, vol. 17, no. 11, pp. 3102–3109, 2006.

[19] H. Li, G. Qi, S. Kato, and T. Nakamoto, "Investigation and improvement of atomization efficiency based on SAW device coated with amorphous fluoropolymer film for olfactory display," *Sens. Actuators B, Chem.*, vol. 263, pp. 266–273, Jun. 2018.

[20] M. C. Meilgaard, G. V. Civille, and B. T. Carr, *Sensory Evaluation Techniques*. Boca Raton, FL, USA: CRC Press, 2016, pp. 79–122.

[21] T. Nakamoto, M. Ohno, and Y. Nihei, "Odor approximation using mass spectrometry," *IEEE Sensors J.*, vol. 12, no. 11, pp. 3225–3231, Nov. 2012.

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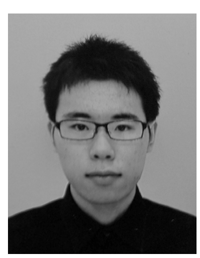

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