Improvement of Olfactory Display Using Electroosmotic Pumps and a SAW Device for VR Application

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ABSTRACT

Previously, air blowing or heating techniques has been used for presentation of the scents. As a consequence, the scents of low-volatile substances are difficult to be released at an acceptable speed. Also, the effect from heat to the nearby environment cannot be avoided. In this research, we proposed an olfactory display using miniaturized electroosmotic pumps and a surface acoustic wave device utilizing SAW atomization technique. In this manner, the olfactory display is miniature in size, works soundlessly, and is able to produce even the scents of low-volatile substances without heat radiation to the adjacent environment. In addition, we optimized the experimental parameters to solve the problem of reproducibility when the number of odor components increase. As a result, by using an odor sensing system we could confirm that the developed device possesses ability to control odor intensity and to blend multiple of odor components. Owing to these benefits it can be expected to be utilized in a variety of virtual reality applications.

KEYWORDS: Olfactory display, low-volatile scent, electroosmotic pump, SAW streaming, QCM gas sensor.

INDEX TERMS: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities;

1 INTRODUCTION

During the past decades, extensive research efforts have been dedicated to the development of virtual reality for entertainment [1], engineering [2], education [3], and medical applications [4]. The virtual reality experience can be made more realistic with a three dimensional stereoscopic vision and audio, or other sensory domains using the experience of tactile and thermal expressions [5], wind blowing, and the emission of aromas [6]. Unlike other senses, as the olfaction system is connected directly to the Paleomammalian brain, it has an intense connection with memory and induces an emotional connection to us. Therefore, the introduction of olfactory information using olfactory display could have a particular impact on the potential of the virtual reality.

The first attempt to add the sense of smell into virtual reality started in 1960s when the Sensorama [7], a crude multimedia movie machine, was developed. This work can be regarded as a predecessor of modern multimedia system. Even though there were a lot of limitations in technology at that time, it can present the odor according to the 3D scene on the display with wind blowing and chair vibration. Since then, there have been discussions whether movies need odor presentation. However, as human perceive the world through five senses, the lack of olfaction in the virtual world may cause users to feel like wearing a space suit without exposure to the air in the real world [8].

To include an olfactory sense into virtual reality, nowadays olfactory displays based on several concepts have been extensively developed by several groups. For example, our group has developed olfactory displays using mass flow controllers [9] and solenoid valves [10]. In the former, odors are mixed with a flow ratio determined by the mass flow controller and in the latter, the high speed solenoid valves which only two states of ON and OFF are used to adjusted the strength of the odor by varying the ON/OFF frequency of the valves. The developed devices equipped with up to 31 different odor components are able to mix the odors at arbitrary recipes, and then deliver it to the user's nose through a tube attached to a headset. Our group also developed the olfactory display using inkjet devices in which the fine droplets of liquid-phase odor samples are spouted using the inkjets on to the heater and evaporated to generate odor [11]. As the liquid droplets are enforced to be vaporized, this device is suitable for presenting the odor of low-volatile substances.

The olfactory display based on inkjet system has also been developed by Okada [12]. As this device presents odor for a short time, it can avoid the adaptation problem that users tend to be unable to detect smell when they inhale it continuously for a period of time. In addition, the olfactory display using functional high polymers coupled with a Peltier device, above which fragrance is encapsulated in a hydrogel chip, has been developed by Kim [13]. Besides, the wearable olfactory display with the capability to present scent information spatially based on the user's position has also developed by Hirose [14]. And, the scent projector with the capability to deliver odor in vortex ring shape to a specific area up to 1.5m has also developed by Yanagida [15].

Taking the current situation into account, olfactory displays based on several techniques have been so far studied and they are useful in certain situations. However, our understanding is that the olfactory display for general usage in virtual reality should possess the 4 following capabilities.

(1) It should be able to present any kinds of smells vividly without the lack of reproducible release over multi cycles. Moreover, the odor presentation should be made at sufficient speed. In other words, the presentation should be able to be started and stopped as fast as possible.
(2) It should be able to adjust the intensity and amount of the emitting odor precisely and in real time according to the user's needs.
(3) As primary smells have not been so far discovered unlike primary colors, it is profitable if the olfactory display can blend multiple odor components for presenting various smells based on a limited number of odor components.
(4) As home electronic apparatuses, such as television, home-theatre, or video game, are getting thinner, smaller, and more delicate, the olfactory display should be also small

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and thin enough. Besides, it should work soundlessly and do not produce heat to the nearby circumstance.

Indeed, no existing device at the moment could fulfill these requirements. For example, the mass flow controllers and solenoid valves based olfactory display has difficulty to present scents of low-volatile substances, as their principles rely on the natural evaporation characteristic of the liquid-phase odor sample to generate smell, and also the noise associated with the valve switching and air blowing cannot be avoided. For the inkjet based olfactory display developed by our group, it requires skill to handle and the odor blending becomes more difficult when the number of odor components increased as it lacks of self-priming capability unlike an EO pump. Moreover, the heat radiated from the heater affects nearby environment. For the olfactory displays developed by other groups, there is no reported regarding the capability to blend smells, and devices are still bulky. For these reason, innovative techniques are needed obviously.

As the primary requirement of the development of an olfactory display is an accurately adjustable odor presenting capability, in this research we employ a kind of miniaturized liquid pump called EO (Electroosmotic) pump to drive the liquid-phase odor sample to another device as the flow rate can be controlled linearly by adjusting the driving voltage with high reproducibility. To produce the odor, we make use of a SAW (Surface Acoustic Wave) device to atomize the liquid-phase odor sample emited from the EO pump into fine particles which are suddenly vaporized in to the air. Therefore, the response time of the odor emission is fast. And as the liquid is atomized forcibly, even the scents of low-volatile substances can be also rapidly generated. Both EO pump and SAW device work soundlessly, do not produce heat to the nearby surrounding, and are miniature. Therefore, the olfactory display based on this concept can be expected to be in a small size enough to be applied to many systems. In addition, by using multiple EO pumps filled with different odor components the ability to blend odors can be expected.

In the previous paper [16], we have successfully employed a basic olfactory display developed based on this new atomization technique to present smells and we were able to confirm its reproducibility. In the present paper, to realize the capability to control the odor intensity and to blend smells, a lot of parameters, such as the rearrangement of the SAW device, the optimization of the SAW parameters, and the improvement of EO pumps driving method, were optimized. Consequently, we can solve the problem of reproducibility when the number of odor components increases and the device also became thinner. Moreover, the odor sensing system used to evaluate the developed device was also improved to reduce the noise occurring in the experiment.

2 SYSTEM OVERVIEW

2.1 Electroosmotic pump

In recent years, micro-fluidic devices and their applications have received a lot of attention due to the rapid growing progress in the field of micro-fluid systems. Micro-pump is one of the most important micro-fluidic components as it can provide the precise flow rate for the micro-channel. EO pump used in this study is a kind of Micro-pump that can produce the flow rate of liquid by utilizing electroosmotic phenomenon [17]. It can drive ethanol or de-ionized water with high stability quietly due to no mechanically moving part. Besides, as the relationship between the flow rate and electric driving voltage is linear according to the electroosmotic phenomenon, the flow rate can be controlled easily by adjusting the applied voltage.

Because of these advantages, it was employed here to supply liquid droplet onto the SAW substrate to atomize sample liquid to generate smell. The EO pumps used in this study were made of Polypropylene with 11.5mm in length and 6mm in diameter. The reservoir (100μL) is equipped on the top of the device as shown in Figure 1.

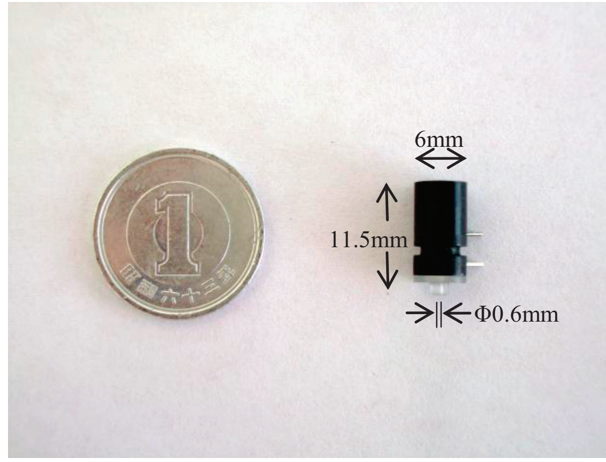

Figure 1. An EO pump used in this study.

2.2 SAW device

SAW device basically consists of an input transducer to convert electrical signal to surface acoustic wave, which then travels along the solid surface to the output transducer where it is reconverted to electrical signal. With this characteristic, it is typically used as a RF filter in communication field. However, when the liquid is dropped onto its substrate as shown in Figure 2, the SAW radiates a longitudinal wave into liquid causing various liquid motions, such as vibration, flow, soaring, and atomization depends on the amplitude of the electric voltage applied to the SAW device. This phenomenon is called SAW streaming [18].

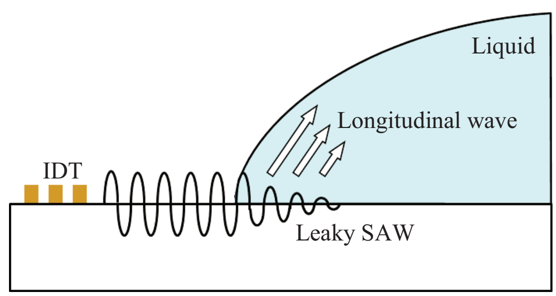

Figure 2. Schematic of SAW streaming.

Although there are several ways to achieve atomization, the size of SAW atomizer is rather smaller than those produced by other methods. Therefore it is employed to atomize the liquid-phase odor sample spouted from EO pumps into smell. In addition, this operation does not radiate heat to nearby environment unlike the heater.

The SAW device designed in this study consists of two ports of 10 finger pairs of an interdigital transducer (IDT) with width of 16μm, and 100 lines of a grating reflector as shown in Figure 3. All of the electrodes are made of gold and fabricated on a piezoelectric substrate made of a 128°rotated Y-cut X-propagation $LiNbO_3$. The device size is 11x19mm, and the center frequencies of this device are about 60.65MHz. Frequency characteristics of the SAW device measured by impedance analyzer (4291A, Hewlett Packard) are shown in Figure 4.

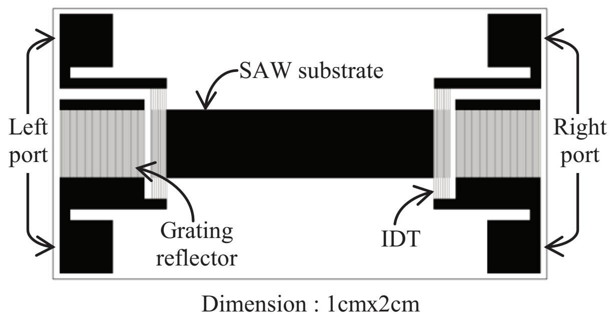

Figure 3. Pattern of the SAW device used in this study.

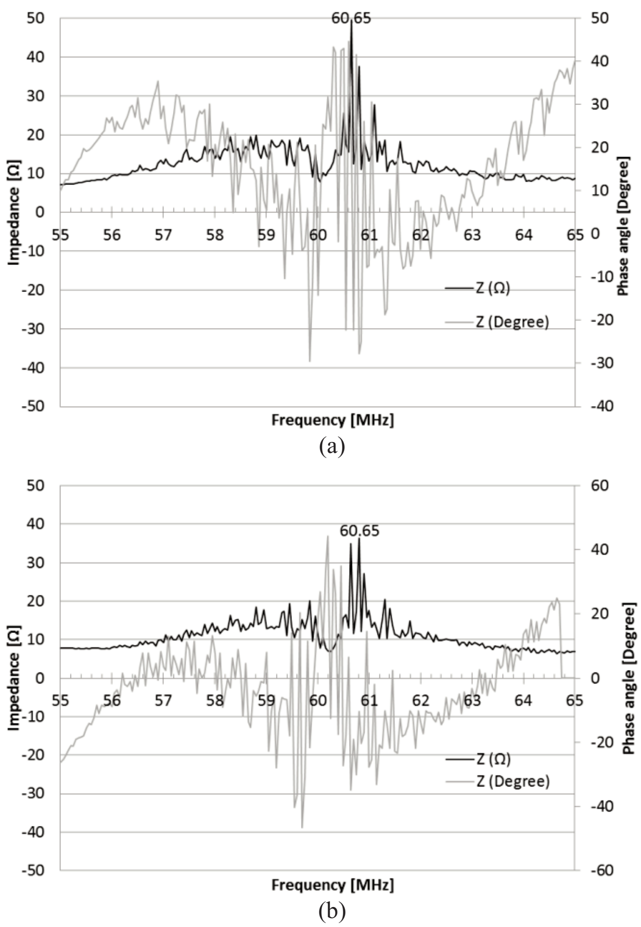

Figure 4. Frequency characteristic of the SAW device at the (a) left port, (b) right port.

2.3 Structure of the system

The structure of an olfactory display using an EO pump and a SAW device is shown in Figure 5. First, the target odor to be presented is dissolved into solvent that is capable to be driven by electroosmotic phenomenon using an EO pump (ex. ethanol, de-ionized water) with the reservoir on its top. By applying electrical pulse to the pump, a droplet of odor sample is supplied onto the surface of the SAW device located under the EO pump, where they are atomized forcibly by SAW streaming into smell and then are delivered to the user's nose by a small fan.

Based on this configuration, by adjusting the electrical voltage applied to an EO pump, we can adjust the volume of liquid droplet. As the odor intensity relies on the amount of liquid-phase odor sample to be atomized, the capability to control the intensity of a presenting odor can be achieved. Furthermore, when we use multiple EO pumps filled with different odor components the ability to blend odors can be realized by adjusting the volumes of liquid droplets in this manner.

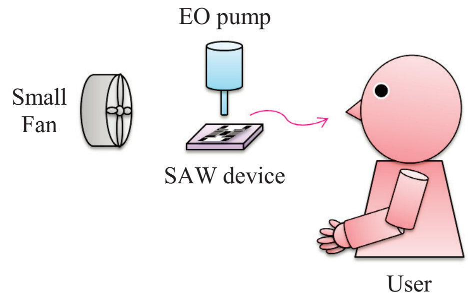

Figure 5. Schematic of an olfactory display using an EO pump and a SAW device.

3 EXPERIMENTAL SYSTEM

To evaluate the proposed olfactory display, our group has used an odor sensing system instead of using the sensory test since human perception is influenced by adaptation and varies from person to person while an odor sensing system can measure the temporal change of the odor intensity numerically with high reproducibility. The whole experimental setup is shown in Figure 6.

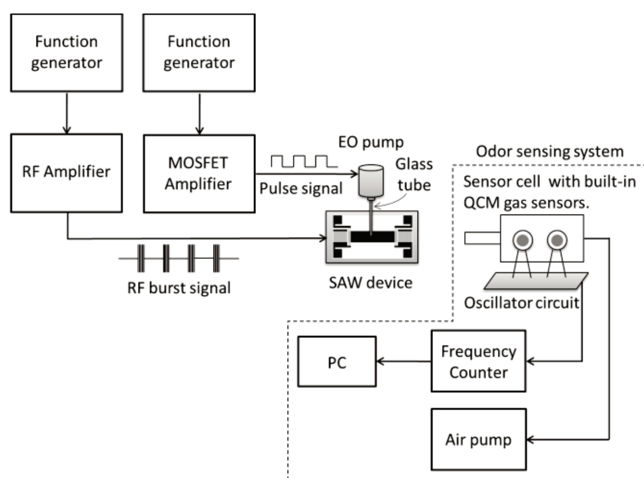

Figure 6. Schematic diagram of experimental set up.

The odor sensing system consists of gas sensors, an oscillator, and a frequency counter circuit. Gas sensors used here was the QCM (Quartz Crystal Microbalance) gas sensors. In the previous paper [16], a fan was used to blow the generated odor to the QCM gas sensor exposed directly to the ambient air. As that configuration create a lot of noise, in this study QCM gas sensors were built in the sensor cell which the generated odor was blew into by using an air pump connected to it. When the molecule of the odor is adsorbed onto the sensing film at the surface of QCM, the mass change causes the shift in resonance frequency of the quartz due to mass loading effect [19]. Therefore, the intensity of the presenting odor can be converted to the frequency shift. The sensing films used in these experiments were Siponate DS-10 and PEG-1000. The electrodes on the QCM surfaces were made of gold, and the center frequencies of the sensors were approximately 20MHz. The frequency shift due to the odor molecule adsorbtion was measured by the frequency counter. Then the measured data were transferred to a computer via serial interface and were stored as a text file.

In the experiments, as an air pump was used to blow the generated odor into the sensor cell, a small fan as shown in Figure 5 was not actually used. The wind speed at the front end of the sensor cell was approximately 0.6m/s and the temperature control was not especially performed. The actual experimental environment is shown in Figure 7. Three EO pumps were prepared in this study, and the center one would be used if not specified in each section. In the previous paper [16], the SAW device was placed perpendicular to the EO pumps as is shown in Figure 5. However, the amount of liquid dropped on to the SAW device was significantly influenced by the distances between the tips of EO pumps and the surface of a SAW device. Thus the reproducibility deteriorated due to the difficulty in controlling this distance accurately when many EO pumps were used. Obviously, this problem needs to be overcome to realize the odor blending capability. Therefore, to solve the problem, in the present paper, the SAW device was placed in the parallel direction to the EO pumps as is shown in Figure 7. Furthermore, the glass tubes with 0.3mm inner diameters were connected to the EO pump tips and laid on to the SAW device's surface. Owing to this configuration, the difficulty in controlling the distance as described above can be avoided and thickness of the overall device can also be reduced. Besides, as the glass tube inner diameters were small, the droplets with tiny volume were obtained.

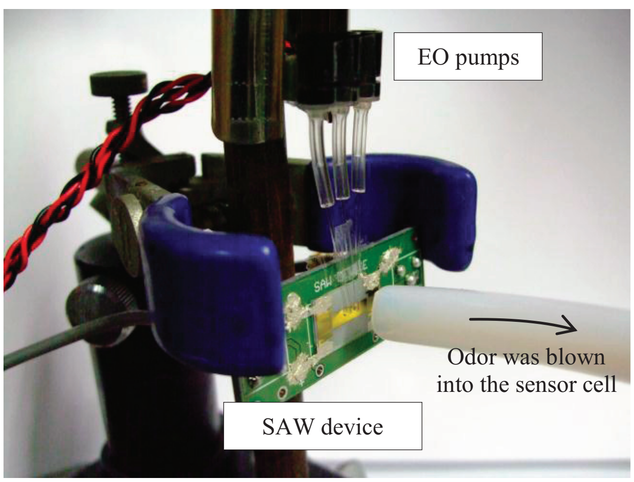

Figure 7. Actual experimental environment.

RF burst was used to drive the SAW device instead of the continuous signal since the latter might exceed the device's tolerance. In the previous paper [16], the duty cycle and repetition period of the RF burst were set to be 50% and 10ms respectively. However, the longer repetition period is, the significantly higher atomization performance is obtained. Thus, those parameters were set to be 1% and 100ms respectively if not specified in each section. And, as the SAW device requires sufficient driving voltage in RF frequency band to perform an atomization, a wide-band RF amplifier (ZHL-5W-1, Mini-Circuits) was used to amplify RF burst signal generated from a function generator (AFG 3251, Tektronix) into $60V_{pp}$ if not specified particularly.

MOSFET amplifier was used to amplify pulse signal from a function generator (33120A, Hewlett Packard) to 75V pulse to drive EO pumps. The amount of droplet dropped onto the SAW device's substrate was controlled by adjusting the duration of the applied pulse.

Samples used in the experiments were 10 % 2-hexanone (MW:100.2, b.p.:127℃), 10 % 1-butanol (MW:74.12, b.p.:117.2 ℃), and 10% beta-ionone (MW:192.3, b.p.:239℃) diluted with ethanol. Since 2-hexanone and 1-butanol are typical compounds with moderate volatility, they were used to evaluate the measurement system and the capability to present the typical scents of the olfactory display. On the other hand, beta-ionone has low-volatility which causes difficulty in smell presentation by conventional olfactory display [9][10]. It was used as a representative to evaluate the capability to present the scent of low-volatile substances of the olfactory display.

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Odor presentation capability evaluation

To evaluate the odor presentation capability of the olfactory display, in the first experiment a 75 V electric pulse with duration for 3s was added to the EO pump. At that time 0.41μl of 2-hexanone solution was dropped on to the SAW substrate and then atomized abruptly. The sensor response to 2-hexanone is shown in Figure 8. The dashed line shows when the sample droplets were dropped onto SAW substrate.

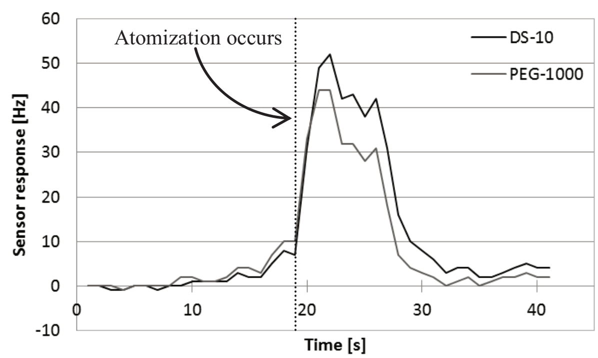

Figure 8. Sensor response to 2-hexanone generated by proposed olfactory display.

As a result, we can see that the abrupt peak of the sensor response was obtained. It means that the olfactory display can present the scent with moderate volatility suddenly and then disappeared in a short time without smell persistence around the sensor. Moreover, the noise of the sensor response was drastically reduced compared with the previous paper because of the sensor cell usage whereas the sensor, which is also sensitive to temperature and humidity variation, was directly exposed to the ambient air in the previous one.

Next, another experiment was conducted to confirm if the olfactory display can present low-volatile scents. In this experiment, the sensor response to scent generated from 0.27μl of beta-ionone solution atomization was measured. The result is shown in Figure 9. In comparison, the sensor response to the same sample presented by the conventional solenoid valve based olfactory display is shown in Figure 10. In that experiment, the QCM coated with Versamid900 was used.

As a result, we can see that the response time or the recovery time of the waveform in Figure 9 was much faster than that in Figure 10. It means that the olfactory display using atomization technique developed in this study can present even the scents of low-volatile substances abruptly and the scents then disappear in a short time while the conventional device requires very long time to reach the steady state and also a very long time until the scents disappear due to the natural evaporation characteristic of the substance and the smell persistence inside the tube.

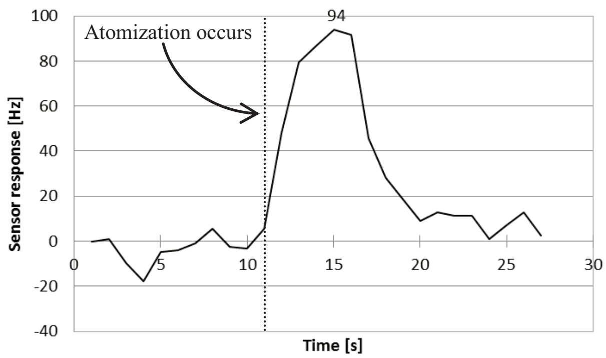

Figure 9. Sensor response to beta-ionone generated by proposed olfactory display.

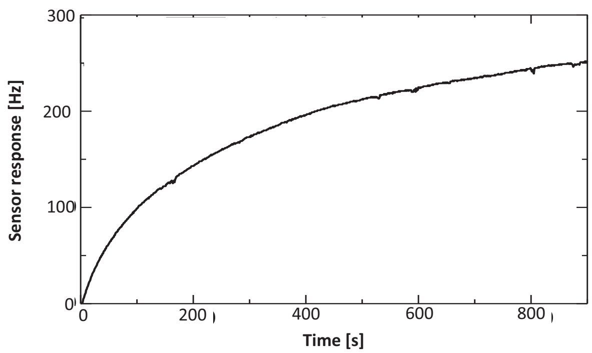

Figure 10. Sensor response to beta-ionone using a conventional solenoid valve type olfactory display (Flow rate:1350L/min).

Then, the next experiment was performed to verify the reproducibility of the odor presentation using developed olfactory display. In this experiment, the sensor response to scent generated from 0.41µl of beta-ionone atomization was measured 3 times. The result is shown in Figure 11. As a result, the certain repeatability of the sensor response can be observed. Thus, we consider that the olfactory display has sufficient reproducibility for practical usage.

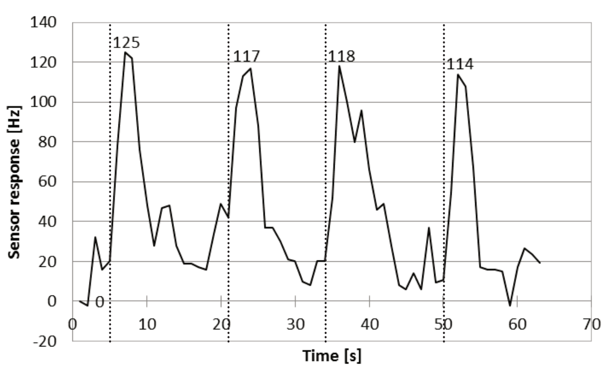

Figure 11. Repeatability of the odor intensity presented by the proposed olfactory display.

4.2 Optimal condition of duty cycle and RF voltage of SAW device

The atomization is caused by RF burst applied to the SAW device. The important parameters for the atomization are RF frequency, RF voltage, duty cycle and repetition period. It is known that the higher RF voltage and the more duty cycle are applied to the SAW device, the fiercer atomization occurs. Since the higher power consumption needs, the larger the size of the RF amplifier in the system requires. To make an olfactory display as miniature as possible, we need to find the way to drive the SAW device most effectively at the same power consumption. Here we made an experiment to investigate whether RF voltage or duty cycle comparatively governs the atomization performance under the condition of the same RF power. The result of this experiment would help us determine the valuable parameter to be adjusted to increase the atomization performance.

In this experiment, scents generated from 0.27µl of 2-hexanone solution atomization under three conditions that RF voltage and duty cycle of the burst wave are set to (1) $100V_{pp}$ and 2%, (2) $50V_{pp}$ and 4%, (3) $20V_{pp}$ and 10% were measured. The odor sensor used in this experiment was the QCM coated with PEG-1000, and the sensor response is shown in Figure 12.

As a result, we can see that RF voltage has more influence to the atomization performance than duty cycle under the same RF power condition. Therefore, according to the result we would set the duty cycle constant, and adjust the RF voltage if the fiercer atomization is required.

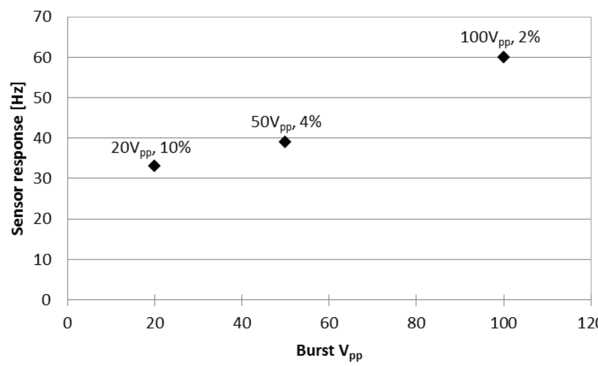

Figure 12. Relationship between RF voltage and sensor response under conditions of same RF power.

4.3 Odor intensity controllability Evaluation

In our previous work [16], we have already showed that the intensity of the presenting odor can be controlled by adjusting the number of liquid droplets injected onto the SAW device. However, the pulse width control requires shorter time than the pulse number control. Therefore, at this point, an experiment was performed to verify whether the intensity of the odor presented by the olfactory display in this study can be controlled by adjusting pulse width applied to the EO pump.

In this experiment, the four conditions that 75 V electric pulses with the duration for 1s, 2s, 3s, and 4s were applied to the EO pump to emit 0.14µL, 0.27µL, 0.41µL, and 0.55µL of 2-hexanone solutions onto the SAW substrate were performed to generate smells respectively. The experiment was done five times at every condition. The odor sensor used in this experiment was the QCM coated with Siponate-DS10, and the typical sensor responses are shown in Figure 13.

From the result, we can see that when the droplet volume increases by applying longer pulse width, the sensor response also increases proportionally. From this reason, we would be able to control the intensity of the presenting odor by adjusting the pulse width applied to EO pump.

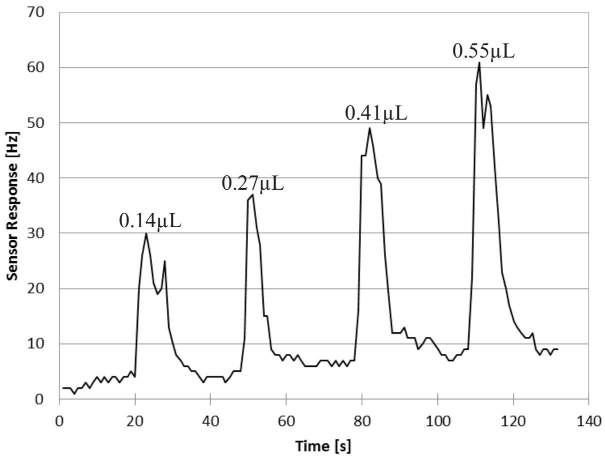

Figure 13. Relationship between pulse width applied to EO pump and sensor response.

4.4 Dependence of droplet position upon atomization

In section 4.3, we confirmed that the olfactory display developed in this study possesses the ability to control the odor intensity. Therefore, we expected the situation where multiple EO pumps were set up to spout different odor components on to any point of the SAW surface area and then atomized them together. In this situation, the mixture odor should be presented. To verify this assumption, in this experiment we divided the SAW area into left, center, and right region as shown in Figure 14. Then 2-hexanone solutions with the volume from 0.27µL to 0.95µL were dropped onto any region on the SAW surface to be atomized. Every condition was done twice. The RF burst used in this experiment was approximately $120V_{pp}$ and the odor sensor was QCM coated with Siponate-DS10. The average sensor responses are shown in Figure 15.

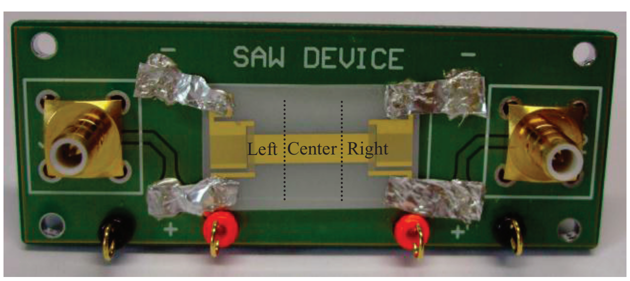

Figure 14. Photo of the SAW atomizer.

From the figure, it was found that there are only slight differences between the sensor responses from any region at any concentration level. As a result, we can conclude that the atomization performance does not change noticeably due to the atomization position. Therefore, it was proven that the multiple odors blending capability can be achieved if a lot of odor components are spouted on to the SAW substrate and then are atomized together.

4.5 Odor blending capability evaluation

Lastly, as the capability to blend smells make an olfactory display profitable for any applications, here the experiment to confirm the possibility to blend odors by using the proposed olfactory display was conducted. In this experiment, we used two EO pumps filled with 2-hexanone and beta-ionone, and presented its smell to the sensor at a certain level of 2-hexanone concentration. In the experiment, the QCM (20MHz, Ag electrode, AT-CUT) coated with Siponate-DS10 was used. The sensor response is shown in Figure 16. As a result, when the two different odors were presented at the same time, superposition characteristic was roughly observed. Thus, the fundamental blending function of the olfactory display developed in this study was confirmed.

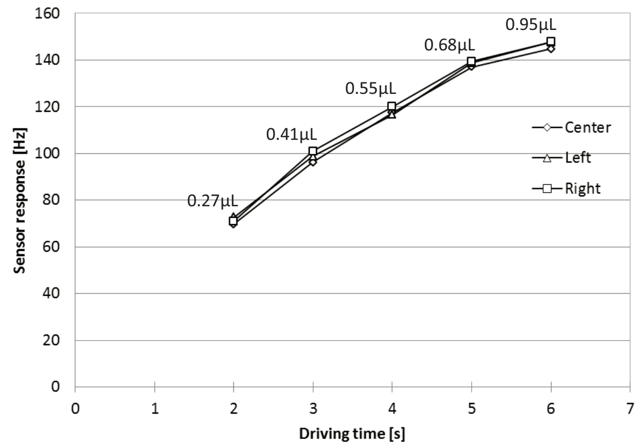

Figure 15. Comparison of the sensor responses when droplets were put onto the center and the right side of the SAW device.

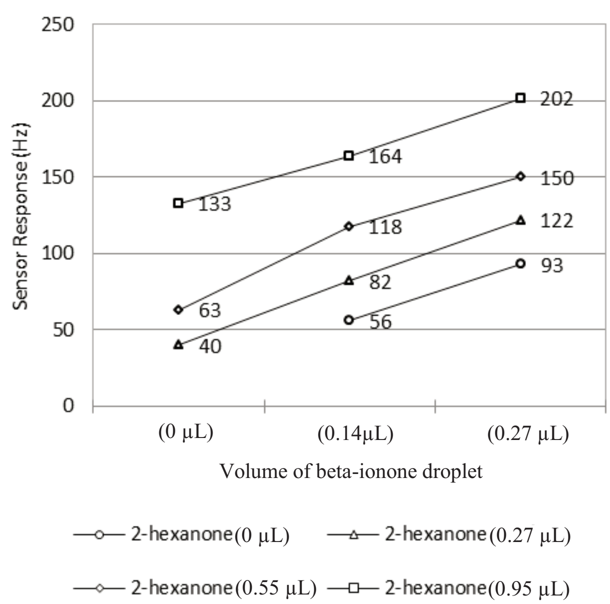

Figure 16. Superposition characteristic of binary-mixture presentation using proposed olfactory display.

5 CONCLUSION

In the present study, the olfactory display, utilizing SAW streaming to atomize liquid-phase odor sample forcibly to present smell, composed of a miniaturized EO pump and a SAW device was proposed. Several oriented validations were performed numerically to achieve its several key characteristics mentioned in introduction using an odor sensing system. As a result, we showed that the scents of substances with wide variety of volatility can be generated abruptly and then disappear within a short time. Even the scents of low-volatile substances can be quickly presented and eliminated while its presentation is difficult using almost other techniques. The reproducibility of the amount of presented odors was also confirmed. Furthermore, the abilities to control the odor intensity and to blend smells were successfully realized by adjusting the driving parameters and by using a few EO pumps together. Moreover, as the device works soundlessly and does not radiate heat to the nearby environment, and its size is small and thin, it is expected to be integrated into other electronic apparatus in the near future to enhance the realistic feeling and enable more applications using olfaction information.

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