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Development of a Shear Horizontal Surface Acoustic Wave Sensor System for Liquids with a Floating Electrode Unidirectional Transducer

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The development of sensors using surface acoustic wave (SAW) devices has been attracting attention. A shear horizontal SAW (SH-SAW) sensor can detect the properties and chemical reactions in liquids. To realize practical applications of the SAW sensor, it is necessary to discuss its properties. In this paper, SH-SAW sensors with a floating electrode unidirectional transducer (FEUDT) or an interdigital transducer (IDT) are compared and the insertion loss and phase characteristics are measured. Also, the phase shift between sample and reference liquids is evaluated. The results indicate that the SH-SAW sensor with the FEUDT is suitable for liquid measurements. The SH-SAW sensor with the FEUDT is then mounted in a newly developed SH-SAW sensing system. The system configuration is the same as that of a vector voltmeter measurement system. However, circuits have been developed that reduce its size. Using this system, several liquids are measured. The obtained results agree well with the theoretical values. [DOI: 10.1143/JJAP.47.4065]

KEYWORDS: shear horizontal surface acoustic wave (SH-SAW), SH-SAW sensor, floating electrode unidirectional transducer, phase distortion, sensing system

1. Introduction

A shear horizontal surface acoustic wave (SH-SAW) has been applied as a practical SAW device.[1,2] Also, the SH-SAW device is used as a liquid-phase sensor.[3,4] If a liquid is loaded on the Rayleigh-SAW propagating surface, a longitudinal wave is radiated into the liquid.[5,6] Therefore, the SH mode must be used to realize an acoustic-wave-based sensor for liquid. Several SH-mode acoustic wave sensors, such as the thickness shear mode (TSM), the SH acoustic plate mode (SH-APM), and the Love wave, have been used as a liquid-phase sensor.[7] The detection mechanisms are based on mechanical and electrical perturbations. The mass loading effect onto the acoustic wave sensor and the product of the density and viscosity of the adjacent liquid are detected by the mechanical perturbation (or mechanical interaction), whereas the conductivity and dielectric constant of the adjacent liquid are detected by the electrical perturbation (or electrical interaction). A 36YX-LiTaO$_3$ substrate is most often used as the SH-SAW sensor substrate.[1,3] A feature of an SH-SAW sensor is the simultaneous detection of the mechanical and electrical properties of a liquid with high sensitivity.

Many sensors, such as mechanical, optical, electrical, and electrochemical-based sensors, have been investigated and commercialized. However, only the SH-SAW sensor can detect mechanical and electrical properties, simultaneously. Therefore, it is important to realize an SH-SAW sensing system. To develop such a system, there are two major tasks. One is to improve the phase property. Reibel *et al.* reported that the frequency shift depended on the phase position.[8] The other is the development of a smart, portable, and inexpensive sensing system. Normally, an oscillation circuit is used for an acoustic wave sensor circuit. Kondoh *et al.* also developed an SH-SAW sensing system with an oscillation circuit.[9] However, for practical applications, we consider that the phase measurement can be adopted to determine the properties of a liquid.[10] In this paper, we describe our approaches to these problems: first, to improve the phase property, a floating electrode unidirectional transducer (FEUDT) is used for generating and receiving the SAW. Second, a SAW sensing system for detecting the phase and amplitude is developed. The SH-SAW sensor with the FEUDT is compared with a sensor with a conventional interdigital transducer (IDT) and the feasibility of the former is confirmed through experiments. Several liquids are measured using the developed SAW sensing system and reasonable results are obtained.

2. Floating Electrode Unidirectional Transducer

An acoustic wave that propagates in or on a piezoelectric material is a coupling wave consisting of strain and an electrical potential. When an SH-SAW propagation surface is in contact with a liquid, evanescent fields of an SH displacement and a piezoelectric potential extend outside from the surface. The evanescent fields are affected by the external properties. These changes of evanescent field profiles lead to measurable changes of the velocity and amplitude of the SH-SAW. The changes in the wave are measured as a frequency shift or phase shift, and an amplitude change, respectively. If the phase property of the device has distortion, as illustrated in Fig. 1, the frequency and phase shifts depend on the phase position and frequency.[8] The main causes of distortion appear to be reflection from the edge of the device and a triple transit echo (TTE). These signals are spurious components, thus it is necessary to reduce them. Figure 2 shows our previous SH-SAW sensor.[11] To reduce reflection from the edge, we coated it with epoxy resin. Figure 2(b) shows the insertion loss and phase as a function of frequency. Whereas the TTE is not reduced, phase distortion is reduced. However, as the fabrication of the SH-SAW sensor shown in the figure is

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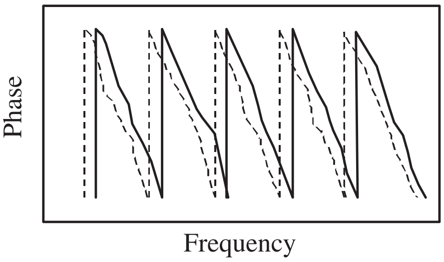
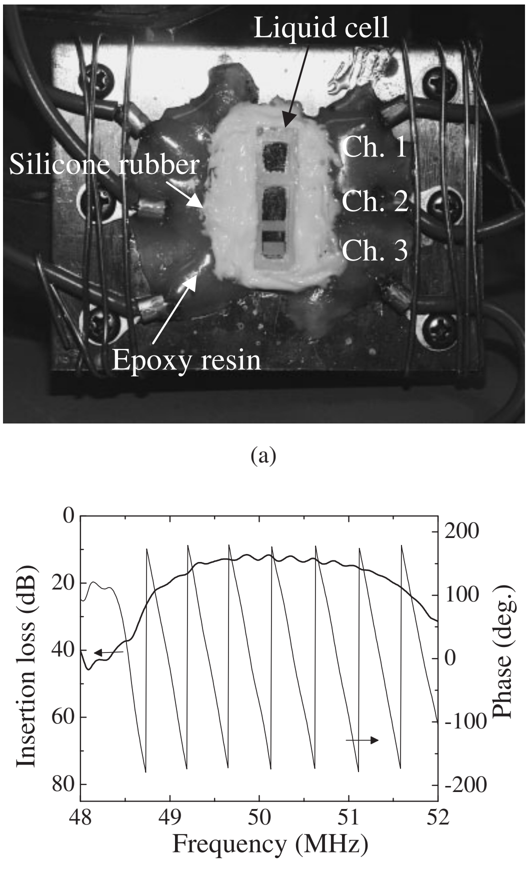


Fig. 1. Schematic illustration of phase distortion. Solid line: before perturbation and dashed line: after perturbation.



(a)

(b)

Fig. 2. (a) Photograph of the previous SH-SAW sensor.[11] (b) Insertion loss and phase as a function of frequency.

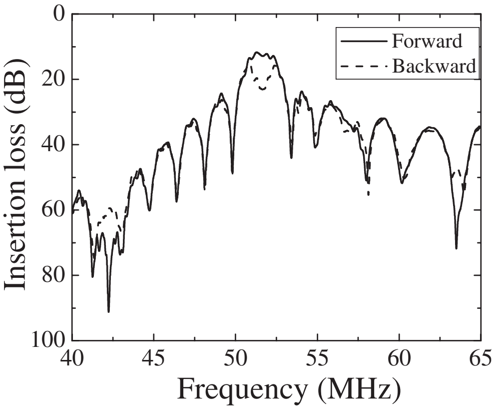


Fig. 3. Frequency characteristics of the SH-SAW device on 36*YX*-$LiTaO_3$.

Table I. Insertion loss at center frequency when the SH-SAW propagating surface is in contact with air or water and is free (open) or metallized (shorted).

	Air (dB)	Water (dB)
Metallized	6.21	7.53
Free	14.6	6.14

complicated, the sensor was not adapted for practical applications. Therefore, we considered sensor configurations that reduce phase distortion and the TTE. Double electrode structures have been utilized to reduce phase distortion.[12] In addition, to realizing a practical sensing system, a low-loss device is desirable, because loss increases upon loading the liquid and lower electricity consumption in the circuits is achieved. Unidirectional transducers are proposed to improve the characteristics of the SAW device. An FEUDT[13] is such a transducer. Yamanouchi and Furuyashiki reported that an FEUDT with open and shorted strips on a 128*YX*-$LiNbO_3$ substrate has good directivity.[13] Takeuchi and coworkers performed a field analysis of an FEUDT and pointed out that an FEUDT with open and shorted strips has high directivity when it is fabricated on a piezoelectric crystal with a high electromechanical coupling coefficient.[14,15] A 36*YX*-$LiTaO_3$ substrate was used as an SH-SAW sensor substrate with a high electromechanical coupling coefficient. Therefore, in this paper, we used an FEUDT with open and shorted strips for the SH-SAW sensor. The design parameters of the FEUDT are as follows: the center frequency is 51.5 MHz, the aperture is 2 mm, the number of pairs is 32, and the propagation length is 11 mm. As there are no reports on FEUDTs on a 36*YX*-$LiTaO_3$ substrate, the directivity was first measured. The FEUDT and two IDTs were fabricated on the 36*YX*-$LiTaO_3$ substrate. The FEUDT was located between the IDTs. Figure 3 shows the frequency characteristics obtained without a matching circuit. A directional property is observed and the directivity is 10.44 dB. Then, we fabricated the SH-SAW sensor with the FEUDT. The insertion losses at the center frequency are summarized in Table I. For the free surface, the insertion loss improved when water was loaded on the propagating surface. The surface skimming bulk wave[16] is suppressed when water is loaded on the free surface. The table indicates that a low-loss device has been realized. In the next section, the fundamental properties of SAW sensors with an FEUDT or IDT are compared.

3. Comparison of SH-SAW Sensors with FEUDT or IDT

The comparison of the SH-SAW sensors with an FEUDT or IDT was carried out using a network analyzer (Agilent E4991A). A liquid cell was loaded on the SAW propagating surface (see Fig. 4). Hereafter, the SH-SAW sensor with the FEUDT is called an FEUDT-SAW and the SH-SAW sensor with the IDT is called an IDT-SAW. The SH-SAW sensor was used to detect electrical properties. It has a free surface area where a potential interacts with the liquid. For the FEUDT-SAW, a matching circuit was used.

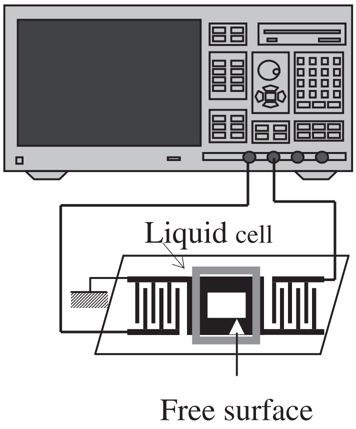
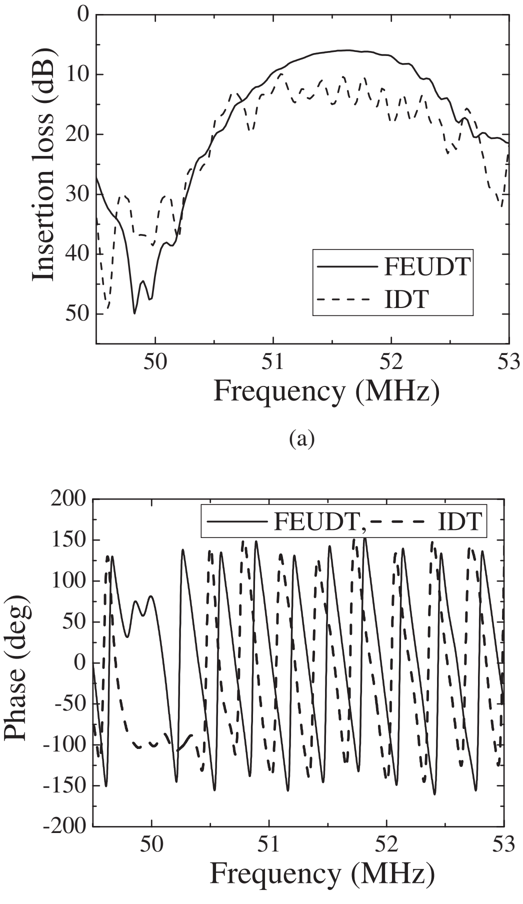


Fig. 4. Experimental setup using network analyzer.



(a)

(b)

Fig. 5. (a) Insertion loss and (b) phase response of the FEUDT-SAW and IDT-SAW. The propagating surface is free and distilled water is loaded on the propagating surface.

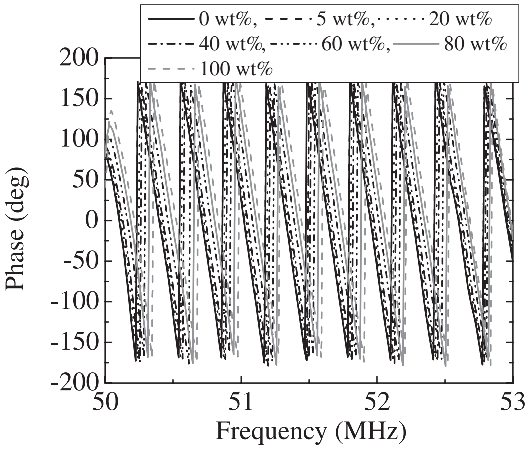


Fig. 6. Sensor responses of the FEUDT-SAW sensor for ethanol/water mixture.

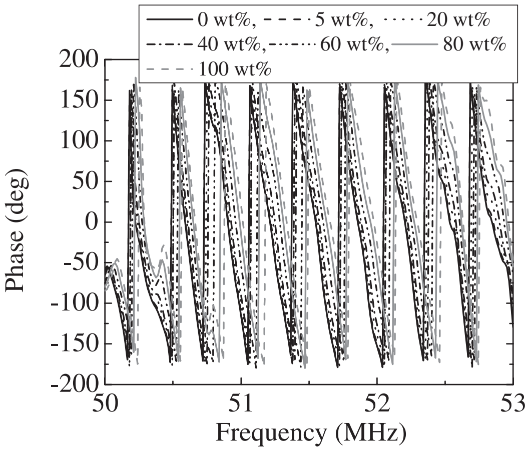


Fig. 7. Sensor responses of the IDT-SAW sensor for ethanol/water mixture.

The fundamental properties of the FEUDT-SAW and IDT-SAW are shown in Fig. 5. Distilled water is loaded on the sensing surface. Note that the IDT-SAW was fabricated in house and was not covered by silicone rubber and epoxy as shown in Fig. 2. Also, its properties are not optimal. The insertion loss is improved and the TTE is reduced using the FEUDT. Also, a good phase property is realized. One application of the SH-SAW sensor is as a methanol sensor for a direct methanol fuel cell.[17] As the change in dielectric constant is monitored, in this paper, an ethanol/water mixture was used as a sample solution. A sample was injected into the liquid cell and was measured using the network analyzer. Both frequency and phase characteristics were observed. In this paper, however, only phase responses are shown (Figs. 6 and 7). From the figure, the changes in the sensor response by changing the concentration are not clear. As the phase shift is normally monitored,[3] the phase shift between the sample solutions and distilled water was calculated. The results are plotted in Fig. 8. For the FEUDT-SAW, the phase shift is constant around the center frequency. On the other hand, for the IDT-SAW, it is not constant because of the ripple and phase distortion, as shown in Fig. 5. Similar results are obtained for glucose/water mixture solutions[18] and aqueous potassium chloride solutions. Therefore, the phase distortion and insertion loss are improved using the FEUDT.

4. Development of SH-SAW Sensing System

A new SH-SAW sensing system was fabricated. The idea of the sensing system is to reduce the size of the vector voltmeter measurement system. Figure 9(a) shows a sche-

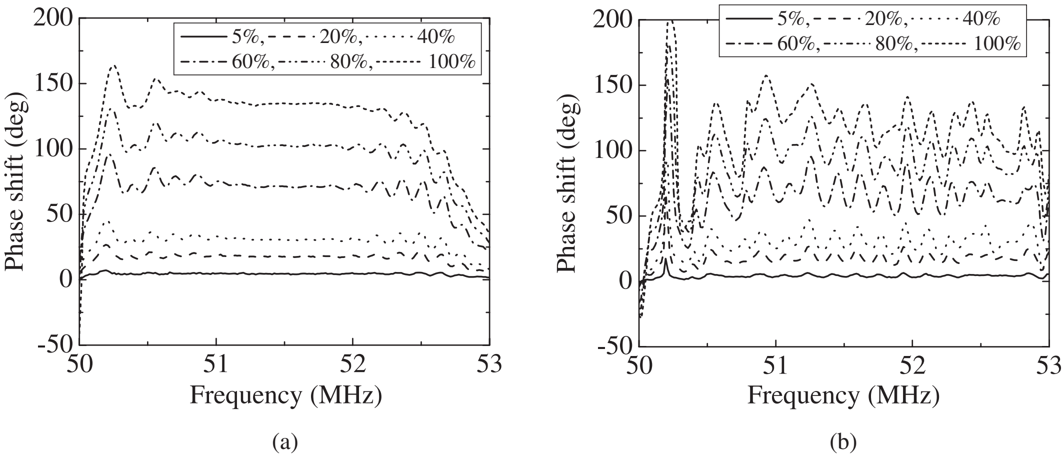


Fig. 8. Phase shift between sample solution and distilled water as a function of frequency. (a) FEUDT and (b) IDT-SAW.

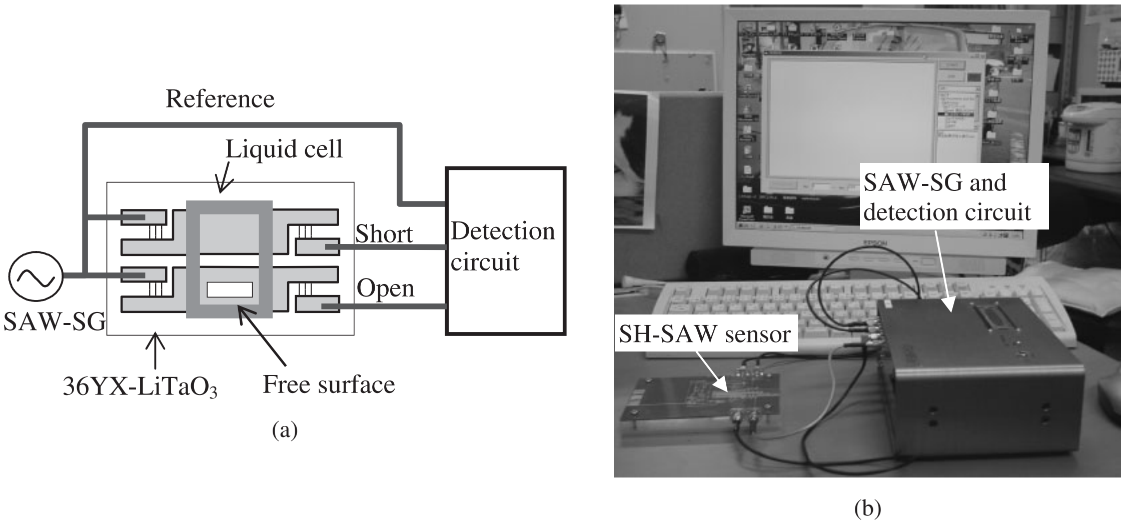
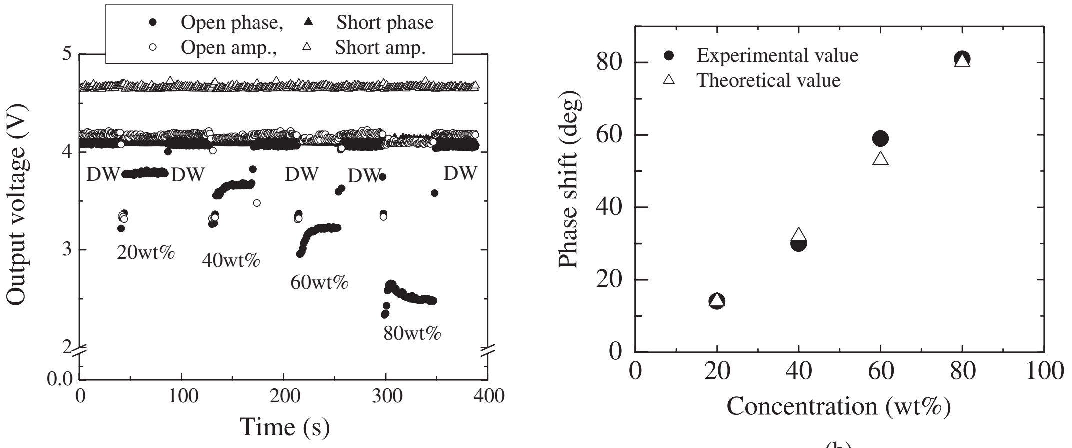


Fig. 9. (a) Schematic diagram of the developed SH-SAW sensing system and (b) photograph. SG: signal generator.

matic diagram of the sensing system. The signal generator was replaced by a SAW signal generator, and a phase shift and amplitude detection circuit was fabricated in place of the vector voltmeter. The phase detection method used is a heterodyne method.[19] Figure 9(b) shows a photograph of the fabricated sensing system. The SAW signal generator and measurement circuit are stored in the case. Output signals from the measurement circuit are connected to a PC via an analog–digital (AD) converter. The FEUDT-SAW was used in the developed sensing system. The sensor configuration was used to detect the electrical properties.[3,4,17] The sensor constituted two delay lines. The propagating surface of one delay line is metallized and electrically shorted. The other has a free surface area. Using the measurement circuit, the amplitudes of the shorted and open channels were monitored. Also the phase shifts between the SAW signal generator and the shorted or open channels were monitored. The frequency of the SAW signal generator was fixed at 51.3 MHz. The reference liquid was distilled water. Figure 10(a) shows the time responses obtained from the ethanol/water mixture measurements. The phase shift between reference and sample liquids was obtained from Fig. 10(a) using a calibration equation between the phase and the output voltage. The saturation value of output voltage was used to derive the phase. The results are shown in Fig. 10(b). Also, theoretical values[3,4] are plotted on the same figure. The responses from the developed system agree well with the theoretical values.

5. Conclusions

The commercialization of the SH-SAW sensing system is important because it has excellent potential for liquid characterization. For this purpose, its phase property is discussed. To improve the phase characteristics, an FEUDT is adopted and an FEUDT-SAW is compared with an IDT-SAW. The results indicate that the FEUDT-SAW has superior liquid-sensing performance. Using the FEUDT-SAW, an SH-SAW sensing system is developed. The detection mechanism of the system is the same as that of the vector voltmeter measurement system. Several samples are measured using the developed system. The obtained results agree well with the theoretical values. Therefore, we conclude that the developed SH-SAW sensing system can be used for the detection of liquid properties.



(a)

(b)

Fig. 10. (a) Time responses from the sensing system. The legend and the concentrations of the samples are shown in the figure. DW: distilled water. (b) Phase shift as a function of ethanol concentration.

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