Identification of taste solutions and their binary mixtures using SH-SAW resonator-based taste sensor

M. Cole, I.I. Leonte and J.W. Gardner
School of Engineering, University of Warwick
Coventry, UK
M.Cole@warwick.ac.uk

P. Hesketh
Department of Mechanical Engineering
Georgia Institute of Technology
Atlanta, USA

***Abstract* — A novel two-port resonator-based shear-horizontal surface acoustic wave (SH-SAW) sensor has been designed for liquid analysis. The device operates at a wireless ISM frequency of 434 MHz and is built on a 36° YX $LiTaO_3$ piezoelectric substrate. It relies on a purely physical detection mechanism and it has been designed to function without the need for analyte-specific coatings. The sensor proved successful in identification of all six tastes: alongside the four classical tastes – saltiness, sweetness, sourness, and bitterness - test samples included solutions simulating the umami and metallic tastes. The taste sensor was also able to separate between samples of the same taste class (e.g. caffeine and quinine hydrochloride of the bitter class) as well as to detect and classify samples of the same substance with different concentrations. Furthermore, the potential to identify binary mixtures and separate them from original component solutions was tested and confirmed experimentally.**

I. Introduction

Taste sensors for liquid analysis have steadily developed over the last few years partly because of their potential applications in the food and beverage industries, and clinical and environmental sectors.

Artificial taste sensors are often referred in scientific literature as "electronic tongues" [1, 2]. They are usually based on electrochemical techniques and composed of several kinds of ion selective electrodes/membranes that convert information of taste substances into electronic signal. The sensors will have different output patterns for chemical substances with different taste qualities such as saltiness and sourness. Based on this principle the taste of liquid foods such as beer, coffee, mineral water, wine, milk, etc. can be discussed quantitatively [3]. By far the most common types of taste sensors used are based on techniques such as potentiometry and voltammetry [4-5]. Potentiometric sensors employ zero-current and utilise either ion selective lipid membranes or ion selective electrodes, and the potential at the working electrode caused by the ion exchange reaction is measured. Voltametric (amperometric) electronic tongues employ a potential to drive an electrode transfer reaction, and the resulting current, which depends on the concentration of the sample, is measured.

Good overviews of the research and development in the field of electronic tongue systems, their different principles of operations and their analytical applications have been publishes in literature [6, 7].

The work described in this paper is based on a shear-horizontal surface acoustic wave (SH-SAW) sensor with no bio-chemical layers, thus relying on a purely physical, rather than electrochemical principle of operation. The resulting device is not just small in size but also is more robust and durable than electrochemical sensors.

The proposed resonator sensor was employed for analysis of several taste solutions and results are presented. The sensor proved successful in identification of six liquid samples: alongside the four classical tastes - saltiness, sweetness, sourness, and bitterness - test samples included aqueous solutions simulating the umami and metallic tastes. The sensor was also able to separate between solutions of the same taste class (e.g. caffeine and quinine hydrochloride of the bitter class) as well as to detect and classify samples with different concentrations. Furthermore, the sensor was exposed to binary mixtures of taste solutions and proved successful in discriminating them and separating form original solutions.

II. SH-SAW Two Port Resonator Sensor

The resonator sensor configuration proposed in this paper has an electrically free cavity, thus the sensor output is a complex combination of both mechanical and acousto-electrical effects. Generally, the sensor's amplitude - A and phase response - Φ, can be expressed as a complex function of the liquid physical properties, e.g. viscosity - η, density - ρ, electrical conductivity - σ, dielectric permittivity - ε and temperature - T as:

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$$A, \Phi = f(\eta, \rho, \sigma, \varepsilon, T)$$

A picture of the two-port resonator sensor is shown in Figure 1.

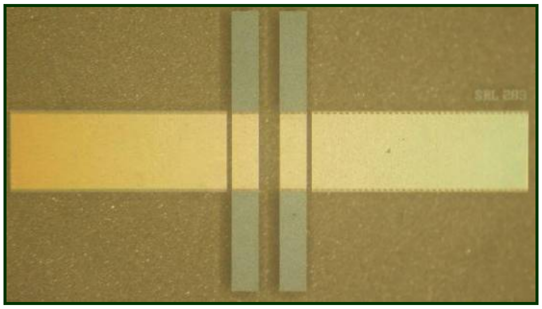

Figure 1. Photograph of the two-port resonator with the overall dimensions of 4600 µm x 3000 µm

Input and output IDTs are identical, having an acoustic aperture of 800 µm and 2.4 µm finger width. The resonating cavity is 192 µm (20 λ) wide and the reflectors on each side of the IDTs consist of 400 strips (positive and negative reflectors) of 2.4 µm pitch. Overall die dimensions are 4600 µm×3000 µm. The sensor was built on a 36° YX $LiTaO_3$ piezoelectric substrate.

The two-port resonator sensor was used in a similar experimental set-up mode to that of a delay line sensor [10]. Electrical measurements were performed with a network analyser (Agilent 8753ES) and amplitude and phase information have been recorded for each measurement. A microstereolithography (MSL) liquid reservoir was placed on top of the sensor to host the test sample.

III. Identification of Taste Solutions

The resonator sensor was employed for analysis of a variety of liquid taste samples as follows:

A. Basic taste solutions

Initial tests were focused on identifying and classifying basic taste solutions with a 0.1 molar concentration. Previous results reported on SH-SAW sensors [8, 9] focused on the four tastes: sweet, salty, sour and bitter. While these are the classical basic tastes, scientists have also accepted the existence of a fifth basic taste called umami (MSG), described as savoury or meaty. The metallic taste (Cu^{2+}, $FeSO_4$ or blood in the mouth) is considered more of a 'taste sensation' rather than a taste per se and is generally associated with a response from the olfactory receptors. Nevertheless, it is often included in taste investigations on its own or in various combinations. To ensure a complete analysis of the resonator's sensing capabilities, it was tested with samples representing the six-extended tastes, where umami and the metallic tastes were added to the four classical ones.

The six liquid samples representing the basic tastes chosen for initial tests were: saline, sucrose, quinine hydrochloride, acetic acid, umami (MSG) and metallic taste ($FeSO_4$) solutions. All the taste solutions for this first set of experiments were made with 0.1 molar concentrations. The sweet solution was prepared dissolving sucrose in DI water, for the salty solution sodium chloride was used, bitter sample was made with quinine hydrochloride and sour taste solution was obtained from acetic acid. The fifth umami solution has been prepared using monosodium glutamate (MSG) and the solution simulating the metallic taste/sensation has been made with iron sulphate ($FeSO_4$). A 0.1 molar caffeine solution and a lower concentration of 0.01 molar quinine hydrochloride solutions have also been included in the first set of experiments.

All of the liquid samples were tested with the resonator sensor in a random sequence. In between two test samples a substantial volume of distilled water was flown through the liquid cell to clean the sensor's surface. Measurements were carried out at the peak frequency [10] and at a constant frequency of 434.7 MHz corresponding to the peak frequency measured in air. The experimental results obtained when the network analyser was set to measure amplitude and phase of the sensor's response at 434.7 MHz are presented as scattered plots in Figure 2.

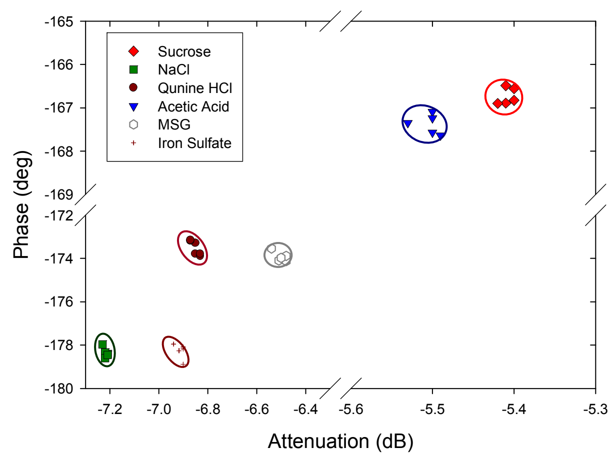

Figure 2. Typical plot showing basic tastes clusters

Figure 2 illustrates a clear clustering of the results around locations specific to each substance, and moreover, shows 100% discrimination between characteristic clusters.

Subsequent experiments were performed to determine whether the resonator is able to separate between samples within the same taste family. Three samples made with caffeine 0.1 mol and two quinine hydrochloride samples with 0.1 mol and 0.01 mol concentrations were chosen to test the sensor's ability to detect solutions belonging to the bitter taste class (Figure 3).

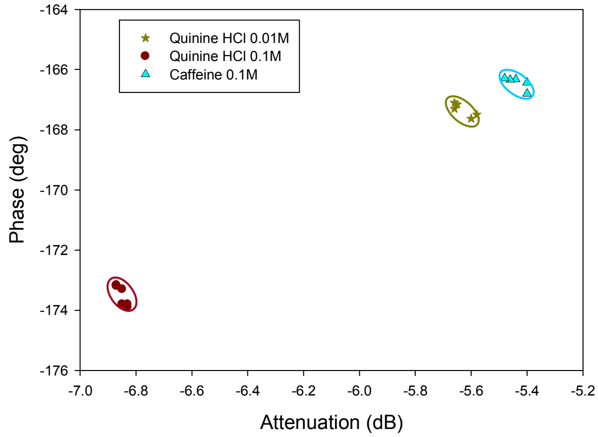

Figure 3. Bitter solutions clusters

By comparing different taste substances, caffeine and quinine hydrochloride, with same concentrations (0.1 mol) shown in Figure 3, it can be seen that they cluster wide apart in opposite corners of the plots. This implies that clustering is achieved according to the physical properties of the sample rather than taste class itself, and thus sample classification can be achieved as an indirect consequence of measuring different physical properties of the taste solutions.

B. Taste solutions with varying concentration

Further experiments were conducted on selected taste solutions with different weight/molar concentrations. The purpose of this set of tests was to further investigate the sensor's ability to differentiate betweens solutions of the same substance in different concentrations as well as to identify patterns in the sensor response related to substance concentration.

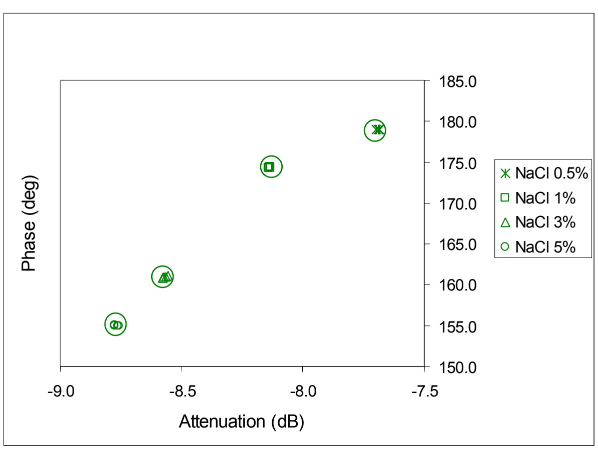

Figure 4. Scatter plot showing discrimination of different concentrations of NaCl solutions

Sodium chloride solutions show clear clustering and linear responses in both amplitude and phase. Again a 100% discrimination is achieved as it can be seen in Figure 4.

C. Binary mixtures of taste solutions

Finally, selected taste solutions were mixed with each other and experiments were performed on solutions combining two fundamental tastes. Equal quantities of acetic acid (AA), sucrose (S) and sodium chloride (NaCl) solutions with the same concentration were mixed to obtain three binary mixtures: AA+S, AA+NaCl and NaCl+S. Two weight concentrations of 1% and 5% were considered for each original solution and the correspondent binary mixtures were annotated according to the weight percent of the constituent solutions.

Figure 5 shoes that binary mixtures samples also cluster well in the attenuation-phase plane and a distinctive separation between the clusters can be observed. The relative location of the mixtures seems to be determined by the new properties of the solution derived from the binary combination. Sodium chloride tends to dominate the properties of its mixtures, as seen by the relative close proximity of its clusters. While still individually separable, the AA+NaCl 1% and NaCl+S 1% clusters are significantly closer to each other than to any other data cluster; similarly AA+NaCl 5% and NaCl+S 5% have neighbouring locations in the positive range of the plot.

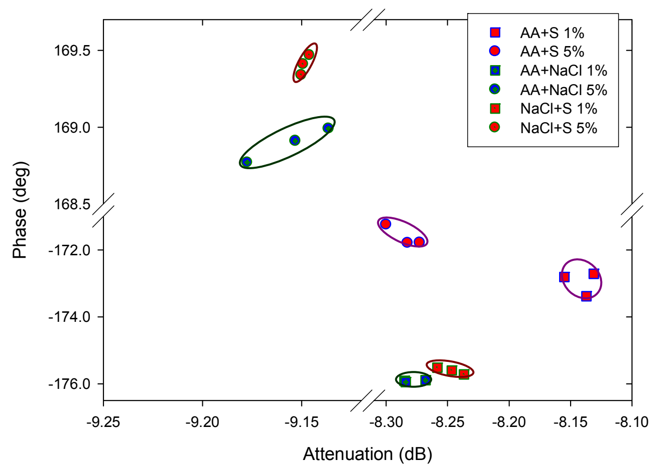

Figure 5. Binary mixtures of solutions

The mixtures and basic solutions combined plot shows that the binary mixtures cluster well apart from their constituent samples, suggesting that the properties of the mixtures which are sufficiently different from the properties of the individual components for the sensor to respond with significant output changes. A typical plot of basic taste solutions and their binary mixtures is shown in Figure 6.

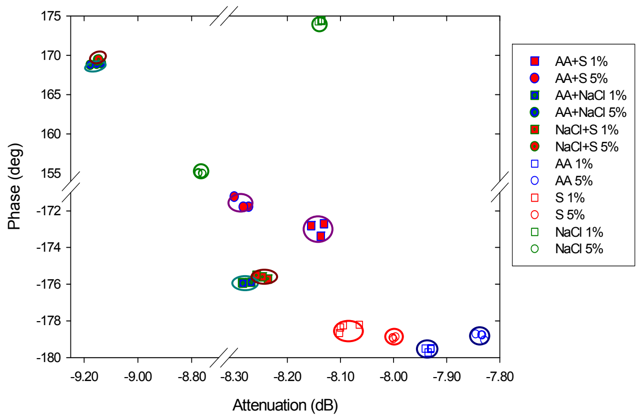

Figure 6. Typical plot showing discrimination of basic taste solutions and their binary mixtures

IV. Conclusions

The SH-SAW resonator-based sensor has been developed for liquid analysis and its capability for successful classification of liquid samples associated with different basic tastes has been demonstrated. Clear clustering, demonstrating 100% discrimination, of all six 0.1 M taste samples was observed. The sensor also has the ability to separate and identify samples belonging to the same taste class (i.e. quinine and caffeine of the bitter taste family). The capability to measure liquid samples with varying concentrations has been demonstrated as well as the ability to detect binary mixtures of taste solutions and to separate them from original component solutions.

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