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# High sensitivity Love-mode liquid density sensors

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**Abstract**

An experimental study into Love-mode liquid sensors using polyimide for a waveguide layer has been carried out. Love devices were built on Y-ST quartz with 40 μm wavelength inter-digitated transducers operating up to 124.7 MHz, and polyimide layers between 0.65 and 1.5 μm thick. The optimum polyimide thickness was 0.85 μm exhibiting a minimum insertion loss of 16 dB. Surface corrugations from 2.5 μm wide and 0.5 μm deep were etched in the polyimide to discriminate the liquid density from the square root of the density–viscosity product. A maximum sensitivity of up to 0.36 $\mu g\,cm^{-3}\,Hz^{-1}$ has been obtained, a higher value than found in most other studies.


*Keywords:* Love; SAW; Polyimide; Liquid density sensor

## 1. Introduction

SAW devices were initially developed for high frequency filtering applications in electronics, but the surface nature of the wave has made them important in the field of sensing [1]. The sensitivity and resolution of acoustic sensors are dependent on their operating frequency. For bulk-wave sensors such as the quartz crystal microbalance (QCM) this is limited to a few MHz due to practical substrate thickness limits, although higher frequencies can be achieved through using micromachining techniques to produce thin membranes [2]. For SAW devices, the maximum frequency is determined by the electrode dimensions allowing frequencies up to around 2 GHz with conventional lithography techniques. SAW sensors typically operate in the region 100–500 MHz, giving high sensitivity and resolution with acceptable noise levels, and simple control electronics.

By physically changing the propagation path with some external influence, the change in SAW frequency and attenuation can be monitored. Exploiting the stress dependence of the piezoelectric substrates allows the construction of stress sensors including pressure sensors using a membrane structure. Temperature dependent substrates allow the fabrication of high-resolution temperature sensors. Surface loading of the SAW propagation path perturbs the wave allowing the monitoring of mass deposition. These mass loading sensors are used extensively for bio and chemical sensing, with chemically selective surfaces discriminating between different substances [3,4].

The surface-normal transverse wave component of Rayleigh waves makes them unsuitable for sensing in liquid environments. Large compressional losses into the liquid give high attenuation. Shear-horizontal SAWs (SH-SAW) are formed by rotating the substrate to exploit the shear piezoelectric coefficients. This gives a transverse wave component, which lies in the surface plane, thus reducing compressional losses into liquids.

Love-modes (also known as guided SH-SAW) offer the highest sensitivity of all acoustic modes [5,6]. They are formed by focussing the surface wave into a thin waveguide layer coated on the device's surface, which has a lower acoustic velocity than the substrate. Sample liquids are viscously entrained with the wave motion, perturbing the wave without causing large losses. An additional advantage for liquid applications is the protection and insulation of the electrodes by the waveguide, allowing submersion of the device surface.

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## 2. Theory

The formation of the Love-mode is dependent on the waveguide layer normalised thickness $h/\lambda$ where $h$ is the layer thickness and $\lambda$ the SAW wavelength. If the layer is too thin, a large proportion of the wave energy remains in the substrate, giving a low energy density near the surface. If too thick, the acoustic field is contained within, but dispersed throughout the waveguide thickness, again giving a low surface energy density. With the correct thickness, the energy is almost entirely focussed within the layer, giving a high surface energy density, coupling strongly to any surface loading. This is the optimum waveguiding of the field.

The ratio of the waveguide and substrate acoustic velocities, $V_w$, and $V_s$, determines $h/\lambda$. To keep the analysis simple, the piezoelectric properties of the substrate can be neglected, and the waveguide layer and substrate can be considered as isotropic. This can be justified due to the confinement of the Love wave into the isotropic waveguide. In this case, the acoustic velocity is related to the elasticity and density as $V = \sqrt{E/\rho}$, where $E$ is the modulus of elasticity and $\rho$ the density. The smaller the ratio $V_w/V_s$ becomes, the greater the focussing effect of the waveguide resulting in smaller thicknesses. With thinner layers, the surface energy density is higher resulting in a higher sensitivity to external perturbations.

Glassy materials such as chemical vapour deposited $SiO_2$ have been extensively investigated for the waveguide layer [7–9]. They have a relatively large $E$ and thus typically require thicker layers (2–6 μm for $SiO_2$) with relatively low sensitivity but small acoustic losses. Polymers on the other hand have a small $E$ resulting in a small $h/\lambda$ and thus high sensitivity, but the polymer-like nature results in larger acoustic losses within the material [10–13]. The densities are usually similar and thus have little effect. Table 1 illustrates these properties. Our study looks at using polyimide as a high sensitivity Love-mode waveguide layer. The material is durable, chemically inert, and should offer cost efficient and simple fabrication. The devices presented here consist of a dual delay line structure, one with a smooth surface and one with a patterned surface, which can be used to discriminate the liquid density [7,14]. The differential response from the dual delay line structure should help to prevent unwanted responses due to other external influences such as temperature and stress, etc.

The loading of Love-mode devices can be analysed using perturbation theory [15]. By considering the complex wave propagation constant $\gamma = \alpha + i\beta$ with the attenuation component $\alpha$ and the phase component $\beta$, we can relate the liquid loading to insertion loss and frequency changes. Love-modes are dispersive, meaning that the phase velocity $V_{ph}$ of the wave is not always equal to the group velocity $V_{gr}$. For very thin waveguides, $V_{ph} \approx V_{gr}$, and both approach the substrate velocity $V_s$ with the majority of the field in the substrate, and for thick waveguides, both $V_{ph}$ and $V_{gr}$ are approximately equal to $V_w$. For the intermediate state, $V_{ph}$ is greater than $V_{gr}$ meaning that the change in frequency of a device is not the same as the change in propagation constant $\beta$ [16].

Table 1
Relative properties of glassy and polymer-like waveguides

| Property | Glassy | Polymer |
|---|---|---|
| Elasticity modulus, $E$ | High | Low |
| Density, $\rho$ | Similar | |
| Wave velocity, $V_w = (E/\rho)^{0.5}$ | High | Low |
| Thickness, $h \propto V_w$ | Thick | Thin |
| Sensitivity, $S \propto h^{-1}$ | Low | High |
| Losses | Low (good) | High (poor) |

For a thin film of liquid with no viscous entrainment with the SAW, we can consider the perturbation purely in terms of mass loading. This affects the phase propagation only, giving a change in peak frequency:

$$\frac{\Delta f}{f} = S_f \omega \frac{m}{A} \tag{1}$$

where $S_f$ is the sensitivity (in terms of frequency), $\omega$ the SAW angular frequency, and $m/A$ the loaded mass per unit area.When the liquid becomes viscously entrained with the SAW, there is a change in both $\alpha$ and $\beta$, resulting in additional attenuation and viscous coupling. The response in terms of frequency is:

$$\frac{\Delta f}{f} = S_f \sqrt{\frac{\omega \eta \rho}{2}} \tag{2}$$

where $\eta$ is the liquid viscosity. This assumes the liquid behaves in a Newtonian manner with a viscosity independent of frequency.

The devices presented here are a dual-delay line structure. One delay line is smooth and couples with the liquid viscoelastically, thus giving a frequency shift proportional to the square root of the density–viscosity product. The other delay line surface is patterned with corrugations to trap the liquid, thus preventing viscous entrainment. The corrugations are aligned in the wave propagation direction to prevent the horizontal shear motion of the liquid coupled to the shear wave. This results in mass loading of the liquid in addition to the viscous loading effects. The difference in relative frequencies between the two delay lines can thus be used to separate the density from the square root of the liquid density–viscosity product as shown in (3) [7].

$$\left(\frac{\Delta f}{f}\right)_{\text{patterned}} - \left(\frac{\Delta f}{f}\right)_{\text{smooth}} \propto -S_d \rho \omega G \tag{3}$$

The volume of the trapped liquid is represented by $G$, a geometrical factor describing the depth and width of the liquid traps. The sensitivity term $S_d$ describes the sensitivity of the device to the liquid density and is different to the sensitivities in (1) and (2). This relation assumes that the two delay lines are only affected by viscous and mass loading as described in (1) and (2). The corrugations may introduce additional electrical loading by placing the sample liquid closer to the IDTs, but this has been neglected to simplify the analysis.